

NeRFactor: Neural Factorization of Shape and Reflectance Under an Unknown Illumination

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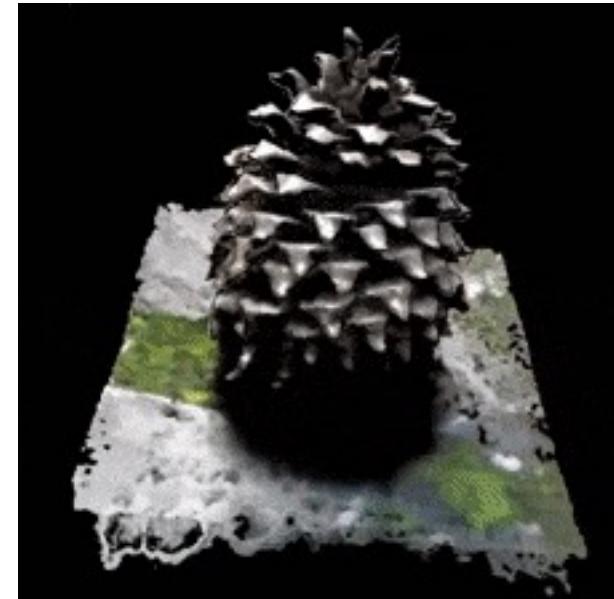
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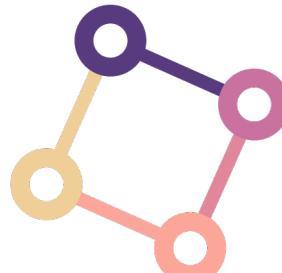


TOG 2021 (Proc. SIGGRAPH Asia)



2022.05.02

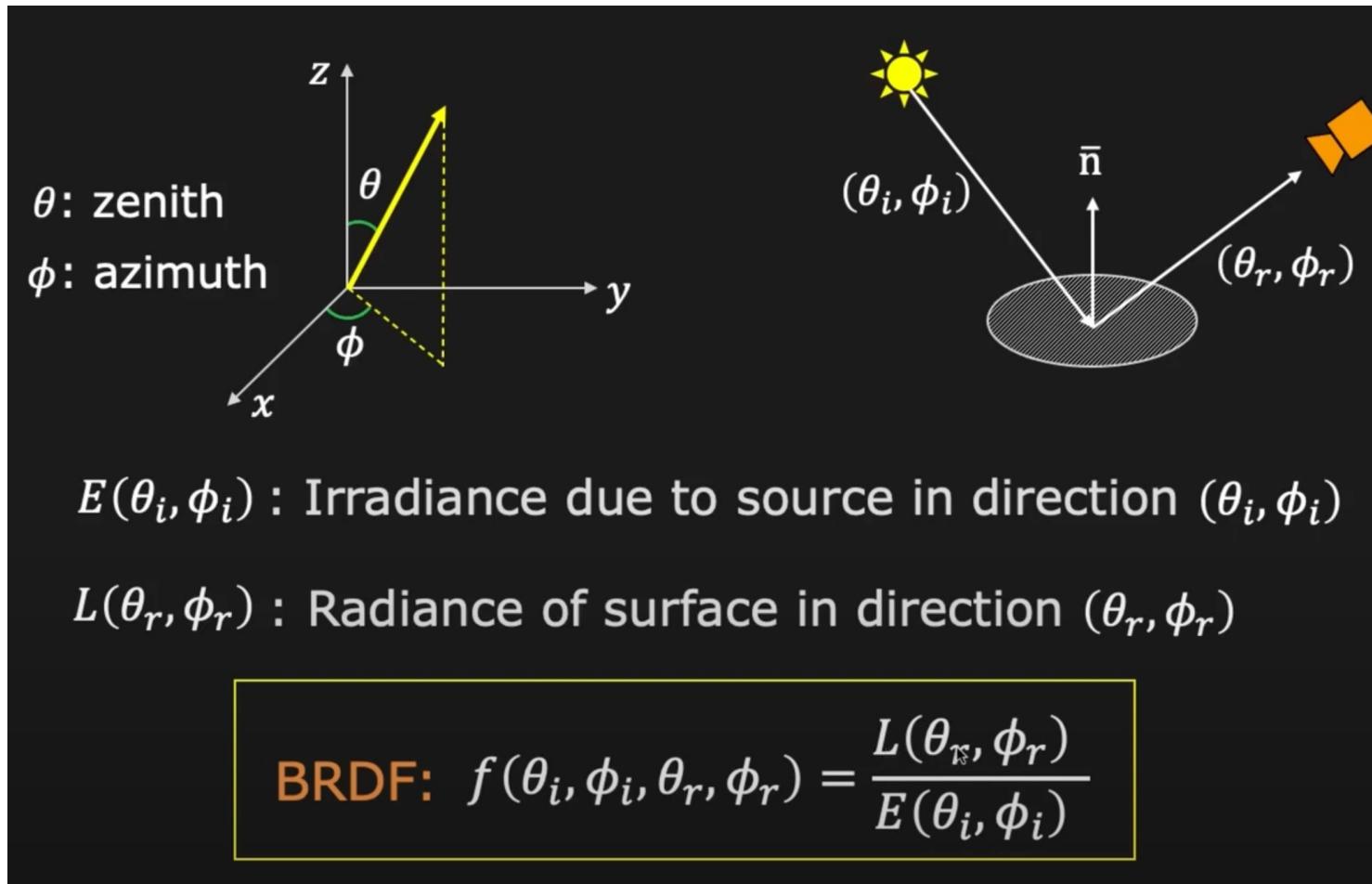
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DAVIAN
Data and Visual Analytics Lab

Prerequisite #1 – Reflectance Model

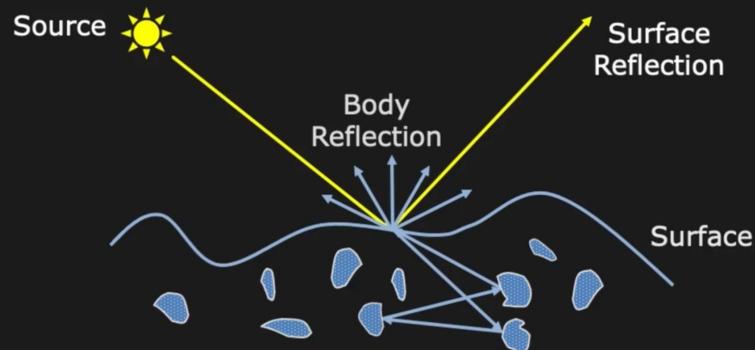
- Bidirectional Reflectance Distribution Function (BRDF)



Prerequisite #1 – Reflectance Model

- Lambertian Surface (100% Body refl.) vs Ideal Specular (100% Surface refl.)

