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

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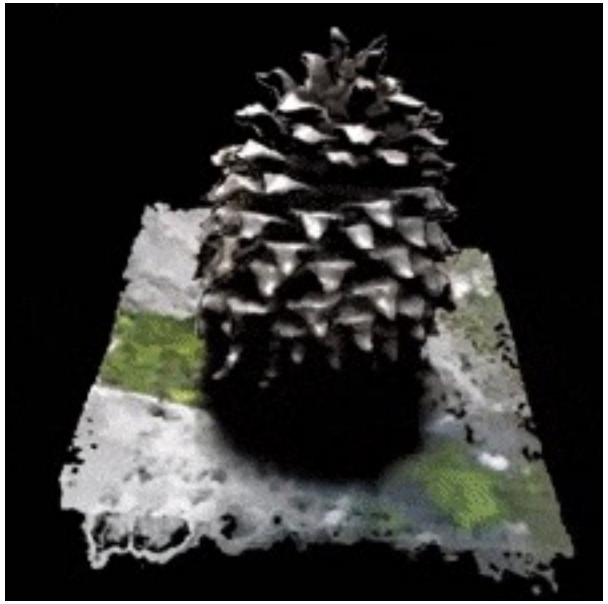

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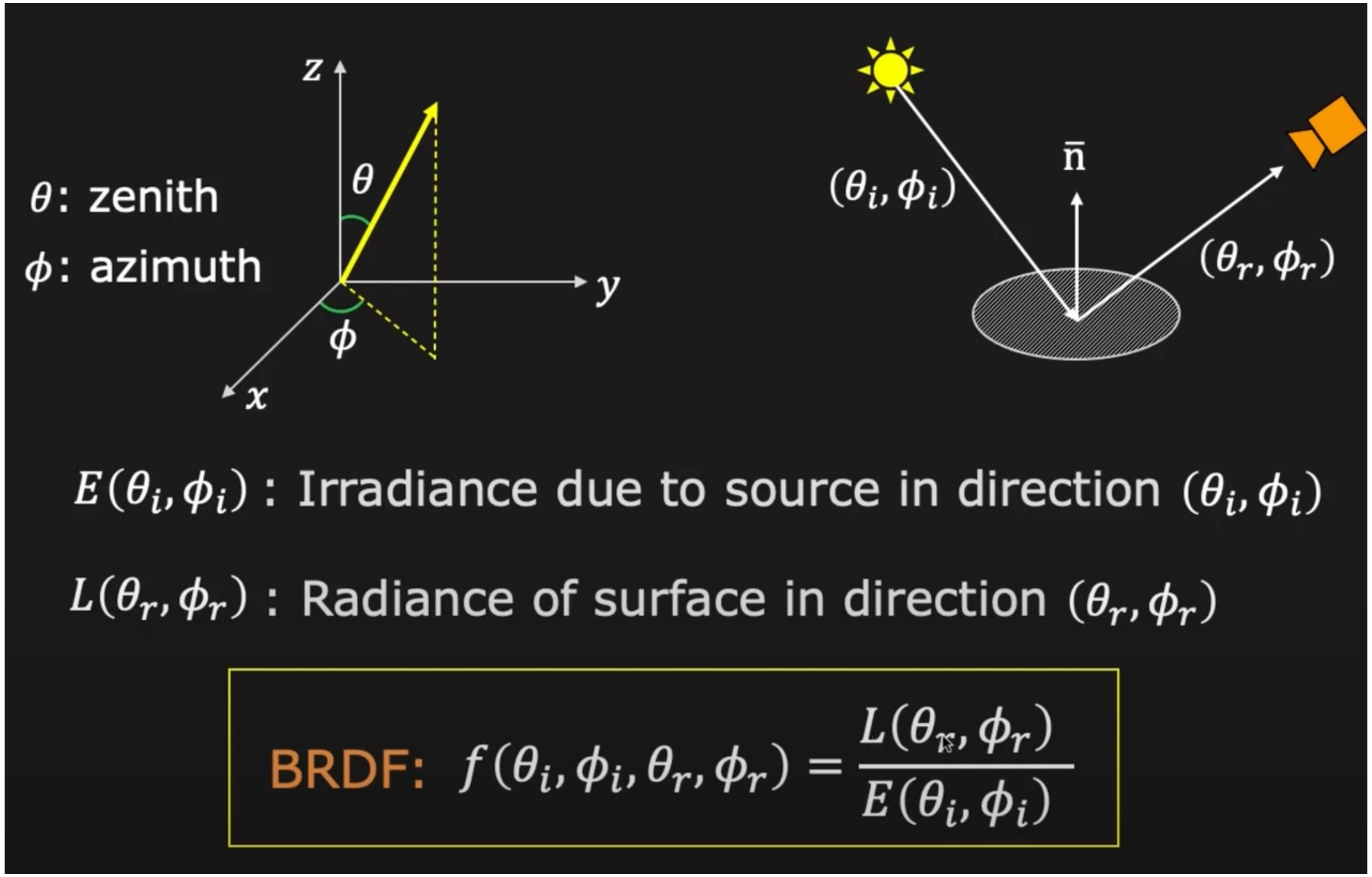
Data and Visual Analytics Lab

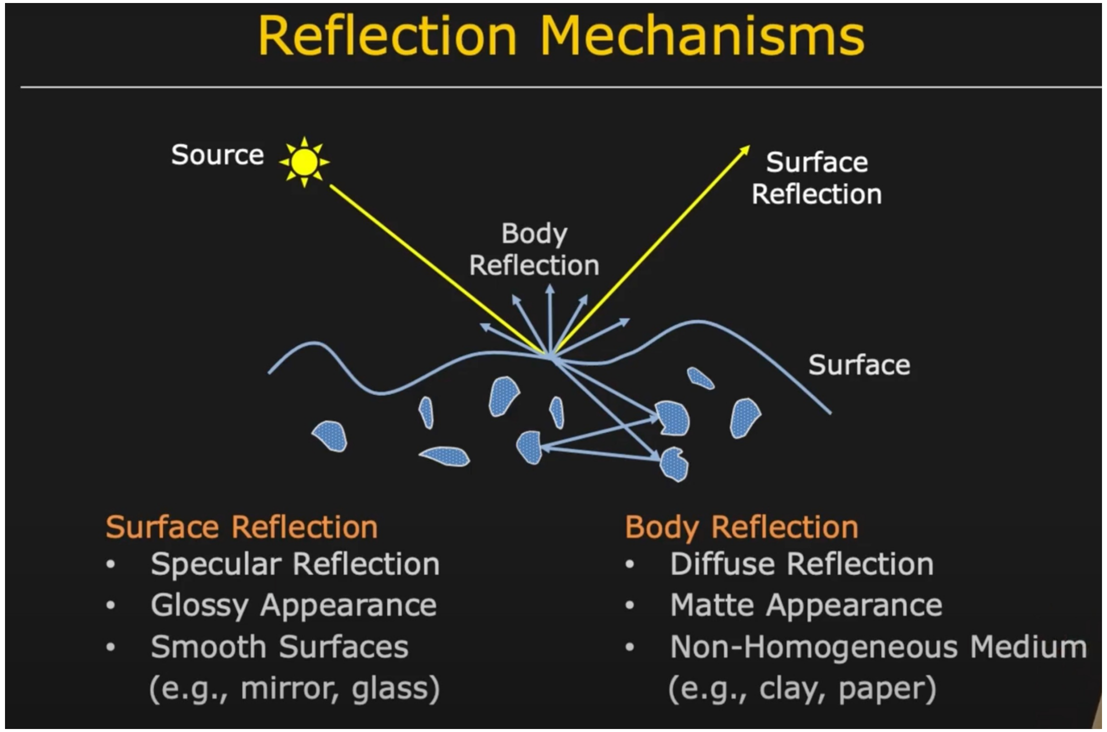
Prerequisite #1 – Reflectance Model

- Bidirectional Reflectance Distribution Function (BRDF)



