

DIFFUSIONRENDERER: Neural Inverse and Forward Rendering with Video Diffusion Models

Ruofan Liang^{1,2,3*}, Zan Gojcic¹, Huan Ling^{1,2,3}, Jacob Munkberg¹, Jon Hasselgren¹, Chih-Hao Lin^{1,4}, Jun Gao^{1,2,3}, Alexander Keller¹, Nandita Vijaykumar^{2,3}, Sanja Fidler^{1,2,3}, Zian Wang^{1,2,3*}
¹NVIDIA ²University of Toronto ³Vector Institute ⁴University of Illinois Urbana-Champaign

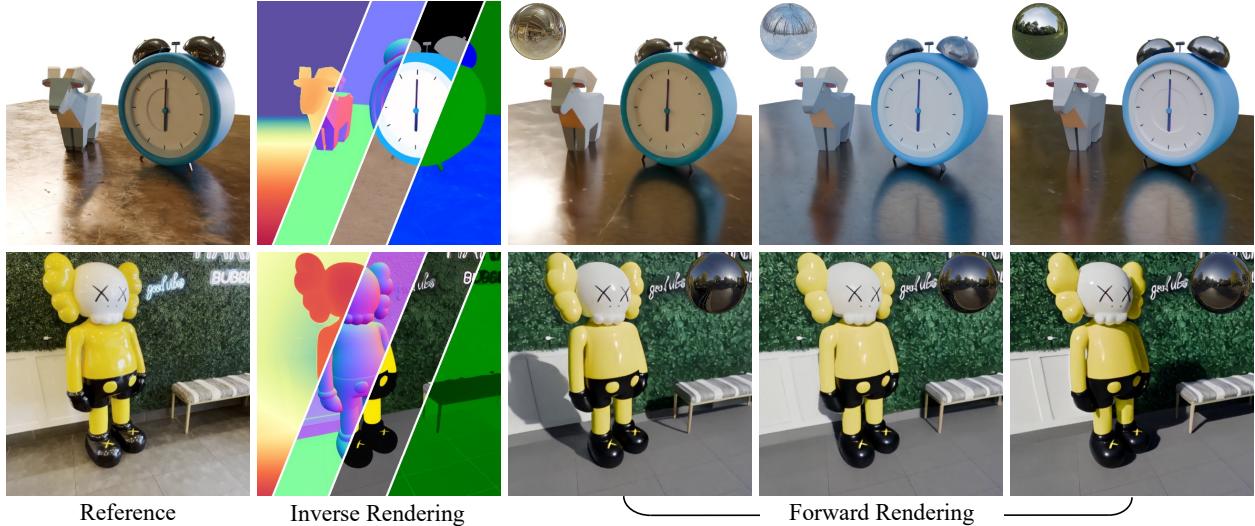


Figure 1. We present DIFFUSIONRENDERER, a general-purpose method for both neural inverse and forward rendering. From input images or videos, it accurately estimates geometry and material buffers, and generates photorealistic images under specified lighting conditions, offering fundamental tools for image editing applications.

Abstract

Understanding and modeling lighting effects are fundamental tasks in computer vision and graphics. Classic physically-based rendering (PBR) accurately simulates the light transport, but relies on precise scene representations—explicit 3D geometry, high-quality material properties, and lighting conditions—that are often impractical to obtain in real-world scenarios. Therefore, we introduce DIFFUSIONRENDERER, a neural approach that addresses the dual problem of inverse and forward rendering within a holistic framework. Leveraging powerful video diffusion model priors, the inverse rendering model accurately estimates G-buffers from real-world videos, providing an interface for image editing tasks, and training data for the rendering model. Conversely, our rendering model generates photorealistic images from G-buffers without explicit light transport simulation. Specifically, we first train a video diffusion model for inverse rendering on synthetic data, which generalizes well to real-world videos and allows us to auto-label diverse real-world videos. We

then co-train our rendering model using both synthetic and auto-labeled real-world data. Experiments demonstrate that DIFFUSIONRENDERER effectively approximates inverse and forwards rendering, consistently outperforming the state-of-the-art. Our model enables practical applications from a single video input—including relighting, material editing, and realistic object insertion.

1. Introduction

Understanding and modeling light transport forms the basis of Physically Based Rendering (PBR) [59]. Modern path tracing algorithms, as regularly used in the gaming and movie industries, simulate light transport to render images that cannot be distinguished from photographs. The quality of such PBR-rendered images heavily depends on the accuracy and realism of the scene’s surface geometry, material properties, and lighting representations. Such a scene description is either designed by artists (synthetic scenes) or reconstructed from data—also known as the inverse rendering problem [2, 3]. Inverse rendering has been extensively stud-

ied, particularly for applications like relighting and object insertion into real-world scenes [20, 41, 75, 88]. However, acquiring high quality surface and material representations is challenging in real-world scenarios, limiting the practicality of PBR methods (Fig. 2).

While physically-based rendering and inverse rendering are usually considered separately, we propose to consider them jointly. Our approach draws inspiration from the success of large-scale generative models [8, 65], which “*render*” photorealistic images from simple text prompts without any explicit understanding of PBR. These models learn the underlying distribution of real-world images from a vast amounts of data, implicitly capturing the complex lighting effects.

Specifically, we propose DIFFUSIONRENDERER, a general-purpose neural rendering engine that can synthesize light transport simulation—such as shadows and reflections—by leveraging the powerful priors of video diffusion models. Conditioned on input geometry, material buffers, and environment map light source, DIFFUSIONRENDERER acts as a neural approximation of path-traced shading. DIFFUSIONRENDERER is designed to remain faithful to the conditioning signals, while adhering to the distribution of real-world images. As a result, we bypass the need for precise scene representations and description, as our model learns to handle imperfections in the input data.

