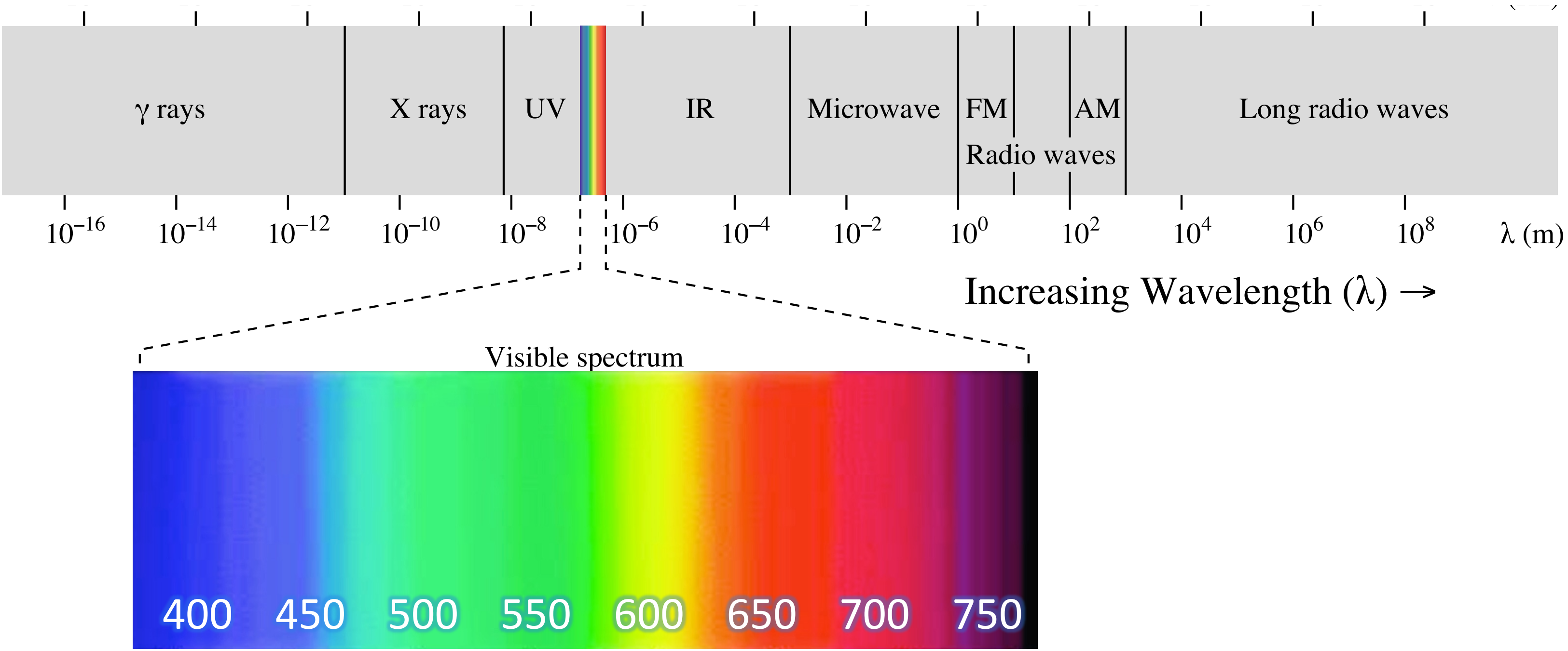
Appearance Acquisition and Relighting

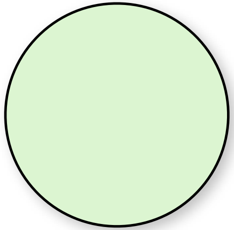
Cengiz Öztireli

Light and Colors



Light and Colors

- Light can be a mixture of many wavelengths
- Spectral power distribution (SPD)
  - $P(\lambda)$ = intensity at wavelength λ
  - intensity as a function of wavelength
- We perceive these distributions as colors



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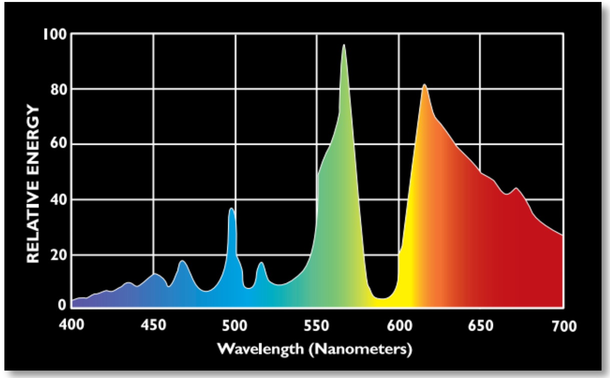
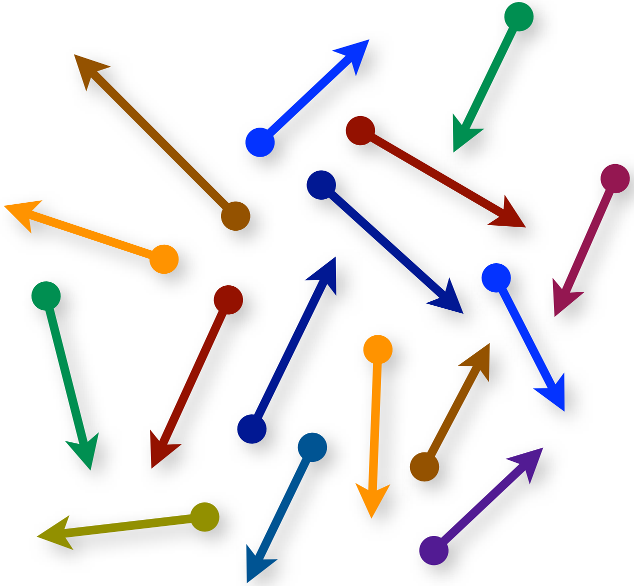


Measuring Light

- How do we measure light



Measuring = Counting photons

Basic Definitions

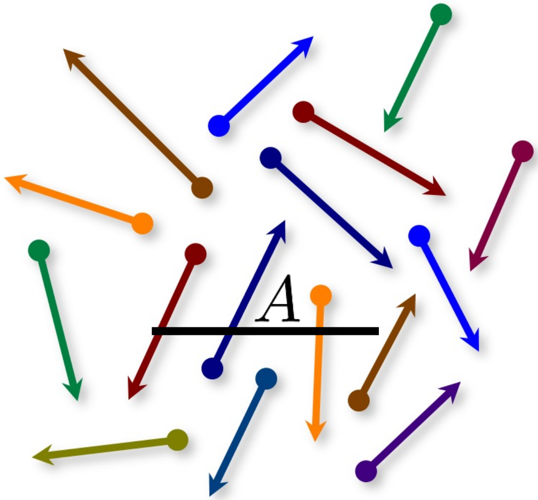
- Assume light consists of photons with
  - $\mathbf{x}$: Position
  - $\vec{\omega}$: Direction of motion
  - λ : Wavelength
- Each photon has an energy of: $\dfrac{hc}{\lambda}$
  - $h \approx 6.63 \cdot 10^{-34}\, m^2 \cdot kg/s$: Planck's constant
  - $c = 299{,}792{,}458\, m/s$: speed of light in vacuum
  - Unit of energy, Joule : $[J = kg \cdot m^2/s^2]$

Radiometry

- Flux (radiant flux, power)
  – total amount of energy passing through surface or space per unit time

$$\Phi(A) \qquad \left[\frac{J}{s} = W\right]$$

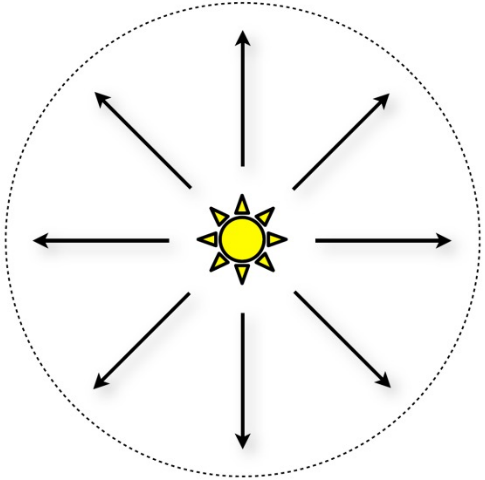
  – examples:
    - number of photons hitting a wall per second
    - number of photons leaving a lightbulb per second



