

Gaussian Herding across Pens: An Optimal Transport Perspective on Global Gaussian Reduction for 3DGS

Tao Wang^{1*} Mengyu Li^{2*} Geduo Zeng¹ Cheng Meng^{1†} Qiong Zhang^{1†}

¹Center for Applied Statistics, Institute of Statistics and Big Data, Renmin University of China

² Department of Statistics and Data Science, Tsinghua University

wang_tao@ruc.edu.cn mengyuli@tsinghua.edu.cn geduo.zeng@ruc.edu.cn
chengmeng@ruc.edu.cn qiong.zhang@ruc.edu.cn

Abstract

3D Gaussian Splatting (3DGS) has emerged as a powerful technique for radiance field rendering, but it typically requires millions of redundant Gaussian primitives, overwhelming memory and rendering budgets. Existing compaction approaches address this by pruning Gaussians based on heuristic importance scores, without global fidelity guarantee. To bridge this gap, we propose a novel optimal transport perspective that casts 3DGS compaction as global Gaussian mixture reduction. Specifically, we first minimize the composite transport divergence over a KD-tree partition to produce a compact geometric representation, and then decouple appearance from geometry by fine-tuning color and opacity attributes with far fewer Gaussian primitives. Experiments on benchmark datasets show that our method (i) yields negligible loss in rendering quality (PSNR, SSIM, LPIPS) compared to vanilla 3DGS with only 10% Gaussians; and (ii) consistently outperforms state-of-the-art 3DGS compaction techniques. Notably, our method is applicable to any stage of vanilla or accelerated 3DGS pipelines, providing an efficient and agnostic pathway to lightweight neural rendering. The code is publicly available at <https://github.com/DrunkenPoet/GHAP>



Figure 1: **Visual comparison.** When reducing the number of Gaussians by 90%, our method outperforms other compaction techniques, such as PUP-3DGS, and remains competitive with the original 3DGS.

1 Introduction

Real-time 3D scene reconstruction and rendering dynamically generates photorealistic 3D representations from sensor data (e.g., multi-view images, LiDAR) with minimal latency, enabling critical applications in augmented/virtual reality (AR/VR), autonomous navigation, and immersive media [1, 2]. The current state-of-the-art, 3D Gaussian Splatting (3DGS) [3], iteratively learns 3D

anisotropic Gaussian primitives with color and opacity attributes to model these scenes. During rendering, these 3D Gaussians are projected to 2D screens and α -blended to achieve real-time photorealistic synthesis.

However, 3DGS faces significant efficiency challenges: its iterative densification process often produces millions of redundant Gaussians for complex scenes [4, 5, 6]. This inefficiency leads to high memory/storage costs and increased per-frame rendering time, limiting deployment on resource-constrained platforms like mobile and AR/VR devices [7].

A common strategy to improve efficiency is compaction [8, 9, 10, 7]—reducing the number of Gaussians while preserving rendering fidelity. Fewer primitives result in reduced storage needs and faster rendering, improving per-frame performance. This approach is viable because 3DGS densification inherently generates redundant primitives [4, 5, 6]. Existing methods achieve compaction via pruning or random subset selection [11, 12, 5, 13, 14, 15, 6, 4, 16]. These strategies naïvely discard Gaussian primitives; while simple to implement, they are often ineffective. In particular, they tend to lose critical structural details (as shown in Fig. 1) or distort the underlying geometry (as shown in Fig. 2). Such losses can degrade rendering quality, particularly in regions with fine-scale features or complex material properties. These limitations motivate our key question:

How to design an efficient compaction method that preserves 3D spatial and structural geometry?

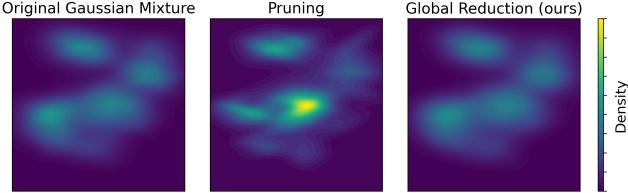


Figure 2: **Comparison of heuristic pruning and our method.** The original mixture (left) with 10^3 components is reduced to 5% using either pruning (middle) or our method (right). Our method better preserves the overall structure.

To address this, we frame compaction as an optimization problem, where the goal is to approximate the original 3DGS representation with fewer Gaussians. Our solution leverages a statistical perspective, treating the scene’s geometric structure as a probabilistic model and employing principled reduction techniques to preserve fidelity.

- (i) **Geometric compaction via GMR.** We first observe that the geometry of a 3DGS representation—defined by the positions, covariances, and opacities of its Gaussian primitives—can be interpreted as a Gaussian mixture model (GMM). Here, the mixture density is a convex combination of individual Gaussian densities, weighted by their opacities. This formulation naturally connects 3DGS compaction to Gaussian Mixture Reduction (GMR), a well-studied problem in statistics where a high-order GMM is approximated by one with fewer components while minimizing a divergence measure.
- (ii) **Appearance optimization.** While geometry is compacted via GMR, the appearance of the scene—governed by the color attributes of the Gaussians—must also be preserved. To achieve this, we decouple the optimization of geometry (position, covariance) and appearance (color, opacity). After GMR-based compaction, we fine-tune the color and opacity of the reduced set of Gaussians using the standard 3DGS training pipeline. This two-stage strategy ensures that the compacted model maintains both geometric accuracy and photorealistic rendering quality.

For GMR, we minimize the composite transportation divergence [17], which is rooted in optimal transport theory [18, 19] and allows an effective algorithm. We tailor this GMR algorithm (detailed in Section 3.2.1) so that it scales well in scenes like 3DGS with an extensive amount of Gaussians. Crucially, our GMR optimizer does not merely select a subset of existing Gaussians; instead, it creates new primitives that can dynamically adjust their positions and covariances to better approximate the underlying geometry (as shown in Figure 2). Our method is fundamentally algorithm-agnostic: it functions as a plug-and-play module that can enhance both the standard 3DGS pipeline and any of its variants (Section 4), applicable at any stage of training to boost computational efficiency.

To summarize, our contributions are:

- We open a new pathway to view 3DGS representations as a Gaussian mixture and perform compaction from the perspective of Gaussian mixture reduction via optimal transport. This contrasts with prior compaction methods that ignore geometric structure and often produce distortions, whereas our approach preserves geometric fidelity, offering a new and impactful direction for 3DGS.
- We are the first to adapt GMR to 3DGS. We introduce a novel cost function that yields closed-form, low-cost updates. We also develop a block-wise GMR algorithm guided by a KD-tree, enabling efficient large-scale scene compaction. These strategies are non-trivial and bridges theory with practical scalability.
- Our method is post-hoc and compatible with any existing 3DGS pipeline, making it highly practical and broadly applicable. With minimal overhead, our approach achieves SOTA compaction performance, both in quality and efficiency.
- Empirical results demonstrate that our method preserves rendering quality at 10% retention ratio.

2 Related Works

Compaction Techniques in 3DGS. 3DGS compaction seeks to minimize the Gaussian count while preserving image quality. Existing work falls into two operations: densification (where to add) and pruning (what to drop). Most current approaches rely on per-Gaussian heuristic scores.

For densification, Taming-3DGS [10] ranks candidate Gaussians by combining gradient, pixel coverage, per-view saliency, and core attributes including opacity, depth, and scale; Color-cued GS [20] considers the view-independent spherical harmonics coefficient gradient to better capture color cues; and GaussianPro [9] guides growth using depth and normal maps. In the pruning phase, LightGaussian [11], Mini-Splatting [12], RadSplat [5], and AtomGS [13] compute an importance score from each Gaussian’s accumulated ray contribution, typically a mix of volume, opacity, transmittance, and hit count, and discard the lowest-ranked Gaussians. Gradient-aware variants prune by per-Gaussian gradients (Trimming-the-Fat) [14] or the second-order sensitivity score derived from the Hessian matrix (PUP-3DGS) [15]. The score can also be trained via a learnable mask, as in LP-3DGS [6], Compact3DGS [4], and HAC [16]. Moreover, multi-view consistency criteria discard Gaussians unseen by keyframes [21] or visible only in real but not virtual views [22]. For a comprehensive survey of 3DGS compression and compaction, we refer readers to [8, 23].

Despite their success, most existing strategies evaluate each Gaussian independently, leaving open the question of whether the retained set is truly the best global surrogate. Our work addresses this gap from a probabilistic perspective via Gaussian mixture reduction.

3DGS from Probabilistic Distribution Point of View. Kheradmand et al. [24] formulate 3DGS as a Markov chain Monte Carlo process and use stochastic gradient Langevin dynamics to migrate dropped Gaussians onto retained ones, partially recycling lost information. However, their update remains pairwise and lacks convergence guarantees under a principled divergence. Moreover, this scheme is coupled with the original 3DGS pipeline, limiting its generalizability to other variants.

3 Method: Gaussian Herding across Pens

3.1 Probabilistic Scene Representation

Let $\phi(x; \mu, \Sigma) = |2\pi\Sigma|^{-1} \exp(-(x - \mu)^\top \Sigma^{-1}(x - \mu))$ be the PDF of a Gaussian distribution with mean μ and covariance Σ . A Gaussian mixture with n components is a distribution with density:

$$\phi_n(x) = \sum_{i=1}^n \alpha_i \phi(x; \mu_i, \Sigma_i),$$

where α_i are the mixture weights satisfying $\alpha_i > 0$ ¹. In the context of 3DGS, let $x \in \mathbb{R}^3$ be spatial coordinates and $f(x)$ represent the implicit surface function (*i.e.*, geometric shape and opacity that

¹In statistics, Gaussian mixtures are defined with the constraint $\sum_{i=1}^n \alpha_i = 1$ to ensure the area under the density function is 1. However, we relax this constraint and consider unnormalized Gaussian mixtures, as in 3DGS, where the integral under the geometric surface need not equal 1.

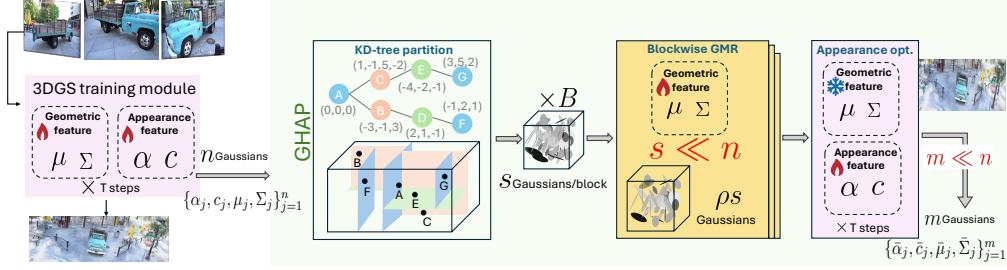


Figure 3: **An illustration of the proposed GHAP approach.** The process begins with full-resolution 3DGS training to obtain initial geometric and appearance features. These Gaussians are then spatially partitioned using a KD-tree and grouped into blocks—**analogous to sheep pens**. We then perform blockwise Gaussian Mixture Reduction (GMR) to approximate the geometric shape within each block using a much smaller number of Gaussians. This step is analogous to the popular **kernel herding** method [25]. Finally, a lightweight appearance refinement step further optimizes the appearance feature of the reduced set. This multi-stage pipeline progressively guides the Gaussians in each block—**analogous to herding across pens**—toward a compact and high-fidelity representation.

excludes color). The training process in 3DGS learns opacity parameter α_i , location parameter μ_i , and shape parameter Σ_i such that

$$\phi_n(x) \approx f(x), \quad \forall x \in \mathcal{X},$$

where \mathcal{X} is the 3D scene volume. Therefore, the *geometry* of the 3D scene can be effectively represented by a Gaussian mixture. Then, each of these Gaussian primitives is associated with its own color c_i . Both the geometry and appearance attributes are important for high quality rendering.

