Computer Vision

Fall 2019 16385

Instructor: S. Narasimhan

Physics Based Vision

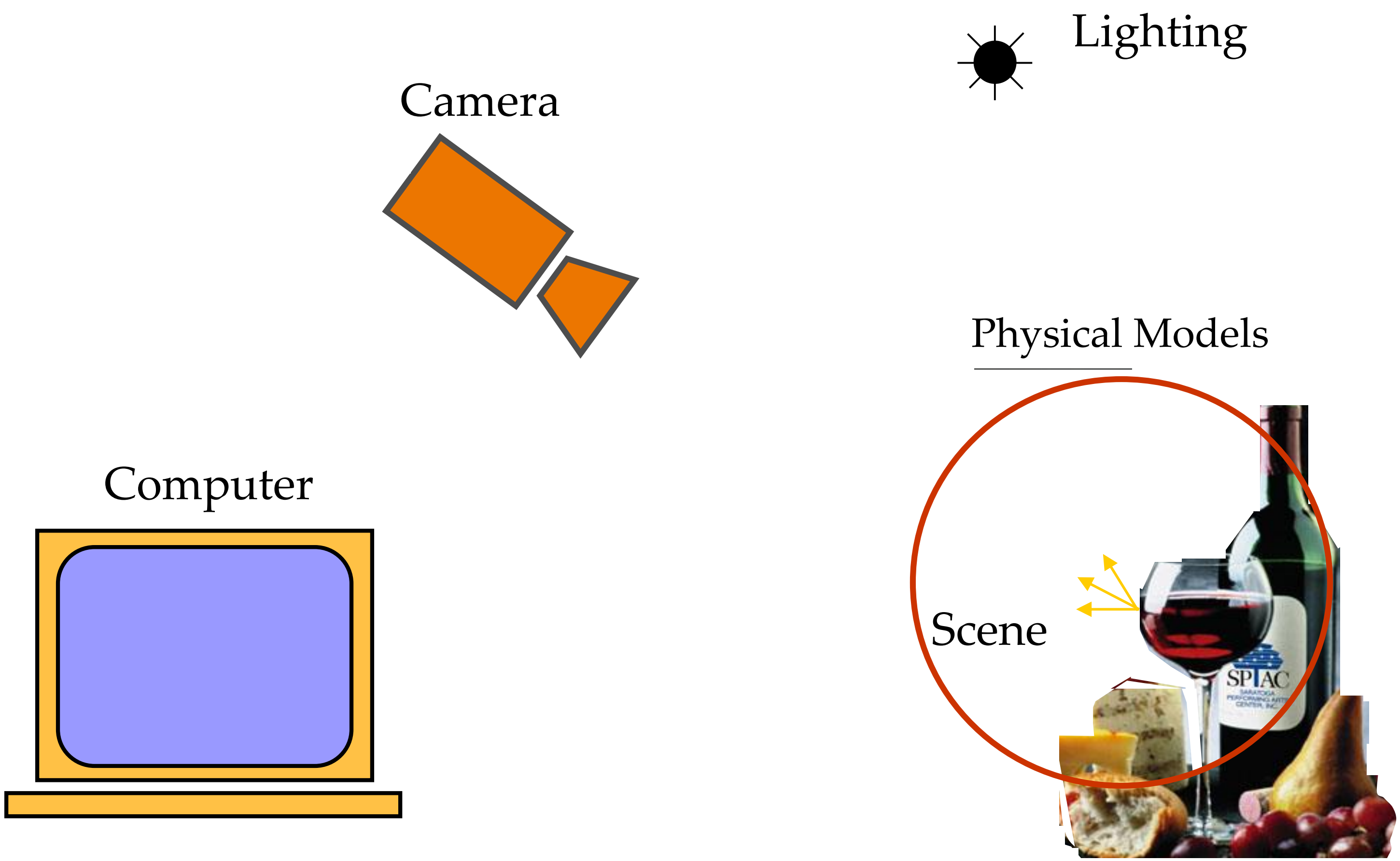
Thanks to Shree Nayar, Ravi Ramamoorthi, Henrik Jensen, Todd Zickler, Pat Hanrahan

What is Appearance?

Or…

How did the pixel get its value?

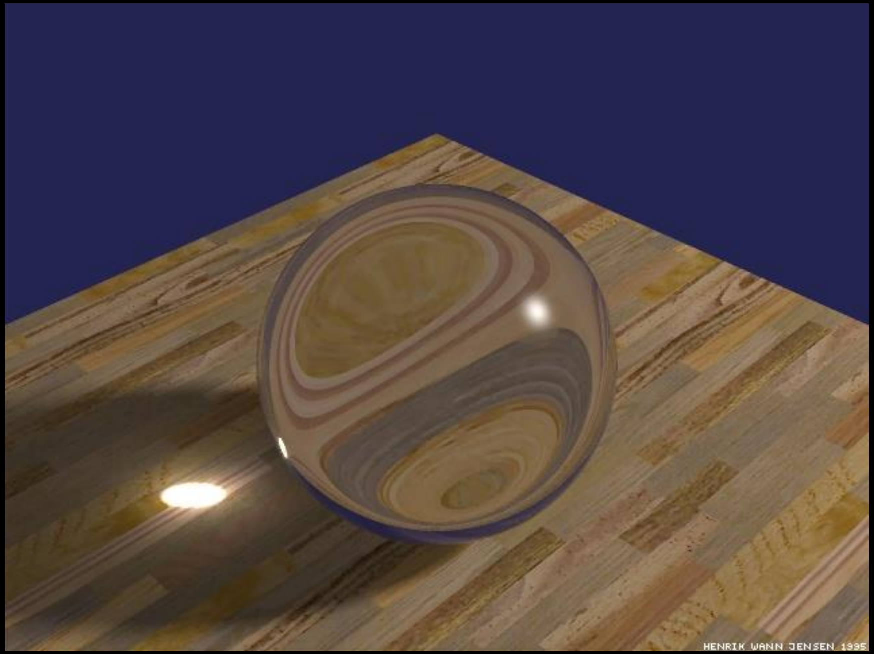
Computer Vision: Building Machines that See



We need to understand the relation between
the lighting, materials, geometry, medium and the image of the scene.



HENRIK WANN JENSEN 1995


HENRIK WANN JENSEN 1995

Haze

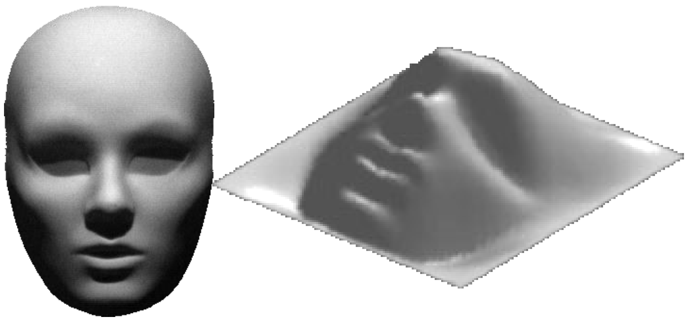
De-hazed


RENDERED BY HENRIK WANN JENSEN - 2001

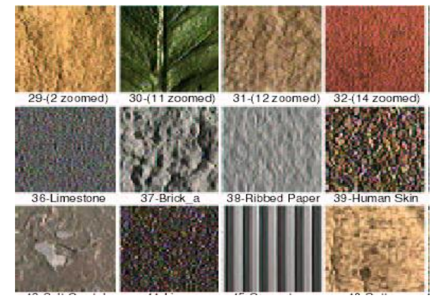

RENDERED BY HENRIK WANN JENSEN - 2001



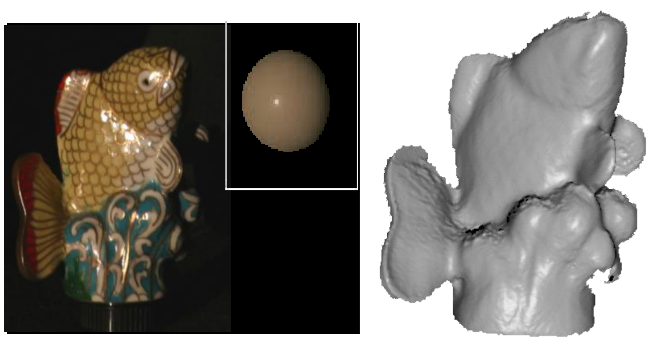
Vision Methods Relying on Surface Appearance



Shape from Shading



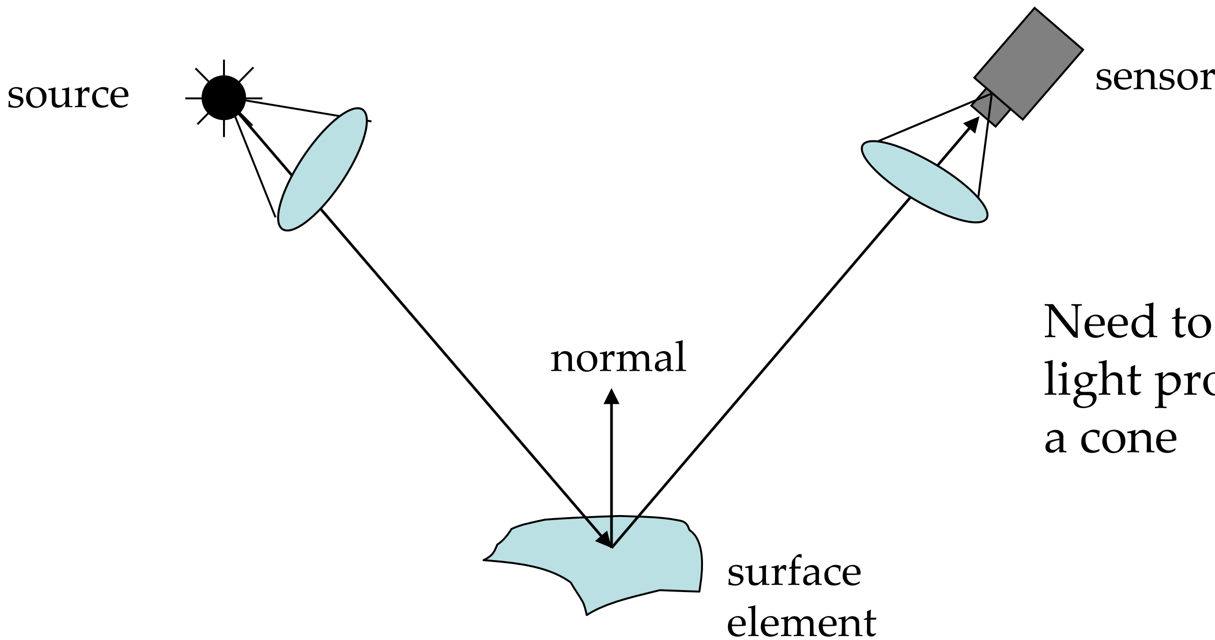
Texture Modeling



Photometric Stereo

Reflection Separation

Image Intensities

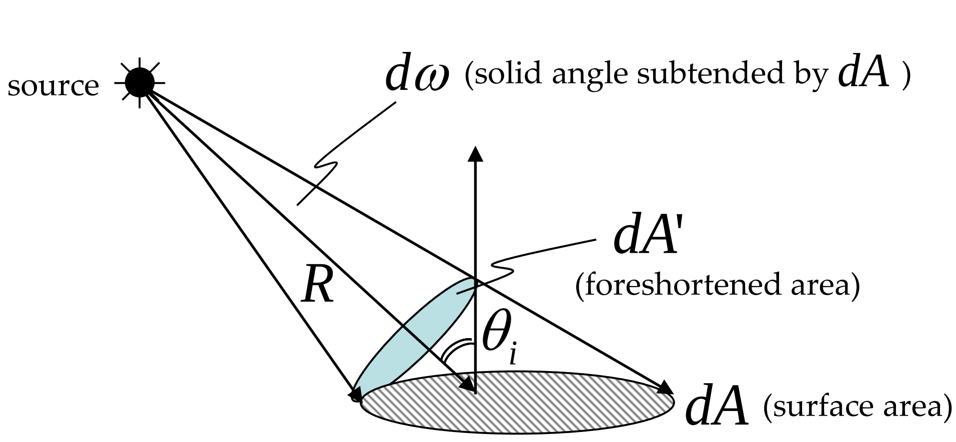


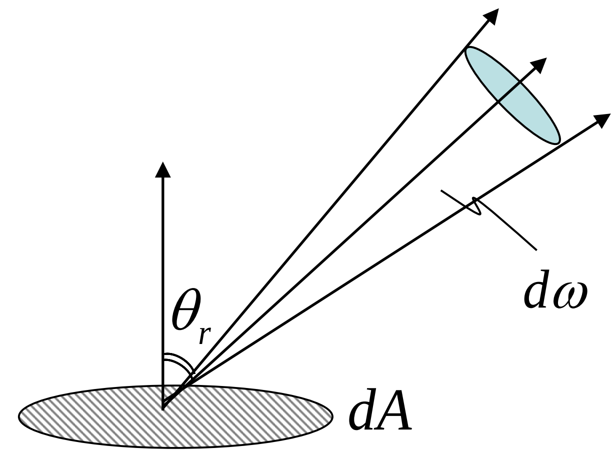
Need to consider light propagation in a cone

Image intensities = f (normal, surface reflectance, illumination)

Note: Image intensity understanding is an under-constrained problem!