Training such a model requires some amount of high quality and diverse data, including data with noisy conditions to ensure robustness. Therefore, we first train an *inverse renderer*, a video diffusion model to map input RGB videos to intrinsic properties. Although trained solely on synthetic data, the inverse rendering model generalizes robustly to real-world scenarios. We then use it to generate “*pseudo-labels*” for diverse real-world videos. Combining both real-world auto-labeled data and synthetic data, we train our *forward renderer* video diffusion model.

DIFFUSIONRENDERER outperforms state-of-the-art methods and effectively approximates the complex functionalities of inverse and forward rendering, allowing us to relight images and videos across diverse scenes and to synthesize consistent shadows and reflections without explicit path tracing and 3D scene representation. Our model can relight any scene from only a single video input, and provides fundamental tools for editing tasks such as material editing and realistic object insertion. To summarize:

- We develop a state-of-the-art inverse rendering method for videos of synthetic and real-world scenes.
- We repurpose a video diffusion model as a neural rendering engine that can synthesize photorealistic images and videos conditioned on noisy G-buffers.
- From a single video input, DIFFUSIONRENDERER enables relighting, material editing, and virtual object insertion in a unified framework, expanding the possibilities for real-world neural rendering applications.

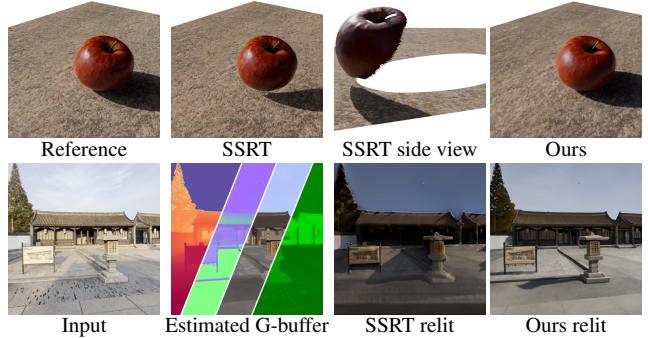


Figure 2. Classic PBR relies on explicit 3D geometry, e.g., meshes. When it is not available, screen space ray tracing (SSRT) struggles to accurately represent shadows and reflections (top). PBR is also sensitive to errors in G-buffers – SSRT with estimated G-buffers from inverse rendering models often fails to deliver quality results (bottom). DIFFUSIONRENDERER bypasses these issues, producing photorealistic results without 3D geometry or perfect G-buffers.

2. Related Work

Neural rendering refers to methods that replace or extend traditional rendering pipelines by neural networks. For example, Deep Shading [56] replaces traditional deferred shading [15] by a CNN to render images with ambient occlusion, global illumination, and depth-of-field from G-buffers. More recently, RGB↔X [83] trains image diffusion models to both estimate a G-buffer from an image and to render an image from a G-buffer. We extend this approach to video diffusion models and provide a novel approach for neural relighting that does not require an irradiance estimate. Other approaches fit rendered data using neural models or introduce neural components into an existing renderer with focus on approximating light transport [28, 31] or radiance caching [25, 53]. A plethora of works on neural and inverse rendering involve volumetric 3D scene representations in the form of NeRF [52] or 3D Gaussian Splats [35]. We refer to [70] for an overview. While providing photo-real view interpolation, these approaches typically bake radiance, and have limited editing capabilities. In contrast, we explicitly target an intermediate scene representation in the form of traditional, easy-to-edit, G-buffers with separate lighting.

Inverse rendering is a fundamental task first formalized in the 1970s [4], aiming to estimate intrinsic scene properties, like geometry, materials, and lighting from input images. Early methods designed hand-crafted priors within an optimization framework [2, 4, 11, 23, 39, 89], typically focusing on low-order effects. These methods lead to errors when the hand-crafted priors do not match reality. Recently, supervised and self-supervised learning has been extensively studied [5, 6, 9, 38, 40–42, 67, 73, 74, 76, 80]. The resulting algorithms are often data-hungry and specific to a certain task or domain. Acquiring sufficient and diverse training data poses a challenge. Recent advances in large image generative models provide new deep learning tools for inverse

rendering [19, 36, 44, 61, 83] resulting in much higher reconstruction quality. Still, the quality is not enough to power physically based rendering pipelines.

Relighting focuses on modifying the lighting conditions of a scene given captured images or videos. Recent methods reconstruct 3D scene representations from multi-view images, performing explicit inverse rendering to recover material properties and enable relighting [10, 13, 24, 29, 43, 45, 54, 66, 68, 75, 78, 84, 85, 87]. These methods often optimize for each scene individually, and their quality may be affected by practical issues such as single-illumination capture, large scene scale, and dynamic content. Learning-based methods that train across multiple scenes have explored latent feature learning [7, 48, 90] and often incorporate neural rendering modules that utilize PBR buffers as inductive priors [22, 37, 57, 60, 79]. To improve relighting quality, recent approaches [30, 37, 62, 82] leverage diffusion models. With very few multi-illumination datasets [55], existing methods often are specialized to a domain, such as portraits, objects, and outdoor scenes, and remain data-hungry.

3. Preliminaries

Physically-based rendering (PBR) is concerned with the simulation of how the incoming radiance contributes to the outgoing radiance

$$L_o(\mathbf{p}, \omega_o) = \int_{\Omega} f_r(\mathbf{p}, \omega_o, \omega_i) L_i(\mathbf{p}, \omega_i) |\mathbf{n} \cdot \omega_i| d\omega_i, \quad (1)$$

at a surface point \mathbf{p} in direction ω_o . The integral over the hemisphere Ω considers the BRDF $f_r(\mathbf{p}, \omega_o, \omega_i)$, incoming radiance $L_i(\mathbf{p}, \omega_i)$, and a cosine factor $|\mathbf{n} \cdot \omega_i|$ for the angle between the normal \mathbf{n} and incoming light. It is evaluated by Monte Carlo methods [59, 71], with meticulously designed BRDF models [12, 14, 72] that approximate real surfaces.