3.2 Compaction via Optimal Transport

Motivated by the observation that many 3DGS algorithms [4, 5, 6] produce a significant number of redundant Gaussians during training, we improve rendering efficiency through compaction—reducing the number of Gaussian primitives to achieve lower memory usage and faster rendering while preserving visual fidelity. The process consists of two key phases:

- 1. Geometric Compaction via GMR:** Leveraging our probabilistic interpretation, we formulate compaction as Gaussian Mixture Reduction (GMR) [26], approximating the original Gaussian mixture with redundant components by one with fewer components. This yields a compacted geometric representation: $\bar{\phi}_m(x) = \sum_{j=1}^m \bar{\alpha}_j \phi(x; \bar{\mu}_j, \bar{\Sigma}_j)$, where $m \ll n$. This step modifies only the Gaussian positions ($\bar{\mu}_j$) and covariances ($\bar{\Sigma}_j$), leaving appearance attributes unchanged.
- 2. Appearance Optimization:** The reduced Gaussians are initialized with appearance attributes (colors, opacities) and fine-tuned for optimal rendering performance. This step optimizes appearance only, maintaining geometric consistency.

Our approach decouples geometry and appearance optimization while using standard 3DGS training to preserve quality. Our training pipeline is visualized in Figure 3 and we describe the details below.

3.2.1 Geometric Compaction via GMR

Following Zhang et al. [17], we formulate compaction as minimizing the composite transportation divergence (CTD) between two Gaussian mixtures:

Definition 1 (Composite transportation divergence). *Let $c(\cdot, \cdot)$ be a divergence between two Gaussians. The composite transportation divergence (CTD) between two Gaussian mixtures $\phi_n(x) = \sum_{i=1}^n \alpha_i \phi(x; \mu_i, \Sigma_i)$ and $\phi'_m(x) = \sum_{j=1}^m \alpha'_j \phi(x; \mu'_j, \Sigma'_j)$ with cost function $c(\cdot, \cdot)$ is*

$$\mathcal{T}_c(\phi_n, \phi'_m) = \inf \left\{ \sum_{i=1}^n \sum_{j=1}^m \pi_{ij} c(\phi(\cdot; \mu_i, \Sigma_i), \phi(\cdot; \mu'_j, \Sigma'_j)) : \sum_{j=1}^m \pi_{ij} = \alpha_i, \sum_{i=1}^n \pi_{ij} = \alpha'_j \right\}.$$

The CTD generalizes *optimal transport* [18] to mixtures, treating each component as a discrete distribution in the space of Gaussian distributions. The cost function measures the cost of moving one unit of Gaussian from one location to another, and π_{ij} measures the corresponding amount of mass that is being moved. The total cost is proportional to the cost and the mass, and the divergence is the smallest transportation cost to move the original mixture to the target mixture. The reduced mixture becomes

$$\{\bar{\alpha}_j, \bar{\mu}_j, \bar{\Sigma}_j\} = \arg \min_{\{\alpha'_j, \mu'_j, \Sigma'_j\}} \mathcal{T}_c(\phi_n, \phi'_m). \quad (1)$$

With this formulation, the Gaussian mixture after compaction has optimal guarantee. The solution also guides the choice of m to balance compactness and fidelity.

As shown in Zhang et al. [17], (1) can be solved using the effective iterative algorithm in Algorithm 1. The algorithm reduces to a k -means variant in Gaussian space: 1) The assignment step follows the same principle as traditional k -means, but replaces the L^2 distance between vectors with a cost function $c(\cdot, \cdot)$ between Gaussian distributions. 2) The update step generalizes the cluster center computation: In traditional k -means, centers are updated as arithmetic averages (barycenters w.r.t. L^2 distance) of vectors in each cluster. In this algorithm, centers become barycenters of Gaussians in each cluster, minimized w.r.t. cost function $c(\cdot, \cdot)$. Thus, standard k -means emerges as a special case when using L^2 distance on vectorized Gaussian parameters.

While the standard GMR algorithm provides optimal theoretical guarantees, its direct application to 3DGS compaction proves computationally prohibitive. Although the algorithm must converge in finite steps [17]², the assignment step involves nm evaluations of the cost function per iteration. In typical 3D scenes, the number of Gaussians scales as $n = \Omega(10^5)$ ³, and even after 95% reduction, each iteration would still require at least 10^8 operations and memory storage. For the update step, the computational cost for the cluster center depends on the pre-specified cost function $c(\cdot, \cdot)$. The KL divergence considered in Zhang et al. [17] suffers from (a) significant overhead of computing $O(\rho s^2 \log n)$ covariance matrices inversions, and (b) numerical instability due to small eigenvalues of covariance matrices. To overcome this challenge, we introduce two key optimizations designed for 3DGS:

- **Blockwise GMR via KD-Tree:** To improve computational and memory efficiency during training, we partition the scene into spatially localized blocks and perform GMR independently within each block. As demonstrated in Remark 1, this blockwise approach yields significant computational savings. While both KD-trees [27] and Octrees [28] are effective for spatial partitioning in 3D space, we employ a KD-tree for two key advantages. First, it produces more balanced partitions across regions. Second, it avoids unnecessary subdivisions in sparse regions that would waste computational resources.

Our KD-tree is constructed solely from Gaussian centers $\{\mu_i\}_{i=1}^n$ (justified by the observed small eigenvalues of covariance matrices). Each split uses the median coordinate value, creating 2^d blocks at depth d . We set $d = \lfloor \log_2(n/s) \rfloor$ to ensure blocks contain at most s Gaussians with $s \ll n$, then reduce each block to $m = \rho s$ components (ρ = retention ratio).

²In particular, we find that in our experiment, the algorithm converges in only around 6 iterations.

³The $a_n = \Omega(b_n)$ ($O(b_n)$) if there exist $C \geq 0$ such that $a_n \geq Cb_n$ ($a_n \leq Cb_n$).

Remark 1 (Computational Cost Comparison). *Our blockwise approach reduces the per-iteration computational cost from $O(\rho n^2)$ to $O(\rho s^2)$ per block.⁴ With $2^{depth} = O(\log n)$ blocks in total, the overall complexity becomes $O(\rho s^2 \log n)$. For typical values of $n = 10^5$, $s = 10^3$ and $\rho = 0.05$, this reduces the cost from 10^8 to approximately 10^5 operations—a substantial improvement. The savings become even more pronounced for larger n . Furthermore, the reduction steps can be executed in parallel across blocks, offering additional computational speedup.*

- **Efficient Cost Function:** We introduce a novel cost function that overcomes the limitations of the KL divergence used in [17] by being computationally efficient without sacrificing approximation quality. Our proposed divergence is:

$$c(\phi(\cdot; \mu, \Sigma), \phi(\cdot; \mu', \Sigma')) = \|\mu - \mu'\|_2^2 + \|\Sigma - \Sigma'\|_F^2, \quad (2)$$

which offers three significant advantages: First, it preserves distributional similarity, as Gaussian distributions are uniquely determined by their mean and covariance. Second, the assignment step requires only efficient vector and matrix norm computations. Third, the update step simplifies to calculating weighted averages, thereby avoiding the computationally expensive covariance matrix inversions required by the KL divergence:

$$\bar{\mu}_j^{(t)} = \frac{\sum_{i \in \mathcal{C}_j} \alpha_i \mu_i}{\sum_{i \in \mathcal{C}_j} \alpha_i}, \quad \bar{\Sigma}_j^{(t)} = \frac{\sum_{i \in \mathcal{C}_j} \alpha_i \Sigma_i}{\sum_{i \in \mathcal{C}_j} \alpha_i}.$$

3.2.2 Appearance Optimization

Following geometric compaction, we initialize the appearance attributes (opacity and color) of the compacted Gaussian primitives. For each primitive in the reduced mixture, we assign the appearance parameters from its closest counterpart in the original Gaussian mixture. Using these initial values, we then optimize the appearance attributes through backpropagation within the standard 3DGS training pipeline used in the first stage. We optimize the opacity instead of directly using the values from the GMR algorithm because its output weights do not necessarily satisfy the constraint that opacity must be between 0 and 1. Fine-tuning the opacity leads to better visualization performance.

3.3 Training Details with GHAP Algorithm

Integrating these components, we present our complete training pipeline in Algorithm 2, called Gaussian Herding Across Pens (GHAP). The process begins with standard 3DGS optimization for T steps, followed by blockwise GMR. We then freeze the geometric parameters (μ and Σ) while fine-tuning the appearance attributes (opacity α and color c) through an additional T -step 3DGS optimization. This procedure can be applied iteratively throughout training as needed.

Algorithm 2 GHAP: 3DGS Compaction via Blockwise GMR

- 1: **Input:** Trained 3DGS model for T steps to obtain $\{(\alpha_i, \mu_i, \Sigma_i, c_i)\}_{i=1}^n$, retention ratio ρ
 - 2: **Output:** Compacted $\{(\bar{\alpha}_j, \bar{\mu}_j, \bar{\Sigma}_j, \bar{c}_j)\}_{j=1}^m$
 - 3: **Stage 1: Geometric Compaction**
 - 4: 1. Build KD-tree from Gaussians $\{\mu_i\}_{i=1}^n$ with depth $d = \lfloor \log_2(n/s) \rfloor \triangleright \mathcal{O}(nd \log n)$
 - 5: 2. For each leaf block \mathcal{B}_k : $\triangleright \mathcal{O}(nmT/2^d)$
 - 6: Run Algorithm 1 to reduce to ρs Gaussians
 - 7: **Stage 2: Appearance Optimization**
 - 8: 1. Initialize appearance for each $\bar{\phi}_j$:
 - 9: $\bar{c}_j \leftarrow c_{i^*}$ and $\bar{\alpha}_j \leftarrow \alpha_{i^*}$ where $i^* = \arg \min_{i \in [n]} \|\mu_i - \bar{\mu}_j\|_2$
 - 10: 2. Fine-tune $\{\bar{\alpha}_j, \bar{c}_j\}$ using standard 3DGS rendering pipeline for T steps
-

4 Experiments

4.1 Experimental Setup

Datasets. For a comprehensive evaluation of GHAP algorithm, we use three real-world datasets: *Tanks & Temples* [29], *Mip-NeRF 360* [30], and *Deep Blending* [31], which cover varying levels of detail, lighting conditions, and scene complexities. For each dataset, we adopt the same scenes as in [8].

