



UNIVERSITY OF
CAMBRIDGE

Department of Computer
Science and Technology

MACHINE VISUAL PERCEPTION
COURSE PROJECT REPORT

Avoiding Local Minimum Problem in 3D Gaussian Splatting

Authors: Mario Pariona, Leo Takashige, Kee Yun Shao

Group number: 9

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1 Introduction and Motivation

Meshes and points are the most common 3D scene representations. However, they are not differentiable, posing significant challenges for gradient-based optimization tasks such as neural rendering and scene reconstruction. The 3D-GS paper [Kerbl et al., 2023] addresses this by introducing 3D Gaussians to represent a 3D scene, but their heuristics for operations like Cloning, Splitting, and Pruning may be sub-optimal due to their non-differentiable nature.

1.1 Introduction to the Problem

3D Gaussian Splatting (3D-GS) has become a cornerstone technique in real-time radiance field rendering due to its ability to represent complex 3D scenes using a minimal number of primitives. However, the algorithm is often hampered by local minima and poor scene alignment. To address these issues, the Evolutive Rendering Models (ERM) paper by Zhan and Liang et al. introduces the concept of Evolutive Primitive Organization (EPO), a learnable mechanism for adjusting the density of the scene representation via dynamic growing and splitting of primitives. This mechanism optimizes scene representation without the need for manually fixed parameters, allowing the model to adapt effectively during training.

1.2 Background and Related Work

Before delving into the specifics of our method, it is essential to understand the evolution of scene reconstruction and rendering techniques. Traditional scene reconstruction and rendering techniques have been primarily based on mesh representations, which often struggle with complex scenes. In contrast, neural rendering methods, including radiance fields and point-based rendering, offer promising alternatives, leveraging neural networks to model 3D scenes more efficiently and with better scalability.

▷ **Traditional Scene Reconstruction and Rendering** Early methods for novel-view synthesis, based on light fields, evolved from densely sampled to unstructured captures [Gortler et al. 1996; Levoy and Hanrahan 1996]. Structure-from-Motion (SfM) [Snavely et al. 2006] enabled sparse point clouds, later refined with Multi-View Stereo (MVS) for full reconstructions [Goesele et al. 2007]. However, these techniques suffered from issues like missing or redundant geometry. Neural rendering has since addressed these issues, eliminating the need for vast datasets on GPUs [Tewari et al. 2022].

▷ **Neural Rendering and Radiance Fields** Neural methods, such as those by Flynn et al. [2016] and Zhou et al. [2016], incorporated CNNs for texture blending. Early volumetric ray-marching methods [Henzler et al. 2019; Sitzmann et al. 2019] represented geometry as

continuous density fields, though they were computationally expensive. NeRF [Mildenhall et al. 2020] improved upon this with techniques like importance sampling, but still faced slow training and rendering times. Recent methods, like Mip-NeRF360 [Barron et al. 2022], have improved image quality but are still inefficient compared to our approach.

▷ **Point-Based Rendering and Radiance Fields** Point-based methods, such as those by Gross and Pfister [2011], efficiently render unstructured point clouds but suffer from aliasing and holes. High-quality point rendering [Botsch et al. 2005] reduces these issues, while recent advancements in differentiable point-based rendering [Wiles et al. 2020] have improved efficiency. Point-based and NeRF-like methods share a similar image formation model but differ in how they handle geometry. Our approach with 3D Gaussians improves on this by offering faster and more scalable rendering without the limitations of MVS-based techniques [Rückert et al. 2022; Lassner and Zollhofer 2021].

These methods highlight the progression from traditional to modern approaches in rendering, with our technique offering an efficient, scalable alternative for complex scenes.

1.3 Overview of the Idea

Prior research on 3D-Gaussian Splatting introduces representing scenes using 3D Gaussians (Splats) [Kerbl et al., 2023]. These Gaussians are instantiated using Structure From Motion (SfM) techniques and optimized via gradient descent. A key limitation is the lack of control over Splat density, making the optimization highly dependent on the initial point cloud quality. Under-reconstructed or over-reconstructed areas result in inappropriate Splat densities. To address this, Kerbl et al. propose *Adaptive Density Control (ADC)*, which periodically performs **Cloning**, **Splitting**, and **Pruning** operations. These operations dynamically adjust Splat density, improving scene representation by increasing density in under-reconstructed regions and reducing it in over-reconstructed areas, thus focusing computational resources on critical parts of the scene.

