Materials and Surface Appearance

Thanks to Shree Nayar, Ravi Ramamoorthi, Pat Hanrahan

Surface Appearance

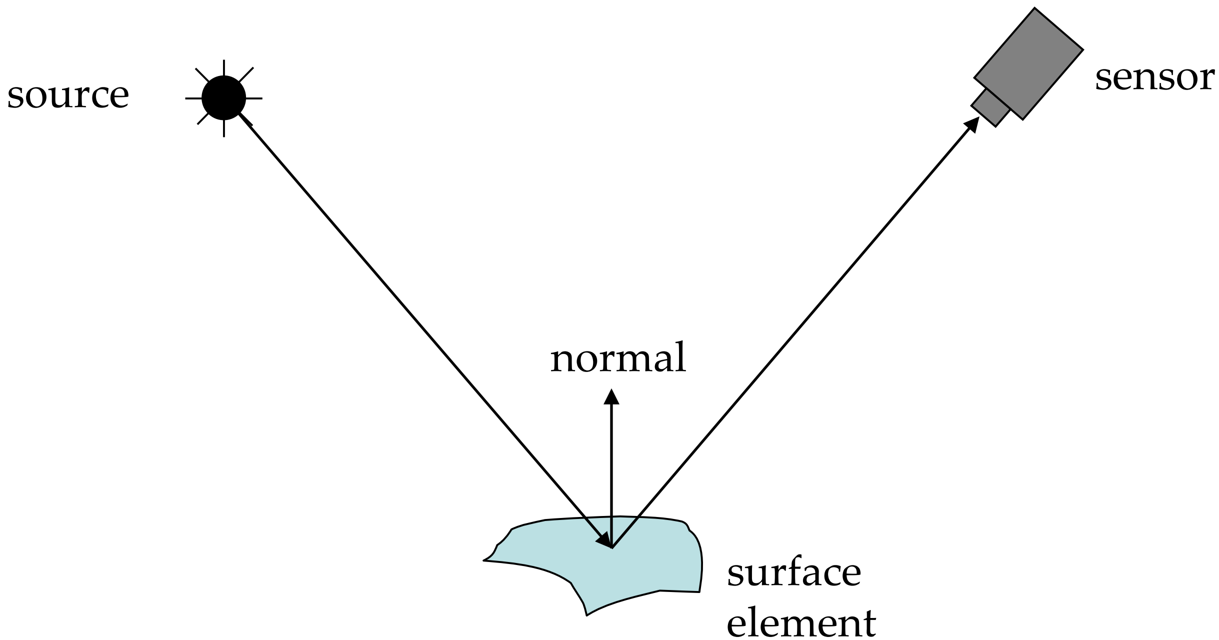
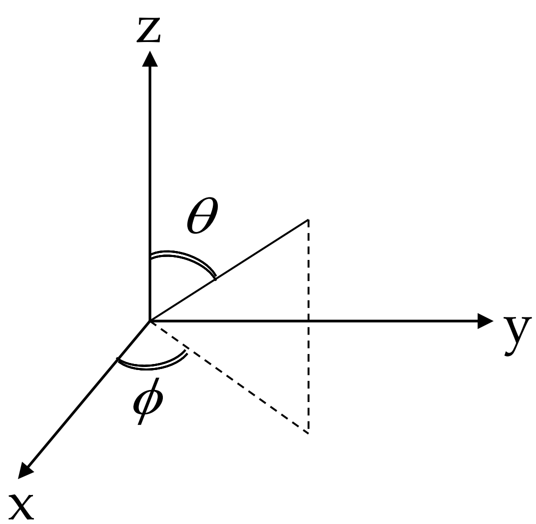
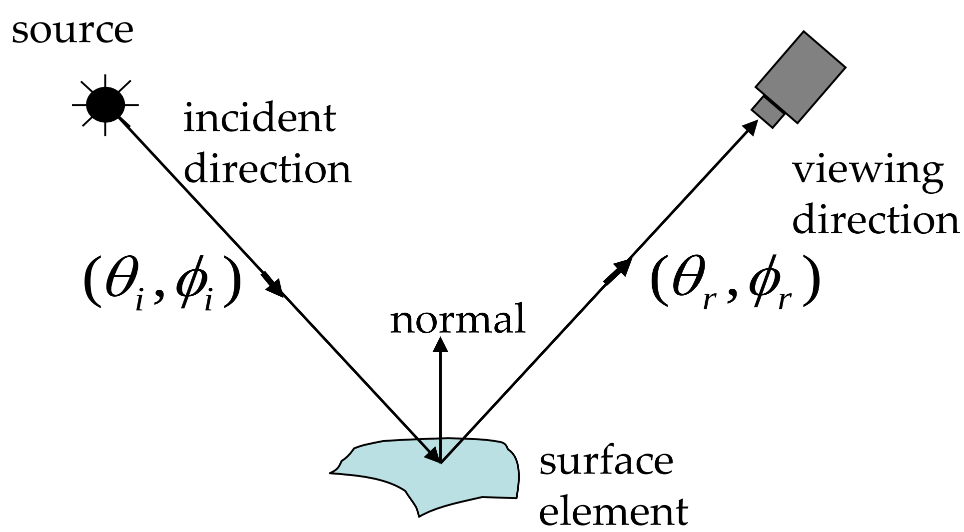


