Compressing Explicit Voxel Grid Representations: fast NeRFs become also small

Chenxi Lola Deng Enzo Tartaglione

LTCI, Télécom Paris, Institut Polytechnique de Paris

Abstract

NeRFs have revolutionized the world of per-scene radiance field reconstruction because of their intrinsic compactness. One of the main limitations of NeRFs is their slow rendering speed, both at training and inference time. Recent research focuses on the optimization of an explicit voxel grid (EVG) that represents the scene, which can be paired with neural networks to learn radiance fields. This approach significantly enhances the speed both at train and inference time, but at the cost of large memory occupation. In this work we propose Re:NeRF, an approach that specifically targets EVG-NeRFs compressibility, aiming to reduce memory storage of NeRF models while maintaining comparable performance. We benchmark our approach with three different EVG-NeRF architectures on four popular benchmarks, showing Re:NeRF’s broad usability and effectiveness.

1. Introduction

The rising of Neural Radiance Fields (NeRF) techniques has heavily impacted the field of 3D scene modeling and reconstruction in recent years [25, 43, 13, 14, 11]. Efficient photo-realistic novel view generation from a fixed set of training images has been a popular area of research in computer vision with broad applications. The ability to distill the essence of the 3D object from 2D representations of it and its compactness is the main reason for making NeRF a high-impact approach in the literature.

The original NeRF [25] consists of a multi-layer perceptron, which implicitly learns the manifold representing the 3D object. Because of its great generalization for synthesizing novel viewpoints and the high compactness of the model itself, which typically consists of a few MB, NeRF has become a prevalent approach for 3D reconstruction. However, the NeRF’s MLP has to be queried million times to render a scene, leading to slow training and rendering time.

In an effort to speed up the vanilla NeRF, follow-up works introduced modifications to the original NeRF architecture [8, 3, 34]. One of the popular approaches, for example, encodes features of a scene in an explicit 3D voxel grid, combined with a tiny MLP. This group of methods, which utilizes an “explicit voxel grid” (EVG), is gaining more and more popularity due to the high training and rendering speed while maintaining or improving the performance of the original NeRF. Unlike traditional NeRF, EVG-NeRF models require larger memory, limiting their deployment in real-life applications, where models need to be shared through communication channels, or many of these models must be stored on memory-constrained devices.

In this work, we propose Re:NeRF, a method that reduces memory storage required by trained EVG-NeRF models. Its goal is to accurately separate the object from its background, discarding unnecessary features for rendering the scene, guided by the loss functions designed for training the specific EVG-NeRFs. Re:NeRF enables generation of highly compressed models with little or no performance loss: it is specifically designed for EVG-NeRFs as it exploits a spatial locality principle for adding-back voxels to the grid, and in such a sense its working flow resembles the one of a sculptor (Fig. 1). We observe that Re:NeRF enables high-level compression of pre-trained EVG-NeRF models, and that traditional general-purpose approaches, such as blind pruning, perform worse than Re:NeRF. We test Re:NeRF on four datasets with three recent EVG-NeRFs validating the effectiveness of the proposed approach.

2. Related works

Rendering photo-realistic novel views of a 3D scene from a set of calibrated 2D images of the given scene has
been a popular area of research in computer vision and computer graphics. Inspired by Mildenhall et al’s work in 2020, which proposed to capture the radiance and density field of a 3D scene entirely using a multi-layer perceptron (MLP) [25], a large number of follow-up studies have adopted the implicit representation of a scene. Here follows an overview of 3D representation models, neural radiance fields, and follow-up works.

**3D representation for novel view synthesis.** Inferring novel views of a scene given a set of images is a longstanding challenge in the field of computer graphics. Various scene representation techniques for 3D reconstruction have been studied in past decades. Light field rendering [4, 19, 31] directly synthesizes unobserved viewpoints by interpolating between sampled rays but it is slow to render and requires substantial computational resources. Meshes are another common technique that is easy to implement and allows rendering in real-time [5, 39, 41]. However, it struggles to capture fine geometry and topological information and its rendering quality is limited to mesh resolution. Differentiable methods have been recently proposed to perform scene reconstruction [6, 21, 33]. They use a differentiable ray-marching operation to encode and decode a latent representation of a scene and achieve excellent rendering quality.