Video diffusion models (VDMs). A diffusion model learns to approximate a data distribution $p_{\text{data}}(\mathbf{I})$ via iterative denoising [18, 26, 69]. Most VDMs operate in a compressed, lower-dimensional latent space [1, 8]. Given an RGB video $\mathbf{I} \in \mathbb{R}^{F \times H \times W \times 3}$, consisting of F frames at resolution $H \times W$, a pre-trained VAE encoder \mathcal{E} first encodes the video into a latent representation $\mathbf{z} = \mathcal{E}(\mathbf{I}) \in \mathbb{R}^{F' \times h \times w \times C}$. The final video $\hat{\mathbf{I}}$ is then reconstructed by decoding \mathbf{z} with a pre-trained VAE decoder \mathcal{D} . Both training and inference stages of the VDM are conducted in this latent space. In this work, we build on Stable Video Diffusion [8], which compresses the video only along the spatial dimensions: $F' = F$, $C = 4$, $h = \frac{H}{8}$, and $w = \frac{W}{8}$.

To train the VDM, noisy versions $\mathbf{z}_\tau = \alpha_\tau \mathbf{z}_0 + \sigma_\tau \epsilon$ are constructed by adding a Gaussian noise ϵ with the noise schedule provided by α_τ and σ_τ following EDM [33]. The diffusion model parameters θ of the denoising function \mathbf{f}_θ are optimized using the denoising score matching objective [33].

Once trained, iteratively applying \mathbf{f}_θ to a sample of Gaussian noise will produce a sample of $p_{\text{data}}(\mathbf{I})$.

Conditioning in VDMs. Two common approaches to inject conditions into VDMs are: (i) concatenating condition channels with image latents \mathbf{z}_τ , which is often used for pixel-wise conditions [8, 34, 36, 83], and (ii) injecting conditions through cross-attention layers [8, 65], which is often used for semantic features such as the CLIP embedding [63]. Note that our method is compatible with any standard VDMs and does not depend on specific architectural details.

4. Method

DIFFUSIONRENDERER is a unified framework comprising two video diffusion models designed for the dual tasks of neural forward and inverse rendering. As illustrated in Fig. 3, the *neural forward renderer* (Sec. 4.1) approximates physically based light transport (Eq. 1), transforming G-buffers [56] and lighting into a photorealistic video. The *neural inverse renderer* (Sec. 4.2) reconstructs geometry and material buffers from input video. The neural forward and inverse renderers are based on pre-trained video diffusion models and fine-tuned for conditional generation [34, 36, 83].

Data is a critical aspect of learning-based methods. We describe our data curation workflow and synthetic-real joint training strategies in Sec. 4.3 and Sec. 4.4. Finally, we discuss image editing applications in Sec. 4.5.

4.1. Neural Forward Rendering

We formulate neural forward rendering as a conditional generation task, producing photorealistic images given geometry, materials, and lighting as conditions. By approximating light transport simulation in a data-driven manner, the model requires neither classic 3D geometry nor explicit path tracing, thus reducing the constraints in real-world applications.

Geometry and material conditions. Similar to the G-buffers in rendering system based on deferred shading [15], we use per-pixel scene attribute maps to represent scene geometry and materials. Specifically, we use surface normals $\mathbf{n} \in \mathbb{R}^{F \times H \times W \times 3}$ in camera space and relative depth $\mathbf{d} \in \mathbb{R}^{F \times H \times W \times 1}$ normalized to $[-1, 1]$ to represent scene geometry. For materials, we use base color $\mathbf{a} \in \mathbb{R}^{F \times H \times W \times 3}$, roughness $\mathbf{r} \in \mathbb{R}^{F \times H \times W \times 1}$, and metallic $\mathbf{m} \in \mathbb{R}^{F \times H \times W \times 1}$ following the Disney BRDF [12].

Lighting conditions. Lighting is represented by environment maps $\mathbf{E} \in \mathbb{R}^{F \times H_{\text{env}} \times W_{\text{env}} \times 3}$, which are panoramic images that capture the lighting intensity from all directions over the sphere. These environment maps are encoded in high dynamic range (HDR), while the VAEs used in typical latent diffusion models are designed for pixel values between -1 and 1 . To address this discrepancy, similar to the light representation in Neural Gaffer [30], we first apply Reinhard tonemapping to convert HDR environment map into an LDR image \mathbf{E}_{ldr} . To more effectively represent HDR values,

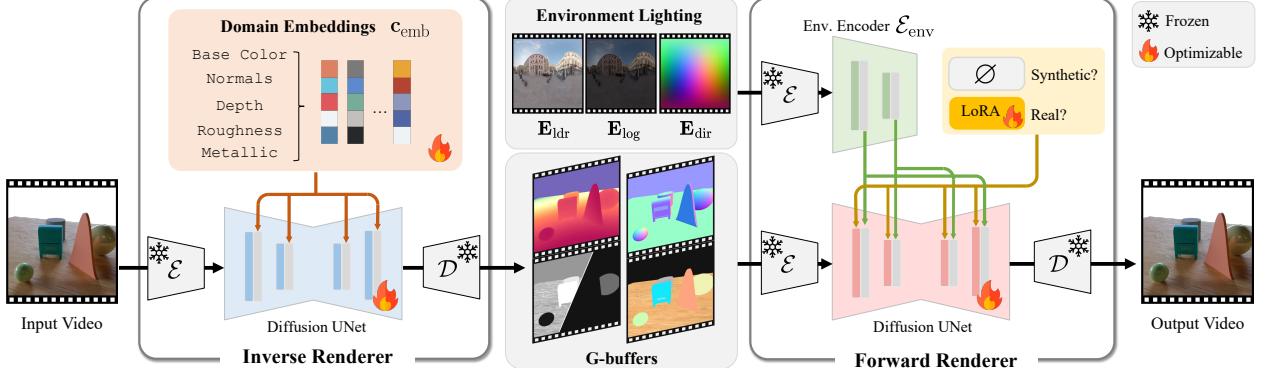


Figure 3. Method overview. Given an input video, the neural inverse renderer estimates geometry and material properties per pixel. It generates one scene attribute at a time, with the domain embedding indicating the target attributes to generate (Sec. 4.2). Conversely, the neural forward renderer produces photorealistic images given lighting information, geometry, and material buffers. The lighting condition is injected into the base video diffusion model through cross-attention layers (Sec. 4.1). During joint training with both synthetic and real data, we use an optimizable LoRA for real data sources (Sec. 4.4).

