

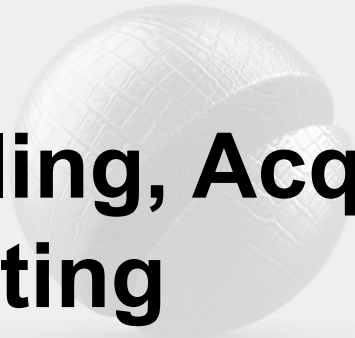
Appearance Modelling, Acquisition, Relighting



fabric



ground



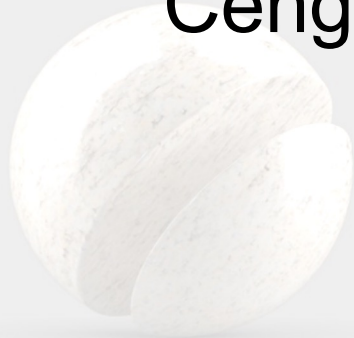
leather



metal



stone-diff



stone-spec



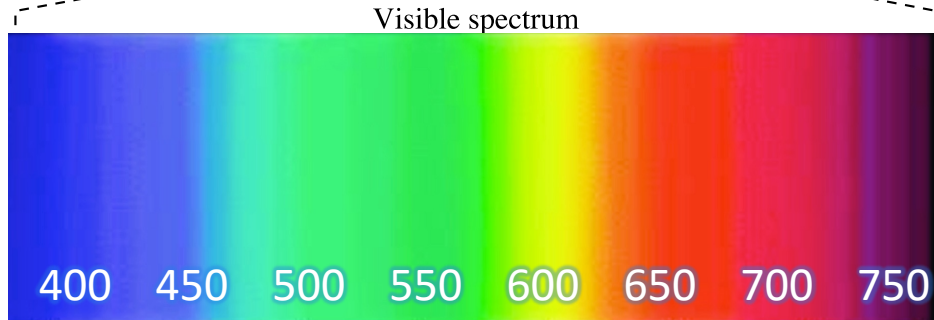
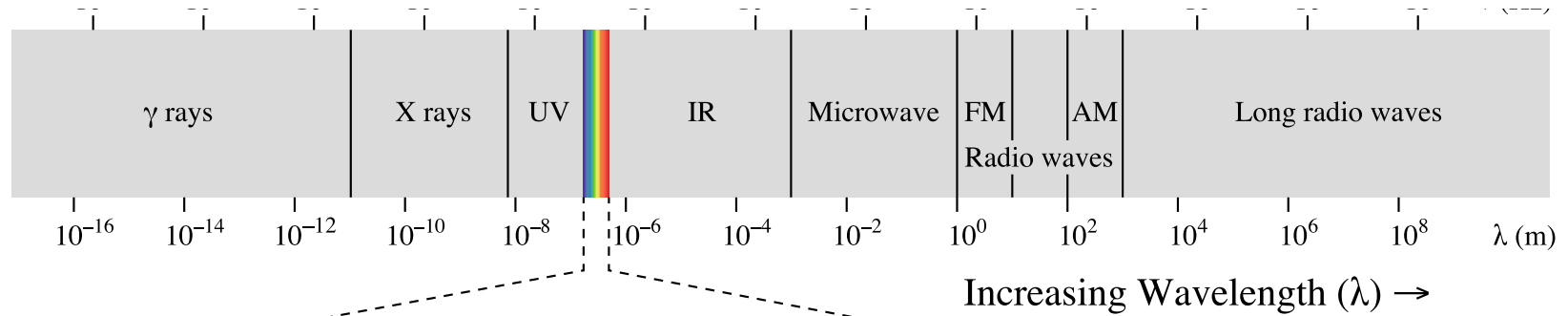
polymer