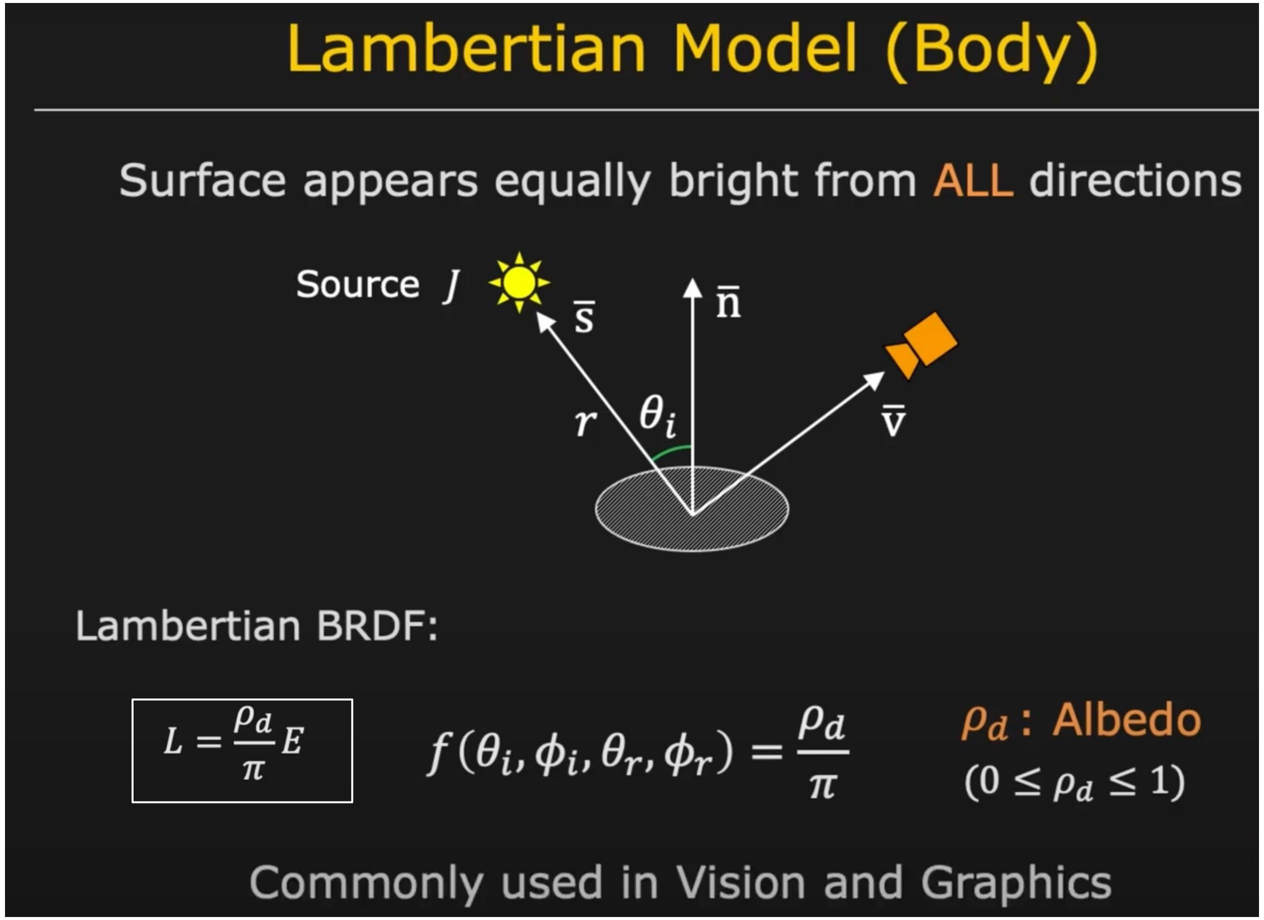
Prerequisite #1 – Reflectance Model

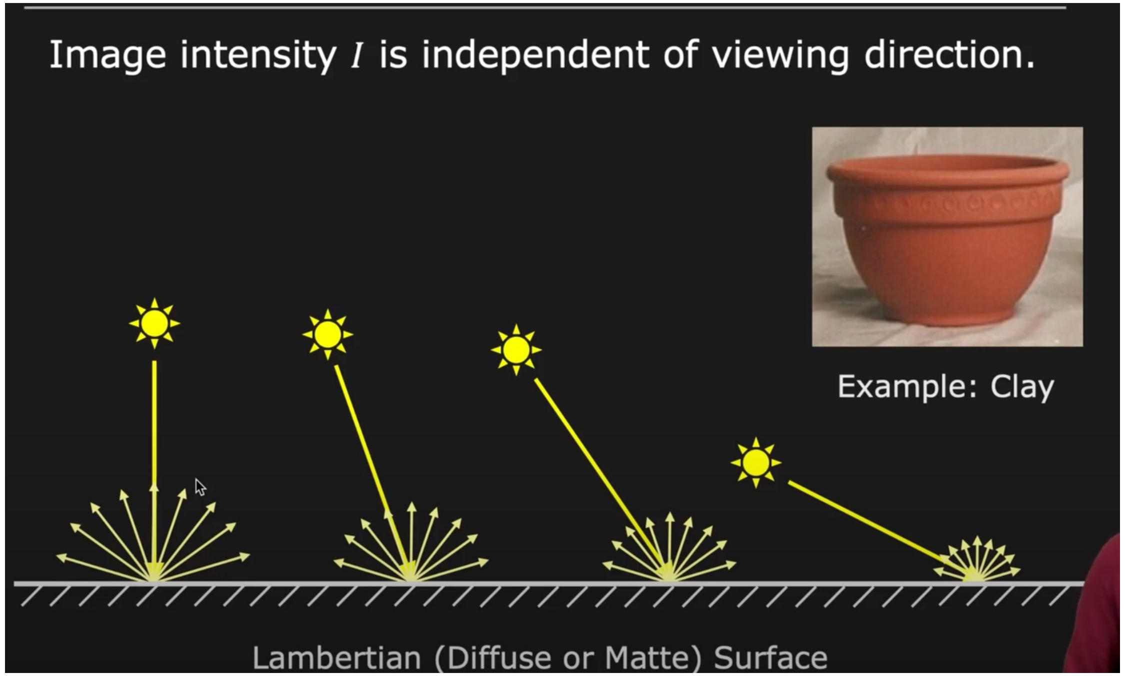
- Lambertian Surface (100% Body refl.) vs Ideal Specular (100% Surface refl.)