Image intensities = f (normal, surface reflectance, illumination)

Surface Reflection depends on both the viewing and illumination direction.

BRDF: Bidirectional Reflectance Distribution Function



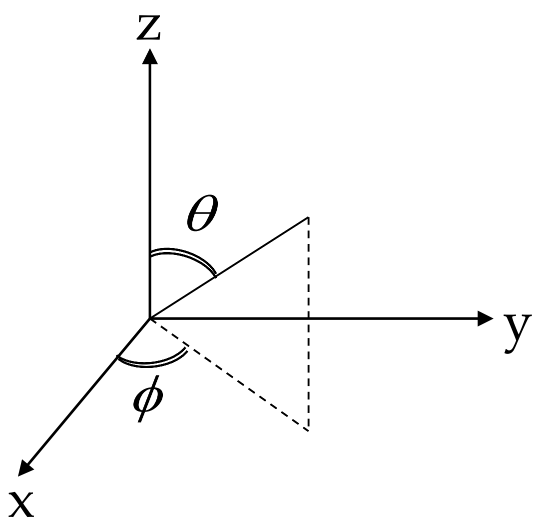


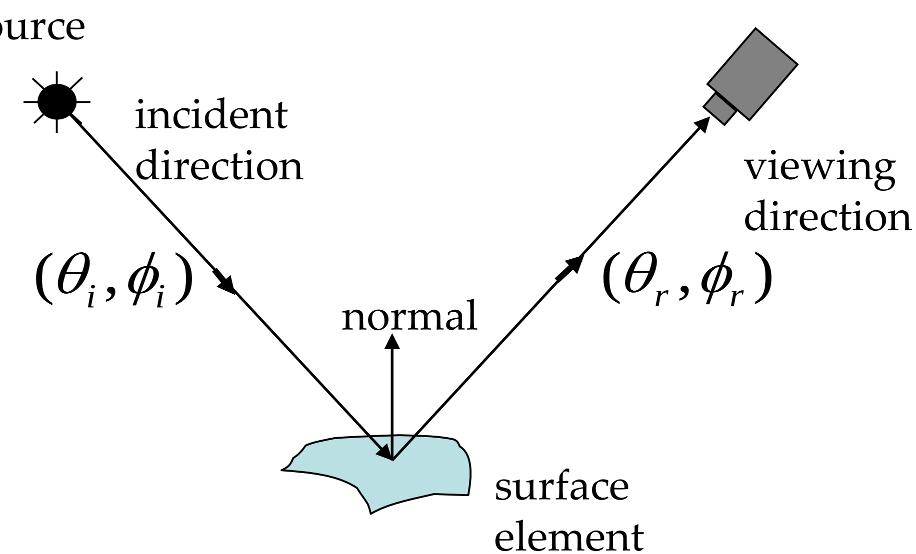
$E^{surface}(\theta_i, \phi_i)$ Irradiance at Surface in direction (θ_i, ϕ_i)

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

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

Important Properties of BRDFs





- Rotational Symmetry:

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

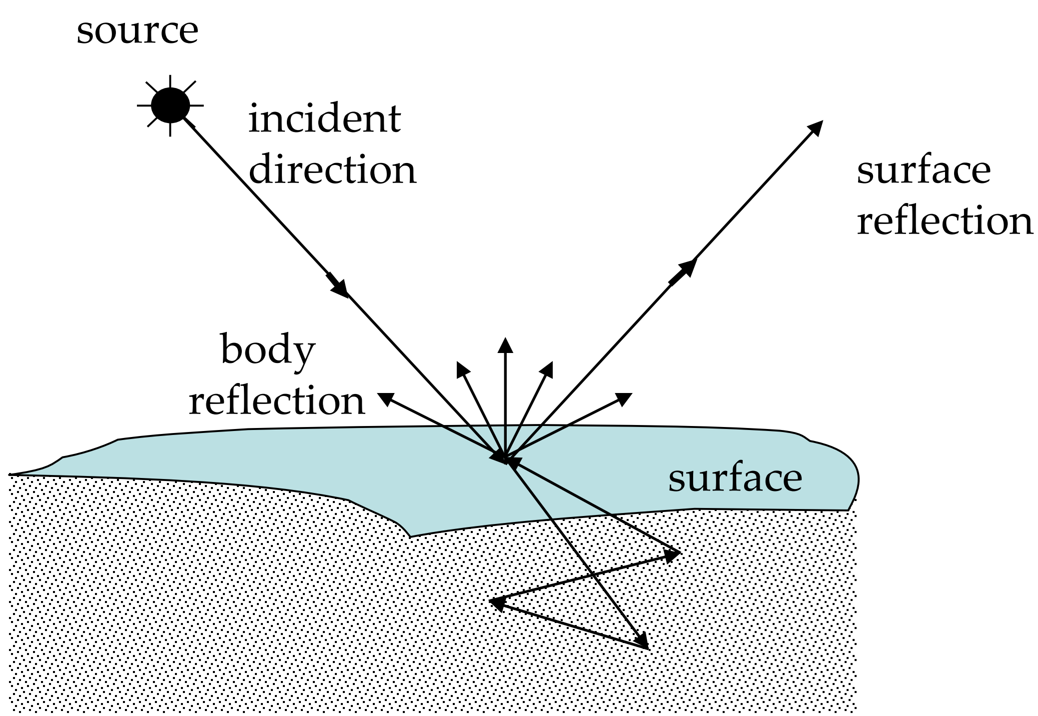
BRDF is only a function of 3 variables : $f(\theta_i, \theta_r, \phi_i - \phi_r)$

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

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

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

Mechanisms of Surface Reflection



Body Reflection:

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

Surface Reflection:

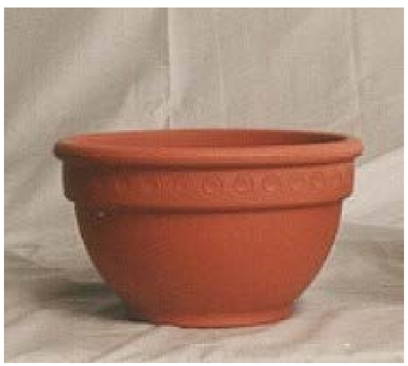
- Specular Reflection
- Glossy Appearance
- Highlights
- Dominant for Metals

Image Intensity = Body Reflection + Surface Reflection

Mechanisms of Surface Reflection

Body Reflection:

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

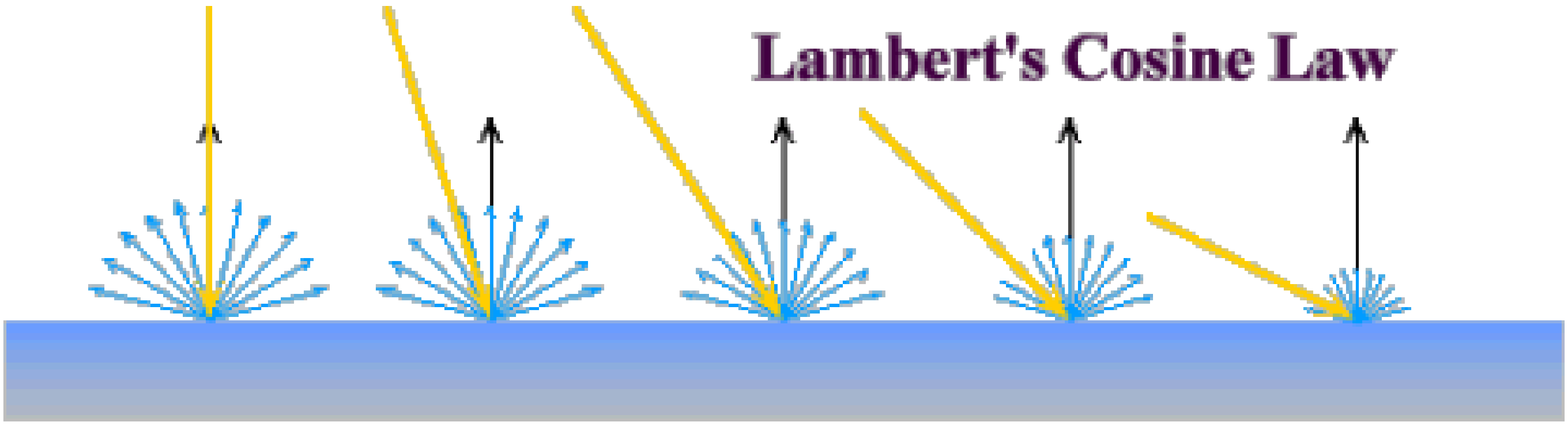


Surface Reflection:

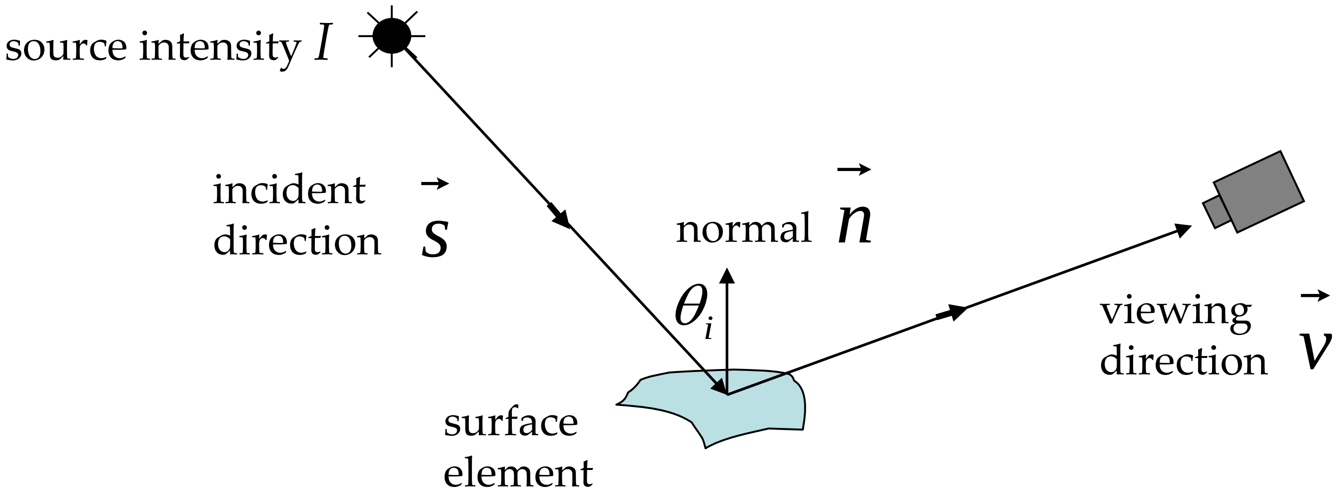
Specular Reflection
Glossy Appearance
Highlights
Dominant for Metals

Many materials exhibit both Reflections:

Diffuse Reflection and Lambertian BRDF



Diffuse Reflection and Lambertian BRDF



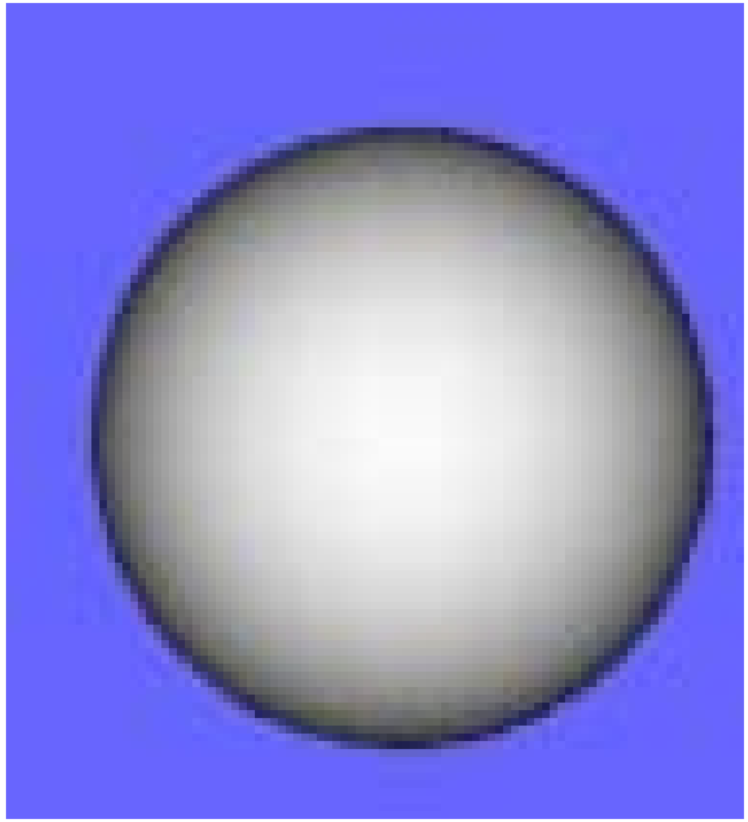
- Surface appears equally bright from ALL directions! (independent of $\vec{v}$)

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

- Surface Radiance : $L = \frac{\rho_d}{\pi} I \cos\theta_i = \frac{\rho_d}{\pi} I \; \vec{n} \cdot \vec{s}$ (I → source intensity)

- Commonly used in Vision and Graphics!

Rendered Sphere with Lambertian BRDF



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

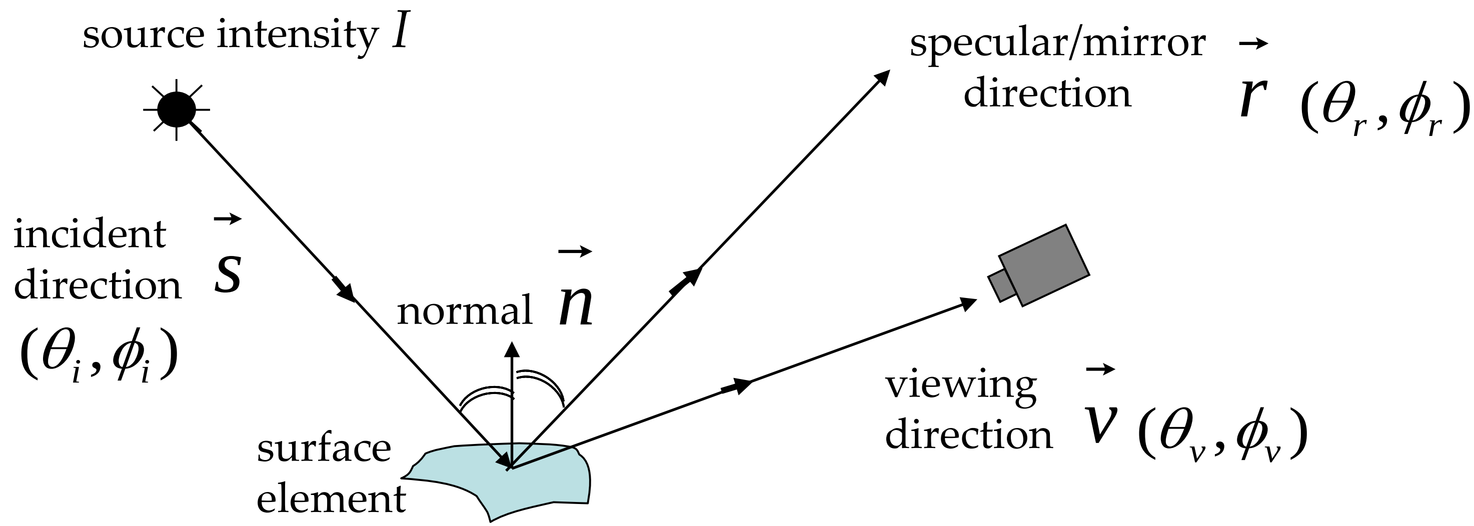
White-out Conditions from an Overcast Sky

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

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

WHY?