Radiometry

- Radiant intensity
  - Power (flux) per solid angle = directional density of flux

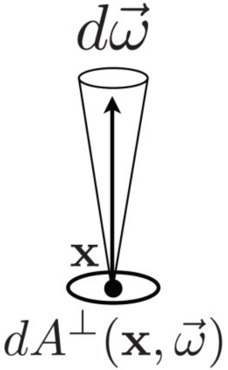
$$I(\vec{\omega}) = \frac{d\Phi}{d\vec{\omega}} \qquad \left[\frac{W}{sr}\right] \qquad \Phi = \int_{S^2} I(\vec{\omega})d\vec{\omega}$$



  - example:
    - power per unit solid angle emanating from a point source

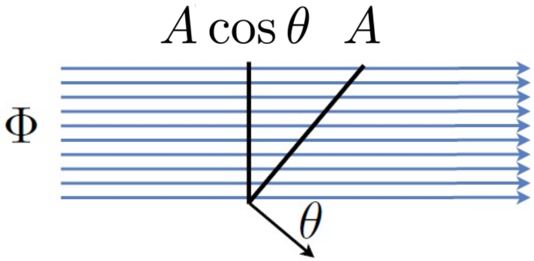
Radiometry

- Radiance
  - Radiant intensity per perpendicular unit area



$$L(\mathbf{x}, \vec{\omega}) = \frac{d^2\Phi(A)}{d\vec{\omega}\, dA^{\perp}(\mathbf{x}, \vec{\omega})}$$

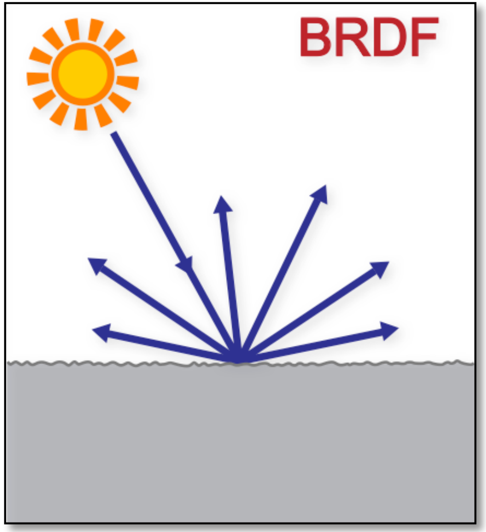
$$= \frac{d^2\Phi(A)}{d\vec{\omega}\, dA(\mathbf{x}) \cos\theta} \quad \left[\frac{W}{m^2 sr}\right]$$



  - remains constant along a ray

Reflection Models

- **B**idirectional **R**eflectance **D**istribution **F**unction (BRDF)

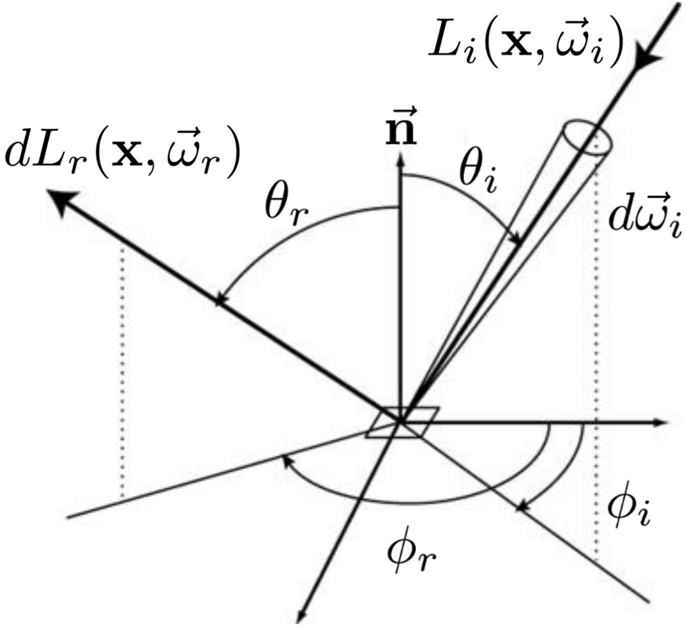


BRDF

- **B**idirectional **R**eflectance **D**istribution **F**unction

$$f_r(\mathbf{x}, \vec{\omega}_i, \vec{\omega}_r) = \frac{dL_r(\mathbf{x}, \vec{\omega}_r)}{L_i(\mathbf{x}, \vec{\omega}_i) \cos\theta_i d\vec{\omega}_i} \quad [1/sr]$$

BRDF — infinitesimal reflected radiance — infinitesimal solid angle



Reflection Equation

- The BRDF provides a relation between incident radiance and differential reflected radiance
- From this we can derive the **Reflection Equation**

$$f_r(\mathbf{x}, \vec{\omega}_i, \vec{\omega}_r) = \frac{dL_r(\mathbf{x}, \vec{\omega}_r)}{L_i(\mathbf{x}, \vec{\omega}_i) \cos\theta_i \, d\vec{\omega}_i}$$

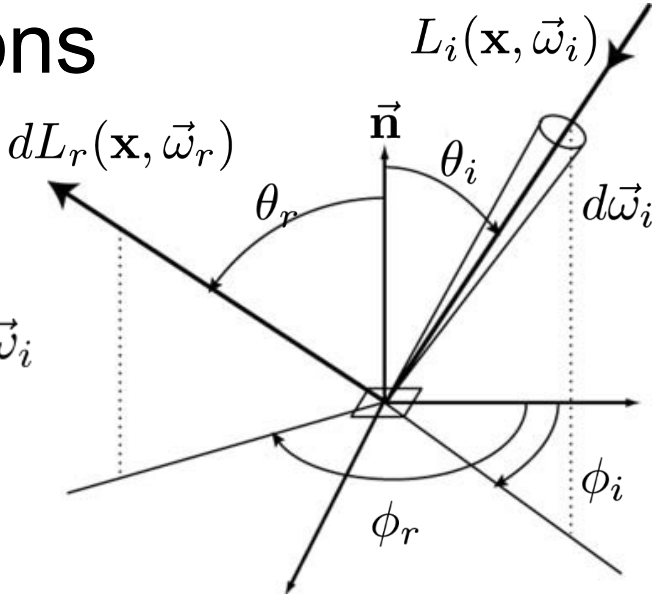
$$f_r(\mathbf{x}, \vec{\omega}_i, \vec{\omega}_r) L_i(\mathbf{x}, \vec{\omega}_i) \cos\theta_i = \frac{dL_r(\mathbf{x}, \vec{\omega}_r)}{d\vec{\omega}_i}$$

$$\int_{H^2} f_r(\mathbf{x}, \vec{\omega}_i, \vec{\omega}_r) L_i(\mathbf{x}, \vec{\omega}_i) \cos\theta_i \, d\vec{\omega}_i = L_r(\mathbf{x}, \vec{\omega}_r)$$

Reflection Equation

- The reflected radiance due to incident illumination from all directions

$$L_r(\mathbf{x}, \vec{\omega}_r) = \int_{H^2} f_r(\mathbf{x}, \vec{\omega}_i, \vec{\omega}_r) L_i(\mathbf{x}, \vec{\omega}_i) \cos\theta_i \, d\vec{\omega}_i$$