Prerequisite #1 – Reflectance Model

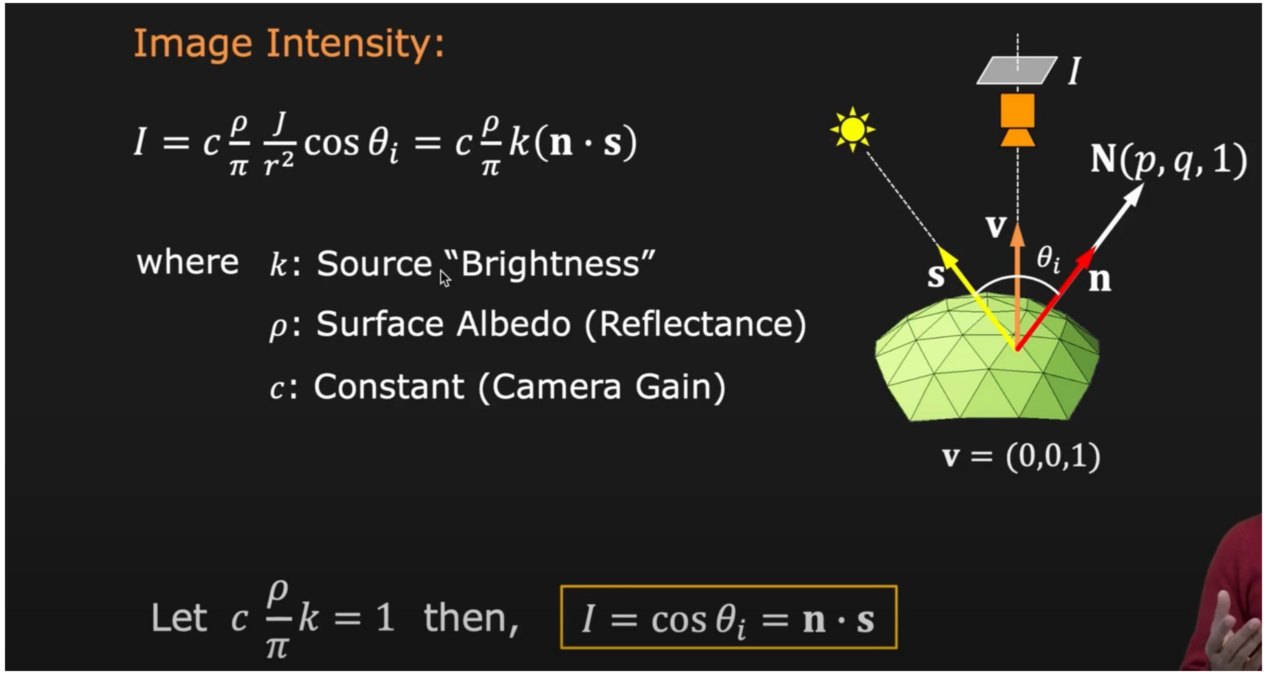
- BRDF of Lambertian Surface

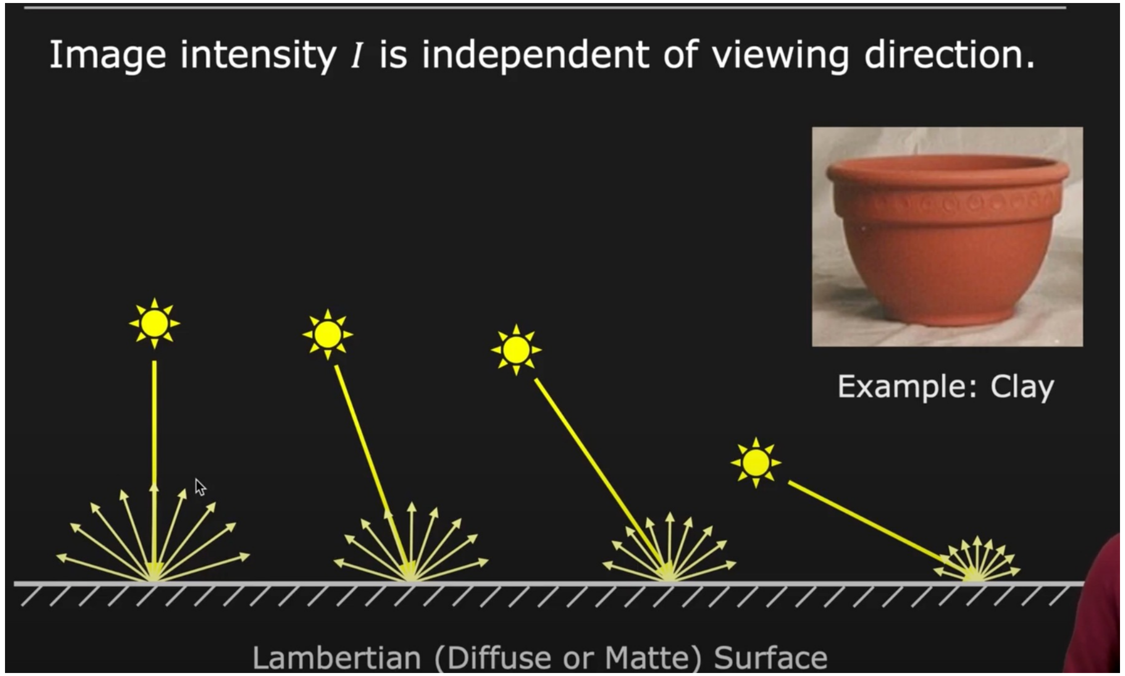




Prerequisite #1 – Reflectance Model

- Image Intensity of Radiated Light from Lambertian Surface

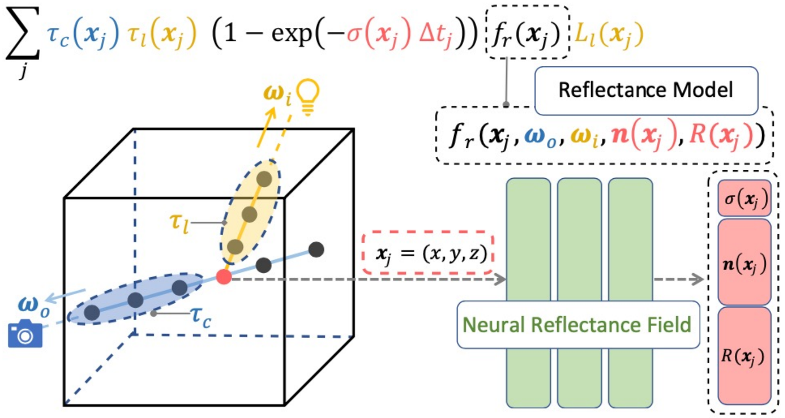


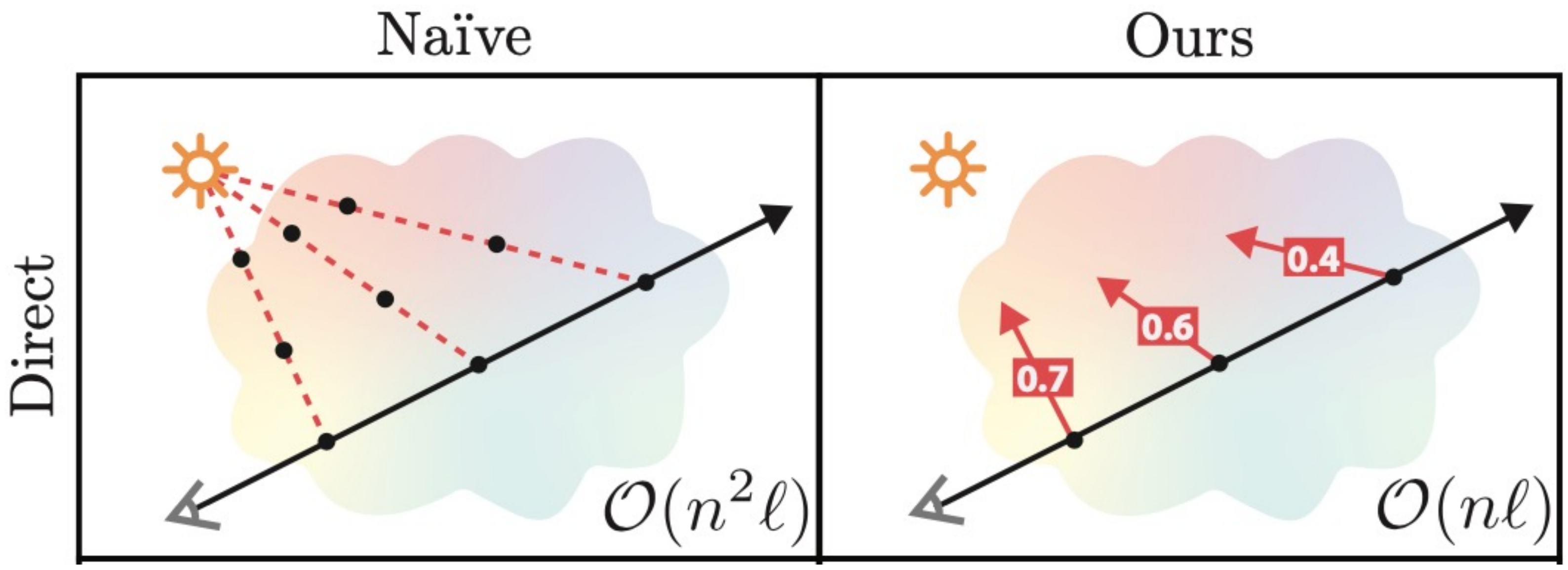


Prerequisite #2 – Visibility

- Visibility Field[1]

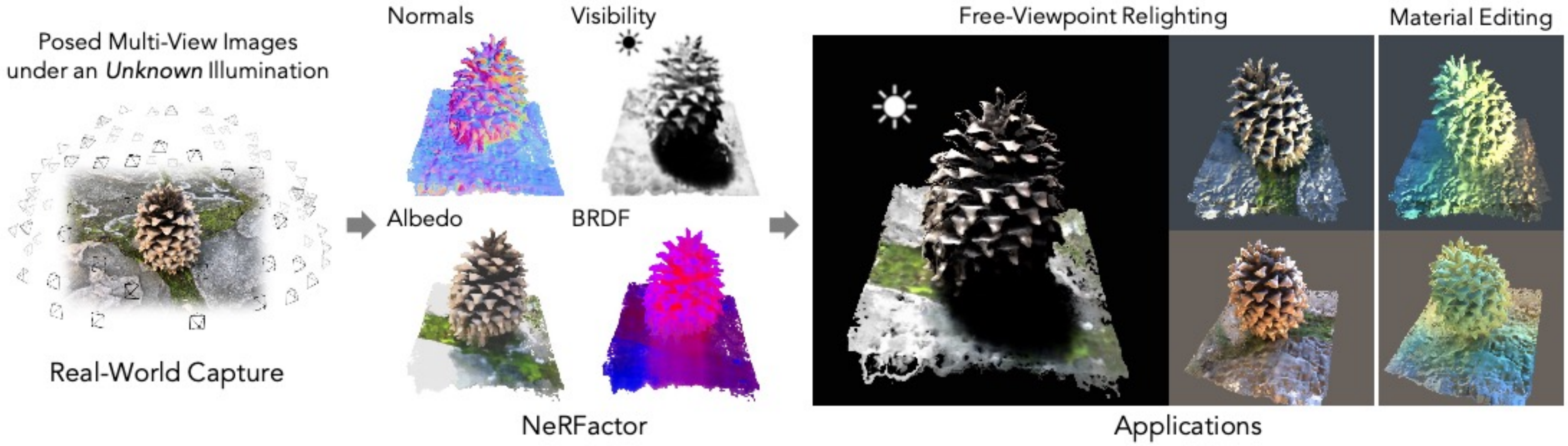
$$\tau_l(\boldsymbol{x}_j) = \exp\left(-\sum_p \sigma(\boldsymbol{x}'_p)\Delta t'_p\right)$$