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

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

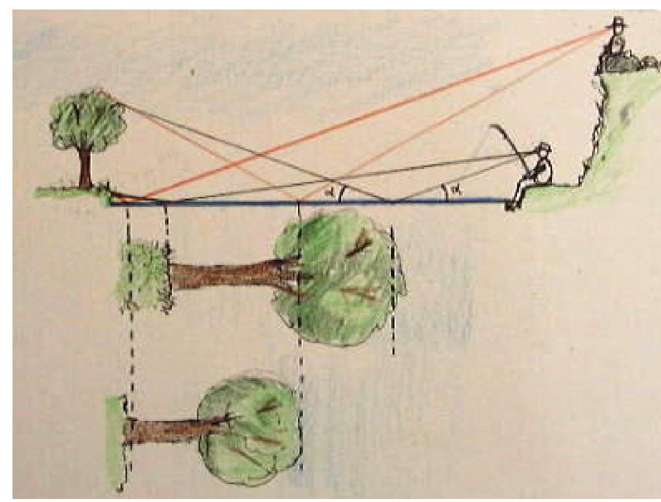
- Surface Radiance : $L = I\ \rho_s\ \delta(\theta_i - \theta_v)\ \delta(\phi_i + \pi - \phi_v)$

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

Glossy Surfaces

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

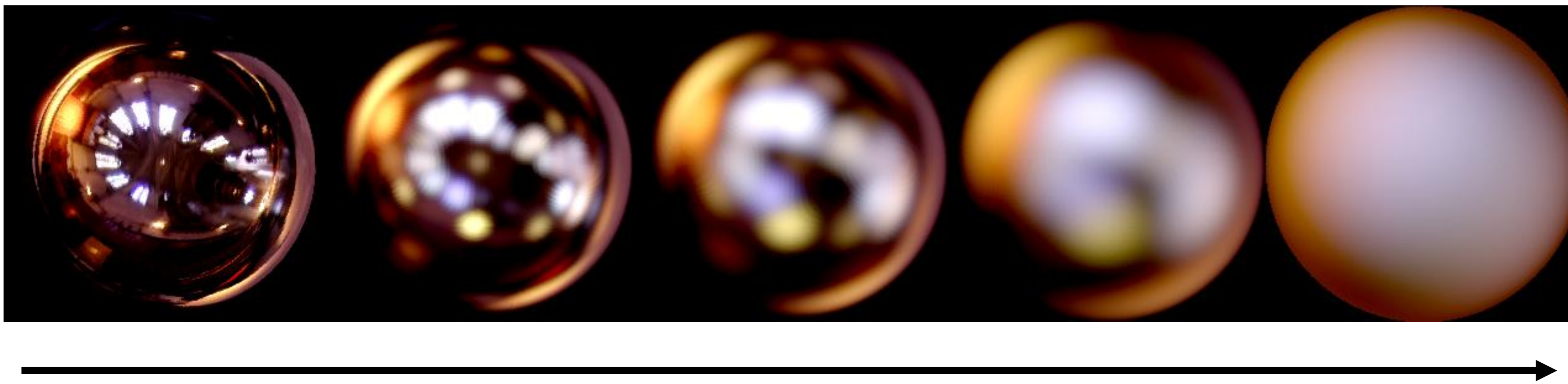
- Many glossy surfaces show broader highlights in addition to mirror reflection.