Reflection Mechanisms



Surface Reflection

- Specular Reflection
- Glossy Appearance
- Smooth Surfaces
(e.g., mirror, glass)

Body Reflection

- Diffuse Reflection
- Matte Appearance
- Non-Homogeneous Medium
(e.g., clay, paper)

Body Reflection:



Surface Reflection:

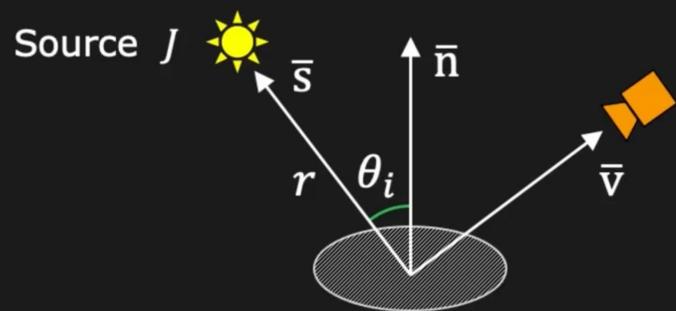


Prerequisite #1 – Reflectance Model

- BRDF of Lambertian Surface

Lambertian Model (Body)

Surface appears equally bright from **ALL** directions



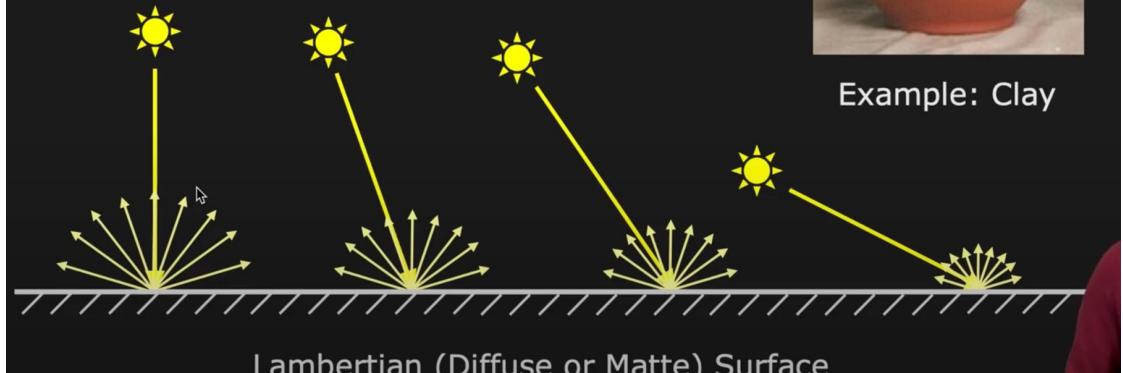
Lambertian BRDF:

$$L = \frac{\rho_d}{\pi} E$$

$$f(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{\rho_d}{\pi} \quad \rho_d : \text{Albedo} \quad (0 \leq \rho_d \leq 1)$$

Commonly used in Vision and Graphics

Image intensity I is independent of viewing direction.



Example: Clay

Prerequisite #1 – Reflectance Model

- Image Intensity of Radiated Light from Lambertian Surface

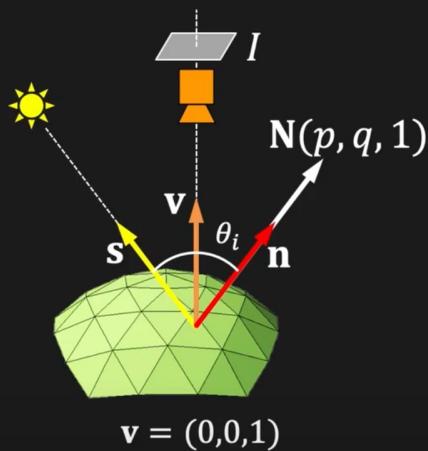
Image Intensity:

$$I = c \frac{\rho}{\pi} \frac{J}{r^2} \cos \theta_i = c \frac{\rho}{\pi} k(\mathbf{n} \cdot \mathbf{s})$$

where k : Source "Brightness"

ρ : Surface Albedo (Reflectance)

c : Constant (Camera Gain)

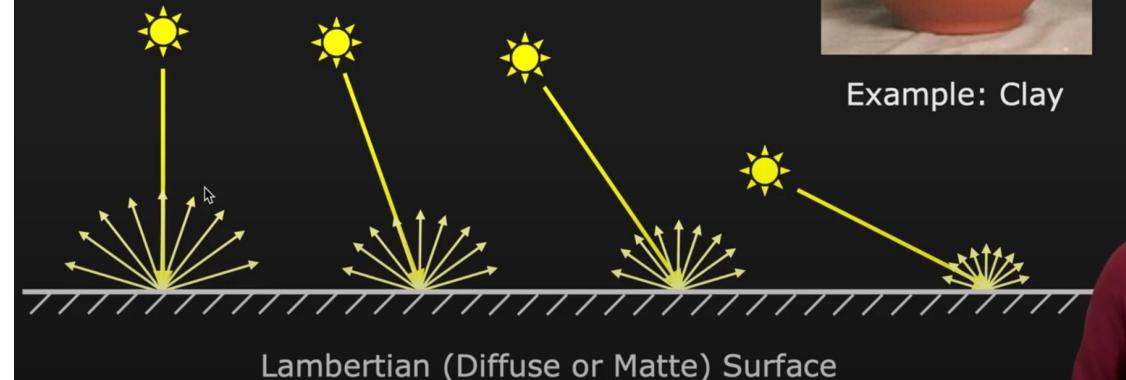


Let $c \frac{\rho}{\pi} k = 1$ then, $I = \cos \theta_i = \mathbf{n} \cdot \mathbf{s}$

Image intensity I is independent of viewing direction.