Radiometric concepts – important!





(1) Solid Angle : $d\omega = \frac{dA'}{R^2} = \frac{dA\cos\theta_i}{R^2}$ (steradian)

What is the solid angle subtended by a hemisphere?

(2) Radiant Intensity of Source : $J = \frac{d\Phi}{d\omega}$ (watts / steradian)

Light Flux (power) emitted per unit solid angle

(3) Surface Irradiance : $E = \frac{d\Phi}{dA}$ (watts / m)

Light Flux (power) incident per unit surface area.

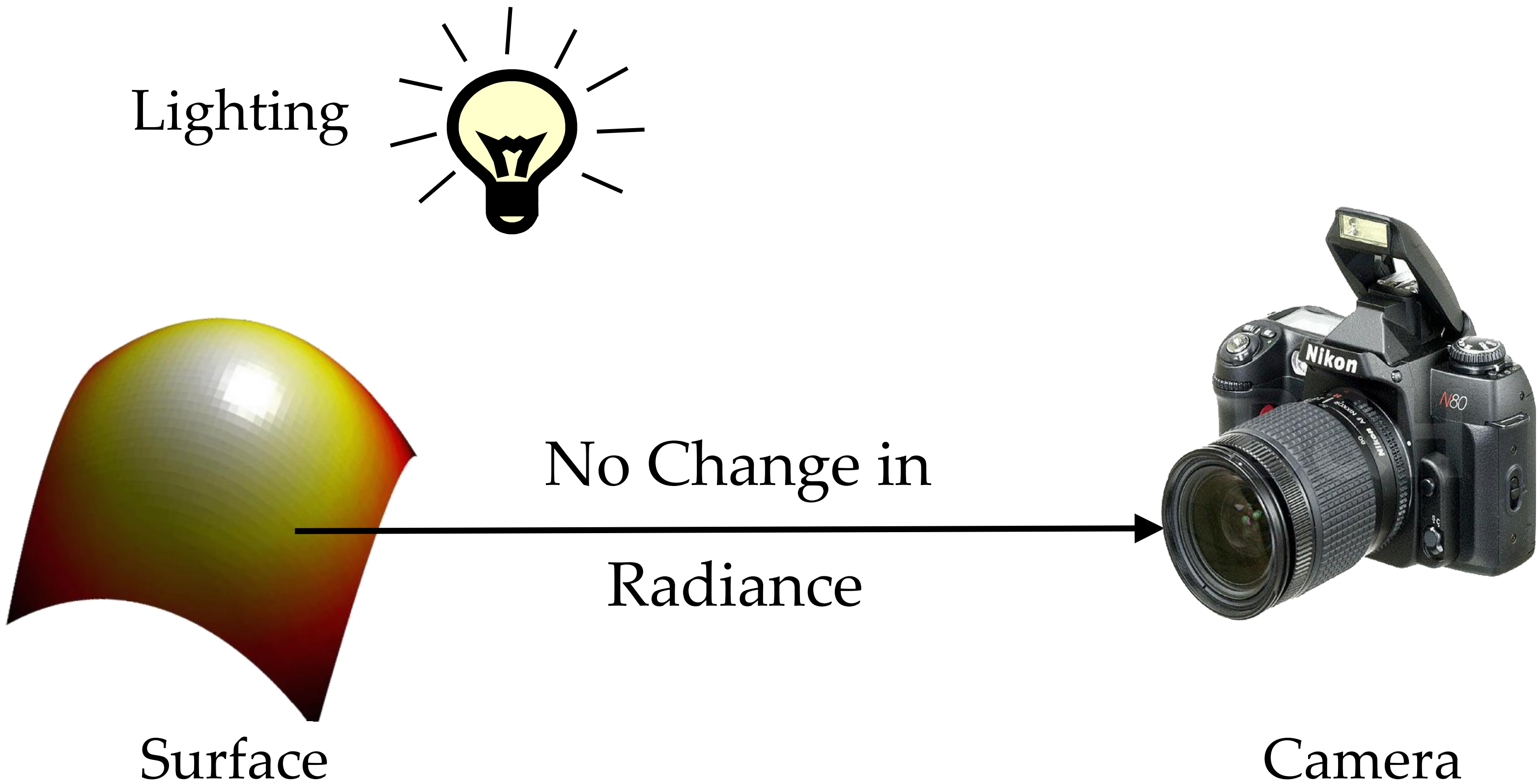
Does not depend on where the light is coming from!

(4) Surface Radiance (tricky) :

$$L = \frac{d^2\Phi}{(dA\cos\theta_r)\ d\omega} \quad \text{(watts / m}^2\text{ steradian)}$$

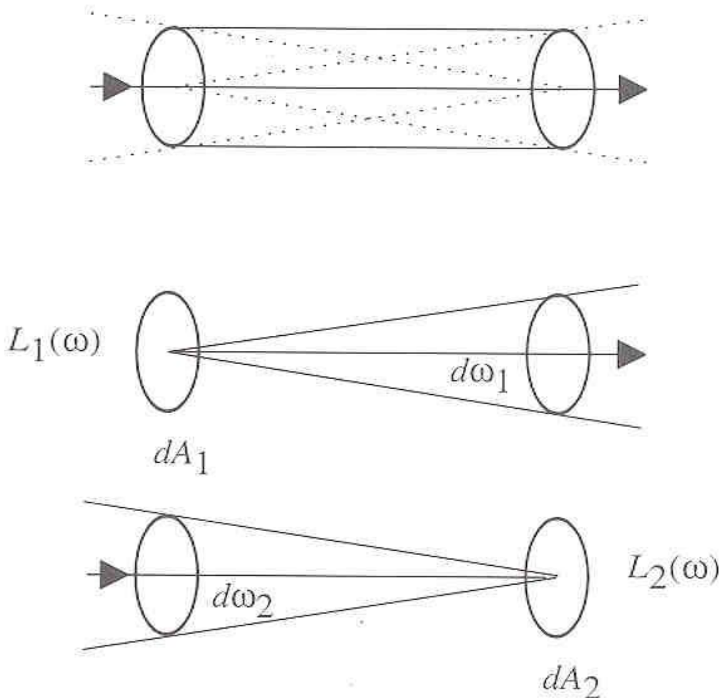
- Flux emitted per unit foreshortened area per unit solid angle.
- L depends on direction θ_r
- Surface can radiate into whole hemisphere.
- L depends on reflectance properties of surface.

The Fundamental Assumption in Vision



Radiance properties

- Radiance is constant as it propagates along ray
  - Derived from conservation of flux
  - Fundamental in Light Transport.



$$d\Phi_1 = L_1 d\omega_1 dA_1 = L_2 d\omega_2 dA_2 = d\Phi_2$$

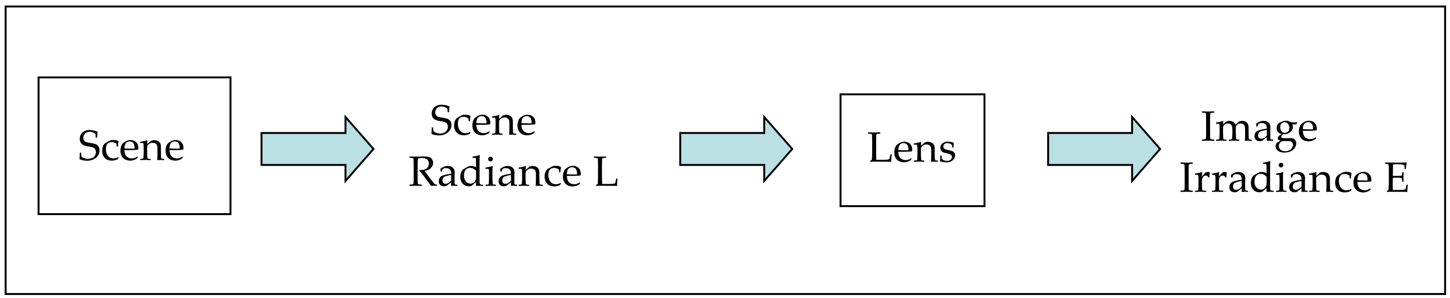
$$d\omega_1 = dA_2 / r^2 \qquad d\omega_2 = dA_1 / r^2$$

$$d\omega_1 dA_1 = \frac{dA_1 dA_2}{r^2} = d\omega_2 dA_2$$

$$\therefore L_1 = L_2$$

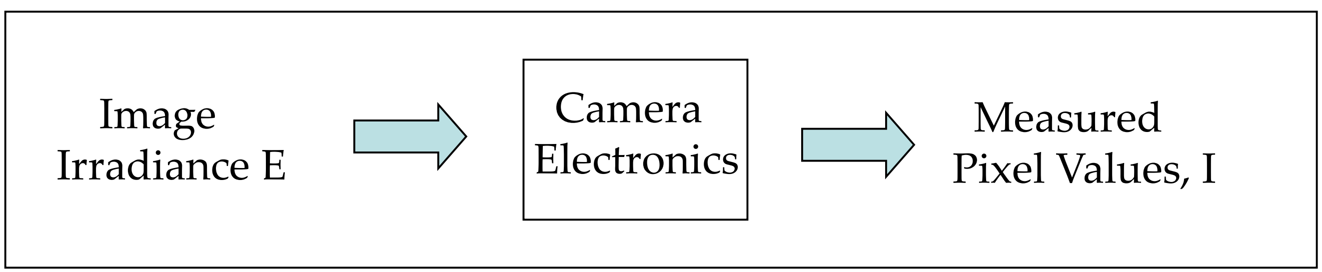
Relationship between Scene and Image Brightness

- Before light hits the image plane:



Linear Mapping!

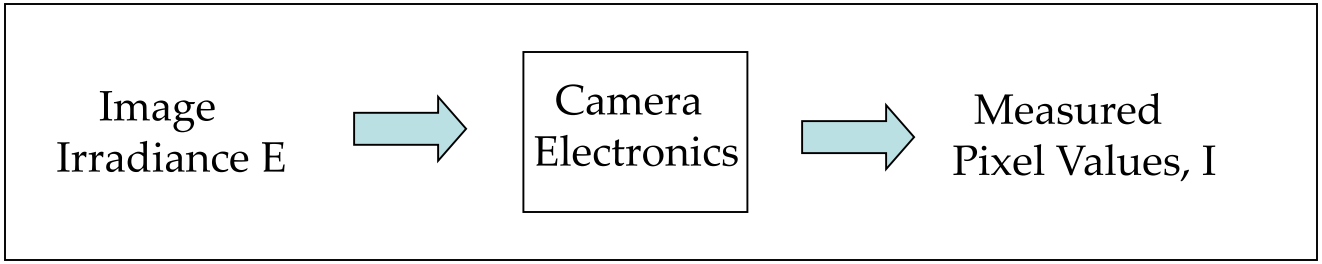
- After light hits the image plane:



Non-linear Mapping!