**Neural Radiance Fields.** Unlike traditional explicit volumetric representation techniques, NeRF [25] stands out in recent years to be the most prevalent method for novel view rendering that infers photo-realistic views given a moderate number of input images. It encodes the entire content of the scene including view-dependent color emission and density into a single multi-layer perceptron (Fig. 2a) and achieves state-of-the-art quality. Besides, Neural Radiance Field-based approaches are proving on-the-field to have good generalization when undergoing several transformations, like changing environmental light [1, 32], image deformation [9, 27, 40] and are even usable in more challenging setups including meta learning [35], learn dynamically-changing scenes [10, 20, 23, 42] and even in generative contexts [2, 16, 29]. Compared to explicit representations, NeRF requires very little storage space, but on the contrary suffers from lengthy training time and very slow rendering speed, as the MLP is queried an extremely high number of times for rendering a single image.

**NeRF with explicit voxel grids.** To reduce inference and training time, explicit prior on the 3D object representation can be imposed. The most intuitive yet effective approach relies on splitting the 3D volume into small blocks, each of which is learned by a tiny NeRF model. With KiloNeRF [28], the advantage of doing this is twofold: the size of a single NeRF model is much smaller than the original one, reducing the latency time; secondly, the rendering process itself becomes parallelizable, as multiple pixels can be rendered simultaneously. The downside of this approach is that the granularity of the KiloNeRFs needs to be properly tuned, and the distillation of the single tinier NeRFs can be quite an expensive process. An interesting approach that leverages radiance fields with no explicit neural component is Plenoxels [8]. In this case, a sparse feature grid is encoded with 3D spherical harmonics (it belongs to EVG approaches without the MLP component in Fig. 2b). Hence, both the training time and the inference times are drastically improved, however, at the cost of a significant increment in-memory storage for the learned model, despite its sparse representation. Showing similar convergence time but maintaining an MLP component for complex view-dependent appearances, DVGO [34] proposes post-activation interpolation. Recently, in order to further improve the execution speed, TensoRF [3] has been proposed, which decomposes a 4D tensor into low-rank components prior to training. With the lower-quality rendering setup, the authors deliver a model of size comparable to the original NeRF, but with higher-quality rendering the memory discrepancy with the vanilla NeRF model is still quite wide.

**Compressing EVG-NeRF.** Whilst dense voxel-based representations increase rendering speed drastically, they require an order of magnitude more memory than implicit...
volumetric representations to achieve comparable rendering quality. Hierarchical structure representations using octrees allow the 3D scene to be encoded in a sparse manner, but the memory occupancy still remains high. Recent work addressed the problem of training a model with neural sparse voxel fields [22] progressively reducing the granularity of voxels and skipping the rendering for empty voxels. This approach, however, is designed for resource reallocation. While it improves the rendering speed, it still suffers from a long training time. To the best of our knowledge, Re:NeRF is the first approach focusing on compression specifically for EVG-NeRFs. While other works leverage the knowledge of sparsity of the 3D scene [22, 8, 34], they are focused on performance enhancement (fighting against artifacts which might appear in the empty space) and are not specific for compression. In this work, we are NeRF architecture agnostic, and our goal is to preserve the performance while reducing the model’s size.

3. Re:NeRF

In this section, we present Re:NeRF, our approach towards storage memory reduction for EVG-NeRFs. To reduce the model size, we iteratively remove parameters with the least ranked importance. Following each round of pruning, we design a strategy that adds back neighbor voxels to avoid a drop in performance.

3.1. Which parameters are important?

One of the key characteristics making EVG-NeRF an effective approach is the possibility of end-to-end training: given some target loss function $\mathcal{L}$ evaluated on the rendered image, using back-propagation, it is possible to train all the parameters $w$ of the model. This learning approach is common with any standard deep neural network, which allows us to build on top of the existing technique with the same set of optimizers (such as SGD and Adam). Methods based on mini-batches of samples have gained popularity, as they allow better generalization than stochastic learning while being memory and time efficient. They also benefit from libraries that exploit parallel computation on GPUs. In such a framework, a network parameter $w_i$ is updated towards the averaged direction which minimizes the averaged loss for the mini-batch. Evidently, if the gradient’s magnitude is zero, the parameter is not updated, meaning that the local loss landscape for it is flat. A typical approach to reduce the number of parameters in a deep neural network is to threshold the parameters according to some hyper-parameters that determine the amount to be removed [36, 7]:

$$w_i = \begin{cases} w_i & \text{if } |w_i| > Q_{|w_i|}(\gamma) \\ 0 & \text{otherwise} \end{cases}$$