particularly for light sources with high-intensity peaks, we compute $\mathbf{E}_{\text{log}} = \log(\mathbf{E} + 1)/E_{\max}$ where the light intensity values are mapped to logarithm space that is closer to human perception and normalized by max log intensity E_{\max} . Additionally, we also compute a directional encoding image, $\mathbf{E}_{\text{dir}} \in \mathbb{R}^{F \times H_{\text{env}} \times W_{\text{env}} \times 3}$, where each pixel is represented by a unit vector indicating its direction in the camera coordinate system. The resulting lighting encodings used by the model consist of three panoramic images: $\{\mathbf{E}_{\text{ldr}}, \mathbf{E}_{\text{log}}, \mathbf{E}_{\text{dir}}\}$.

Model architecture. Our models are based on Stable Video Diffusion [8], an image-to-video diffusion model with its core architecture including a VAE encoder-decoder pair $\{\mathcal{E}, \mathcal{D}\}$, and a UNet-based denoising function f_θ .

We use the VAE encoder \mathcal{E} to separately encode each G-buffer from $\{\mathbf{n}, \mathbf{d}, \mathbf{a}, \mathbf{r}, \mathbf{m}\}$ into the latent space and concatenate them to produce the pixel-aligned scene attribute latent map $\mathbf{g} = \{\mathcal{E}(\mathbf{n}), \mathcal{E}(\mathbf{d}), \mathcal{E}(\mathbf{a}), \mathcal{E}(\mathbf{r}), \mathcal{E}(\mathbf{m})\} \in \mathbb{R}^{F \times h \times w \times 20}$.

Environment maps are usually in equi-rectangular projection and are not pixel-aligned with the generated images, thus requiring extra consideration. Prior works explored directly concatenating environment maps to the image latents [30] or concatenate split-sum shading buffers [17], which we also experimented with, but found suboptimal (Table 1). Instead, we take the cross-attention layers which originally operate on the text/image CLIP features, and re-purpose them for lighting conditions. To preserve spatial details of the environment maps, we generalize the conditional signals to a list of multi-resolution feature maps.

Specifically, we first pass the environment map information through VAE encoder \mathcal{E} to obtain $\mathbf{h}_E = \{\mathcal{E}(\mathbf{E}_{\text{ldr}}), \mathcal{E}(\mathbf{E}_{\text{log}}), \mathcal{E}(\mathbf{E}_{\text{dir}})\} \in \mathbb{R}^{F \times h_{\text{env}} \times w_{\text{env}} \times 12}$. We additionally use an environment map encoder \mathcal{E}_{env} to further operate on \mathbf{h}_E . \mathcal{E}_{env} is the simplified encoder part of diffusion UNet with attention and temporal layers removed. It contains several convolutional layers to downsample and extract

K levels of multi-resolution features as lighting conditions:

$$\mathbf{c}_{\text{env}} := \{\mathbf{h}_{\text{env}}^i\}_{i=1}^K = \mathcal{E}_{\text{env}}(\mathbf{h}_E) \quad (2)$$

As a result, the diffusion UNet f_θ takes the noisy latent \mathbf{z}_τ and G-buffer latent \mathbf{g} as pixel-wise input. At each UNet level k , the diffusion UNet *queries* the latent environment map features at the corresponding level $\mathbf{h}_{\text{env}}^k$, and aggregates based on its *keys* and *values*. Through the multi-level self-attention and cross-attention layers, the diffusion model is given the capacity to learn to shade G-buffers with lighting. During inference, the diffusion target can be computed as $f_\theta(\mathbf{z}_\tau; \mathbf{g}, \mathbf{c}_{\text{env}}, \tau)$ to produce photorealistic images with iterative denoising.

4.2. Neural Inverse Rendering

We similarly formulate inverse rendering as a conditional generation task. Given an input video \mathbf{I} as a condition, the inverse renderer estimates scene attribute maps $\{\mathbf{n}, \mathbf{d}, \mathbf{a}, \mathbf{r}, \mathbf{m}\}$ which are the G-buffers used by the forward renderer.

Model architecture. The input video \mathbf{I} is encoded into latent space $\mathbf{z} = \mathcal{E}(\mathbf{I})$, and concatenated with the noisy G-buffer latent, which we denote as $\mathbf{g}_\tau = \alpha_\tau \mathbf{g}_0 + \sigma_\tau \epsilon$.

Given an input video, the inverse renderer generates all five attributes $\{\mathbf{n}, \mathbf{d}, \mathbf{a}, \mathbf{r}, \mathbf{m}\}$ using the same model. To preserve the high-quality generation and maximally leverage the diffusion model pre-trained knowledge, each attribute is generated in a dedicated pass, instead of generating all at once. We follow prior works [21, 49, 83] and use a domain embedding to indicate to the model which attribute should be generated. Specifically, we introduce an optimizable domain embedding $\mathbf{c}_{\text{emb}} \in \mathbb{R}^{K_{\text{emb}} \times C_{\text{emb}}}$, where $K_{\text{emb}} = 5$ is the number of buffers and C_{emb} is the dimension of the embedding vector. We re-purpose the cross-attention layers with image CLIP features to take domain embeddings. When estimating an attribute indexed by P , we feed its embedding $\mathbf{c}_{\text{emb}}^P$ as a condition and predict the diffusion target with $f_\theta(\mathbf{g}_\tau^P; \mathbf{z}, \mathbf{c}_{\text{emb}}^P, \tau)$.