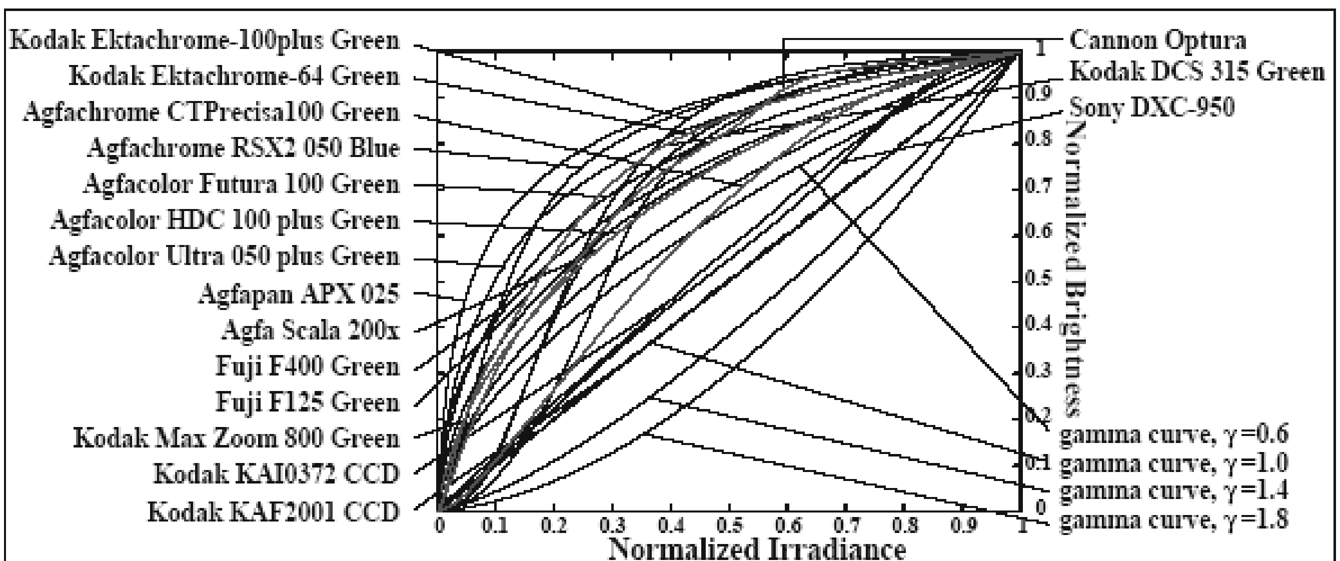
Can we go from measured pixel value, I, to scene radiance, L?

Relation between Pixel Values I and Image Irradiance E



- The camera response function relates image irradiance at the image plane to the measured pixel intensity values.

$$g : E \rightarrow I$$



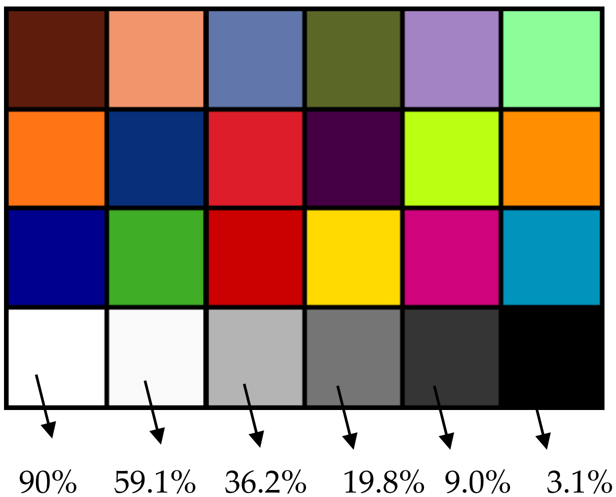
(Grossberg and Nayar)

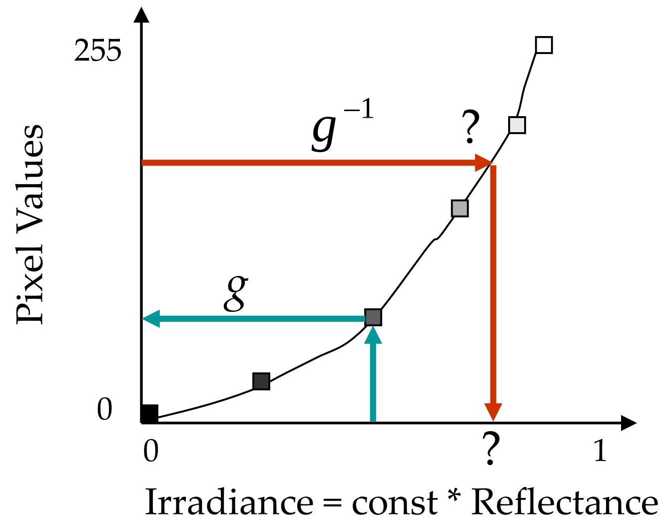
Radiometric Calibration

- Important preprocessing step for many vision and graphics algorithms such as photometric stereo, invariants, de-weathering, inverse rendering, image based rendering, etc.

$$g^{-1} : I \rightarrow E$$

- Use a color chart with precisely known reflectances.





- Use more camera exposures to fill up the curve.
- Method assumes constant lighting on all patches and works best when source is far away (example sunlight).

- Unique inverse exists because g is monotonic and smooth for all cameras.

Surface Appearance

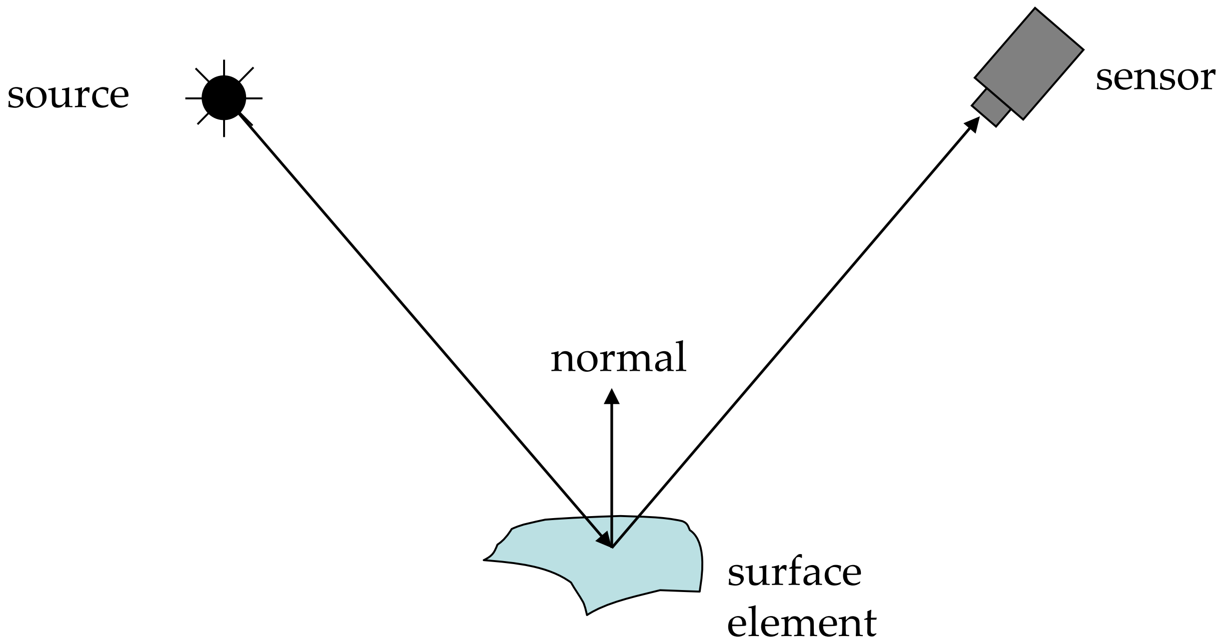
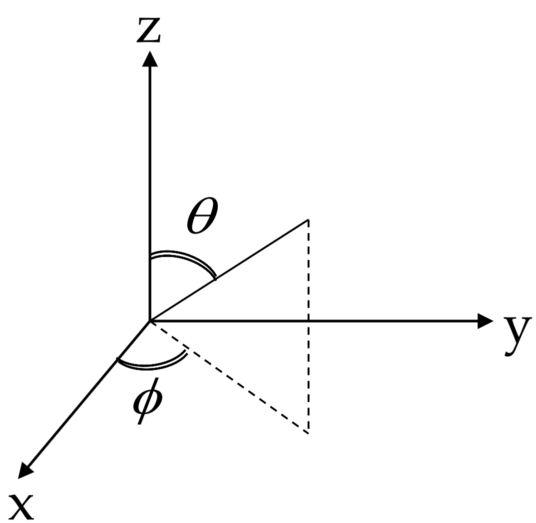
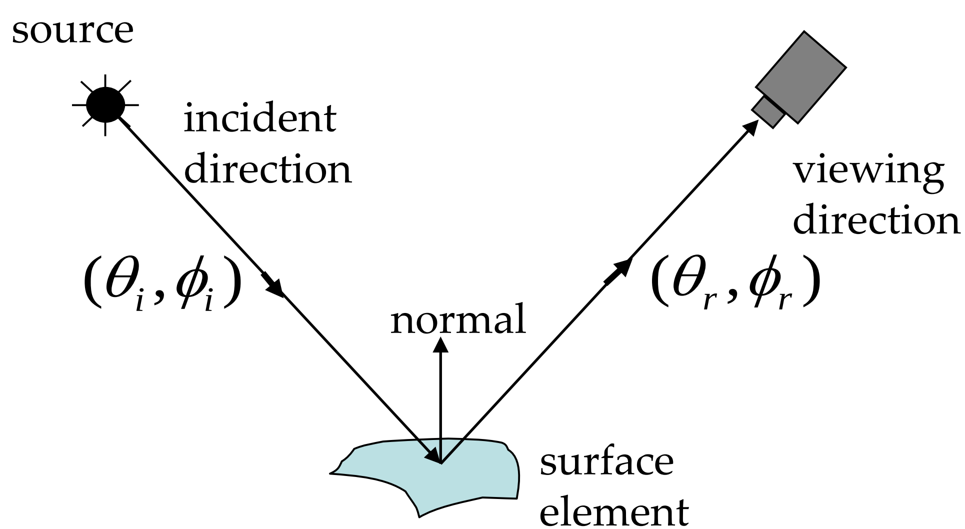


Image intensities = f (normal, surface reflectance, illumination)

Surface Reflection depends on both the viewing and illumination direction.