(1)

where $Q_{|w|}(\gamma)$ is the quantile function for the $\ell_1$ norm of the parameters and $\gamma \in [0;1]$ is the percentage of parameters to be removed. Despite its simplicity and broad application, this approach has a potential issue: parameters having very low magnitude can be important for the model. For example, a parameter can have a very low magnitude but a high gradient: hard-setting it to zero according to (1) can significantly influence the loss value/performance. Because of this, other works have suggested evaluating the importance of a parameter using the gradient of a parameter as a criterion [17, 37]. A parameter $w_i$ can have a low gradient locally, but removing it may potentially impose a drastic change in both the loss value and its gradient. It is necessary, hence, to find a compromise between these two conditions. We can estimate the variation of the loss value using a Taylor series expansion truncated to the first order:

$$\Delta \mathcal{L}(w_i) \approx \frac{\partial \mathcal{L}}{\partial w_i} w_i,$$

(2)

and from (2) we can define how to remove the parameters according to

$$w_i = \begin{cases} w_i & \text{if } |\mathcal{L}(w_i)| > Q_\mathcal{L}(\Delta \mathcal{L}(w_i))(\gamma) \\ 0 & \text{otherwise} \end{cases}$$

(3)

It is a known fact, however, that both gradient and weight magnitudes for the parameters change depending on the topology of layers taken into consideration [18]. Hence, in order to address a parameter-removing strategy that could be applied globally (hence, removing a given ratio of the parameters from the whole model, without imposing uniformity in this removal), the quantile function should be evaluated on the layer-normalized quantity

$$\Delta \hat{\mathcal{L}}(w_i) = \max \frac{\partial \mathcal{L}}{\partial w_i} w_i \text{ in same layer as } w_i.$$ 

(4)

Consequently, (3) becomes

$$w_i = \begin{cases} w_i & \text{if } |\mathcal{L}(w_i)| > Q_\mathcal{L}(\Delta \hat{\mathcal{L}}(w_i))(\gamma) \\ 0 & \text{otherwise} \end{cases}$$

(5)

This strategy, however, evaluates the loss variation for each parameter $w_i$ independently as in (2), which is known to be sub-optimal, as there is a dependence between parameters inside the model. How can we correct a potential “excessive” removal of parameters?

3.2. Removing only?

Removing parameters from a model is always a matter of delicacy: if the parameters are removed too fast, at some point the performance can not be recovered. On the contrary, if they are removed too slowly, the training complexity becomes large. Furthermore, the strategy to identify which parameters can be removed from the model, for a
where \( \Omega(w_i) \) is the subset of parameters that are neighbors of \( w_i \). Fig. 3a displays a practical case where there are some voxels not included (white space), voxels in the model (red), voxels removed which satisfy (7) (blue) and voxels which satisfy the condition on the gradient, but are not neighbors of any voxel in the model (green). After one re-inclusion iteration, the blue voxels are included, and some green voxels (the neighbors of the blue ones) become the new candidates for the re-inclusion (Fig. 3b). In order to find the whole subset of voxels to be added-back, it is necessary to iterate over the re-inclusion mechanism, until there are no voxels in blue to add. Follows an overview on Re:NeRF.

### 3.3. Overview on the Re:NeRF scheme

**Algorithm 1 Re:NeRF.**

1. **procedure** RE:NeRF\((W_{beg}, \gamma, \delta)\)
2. \( T_{rem} \leftarrow Q|\Delta L(w)|, w \in W_{beg}\) \((\gamma)\)
3. \( W, \bar{W} \leftarrow \text{REMOVE}(W_{beg}, T_{rem})\)
4. \( T_{inc} \leftarrow Q|\Delta L(w)|, w \in \bar{W}\) \((\delta)\)
5. \( W_{end} \leftarrow \text{RE-INCLUDE}(W, \bar{W}, T_{inc})\)
6. **return** \( W_{end}\)
7. **end procedure**
8. **procedure** REMOVE\((W_{beg}, T_{rem})\)
9. \( W \leftarrow \emptyset\)
10. \( \bar{W} \leftarrow \emptyset\)
11. **for** \( w_i \in W_{beg} \)
12. **if** \( |\Delta L(w_i)| \geq T_{rem} \)
13. \( W \leftarrow W \cup \{w_i\}\)
14. **else**
15. \( \bar{W} \leftarrow \bar{W} \cup \{w_i\}\)
16. **end if**
17. **end for**
18. **return** \( W, \bar{W}\)
19. **end procedure**
20. **procedure** RE-INCLUDE\((W, \bar{W}, T_{inc})\)
21. \( \text{one}_{added} \leftarrow \text{True}\)
22. **while** \( \text{one}_{added} \)
23. **for** \( w_i \in \bar{W} \)
24. **if** \( |\frac{\partial L}{\partial w_i}| \geq T_{inc} \)
25. \( \Omega \leftarrow \text{NEIGHBORS}(w_i)\)
26. **if** \( \Omega \cap W = \emptyset \)
27. \( W \leftarrow W \cup \{w_i\}\)
28. \( \text{one}_{added} \leftarrow \text{True}\)
29. **end if**
30. **end if**
31. **end for**
32. **end while**
33. **return** \( W\)
34. **end procedure**
In this section, we present the empirical results obtained on state-of-the-art datasets and three different EVG-NeRF approaches, on top of which Re:NeRF has been executed in order to reduce the storage memory. For all the experiments the models have been pre-trained using the hyper-parameter setup indicated in the respective original work. As a common stop criterion, we impose a maximum worsening in performance $\Delta T$ of $1$ dB on the original model’s PSNR. All the other hyper-parameters have been optimized using a grid-search algorithm. Although every technique requires a specific CUDA and PyTorch version, the Re:NeRF code is compatible with pytorch 1.12 and back-compatible with PyTorch 1.6. For all the experiments an NVIDIA A40 equipped with 40 GB has been used.\textsuperscript{1}