- **Tanks & Temples:** We evaluate two unbounded outdoor scenes, “Truck” and “Train”, both featuring centered viewpoints.

⁴Each block reduces from s Gaussian components to ρs .

- **Mip-NeRF 360**: We test on a mix of indoor and outdoor scenes, including “Bicycle”, “Bonsai”, “Counter”, “Flowers”, “Garden”, “Kitchen”, “Room”, “Stump”, and “Treehill”, all with centered viewpoints.
- **Deep Blending**: We include two indoor scenes, “Dr. Johnson” and “Playroom”, where the viewpoint is directed outward.

Baselines. To evaluate the effectiveness of our proposed method, we compared it against four strong compaction techniques: **LightGaussian** [11], **PUP-3DGS** [15], **Trimming the Fat** [14], and **MesonGS** [32], as well as four end-to-end 3DGS variants: **Mini-Splatting-(D)** [12], **AtomGS** [13], **3DGS-MCMC** [24], and **LocoGS** [33]. Notably, Mini-Splatting-D and AtomGS were employed as backbone models in our approach, while the other variants were used for direct comparative evaluation against the compaction methods. A consistent evaluation protocol was established to ensure fair and reliable conclusions. For post-training compaction methods applicable to pre-trained models—including GHAP, LightGaussian, PUP-3DGS, Trimming the Fat, and MesonGS—we initialized all from the same backbone model (trained using vanilla 3DGS, Mini-Splatting-D, or AtomGS for 15k iterations) and applied their respective compaction procedures directly, excluding any compression-specific modules. All models subsequently underwent identical fine-tuning for 15k iterations to achieve the target retention ratio. For the other end-to-end variants (MiniSplatting, 3DGS-MCMC and LocoGS), we executed training for 30k iterations under their default configurations. Detailed experimental steps for each method can be found in the appendix.

Evaluation Metrics. We assess 3DGS compaction using standard metrics for rendering quality. We report: (1) **PSNR**, measuring pixel-level accuracy; (2) **SSIM**, evaluating perceptual similarity based on luminance, contrast, and structure; and (3) **LPIPS**, capturing perceptual distance via a learned model. Higher PSNR/SSIM and lower LPIPS indicate better quality. For each method, we also report the corresponding **number of Gaussian primitives**.

4.2 Quantitative Results

We first show that our approach outperforms other SOTA compaction techniques. Second, we demonstrate the effectiveness of our GHAP compaction method as a plug-in module within 3DGS and its variants. We present the experimental results followed by our key findings.

Comparison with SOTA. We compare our method against a comprehensive set of baselines, which can be categorized into two groups:

- **End-to-End Compact 3DGS Variants**: Mini-Splatting [12], 3DGS-MCMC [24], and LocoGS [33]. Note that for LocoGS, the final number of Gaussians is not a user-controllable parameter.
- **Post-Training Compaction Baselines**: LightGaussian [11], PUP-3DGS [15], Trimming the Fat [14], and MesonGS [32]. These methods all use a standard 3DGS backbone and apply pruning-based techniques for compaction.

Our approach is evaluated in two configurations: **3DGS+GHAP** and **MiniSplatting+GHAP**. The former uses the same vanilla 3DGS backbone and 10% retention rate as the pruning baselines for a direct comparison of compaction strategies. The latter replaces the built-in pruning step in Mini-Splatting with our GHAP algorithm to demonstrate its effectiveness on a different backbone.

Quantitative results are summarized in Table 1, with methods grouped by their final primitive count. As expected, LocoGS achieves strong performance due to its larger primitive count. Among methods with comparable primitive counts (Group 2), our **3DGS+GHAP** achieves superior performance in SSIM and PSNR, with a marginally lower LPIPS score. The advantage of our compaction strategy is further evident when using the Mini-Splatting backbone. Our **MiniSplatting+GHAP** outperforms other compaction-based approaches while often using fewer primitives. As shown in Fig. 4 (left), this performance lead is consistent across a wide range of retention ratios, not just at $\rho = 0.1$.

Runtime & Memory Usage Comparison. Crucially, the improved performance of our method does not come at a computational cost. As depicted in Fig. 4 (middle), our method’s runtime is faster than all baselines except the exceptionally swift Trimming the Fat. While our method exhibits a slightly higher memory footprint (in Fig. 4 right) during compaction due to pairwise distance computation in each KD-tree block, the difference is not substantial (less than an order of magnitude).

Table 1: **Quantitative comparison of rendering quality against SOTA methods.** Our method (GHAP), applied to two different backbones (3DGS and Mini-Splatting), consistently matches or surpasses pruning-based baselines, even at a low retention rate (10%), while maintaining competitive runtime and memory usage. The best results for a given number of Gaussians are shown in **bold**; second best are underlined.

Method	Tanks&Temples				MipNeRF-360				Deep Blending			
	SSIM↑	PSNR↑	LPIPS↓	k Gaussians	SSIM↑	PSNR↑	LPIPS↓	k Gaussians	SSIM↑	PSNR↑	LPIPS↓	k Gaussians
Vanilla 3DGS	0.853	23.785	0.169	1577	0.813	27.554	0.221	2627	0.907	29.816	0.238	2475
LocoGS	0.843	23.655	0.191	571	0.798	27.049	0.257	674	0.903	29.972	0.261	529
3DGS+GHAP (ours)	0.818	23.312	0.242	157	0.764	26.404	0.314	263	0.905	29.647	0.264	248
LightGaussian	0.756	22.113	0.306	158	0.735	25.674	0.331	263	0.869	28.010	0.327	248
PUP-3DGS	0.767	21.519	0.280	158	0.753	25.332	<u>0.309</u>	262	0.895	<u>29.153</u>	<u>0.274</u>	248
Trimming the Fat	0.776	21.535	0.293	156	0.731	25.255	0.343	263	0.887	28.056	0.302	247
MesongS	0.811	20.714	0.208	157	0.773	24.924	0.264	263	<u>0.896</u>	28.693	0.264	248
3DGS-MCMC	0.779	<u>22.141</u>	0.282	157	0.763	<u>25.957</u>	<u>0.309</u>	263	0.885	28.976	0.298	248
MiniSplatting	0.799	22.661	0.265	78	0.759	26.022	0.318	111	0.895	29.395	0.289	125
MiniSplatting+GHAP (ours)	0.835	23.232	0.198	79	0.802	27.090	0.250	112	0.909	30.042	0.254	127

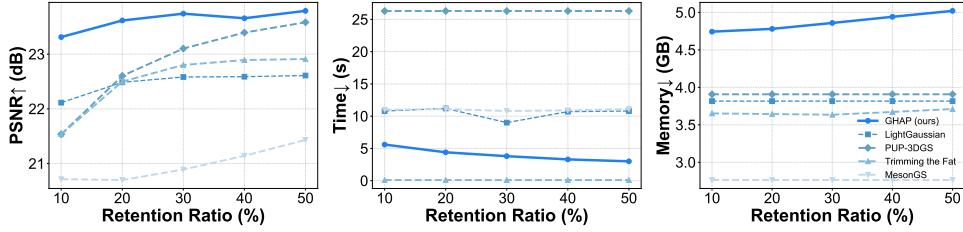


Figure 4: **Comparison of compaction methods on the Tanks & Temples dataset.** Left: Rate-Distortion (RD) curves; middle: computational time, and right: memory consumption.

As a Plug-In Compaction Method. Our method can be used as a plug-in compaction method in various 3DGS training algorithms. This demonstrates the broad applicability of our proposed method. To verify this, we apply our compaction method within various 3DGS pipelines. Specifically, we consider three representative variants as the backbone: 3DGS [3], AtomGS [13], and Mini-Splatting-D [12]. Each of them employs a distinct densification strategy, and our method can be directly embedded into the pipeline without extensive engineering effort. For each backbone, we evaluate performance under two retention ratios (10% and 20%). Tab. 2 summarizes our experimental results.

Table 2: **Quantitative results with different backbones.** The compaction performance of our GHAP method when used with different 3DGS variants as backbones under varying retention ratios.

Backbone	ρ	Tanks&Temples				MipNeRF-360				Deep Blending			
		SSIM↑	PSNR↑	LPIPS↓	k Gaussians	SSIM↑	PSNR↑	LPIPS↓	k Gaussians	SSIM↑	PSNR↑	LPIPS↓	k Gaussians
3DGS-30k	10%	0.818	23.312	0.242	157	0.764	26.404	0.314	263	0.905	29.647	0.264	248
	20%	0.835	23.615	0.212	314	0.788	26.973	0.275	526	0.907	29.864	0.252	596
	100%	0.853	23.785	0.169	1577	0.813	27.554	0.221	2627	0.907	29.816	0.238	2475
Mini-Splatting-D	10%	0.835	23.232	0.198	313	0.802	27.090	0.250	357	0.909	30.042	0.254	331
	20%	0.855	23.403	0.171	626	0.821	27.310	0.214	614	0.912	30.170	0.238	662
	100%	0.848	23.338	0.140	3132	0.832	27.486	0.176	3578	0.907	29.980	0.211	3316
AtomGS	10%	0.793	22.988	0.274	189	0.764	26.535	0.307	293	0.899	29.347	0.282	271
	20%	0.812	23.282	0.240	378	0.788	27.025	0.269	586	0.902	29.347	0.268	542
	100%	0.814	23.289	0.235	1897	0.796	27.135	0.251	2928	0.902	29.314	0.267	2709

The quantitative results in Tab. 2 demonstrate that our method effectively preserves the backbone models’ visual quality, even at an extreme retention rate of 10%. Notably, on some scenes (highlighted in bold), the compacted model’s performance surpasses that of the uncompact backbone.

Beyond quantitative metrics, we provide a qualitative analysis by visualizing multiple scenes before and after compaction in Fig. 5. As evidenced in the figure, our method successfully preserves rendering quality across most scenes while using only 10% of the Gaussian primitives. Interestingly,



Figure 5: **Visual Quality Before and After Compaction.** Visual results for various scenes under different 3DGS backbones, compacted to 10% of their primitives using our GHAP method. Our approach preserves rendering quality with negligible loss. In some cases (e.g., “Kitchen”), compaction even improves quality by regularizing an over saturated Gaussian distribution.

in certain cases, our compaction not only preserves but *surpasses* the original quality. A representative example is the “Kitchen” scene (Mini-Splatting-D backbone). We conjecture this improvement occurs because Mini-Splatting-D lacks a pruning mechanism, often generating an over saturated set of Gaussians that introduce visual artifacts (*e.g.*, the unnatural shadows in the lower-left region). Our method acts as a global regularizer, mitigating this issue by reducing unnecessary density while improving the overall expressiveness and preserving the underlying 3D structure. Naturally, our approach is inherently limited by the quality of its input. If the original model suffers from significant artifacts due to a lack of primitives in certain regions, our compaction cannot resolve these fundamental issues. This limitation is demonstrated in the “Bicycle” scene, where artifacts present in the Atom-GS backbone persist after compaction.