The Rendering Equation

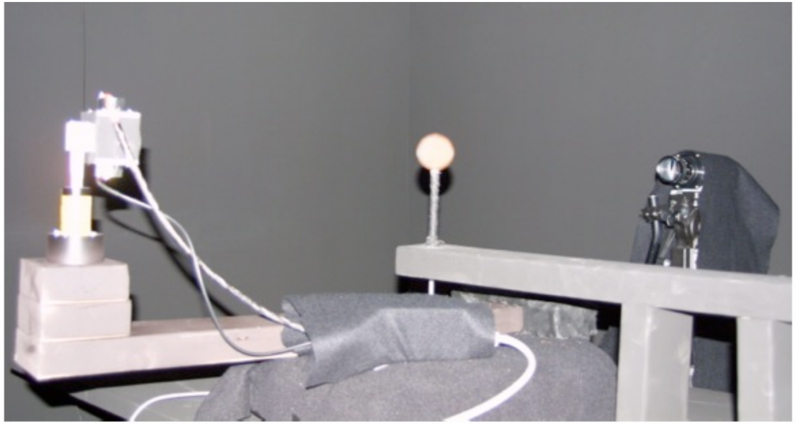
- The outgoing light is the sum of emitted and incoming

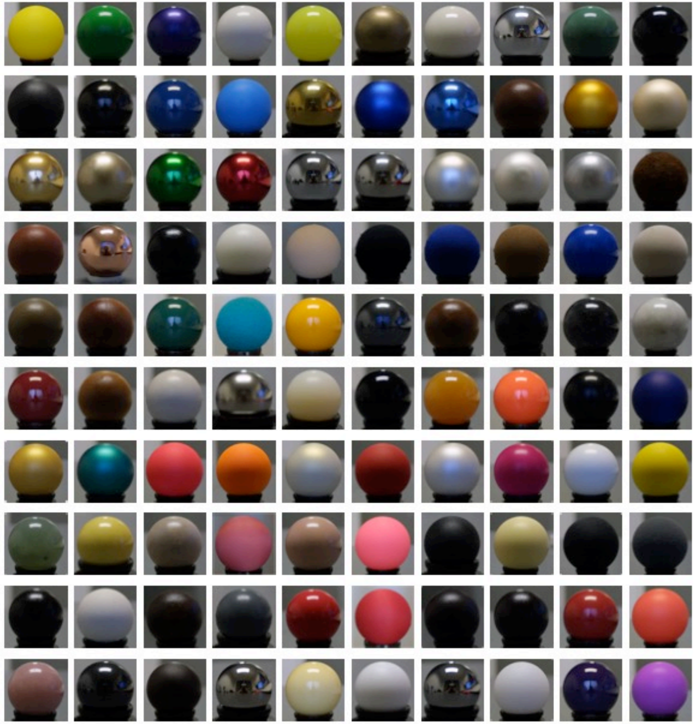
$$L_o(\mathbf{x}, \vec{\omega}_o) = L_e(\mathbf{x}, \vec{\omega}_o) + L_r(\mathbf{x}, \vec{\omega}_o)$$

$$\underbrace{L_o(\mathbf{x}, \vec{\omega}_o)}_{\text{outgoing light}} = \underbrace{L_e(\mathbf{x}, \vec{\omega}_o)}_{\text{emitted light}} + \underbrace{\int_{H^2} f_r(\mathbf{x}, \vec{\omega}_i, \vec{\omega}_o) L_i(\mathbf{x}, \vec{\omega}_i) \cos\theta_i \, d\vec{\omega}_i}_{\text{reflected light}}$$

Energy is conserved!

Measuring BRDFs





Matusik et al.: Efficient Isotropic BRDF Measurement, Eurographics Symposium on Rendering 2003

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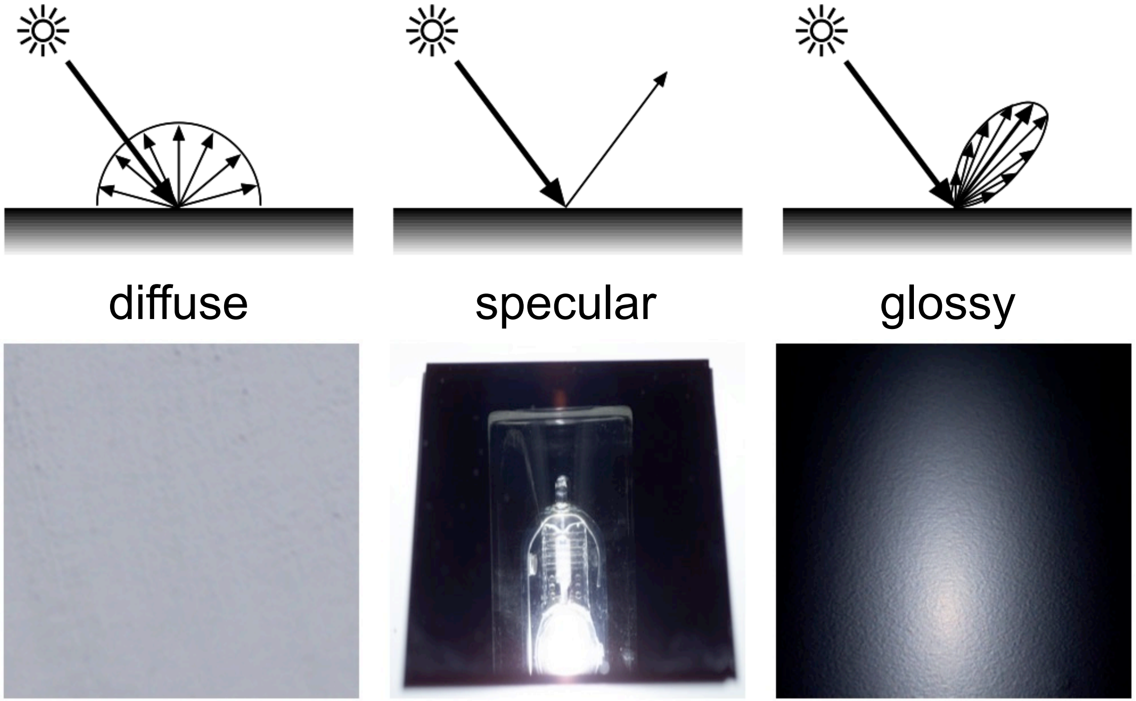
Simpler Reflections



Hendrik Lensch, Efficient Image-Based Appearance Acquisition of Real-World Objects, Ph.D. thesis, 2004

Diffuse Reflection

- For diffuse reflection, the BRDF is a constant:

$$L_r(\mathbf{x}, \vec{\omega}_r) = \int_{H^2} f_r(\mathbf{x}, \vec{\omega}_i, \vec{\omega}_r) L_i(\mathbf{x}, \vec{\omega}_i) \cos\theta_i \, d\vec{\omega}_i$$

$$L_r(\mathbf{x}) = f_r \int_{H^2} L_i(\mathbf{x}, \vec{\omega}_i) \cos\theta_i \, d\vec{\omega}_i$$

$$L_r(\mathbf{x}) = f_r \, E_i(\mathbf{x})$$

Photometric Stereo

Goal: estimate surface normal from observed light, e.g. camera

$$\underbrace{L_o(\mathbf{x}, \vec{\omega_o}, \lambda_{RGB})}_{\text{known}} = \int_{H^2} f_r(\mathbf{x}, \vec{\omega_i}, \vec{\omega_o}, \lambda_{RGB}) \underbrace{L_i(\mathbf{x}, \vec{\omega_i}, \lambda_{RGB})}_{\text{known}} (\vec{\omega_i} \cdot \vec{n}) d\vec{\omega_i}$$

Photometric Stereo

Goal: estimate surface normal from observed light, e.g. camera

$$\underbrace{L_o(\mathbf{x}, \vec{\omega_o}, \lambda_{RGB})}_{\text{known}} = \int_{H^2} f_r(\mathbf{x}, \vec{\omega_i}, \vec{\omega_o}, \lambda_{RGB}) \underbrace{L_i(\mathbf{x}, \vec{\omega_i}, \lambda_{RGB})}_{\text{known}} (\vec{\omega_i} \cdot \vec{n}) d\vec{\omega_i}$$

Assumptions:

Delta directional lighting $L_i(\mathbf{x}, \vec{\omega_i}, \lambda_{RGB}) = L_i(\vec{\omega_i}) = \mathbb{1}_3$

Lambertian BRDF $f_r(\mathbf{x}, \vec{\omega_i}, \vec{\omega_o}, \lambda_{RGB}) = f_r(\lambda_{RGB}) = \frac{\rho_{d,RGB}}{\pi}$

Orthographic projection

Photometric Stereo

Goal: estimate surface normal from observed light, e.g. camera

$$\underbrace{L_o(\mathbf{x}, \vec{\omega_o}, \lambda_{RGB})}_{I} = \frac{\rho_{d,RGB}}{\pi}(\vec{n} \cdot \vec{\omega_i})$$

Photometric Stereo

Goal: estimate surface normal from observed light, e.g. camera

$$\underbrace{L_o(\mathbf{x}, \vec{\omega_o}, \lambda_{RGB})}_{I} = \frac{\rho_{d,RGB}}{\pi}(\vec{n} \cdot \vec{\omega_i})$$

$$A_{n\times 3} * x_{3\times 1} = b_{n\times 1}$$

$$A = \begin{bmatrix} \omega_{i,1}^T \\ \vdots \\ \omega_{i,n}^T \end{bmatrix} \quad b = \begin{bmatrix} I_{\lambda,1} \\ \vdots \\ I_{\lambda,n} \end{bmatrix} \quad x = \frac{\rho_{d,\lambda}}{\pi} * \vec{n}^T$$

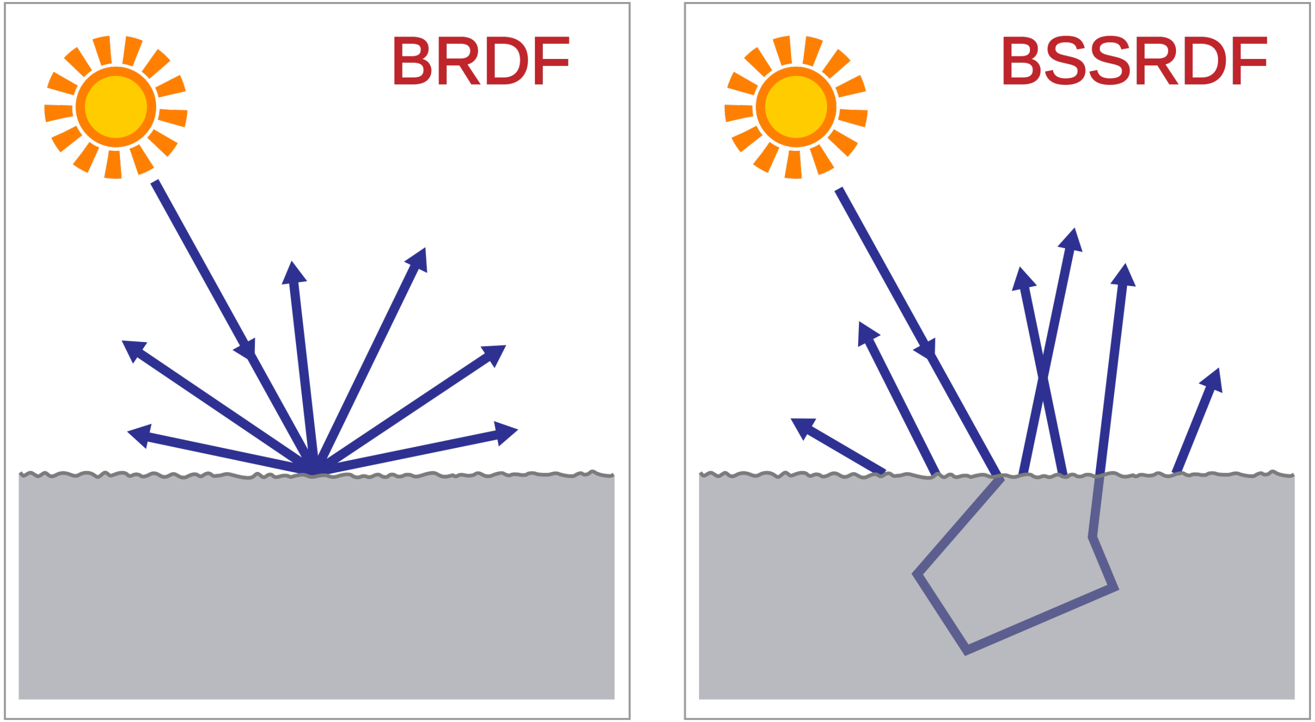
Solution for arbitrary frequency:

$$\vec{n} \rightarrow (\theta, \phi)$$

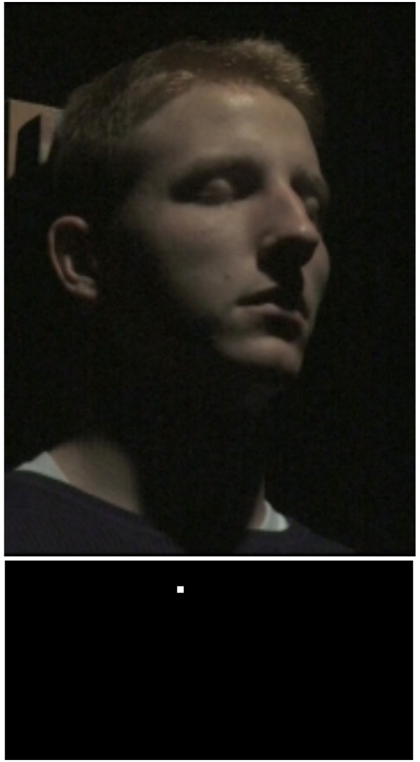
$$\rho_d$$

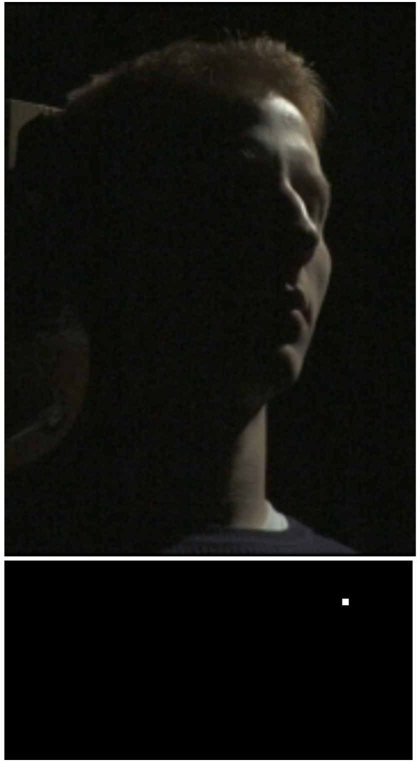
$$\rho_{d,\lambda} = \|x\| \quad \vec{n} = \frac{x}{\|x\|}$$

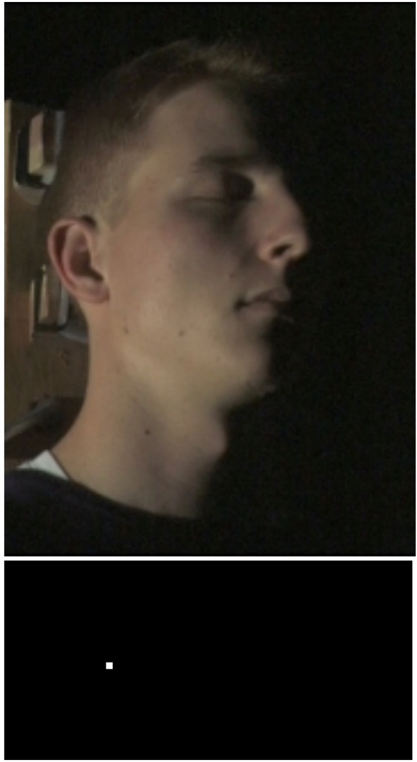
Bidirectional scattering-surface reflectance distribution function