Our work builds upon the idea of ADC by implementing the concept of Evolutive Primitive Organization (EPO) as proposed by Zhan and Liang et al. EPO enhances the ADC mechanism by introducing learnable parameters for both the Cloning and Splitting operations. This allows the system to learn optimal strategies for growing and splitting primitives during training, removing the need for pre-defined heuristics. We are essentially replicating the same idea shown in their paper to validate their findings.

For the Cloning operation, the key idea is to introduce learnable parameters for the growth direction and growth length of the newly Cloned Splats, which are optimized using gradient descent. This allows the model to dynamically adjust the position and scale of the newly Cloned Splats based on the training objectives.

Similarly, the Split operation is enhanced by introducing learnable parameters for the split mean shift and scaling factor of the newly Split Splats. This allows the system to determine when and where to split primitives based on scene complexity and optimization needs. By optimizing these parameters using gradient descent, the model can dynamically adjust the position and scale of the newly Split Splats, leading to a more efficient and accurate representation of the scene.

2 Implementation

2.1 Original Algorithm

In this section, we describe the baseline architecture used as the foundation for our algorithm. The baseline is based on the 3D Gaussian Splatting (3D-GS) technique, which models a scene using 3D Gaussians.

Firstly, we initialize our initial scene representation using the point cloud generated by the SfM process on a set of input images. We also obtain and store the camera position of each input image from the SfM process.

At every iteration, we select one of the camera positions, and render the scene using that camera position. The rendered image is then compared with the corresponding input image, and a loss value is calculated. Gradients from the loss are then backpropagated to the parameters of the Splats, and used for their optimization.

At fixed intervals in the optimization process, we also carry out Adaptive Density Control, which comprises the following 3 operations: **Cloning**, **Splitting**, and **Pruning**, as shown in Algorithm 1.

2.1.1 Cloning

The Clone operation selects and replicates a subset of Splats in the model based on a gradient threshold. Specifically, Splats with positional gradients exceeding this threshold and located in under-reconstructed regions are selected for cloning. For each selected Splat, an exact copy is made, including all its parameters such as position, scaling, rotation, color, and transparency. Importantly, the gradients of the original Splat’s attributes are not copied to the new Splat. During the optimization step, the original Splat’s attributes are updated according to their gradients, while the newly cloned Splat remains unchanged.

2.1.2 Splitting

The Split operation selects and splits a subset of Splats in the model. Eligible Splats are chosen based on a gradient threshold and their scaling relative to the scene density. Each selected Splat is split into two copies, with their scale divided by a factor of $\phi = 1.6$. The positions of the two newly instantiated Splats are determined by sampling from the original 3D Gaussian’s probability density function.

Algorithm 1 Optimisation and Densification

```
1:  $M \leftarrow$  SfM Points                                 $\triangleright$  Positions
2:  $S, C, A \leftarrow$  InitAttributes()                   $\triangleright$  Covariances, Colors, Opacities
3:  $i \leftarrow 0$                                           $\triangleright$  Iteration Count
4: while not converged do
5:    $V, \hat{I} \leftarrow$  SampleTrainingView()            $\triangleright$  Camera  $V$  and Image
6:    $I \leftarrow$  Rasterize( $M, S, C, A, V$ )
7:    $L \leftarrow$  Loss( $I, \hat{I}$ )                                $\triangleright$  Loss
8:    $M, S, C, A \leftarrow$  Adam( $\nabla L$ )                 $\triangleright$  Backprop & Step
9:   if IsRefinementIteration( $i$ ) then
10:    for all Gaussians  $(\mu, \Sigma, c, \alpha)$  in  $(M, S, C, A)$  do
11:      if  $\alpha < \epsilon$  or IsTooLarge( $\mu, \Sigma$ ) then           $\triangleright$  Pruning
12:        RemoveGaussian()
13:      end if
14:      if  $\nabla_p L > \tau_p$  then                       $\triangleright$  Densification
15:        if  $\|\Sigma\| > \tau_S$  then                       $\triangleright$  Over-reconstruction
16:          SplitGaussian( $\mu, \Sigma, c, \alpha$ )
17:        else                                      $\triangleright$  Under-reconstruction
18:          CloneGaussian( $\mu, \Sigma, c, \alpha$ )
19:        end if
20:      end if
21:    end for
22:   end if
23:    $i \leftarrow i + 1$ 
24: end while
```

2.1.3 Pruning

The Prune operation selects and removes a subset of Splats from the model, by comparing their transparency values, α , against a minimum acceptable transparency, ϵ_α . Any splats in the scene with $\alpha < \epsilon_\alpha$ are removed from the representation, and are not rendered as part of the output image.