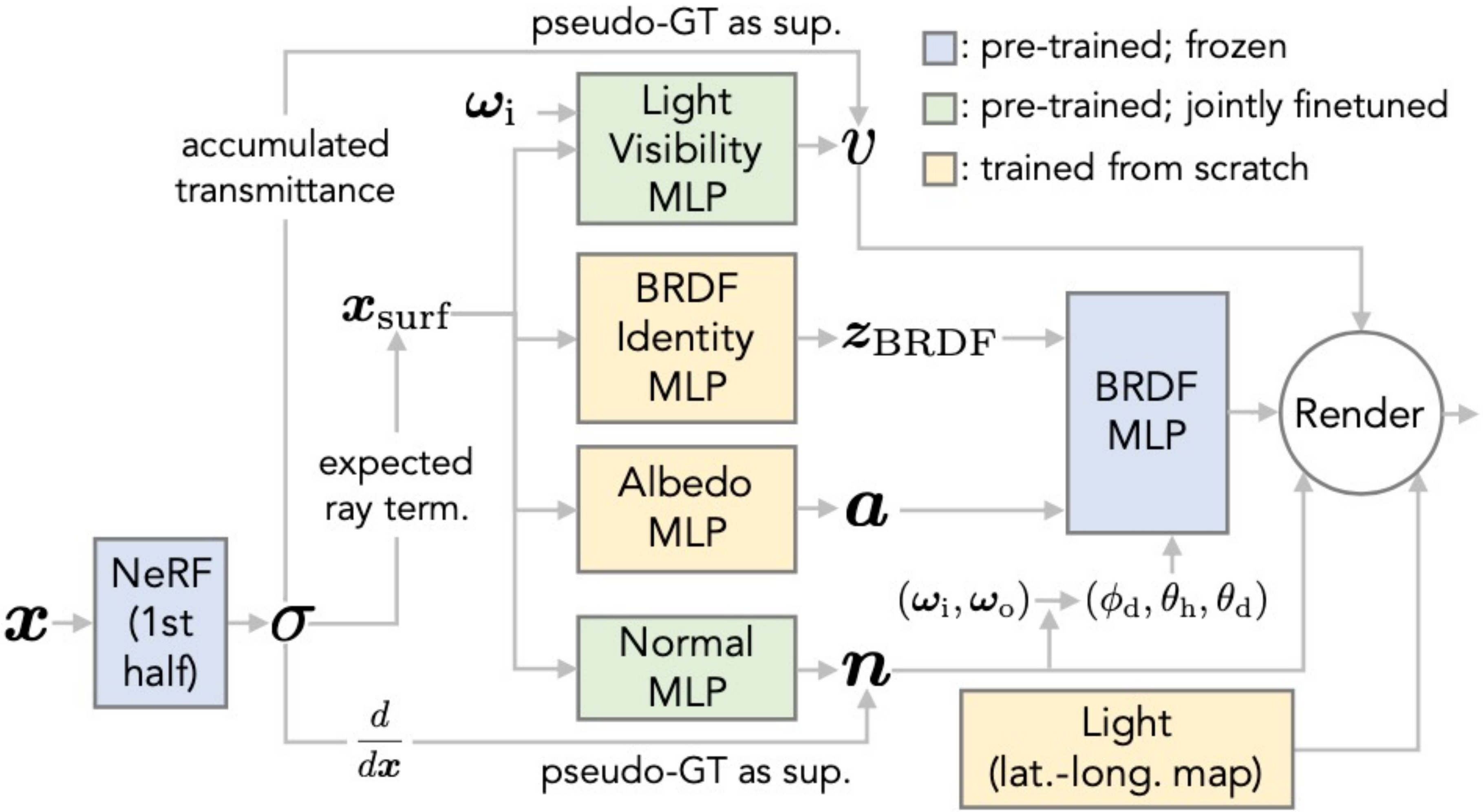


Problem Definition

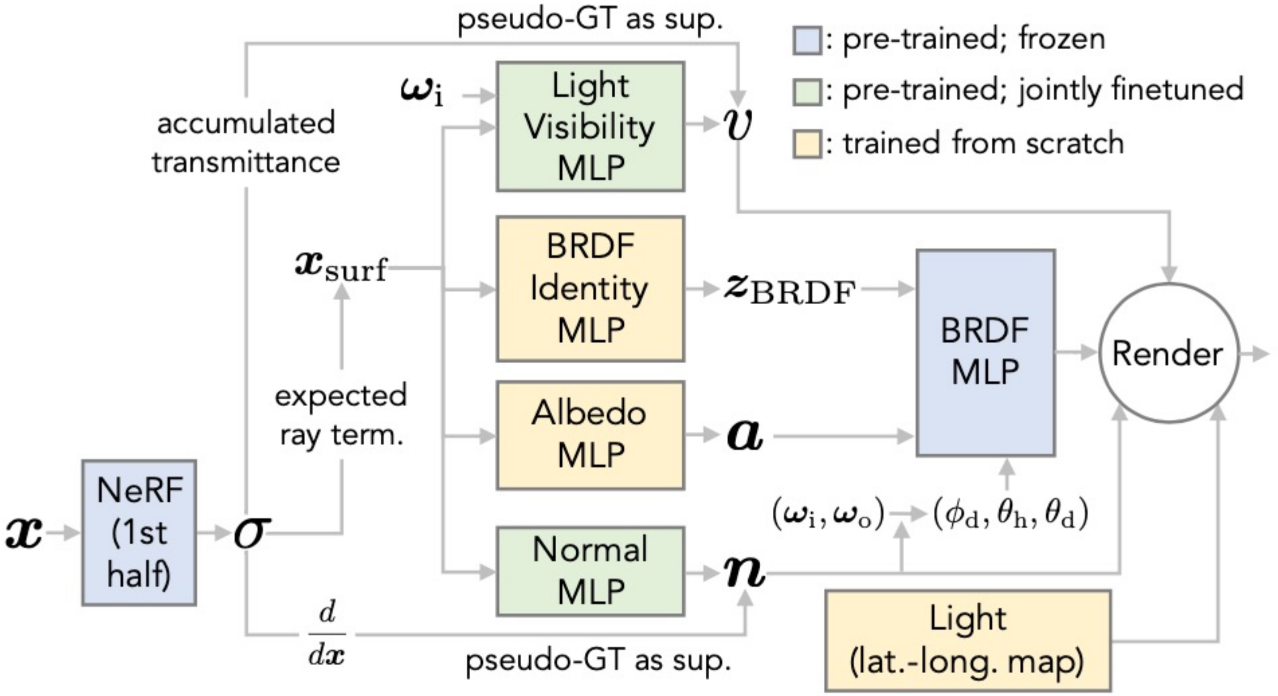
- Disentangling Reflectance Model Parameters