4.3. Data Strategy

Synthetic data curation. To train our models, we require high-quality video data with paired ground-truth for material, geometry, and lighting information. Specifically, each video data sample should include paired frames of RGB, base color, roughness, metallic, normals, depth, and environment map: $\{\mathbf{I}, \mathbf{a}, \mathbf{r}, \mathbf{m}, \mathbf{n}, \mathbf{d}, \mathbf{E}\}$. These buffers are typically only available in synthetic data, and most existing public datasets contain only a subset of them.

To address the data scarcity, we designed a synthetic data generation workflow to produce a large amount of high-quality data covering diverse and complex lighting effects. We start by curating a collection of 3D assets, PBR materials, and HDRI environment maps. We use 36,500 3D assets from Objaverse LVIS split. For materials and lighting, we collected 4,260 high-quality PBR material maps, and 766 HDR environment maps from publicly available resources.

In each scene, we place a plane with a randomly selected PBR material, and sample up to three 3D objects, and place them on the plane. We perform collision detection to avoid intersecting objects. We also place up to three primitives (cube, sphere, and cylinder) with randomized shape and materials to cover complex lighting effects such as inter-reflections. A randomly selected HDR environment map illuminates the scene. We generate motions including camera orbits, camera oscillation, lighting rotation, object rotation and translation.

We use a custom path tracer based on OptiX [58] to render the videos. In total, we generate 150,000 videos with paired ground-truth G-buffers and environment maps, at 24 frames per video in 512x512 resolution. This dataset can be used to train both rendering and inverse rendering models.

Real world auto-labeling. Synthetic data provides accurate supervision signals, and when combined with powerful image diffusion models, it demonstrates impressive generalization to unseen domains for inverse rendering tasks [21, 34]. However, when it comes to training the forward rendering model, synthetic data alone is insufficient. Since the output of the forward renderer is an RGB video, training only on synthetic renderings biases the model toward synthetic visual styles. Compared to inverse rendering, we observe a much more significant domain gap in complex real-world scenes for forward rendering tasks (Fig. 7).

Acquiring real-world data with paired geometry, material, and lighting ground truth requires complex and impractical capturing setups. Based on the observation that our inverse rendering model generalizes to real-world videos, we apply it to automatically label real-world videos. Specifically, we use the DL3DV10k [47] dataset, which is a large-scale dataset consisting of 10,510 videos featuring diverse real-world environments. We use our inverse rendering model (Sec. 4.2) to generate G-buffer labels and use an off-the-shelf method DiffusionLight [61] to estimate environment

maps. Each video is divided into 15 segments, resulting in around 150,000 real-world video samples with auto-labeled geometry, material, and lighting attributes.

4.4. Training pipeline

Neural inverse renderer. We first co-train the inverse rendering model on the combination of the curated synthetic video dataset and public image intrinsics datasets InteriorVerse [91] and HyperSim [64]. For image datasets, we treat images as single-frame videos. Each data sample consists of a video \mathbf{I} , an attribute index P , and the scene attribute map \mathbf{s}^P . The target latent variable is the latents of the scene attribute $\mathbf{g}_0^P := \mathcal{E}(\mathbf{s}^P)$, and noise is added to \mathbf{g}_0^P to produce \mathbf{g}_τ^P . The model is trained using the objective function [33]:

$$\mathcal{L}(\theta, \mathbf{c}_{\text{emb}}) = \|\mathbf{f}_\theta(\mathbf{g}_\tau^P; \mathbf{z}, \mathbf{c}_{\text{emb}}^P, \tau) - \mathbf{g}_0^P\|_2^2. \quad (3)$$

We fine-tune the diffusion model parameters θ and domain embeddings \mathbf{c}_{emb} , while keeping the latent encoder \mathcal{E} and decoder \mathcal{D} frozen. Once trained, the inverse renderer is used to auto-label real-world videos, generating training data for the forward renderer.

Environment map encoder pre-training. Following the approach of latent diffusion models [65], we pre-train the environment map encoder \mathcal{E}_{env} along with a decoder \mathcal{D}_{env} using an L2 image reconstruction objective on environment maps, similar to an auto-encoder. The decoder architecture is based on the UNet decoder, containing a set of upsampling layers. After training, we discard the decoder \mathcal{D}_{env} and freeze the environment map encoder \mathcal{E}_{env} while training the neural forward rendering model.

Neural forward renderer. We train our rendering model on a combination of a synthetic video dataset and real-world auto-labeled data, using paired G-buffer, lighting, and RGB videos. Although the auto-labeled real-world data is of sufficient quality, it may still contain inaccuracies. To address discrepancies between the synthetic and real-world data sources, we introduce an additional LoRA [27] with a small set of optimizable parameters $\Delta\theta$ during training on real data. We empirically find it improves the rendering quality (Fig. 7).