2.2 Algorithm Improvements

One issue with the implementation of the ADC is that the operations are heuristic in nature, and may hence be sub-optimal, because they are non-differentiable and may misalign with the final training objective [Zhan and Liang et al., 2024]. Zhan and Liang et al. instead propose the technique of Evolutive Primitive Organization, which builds upon the original implementation of ADC by introducing optimizable parameters, used in the Cloning and Splitting operations that allow them to be optimized using the backpropagation of gradients from the loss to the parameters.

2.2.1 Cloning

By incorporating backpropagation, we allow the system to learn optimal cloning strategies during training, removing the need for pre-defined heuristics. The key idea is to introduce

learnable parameters for the growth direction and growth length of the newly Cloned Splat, which are optimized using gradient descent. This allows the model to dynamically adjust the position and scale of the newly Cloned Splat based on the training objectives.

We aim to optimize the position of the newly Cloned Splat, which is determined by its growth direction d and growth length l , relative to the original Splat (its Parent). Let μ_k denote the position of the original Splat, and $\delta\mu_k$ denote the relative position of the newly Cloned Splat. The relationship can be expressed as $\delta\mu_k = d \cdot l$.

To achieve this, we introduce two new learnable parameters for each Splat: **growth direction probabilities** gp and **growth length** gl . These parameters will be used to calculate the growth direction d and growth length l respectively, as shown in Figure 2.1.

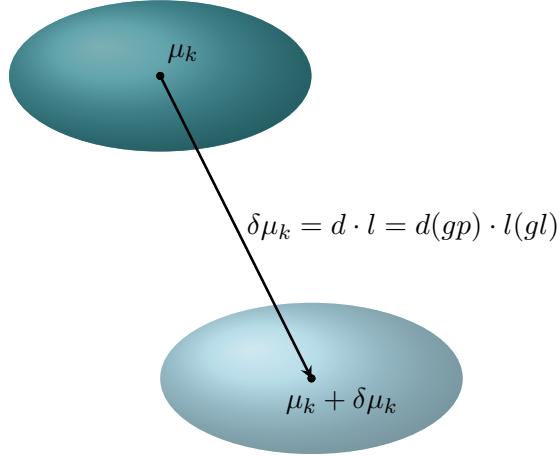


Figure 2.1: Position of newly Cloned Splat.

2.2.2 Splitting

The Split operation is similarly modified to allow for the optimization of the splitting strategy during training. The key idea is to introduce learnable parameters for the split mean shift and scaling factor of the newly Split Splats, which are optimized using gradient descent. This allows the model to dynamically adjust the position and scale of the newly Split Splats based on the training objectives.

We aim to optimize the relative positions of the two newly split Splats. Let μ denote the position of the original Splat, and $\delta\mu$ and $-\delta\mu$ denote the relative positions of the two newly split Splats. The parameter $\delta\mu$ is optimized through the introduction of a learnable parameter s' , which is used in its calculation.

We also aim to optimize the scale Σ of the two newly split Splats with respect to their Parent. We introduce the variable ϕ , which is used as a scaling factor such that $\Sigma_{\text{new}} = \frac{\Sigma_{\text{old}}}{\phi}$. The parameter ϕ is optimized through the introduction of another learnable parameter v , which is used in its calculation.

2.2.3 Pruning

We did not modify the original implementation of the Prune operation, focusing instead on the Clone and Split operations. However, we believe our methodology can be extended to the Prune operation in future work, as the baseline algorithm also heuristically determines which splats to remove. Specifically, the minimum transparency threshold, ϵ_α , is chosen heuristically.