BRDF: Bidirectional Reflectance Distribution Function



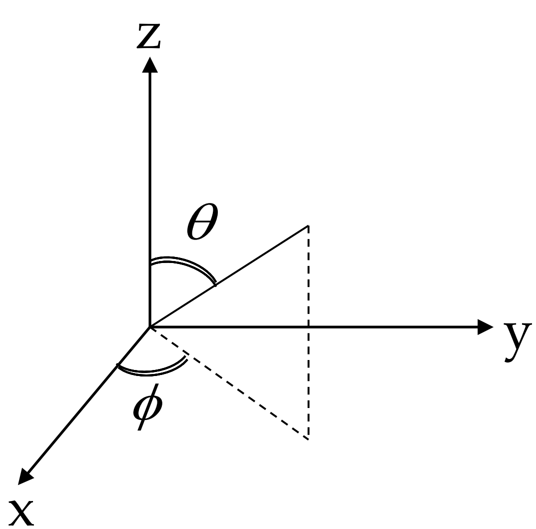


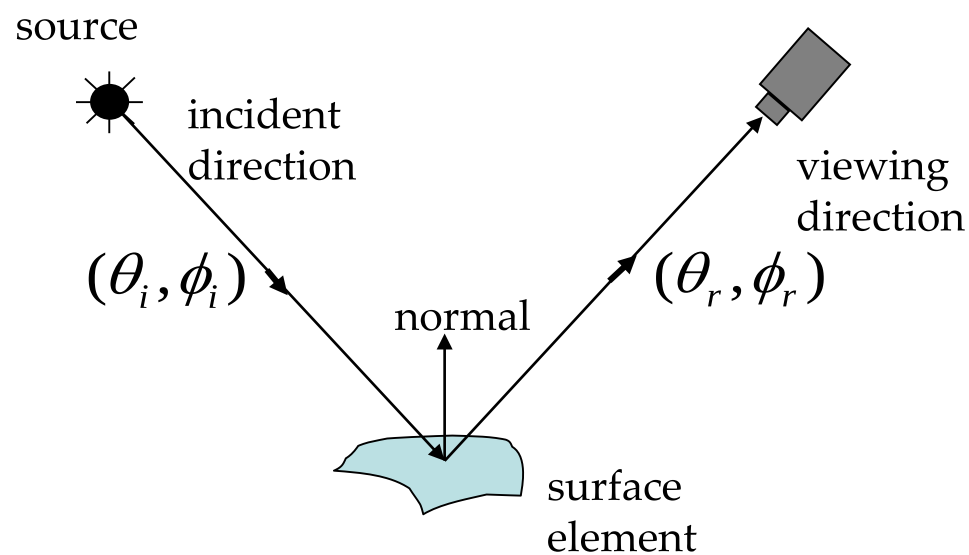
$E^{surface}(\theta_i, \phi_i)$ Irradiance at Surface in direction (θ_i, ϕ_i)

$L^{surface}(\theta_r, \phi_r)$ Radiance of Surface in direction (θ_r, ϕ_r)

$$\boxed{\text{BRDF}: f(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{L^{surface}(\theta_r, \phi_r)}{E^{surface}(\theta_i, \phi_i)}}$$

Important Properties of BRDFs





- Rotational Symmetry (Isotropy):

  BRDF does not change when surface is rotated about the normal.

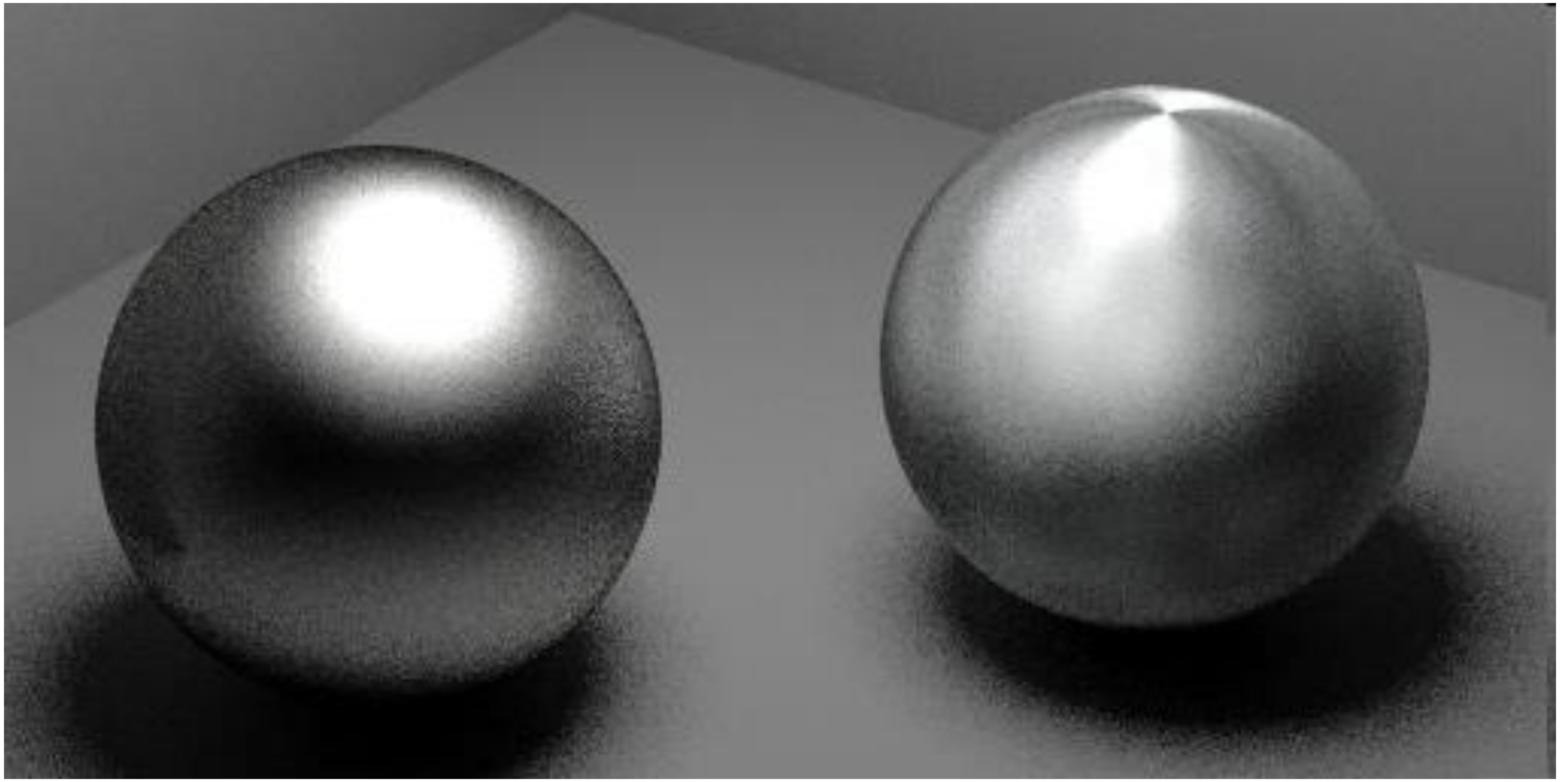
  BRDF is only a function of 3 variables : $f(\theta_i, \theta_r, \phi_i - \phi_r)$

- Helmholtz Reciprocity: (follows from 2nd Law of Thermodynamics)

  BRDF does not change when source and viewing directions are swapped.

$$f(\theta_i, \phi_i; \theta_r, \phi_r) \quad = \quad f(\theta_r, \phi_r; \theta_i, \phi_i)$$

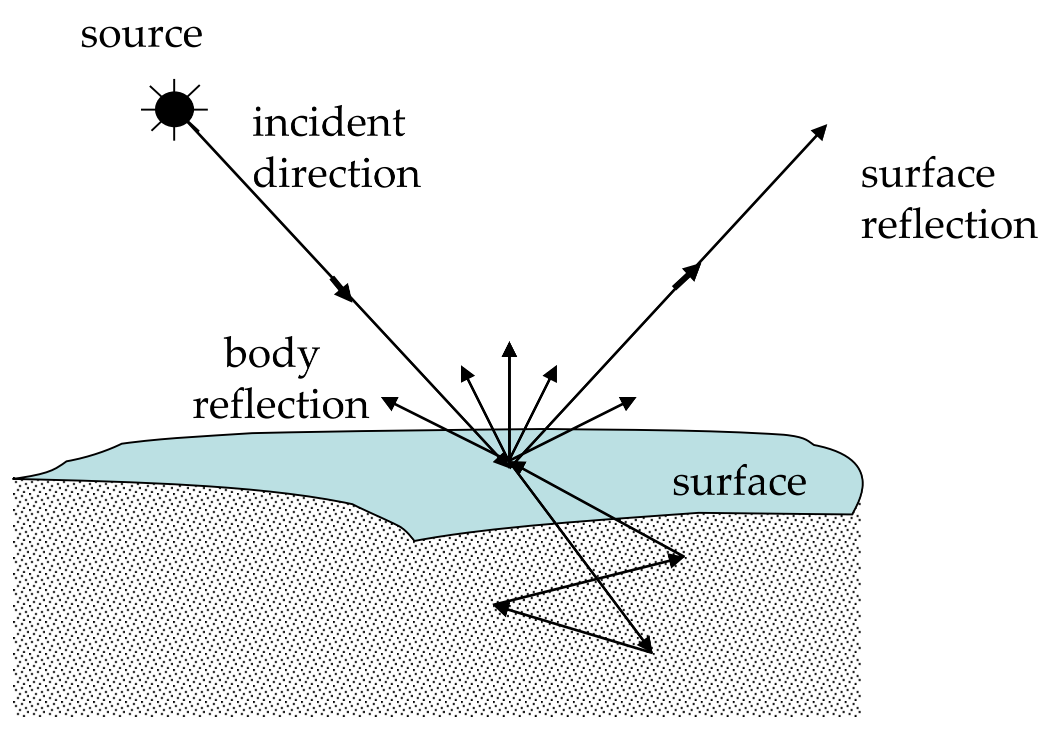
Isotropic BRDF and Anisotropic BRDF



[Westin 1992]

Anisotropic BRDF – more examples

Mechanisms of Reflection



Body Reflection:

Diffuse Reflection
Matte Appearance
Non-Homogeneous Medium
Clay, paper, etc

Surface Reflection:

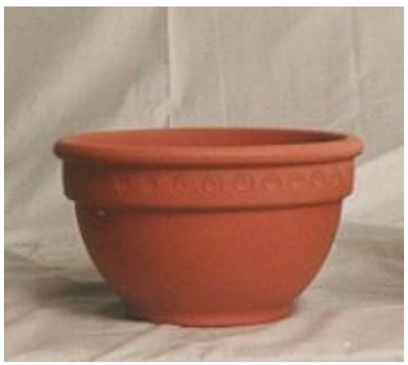
Specular Reflection
Glossy Appearance
Highlights
Dominant for Metals

Image Intensity = Body Reflection + Surface Reflection

Mechanisms of Surface Reflection

Body Reflection:

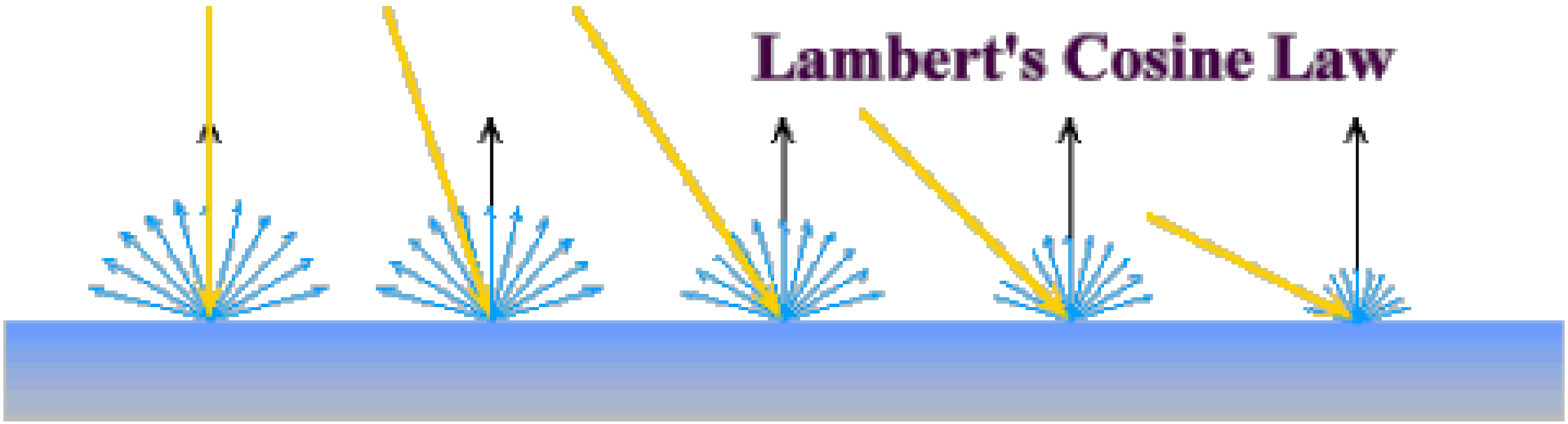
Diffuse Reflection
Matte Appearance
Non-Homogeneous Medium
Clay, paper, etc