4.3 Ablation Studies

Influence of KD Tree Depth. To validate the effectiveness of the KD-tree partitioning strategy, we provide an ablation study on it. Due to the large scale of the three primary datasets, low KD-tree depths result in an excessive number of points per block, making it infeasible to run the GMR algorithm. Therefore, we conduct ablation experiments on the smaller mic scene from NeRF-Synthetic. Results in Fig. 6 show that increasing KD-tree depth reduces memory usage and runtime, while PSNR first improves and then declines. This indicates that moderately finer partitions allow GMR to compact regions more effectively, whereas overly fine splits may fragment primitives and degrade quality.

Loss Function Design. As shown in Tables 1 and 2, our method exhibits a slight underperformance on the LPIPS metric. To address this, we investigate whether incorporating an LPIPS loss term can yield improvements.

Our baseline loss function follows the vanilla 3DGS formulation, using an L1-to-SSIM ratio of 8:2. We experiment with two new weighting schemes that include LPIPS: (1) L1:SSIM:LPIPS = 8:1:1, and (2) L1:SSIM:LPIPS = 6:2:2. The results of this ablation study on the Tanks&Temples dataset are shown in Fig. 7 (with additional results in the Appendix). Our analysis reveals a trade-off between

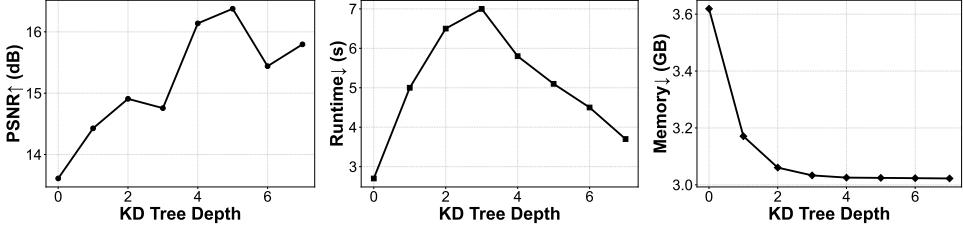


Figure 6: **Hyperparameters.** The impact of KD tree depth on runtime performance, memory footprint, and rendering quality.

perceptual and distortion metrics: increasing the weight of the LPIPS loss improves LPIPS scores but leads to a slight deduction in PSNR and SSIM.

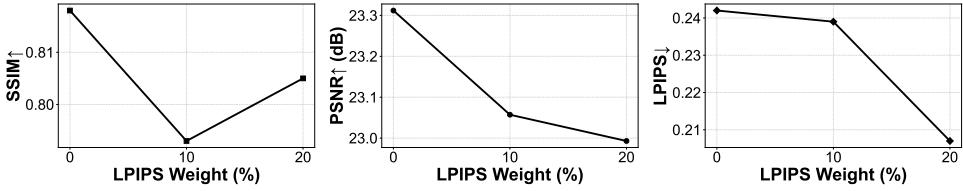


Figure 7: **Comparison of different loss weights.** A trade-off between perceptual and distortion metrics.

GMR versus Random Subsampling. We conduct an ablation study on the Tanks&Temples dataset to evaluate the contribution of each stage in our pipeline: geometric compaction and appearance optimization. A random subsampling baseline is included to assess the effectiveness of our design choices.

The results, presented in Table 3, compare two compaction schemes followed by the same fine-tuning procedure. Our findings demonstrate that: first, our compaction procedure is significantly more effective than random subsampling and other pruning baselines (as shown in Tab. 1). Second, the subsequent appearance optimization stage provides substantial quantitative improvements for both compaction approaches. The significant performance gain over the baseline validates the necessity and effectiveness of both stages in our proposed pipeline.

Table 3: **Ablation study.** Mean PSNR, SSIM, and LPIPS on the Tanks and Temples dataset at each stage of GHAP pipeline, with random subsampling as a control. Each operation is applied cumulatively to all subsequent stages.

Method	Tanks&Temples		
	SSIM↑	PSNR↑	LPIPS↓
3DGS-15K	0.839	23.084	0.194
+ 10% GHAP Compaction	0.502	14.015	0.483
+ 10% Random Compaction	0.333	9.573	0.555
+15K Fine-tuning	0.818	23.312	0.242
+15K Fine-tuning	0.712	21.312	0.282

5 Conclusion and Discussion

We propose an optimal transport-based Gaussian mixture reduction framework for 3D Gaussian Splatting, achieving compact yet faithful representations. By minimizing composite transport divergence with appearance fine-tuning, our method preserves high visual fidelity while retaining only 10% of Gaussians, outperforming prior compaction techniques. The framework scales efficiently via block-wise KD-tree partitioning and integrates seamlessly with diverse 3DGS pipelines.

Future directions include enhancing robustness across challenging scene types, incorporating perceptual objectives, developing multi-scale and overlap-aware partitioning, adopting auto-tuned schedules, and extending to dynamic 3DGS for real-time temporal rendering.

Acknowledgments and Disclosure of Funding

Qiong Zhang is supported by the National Natural Science Foundation of China Grant 12301391. The authors would like to thank the anonymous reviewers for their constructive suggestions.

References

- [1] Ben Fei, Jingyi Xu, Rui Zhang, Qingyuan Zhou, Weidong Yang, and Ying He. 3D Gaussian splatting as new era: A survey. *IEEE Transactions on Visualization and Computer Graphics*, 2024.
- [2] Guikun Chen and Wenguan Wang. A survey on 3D Gaussian splatting. *arXiv preprint arXiv:2401.03890*, 2024.
- [3] Bernhard Kerbl, Georgios Kopanas, Thomas Leimkühler, and George Drettakis. 3D Gaussian splatting for real-time radiance field rendering. *ACM Transactions on Graphics*, 42(4):1–14, 2023.
- [4] Joo Chan Lee, Daniel Rho, Xiangyu Sun, Jong Hwan Ko, and Eunbyung Park. Compact 3D Gaussian representation for radiance field. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 21719–21728, 2024.
- [5] Michael Niemeyer, Fabian Manhardt, Marie-Julie Rakotosaona, Michael Oechsle, Daniel Duckworth, Rama Gosula, Keisuke Tateno, John Bates, Dominik Kaeser, and Federico Tombari. RadSplat: Radiance field-informed Gaussian splatting for robust real-time rendering with 900+ FPS. *arXiv preprint arXiv:2403.13806*, 2024.
- [6] Zhaoliang Zhang, Tianchen Song, Yongjae Lee, Li Yang, Cheng Peng, Rama Chellappa, and Deliang Fan. LP-3DGS: Learning to prune 3D Gaussian splatting. *Advances in Neural Information Processing Systems*, 38, 2024.
- [7] Kerui Ren, Lihan Jiang, Tao Lu, Mulin Yu, Linning Xu, Zhangkai Ni, and Bo Dai. Octree-GS: Towards consistent real-time rendering with LOD-structured 3D Gaussians. *arXiv preprint arXiv:2403.17898*, 2024.
- [8] Milena T Bagdasarian, Paul Knoll, Yi-Hsin Li, Florian Barthel, Anna Hilsmann, Peter Eisert, and Wieland Morgenstern. 3DGS.zip: A survey on 3D Gaussian splatting compression methods. *arXiv preprint arXiv:2407.09510*, 2024.
- [9] Kai Cheng, Xiaoxiao Long, Kaizhi Yang, Yao Yao, Wei Yin, Yuexin Ma, Wenping Wang, and Xuejin Chen. GaussianPro: 3D Gaussian splatting with progressive propagation. In *Forty-first International Conference on Machine Learning*, 2024.
- [10] Saswat Subhajyoti Mallick, Rahul Goel, Bernhard Kerbl, Markus Steinberger, Francisco Vicente Carrasco, and Fernando De La Torre. Taming 3DGS: High-quality radiance fields with limited resources. In *SIGGRAPH Asia 2024 Conference Papers*, pages 1–11, 2024.
- [11] Zhiwen Fan, Kevin Wang, Kairun Wen, Zehao Zhu, Dejia Xu, Zhangyang Wang, et al. Light-Gaussian: Unbounded 3D Gaussian compression with 15x reduction and 200+ FPS. *Advances in Neural Information Processing Systems*, 37:140138–140158, 2024.
- [12] Guangchi Fang and Bing Wang. Mini-splatting: Representing scenes with a constrained number of Gaussians. In *European Conference on Computer Vision*, pages 165–181. Springer, 2024.
- [13] Rong Liu, Rui Xu, Yue Hu, Meida Chen, and Andrew Feng. AtomGS: Atomizing Gaussian splatting for high-fidelity radiance field. *arXiv preprint arXiv:2405.12369*, 2024.
- [14] Muhammad Salman Ali, Maryam Qamar, Sung-Ho Bae, and Enzo Tartaglione. Trimming the fat: Efficient compression of 3D Gaussian splats through pruning. *arXiv preprint arXiv:2406.18214*, 2024.
- [15] Alex Hanson, Allen Tu, Vasu Singla, Mayuka Jayawardhana, Matthias Zwicker, and Tom Goldstein. PUP 3D-GS: Principled uncertainty pruning for 3D Gaussian splatting. *arXiv preprint arXiv:2406.10219*, 2024.

- [16] Yihang Chen, Qianyi Wu, Weiyao Lin, Mehrtash Harandi, and Jianfei Cai. HAC: Hash-grid assisted context for 3D Gaussian splatting compression. In *European Conference on Computer Vision*, pages 422–438. Springer, 2024.
- [17] Qiong Zhang, Archer Gong Zhang, and Jiahua Chen. Gaussian mixture reduction with composite transportation divergence. *IEEE Transactions on Information Theory*, 70(7):5191–5212, 2023.
- [18] Gabriel Peyré, Marco Cuturi, et al. Computational optimal transport: With applications to data science. *Foundations and Trends® in Machine Learning*, 11(5-6):355–607, 2019.
- [19] Cédric Villani. *Optimal Transport: Old and New*. Springer Berlin, Heidelberg, 2009.
- [20] Sieun Kim, Kyungjin Lee, and Youngki Lee. Color-cued efficient densification method for 3D Gaussian splatting. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 775–783, 2024.
- [21] Hidenobu Matsuki, Riku Murai, Paul HJ Kelly, and Andrew J Davison. Gaussian splatting SLAM. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 18039–18048, 2024.
- [22] Yiming Ji, Yang Liu, Guanghu Xie, Boyu Ma, Zongwu Xie, and Hong Liu. NEDS-SLAM: A neural explicit dense semantic SLAM framework using 3D Gaussian splatting. *IEEE Robotics and Automation Letters*, 9(10):8778–8785, 2024.
- [23] Yanqi Bao, Tianyu Ding, Jing Huo, Yaoli Liu, Yuxin Li, Wenbin Li, Yang Gao, and Jiebo Luo. 3D Gaussian splatting: Survey, technologies, challenges, and opportunities. *IEEE Transactions on Circuits and Systems for Video Technology*, 2025.
- [24] Shakiba Kheradmand, Daniel Rebain, Gopal Sharma, Weiwei Sun, Yang-Che Tseng, Hossam Isack, Abhishek Kar, Andrea Tagliasacchi, and Kwang Moo Yi. 3D Gaussian splatting as Markov Chain Monte Carlo. *Advances in Neural Information Processing Systems*, 37:80965–80986, 2024.
- [25] Yutian Chen, Max Welling, and Alexander J. Smola. Super-samples from kernel herding. *CoRR*, abs/1203.3472, 2012.
- [26] David F Crouse, Peter Willett, Krishna Pattipati, and Lennart Svensson. A look at Gaussian mixture reduction algorithms. In *14th International Conference on Information Fusion*, pages 1–8. IEEE, 2011.
- [27] Jon Louis Bentley. Multidimensional binary search trees used for associative searching. *Communications of the ACM*, 18(9):509–517, 1975.
- [28] Donald Meagher. Geometric modeling using octree encoding. *Computer graphics and image processing*, 19(2):129–147, 1982.
- [29] Arno Knapitsch, Jaesik Park, Qian-Yi Zhou, and Vladlen Koltun. Tanks and temples: Benchmarking large-scale scene reconstruction. *ACM Transactions on Graphics (ToG)*, 36(4):1–13, 2017.
- [30] Peter Hedman, Julien Philip, True Price, Jan-Michael Frahm, George Drettakis, and Gabriel Brostow. Deep blending for free-viewpoint image-based rendering. *ACM Transactions on Graphics (ToG)*, 37(6):1–15, 2018.
- [31] Jonathan T Barron, Ben Mildenhall, Dor Verbin, Pratul P Srinivasan, and Peter Hedman. Mip-nerf 360: Unbounded anti-aliased neural radiance fields. In *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition*, pages 5470–5479, 2022.
- [32] Shuzhao Xie, Weixiang Zhang, Chen Tang, Yunpeng Bai, Rongwei Lu, Shijia Ge, and Zhi Wang. Mesongs: Post-training compression of 3d gaussians via efficient attribute transformation. In *European Conference on Computer Vision*, pages 434–452. Springer, 2024.
- [33] Seungjoo Shin, Jaesik Park, and Sunghyun Cho. Locality-aware gaussian compression for fast and high-quality rendering. *arXiv preprint arXiv:2501.05757*, 2025.