4. Results

In this section, we present the empirical results obtained on state-of-the-art datasets and three different EVG-NeRF approaches, on top of which Re:NeRF has been executed in order to reduce the storage memory. For all the experiments the models have been pre-trained using the hyper-parameter setup indicated in the respective original work. As a common stop criterion, we impose a maximum worsening in performance $\Delta T$ of $1$ dB on the original model’s PSNR. All the other hyper-parameters have been optimized using a grid-search algorithm. Although every technique requires a specific CUDA and PyTorch version, the Re:NeRF code is compatible with pytorch 1.12 and back-compatible with PyTorch 1.6. For all the experiments an NVIDIA A40 equipped with 40 GB has been used.\textsuperscript{1}

4.1. Setup

Datasets. We have evaluated our approach on four datasets. Synthetic-NeRF [25] and Synthetic-NSVF [22] are two popular datasets, containing 8 different realistic objects each, which are synthesized from NeRF (chair, drums, ficus, hotdog, lego, materials, mic and ship) and NSVF (bike, lifestyle, palace, robot, spaceship, steamtrain, toad and wineholder), respectively. For both, the image resolution has been set up to $800 \times 800$ pixels, having 100 views for training, 100 for validation, and 100 for testing. The third dataset we have tested is Tanks&Temples [15]: our choice fell on this dataset as it is a collection of real-world images. Here we use a subset of the provided samples (namely: ignatius, truck, barn, caterpillar and family). We use here FullHD resolution, and we use also in this case 10% of the images used for validation and 10% for testing. Finally, the fourth dataset we we run our experiments is LLFF-NeRF [24]. Differently from the other three datasets, this dataset contains realistic images, and non blank background. Each scene consists of 20 to 60 forward-facing images with resolution $1008 \times 756$. In this case, we have used all the 8 available samples (fern, flower, fortress, horns, leaves, orchids, room and trex).

Architectures and compressibility configuration. We have tested Re:NeRF on three very different EVG-NeRF approaches: DVGO [34], TensoRF [3] and Plenoxels [8].\textsuperscript{2} DVGO models are trained using the same configuration as in the paper, in the $160^3$ voxel grid size configuration.

\textsuperscript{1}The source code is available at https://github.com/enzotarta/re-nerf.

\textsuperscript{2}Although Plenoxels is a method for learning radiance fields and does not have any “neural network”, it still leverages the same optimization tools. We include it in our experimental setup to show the even broader adaptability of Re:NeRF to any approach minimizing a differentiable loss function.
### Table 1: Results obtained on low compressibility regime (LOW) and high compressibility (HIGH). The first line indicates the baseline. In every dataset, the various metrics are averaged for the samples in them.