Surface Reflection:

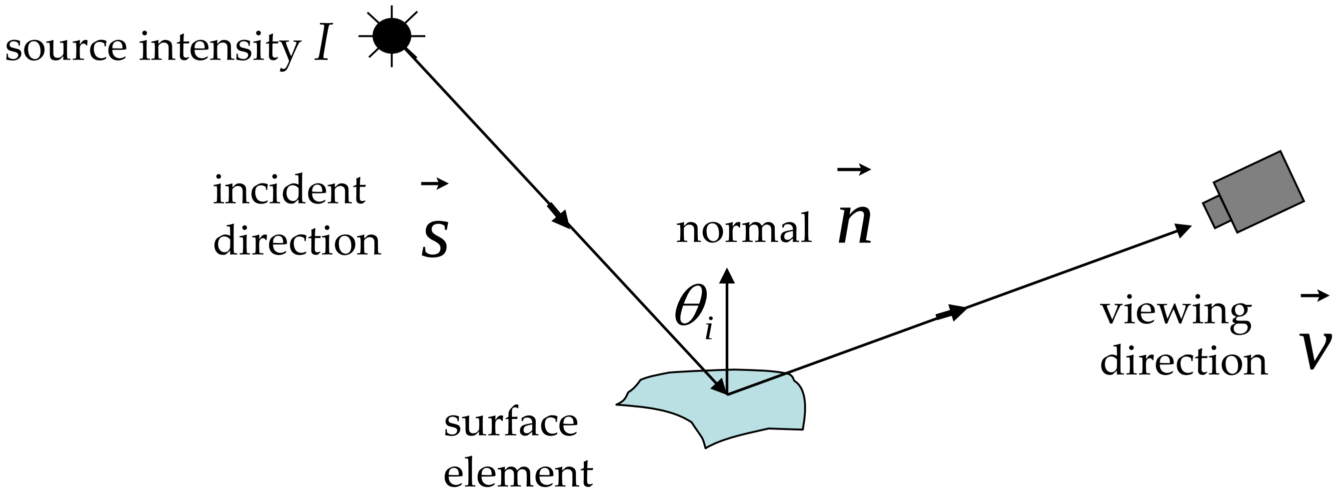
Specular Reflection
Glossy Appearance
Highlights
Dominant for Metals

Many materials exhibit both Reflections:



Lambert's Cosine Law

Diffuse Reflection and Lambertian BRDF



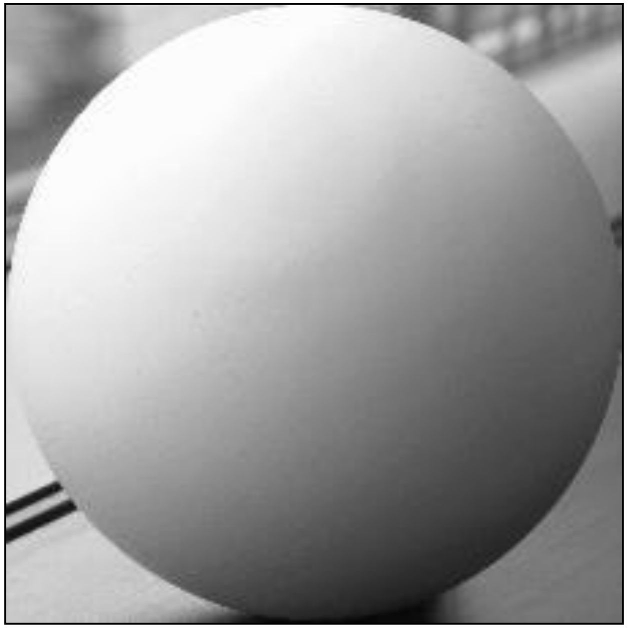
- Surface appears equally bright from ALL directions! (independent of $\vec{v}$)

- Lambertian BRDF is simply a constant : $f(\theta_i, \phi_i; \theta_r, \phi_r) = \dfrac{\rho_d}{\pi}$ albedo

- Surface Radiance : $L = \dfrac{\rho_d}{\pi} I \cos\theta_i = \dfrac{\rho_d}{\pi} I \; \vec{n} \,.\, \vec{s}$ source intensity

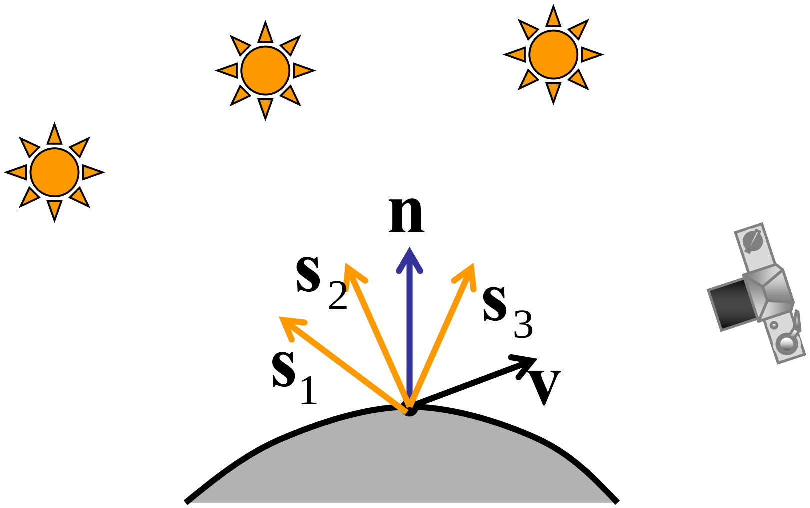
- Commonly used in Vision and Graphics!

Image Intensity and 3D Geometry



- Shading as a cue for shape reconstruction

Photometric Stereo



Lambertian case:

$$I = \frac{\rho}{\pi} kc \cos\theta_i = \rho\, \mathbf{n} \cdot \mathbf{s} \qquad \left(\frac{kc}{\pi} = 1\right)$$

Image irradiance:

$$I_1 = \rho\, \mathbf{n} \cdot \mathbf{s}_1$$
$$I_2 = \rho\, \mathbf{n} \cdot \mathbf{s}_2$$
$$I_3 = \rho\, \mathbf{n} \cdot \mathbf{s}_3$$

- We can write this in matrix form:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_2 \end{bmatrix} = \rho \begin{bmatrix} \mathbf{s}_1^T \\ \mathbf{s}_2^T \\ \mathbf{s}_3^T \end{bmatrix} \mathbf{n}$$

Solving the Equations

$$\underbrace{\begin{bmatrix} I_1 \\ I_2 \\ I_2 \end{bmatrix}}_{\substack{\mathbf{I} \\ 3\times 1}} = \underbrace{\begin{bmatrix} \mathbf{s}_1^T \\ \mathbf{s}_2^T \\ \mathbf{s}_3^T \end{bmatrix}}_{\substack{\mathbf{S} \\ 3\times 3}} \underbrace{\rho\,\mathbf{n}}_{\substack{\tilde{\mathbf{n}} \\ 3\times 1}}$$

$$\tilde{\mathbf{n}} = \mathbf{S}^{-1}\mathbf{I}$$

inverse

$$\rho = \left|\tilde{\mathbf{n}}\right|$$

$$\mathbf{n} = \frac{\tilde{\mathbf{n}}}{\left|\tilde{\mathbf{n}}\right|} = \frac{\tilde{\mathbf{n}}}{\rho}$$

More than Three Light Sources

- Get better results by using more lights

$$\begin{bmatrix} I_1 \\ \vdots \\ I_N \end{bmatrix} = \begin{bmatrix} \mathbf{s}_1^T \\ \vdots \\ \mathbf{s}_N^T \end{bmatrix} \rho\, \mathbf{n}$$

- Least squares solution:

$$\mathbf{I} = \mathbf{S}\tilde{\mathbf{n}} \qquad N \times 1 = \underline{(N \times 3)}(3 \times 1)$$

$$\mathbf{S}^T\mathbf{I} = \mathbf{S}^T\mathbf{S}\tilde{\mathbf{n}}$$

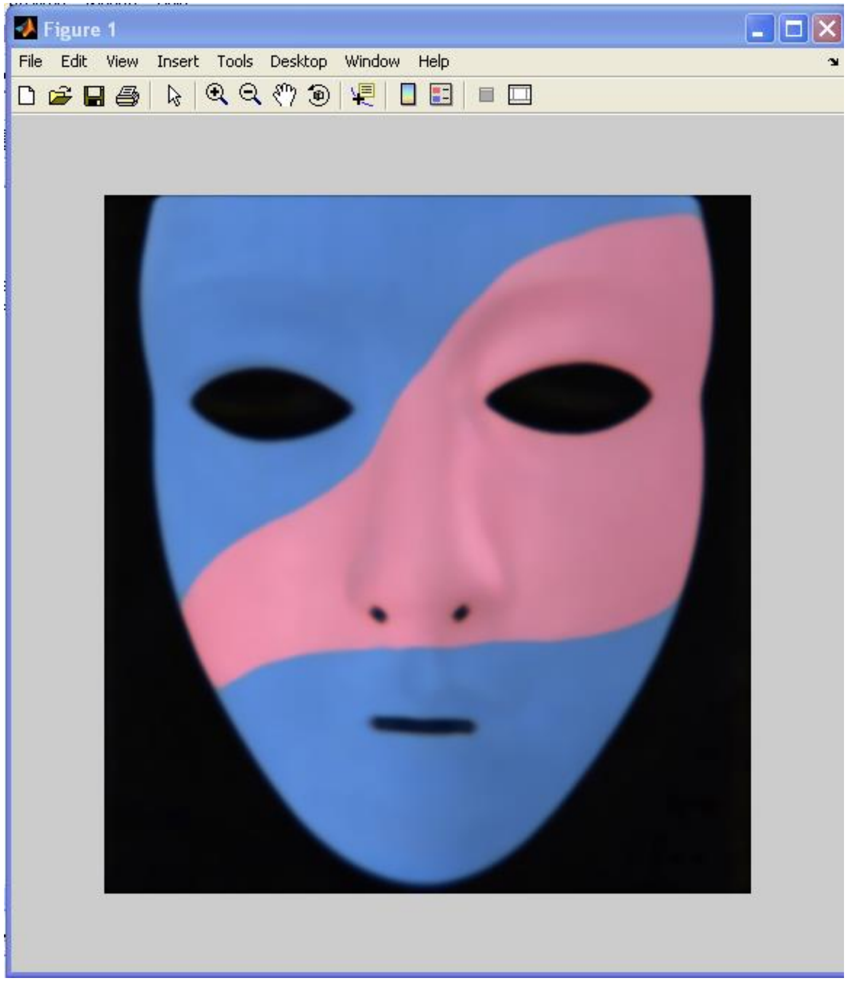
$$\tilde{\mathbf{n}} = \boxed{\left(\mathbf{S}^T\mathbf{S}\right)^{-1}\mathbf{S}^T}\,\mathbf{I}$$