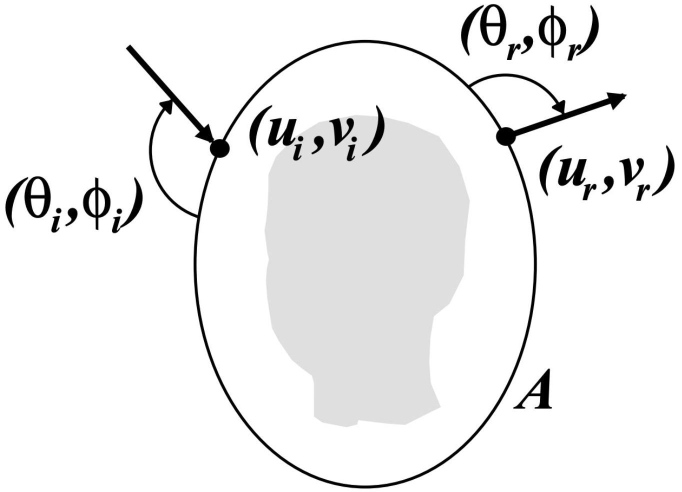
Measuring the Human Face







Measuring the Human Face



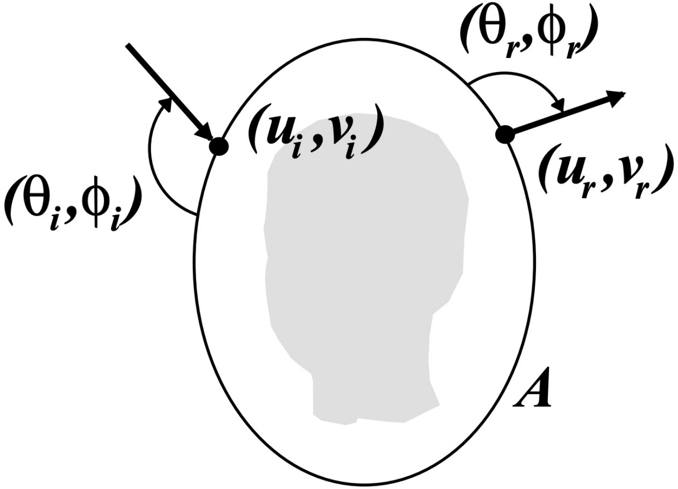
Surface enclosing the scene

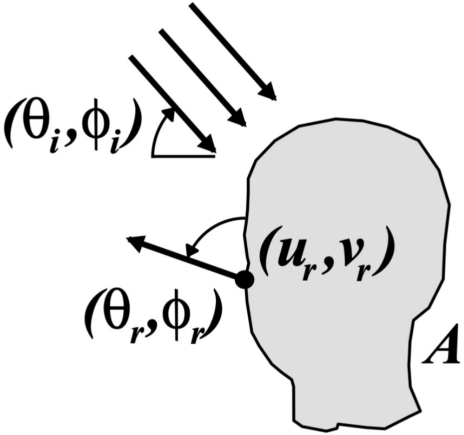
Assumption: integrated radiance is independent of the ray origin. Hence, the surface parameterization

Incident illumination $R_i(u_i, v_i, \theta_i, \phi_i)$

Radiant field of illumination $R_r(u_r, v_r, \theta_r, \phi_r)$

Measuring the Human Face





Assume directional lighting for incident illumination

Measuring the Human Face

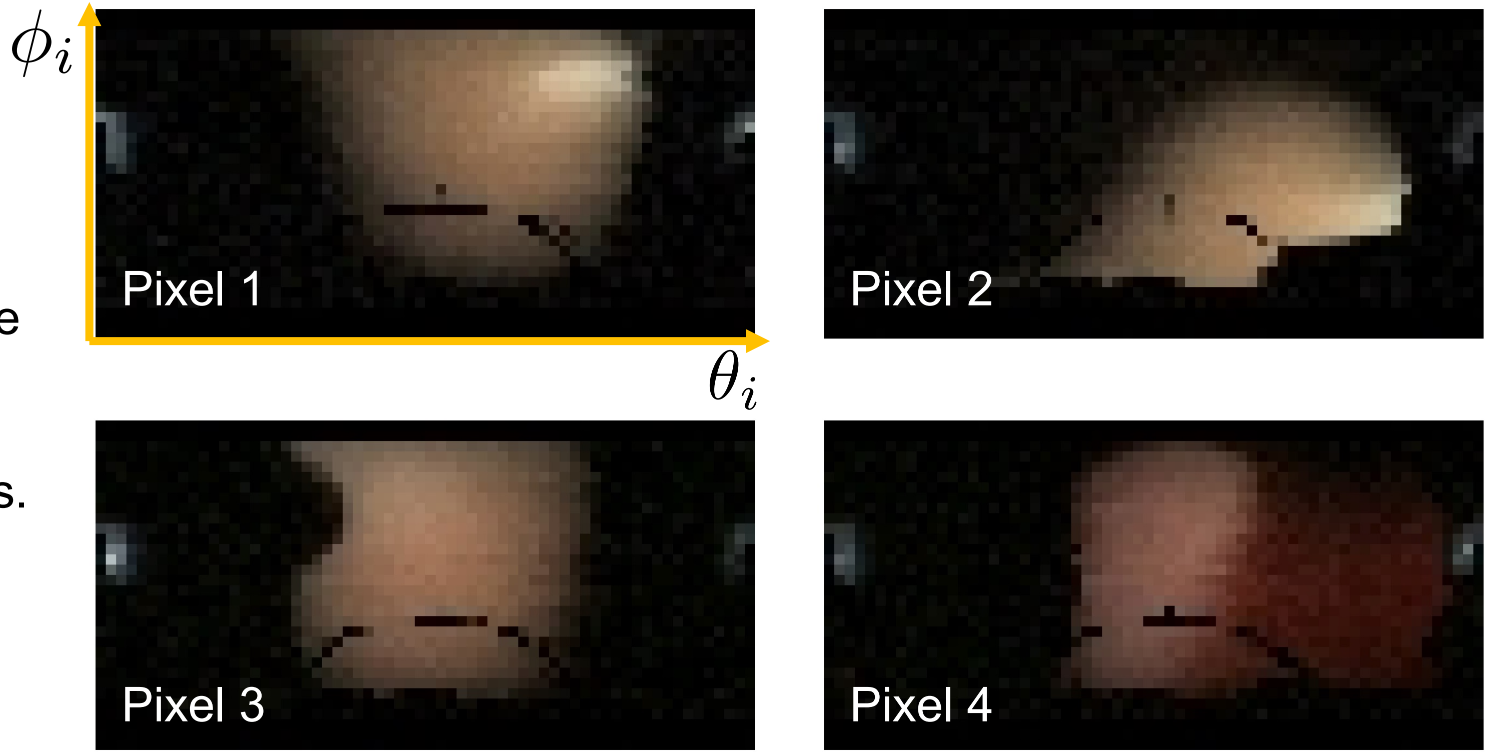
Idea:

1. Turn one light on at a time and capture an image from the same view

2. Construct a new lighting setup as a sum of the images

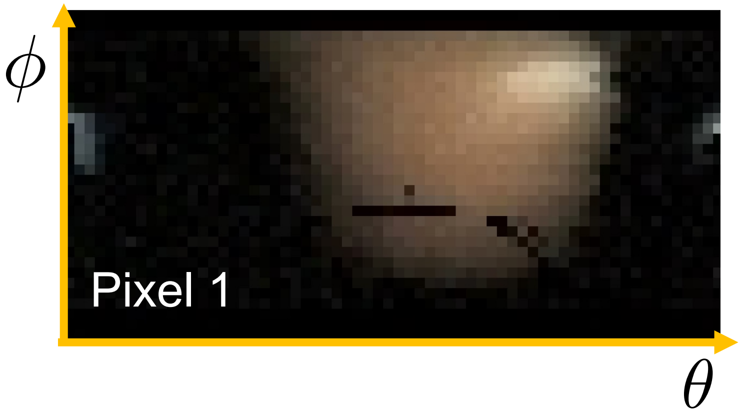
Measuring the Human Face

At each pixel, we have radiance that correspond to different lighting directions.