| Approach            | Compress | Synthetic-NeRF | Synthetic-NSVF | Tanks&Temps | LLFF-NeRF |
|---------------------|----------|----------------|----------------|-------------|-----------|
|                     | PSNR [dB][↑] | SSIM (↑) | Size [MB][↓] | PSNR [dB][↑] | SSIM (↑) | Size [MB][↓] | PSNR [dB][↑] | SSIM (↑) | Size [MB][↓] |
| NSVF [22]           | -        | 31.74 0.953  ~16 | 35.13 0.979  ~16 | 28.40 0.900  ~16 | - - - |
| Instant-NGP [26]    | -        | 33.04 0.934 28.64 | 36.11 0.966 46.09 | 28.81 0.917 46.09 | 20.18 0.662 46.09 |
| DVGO [34]           | LOW      | 31.47 0.952 3.99 | 35.29 0.974 4.37 | 28.22 0.910 4.69 | - - - |
|                     | HIGH     | 31.08 0.944 2.00 | 34.90 0.969 2.46 | 27.90 0.894 1.62 | - - - |
|                     | LOW      | 33.14 0.963 69.26 | 36.52 0.982 69.05 | 28.56 0.920 64.04 | 26.73 0.839 151.79 |
|                     | HIGH     | 32.81 0.956 7.94 | 36.44 0.982 11.60 | 28.50 0.916 9.99 | 26.80 0.820 32.34 |
| TensoRF [3]         | LOW      | 31.26 0.952 11.47 | 36.44 0.982 11.60 | 28.50 0.916 9.99 | 26.80 0.820 32.34 |
|                     | HIGH     | 31.48 0.956 189.08 | - - - | 27.37 0.904 147.96 | 25.90 0.838 148.496 |
| Plenoxels [8]       | LOW      | 31.52 0.952 91.77 | - - - | 27.66 0.909 102.26 | 26.24 0.838 457.73 |
|                     | HIGH     | 30.97 0.944 54.68 | - - - | 27.34 0.896 85.47 | 25.95 0.828 338.02 |

#### 4.2. Discussion

All the results are reported in Table 1. Here the “LOW” compressibility refers to compressibility achieved with the best PSNR evaluated on the validation set, while “HIGH” refers to the model achieved right before reaching the stop criterion (which consists of a worsening of the original performance of at most 1dB on the original PSNR). Some qualitative results are also displayed in Fig. 5.

In general, we observe that Re:NeRF effectively reduces the size of the models in all the combinations of tested datasets/EVG-NeRFs, with different impacts depending on...
the EVG-NeRF it is applied. In general, the approach having higher average sizes while also having slightly worse performance is Plenoxels [8], which is an EVG approach with no neural elements in it. Nevertheless, Re:NeRF is able to compress it effectively. In particular, in the low compressibility setup, the performance is improved with an overall size reduction. DVGO [34], consisting of a voxel grid and of an MLP component, is massive, achieving for example compression ratios of 80× for Synthetic-NeRF and 65× within the 1dB performance loss. The approach generally achieving better performance is TensoRF [3], where the low compression setup maintains almost the same performance still enabling 6× compression. When compared to DVGO, TensoRF occupies less memory as it relies on factorized neural radiance fields in the 4D voxel grid, namely it is by design more efficient at training time, and of course in order to maintain such a higher performance the possible compressibility of the model is relatively limited. When compared with other approaches, we observe in general a significant improvement in performance for similar model’s size (LLFF-NeRF) or a significantly lower memory for similar performance (in the other three cases).

4.3. Ablation study

In this section, we propose the ablation study for Re:NeRF. In particular, we want to evidence the single contributions of the proposed technique, emphasizing their effect. Towards this end, we have conducted experiments on “Mic” from the Synthetic-NeRF dataset and used DVGO [34] as the EVG-NeRF approach. The summary for the ablation study is enclosed in Table 2. All the measures here proposed are averaged on 3 different runs.

Remove all the layers or a subset of them? Considering the heterogeneity of the layers in the EVG-NeRF approaches, it is not straightforward that removing parameters from all the layers is the best approach. Indeed, we observe that focusing on the layers with explicit voxel representation (indicated as “Voxel”) leads to a similar PSNR as the baseline (33.19 dB) with a very high size reduction (from 67.69MB to 7.02MB). Focusing on all the layers of the model, as it would be done in a generic model pruning scheme [12, 38, 7] leads to a very high drop in performance (26.72dB, namely -6.42dB when compared to the baseline). This shows how important it is to focus on voxels and designing specific solutions rather than relying on generic approaches.

Re-including helps. The proposed strategy needs a “balancing” for the voxel removal phase, which can be extreme. Towards this end, re-including some removed voxels slightly increases the size of the model, which however turns into performance recovery. In particular, by adding just 0.10MB we gain 0.07dB: please notice that the baseline PSNR is lower than the achieved performance with remove+re-include. This phenomenon is even more evident in the high compressibility regime, where we gain approximately 2dB with just 0.16MB added.

Effect of quantization. In traditional NeRF models quantizing is a delicate process, requiring non-uniform, custom quantization strategies [30]. In our case, however, quantizing on 8 bits maintains the performance to high PSNR values (losing 0.16 dB without additional fine-tuning) but significantly reduces the size of the compressed model (from 7.12MB to 1.48MB). This is very evident in the high compressibility result, where we move from 1.24MB to 0.34MB only.