During training, for an RGB video \mathbf{I} , the target latent variable is defined as $\mathbf{z}_0 := \mathcal{E}(\mathbf{I})$. Noise is added to \mathbf{z}_0 to produce noisy image latent \mathbf{z}_τ . The training objective is:

$$\begin{aligned} \mathcal{L}(\theta, \Delta\theta) = & \|\mathbf{f}_\theta(\mathbf{z}_\tau^{\text{synth}}; \mathbf{g}^{\text{synth}}, \mathbf{c}_{\text{env}}^{\text{synth}}, \tau) - \mathbf{z}_0^{\text{synth}}\|_2^2 + \\ & \|\mathbf{f}_{\theta+\Delta\theta}(\mathbf{z}_\tau^{\text{real}}; \mathbf{g}^{\text{real}}, \mathbf{c}_{\text{env}}^{\text{real}}, \tau) - \mathbf{z}_0^{\text{real}}\|_2^2 \end{aligned} \quad (4)$$

4.5. Editing Applications

Our proposed framework provides fundamental solutions for inverse and forward rendering, enabling photorealistic image editing applications through a three-step process: neural inverse rendering, G-buffer and lighting editing, and neural

	SyntheticObjects			SyntheticScenes		
	PSNR ↑ SSIM ↑ LPIPS ↓					
SSRT	29.4	0.951	0.037	24.8	0.899	0.113
SplitSum [32]	28.7	0.951	0.038	23.1	0.883	0.116
RGB↔X [83]	25.2	0.896	0.077	18.5	0.645	0.302
DiLightNet [82]	26.6	0.914	0.067	20.7	0.630	0.300
Ours	28.3	0.935	0.048	26.0	0.780	0.201
Ours (image)	27.4	0.916	0.062	25.4	0.760	0.215
Ours (w/o env. encoder)	27.8	0.927	0.057	25.3	0.756	0.237
Ours (+ shading cond.)	28.7	0.930	0.056	25.6	0.761	0.245

Table 1. Quantitative evaluation of neural rendering.

	SyntheticObjects			SyntheticScenes		
	PSNR ↑ SSIM ↑ LPIPS ↓					
DiLightNet [82]	23.79	0.872	0.087	18.88	0.576	0.344
Neural Gaffer [30]	26.39	0.903	0.086	20.75	0.633	0.343
Ours	27.50	0.918	0.067	24.63	0.756	0.257

Table 2. Quantitative evaluation of relighting.

rendering. For the example of relighting, given a video \mathbf{I} as input, the inverse rendering model estimates the G-buffers

$$\{\hat{\mathbf{n}}, \hat{\mathbf{d}}, \hat{\mathbf{a}}, \hat{\mathbf{r}}, \hat{\mathbf{m}}\} = \text{InverseRenderer}(\mathbf{I}). \quad (5)$$

With a user-specified target environment map \mathbf{E}_{tgt} , the rendering model produces relit videos

$$\hat{\mathbf{I}}_{tgt} = \text{ForwardRenderer}(\{\hat{\mathbf{n}}, \hat{\mathbf{d}}, \hat{\mathbf{a}}, \hat{\mathbf{r}}, \hat{\mathbf{m}}, \mathbf{E}_{tgt}\}). \quad (6)$$

Similarly, editing the G-buffers and rendering the videos can enable material editing and virtual object insertion.

5. Experiments

We extensively evaluate DIFFUSIONRENDERER on a diverse range of synthetic and real-world datasets. Sec. 5.1 details our experimental settings. We compare and ablate across three main tasks: image generation from G-buffers (Sec. 5.2), inverse rendering (Sec. 5.3), and relighting (Sec. 5.4). Finally, we show applications of our method in Sec. 5.5.

5.1. Experiment Settings

We refer to model implementation details in the Supplement.

Task definitions. We evaluate our method on three fundamental tasks: forward rendering, inverse rendering, and relighting. For forward rendering, the methods take the G-buffers and lighting information $\{\mathbf{n}, \mathbf{d}, \mathbf{a}, \mathbf{r}, \mathbf{m}, \mathbf{E}\}$ as input, and output rendered images $\hat{\mathbf{I}}$. We evaluate the consistency between the rendered outputs and the ground-truth images \mathbf{I} .

For inverse rendering, each method uses RGB images \mathbf{I} as input to estimate scene attributes $\{\hat{\mathbf{a}}, \hat{\mathbf{r}}, \hat{\mathbf{m}}, \hat{\mathbf{n}}\}$, and compare against ground truth values. Our focus is primarily on the attributes related to PBR – specifically, base color, roughness, and metallic properties. We recognize dedicated works on normal and depth estimation [21, 34] and do not aim to provide an exhaustive evaluation. For relighting, each method takes RGB images and target lighting conditions $\{\mathbf{I}^{src}, \mathbf{E}^{tgt}\}$

as input, output re-lit image sequence $\hat{\mathbf{I}}^{tgt}$ under the target lighting conditions, and compare with ground truth \mathbf{I}^{tgt} .

Baselines. For forward rendering, we compare with Split Sum [32] and Screen Space Ray Tracing (SSRT). For SSRT, we extract a mesh from the depth buffer and render the mesh with material parameters from the G-buffers and a provided HDR probe in a path tracer. We additionally compare against the neural rendering components of recent state-of-the-art methods RGB↔X [83] and DiLightNet [82]. For inverse rendering, we compare with recent diffusion-based methods Kocsis *et al.* [36], RGB↔X [83] and earlier methods [5, 41, 91]. For relighting, we compare with 2D methods DiLightNet [82], Neural Gaffer [30]. We also compare with 3D reconstruction-based methods [46, 75] in supplement.

Metrics. We use PSNR, SSIM, and LPIPS [86] for forward rendering and relighting. For inverse rendering, we evaluate albedo with PSNR and LPIPS following [36, 83]. Since albedo estimation involves scale ambiguity [23], we additionally solve and apply a three-channel scaling factor using least-squares error minimization before computing metrics, referred to as si-PSNR and si-LPIPS. We use root mean square error (RMSE) for metallic and roughness evaluation, and mean angular error for normals.

Datasets. We curate two high-quality synthetic datasets for quantitative evaluation, named *SyntheticScenes* and *SyntheticObjects*. The datasets consist of 3D assets from Poly-Haven [81] and Objaverse [16] that are not included in the training data of our method or the baseline methods. *SyntheticScenes* contains 40 scenes, each featuring multiple objects arranged on a plane textured with high-quality PBR materials. Each scene is rendered into 24-frame videos under four lighting conditions, with motions such as camera orbiting and oscillation. As some baseline methods perform best with object-centric setups, we also create *SyntheticObjects*, a dataset of 30 individual objects. For each object, we render 24-frame videos under four different lighting conditions, with lighting rotated across frames.