Relighting the Human Face

$$R_{xy}(\theta, \phi)$$



$$\hat{L}(x, y) = \sum_{\theta,\phi} R_{xy}(\theta, \phi) L_i(\theta, \phi) \delta A(\theta, \phi)$$

Output pixel value

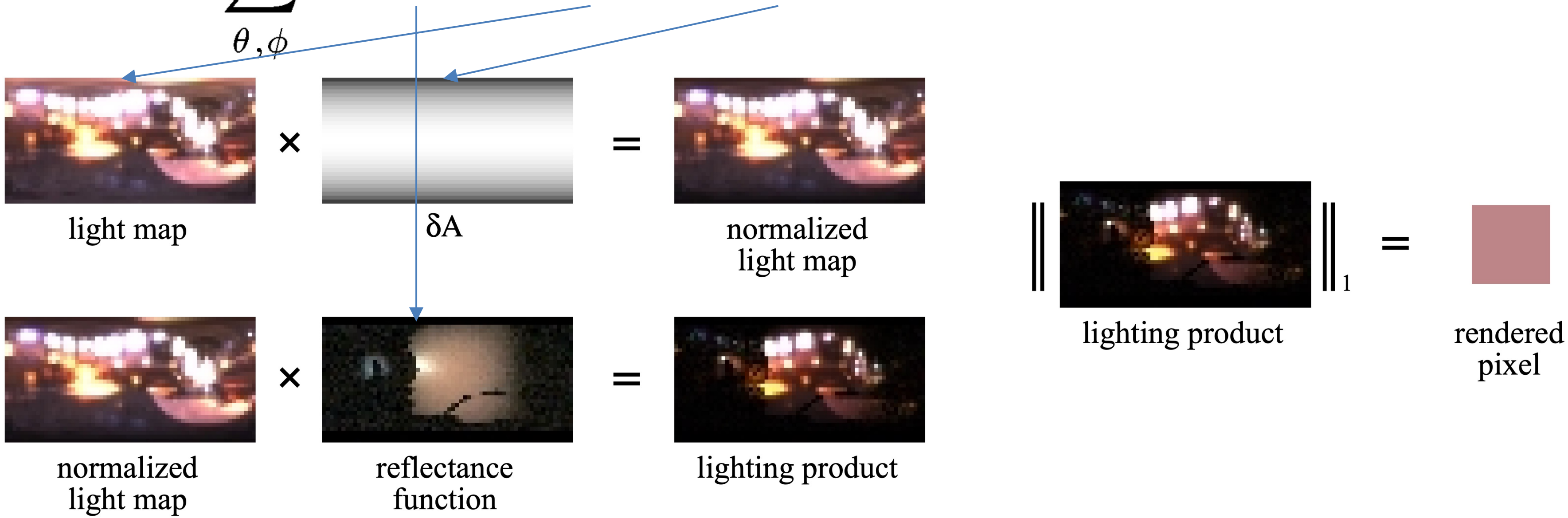
Reflectance function for this pixel

Map of incident Illumination at this pixel

$$\delta A(\theta, \phi) = \sin \phi$$

Relighting the Human Face

$$\hat{L}(x,y) = \sum_{\theta,\phi} R_{xy}(\theta,\phi) L_i(\theta,\phi) \delta A(\theta,\phi) \qquad \delta A(\theta,\phi) = \sin\phi$$



Relighting the Human Face

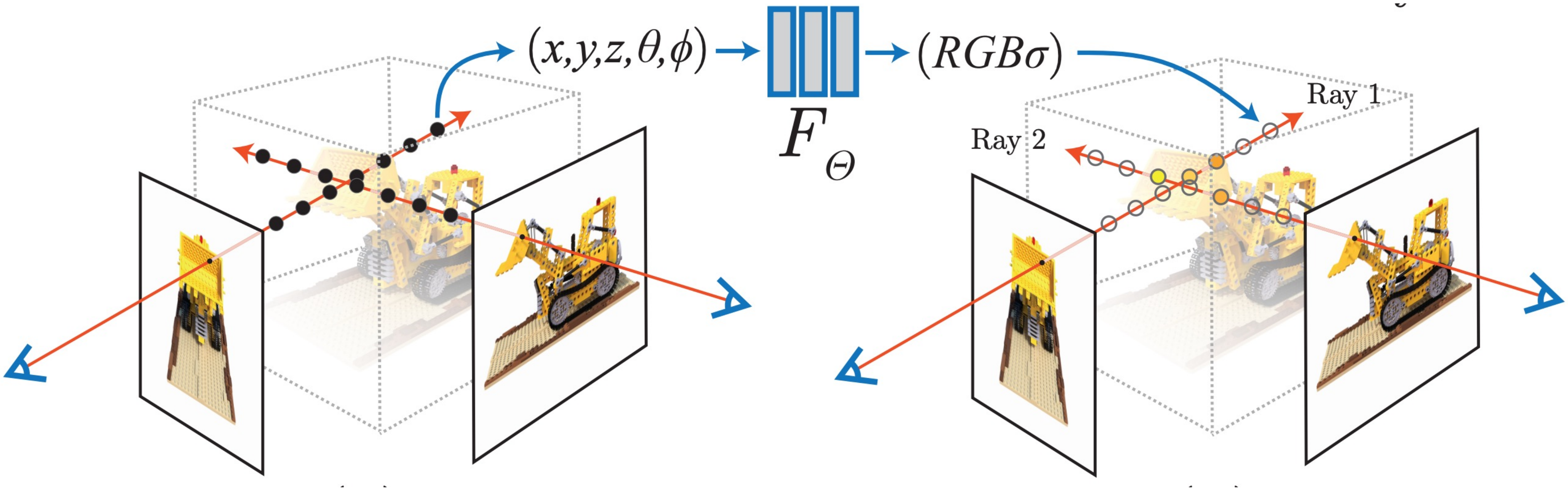
Real image

Environment

Relit face

Neural Materials and Lighting

Volume rendering

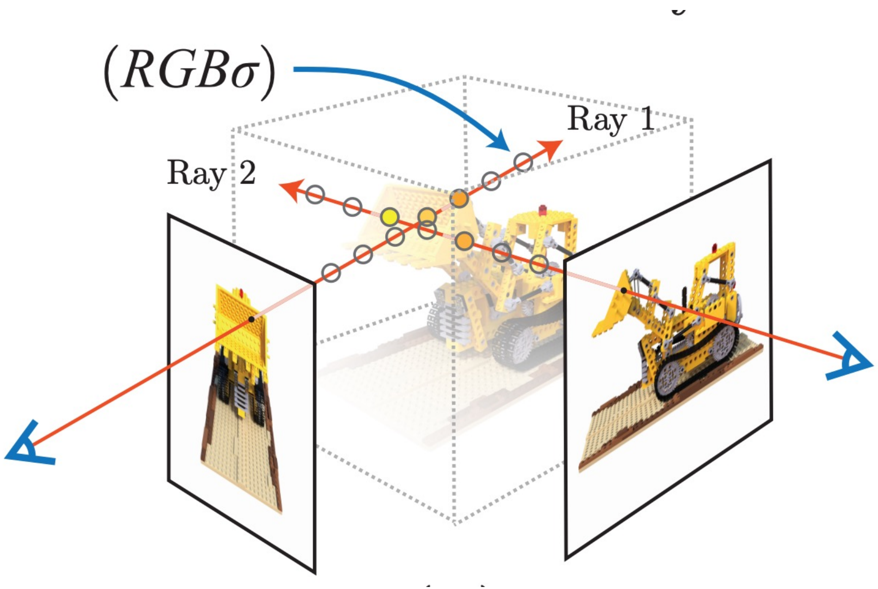


Input: position and direction

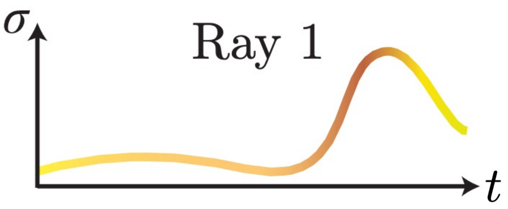
Output: colour and density

Neural Materials and Lighting

Volume rendering



Output: colour and density



Integrate to get the final pixel colour

$$C(\mathbf{r}) = \int_{t_n}^{t_f} T(t)\sigma(\mathbf{r}(t))\underbrace{\mathbf{c}(\mathbf{r}(t),\mathbf{d})}_{RGB}dt$$