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

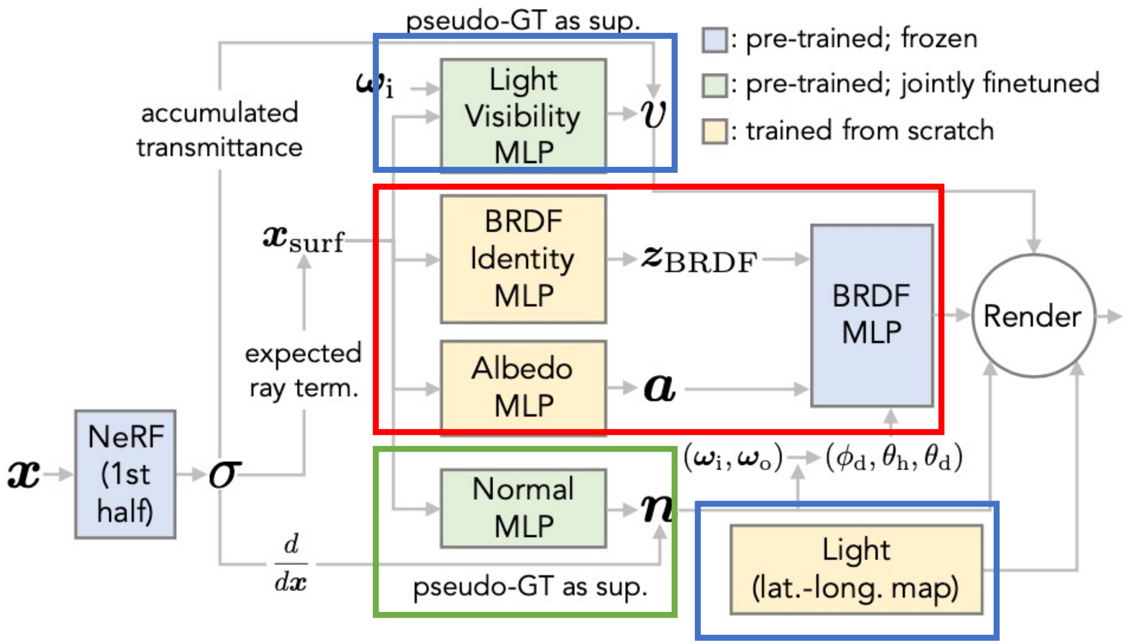
(3-2) Albedo MLP

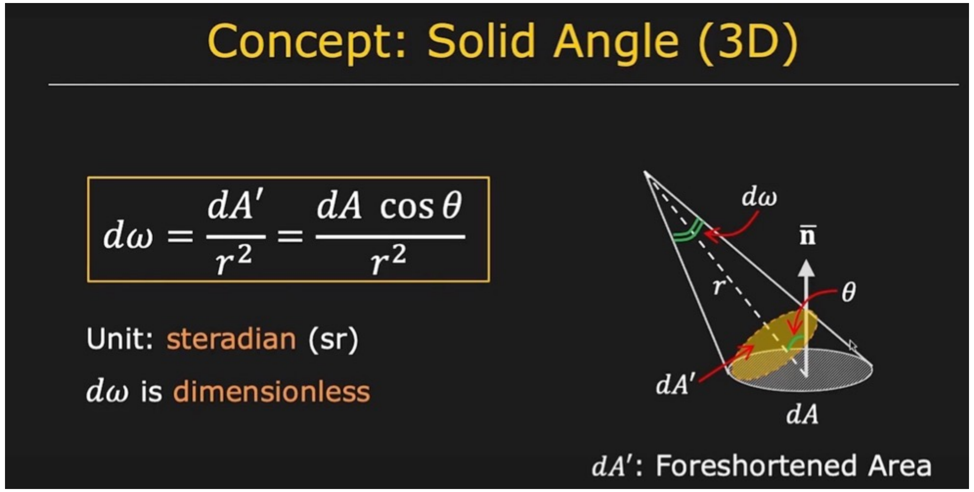
(3-3) Light Probe Map (Lateral / Longitudinal)

Methodology

- **Reflectance-Model based Renderer**
  - NO ray-tracing integration will be used (x represents a point in surface)

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

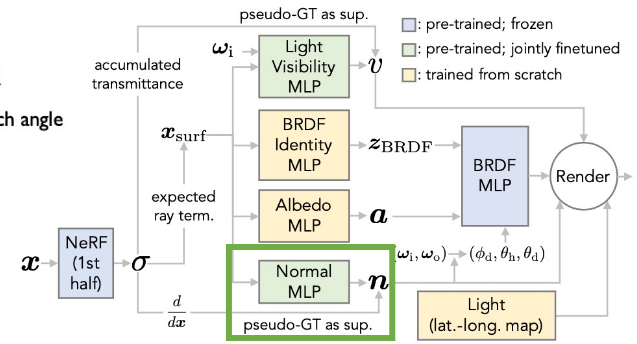




Methodology

- **Shape**

$$L_\mathrm{o}(\boldsymbol{x}, \boldsymbol{\omega}_\mathrm{o}) = \int_\Omega \underbrace{R(\boldsymbol{x}, \boldsymbol{\omega}_\mathrm{i}, \boldsymbol{\omega}_\mathrm{o})}_{\text{Reflectance (BRDF)}} \overbrace{L_\mathrm{i}(\boldsymbol{x}, \boldsymbol{\omega}_\mathrm{i})}^{\text{Source Intensity}} \underbrace{\big(\boldsymbol{\omega}_\mathrm{i} \cdot \boldsymbol{n}(\boldsymbol{x})\big)}_{\text{Source light approach angle}} d\boldsymbol{\omega}_\mathrm{i}$$



A. Train Vanilla NeRF

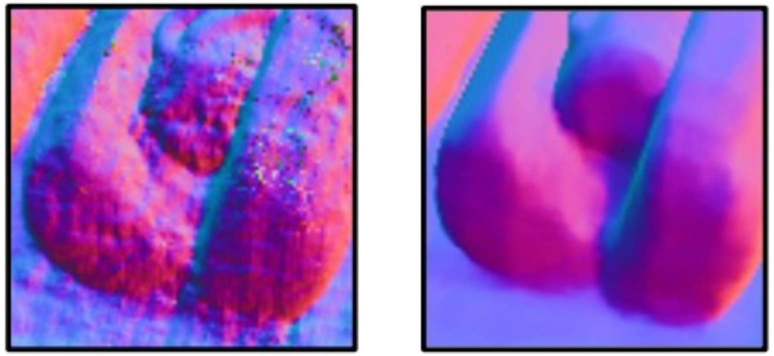
B-1. **Surface Points**: Outgoing radiance calculated only at this point.

$$\boldsymbol{x}_\mathrm{surf} = \boldsymbol{o} + \left(\int_0^\infty T(t)\sigma\big(\boldsymbol{r}(t)\big)t\,dt\right)\boldsymbol{d} \qquad \text{where } T(t) = \exp\left(-\int_0^t \sigma\big(\boldsymbol{r}(s)\big)\,ds\right)$$

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.

$$\ell_\mathrm{n} = \sum_{\boldsymbol{x}_\mathrm{surf}} \left(\frac{\lambda_1}{3}\left\|f_\mathrm{n}(\boldsymbol{x}_\mathrm{surf}) - \boldsymbol{n}_\mathrm{a}(\boldsymbol{x}_\mathrm{surf})\right\|_2^2 + \frac{\lambda_2}{3}\left\|f_\mathrm{n}(\boldsymbol{x}_\mathrm{surf}) - f_\mathrm{n}(\boldsymbol{x}_\mathrm{surf} + \boldsymbol{\epsilon})\right\|_1\right)$$



Methodology

- **Reflectance**

Source Intensity

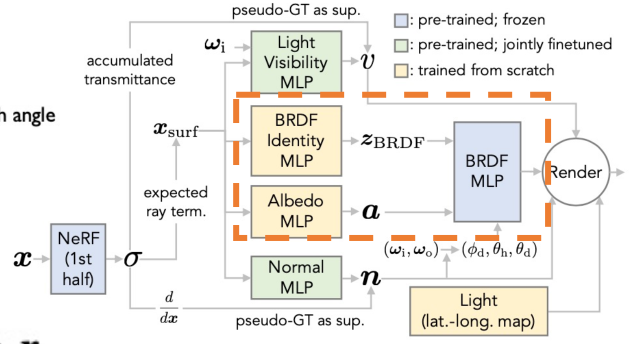
$$L_o(x,\omega_o) = \int_\Omega \underbrace{R(x,\omega_i,\omega_o)}_{\text{Reflectance (BRDF)}} L_i(x,\omega_i) \underbrace{(\omega_i \cdot n(x))}_{\text{Source light approach angle}} d\omega_i$$

Lambertian factor

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

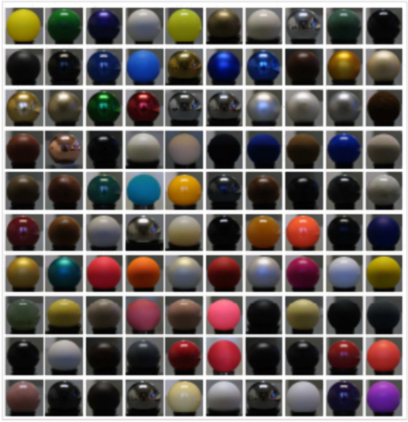
Non-Lambertian (specular) factor

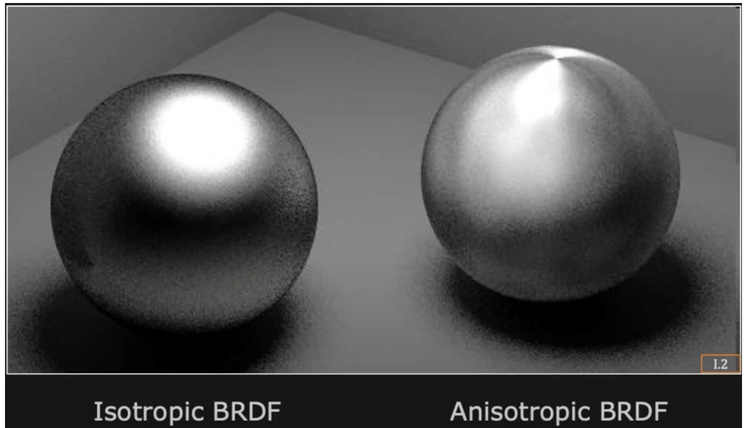
$$= \frac{\boxed{f_a(x)}}{\pi} + f_r'\Big(f_z(x), g\big(f_n(x),\omega_i,\omega_o\big)\Big) \qquad f_r' : (z_{BRDF}, (\phi_d,\theta_h,\theta_d)) \mapsto r$$