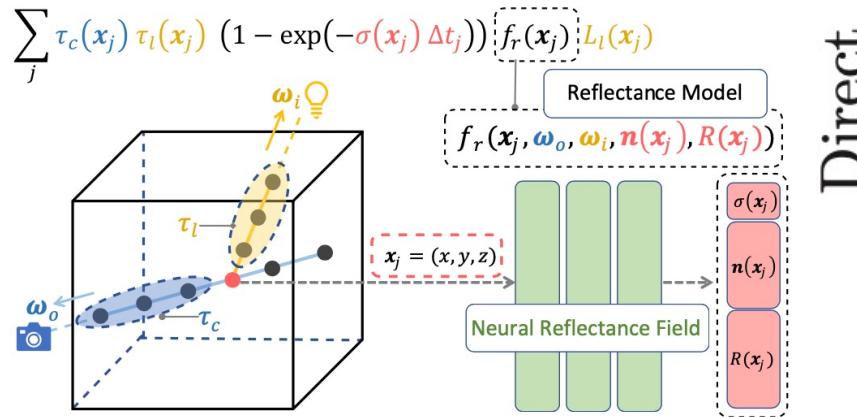
Example: Clay



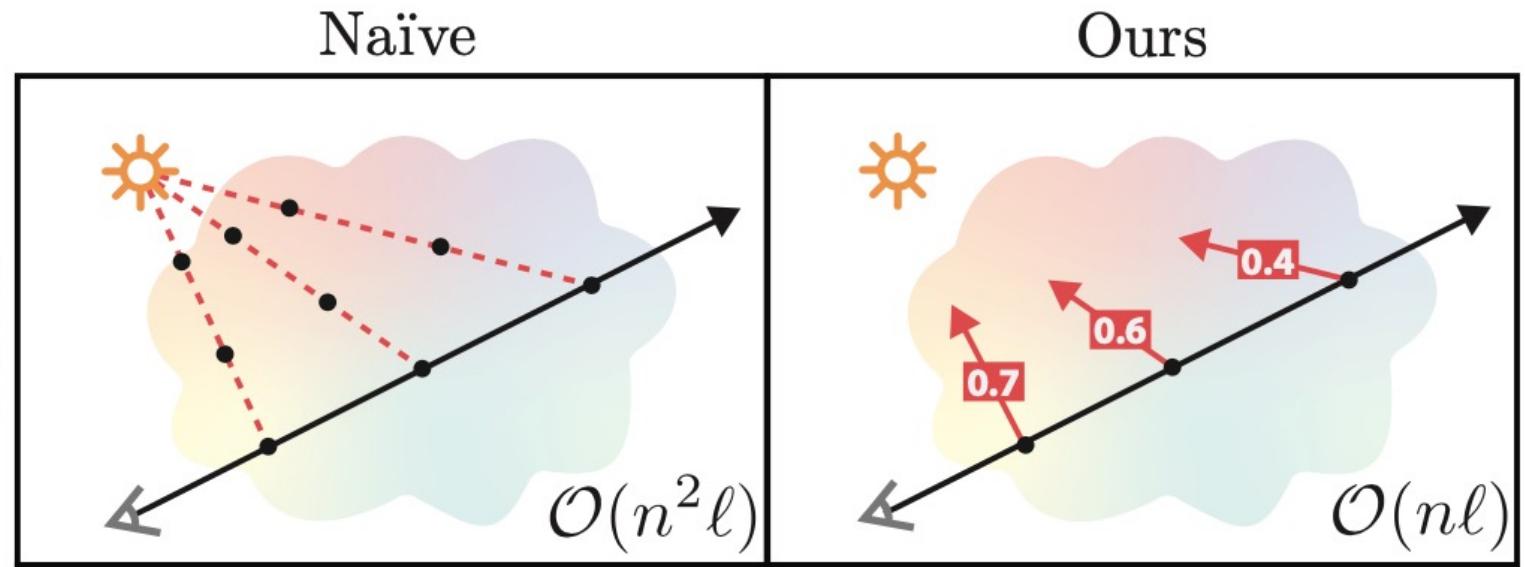
Prerequisite #2 – Visibility

- Visibility Field^[1]