- [34] Yongxin Chen, Tryphon T Georgiou, and Allen Tannenbaum. Optimal transport for Gaussian mixture models. *IEEE Access*, 7:6269–6278, 2018.
- [35] Julie Delon and Agnès Desolneux. A Wasserstein-type distance in the space of Gaussian mixture models. *SIAM Journal on Imaging Sciences*, 13(2):936–970, 2020.
- [36] Shoukang Hu, Tao Hu, and Ziwei Liu. GauHuman: Articulated Gaussian splatting from monocular human videos. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 20418–20431, 2024.
- [37] Shunyuan Zheng, Boyao Zhou, Ruizhi Shao, Boning Liu, Shengping Zhang, Liqiang Nie, and Yebin Liu. GPS-Gaussian: Generalizable pixel-wise 3D Gaussian splatting for real-time human novel view synthesis. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 19680–19690, 2024.
- [38] Jiaxiang Tang, Jiawei Ren, Hang Zhou, Ziwei Liu, and Gang Zeng. DreamGaussian: Generative Gaussian splatting for efficient 3D content creation. In *The Twelfth International Conference on Learning Representations*, 2024.
- [39] Xiaoyu Zhou, Zhiwei Lin, Xiaojun Shan, Yongtao Wang, Deqing Sun, and Ming-Hsuan Yang. DrivingGaussian: Composite Gaussian splatting for surrounding dynamic autonomous driving scenes. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 21634–21643, 2024.
- [40] Guanjun Wu, Taoran Yi, Jiemin Fang, Lingxi Xie, Xiaopeng Zhang, Wei Wei, Wenyu Liu, Qi Tian, and Xinggang Wang. 4D Gaussian splatting for real-time dynamic scene rendering. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 20310–20320, 2024.
- [41] Pinxuan Dai, Jiamin Xu, Wenxiang Xie, Xinguo Liu, Huamin Wang, and Weiwei Xu. High-quality surface reconstruction using Gaussian surfels. In *ACM SIGGRAPH 2024 Conference Papers*, pages 1–11, 2024.
- [42] Yiwen Chen, Zilong Chen, Chi Zhang, Feng Wang, Xiaofeng Yang, Yikai Wang, Zhongang Cai, Lei Yang, Huaping Liu, and Guosheng Lin. GaussianEditor: Swift and controllable 3D editing with Gaussian splatting. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 21476–21485, 2024.

NeurIPS Paper Checklist

1. Claims

Question: Do the main claims made in the abstract and introduction accurately reflect the paper's contributions and scope?

Answer: [Yes]

Justification: Our main claim are summarized in Section 1 and Figure 1, Section 3 and Section 4 offer detailed explanations.

Guidelines:

- The answer NA means that the abstract and introduction do not include the claims made in the paper.
- The abstract and/or introduction should clearly state the claims made, including the contributions made in the paper and important assumptions and limitations. A No or NA answer to this question will not be perceived well by the reviewers.
- The claims made should match theoretical and experimental results, and reflect how much the results can be expected to generalize to other settings.
- It is fine to include aspirational goals as motivation as long as it is clear that these goals are not attained by the paper.

2. Limitations

Question: Does the paper discuss the limitations of the work performed by the authors?

Answer: [Yes]

Justification: We include the limitations of our work in Appendix.

Guidelines:

- The answer NA means that the paper has no limitation while the answer No means that the paper has limitations, but those are not discussed in the paper.
- The authors are encouraged to create a separate "Limitations" section in their paper.
- The paper should point out any strong assumptions and how robust the results are to violations of these assumptions (e.g., independence assumptions, noiseless settings, model well-specification, asymptotic approximations only holding locally). The authors should reflect on how these assumptions might be violated in practice and what the implications would be.
- The authors should reflect on the scope of the claims made, e.g., if the approach was only tested on a few datasets or with a few runs. In general, empirical results often depend on implicit assumptions, which should be articulated.
- The authors should reflect on the factors that influence the performance of the approach. For example, a facial recognition algorithm may perform poorly when image resolution is low or images are taken in low lighting. Or a speech-to-text system might not be used reliably to provide closed captions for online lectures because it fails to handle technical jargon.
- The authors should discuss the computational efficiency of the proposed algorithms and how they scale with dataset size.
- If applicable, the authors should discuss possible limitations of their approach to address problems of privacy and fairness.
- While the authors might fear that complete honesty about limitations might be used by reviewers as grounds for rejection, a worse outcome might be that reviewers discover limitations that aren't acknowledged in the paper. The authors should use their best judgment and recognize that individual actions in favor of transparency play an important role in developing norms that preserve the integrity of the community. Reviewers will be specifically instructed to not penalize honesty concerning limitations.

3. Theory assumptions and proofs

Question: For each theoretical result, does the paper provide the full set of assumptions and a complete (and correct) proof?

Answer: [Yes]

Justification: We have stated all assumptions explicitly within the theorem and include the complete proof of our theoretical results in Appendix.

Guidelines:

- The answer NA means that the paper does not include theoretical results.
- All the theorems, formulas, and proofs in the paper should be numbered and cross-referenced.
- All assumptions should be clearly stated or referenced in the statement of any theorems.
- The proofs can either appear in the main paper or the supplemental material, but if they appear in the supplemental material, the authors are encouraged to provide a short proof sketch to provide intuition.
- Inversely, any informal proof provided in the core of the paper should be complemented by formal proofs provided in appendix or supplemental material.
- Theorems and Lemmas that the proof relies upon should be properly referenced.

4. Experimental result reproducibility

Question: Does the paper fully disclose all the information needed to reproduce the main experimental results of the paper to the extent that it affects the main claims and/or conclusions of the paper (regardless of whether the code and data are provided or not)?

Answer: [Yes]

Justification: We explained our settings and hyperparameters in Section 4 and Appendix .

Guidelines:

- The answer NA means that the paper does not include experiments.
- If the paper includes experiments, a No answer to this question will not be perceived well by the reviewers: Making the paper reproducible is important, regardless of whether the code and data are provided or not.
- If the contribution is a dataset and/or model, the authors should describe the steps taken to make their results reproducible or verifiable.
- Depending on the contribution, reproducibility can be accomplished in various ways. For example, if the contribution is a novel architecture, describing the architecture fully might suffice, or if the contribution is a specific model and empirical evaluation, it may be necessary to either make it possible for others to replicate the model with the same dataset, or provide access to the model. In general, releasing code and data is often one good way to accomplish this, but reproducibility can also be provided via detailed instructions for how to replicate the results, access to a hosted model (e.g., in the case of a large language model), releasing of a model checkpoint, or other means that are appropriate to the research performed.
- While NeurIPS does not require releasing code, the conference does require all submissions to provide some reasonable avenue for reproducibility, which may depend on the nature of the contribution. For example
 - (a) If the contribution is primarily a new algorithm, the paper should make it clear how to reproduce that algorithm.
 - (b) If the contribution is primarily a new model architecture, the paper should describe the architecture clearly and fully.
 - (c) If the contribution is a new model (e.g., a large language model), then there should either be a way to access this model for reproducing the results or a way to reproduce the model (e.g., with an open-source dataset or instructions for how to construct the dataset).
 - (d) We recognize that reproducibility may be tricky in some cases, in which case authors are welcome to describe the particular way they provide for reproducibility. In the case of closed-source models, it may be that access to the model is limited in some way (e.g., to registered users), but it should be possible for other researchers to have some path to reproducing or verifying the results.

5. Open access to data and code

Question: Does the paper provide open access to the data and code, with sufficient instructions to faithfully reproduce the main experimental results, as described in supplemental material?

Answer: [Yes]

Justification: The data is open-source and the GitHub link is provided.

Guidelines:

- The answer NA means that paper does not include experiments requiring code.
- Please see the NeurIPS code and data submission guidelines (<https://nips.cc/public/guides/CodeSubmissionPolicy>) for more details.
- While we encourage the release of code and data, we understand that this might not be possible, so “No” is an acceptable answer. Papers cannot be rejected simply for not including code, unless this is central to the contribution (e.g., for a new open-source benchmark).
- The instructions should contain the exact command and environment needed to run to reproduce the results. See the NeurIPS code and data submission guidelines (<https://nips.cc/public/guides/CodeSubmissionPolicy>) for more details.
- The authors should provide instructions on data access and preparation, including how to access the raw data, preprocessed data, intermediate data, and generated data, etc.
- The authors should provide scripts to reproduce all experimental results for the new proposed method and baselines. If only a subset of experiments are reproducible, they should state which ones are omitted from the script and why.
- At submission time, to preserve anonymity, the authors should release anonymized versions (if applicable).
- Providing as much information as possible in supplemental material (appended to the paper) is recommended, but including URLs to data and code is permitted.

6. Experimental setting/details

Question: Does the paper specify all the training and test details (e.g., data splits, hyper-parameters, how they were chosen, type of optimizer, etc.) necessary to understand the results?

Answer: [Yes]

Justification: We placed the detailed experimental settings of the experiments in Section 4 and the Appendix of the paper and the complete details with the code in the supplementary materials.