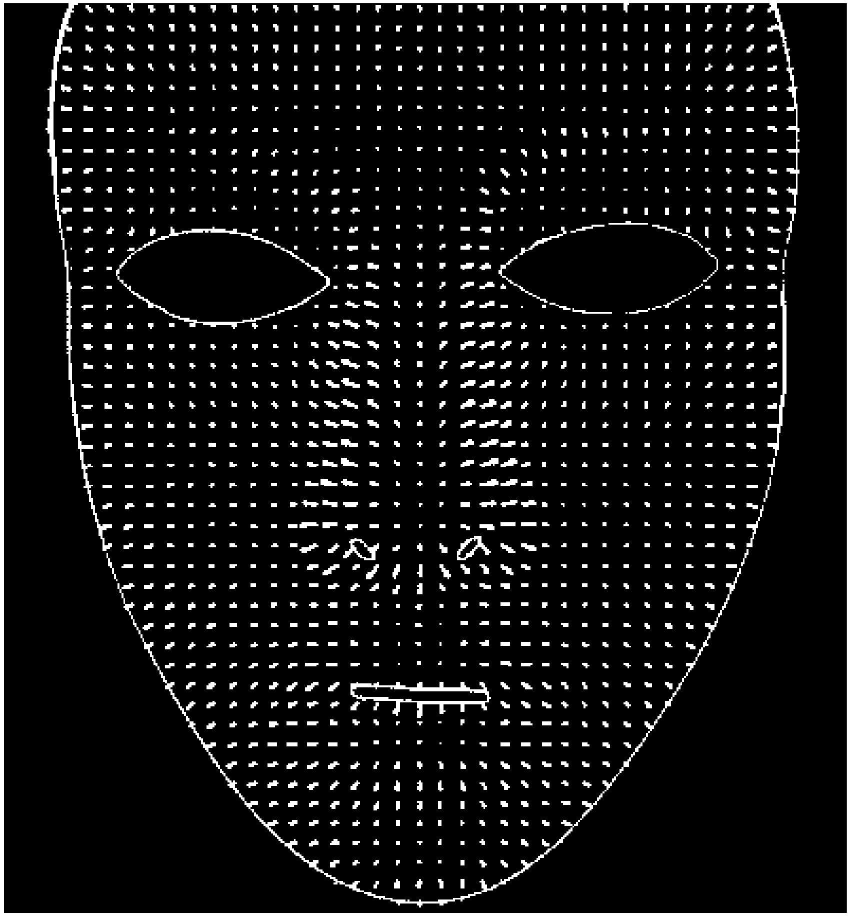
Moore-Penrose pseudo inverse

- Solve for $\rho, \mathbf{n}$ as before

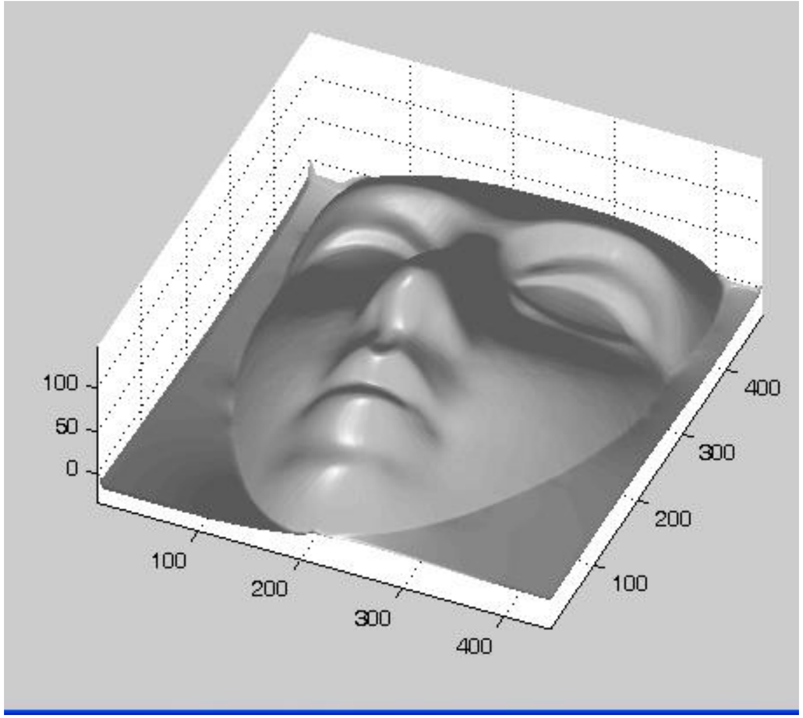
Lambertian Mask

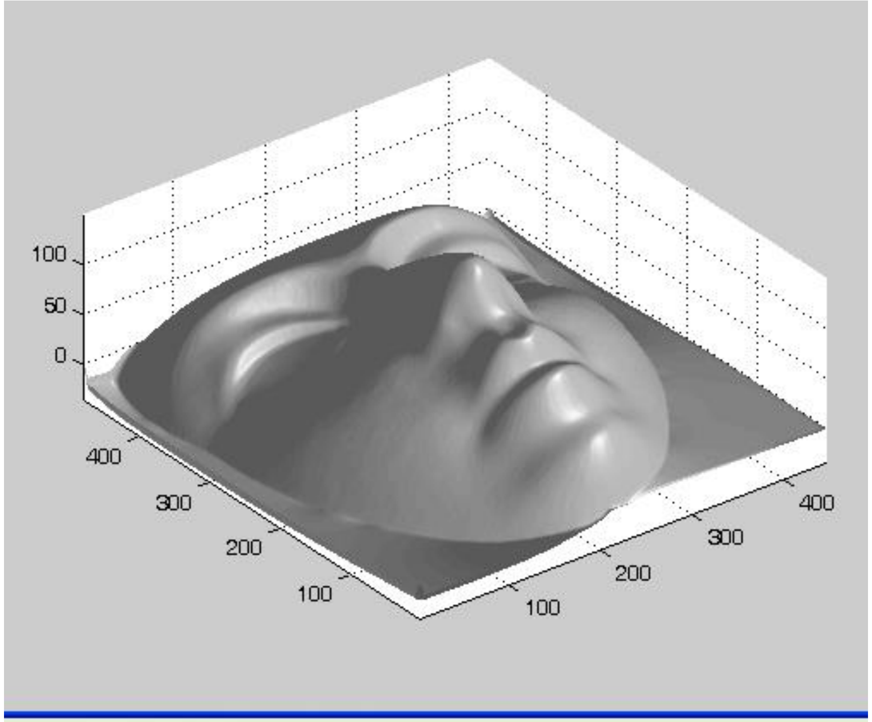
Results – Albedo and Surface Normal





Results – Shape of Mask





Results: Lambertian Toy

Results

1. Estimate light source directions
2. Compute surface normals
3. Compute albedo values
4. Estimate depth from surface normals
5. Relight the object (with original texture and uniform albedo)

White-out Conditions from an Overcast Sky

CAN'T perceive the shape of the snow covered terrain!

CAN perceive shape in regions lit by the street lamp!!

WHY?

Rendered Sphere with Lambertian BRDF

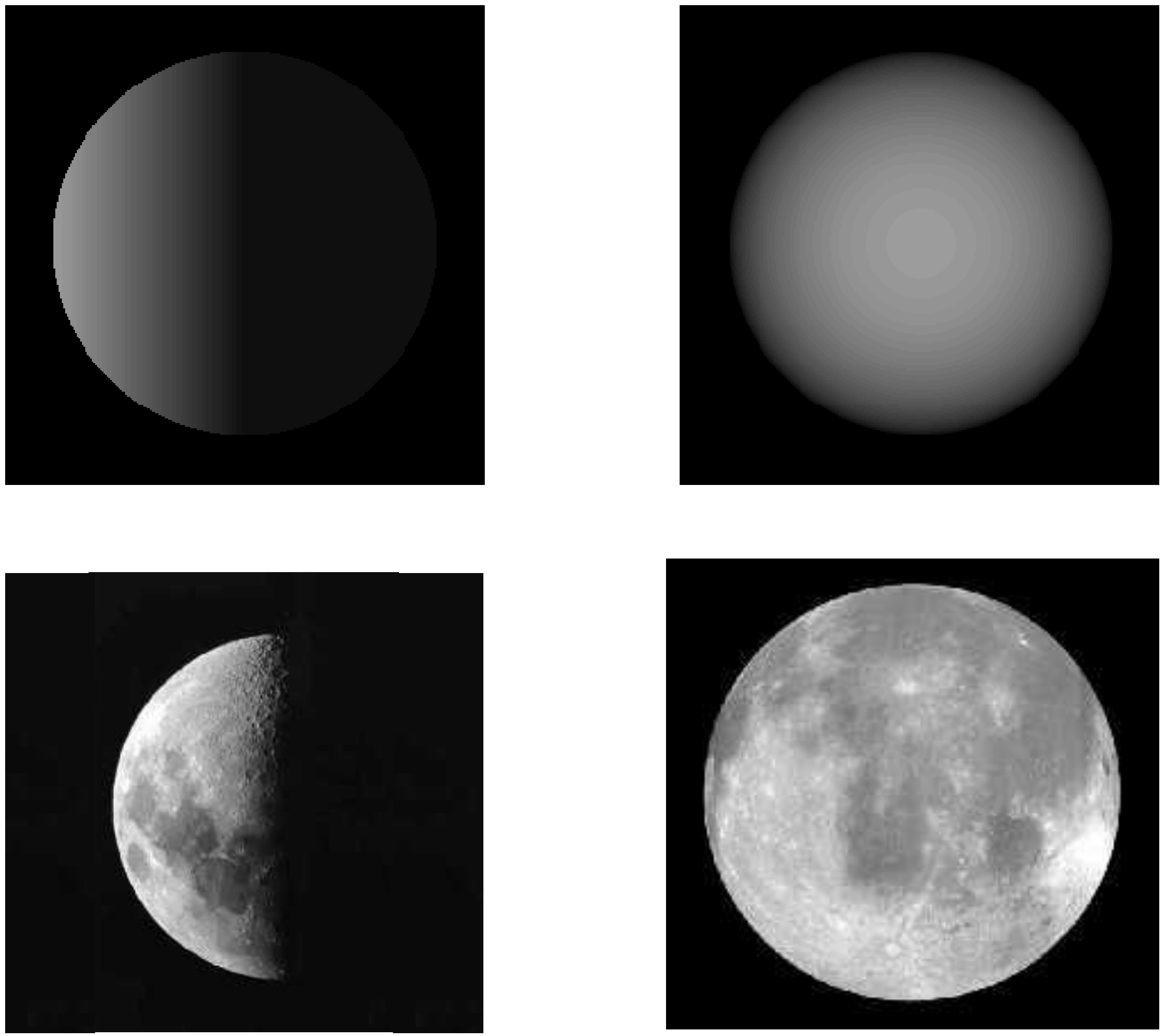
- Edges are dark (N.S = 0) when lit head-on
- See shading effects clearly.

Why does the Full Moon have a flat appearance?

- The moon appears matte (or diffuse)

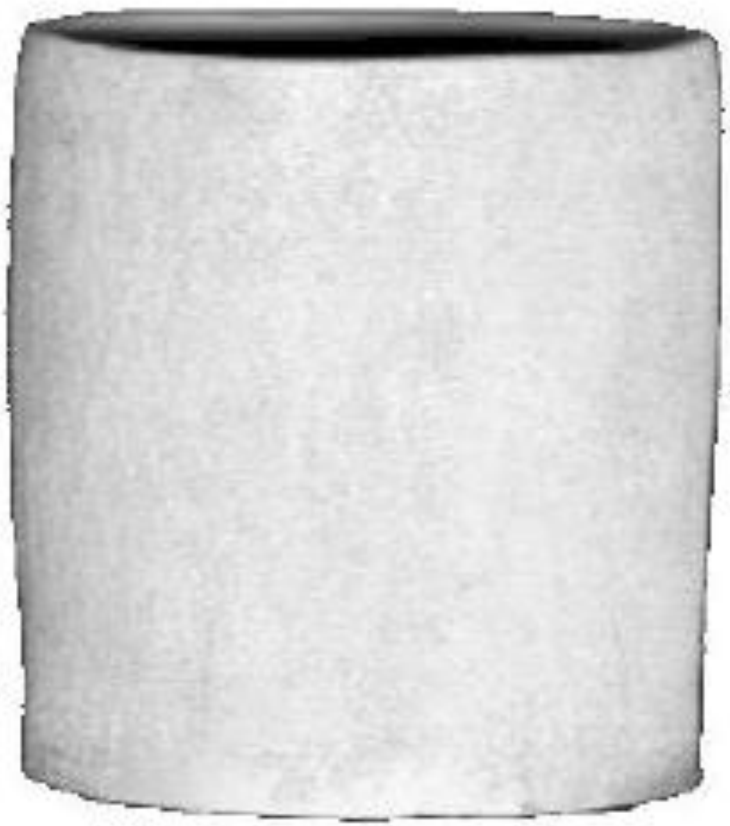
- But still, edges of the moon look bright (not close to zero) when illuminated by earth's radiance.

Why does the Full Moon have a flat appearance?