$$\tau_l(x_j) = \exp \left(- \sum_p \sigma(x'_p) \Delta t'_p \right)$$

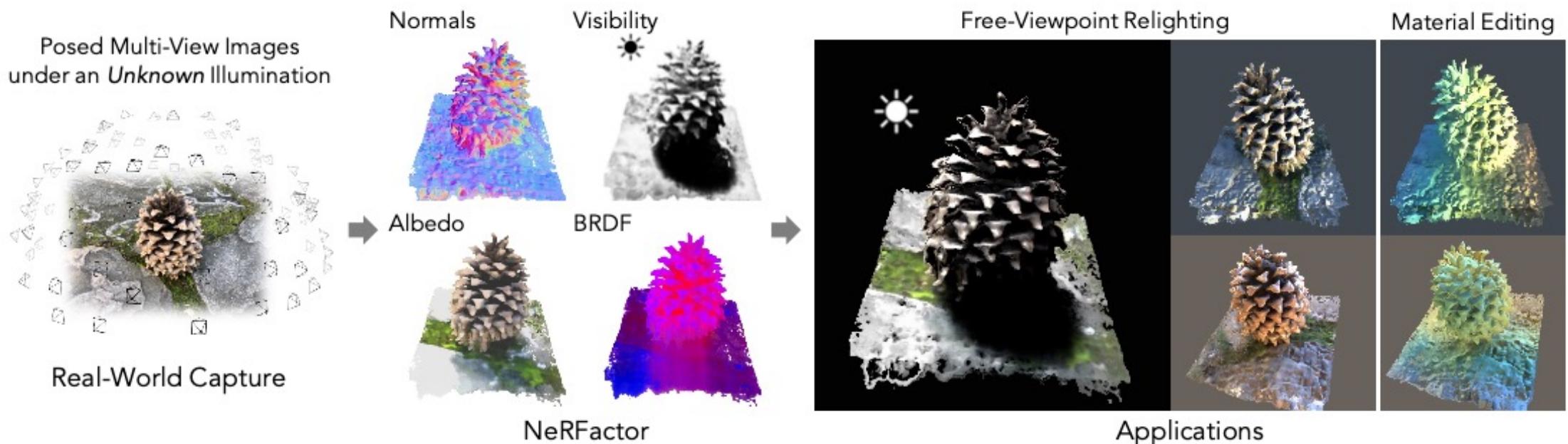


Direct

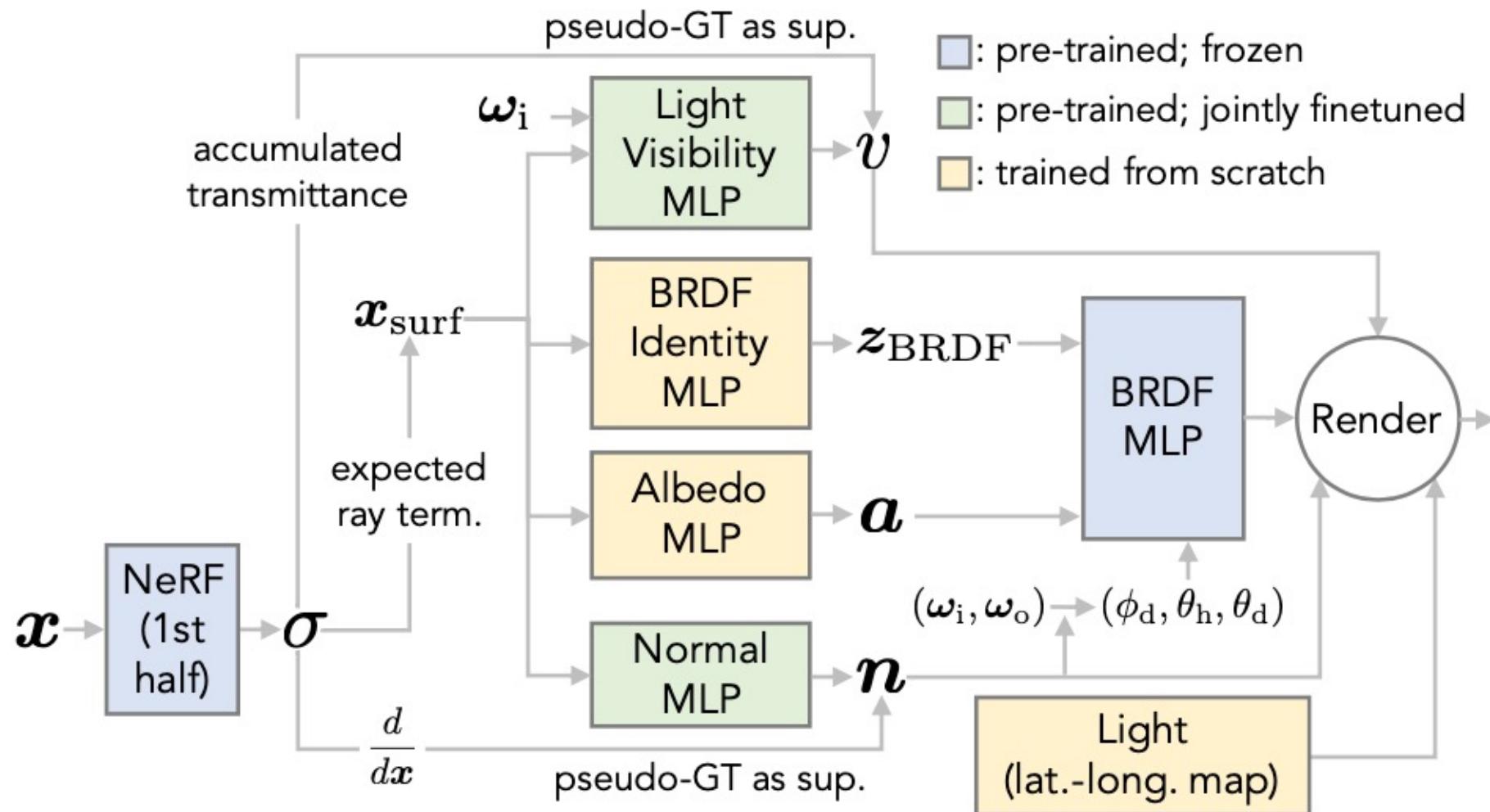


Problem Definition

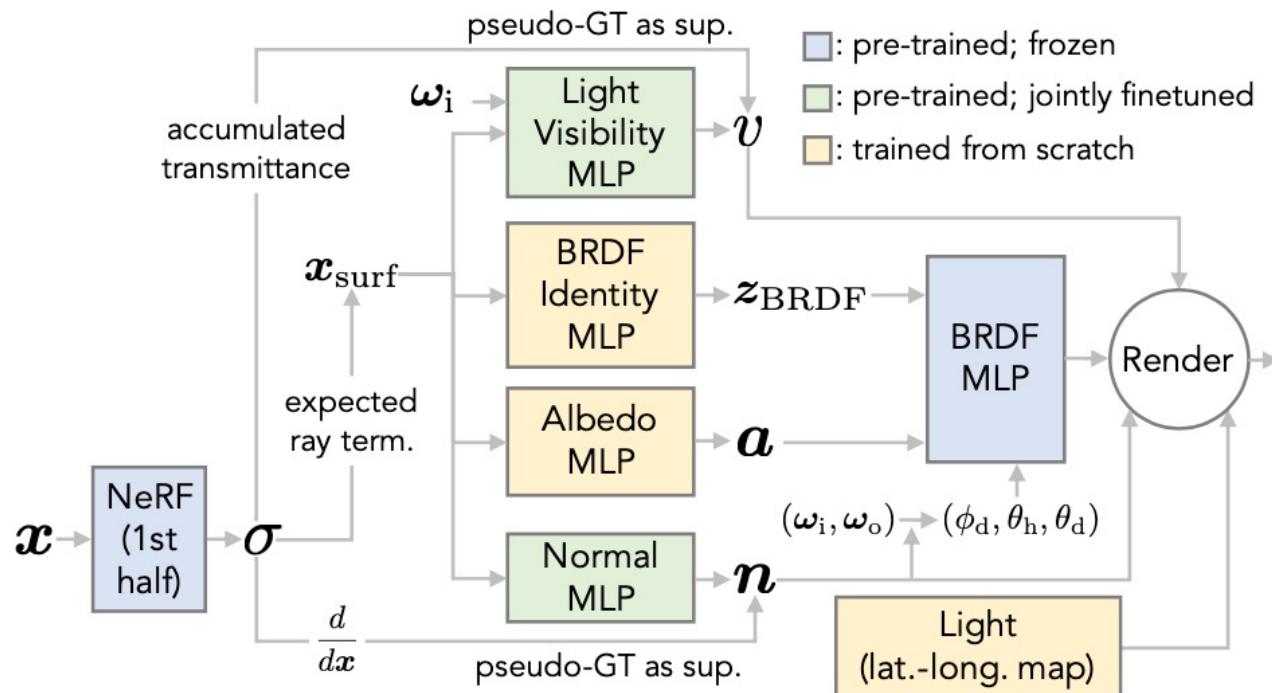
- Disentangling Reflectance Model Parameters



Methodology



Methodology



[0] Reflectance-Model based Renderer

[1] Pre-train and freeze

(1-1) Shape from NeRF

(1-2) BRDF MLP

[2] Pretrained & Finetuned at Main

(2-1) Light Visibility MLP

(2-2) Normal MLP

[3] Optimize at Main only

(3-1) BRDF identity MLP

(3-2) Albedo MLP

(3-3) Light Probe Map (Lateral / Longitudinal)

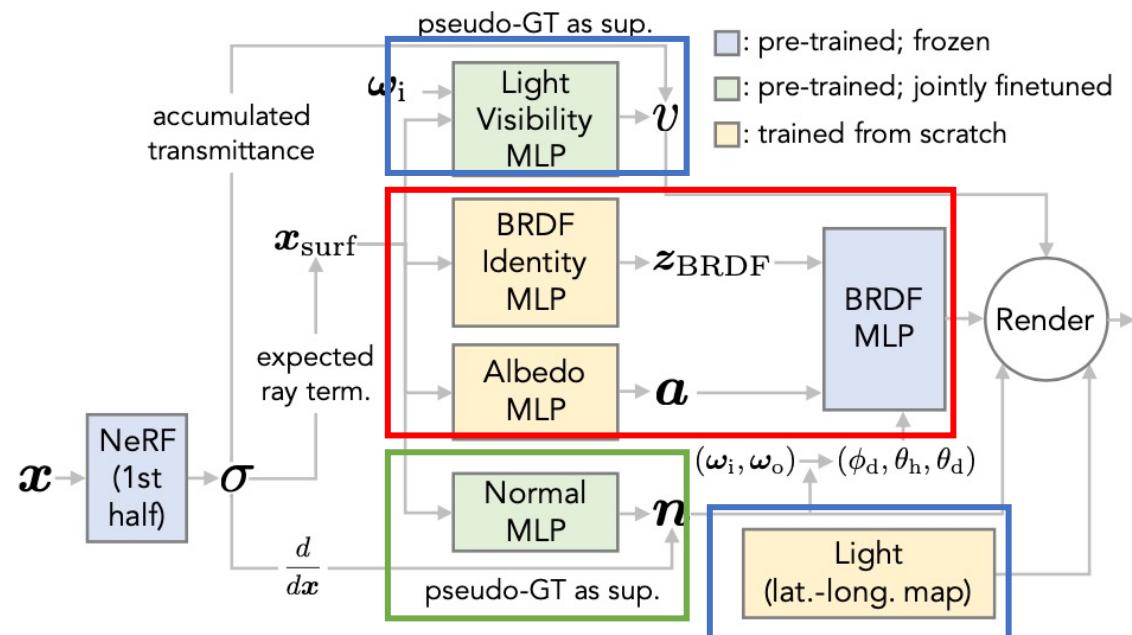
Methodology

- **Reflectance-Model based Renderer**

- NO ray-tracing integration will be used (x represents a point in surface)

$$L_o(x, \omega_o) = \int_{\Omega} \frac{R(x, \omega_i, \omega_o)}{\text{Reflectance (BRDF)}} \frac{L_i(x, \omega_i)}{\text{Source Intensity}} (\omega_i \cdot n(x)) d\omega_i$$

Source light approach angle

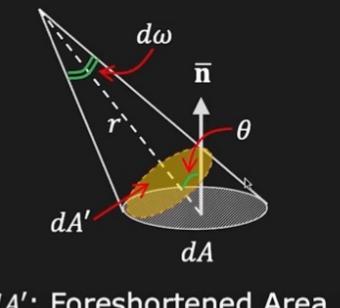


Concept: Solid Angle (3D)

$$d\omega = \frac{dA'}{r^2} = \frac{dA \cos \theta}{r^2}$$

Unit: steradian (sr)

$d\omega$ is dimensionless



Methodology

- **Shape**

A. Train Vanilla NeRF

B-1. **Surface Points**: Outgoing radiance calculated only at this point.

$$\mathbf{x}_{\text{surf}} = \mathbf{o} + \left(\int_0^{\infty} T(t) \sigma(\mathbf{r}(t)) t dt \right) \mathbf{d}$$