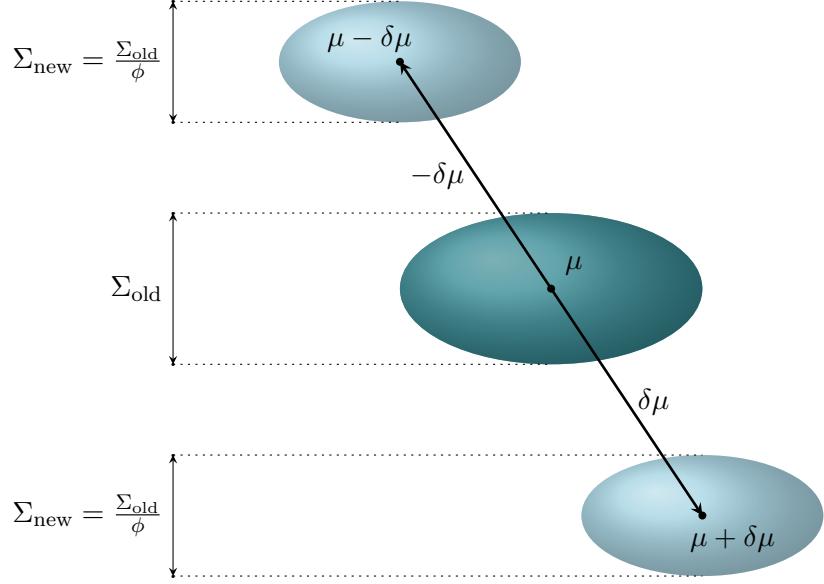


Figure 2.2: Position and scale of newly split Splats.

An improved implementation might be able to somehow treat ϵ_α as an optimizable parameter, allowing the Pruning operation to be optimized using gradient descent based on training objectives.

2.3 Implementation Details

The implementation of Evolutive Primitive Organization (EPO) requires a few key modifications to the traditional Gaussian splatting technique. Primarily, the Gaussian splats are allowed to evolve, growing or splitting based on optimization feedback. The system is also trained using gradient descent, with learnable parameters that control the clone and split operations, as shown in Algorithm 2.

The improvements were implemented in Python, using the PyTorch framework. The enhanced ADC mechanism was integrated into the training loop, allowing for dynamic adjustment of Gaussians during training.

2.3.1 Cloning

The cloning mechanism is integrated with a differentiable framework, allowing it to be trained alongside other parameters. This reduces the reliance on static heuristics and enables the optimization of splats based on scene-specific needs.

▷ **Forward Pass** Zhan and Liang et al. provided pseudocode for implementing an algorithm to optimize either the growth direction d or the growth length l . The chosen parameter is discretized into a set of uniformly distributed possible values. Each Splat is assigned a learnable set of probabilities, with each probability representing the likelihood of selecting the corresponding value for the parameter.

In the forward pass, the Argmax function selects the value with the highest probability for the parameter, which is then used to calculate $\delta\mu_k$. However, the Argmax function disrupts the

Algorithm 2 Optimisation and Densification with EPO

```

1:  $M \leftarrow$  SfM Points                                 $\triangleright$  Positions
2:  $S, C, A, S', V, GP, GL \leftarrow$  InitAttributes()           $\triangleright$ 
   Covariances, Colors, Opacities, Splitting Distance, Splitting Scaling,
   Growth Probabilities, Growth Lengths
3:  $i \leftarrow 0$                                           $\triangleright$  Iteration Count
4: while not converged do
5:   if IsRefinementIteration( $i$ ) then
6:      $V, \hat{I} \leftarrow$  SampleTrainingView()            $\triangleright$  Camera  $V$  and Image
7:      $I \leftarrow$  Rasterize( $M, S, C, A, V, S', V, GP, GL$ )
8:      $L \leftarrow$  Loss( $I, \hat{I}$ )                          $\triangleright$  Loss
9:     for all Gaussians  $(\mu, \Sigma, c, \alpha, s', v, gp, gl)$  in
   ( $M, S, C, A, S', V, GP, GL$ ) do
10:    if  $\alpha < \epsilon$  or IsTooLarge( $\mu, \Sigma$ ) then            $\triangleright$  Pruning
11:      RemoveGaussian()
12:    end if
13:    if  $\nabla_p L > \tau_p$  then                       $\triangleright$  Densification
14:      if  $\|\Sigma\| > \tau_S$  then                   $\triangleright$  Over-reconstruction
15:        SplitGaussian( $\mu, \Sigma, c, \alpha, s', v$ )
16:      else                                      $\triangleright$  Under-reconstruction
17:        CloneGaussian( $\mu, \Sigma, c, \alpha, gp, gl$ )
18:      end if
19:    end if
20:  end for
21: end if
22:  $I \leftarrow$  Rasterize( $M, S, C, A, V, S', V, GP, GL$ )
23:  $L \leftarrow$  Loss( $I, \hat{I}$ )
24:  $M, S, C, A, S', V, GP, GL \leftarrow$  Adam( $\nabla L$ )        $\triangleright$  Backprop & Step
25:  $i \leftarrow i + 1$ 
26: end while

```

flow of gradients from the loss to the input parameters (the set of probabilities). To address this, the algorithm propagates gradients as though the Softmax function had been used instead. This approach allows for effective optimization of the set of probabilities according to training objectives.