For inverse rendering, we also evaluate on the indoor scene benchmark InteriorVerse [91]. We include qualitative comparisons on the DL3DV10k [47] dataset.

5.2. Evaluation of Forward Rendering

We compare our method with baseline methods in Table 1 and Fig. 4. For the neural methods RGB↔X [83] and DiLightNet [82], we use their rendering models with ground-truth G-buffers to generate the images.

Both classic PBR and neural methods perform well on the *SyntheticObjects* dataset in single-object settings but show significant quality drops on the *SyntheticScenes* dataset due to complex inter-reflections and occlusions. For example, our method exhibits a minor PSNR decrease of 2.3 dB from *SyntheticObjects* to *SyntheticScenes*, while other baselines show more substantial drops.

	Albedo				Metallic	Roughness	Normals
	PSNR ↑	LPIPS ↓	si-PSNR ↑	si-LPIPS ↓	RMSE ↓	RMSE ↓	Angular Error ↓
RGB↔X [83]	14.3	0.323	19.6	0.286	0.441	0.321	23.80°
Ours	25.0	0.205	26.7	0.204	<u>0.039</u>	0.078	<u>5.97°</u>
Ours (det.)	26.0	0.219	27.7	0.217	0.028	0.060	5.85°
Ours (image)	23.4	<u>0.213</u>	26.0	<u>0.209</u>	0.066	0.098	6.67°
Ours (image, det.)	24.8	0.231	27.2	0.228	0.043	<u>0.069</u>	6.17°

Table 3. Quantitative evaluation of inverse rendering on *SyntheticScenes* video dataset. image: per-frame inference as image model. det.: 1-step deterministic inference.

	PSNR ↑	SSIM ↑	LPIPS ↓
IIW [5]	9.7	0.62	0.47
Li <i>et al.</i> [41]	12.3	0.68	0.52
Zhu <i>et al.</i> [91]	15.9	0.78	0.34
Kocsis <i>et al.</i> [36]	17.4	<u>0.80</u>	0.22
RGB↔X [83]	16.4	0.78	<u>0.19</u>
Ours (image)	<u>21.9</u>	0.87	0.17
Ours (image, det.)	22.4	0.87	<u>0.19</u>

Table 4. Quantitative benchmark of albedo estimation on InteriorVerse dataset [91].

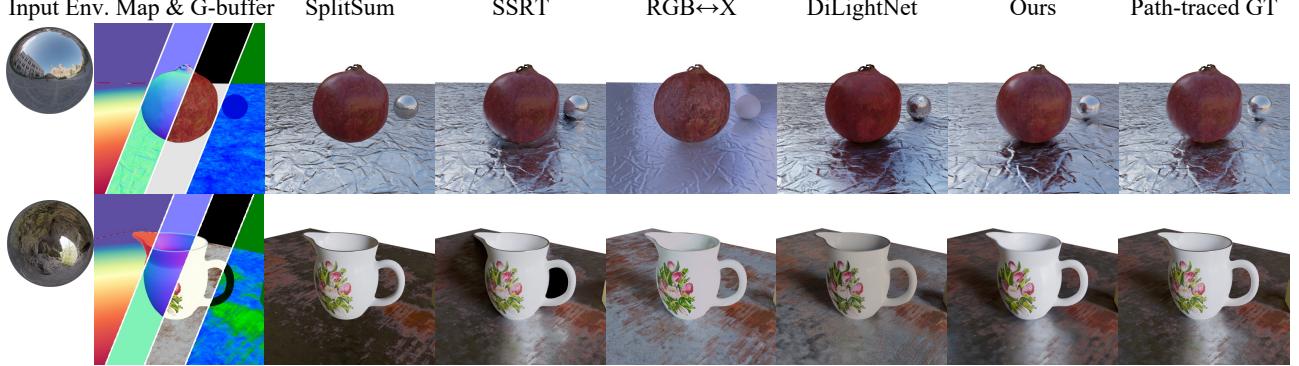


Figure 4. **Qualitative comparison of forward rendering.** Our method generates high-quality inter-reflections (*top*) and shadows (*bottom*), producing more accurate results than the neural baselines.

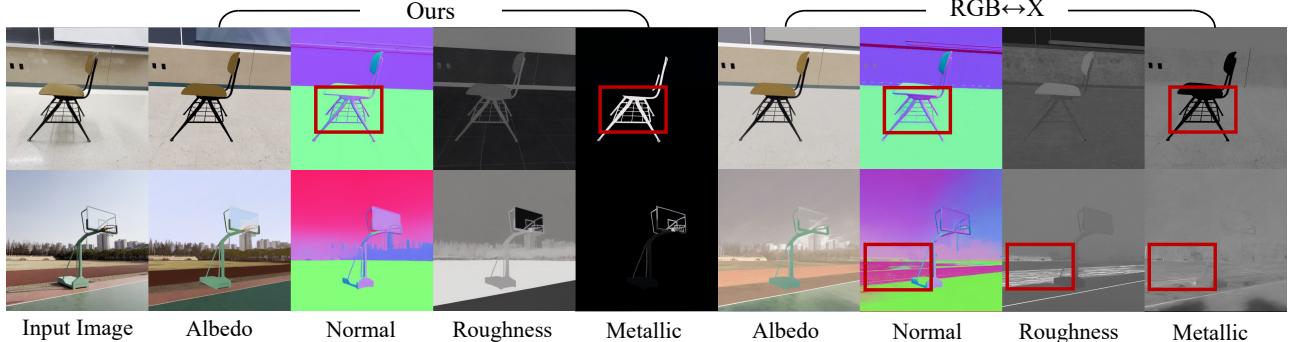


Figure 5. **Qualitative comparison of inverse rendering.** We compare with RGB↔X [83] on DL3DV10k dataset. Both methods work well on indoor scenes, while our method predicts finer details in thin structures and more accurate metallic and roughness channels (top), likely benefiting from our curated training data. As compared to RGB↔X, our method generalizes better to outdoor scenes (bottom).