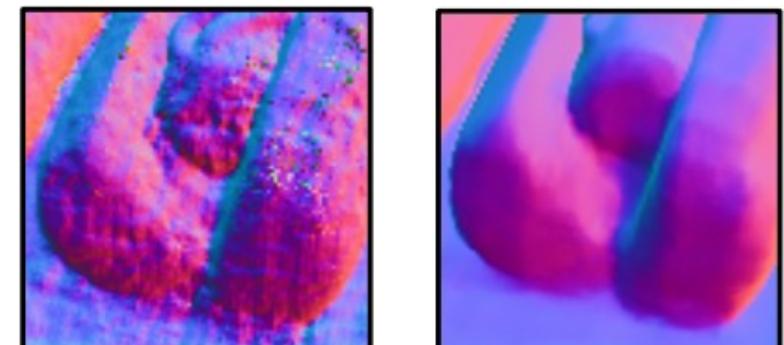
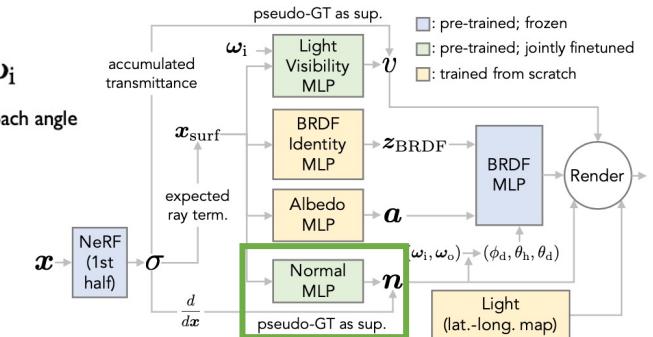
where $T(t) = \exp \left(- \int_0^t \sigma(\mathbf{r}(s)) ds \right)$

B-2. **Surface Normal**: Used to compare its angle to incident light.

- Conventionally, $n_a(x) = \frac{\partial \sigma}{\partial x}$, but this has too much noise
- Instead, let the network infer smooth surface normal.

$$\ell_n = \sum_{\mathbf{x}_{\text{surf}}} \left(\frac{\lambda_1}{3} \|f_n(\mathbf{x}_{\text{surf}}) - \mathbf{n}_a(\mathbf{x}_{\text{surf}})\|_2^2 + \frac{\lambda_2}{3} \|f_n(\mathbf{x}_{\text{surf}}) - f_n(\mathbf{x}_{\text{surf}} + \epsilon)\|_1 \right)$$

$$L_o(\mathbf{x}, \omega_o) = \int_{\Omega} \underbrace{R(\mathbf{x}, \omega_i, \omega_o)}_{\text{Reflectance (BRDF)}} \underbrace{L_i(\mathbf{x}, \omega_i)}_{\text{Source Intensity}} \underbrace{(\omega_i \cdot \mathbf{n}(\mathbf{x}))}_{\text{Source light approach angle}} d\omega_i$$



Methodology

• Reflectance

Lambertian factor

$$R(x_{\text{surf}}, \omega_i, \omega_o) = \frac{a(x_{\text{surf}})}{\pi} + f_r(x_{\text{surf}}, \omega_i, \omega_o)$$

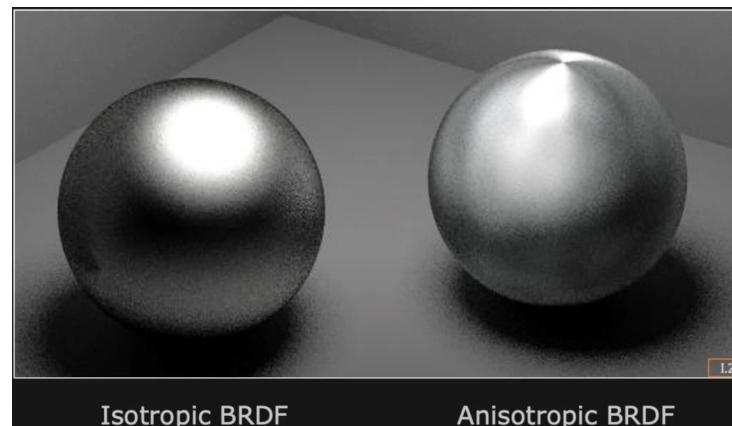
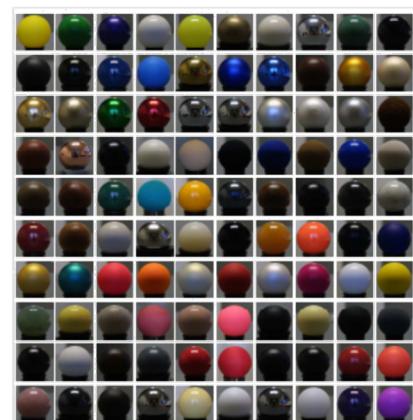
Non-Lambertian (specular) factor

$$= \frac{|f_a(x)|}{\pi} + f'_r(f_z(x), g(f_n(x), \omega_i, \omega_o)) \quad f'_r : (z_{\text{BRDF}}, (\phi_d, \theta_h, \theta_d)) \mapsto r$$

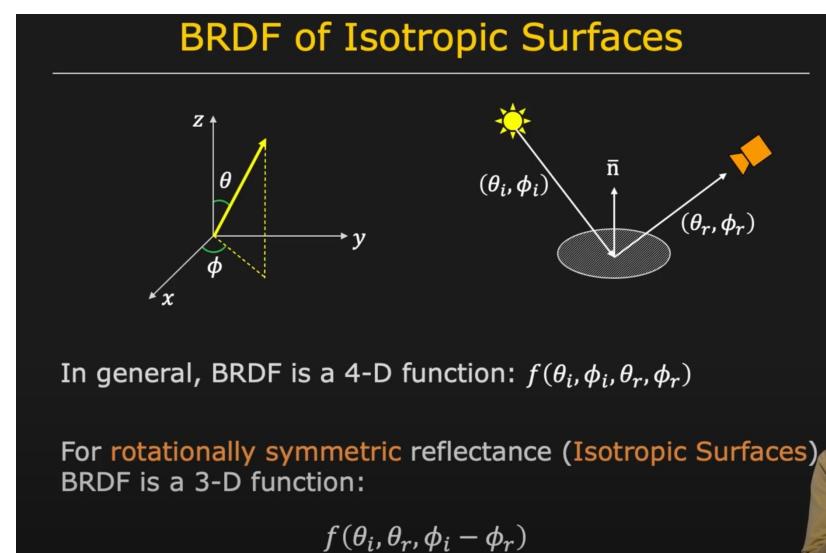
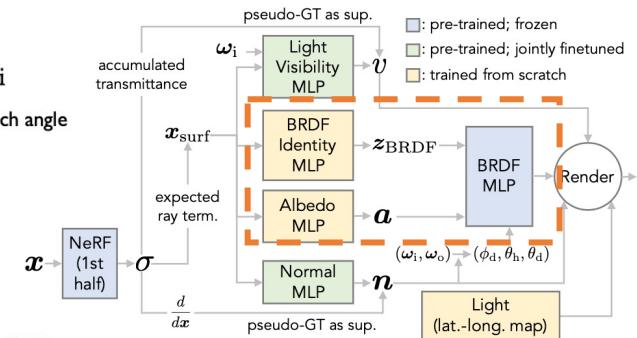
- BRDF MLP (f'_r) learned from real-world distribution (Learned as a prior & fixed)

- Given: Sphere's geometry (thus the incident / radiant angle) / “Achromatic” reflectance
- Learn: BRDF MLP / Latent BRDF parameters ($z_{\text{BRDF}, \text{REAL}}$)
- g : conversion to Rusinkiewicz coordinate (Assuming isotropic surface)

BRDF Database



$$L_o(x, \omega_o) = \int_{\Omega} \underbrace{R(x, \omega_i, \omega_o)}_{\text{Reflectance (BRDF)}} \underbrace{L_i(x, \omega_i)}_{\text{Source Intensity}} \underbrace{(\omega_i \cdot n(x))}_{\text{Source light approach angle}} d\omega_i$$