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

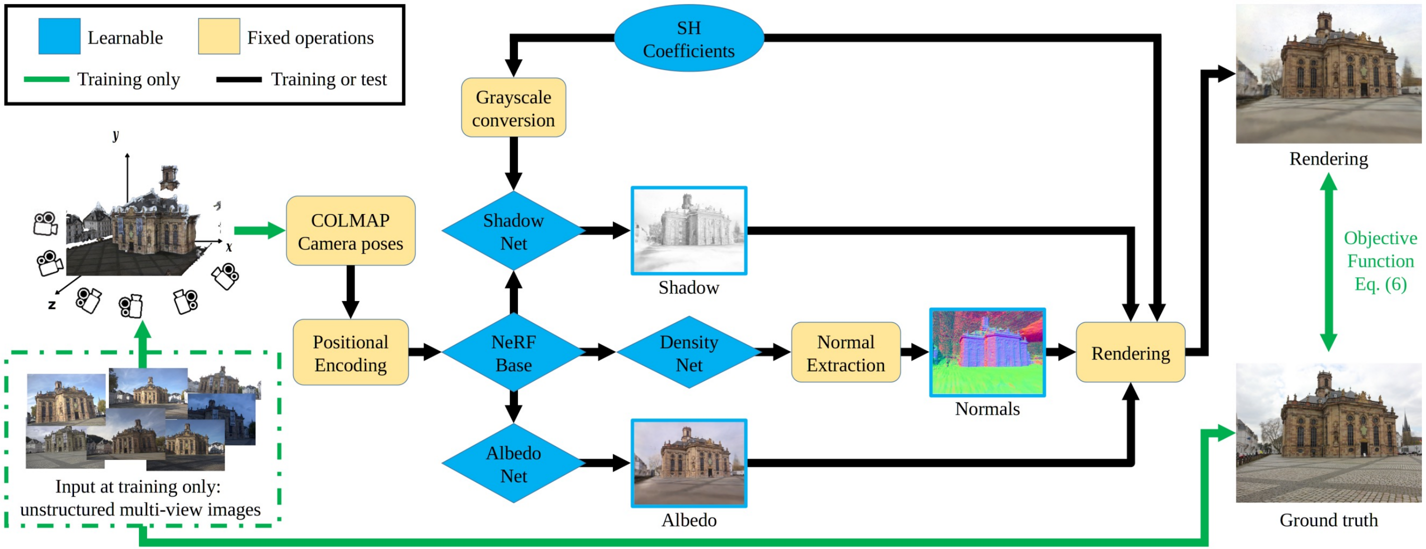
Neural Materials and Lighting

Given a set of views,

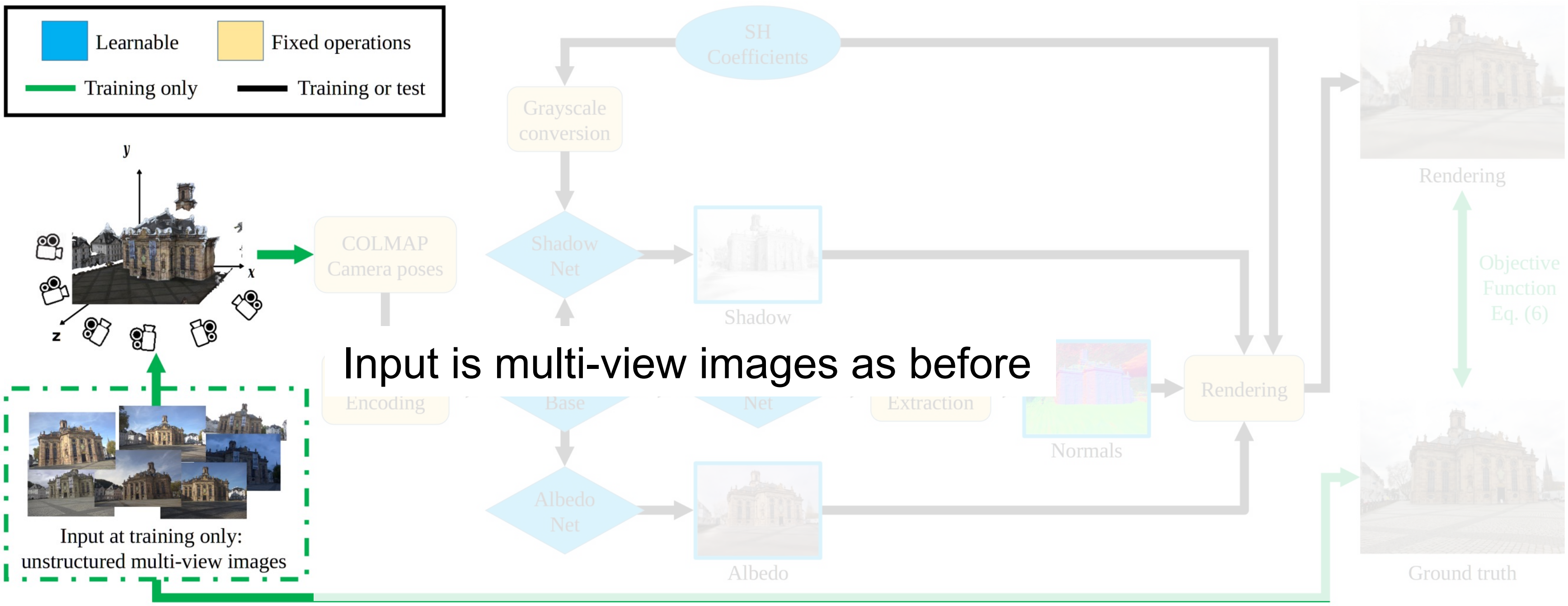
the network parameters are optimized and new views can be synthesized.

Neural Materials and Lighting

Problem radiance = combination of geometry, materials, and lighting
Solution disentangle them