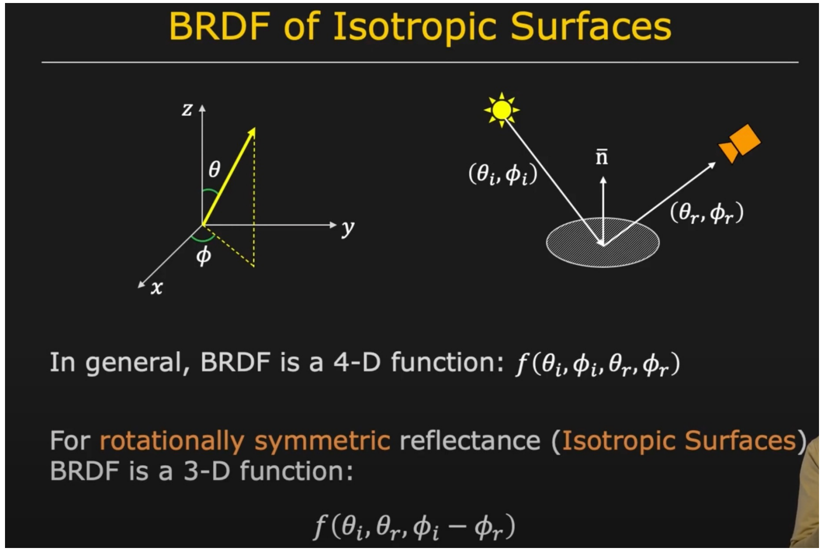


- BRDF MLP (f_r') learned from real-world distribution (Learned as a prior & fixed)
  - Given: Sphere's geometry (thus the incident / radiant angle) / "Achromatic" reflectance
  - Learn: BRDF MLP / Latent BRDF parameters ($z_{BRDF,REAL}$)
  - g: conversion to Rusinkiewicz coordinate (Assuming isotropic surface)

BRDF Database



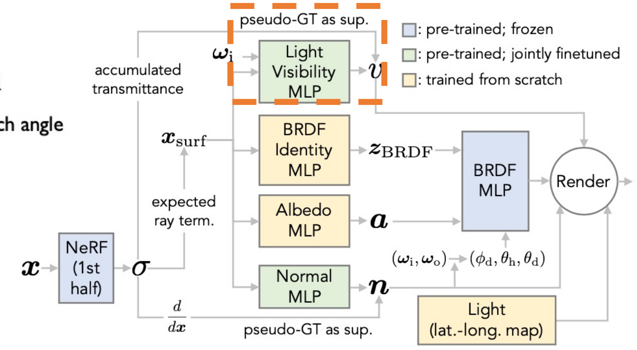




Methodology

- **Light Visibility**

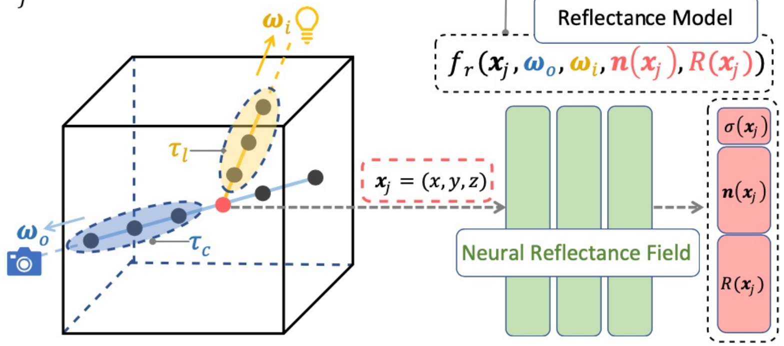
$$L_o(\boldsymbol{x}, \boldsymbol{\omega}_o) = \int_\Omega \underbrace{R(\boldsymbol{x}, \boldsymbol{\omega}_i, \boldsymbol{\omega}_o)}_{\text{Reflectance (BRDF)}} \overbrace{L_i(\boldsymbol{x}, \boldsymbol{\omega}_i)}^{\text{Source Intensity}} \underbrace{(\boldsymbol{\omega}_i \cdot \boldsymbol{n}(\boldsymbol{x}))}_{\text{Source light approach angle}} d\boldsymbol{\omega}_i$$



$$\ell_v = \sum_{\boldsymbol{x}_{surf}} \sum_{\boldsymbol{\omega}_i} \Big(\lambda_3 \big(f_v(\boldsymbol{x}_{surf}, \boldsymbol{\omega}_i) - v_a(\boldsymbol{x}_{surf}, \boldsymbol{\omega}_i)\big)^2 + \lambda_4 \big| f_v(\boldsymbol{x}_{surf}, \boldsymbol{\omega}_i) - f_v(\boldsymbol{x}_{surf} + \boldsymbol{\epsilon}, \boldsymbol{\omega}_i) \big| \Big)$$

$$\tau_l(\boldsymbol{x}_j) = \exp\left(-\sum_p \sigma(\boldsymbol{x}'_p)\Delta t'_p\right) \longrightarrow n_a(x_{surf})$$

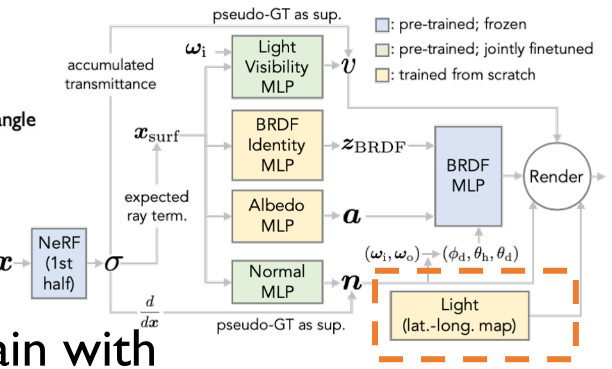
$$\sum_j \tau_c(\boldsymbol{x}_j)\, \tau_l(\boldsymbol{x}_j)\, \big(1 - \exp(-\sigma(\boldsymbol{x}_j)\, \Delta t_j)\big)\, f_r(\boldsymbol{x}_j)\, L_l(\boldsymbol{x}_j)$$



Methodology

- **Light Probe (radiance map)**

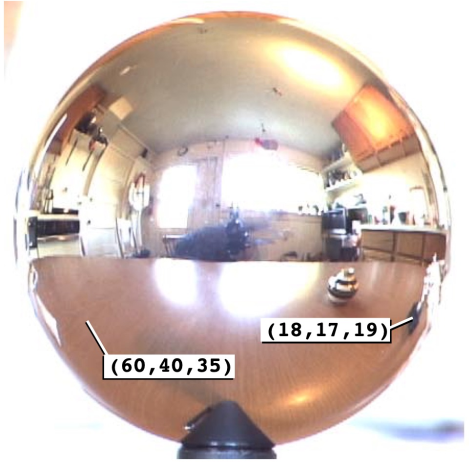
$$L_o(x,\omega_o) = \int_\Omega \underbrace{R(x,\omega_i,\omega_o)}_{\text{Reflectance (BRDF)}} \overbrace{L_i(x,\omega_i)}^{\text{Source Intensity}} \underbrace{(\omega_i \cdot n(x))}_{\text{Source light approach angle}} d\omega_i$$



  - Light probe: A function that maps from irradiant light angle to its intensity
  - 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 *****