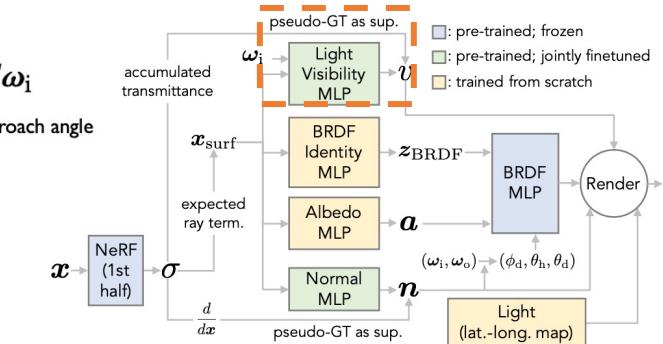


Methodology

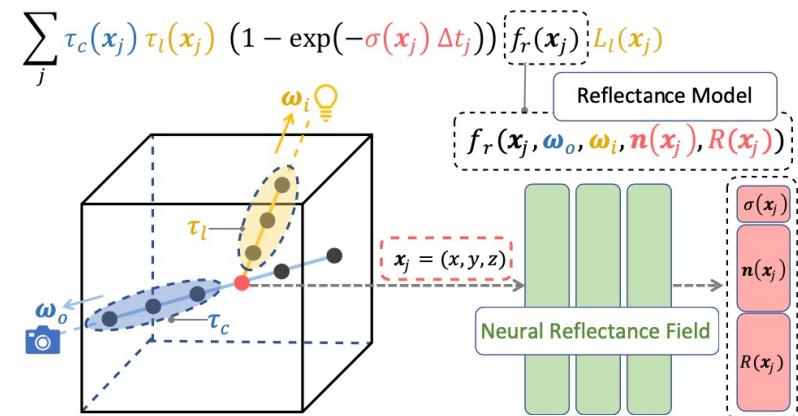
- **Light Visibility**

$$L_o(x, \omega_o) = \int_{\Omega} \frac{R(x, \omega_i, \omega_o) L_i(x, \omega_i)}{\text{Reflectance (BRDF)}} \frac{(\omega_i \cdot n(x))}{\text{Source light approach angle}} d\omega_i$$

$$\ell_v = \sum_{x_{\text{surf}}} \sum_{\omega_i} \left(\lambda_3 (f_v(x_{\text{surf}}, \omega_i) - v_a(x_{\text{surf}}, \omega_i))^2 + \lambda_4 |f_v(x_{\text{surf}}, \omega_i) - f_v(x_{\text{surf}} + \epsilon, \omega_i)| \right)$$



$$\tau_l(x_j) = \exp \left(- \sum_p \sigma(x'_p) \Delta t'_p \right) \rightarrow n_a(x_{\text{surf}})$$



Methodology

- **Light Probe (radiance map)**

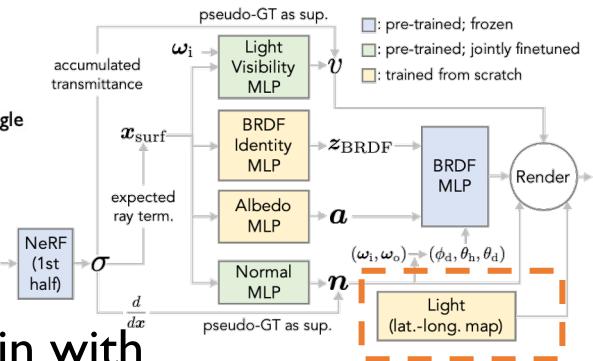
- Light probe: A function that maps from irradiant light angle to its intensity x
- Conventionally it's spherical, but this paper uses “longitude-latitude” domain with resolution of 16x32 (is thus the number of approximated irradiance)

***** Radiance map becomes a set of learnable parameters *****

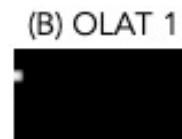


Spherical radiance map (Debevec, 1998)

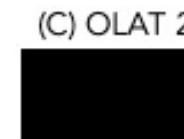
$$L_o(x, \omega_o) = \int_{\Omega} \frac{R(x, \omega_i, \omega_o) L_i(x, \omega_i) (\omega_i \cdot n(x)) d\omega_i}{\text{Reflectance (BRDF)}} \frac{\text{Source Intensity}}{\text{Source light approach angle}}$$



$$\ell_i = \lambda_7 \left(\left\| \begin{bmatrix} -1 & 1 \end{bmatrix} * L \right\|_2^2 + \left\| \begin{bmatrix} -1 \\ 1 \end{bmatrix} * L \right\|_2^2 \right)$$



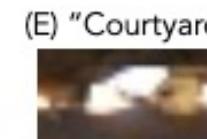
(B) OLAT 1



(C) OLAT 2



(D) OLAT 3



(E) "Courtyard"

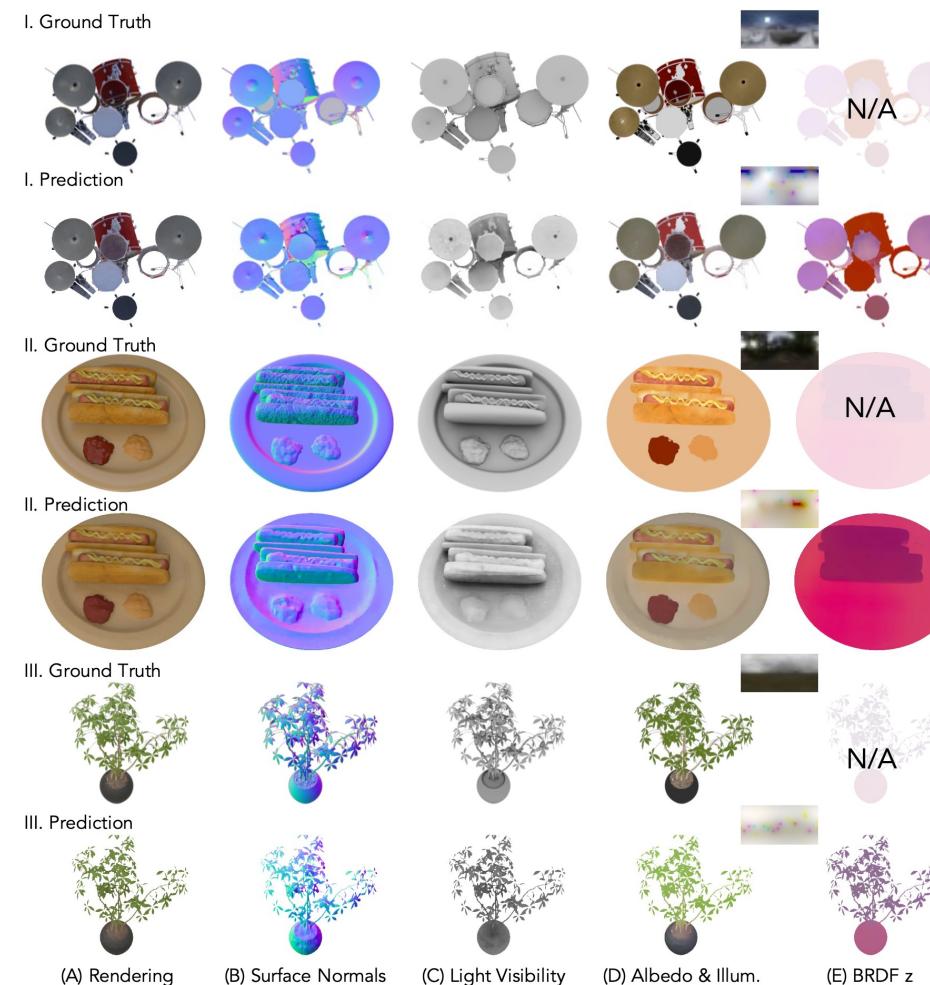


(F) "Sunrise"