Guidelines:

- The answer NA means that the paper does not include experiments.
- The experimental setting should be presented in the core of the paper to a level of detail that is necessary to appreciate the results and make sense of them.
- The full details can be provided either with the code, in appendix, or as supplemental material.

7. Experiment statistical significance

Question: Does the paper report error bars suitably and correctly defined or other appropriate information about the statistical significance of the experiments?

Answer: [Yes]

Justification: We show results in Appendix.

Guidelines:

- The answer NA means that the paper does not include experiments.
- The authors should answer "Yes" if the results are accompanied by error bars, confidence intervals, or statistical significance tests, at least for the experiments that support the main claims of the paper.
- The factors of variability that the error bars are capturing should be clearly stated (for example, train/test split, initialization, random drawing of some parameter, or overall run with given experimental conditions).
- The method for calculating the error bars should be explained (closed form formula, call to a library function, bootstrap, etc.)
- The assumptions made should be given (e.g., Normally distributed errors).

- It should be clear whether the error bar is the standard deviation or the standard error of the mean.
- It is OK to report 1-sigma error bars, but one should state it. The authors should preferably report a 2-sigma error bar than state that they have a 96% CI, if the hypothesis of Normality of errors is not verified.
- For asymmetric distributions, the authors should be careful not to show in tables or figures symmetric error bars that would yield results that are out of range (e.g. negative error rates).
- If error bars are reported in tables or plots, The authors should explain in the text how they were calculated and reference the corresponding figures or tables in the text.

8. Experiments compute resources

Question: For each experiment, does the paper provide sufficient information on the computer resources (type of compute workers, memory, time of execution) needed to reproduce the experiments?

Answer: [Yes]

Justification: All experiments were conducted on a server with 256 GB RAM and 64 cores Intel ® Xeon ® Gold 6330 CPU, and a standard workstation equipped with a single NVIDIA RTX 3090 GPU.

Guidelines:

- The answer NA means that the paper does not include experiments.
- The paper should indicate the type of compute workers CPU or GPU, internal cluster, or cloud provider, including relevant memory and storage.
- The paper should provide the amount of compute required for each of the individual experimental runs as well as estimate the total compute.
- The paper should disclose whether the full research project required more compute than the experiments reported in the paper (e.g., preliminary or failed experiments that didn't make it into the paper).

9. Code of ethics

Question: Does the research conducted in the paper conform, in every respect, with the NeurIPS Code of Ethics <https://neurips.cc/public/EthicsGuidelines>?

Answer: [Yes]

Justification: The research conducted in this paper complies with the NeurIPS Code of Ethics in all aspects.

Guidelines:

- The answer NA means that the authors have not reviewed the NeurIPS Code of Ethics.
- If the authors answer No, they should explain the special circumstances that require a deviation from the Code of Ethics.
- The authors should make sure to preserve anonymity (e.g., if there is a special consideration due to laws or regulations in their jurisdiction).

10. Broader impacts

Question: Does the paper discuss both potential positive societal impacts and negative societal impacts of the work performed?

Answer: [Yes]

Justification: This paper proposes a novel method of compaction for 3D Gaussian Splatting, which is broadly applicable to 3D real-time radiance field rendering. Its potential impact is further analyzed in Section 5.

Guidelines:

- The answer NA means that there is no societal impact of the work performed.
- If the authors answer NA or No, they should explain why their work has no societal impact or why the paper does not address societal impact.

- Examples of negative societal impacts include potential malicious or unintended uses (e.g., disinformation, generating fake profiles, surveillance), fairness considerations (e.g., deployment of technologies that could make decisions that unfairly impact specific groups), privacy considerations, and security considerations.
- The conference expects that many papers will be foundational research and not tied to particular applications, let alone deployments. However, if there is a direct path to any negative applications, the authors should point it out. For example, it is legitimate to point out that an improvement in the quality of generative models could be used to generate deepfakes for disinformation. On the other hand, it is not needed to point out that a generic algorithm for optimizing neural networks could enable people to train models that generate Deepfakes faster.
- The authors should consider possible harms that could arise when the technology is being used as intended and functioning correctly, harms that could arise when the technology is being used as intended but gives incorrect results, and harms following from (intentional or unintentional) misuse of the technology.
- If there are negative societal impacts, the authors could also discuss possible mitigation strategies (e.g., gated release of models, providing defenses in addition to attacks, mechanisms for monitoring misuse, mechanisms to monitor how a system learns from feedback over time, improving the efficiency and accessibility of ML).

11. Safeguards

Question: Does the paper describe safeguards that have been put in place for responsible release of data or models that have a high risk for misuse (e.g., pretrained language models, image generators, or scraped datasets)?

Answer: [NA]

Justification: This paper involves no such risks.

Guidelines:

- The answer NA means that the paper poses no such risks.
- Released models that have a high risk for misuse or dual-use should be released with necessary safeguards to allow for controlled use of the model, for example by requiring that users adhere to usage guidelines or restrictions to access the model or implementing safety filters.
- Datasets that have been scraped from the Internet could pose safety risks. The authors should describe how they avoided releasing unsafe images.
- We recognize that providing effective safeguards is challenging, and many papers do not require this, but we encourage authors to take this into account and make a best faith effort.

12. Licenses for existing assets

Question: Are the creators or original owners of assets (e.g., code, data, models), used in the paper, properly credited and are the license and terms of use explicitly mentioned and properly respected?

Answer: [Yes]

Justification: We have ensured that all assets used in this paper are properly cited and their owners credited.

Guidelines:

- The answer NA means that the paper does not use existing assets.
- The authors should cite the original paper that produced the code package or dataset.
- The authors should state which version of the asset is used and, if possible, include a URL.
- The name of the license (e.g., CC-BY 4.0) should be included for each asset.
- For scraped data from a particular source (e.g., website), the copyright and terms of service of that source should be provided.

- If assets are released, the license, copyright information, and terms of use in the package should be provided. For popular datasets, paperswithcode.com/datasets has curated licenses for some datasets. Their licensing guide can help determine the license of a dataset.
- For existing datasets that are re-packaged, both the original license and the license of the derived asset (if it has changed) should be provided.
- If this information is not available online, the authors are encouraged to reach out to the asset's creators.

13. New assets

Question: Are new assets introduced in the paper well documented and is the documentation provided alongside the assets?

Answer: [Yes]

Justification: Our implementation code is available in supplementary materials.

Guidelines:

- The answer NA means that the paper does not release new assets.
- Researchers should communicate the details of the dataset/code/model as part of their submissions via structured templates. This includes details about training, license, limitations, etc.
- The paper should discuss whether and how consent was obtained from people whose asset is used.
- At submission time, remember to anonymize your assets (if applicable). You can either create an anonymized URL or include an anonymized zip file.

14. Crowdsourcing and research with human subjects

Question: For crowdsourcing experiments and research with human subjects, does the paper include the full text of instructions given to participants and screenshots, if applicable, as well as details about compensation (if any)?

Answer: [NA]

Justification: This paper does not involve crowdsourcing nor human subjects.

Guidelines:

- The answer NA means that the paper does not involve crowdsourcing nor research with human subjects.
- Including this information in the supplemental material is fine, but if the main contribution of the paper involves human subjects, then as much detail as possible should be included in the main paper.
- According to the NeurIPS Code of Ethics, workers involved in data collection, curation, or other labor should be paid at least the minimum wage in the country of the data collector.

15. Institutional review board (IRB) approvals or equivalent for research with human subjects

Question: Does the paper describe potential risks incurred by study participants, whether such risks were disclosed to the subjects, and whether Institutional Review Board (IRB) approvals (or an equivalent approval/review based on the requirements of your country or institution) were obtained?

Answer: [NA]

Justification: This paper does not involve crowdsourcing nor human subjects.

Guidelines:

- The answer NA means that the paper does not involve crowdsourcing nor research with human subjects.
- Depending on the country in which research is conducted, IRB approval (or equivalent) may be required for any human subjects research. If you obtained IRB approval, you should clearly state this in the paper.

- We recognize that the procedures for this may vary significantly between institutions and locations, and we expect authors to adhere to the NeurIPS Code of Ethics and the guidelines for their institution.
- For initial submissions, do not include any information that would break anonymity (if applicable), such as the institution conducting the review.

16. Declaration of LLM usage

Question: Does the paper describe the usage of LLMs if it is an important, original, or non-standard component of the core methods in this research? Note that if the LLM is used only for writing, editing, or formatting purposes and does not impact the core methodology, scientific rigorousness, or originality of the research, declaration is not required.

Answer: [NA]

Justification: The development of the core method in this research did not involve LLMs as any important, original, or non-standard components.

Guidelines:

- The answer NA means that the core method development in this research does not involve LLMs as any important, original, or non-standard components.
- Please refer to our LLM policy (<https://neurips.cc/Conferences/2025/LLM>) for what should or should not be described.

Appendix

A More Details about the Blockwise GMR Compaction

A.1 Introduction to Optimal Transport (OT)

The Optimal Transport (OT) problem dates back to 1781, when French mathematician *Gaspard Monge* (1746–1818) first formulated it as finding the minimal-cost way to move sand into a hole. This “transport plan” minimizes the transportation cost, hence the term “optimal transport”. The original formulation is known as Monge’s problem. In 1947, Russian economist *Leonid Kantorovich* (1912–1986) relaxed Monge’s formulation, leading to the so-called Monge-Kantorovich problem.

Specifically, let P and Q be two distributions over a metric space \mathcal{X} , let $c : \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}_+$ be a cost function, and let the coupling

$$\Pi(P, Q) = \left\{ \pi(x, y) : \int \pi(dx, \cdot) = Q(\cdot), \int \pi(\cdot, dy) = P(\cdot) \right\}$$

be the set of joint distributions with marginals P and Q . For any cost function c , the total transportation cost induced by a plan $\pi \in \Pi(P, Q)$ is defined as

$$\mathcal{I}_c(\pi) = \int_{\mathcal{X} \times \mathcal{X}} c(x, y) \pi(dx, dy).$$

Here, $\pi(x, y)$ indicates how much “mass” is transported from x to y . The first constraint, $\int \pi(x, dy) = P(x)$, ensures that the mass at location x is spread over \mathcal{X} , while the second constraint, $\int \pi(dx, y) = Q(y)$, ensures that the destination at y receives the required mass. The OT problem seeks the optimal plan

$$\pi^* = \arg \min \{ \mathcal{I}_c(\pi) : \pi \in \Pi(P, Q) \},$$

minimizing the transportation cost. The corresponding minimal cost,

$$\mathcal{T}_c(P, Q) = \mathcal{I}_c(\pi^*),$$

induces a divergence between P and Q . This OT divergence provides a principled way to measure distributional similarity, enabling applications in density matching, generative modeling, and dimensionality reduction.

The optimal plan π^* and OT divergence typically lack closed-form solutions. Numerical algorithms [18] are used to compute the OT between discrete measures. When P and Q are discrete, the OT divergence reduces to:

Example 1 (OT Divergence Between Discrete Distributions). For $P = \sum_{i=1}^n u_i \delta_{x_i}$ and $Q = \sum_{j=1}^m v_j \delta_{y_j}$, the OT divergence is

$$\mathcal{T}_c(P, Q) = \min \left\{ \sum_{i=1}^n \sum_{j=1}^m \pi_{ij} c(x_i, y_j) : \sum_{i=1}^n \pi_{ij} = v_j, \sum_{j=1}^m \pi_{ij} = u_i \right\}. \quad (3)$$

Exact solutions can be found via linear programming, while approximations are obtained using algorithms like Sinkhorn.