wood ₁

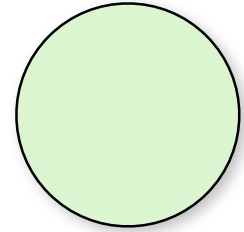
Cengiz Öztireli

Light and Colors

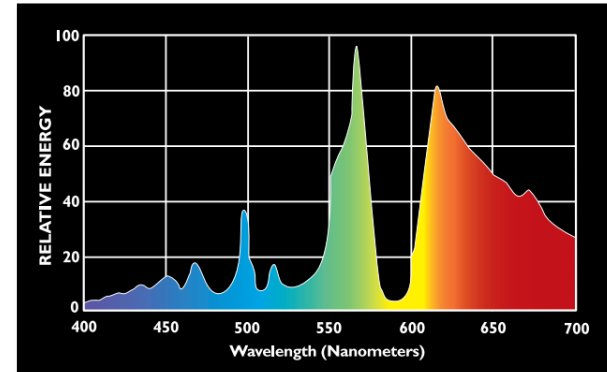


Light and Colors

- 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

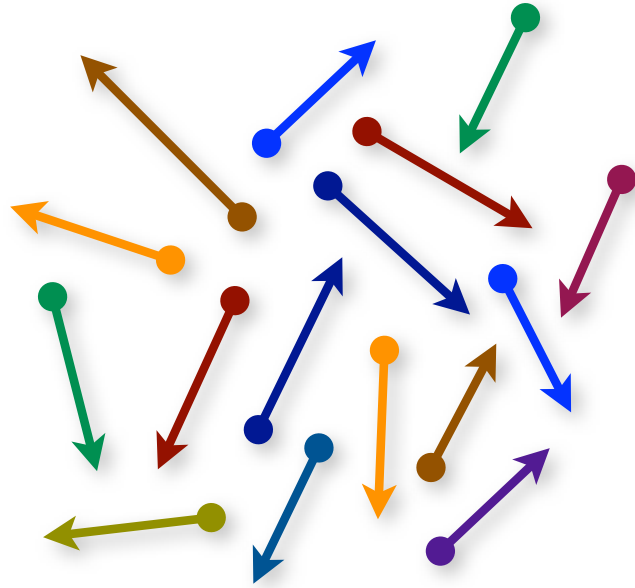


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Measuring Light

- How do we measure light



Measuring = Counting photons

Basic Definitions

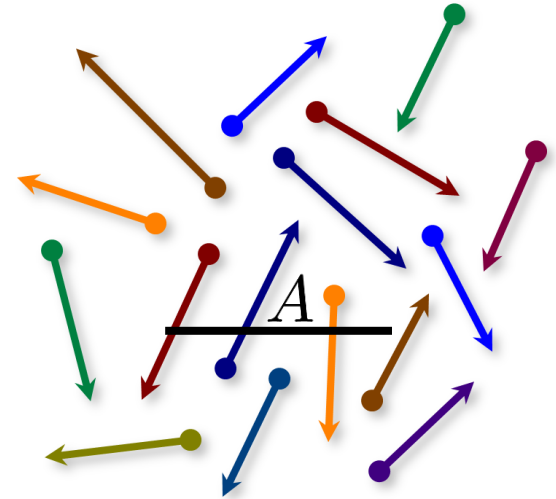
- Assume light consists of photons with
 - \mathbf{x} : Position
 - $\vec{\omega}$: Direction of motion
 - λ : Wavelength
- Each photon has an energy of: $\frac{hc}{\lambda}$
 - $h \approx 6.63 \cdot 10^{-34} \text{ m}^2 \cdot \text{kg}/\text{s}$: Planck's constant
 - $c = 299,792,458 \text{ m}/\text{s}$: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

Radiometry

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

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

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

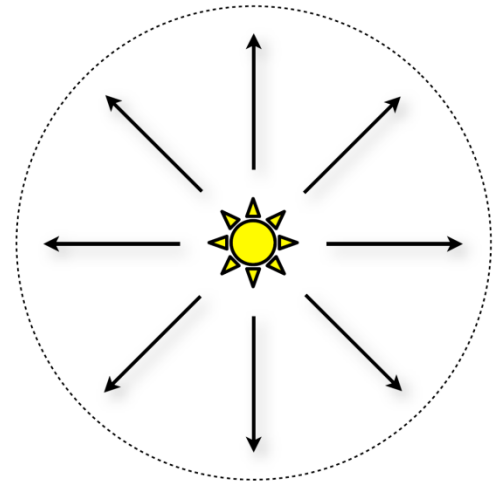


Radiometry

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

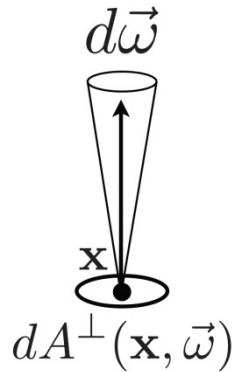
$$I(\vec{\omega}) = \frac{d\Phi}{d\vec{\omega}} \quad \left[\frac{W}{sr} \right] \quad \Phi = \int_{S^2} I(\vec{\omega}) d\vec{\omega}$$

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

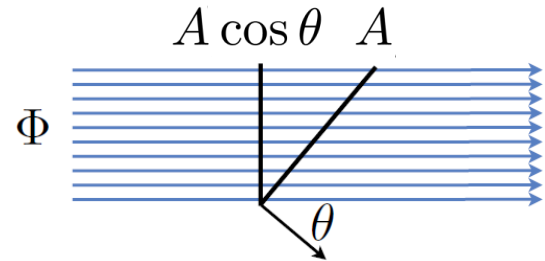


Radiometry

- Radiance
 - Radiant intensity per perpendicular unit area



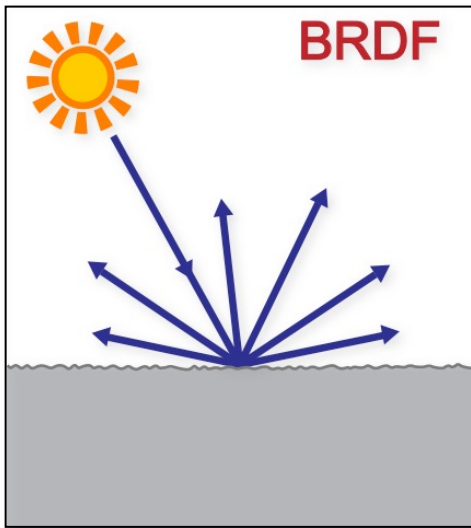
$$L(\mathbf{x}, \vec{\omega}) = \frac{d^2\Phi(A)}{d\vec{\omega}dA^\perp(\mathbf{x}, \vec{\omega})}$$
$$= \frac{d^2\Phi(A)}{d\vec{\omega}dA(\mathbf{x}) \cos \theta} \left[\frac{W}{m^2 sr} \right]$$