Longitude/latitude radiance map

Result

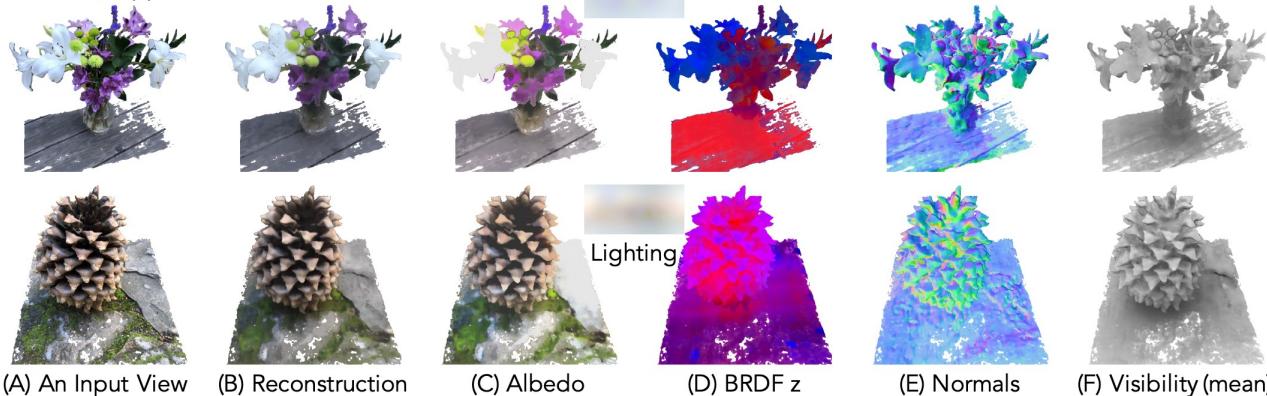
- **Jointly Optimized / Factorized (Disentangled) shape, reflectance, and lightening**