Our method consistently outperforms all neural methods on both datasets and performs comparably to classic methods. In real-world editing applications, however, these PBR techniques often face significant limitations due to missing 3D geometry and noisy G-buffers (Fig. 2). Furthermore, SplitSum does not model shadows and inter-reflections.

Ablation study. We ablate our model design choices in Table 1. While our method generalizes from images to videos, it can treat images as a special case of single-frame videos. To evaluate the benefits introduced by the video model, we compare with an ablated version of our method that performs per-frame inference (Ours, *image*). The video model consistently improves rendering quality across both datasets. In the ablated variant Ours (w/o env. encoder), we concatenate the VAE encoded environment maps directly to the image channels [30] rather than using a separate environment map

encoder. We demonstrate that a dedicated environment map encoder improves performance. For Ours (+ shading cond.), we include split-sum shading buffers as a conditioning input, following [17]. However, we observed no significant improvement with this addition and chose to exclude it from our final method for simplicity.

5.3. Evaluation of Inverse Rendering

We quantitatively compare our method with baseline methods on *SyntheticScenes* in Table 3 and InteriorVerse [91] benchmark in Table 4. Our methods consistently outperforms baseline methods in both datasets, indicating the effectiveness of our data curation workflow and method designs. We show a qualitative comparison with RGB↔X [83] on DL3DV10k [47] dataset in Fig. 5.

Image vs. video model. Comparing Ours (*image*) and Ours, the video model consistently enhances the quality of



Figure 6. **Qualitative comparison of relighting.** Our method produces more accurate specular reflections compared to the baselines.



Figure 7. **Qualitative ablation of relighting.** Joint training with real-world data and adding LoRA during training significantly improve relighting quality for real-world scenes.

inverse rendering across all attributes. Notably, for properties associated with specular materials, the video model reduces RMSE by 41% for metallic (from 0.066 to 0.039) and 20% for roughness (from 0.098 to 0.078) compared to the image model. This suggests that the model learns to leverage view changes in video data, effectively capturing view-dependent effects to predict specular properties more accurately.

One-step deterministic fine-tuning. We also ablate the design choice of 1-step deterministic fine-tuning in Table 3 and 4. By default, the inverse renderer performs 20 denoising steps during inference. Building on recent findings in image diffusion models [51], we demonstrate that strongly conditioned *video* diffusion models can also be fine-tuned as 1-step deterministic models. Despite the significantly reduced computational cost, we observe that 1-step models consistently produce more “accurate” predictions and outperform multi-step stochastic models in photometric evaluations such as PSNR scores. However, the 1-step model enforces deterministic output, which can result in blurrier predictions for ambiguous regions with high-frequency details, thus yielding lower perceptual metrics, such as LPIPS. For neural forward rendering and relighting tasks, we use multi-step stochastic models to capture more realistic details, though we note that 1-step models can be a competitive choice for error-sensitive tasks and enhancing runtime efficiency.

5.4. Evaluation of Relighting

In Table 2 and Fig. 6, we compare with recent state-of-the-art relighting methods DiLightNet [82] and Neural Gaffer [30]. Our method outperforms these baselines, particularly in scenes with complex shadows and inter-reflections. Overall, it produces high-quality lighting effects and more accurate color and scale.

Ablation study. We ablate the design choices of synthetic-



Figure 8. **Image editing applications.** Top: Realistic material editing, adjusting the sphere’s roughness and the horse’s metallic. Bottom: Object insertion of a bathtub and table into scene images.

real joint training in Fig. 7. While synthetic data provides accurate supervision signals, it is limited to a specific domain and lacks the diversity and complexity found in real-world data. When training exclusively on synthetic data (Ours Synth.), the model struggles with complex structures, such as trees, which are rarely represented in synthetic datasets. Since the real-world auto-labels are estimated using inverse rendering models and contain imperfections, we find that incorporating a LoRA [27] during training with real data consistently improves visual quality.

5.5. Applications

We show material editing and object insertion applications in Fig. 8. In the top row, we adjust the sphere’s roughness from 0.15 to 0.6 and increase the horse’s metallic property from 0 to 1, achieving photorealistic material edits. In the bottom row, we insert a bathtub and table in the G-buffer space of the input image, and use our forward renderer to produce the edited result. The inserted objects blend naturally into the scene, generating realistic reflections and shadows.

6. Discussion

DIFFUSIONRENDERER provides a scalable, data-driven approach to inverse and forward rendering, achieving high-quality G-buffer estimation and photorealistic image generation without relying on explicit path tracing or precise 3D scene representations. Jointly trained on synthetic and auto-labeled real-world data, DIFFUSIONRENDERER consistently outperforms state-of-the-art methods.

Limitations and future work. Our method is based on Stable Video Diffusion, which operates offline and would benefit from distillation techniques to improve inference speed. For editing tasks, the inverse and forward rendering models preserve most of the original content but may introduce slight variations in color or texture. Future work could explore task-specific fine-tuning [37] and develop neural intrinsic features to enhance content consistency and handle more complex visual effects. Additionally, our real-world auto-labeling currently adopts off-the-shelf lighting estimation model [61] which could benefit from better accuracy and robustness. With rapid advancements in video diffusion models [1] toward higher quality and faster inference speeds, we are optimistic that DIFFUSIONRENDERER will inspire future research in high-quality image synthesis and editing.

Acknowledgments. The authors thank Shiqiu Liu, Yichen Sheng, and Michael Kass for their insightful discussions that contributed to this project. We also appreciate the discussions with Xuanchi Ren, Tianchang Shen and Zheng Zeng during the model development process.

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