A.2 Relationship Between Composite Transportation Divergence and OT

The Composite Transportation Divergence (CTD) [34, 35] extends OT to Gaussian mixtures. For two mixtures $\phi_n = \sum_{i=1}^n \alpha_i \phi(\cdot; \mu_i, \Sigma_i)$ and $\phi'_m = \sum_{j=1}^m \alpha'_j \phi(\cdot; \mu'_j, \Sigma'_j)$, the CTD is:

$$\mathcal{T}_c(\phi_n, \phi'_m) = \inf \left\{ \sum_{i=1}^n \sum_{j=1}^m \pi_{ij} c(\phi(\cdot; \mu_i, \Sigma_i), \phi(\cdot; \mu'_j, \Sigma'_j)) : \sum_{j=1}^m \pi_{ij} = \alpha_i, \sum_{i=1}^n \pi_{ij} = \alpha'_j \right\},$$

Comparing this with the discrete OT divergence (3), the CTD treats Gaussian mixtures as discrete distributions over the space of Gaussians, defining the divergence as the OT between them.

To illustrate, consider n warehouses and m factories in the space of Gaussian distributions \mathcal{F} . The i th warehouse, at $\phi(\cdot; \mu_i, \Sigma_i)$, holds α_i units of material, while the j th factory, at $\phi(\cdot; \mu'_j, \Sigma'_j)$, requires α'_j units. The cost to transport material from i to j is $c(\phi(\cdot; \mu_i, \Sigma_i), \phi(\cdot; \mu'_j, \Sigma'_j))$, and $\pi_{ij} \geq 0$ denotes the transported amount. The total cost under plan π is $\sum_{i,j} \pi_{ij} c(\phi(\cdot; \mu_i, \Sigma_i), \phi(\cdot; \mu'_j, \Sigma'_j))$. The coupling set $\Pi(\alpha, \alpha') = \{\pi_{ij} : \sum_{j=1}^m \pi_{ij} = \alpha_i, \sum_{i=1}^n \pi_{ij} = \alpha'_j\}$ ensures: (a) correct material removal from warehouses, and (b) correct delivery to factories. The OT problem seeks the plan $\pi^* \in \Pi(\alpha, \alpha')$ minimizing the total cost. The minimal cost corresponds to the CTD between the mixtures, quantifying the optimal transport cost between them.

Our compaction method leverages this interpretation, approximating a mixture with fewer Gaussians by minimizing their CTD-based dissimilarity.

A.3 Algorithm Intuition

At first glance, the optimization problem in (1) is bilevel: the OT plan must be found for any candidate $\{\bar{\alpha}_j, \bar{\mu}_j, \bar{\Sigma}_j\}_{j=1}^m$, and the objective must be minimized. However, as shown by Zhang et al. [17], this simplifies with a clear interpretation. The column-wise marginal constraints on π are redundant, and each Gaussian primitive (μ_i, Σ_i) transports its full mass to its “closest” counterpart. The optimal plan thus corresponds to clustering $\{(\mu_i, \Sigma_i)\}_{i=1}^n$ into m clusters $\{\mathcal{C}_j\}_{j=1}^m$, with the original Gaussians forming cluster “barycenters”. Mathematically, the simplified program is:

$$\min \left\{ \sum_{j=1}^m \sum_{i \in \mathcal{C}_j} \pi_{ij} c(\phi(\cdot; \mu_i, \Sigma_i), \phi(\cdot; \bar{\mu}_j, \bar{\Sigma}_j)) : [n] = \mathcal{C}_1 \sqcup \dots \sqcup \mathcal{C}_m \right\},$$

where \sqcup denotes disjoint union. The optimal plan has a closed form:

$$\pi_{ij} = \begin{cases} \alpha_i & \text{if } j = \arg \min_k c(\phi(\cdot; \mu_i, \Sigma_i), \phi(\cdot; \bar{\mu}_k, \bar{\Sigma}_k)), \\ 0 & \text{otherwise.} \end{cases}$$

With this, π and the reduced mixture parameters can be updated alternately, formalized in the following k -means-like algorithm:

- **Assignment Step:** Each Gaussian $\phi(\cdot; \mu_i, \Sigma_i)$ is assigned to cluster \mathcal{C}_j by minimizing $c(\phi(\cdot; \mu_i, \Sigma_i), \phi(\cdot; \bar{\mu}_j, \bar{\Sigma}_j))$, analogous to k -means’ nearest-centroid assignment.
- **Update Step:** For the cost function

$$c(\phi, \phi') = \|\mu - \bar{\mu}\|_2^2 + \|\Sigma - \bar{\Sigma}\|_F^2,$$

the parameters $(\bar{\mu}_j, \bar{\Sigma}_j)$ are updated as weighted averages:

$$\bar{\mu}_j = \frac{\sum_{i \in \mathcal{C}_j} \alpha_i \mu_i}{\sum_{i \in \mathcal{C}_j} \alpha_i}, \quad \bar{\Sigma}_j = \frac{\sum_{i \in \mathcal{C}_j} \alpha_i \Sigma_i}{\sum_{i \in \mathcal{C}_j} \alpha_i}.$$

This mirrors k -means' centroid update.

A.4 Algorithm Convergence

The following theorem guarantees convergence of the CTD sequence generated by Algorithm 1. In the worst case, the algorithm requires exponentially many steps, but it typically converges in about 5 iterations. A full proof is given in Zhang et al. [17].

Theorem 1 (Convergence of the Algorithm). *Suppose $c(\cdot, \cdot)$ is continuous, and for any $\Delta > 0$ and ϕ^* , the set $\{\phi : c(\phi^*, \phi) \leq \Delta\}$ is compact under some Gaussian space metric. Let $\{\bar{\phi}_m^{(t)}\}$ be the sequence generated by the update step with initial $\{\bar{\alpha}_j^{(0)}, \bar{\mu}_j^{(0)}, \bar{\Sigma}_j^{(0)}\}$, and let $\mathcal{T}_c^{(t+1)}$ be the CTD at iteration t . Then:*

1. *There exists T and $\{\bar{\alpha}_j^*, \bar{\mu}_j^*, \bar{\Sigma}_j^*\}$ such that for all $t \geq T$, $\{\bar{\alpha}_j^{(t)}, \bar{\mu}_j^{(t)}, \bar{\Sigma}_j^{(t)}\} = \{\bar{\alpha}_j^*, \bar{\mu}_j^*, \bar{\Sigma}_j^*\}$ and $\mathcal{T}_c^{(t+1)} = \mathcal{T}_c^{(*)}$, where $\mathcal{T}_c^{(*)}$ is the CTD between the original mixture and $\{\bar{\alpha}_j^*, \bar{\mu}_j^*, \bar{\Sigma}_j^*\}$.*
2. *The limit point $\{\bar{\alpha}_j^*, \bar{\mu}_j^*, \bar{\Sigma}_j^*\}$ is a local minimum of \mathcal{T}_c .*
3. *An MM-based exhaustive algorithm with $O(m^n)$ complexity solves (1).*

B Experiment Steps and Complexity Analysis in More Detail

B.1 Detailed 3DGS Pipeline

The advantages of 3DGS in rendering speed and image fidelity have made it applicable to a wide range of tasks, including human reconstruction, AI-generated content, autonomous driving, and beyond [36, 37, 38, 39]. Extensions to dynamic 3DGS, editable 3DGS, and surface representation have further broadened its utility [40, 41, 42]. 3D Gaussian Splatting (3DGS) represents a scene as a set of anisotropic 3D Gaussian primitives, each parameterized by its spatial location, shape, opacity, and radiance. The pipeline consists of the following key steps:

1. **Initialization.** From Structure-from-Motion (SfM), obtain calibrated camera poses and a sparse point cloud. Each point is initialized as a 3D Gaussian with an opacity α_i :

$$\phi(x; \mu_i, \Sigma_i) = |2\pi\Sigma|^{-1} \exp\left(-\frac{1}{2}(x - \mu_i)^T \Sigma_i^{-1} (x - \mu_i)\right),$$

where $\mu_i \in \mathbb{R}^3$ is the position (mean), $\Sigma_i \in \mathbb{R}^{3 \times 3}$ is the covariance matrix (anisotropic shape), and $\alpha_i \in [0, 1]$.

2. **Projection & Rasterization.** Each 3D Gaussian is projected to 2D using the camera model,

$$\Sigma'_i = JW \Sigma_i J W^T,$$

where W is a view transformation matrix and J is the Jacobian of the projective transform. Rasterization is done using a differentiable splatting approach which makes optimization possible.

3. **Image Formation (Alpha Blending).** The pixel color is computed via volumetric blending:

$$C = \sum_{i=1}^N T_i \cdot \alpha_i \cdot c_i \text{ with } T_i = \prod_{j=1}^{i-1} (1 - \alpha_j),$$

where c_i is the SH-predicted color of the i -th Gaussian in front-to-back order.

4. **Optimization.** The Gaussian parameters $\{\mu_i, \Sigma_i, \alpha_i, c_i\}$ are optimized to minimize a photometric loss:

$$\mathcal{L} = (1 - \lambda) \left\| \hat{C} - C^* \right\|_1 + \lambda \cdot \mathcal{L}_{\text{SSIM}},$$

where \hat{C} is the rendered image, C^* the ground truth, and $\lambda \in [0, 1]$ balances the two loss terms.

5. **Adaptive Densification & Pruning.** During training, Gaussians are cloned (under-reconstruction) or split (over-reconstruction) based on view-space gradient magnitude, and low-contribution Gaussians are pruned.

B.2 Algorithm Complexity

For Algorithm 1, we discuss its computational cost for reducing n Gaussians to m Gaussians. The assignment step requires computing pairwise distances between all n input Gaussians and m cluster centers, resulting in a complexity of $\mathcal{O}(nm)$. The update step involves computing the barycenters. Since the assignments are already known and the update for each cluster is linear in the number of assigned Gaussians, this step has a complexity of $\mathcal{O}(n)$. The overall time complexity of Algorithm 1 is $\mathcal{O}(nm)$.

Our GHAP algorithm consists of two components: *Geometric Compaction* and *Appearance Optimization* (fine-tuning). In this analysis, we focus only on the time complexity of the geometric compaction stage. The KD-tree is constructed by recursively splitting the dataset along the median of a selected coordinate axis until a maximum depth $d = \lfloor \log_2(n/s) \rfloor$ is reached. Let the input size be n , and the time complexity of building the tree be $T(n)$. This follows the recurrence: $T(n) = 2T(n/2) + \mathcal{O}(n \log_2 n)$. The recursion terminates after d levels, yielding a total KD-tree construction complexity of $\mathcal{O}(nd \log_2(n))$. In the second step of geometric compaction, Algorithm 1 is applied independently within each KD-tree block with s Gaussians reduced to ρs Gaussians. Based on our analysis in the previous paragraph, the per-block cost is $\mathcal{O}(\rho s^2)$. This along with the fact that there are $2^d = n/s$ blocks, the total complexity becomes: $\mathcal{O}((n/s) \cdot \rho s^2) = \mathcal{O}(\rho ns) = \mathcal{O}(ms)$. Combining with the KD-tree construction cost, the total time complexity of the geometric compaction step is $\mathcal{O}(n(d \log n + mT/2^d))$.