- remains constant along a ray

Reflection Models

- **Bidirectional Reflectance Distribution Function (BRDF)**



BRDF

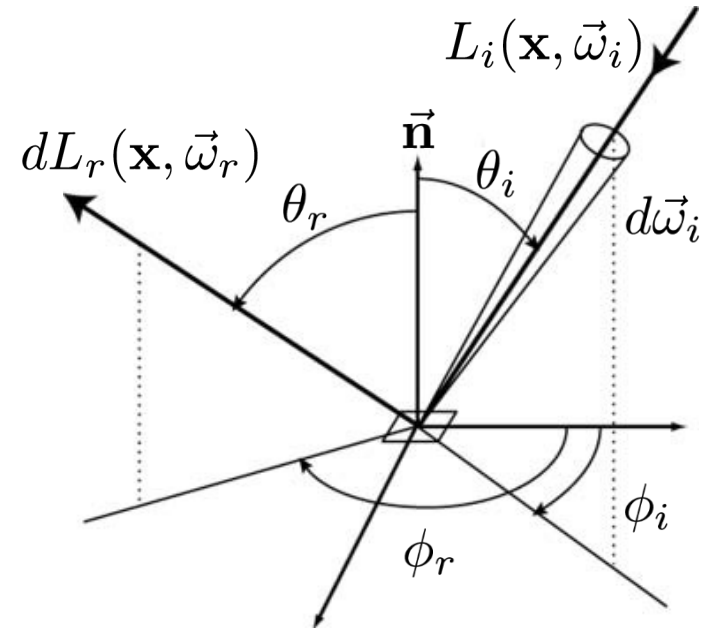
- **Bidirectional Reflectance Distribution Function**

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

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**

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

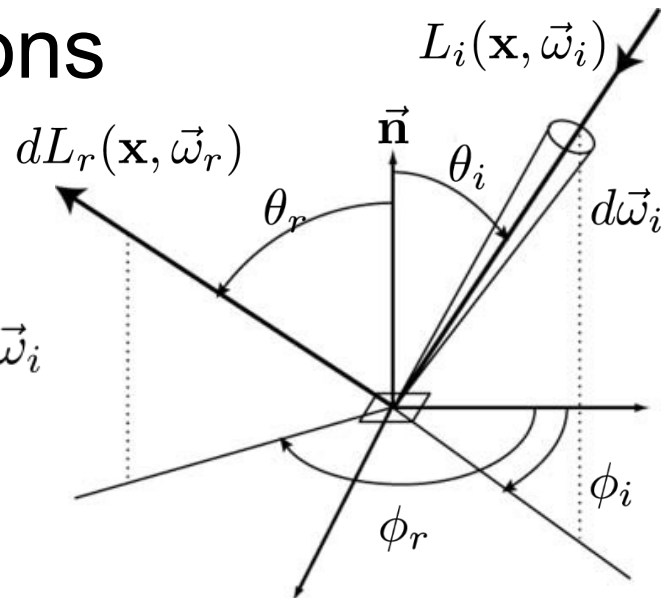
$$f_r(\mathbf{x}, \vec{\omega}_i, \vec{\omega}_r) L_i(\mathbf{x}, \vec{\omega}_i) \cos \theta_i = \frac{dL_r(\mathbf{x}, \vec{\omega}_r)}{d\vec{\omega}_i}$$

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

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

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

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

outgoing light

emitted light

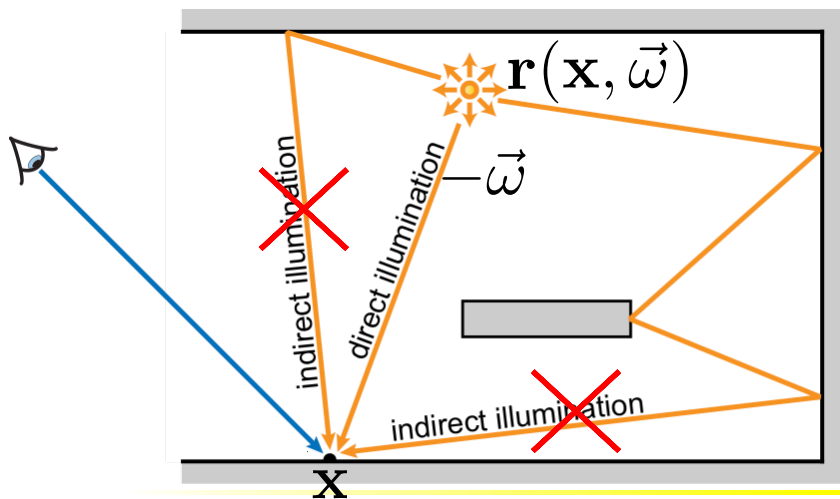
reflected light

Energy is conserved!