4.4. A deeper view on Re:NeRF’s effect

As a final analysis, we wish to test what happens in the voxel grid for a baseline model and for the same with Re:NeRF applied. Fig. 6 visualizes the content of the density.grid layer for the baseline (up, in red) and for the compressed one (down, in blue). Looking at the spatial occupancy for the density grid, without Re:NeRF evidently we have a much higher than necessary voxel occupation (Fig. 6a) which is trimmed to the real object shape by Re:NeRF (Fig. 6d). Looking at the effective value of each voxel (here normalized and modeled as transparency) we can easily guess the structure of the object in the Re:NeRF case (Fig. 6e) while the density is so spread in the space for the baseline case that the object is almost impossible to distinguish (Fig. 6b). This has a clear effect on the distribution of the parameter’s value for the layer: while in the baseline case we observe very different behavior for positive and negative values, making problems like compression and quantization harder (Fig. 6c), the distribution tends to be more specular when applying Re:NeRF (Fig. 6f): this is due to both the suppression of irrelevant parameters in the model and to the exclusive re-inclusion of parameters having as neighbors others already included.

5. Conclusion & future works

In this work we have presented Re:NeRF, an approach to compress NeRF models that utilizes explicit voxel grid representations. This approach removes parameters from the model, while at the same time ensures not to have a large drop in performance. This is achieved by a re-inclusion mechanism, which allows previously removed parameters that are neighbors of the remaining parameters to be re-included if they show high gradient loss. Re:NeRF is easily deployable for any model, having different architecture, training strategy, or objective function. For this reason, we have tested its effectiveness on three very different approaches: DVGO [34], where a part of the model learns the density and the other maps complex voxel dependencies with an MLP, TensoRF [3] which learns a 4D grid and per-
forms low-rank decomposition on the radiance fields, and Plenoxels [8] which optimized the voxel grid directly with no MLP supporting the learning. These approaches have been tested on four popular datasets, two synthetic and two from real images.

In all the cases, Re:NeRF is able to compress the approaches with compression rates scaling up to 80×. Reducing the storage memory required by these models, designed mainly to improve training and inference time but sacrificing storage memory when compared to the original NeRF [25], further emphasizes EVG-NeRF’s benefits and pushes towards their large-scale deployability in memory-constrained or bandwidth-limited applications. Interestingly, in a low compressibility setup, the performance is essentially unharmed, while the model is effectively compressed. This opens the road towards the model’s budget re-allocation, like efficient ensembling, towards further performance enhancement with specific memory constraints.

Table 2: Ablation study conducted on “Mic” from Synthetic-NeRF. The approach used here is DVGO [34]. The first line is the reference baseline.

| Layers   | Remove | Re-include | Quantization | LOW compressibility | HIGH compressibility |
|----------|--------|------------|--------------|---------------------|----------------------|
|          | ✓      | ✓          | ✓            | PSNR[dB]            | Size[MB]             |
| All      | ✗      | ✓          | ✓            | 33.15               | 67.69                |
| Voxels   | ✓      | ✗          | ✓            | 26.72               | 6.88                 |
| Voxels   | ✓      | ✓          | ✗            | 33.19               | 7.02                 |
| Voxels   | ✓      | ✓          | ✓            | 33.26               | 7.12                 |
|          | ✓      | ✓          | ✓            | 33.10               | 1.48                 |
References

[1] Mark Boss, Raphael Braun, Varun Jampani, Jonathan T Barron, Ce Liu, and Hendrik Lensch. Nerf: Neural reflectance decomposition from image collections. In Proceedings of the IEEE/CVF International Conference on Computer Vision, pages 12684–12694, 2021.

[2] Eric R Chan, Marco Monteiro, Petr Kellnhofer, Jiajun Wu, and Gordon Wetzstein. pi-gan: Periodic implicit generative adversarial networks for 3d-ard image synthesis. In Proceedings of the IEEE/CVF conference on computer vision and pattern recognition, pages 5799–5809, 2021.

[3] Anpei Chen, Zexiang Xu, Andreas Geiger, Jingyi Yu, and Hao Su. Tensorf: Tensorial radiance fields. ECCV, 2022.

[4] Abe Davis, Marc Levoy, and Fredo Durand. Unstructured light fields. In Computer Graphics Forum, volume 31, pages 305–314. Wiley Online Library, 2012.