B.3 Detailed Experiments Steps

To ensure a fair comparison in our experiments, all methods undergo 30,000 total iterations under consistent training conditions. MCMC uses 30K iterations of its own update process in [24]. For other baselines, we summarize the backbone architecture, compaction methods, and fine-tuning steps in the table below.

Method	Backbone (0-15k iterations)	Compaction (15001th iteration)	Fine-tune (150001-30K iterations)
3DGS	a	None	d
3DGS+GHAP	a	Our compaction	d
LightGaussian	a	LightGaussian compaction	d
PUP-3DGS	a	PUP-3DGS compaction	d
Trimming the FAT	a	Trimming the FAT compaction	d
MesonGS	a	MesonGS compaction	d
MiniSplatting	b	MiniSplatting compaction	d
MiniSplatting-D+GHAP	b	Our compaction	d
LocoGS	c	LocoGS compaction	d

a Vanilla 3DGS densification and pruning in [3].

b Mini-Splatting densification and pruning in [12].

c LocoGS 3DGS update in [33].

d 3DGS fine-tuning in [3].

Key implementation details:

- For compaction methods applicable to pre-trained models (e.g., LightGaussian, PUP-3DGS, Trimming the FAT, MesonGS), we initialize from the same backbone model (trained using vanilla 3DGS) and apply their respective compaction directly—excluding any compression modules.

- All methods undergo identical fine-tuning (15k iterations) to achieve the target retention ratio.

This standardized protocol ensures that performance differences stem solely from the methods themselves, eliminating variations due to training procedures. All experiments are conducted on a server with 256 GB RAM and a 96-core Intel Xeon Platinum 8255C CPU, and on a workstation equipped with five NVIDIA RTX 3090 GPUs, each with 24 GB of VRAM.

C An Additional Comparison Experiments

As documented in prior work, 3DGS-MCMC [24] reinterprets the 3D Gaussian Splatting (3DGS) process through the lens of Markov Chain Monte Carlo (MCMC), thereby naturally exploring a broader parameter space. In particular, it formulates pruning as a state transition within the MCMC framework and incorporates L_1 regularization, avoiding abrupt hard-threshold deletions and enabling the natural removal of unnecessary Gaussian elements. Given these properties, a further comparative analysis with 3DGS-MCMC is warranted.

To facilitate a fair comparison, we configured 3DGS-MCMC under two settings: one constrained to 300k Gaussians, and another initialized with 3000k Gaussians followed by compaction using our method to reduce the count to 300k. Quantitative results on Tandt & Temples are summarized in the table below. As evidenced by the results presented in the table, GHAP combined with 3DGS-MCMC

Method	SSIM↑	PSNR↑	LPIPS↓
3DGS-MCMC-300k	0.813	22.925	0.239
3DGS-MCMC-3000k+GHAP	0.827	22.786	0.209

yields superior performance compared to the native 3DGS-MCMC approach constrained to 300k Gaussians. This demonstrates the effectiveness of our method in accurately approximating the surface geometry of 3DGS, highlighting the advantage of our compaction strategy.

D Ablation on Joint Geometry and Appearance Fine-tuning

In our configured compaction process, compaction was performed only once at the 15,001st iteration. We conducted an ablation study on the timing of compaction to examine the impact of varying compaction frequencies on the final outcome. Two alternative compaction strategies were considered: the first involved compacting to 20% at the 15,001st iteration, followed by an additional 50% compaction at the 20,001st iteration; the second strategy applied compaction of 40%, 50%, and 50% at the 15,001st, 20,001st, and 25,001st iterations, respectively. All three strategies ultimately resulted in a final retention rate of 10%. Experimental results, as presented in the table below, indicate that jointly refining geometry and appearance over multiple stages does not lead to evidently improved performance. Therefore, in practical applications, emphasis should be placed on executing appearance optimization for as long as possible, rather than pursuing multi-stage compaction.

Compacting Iteration	ρ	SSIM↑	PSNR↑	LPIPS↓
15001	0.1	0.817	23.313	0.242
15001, 20001	0.2,0.5	0.817	23.44	0.247
15001, 20001, 25001	0.4,0.5,0.5	0.811	23.359	0.255

E Additional Numerical Results and Scene Visualizations

We report a more comprehensive set of results for the comparison experiments in Table 4, including one different retention ratio: 20%. As shown in the updated results, our compaction method significantly outperforms other methods either post-processing compression methods or end-to-end methods.

In addition to the previously shown Figure 5, we present more detailed qualitative comparisons across multiple scenes in Figure 8. Our method consistently preserves the visual quality of the original models. In particular, when applied to stronger 3DGS variants with improved densification strategies, such as Mini-Splatting-D, our compaction framework performs even better. This is reflected in the fact that, after compaction, Mini-Splatting-D often achieves higher rendering quality than the original 3DGS baseline.

Table 4: We compared GHAP with four post-processing methods (LightGaussian, PUP-3DGS, Trimming the Fat, MesonGS) at 20% retention, as well as two end-to-end methods (LocoGS, 3DGS-MCMC). GHAP also replaces the pruning in Mini-Splatting. Results show that our method substantially outperforms both post-processing and end-to-end approaches.

Method	Tanks&Temples				MipNeRF-360				Deep Blending			
	SSIM↑	PSNR↑	LPIPS↓	k Gaussians	SSIM↑	PSNR↑	LPIPS↓	k Gaussians	SSIM↑	PSNR↑	LPIPS↓	k Gaussians
original 3DGS	0.853	23.785	0.169	1577	0.813	27.554	0.221	2627	0.907	29.816	0.238	2475
LocoGS	0.843	23.655	0.191	571	0.798	27.049	0.257	674	0.903	29.972	0.261	529
3DGS+GHAP (ours)	0.835	23.615	0.212	314	0.788	26.973	0.275	527	0.907	29.864	0.252	496
LightGaussian-20%	0.779	22.486	0.271	315	0.765	26.353	0.288	526	0.873	28.011	0.315	495
PUP-3DGS-20%	0.809	22.603	0.228	315	0.790	26.671	0.257	525	0.905	29.719	0.248	495
Trimming the Fat-20%	0.819	22.498	0.232	315	0.781	26.494	0.280	524	0.900	29.082	0.272	494
MesonGS-20%	0.822	20.699	0.207	314	0.776	25.006	0.262	527	0.897	28.696	0.262	496
3DGS-MCMC	0.779	22.141	0.282	315	0.763	25.957	0.309	263	0.885	28.976	0.298	496
MiniSplatting-20%	0.824	22.953	0.223	142	0.794	26.728	0.267	215	0.904	29.763	0.265	240
MiniSplatting+GHAP (ours)	0.855	23.403	0.171	155	0.821	27.310	0.214	219	0.912	30.170	0.238	250

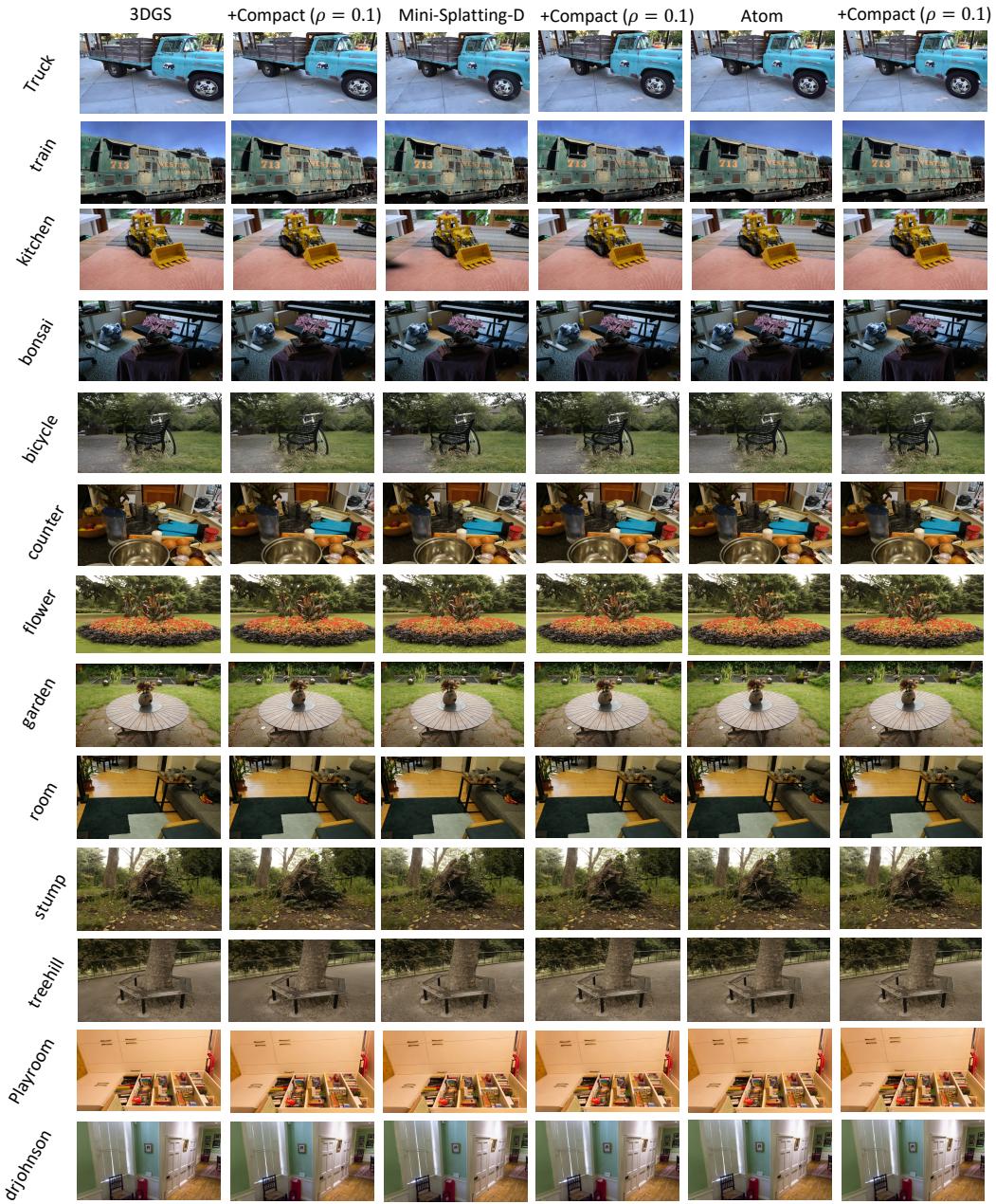


Figure 8: **More scenes visualization.** Visual comparisons across additional scenes before and after compaction.