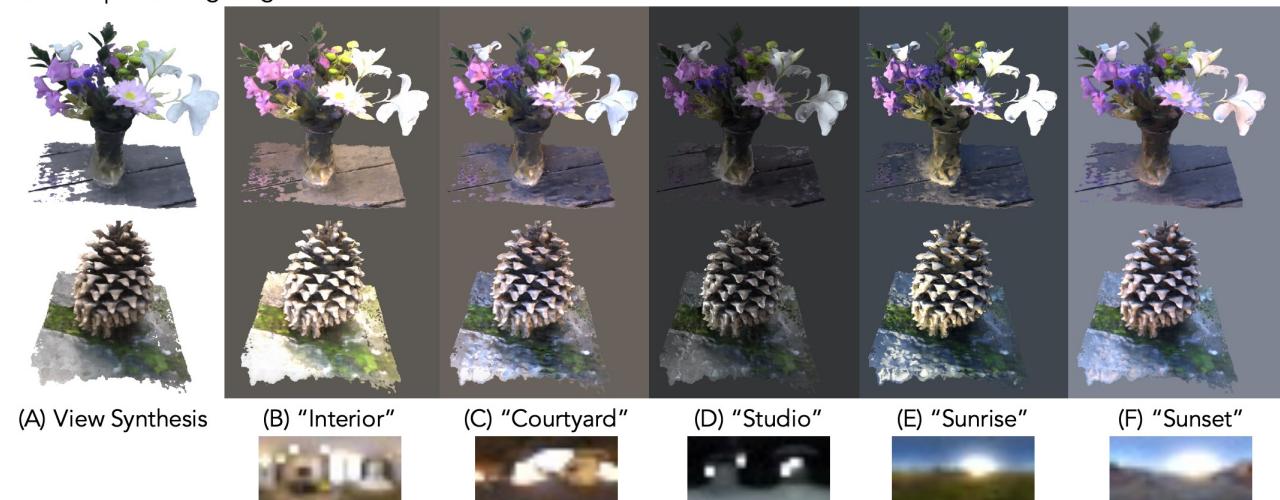
Result

- **Results of real-world captures**

I. Factorizing Appearance

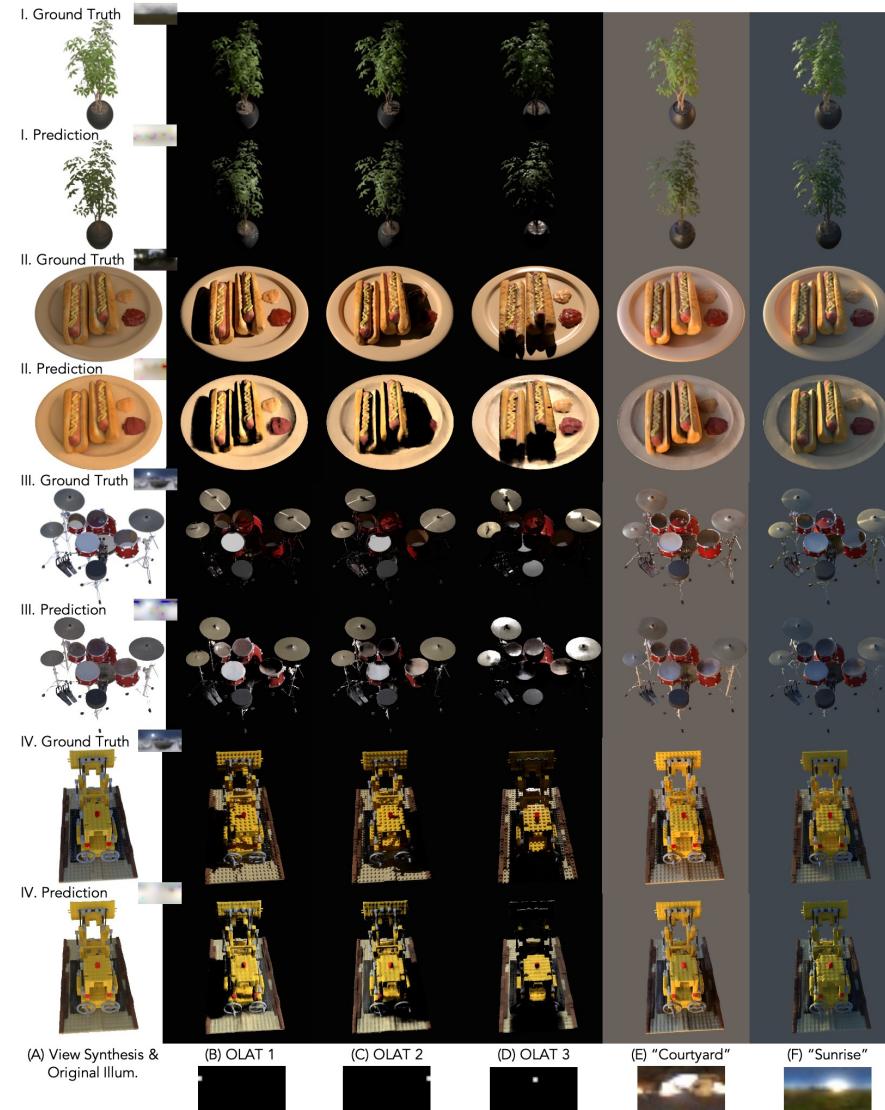


II. Free-Viewpoint Relighting



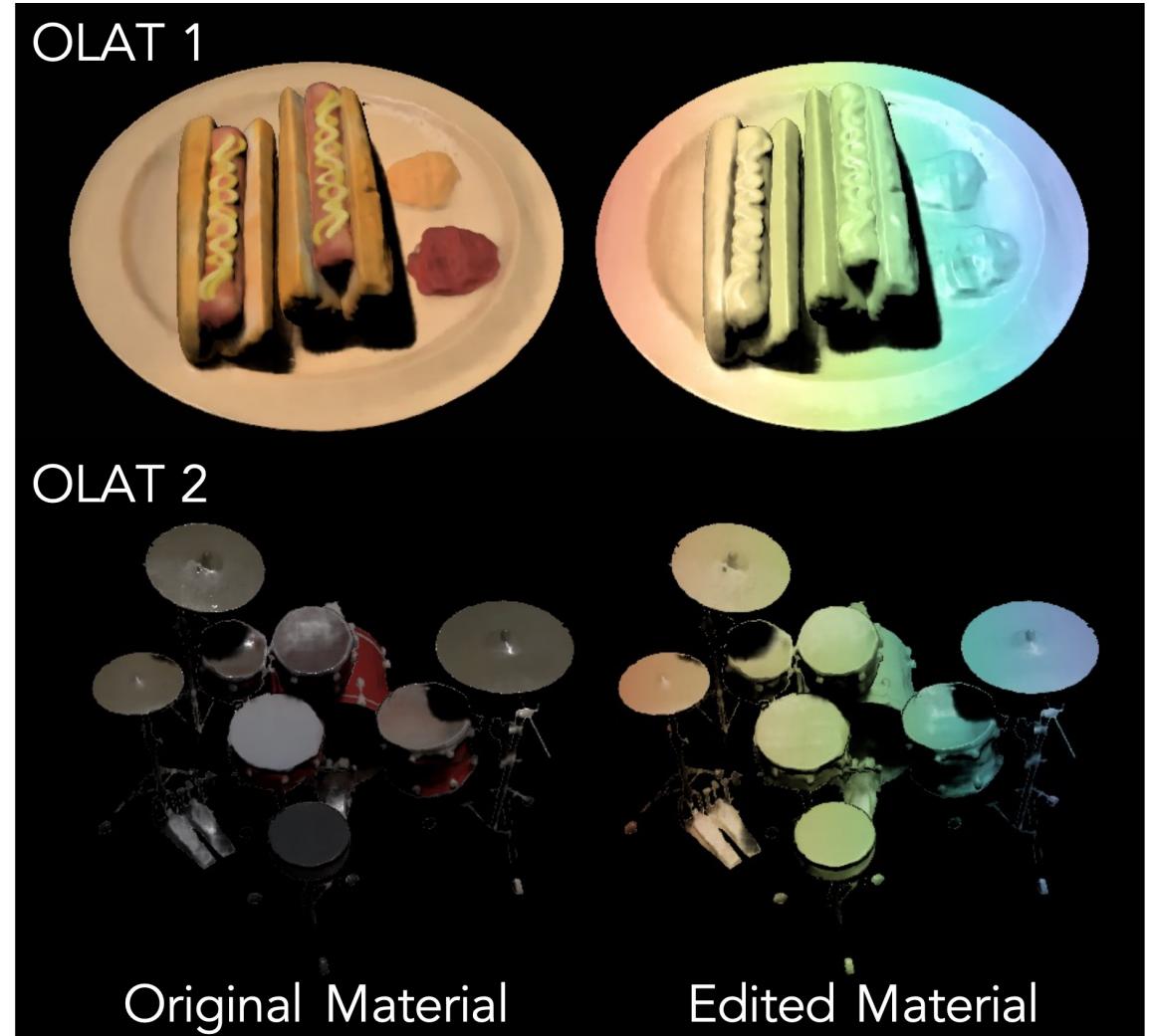
Result

- Novel-view relighting



Result

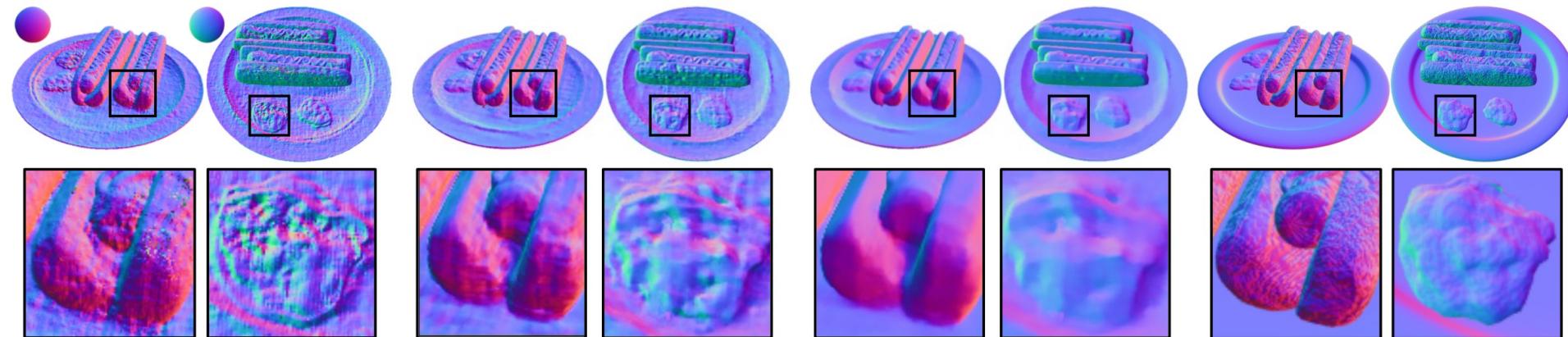
- **Material Editing and relighting**
 - **BRDF:** That from ‘pearl-paint’ in MERL dataset.
 - **Albedo:** colors linearly interpolated (in Euclidean space) from the ‘turbo’ colormap.



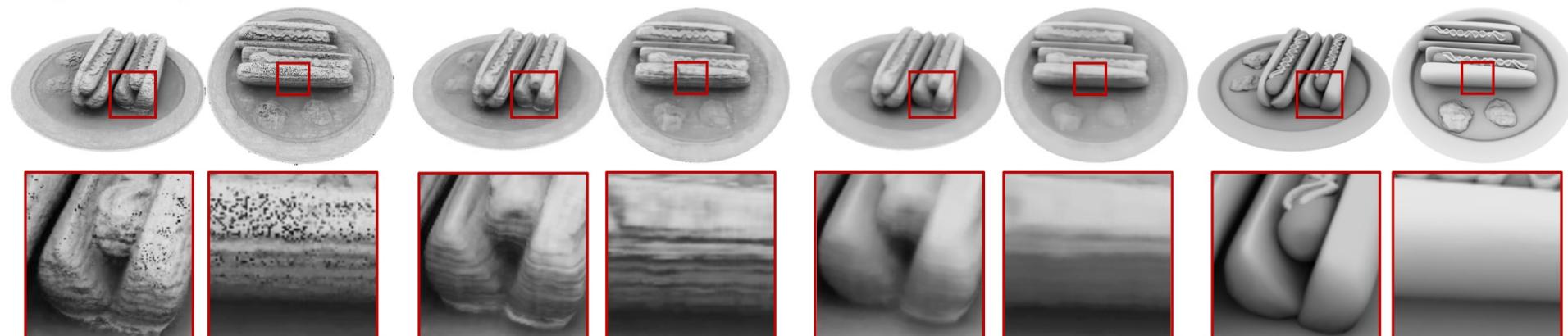
Result

- **Surface Normals and Light Visibility Visualizations**

I. Surface Normals



II. Light Visibility (mean)



(A) Derived from NeRF

(B) Jointly Optimized

(C) NeRFactor: Jointly Optimized
w/ Smoothness Constraints

(D) Ground Truth