In their implementation, Zhan and Liang et al. chose to optimize the growth direction d using the aforementioned algorithm. For the growth length l , they directly learned the growth distance by using the standard deviation of the Parent Splat as a constraint. Specifically, they set $l = v \times \frac{1}{1+e^{-s}}$, where s is a learnable parameter and $v = 2\sigma$, with σ being the maximum standard deviation of the Parent Splat.

\triangleright **Backward Pass** In the backward pass of the original 3D-GS implementation by Kerbl et al., the gradients for the original parameters of the Splats, including their positions μ , are calculated during the image rendering process. However, the computation of gradients does not extend to our newly introduced learnable parameters p and s .

To address this, we manually calculate and propagate the gradients of p and s using the chain rule. For the Clone operation, the formulas are as follows:

$$\mu_{\text{new}} = \mu_{\text{old}} + \delta\mu_k$$

Algorithm 3 Pseudo-code of forward & backward propagation in primitive growth spherical/radial distribution optimization

Input:

potential grow directions $D = \{d_1, d_2, \dots, d_N\}$ / potential grow distance $T = \{t_1, t_2, \dots, t_N\}$

grow direction/distance probability $Q = [p_1, p_2, \dots, p_N]$

Forward propagation:

1. index = Argmax(Q)
2. index-hard = One-Hot(index)
3. grow direction $d = \text{Matmul}(\text{index-hard}, D)$ / grow distance $t = \text{Matmul}(\text{index-hard}, T)$

Backward propagation:

1. index-soft = Softmax(Q)
 2. grow direction $d = \text{Matmul}(\text{index-soft}, D)$ / grow distance $t = \text{Matmul}(\text{index-soft}, T)$
-

$$\delta\mu_k = d(p) \cdot l(s)$$

Since p and s only affect μ_{new} , their impact on the loss value is dependent solely on their impact on μ_{new} . Therefore, we have:

$$\begin{aligned}\frac{\partial \text{loss}}{\partial p} &= \frac{\partial \text{loss}}{\partial \mu_{\text{new}}} \cdot \frac{\partial \mu_{\text{new}}}{\partial p} \\ \frac{\partial \text{loss}}{\partial s} &= \frac{\partial \text{loss}}{\partial \mu_{\text{new}}} \cdot \frac{\partial \mu_{\text{new}}}{\partial s}\end{aligned}$$

The term $\frac{\partial \text{loss}}{\partial \mu_{\text{new}}}$ is obtained from the back-propagation of gradients to the means of the Splats, as calculated in the original implementation by Kerbl et al. We store a mask of the newly Cloned points when they are created to isolate the gradients for these Splats.

To compute $\frac{\partial \mu_{\text{new}}}{\partial p}$ and $\frac{\partial \mu_{\text{new}}}{\partial s}$, we use PyTorch's automatic gradient calculation based on the positions of the newly Cloned Splats.

In practice, $\frac{\partial \text{loss}}{\partial \mu}$ is an $N \times 3$ matrix, where N is the total number of Splats. Each element $\frac{\partial \text{loss}}{\partial \mu}_{ij}$ represents the contribution to the loss from the a -coordinate of μ_i , where:

$$a = \begin{cases} x & \text{if } j = 1 \\ y & \text{if } j = 2 \\ z & \text{if } j = 3 \end{cases}$$

We split $\frac{\partial \mu_{\text{new}}}{\partial p}$ into an $N \times 3 \times m$ tensor, where m represents the number of discrete growth directions. Here, $\frac{\partial \mu_{\text{new}}}{\partial p}_{ijk}$ represents the contribution to the a -coordinate in μ_{new} by the k -th probability in p_i . The final multiplication gives us the desired shape $N \times m$, with each $\frac{\partial \text{loss}}{\partial p}_{ik}$ representing the contribution to the loss by the k -th probability in p_i .