Direct Illumination

- All light comes directly from emitters, i.e. light sources

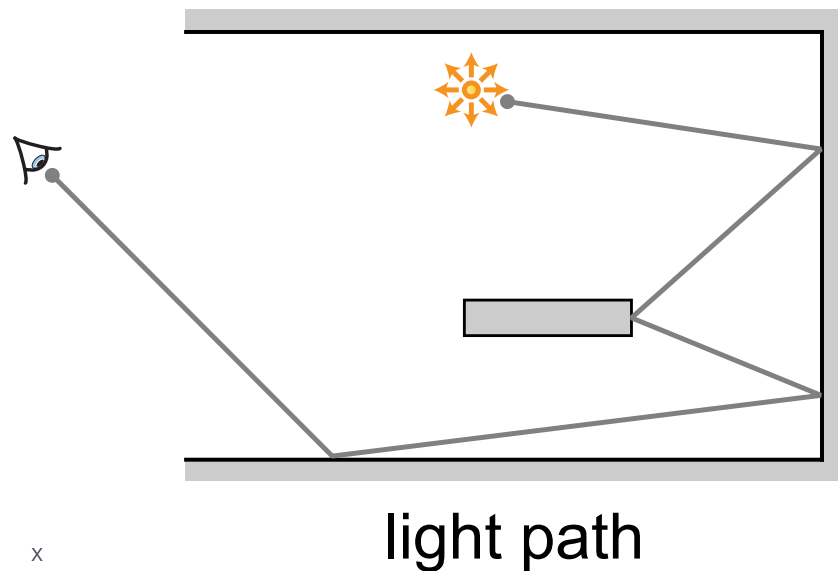
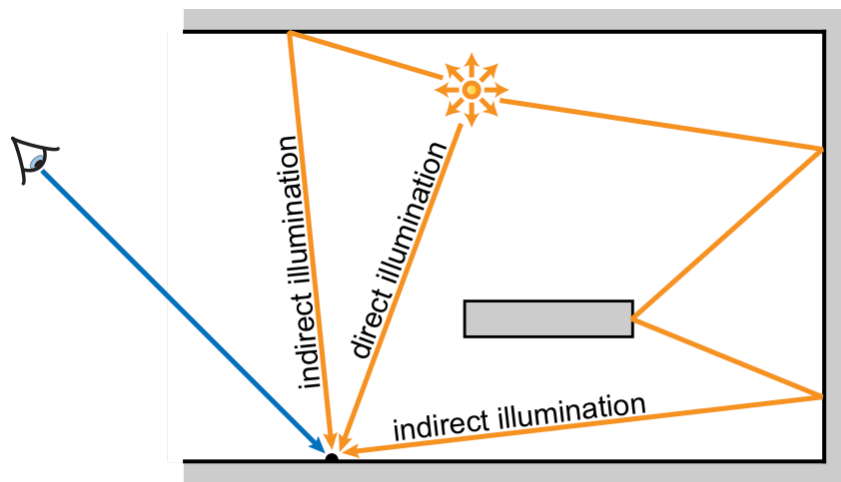
$$L_o(\mathbf{x}, \vec{\omega}_o) = L_e(\mathbf{x}, \vec{\omega}_o) + \int_{H^2} f_r(\mathbf{x}, \vec{\omega}_i, \vec{\omega}_o) L_i(\mathbf{x}, \vec{\omega}_i) \cos \theta_i d\vec{\omega}_i$$



$$L_i(\mathbf{x}, \vec{\omega}) = L_e(\mathbf{r}(\mathbf{x}, \vec{\omega}), -\vec{\omega})$$