Lambertian Spheres and Moon Photos illuminated similarly

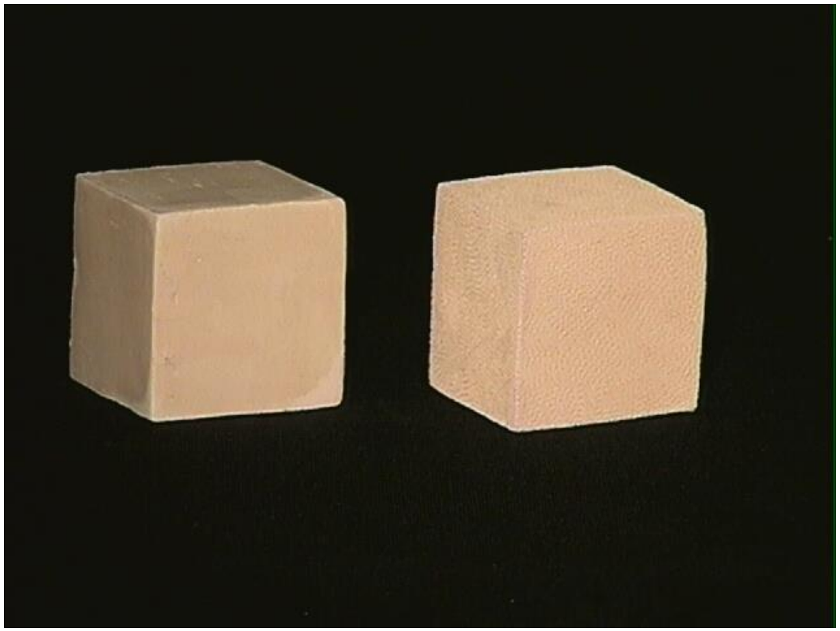
Surface Roughness Causes Flat Appearance

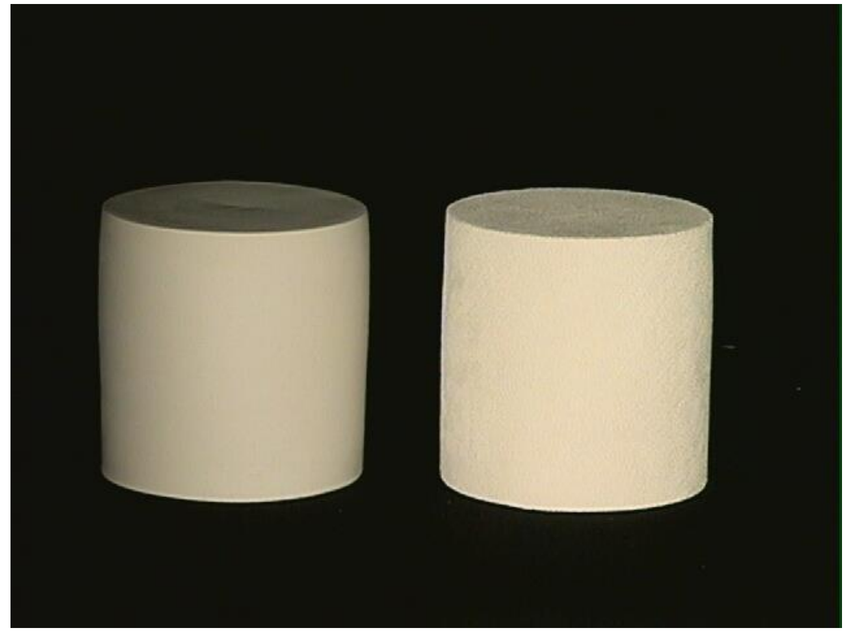


Actual Vase

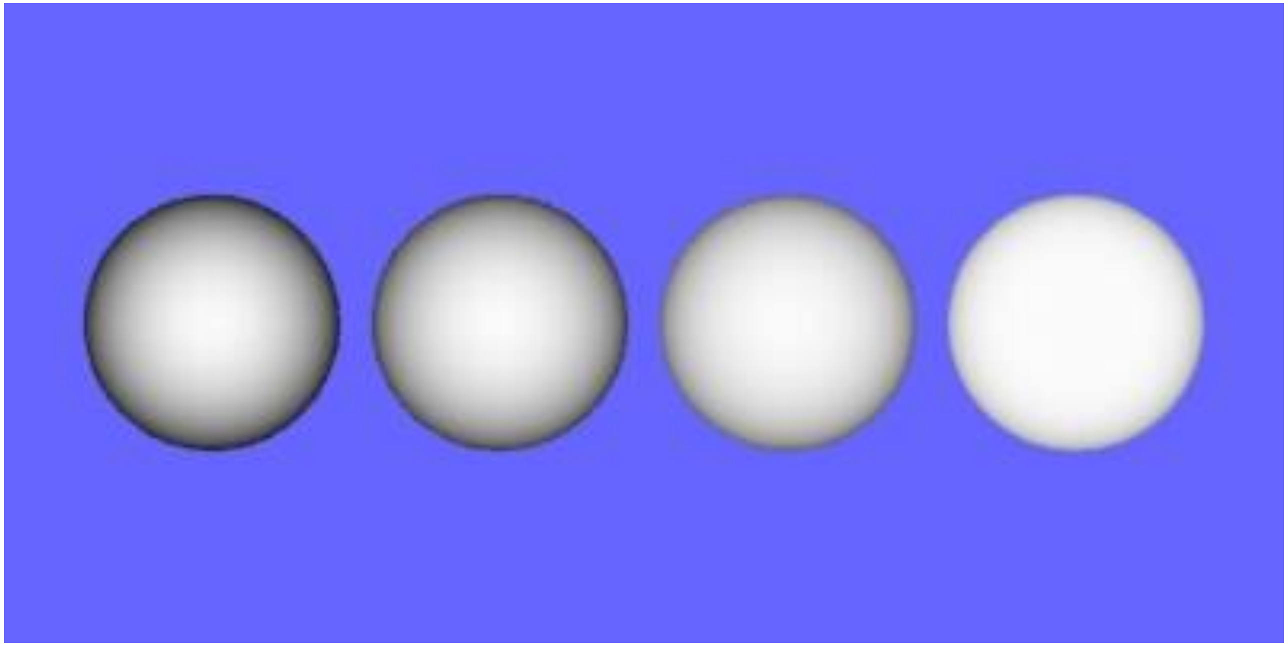
Lambertian Vase

Surface Roughness Causes Flat Appearance – More Examples





Surface Roughness Causes Flat Appearance



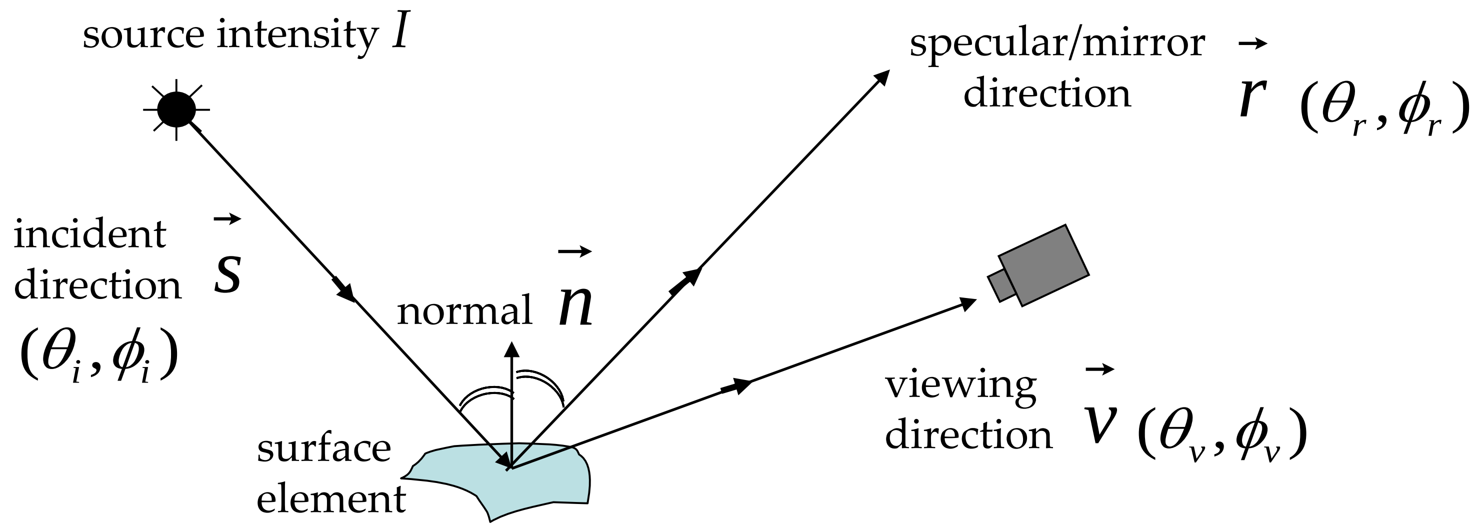
Increasing surface roughness →

Lambertian model

Valid for only SMOOTH MATTE surfaces.

Bad for ROUGH MATTE surfaces.

Specular Reflection and Mirror BRDF



- Very smooth surface.
- All incident light energy reflected in a SINGLE direction. (only when $\vec{v} = \vec{r}$)
- Mirror BRDF is simply a double-delta function :

specular albedo

$$f(\theta_i, \phi_i; \theta_v, \phi_v) = \rho_s\ \delta(\theta_i - \theta_v)\ \delta(\phi_i + \pi - \phi_v)$$

- Surface Radiance : $L = I\ \rho_s\ \delta(\theta_i - \theta_v)\ \delta(\phi_i + \pi - \phi_v)$

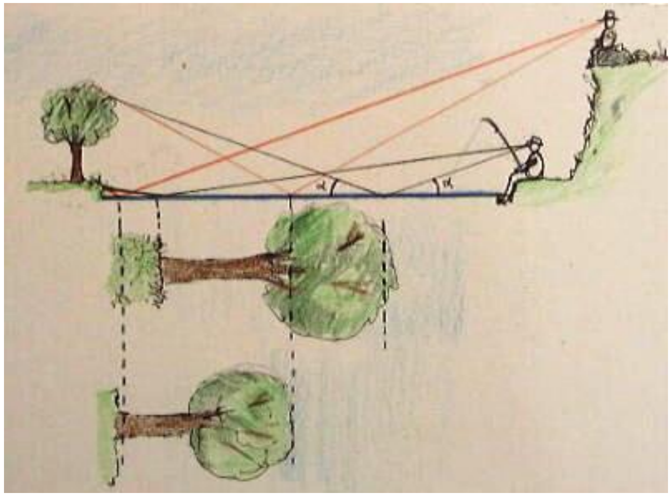
Specular Reflections in Nature



It's surprising how long the reflections are when viewed sitting on the river bank.

Compare sizes of objects and their reflections!

The reflections when seen from a lower view point are always longer than when viewed from a higher view point.



Specular Reflections in Nature

The reflections of bright objects have better perceived contrast.

Intensity of reflected light is a fraction of the direct light –
[Fresnel term (derivation in a later class)]

Glossy Surfaces

- Delta Function too harsh a BRDF model
  (valid only for highly polished mirrors and metals).