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

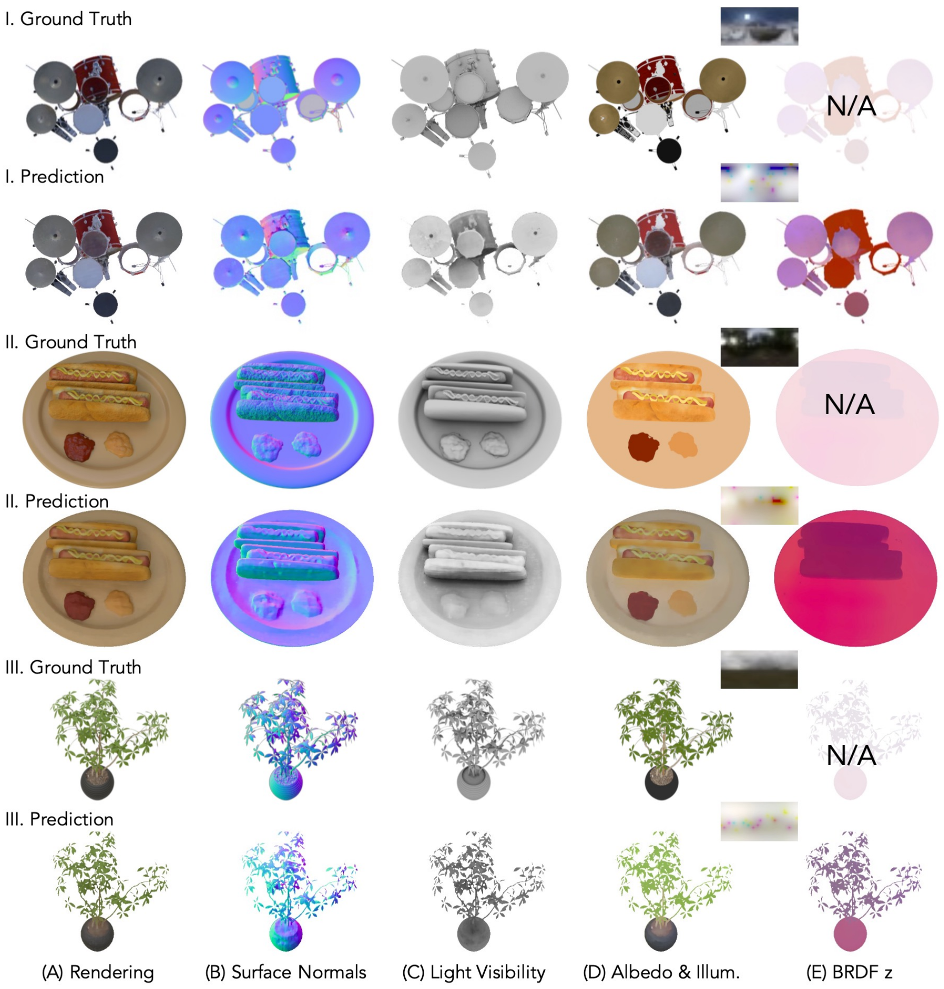


Spherical radiance map (Debevec, 1998)