Similarly, we split $\frac{\partial \mu_{\text{new}}}{\partial s}$ into an $N \times 3$ tensor, with $\frac{\partial \mu_{\text{new}}}{\partial s}_{ij}$ representing the contribution to the a -coordinate in μ_{new} by s_i . The final calculation of $\frac{\partial \text{loss}}{\partial s}$ hence gives the desired shape $N \times 1$.

We chose to update gradients for the Parent Splats, not the newly Cloned Splats, because the effect on the loss was due to the clone operation using the Parent Splats' parameters.

2.3.2 Splitting

The Split operation is similarly modified to allow for the optimization of the splitting strategy during training. The key idea is to introduce learnable parameters for the split mean shift and scaling factor of the newly Split Splats, which are optimized using gradient descent. This allows the model to dynamically adjust the position and scale of the newly Split Splats based on the training objectives.

▷ **Forward Pass** The implementation of the Split operation by Zhan and Liang et al. optimizes the split mean shift, $\delta\mu$, as well as the scaling factor of newly Split Splats, ϕ .

For the optimization of $\delta\mu$, each Splat in the scene is initialized with a learnable parameter s' . The formula $\delta\mu = R(\sigma_k \times \frac{1}{1+e^{-s'}})$ is then applied to calculate $\delta\mu$, where σ_k and R are the standard deviation and rotation matrix of the Parent Splat. Once $\delta\mu$ is calculated, the positions of the 2 newly Split Splats are initialized at $\mu + \delta\mu$ and $\mu - \delta\mu$ respectively.

For the optimization of ϕ , each Splat is initialized with another learnable parameter v . The scaling factor ϕ is then calculated using the formula $\phi = 1.2 \times \frac{1}{1+e^{-v}}$. Once ϕ is calculated, it is used to calculate the scale φ of the newly Split Splats, using the formula $\varphi_{\text{new}_1} = \varphi_{\text{new}_2} = \frac{\varphi_{\text{old}}}{\phi}$.

▷ **Backward Pass** To obtain the gradients for s' , we again note that the impact of s' on the rendered image, and hence the loss, is limited to its impact on the positions of the newly Split Splats. Thus, we can again use the chain rule to calculate its gradient:

$$\frac{\partial \text{loss}}{\partial s'} = \frac{\partial \text{loss}}{\partial \mu_{\text{new}}} \times \frac{\partial \mu_{\text{new}}}{\partial s'}$$

The impact of v on the loss is limited to its impact on the scaling of the newly Split Splats.

$$\frac{\partial \text{loss}}{\partial v} = \frac{\partial \text{loss}}{\partial \varphi_{\text{new}}} \times \frac{\partial \varphi_{\text{new}}}{\partial s'}$$

Similarly, $\frac{\partial \text{loss}}{\partial \mu_{\text{new}}}$ and $\frac{\partial \text{loss}}{\partial \varphi_{\text{new}}}$ are obtained from the back-propagation of gradients in the original 3D-GS implementation by Kerbl et al., and $\frac{\partial \mu_{\text{new}}}{\partial s'}$ and $\frac{\partial \varphi_{\text{new}}}{\partial s'}$ are obtained from invoking Pytorch's backward pass when μ_{new} and φ_{new} are calculated respectively.

Importantly, φ is also a $N \times 3$ tensor, representing the scaling of each Splat in each of its principal axes. Hence, the same logic is applied here to calculate $\frac{\partial \varphi_{\text{new}}}{\partial s'}$ as a $N \times 3$ tensor, with each $\frac{\partial \varphi_{\text{new}}}{\partial s'}_{ij}$ representing the contribution of s'_i to the scaling of φ_{new} in the axis corresponding to j .

For the Split operation, we update the gradients of the parameters of the newly Split Splats, since the Parent Splat is removed from the model entirely.

3 Evaluation

The effectiveness of the proposed Evolutive Primitive Organization (EPO) is evaluated through a series of tests on standard datasets, such as LLFF and Mipnerf360. These datasets are commonly used for evaluating 3D Gaussian Splatting methods.

3.1 Datasets

The LLFF (Local Light Field Fusion) and Mipnerf360 datasets provide high-quality images and scenes for evaluating 3D scene reconstruction and optimization methods. These datasets include complex geometry and radiance fields that allow for an effective comparison of different optimization strategies, including EPO.

We used the well-known Mip-NeRF360 dataset [Mildenhall et al. 2019] and LLFF dataset [Knapitsch et al. 2017] for training and testing our model. Additionally, we created two scenes for our own dataset and used synthetic scenes from the Synthetic Blender dataset. The datasets were preprocessed to extract training and testing images, which were then fed into the model for training and evaluation.