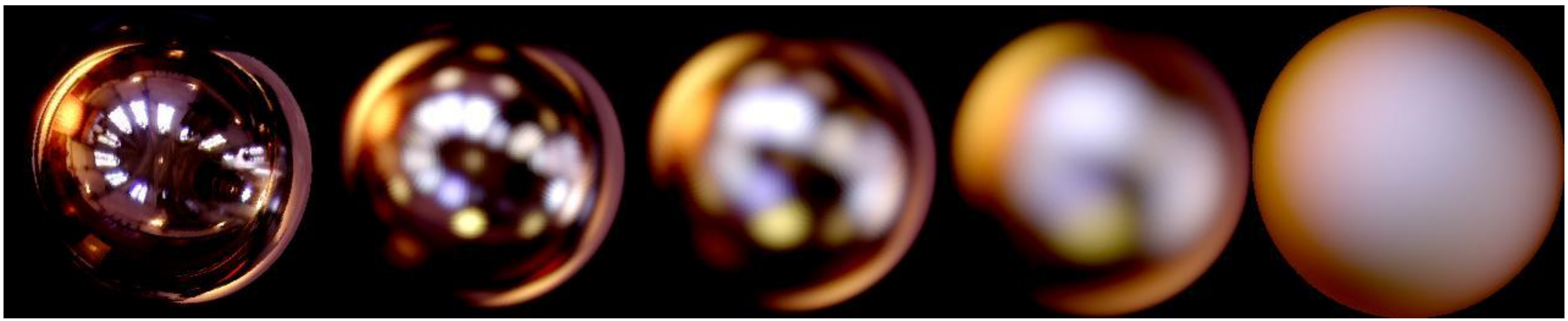
- Many glossy surfaces show broader highlights in addition to mirror reflection.

- Surfaces are not perfectly smooth – they show micro-surface geometry (roughness).

- Example Models : Phong model

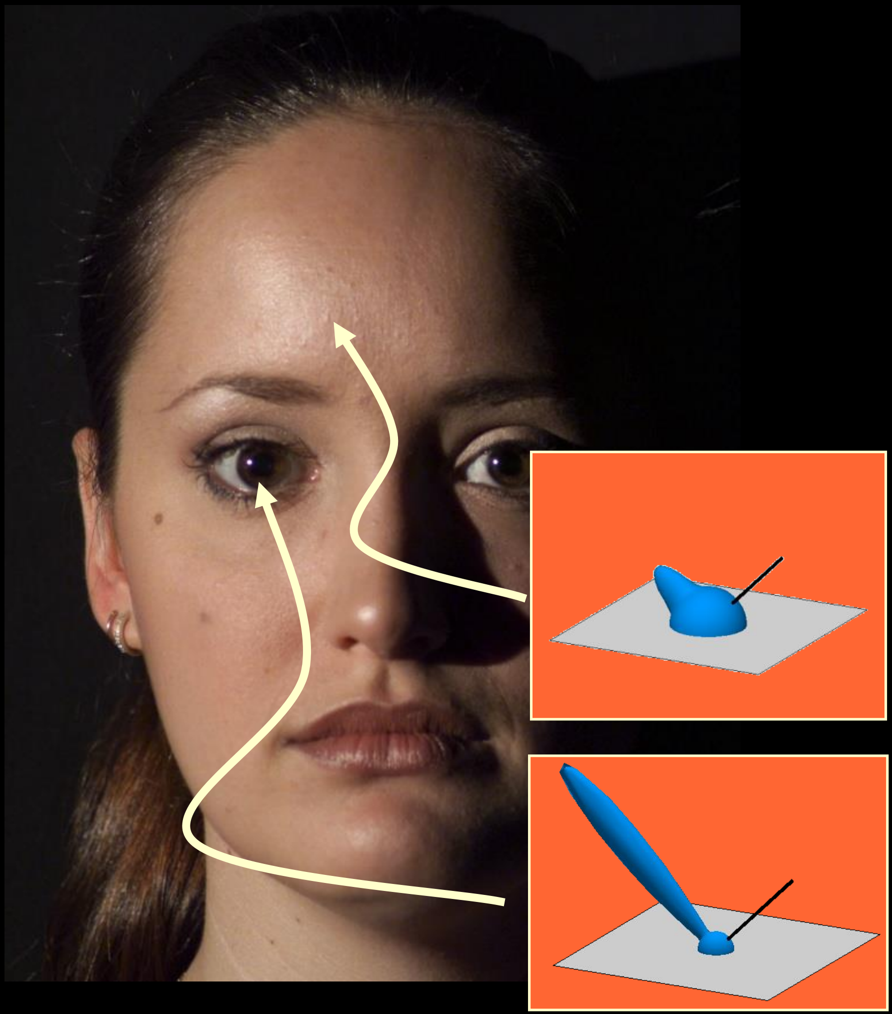
  Torrance Sparrow model

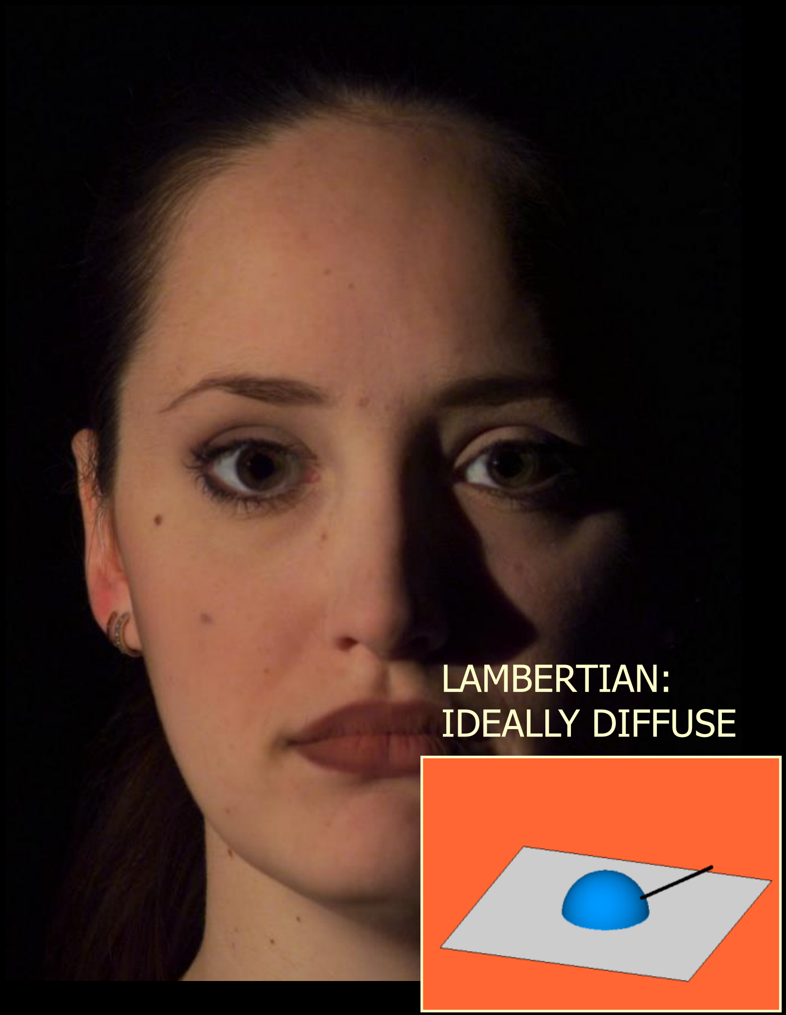
Blurred Highlights and Surface Roughness

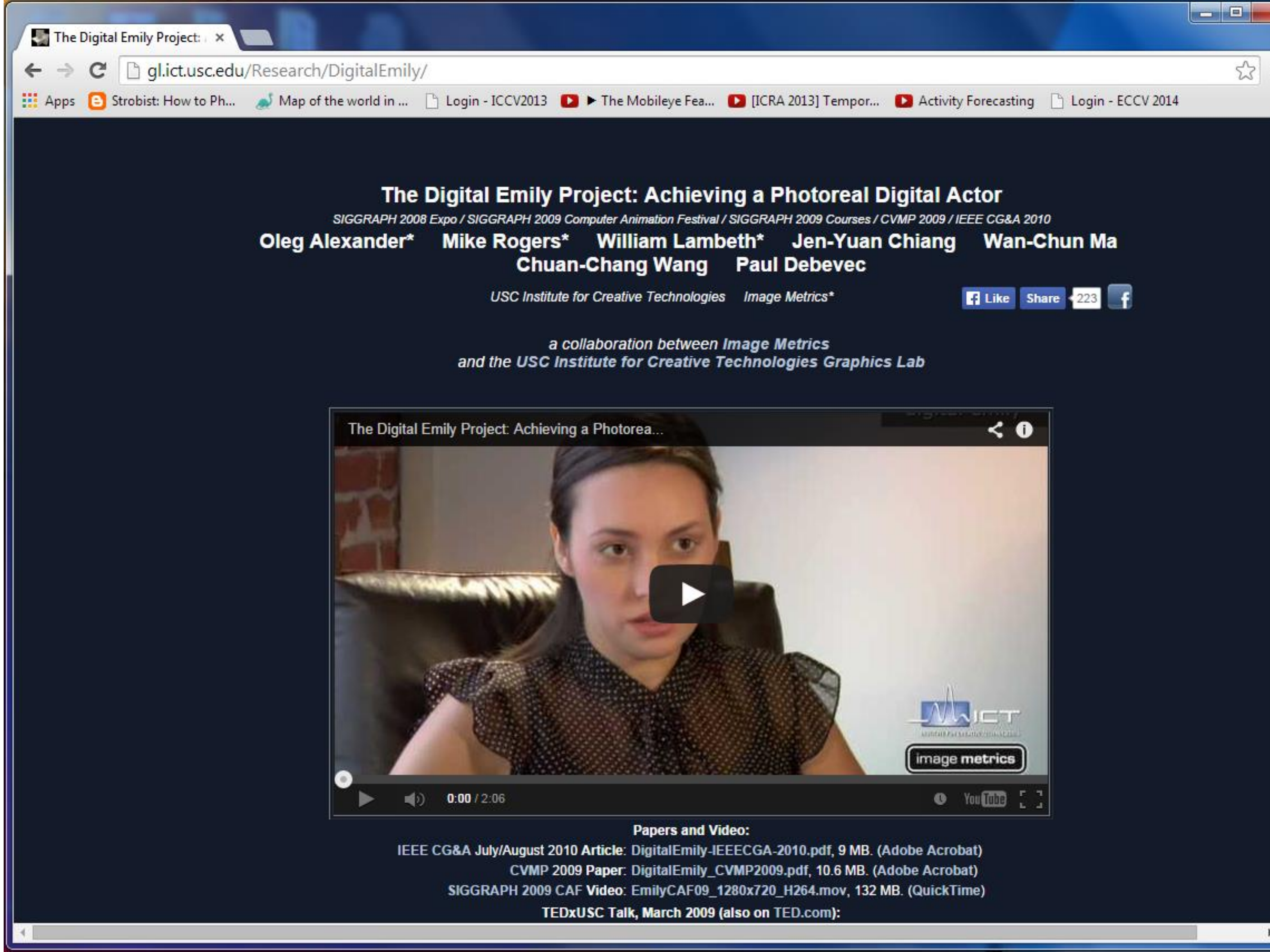


Roughness

Conventional 3D Reconstruction: Restrictive Assumptions






The Digital Emily Project:
gl.ict.usc.edu/Research/DigitalEmily/
Apps
Strobist: How to Ph...
Map of the world in ...
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The Digital Emily Project: Achieving a Photoreal Digital Actor
SIGGRAPH 2008 Expo / SIGGRAPH 2009 Computer Animation Festival / SIGGRAPH 2009 Courses / CVMP 2009 / IEEE CG&A 2010
Oleg Alexander* Mike Rogers* William Lambeth* Jen-Yuan Chiang Wan-Chun Ma
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Papers and Video:
IEEE CG&A July/August 2010 Article: DigitalEmily-IEEECGA-2010.pdf, 9 MB. (Adobe Acrobat)
CVMP 2009 Paper: DigitalEmily_CVMP2009.pdf, 10.6 MB. (Adobe Acrobat)
SIGGRAPH 2009 CAF Video: EmilyCAF09_1280x720_H264.mov, 132 MB. (QuickTime)
TEDxUSC Talk, March 2009 (also on TED.com):

Papers to Read

Shape and Materials by Example: A Photometric Stereo Approach

http://grail.cs.washington.edu/projects/sam/

Helmholtz Stereopsis

http://www.eecs.harvard.edu/~zickler/helmholtz.html

Specularity Removal and Dichromatic Editing

http://www.eecs.harvard.edu/~zickler/dichromaticediting.html

Color Subspaces as Photometric Invariants

http://www.eecs.harvard.edu/~zickler/projects/colorsubspaces.html