Longitude/latitude radiance map

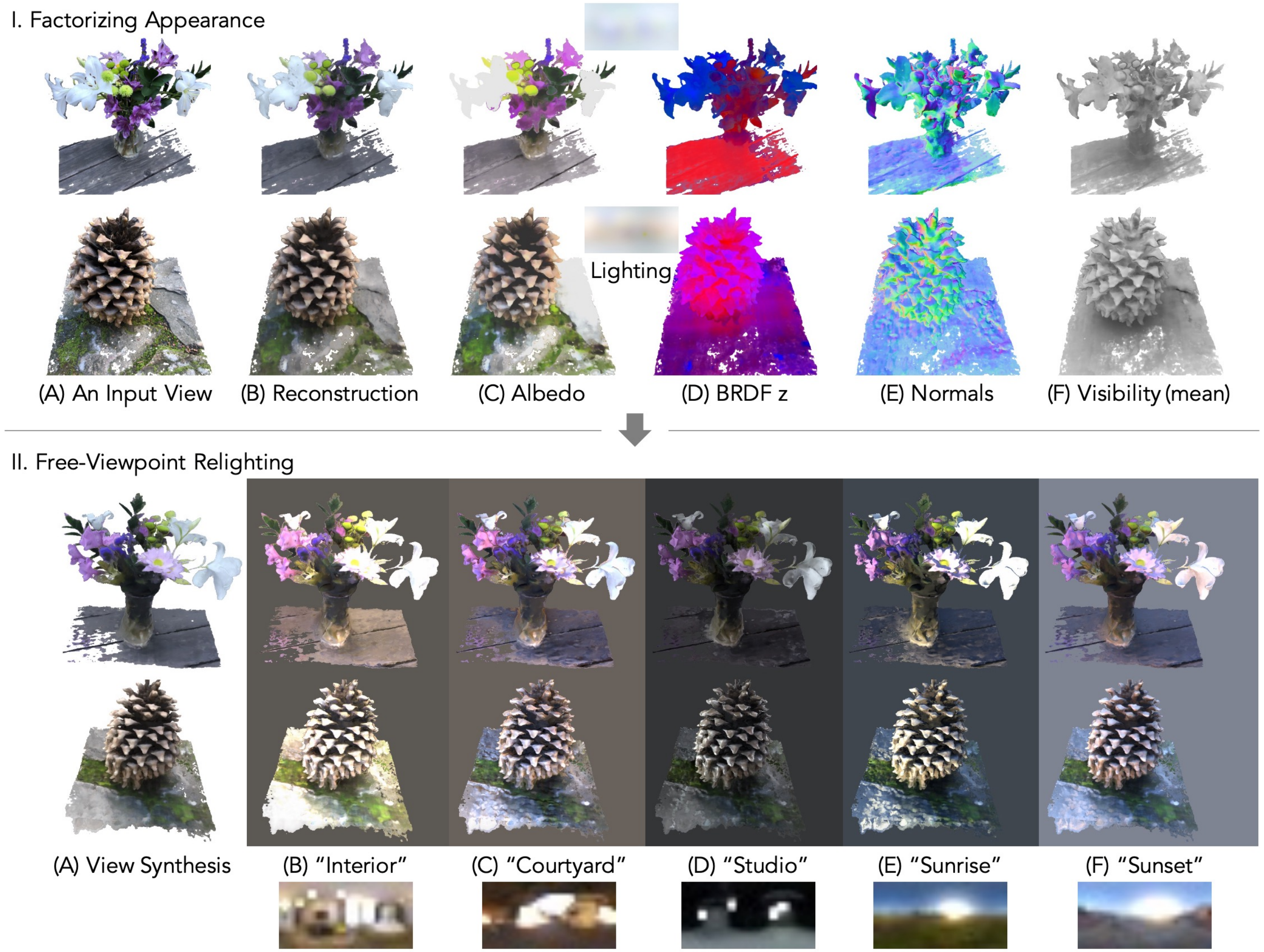
Result

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



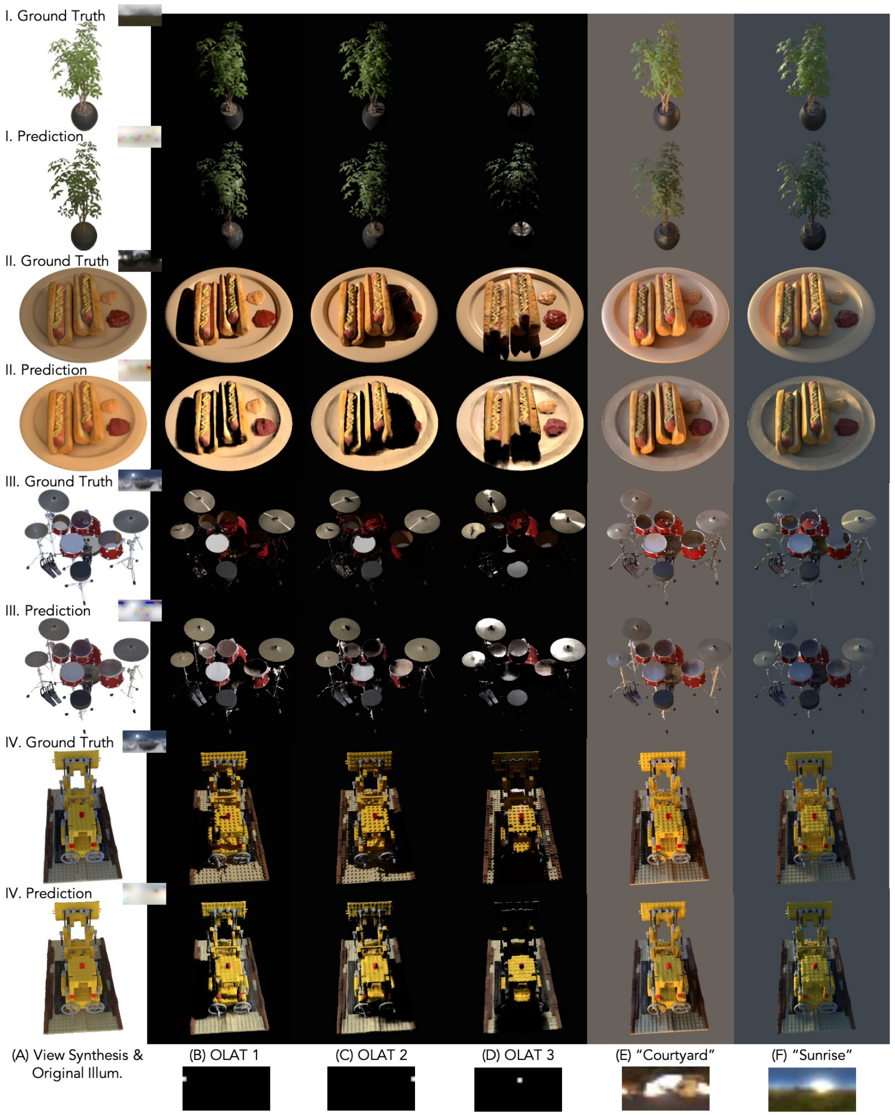
Result

- **Results of real-world captures**



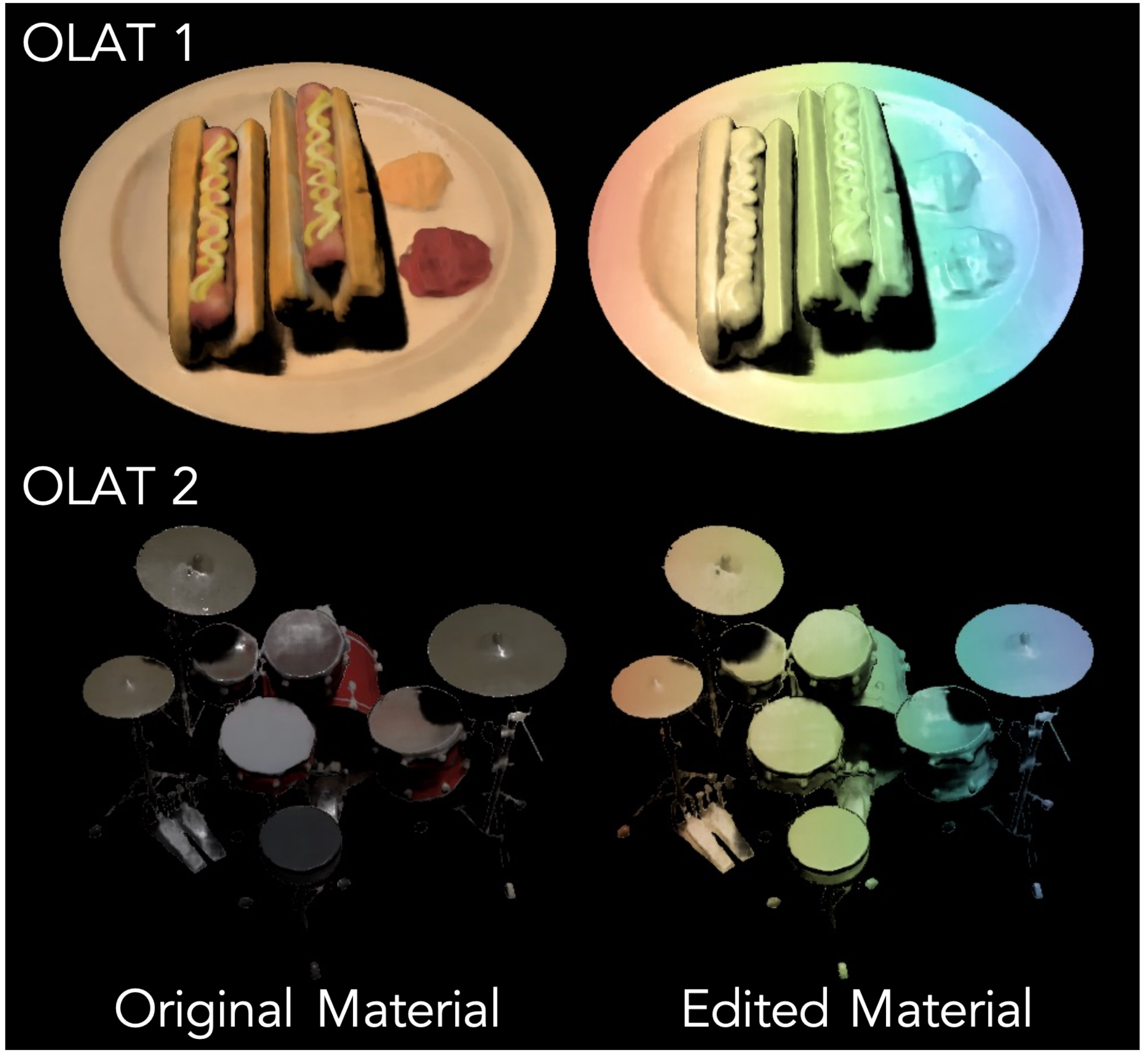
Result

- **Novel-view relighting**



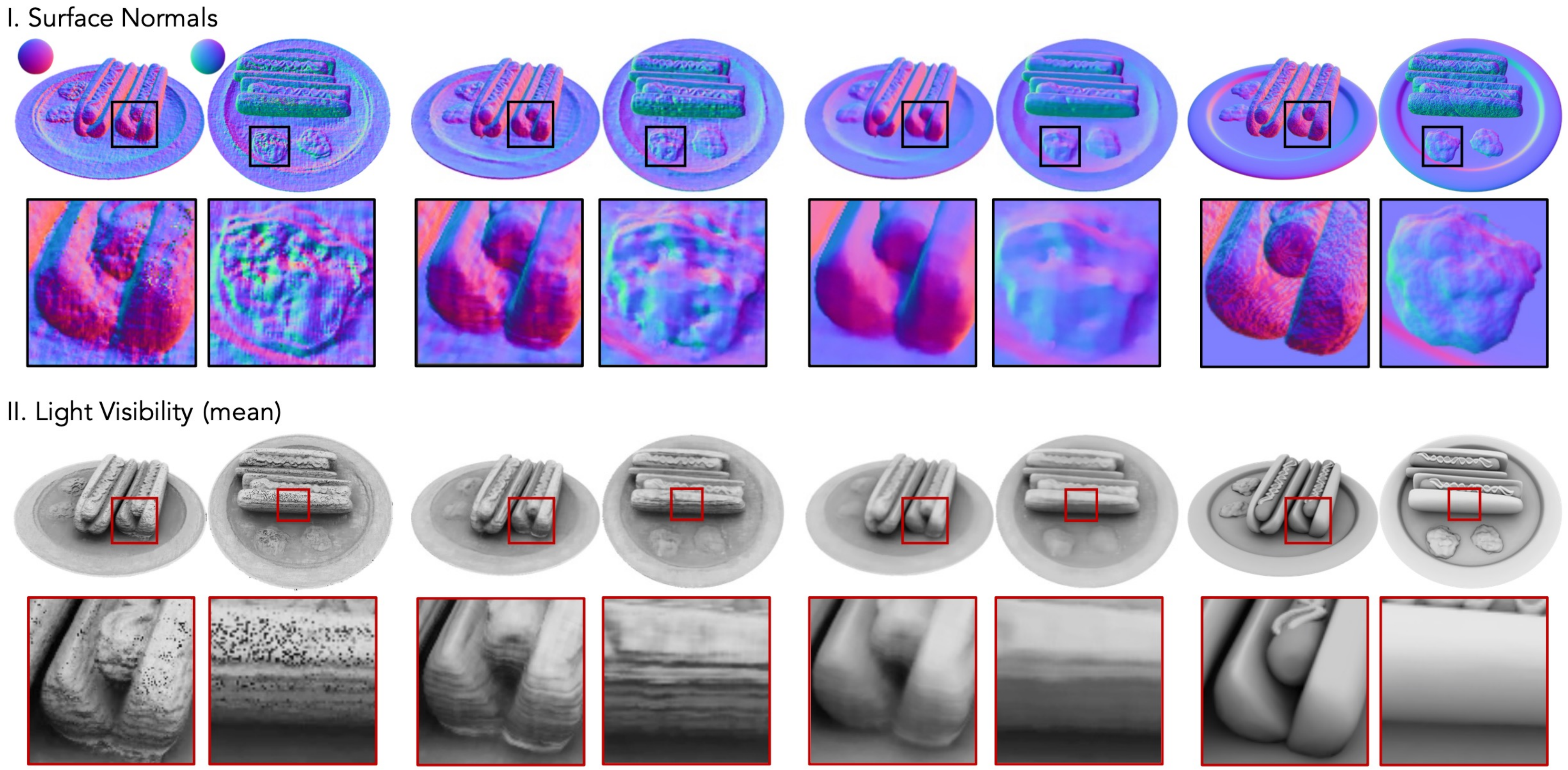
Result

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



Result

- **Surface Normals and Light Visibility Visualizations**



(A) Derived from NeRF (B) Jointly Optimized (C) NeRFactor: Jointly Optimized w/ Smoothness Constraints (D) Ground Truth