MipNeRF360 outdoor:

- Bicycle
- Stump

MipNeRF360 Indoor:

- Counter (indoor)

Deep Blending:

- Playroom

Tanks and Temples:

- Truck
- Train

LLFF:

- Horns (62 images)
- T-rex (55 images)

Same as NeRF, 3D-GS and the ERM, we take each 8th image for the test set and others for the training set.

3.2 Training and Testing Results

[Explain the training and testing results with graphs and elaborating on why they make sense, what could be improved.]

The results show that the EPO-enhanced algorithm performs significantly better than traditional methods, particularly in avoiding local minima and improving scene alignment. The learnable growing and splitting operations allow the system to adapt more effectively to different scenes, leading to better overall optimization.

3.3 Qualitative Results

The qualitative analysis demonstrates that scenes rendered with the EPO-enhanced method are more accurate and visually appealing. The evolved primitives are better aligned with the geometry and radiance fields, resulting in sharper and more realistic images.

We test our model on both real-world scenes from previously published datasets, including the Mip-NeRF360 dataset, LLFF dataset, and synthetic scenes from the Deep Blending dataset. The specific scenes used from each dataset are as follows:

For the MipNeRF360 outdoor dataset, we used the Bicycle and Stump scenes. From the Mip-NeRF360 indoor dataset, we used the Counter scene. For the Deep Blending dataset, we used the Playroom scene. From the Tanks and Temples dataset, we used the Truck and Train scenes. Lastly, from the LLFF dataset, we used the Horns scene with 62 images and the T-rex scene with 55 images.

[Big picture of as Figure 5 in 3DGS]