Global Illumination

- Consider all light – including bounces



Global Illumination

Direct illumination



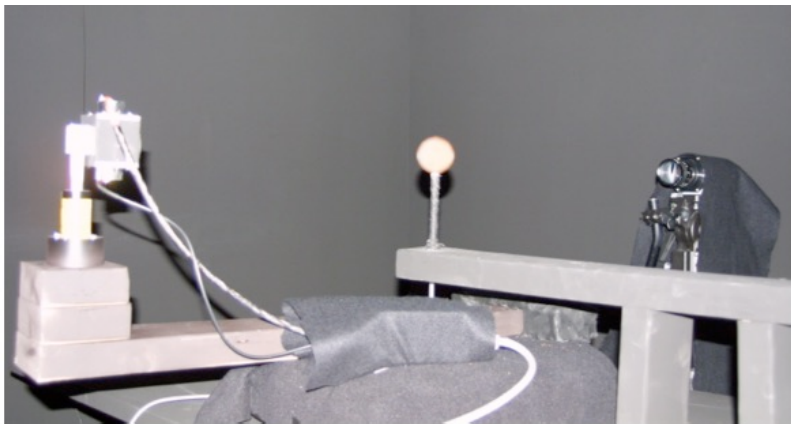
Indirect illumination



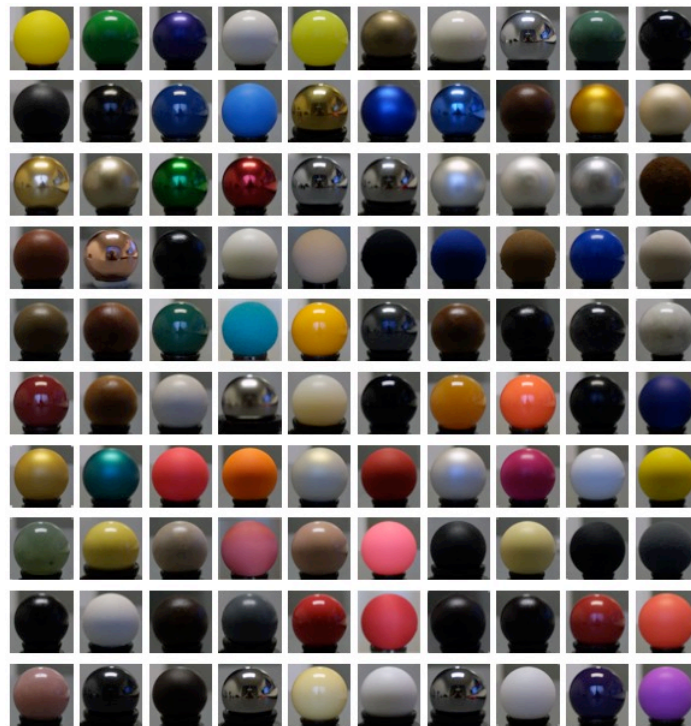
Direct + Indirect



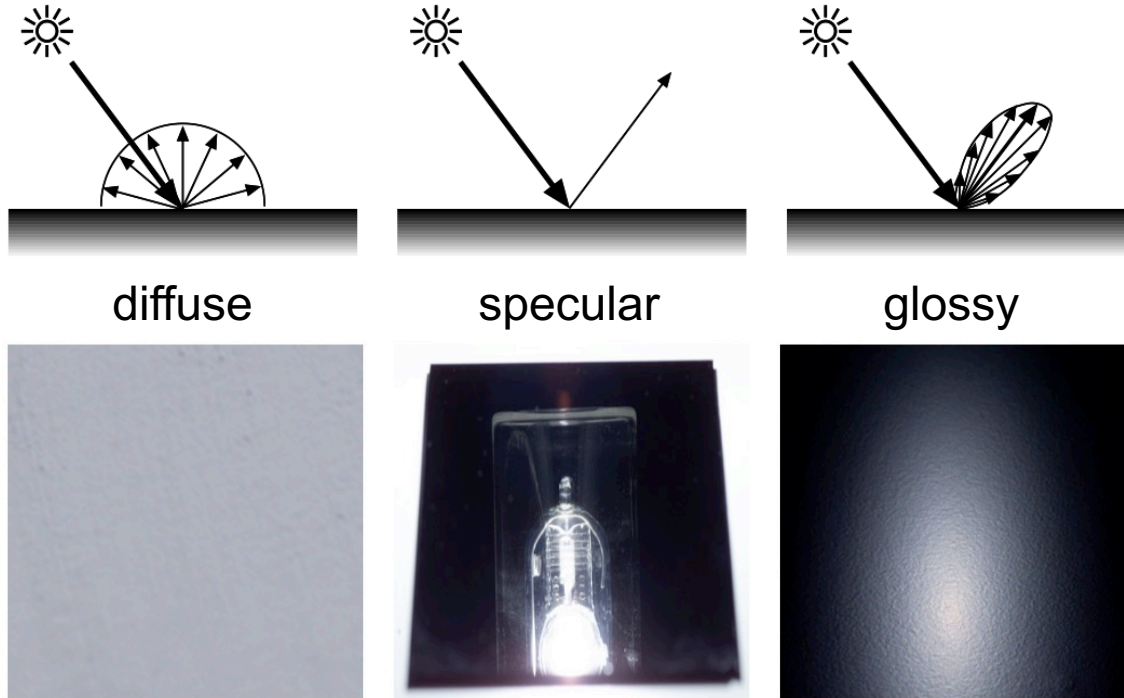
Measuring BRDFs



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



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

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

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

Assumptions: 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

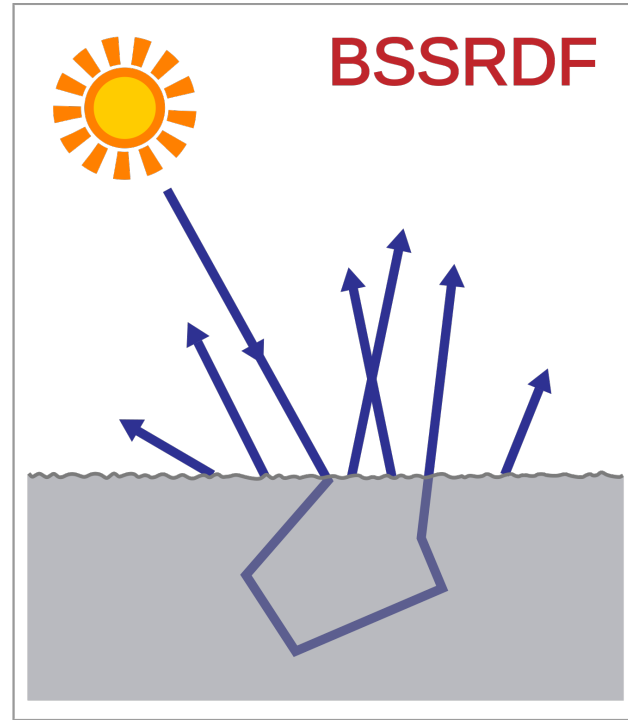
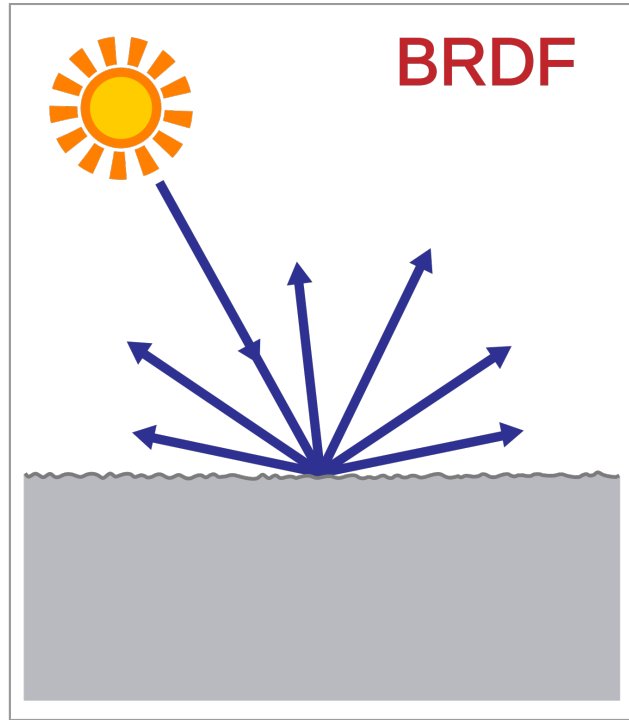
Goal: estimate surface normal from observed light, e.g. camera

$$\underbrace{L_o(\mathbf{x}, \vec{\omega}_o, \lambda_{RGB})}_I = \frac{\rho_{d,RGB}}{\pi} (\vec{n} \cdot \vec{\omega}_i)$$