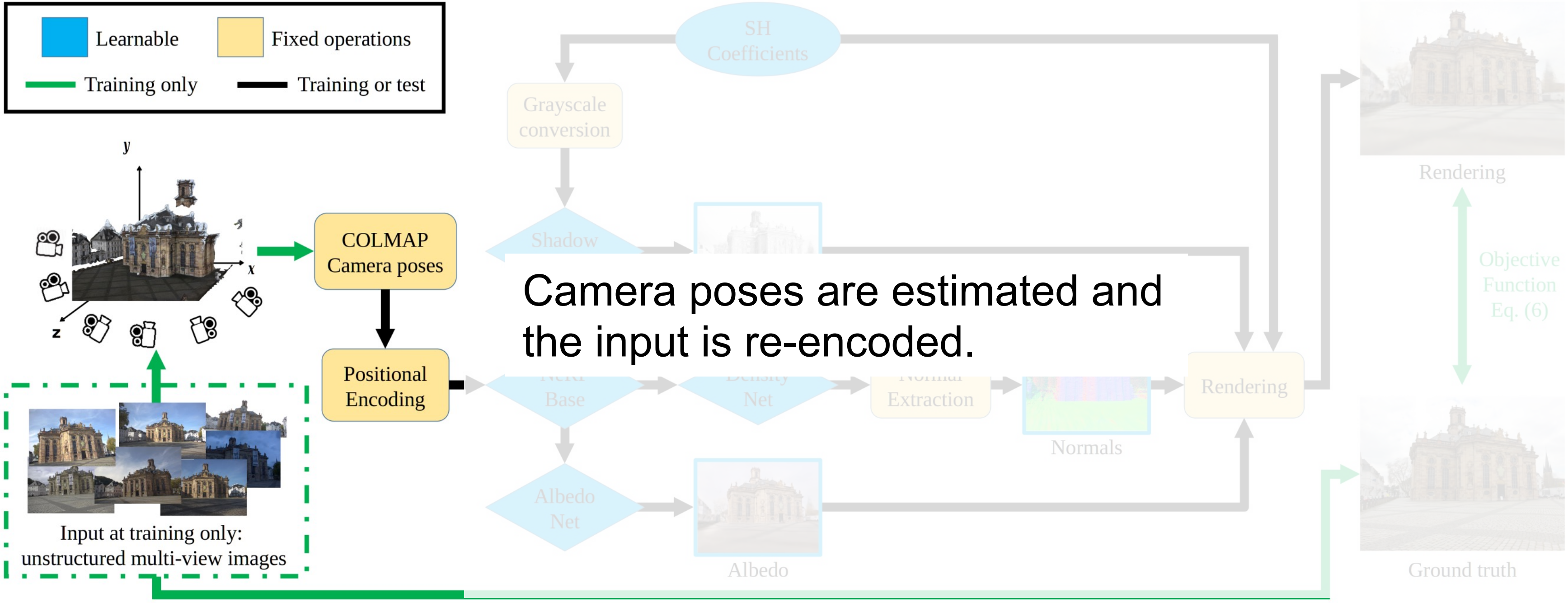


Neural Materials and Lighting



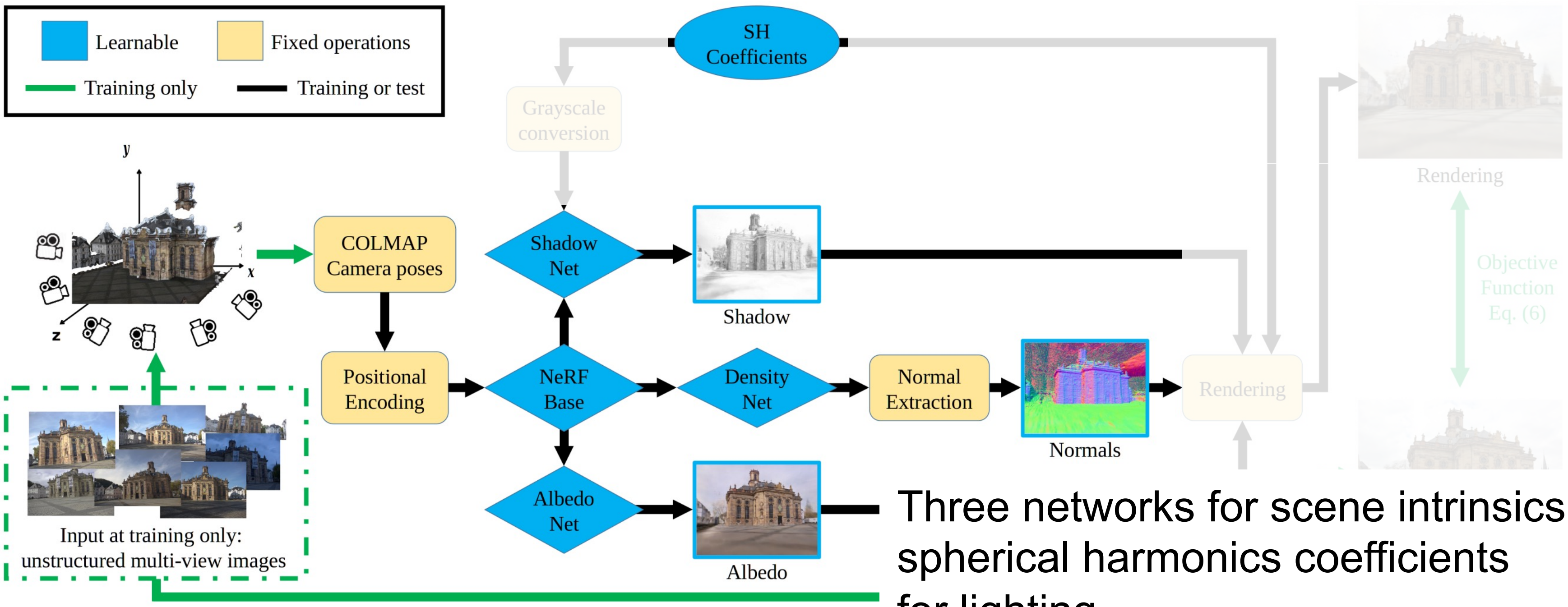
Input is multi-view images as before

Neural Materials and Lighting



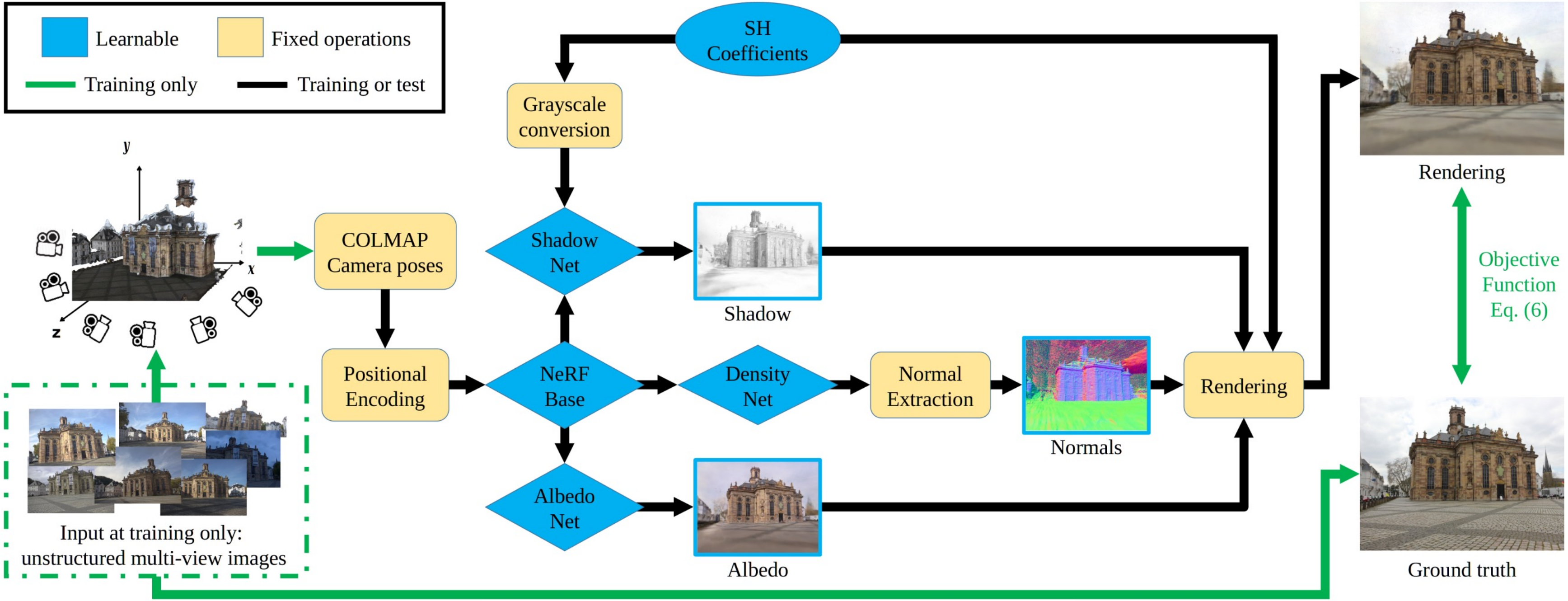
Camera poses are estimated and the input is re-encoded.

Neural Materials and Lighting



Three networks for scene intrinsics, spherical harmonics coefficients for lighting

Neural Materials and Lighting



The outputs are put together to render a realistic image.

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