[5] Paul E Debevec, Camillo J Taylor, and Jitendra Malik. Modeling and rendering architecture from photographs: A hybrid geometry-and image-based approach. In Proceedings of the 23rd annual conference on Computer graphics and interactive techniques, pages 11–20, 1996.

[6] John Flynn, Michael Brouxton, Paul Debevec, Matthew DuVall, Graham Fyffe, Ryan Overbeck, Noah Snavely, and Richard Tucker. Deepview: View synthesis with learned gradient descent. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pages 2367–2376, 2019.

[7] Jonathan Franke and Michael Carbin. The lottery ticket hypothesis: Finding sparse, trainable neural networks. ICLR, 2019.

[8] Sara Fridovich-Keil, Alex Yu, Matthew Tancik, Qinhong Chen, Benjamin Recht, and Angjoo Kanazawa. Plenoxels: Radiance fields without neural networks. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pages 5501–5510, 2022.

[9] Guy Gafni, Justus Thies, Michael Zollhofer, and Matthias Nießner. Dynamic neural radiance fields for monocular 4d facial avatar reconstruction. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pages 8649–8658, 2021.

[10] Chen Gao, Ayush Saraf, Johannes Kopf, and Jia-Bin Huang. Dynamic view synthesis from dynamic monocular video. In Proceedings of the IEEE/CVF International Conference on Computer Vision, pages 5712–5721, 2021.

[11] Pengcheng Guo, Miguel Angel Bautista, Alex Colburn, Liang Yang, Daniel Ulbricht, Joshua M Susskind, and Qi Shan. Fast and explicit neural view synthesis. In Proceedings of the IEEE/CVF Winter Conference on Applications of Computer Vision, pages 3791–3800, 2022.

[12] Song Han, Jeff Pool, John Tran, and William Dally. Learning both weights and connections for efficient neural network. Advances in neural information processing systems, 28, 2015.

[13] Yi-Hua Huang, Yue He, Yu-Jie Yuan, Yu-Kun Lai, and Lin Gao. Stylizednerf: consistent 3d scene stylization as stylized nerf via 2d-3d mutual learning. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pages 18342–18352, 2022.

[14] Berk Kaya, Suryansh Kumar, Francesco Sarno, Vittorio Ferrari, and Luc Van Gool. Neural radiance fields approach to deep multi-view photometric stereo. In Proceedings of the IEEE/CVF Winter Conference on Applications of Computer Vision, pages 1965–1977, 2022.

[15] Arno Knipitsch, 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.

[16] Adam R Kosiorek, Heiko Strathmann, Daniel Zoran, Pol Moreno, Rosalia Schneider, Sona Mokrý, and Danilo Jimenez Rezende. Nerf-vae: A geometry aware 3d scene generative model. In International Conference on Machine Learning, pages 5742–5752. PMLR, 2021.

[17] Yann LeCun, John Denker, and Sara Solla. Optimal brain damage. Advances in neural information processing systems, 2, 1989.

[18] Namhoon Lee, Thalaiyasingam Ajanthan, and Philip HS Torr. Snip: Single-shot network pruning based on connection sensitivity. ICLR, 2019.

[19] Anat Levin and Fredo Durand. Linear view synthesis using a dimensionality gap light field prior. In 2010 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, pages 1831–1838. IEEE, 2010.

[20] Zhengqi Li, Simon Niklaus, Noah Snavely, and Oliver Wang. Neural scene flow fields for space-time view synthesis of dynamic scenes. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pages 6498–6508, 2021.

[21] Zhengqi Li, Wenqi Xian, Abe Davis, and Noah Snavely. Crowdsampling the plenoptic function. In European Conference on Computer Vision, pages 178–196. Springer, 2020.

[22] Lingjie Liu, Jiatao Gu, Kyaw Zaw Lin, Tat-Seng Chua, and Christian Theobalt. Neural sparse voxel fields. Advances in Neural Information Processing Systems, 33:15651–15663, 2020.

[23] Ricardo Martin-Brualla, Noha Radwan, Mehdi SM Sajjadi, Jonathan T Barron, Alexey Dosovitskiy, and Daniel Duckworth. Nerf in the wild: Neural radiance fields for unconstrained photo collections. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pages 7210–7219, 2021.

[24] Ben Mildenhall, Pratul P Srinivasan, Rodrigo Ortiz-Cayon, Nima Khademi Kalantari, Ravi Ramamoorthi, Ren Ng, and Abhishek Kar. Local light field fusion: Practical view synthesis with prescriptive sampling guidelines. ACM Transactions on Graphics (TOG), 38(4):1–14, 2019.