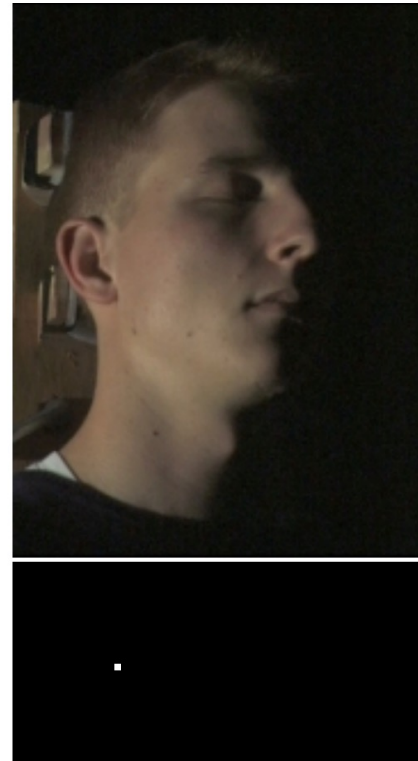
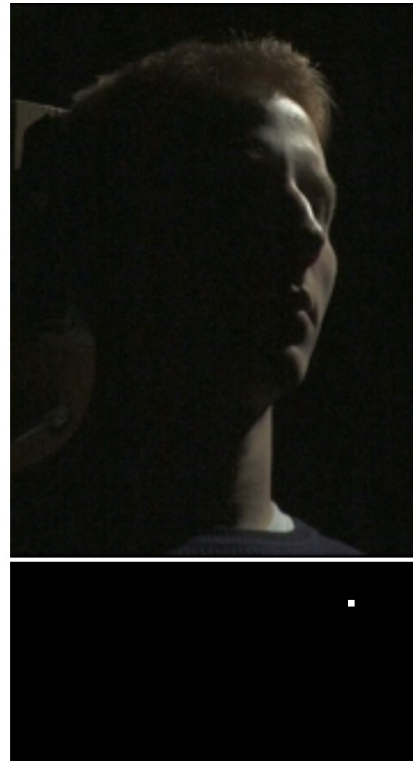
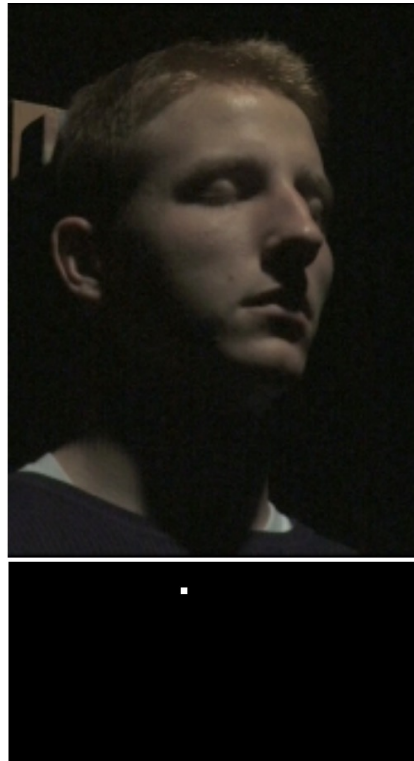
$$A_{n \times 3} * x_{3 \times 1} = b_{n \times 1}$$

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

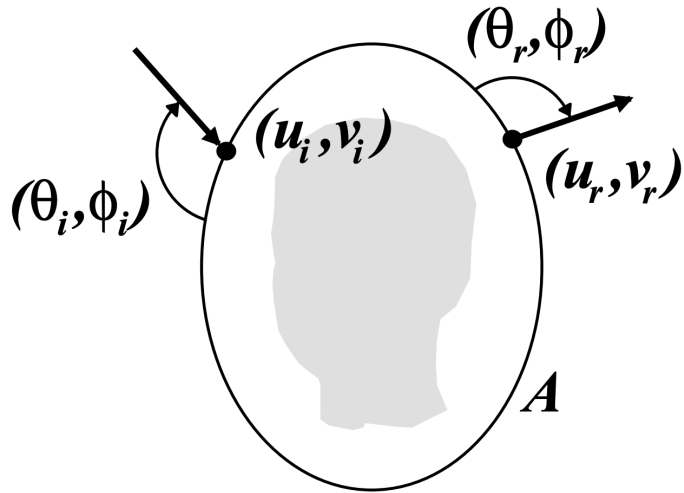
Bidirectional scattering-surface reflectance distribution function