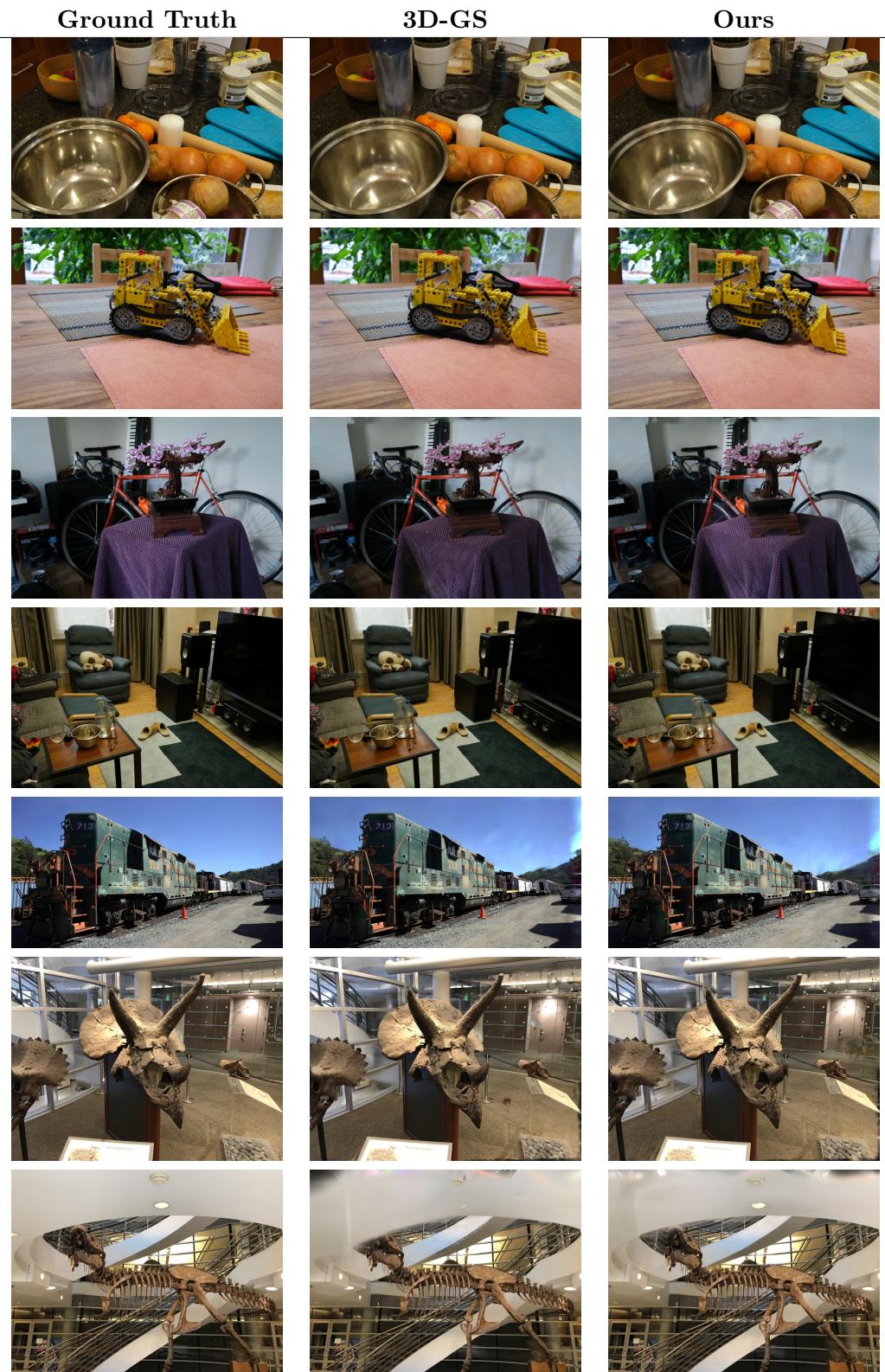


Figure 3.1: Comparison of Ground Truth, 3D-GS, and Ours across different scenes.

Category	Scene	Method	SSIM↑	PSNR↑	LPIPS↓	Mem
MipNeRF360 Indoor	Counter	3D-GS	0.909	29.10	0.199	255MB
		Our Model	0.909	29.07	0.198	275MB
	Kitchen	3D-GS	0.928	31.49	0.125	378MB
		Our Model	0.928	31.40	0.126	393MB
	Bonsai	3D-GS	0.943	32.34	0.204	252MB
		Our Model	0.942	32.35	0.203	263MB
	Room	3D-GS	0.921	31.65	0.217	309MB
		Our Model	0.920	31.66	0.215	340MB
	Train	3D-GS	0.821	22.13	0.196	257MB
		Our Model	0.821	22.19	0.197	273MB
LLFF	Horns	3D-GS	0.887	27.21	0.132	157MB
		Our Model	0.887	27.32	0.134	163MB
	Trex	3D-GS	0.899	25.59	0.130	110MB
		Our Model	0.909	26.66	0.116	116MB

Table 3.1: Comparison of 3D-GS and Our Model across different scenes and categories. Metrics: SSIM, PSNR, LPIPS, and Memory Usage. Arrows indicate the desired trend for each metric.

4 Conclusions and Future Directions

4.1 Conclusions

The integration of Evolutive Primitive Organization (EPO) into 3D Gaussian Splatting provides a robust solution to the local minima problem. By introducing learnable growing and splitting operations, the algorithm becomes more adaptive and efficient, enhancing the overall performance of 3D rendering models.

In this project, we explored the use of 3D Gaussian Splatting for real-time radiance field rendering. We introduced an adaptive density control mechanism to dynamically adjust the number of Gaussians in the scene, leading to improved representation and rendering quality. Our results demonstrate the effectiveness of this approach in various scenes.

4.2 Discussion of Limitations

While the approach shows promising results, it is still limited by the need for large-scale datasets to train the system effectively. Additionally, the computational cost of the learnable primitives may be high, especially for complex scenes.

While our method shows significant improvements, it has some limitations. The adaptive density control mechanism can be computationally expensive, and the choice of parameters such as the threshold ϵ_α can significantly impact the results. Additionally, our method may struggle with extremely complex scenes where the number of Gaussians required becomes prohibitively large.

4.3 Future Directions

Future work will explore further optimization of the EPO mechanism, including better training strategies, more efficient backpropagation methods, and applying this technique to a broader range of rendering applications.

Future research could focus on optimizing the adaptive density control mechanism to reduce computational overhead. Exploring alternative representations and hybrid approaches could further enhance the scalability and efficiency of the method. Additionally, investigating the integration of our approach with other neural rendering techniques could lead to even more robust and versatile solutions.

Another promising direction is to explore the possibility of learning the threshold ϵ_α in the Pruning operation (subsection 2.2.3). Instead of using a fixed heuristic threshold, ϵ_α could be treated as a learnable parameter that is optimized during training. This would allow the model to dynamically adjust the pruning criteria based on the specific characteristics of the scene and

the training objectives, potentially leading to more effective and efficient pruning.