[25] Ben Mildenhall, Pratul P Srinivasan, Matthew Tancik, Jonathan T Barron, Ravi Ramamoorthi, and Ren Ng. Nerf: Representing scenes as neural radiance fields for view synthesis. In European conference on computer vision, pages 405–421. Springer, 2020.

[26] Thomas Müller, Alex Evans, Christoph Schied, and Alexander Keller. Instant neural graphics primitives with a multiresolution hash encoding. ACM Trans. Graph., 41(4):102:1–102:15, July 2022.
[27] Atsuhiro Noguchi, Xiao Sun, Stephen Lin, and Tatsuya Harada. Neural articulated radiance field. In Proceedings of the IEEE/CVF International Conference on Computer Vision, pages 5762–5772, 2021.

[28] Christian Reiser, Songyou Peng, Yiyi Liao, and Andreas Geiger. Kilonerf: Speeding up neural radiance fields with thousands of tiny mlps. In Proceedings of the IEEE/CVF International Conference on Computer Vision, pages 14335–14345, 2021.

[29] Katja Schwarz, Yiyi Liao, Michael Niemeyer, and Andreas Geiger. Graf: Generative radiance fields for 3d-aware image synthesis. Advances in Neural Information Processing Systems, 33:20154–20166, 2020.

[30] Jinglei Shi and Christine Guillemot. Distilled low rank neural radiance field with quantization for light field compression. arXiv preprint arXiv:2208.00164, 2022.

[31] Lixin Shi, Haitham Hassanieh, Abe Davis, Dina Katabi, and Fredo Durand. Light field reconstruction using sparsity in the continuous fourier domain. ACM Transactions on Graphics (TOG), 34(1):1–13, 2014.

[32] Pratul P Srinivasan, Boyang Deng, Xiaoming Zhang, Matthew Tancik, Ben Mildenhall, and Jonathan T Barron. Nerv: Neural reflectance and visibility fields for relighting and view synthesis. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pages 7495–7504, 2021.

[33] Pratul P Srinivasan, Richard Tucker, Jonathan T Barron, Ravi Ramamoorthi, Ren Ng, and Noah Snavely. Pushing the boundaries of view extrapolation with multiplane images. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pages 175–184, 2019.

[34] Cheng Sun, Min Sun, and Hwann-Tzong Chen. Direct voxel grid optimization: Super-fast convergence for radiance fields reconstruction. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pages 5459–5469, 2022.

[35] Matthew Tancik, Ben Mildenhall, Terrance Wang, Divi Schmidt, Pratul P Srinivasan, Jonathan T Barron, and Ren Ng. Learned initializations for optimizing coordinate-based neural representations. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pages 2846–2855, 2021.

[36] Enzo Tartaglione, Andrea Bragagnolo, Attilio Fiandrotti, and Marco Grangetto. Loss-based sensitivity regularization: towards deep sparse neural networks. Neural Networks, 146:230–237, 2022.

[37] Enzo Tartaglione, Andrea Bragagnolo, Francesco Odierna, Attilio Fiandrotti, and Marco Grangetto. Serene: Sensitivity-based regularization of neurons for structured sparsity in neural networks. IEEE Transactions on Neural Networks and Learning Systems, 2021.

[38] Enzo Tartaglione, Skjalg Lepsøy, Attilio Fiandrotti, and Gianluca Francini. Learning sparse neural networks via sensitivity-driven regularization. Advances in neural information processing systems, 31, 2018.

[39] Justus Thies, Michael Zollhöfer, and Matthias Nießner. Deferred neural rendering: Image synthesis using neural textures. ACM Transactions on Graphics (TOG), 38(4):1–12, 2019.

[40] Edgar Tretschk, Ayush Tewari, Vladislav Golyanik, Michael Zollhöfer, Christoph Lassner, and Christian Theobalt. Non-rigid neural radiance fields: Reconstruction and novel view synthesis of a dynamic scene from monocular video. In Proceedings of the IEEE/CVF International Conference on Computer Vision, pages 12959–12970, 2021.

[41] Michael Waechter, Nils Moehrle, and Michael Goesele. Let there be color! large-scale texturing of 3d reconstructions. In European conference on computer vision, pages 836–850. Springer, 2014.

[42] Wenqi Xian, Jia-Bin Huang, Johannes Kopf, and Changil Kim. Space-time neural irradiance fields for free-viewpoint video. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pages 9421–9431, 2021.

[43] Alex Yu, Vickie Ye, Matthew Tancik, and Angjoo Kanazawa. Pixelnerf: Neural radiance fields from one or few images. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pages 4578–4587, 2021.