Measuring the Human Face



Measuring the Human Face

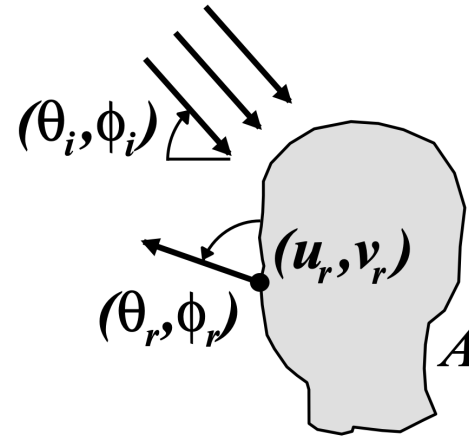
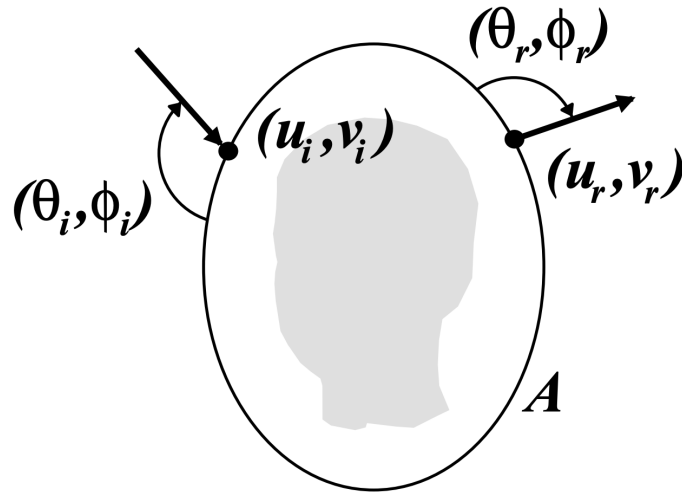


Surface enclosing the scene

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

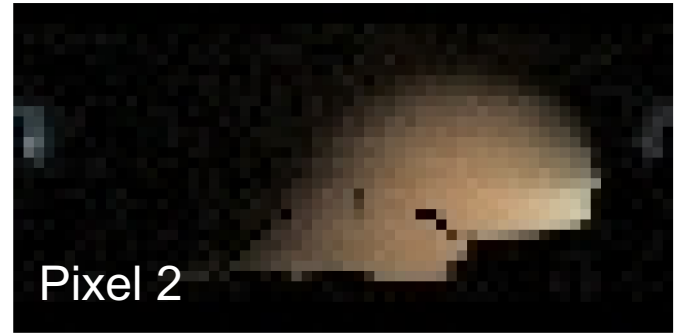


Idea:

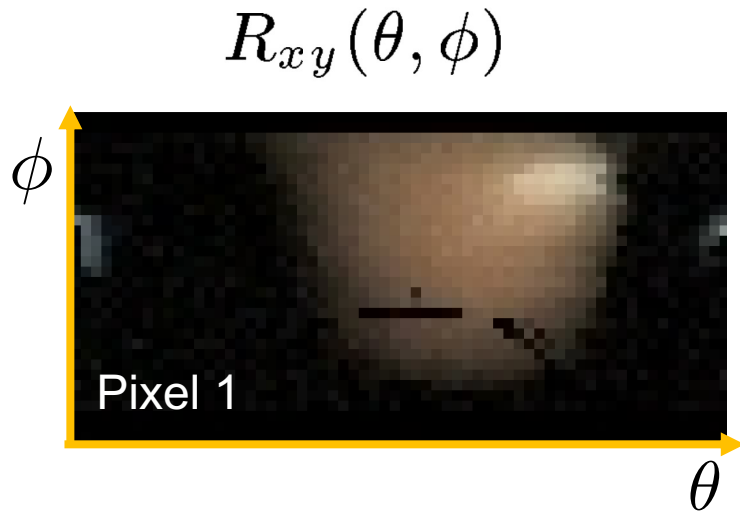
1. Turn one light on at a time and capture an image from the same view
2. Construct a new lighting setup as a sum of the images

Measuring the Human Face

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



Relighting the Human Face



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

Output pixel
value

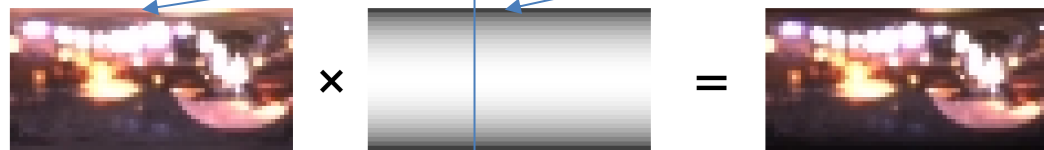
Reflectance function
for this pixel

Map of incident
illumination at this pixel

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

Relighting the Human Face

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



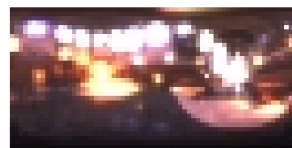
light map

×

δA

=

normalized
light map



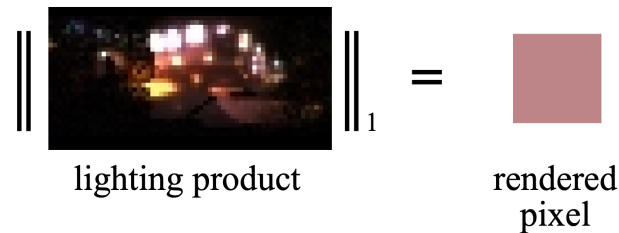
normalized
light map

×

reflectance
function

=

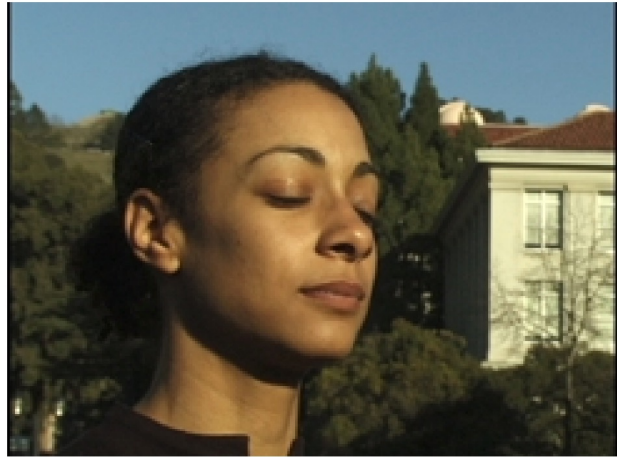
lighting product



lighting product

rendered
pixel

Relighting the Human Face



Real image



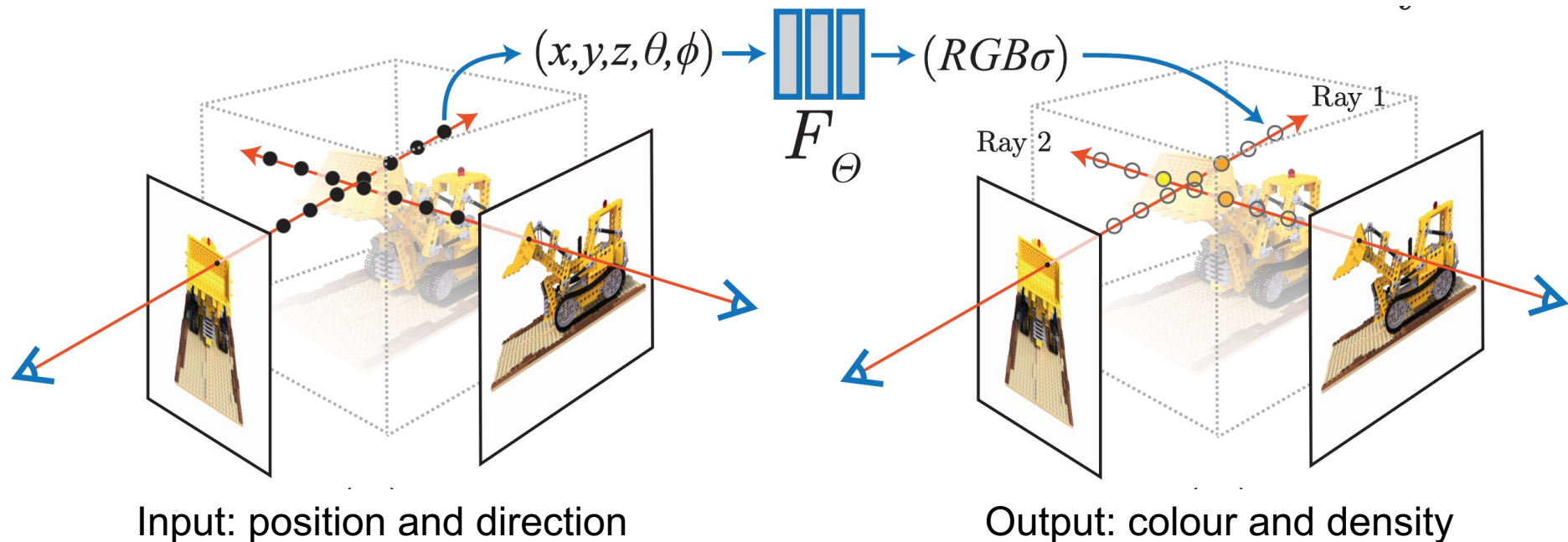
Environment



Relit face

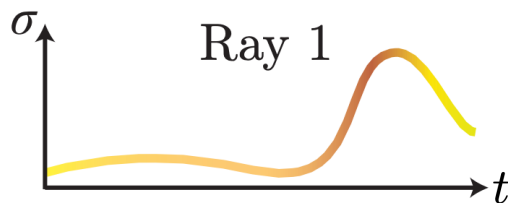
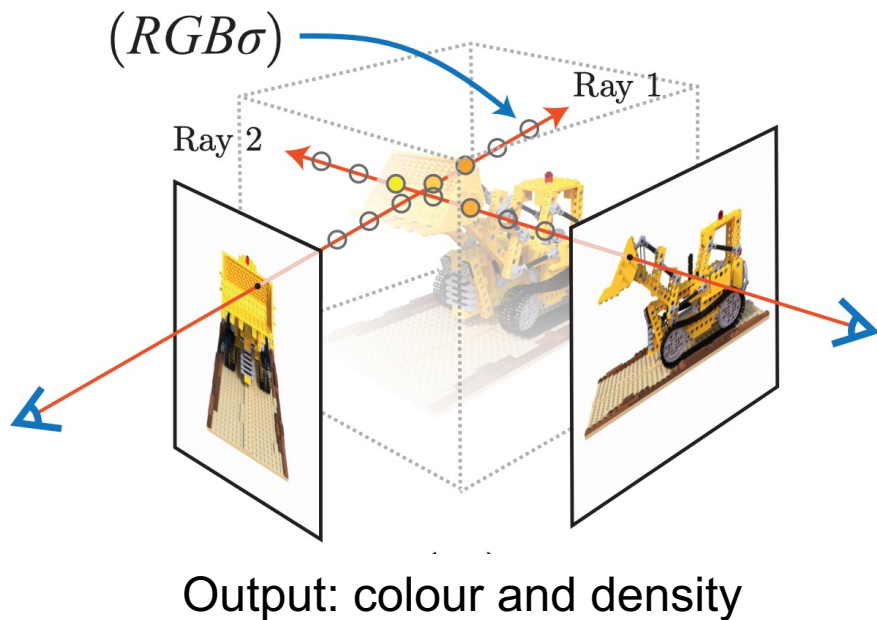
Neural Materials and Lighting

Volume rendering



Neural Materials and Lighting

Volume rendering



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