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

- Example Models : Phong model

  Torrance Sparrow model

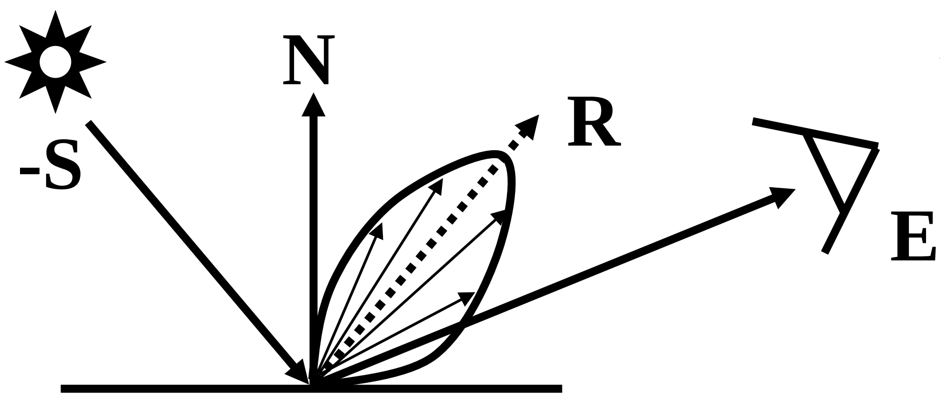
Blurred Highlights and Surface Roughness



Roughness

Phong Model: An Empirical Approximation

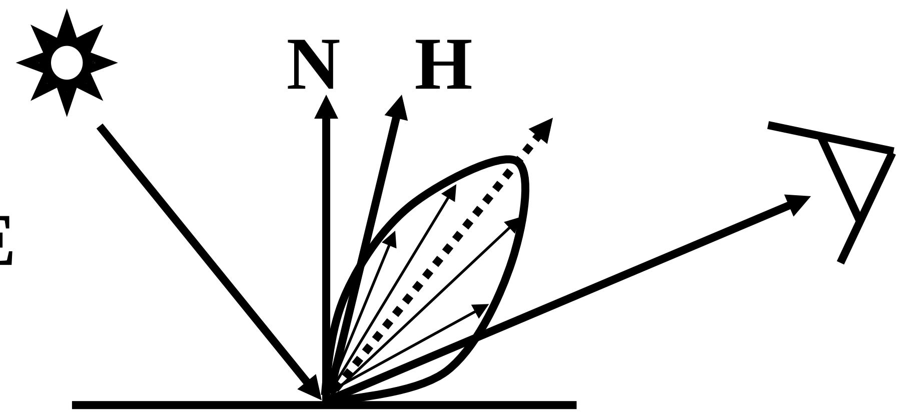
- How to model the angular falloff of highlights:



$$L = I\ \rho_s\ (R.E)^{n_{shiny}}$$

$$R = -S + 2(N.S)N$$

Phong Model



$$L = I\ \rho_s\ (N.H)^{n_{shiny}}$$

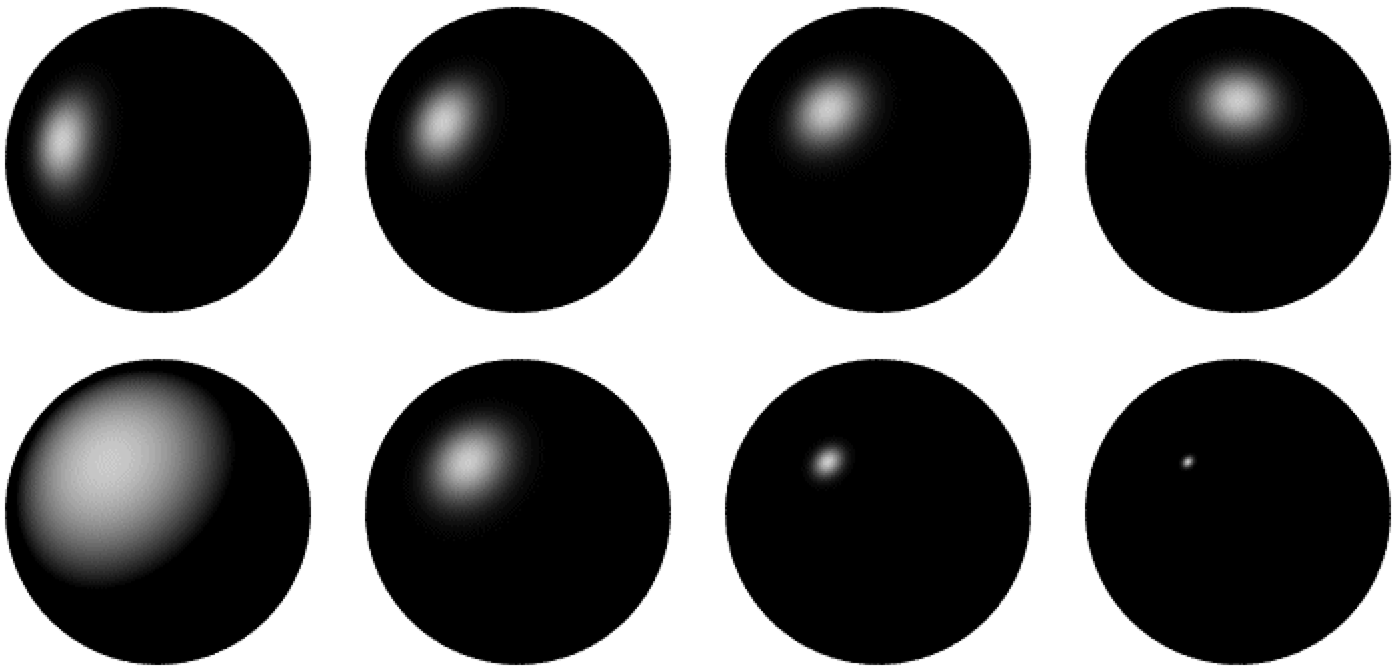
$$H = (E+S)/2$$

Blinn-Phong Model

- Sort of works, easy to compute
- But not physically based (no energy conservation and reciprocity).
- Very commonly used in computer graphics.

Phong Examples

- These spheres illustrate the Phong model as *lighting direction* and n_{shiny} are varied:



Those Were the Days

- "In trying to improve the quality of the synthetic images, we do not expect to be able to display the object exactly as it would appear in reality, with texture, overcast shadows, etc. We hope only to display an image that approximates the real object closely enough to provide a certain degree of realism."

  – Bui Tuong Phong, 1975

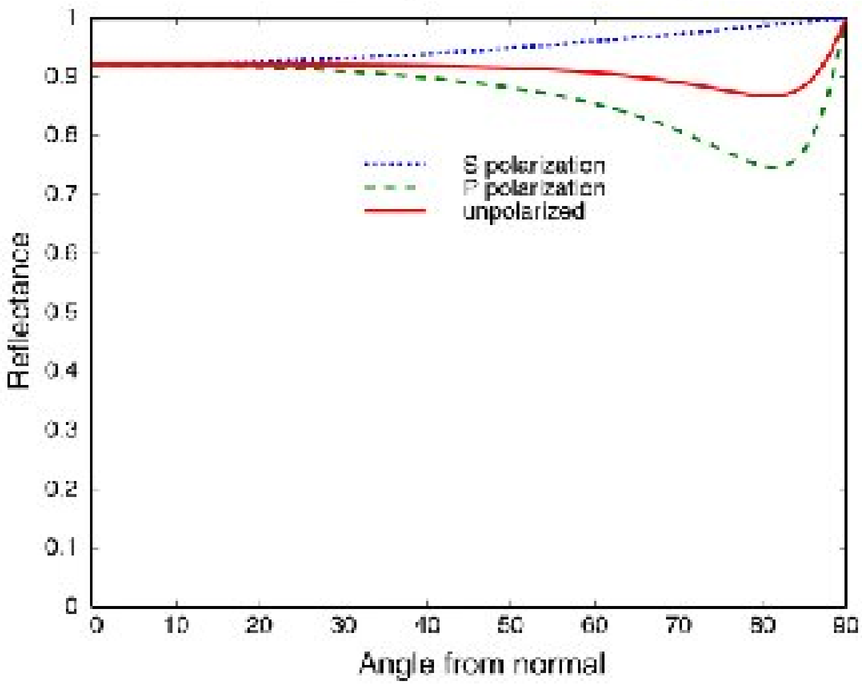
Experiment

Reflections from a shiny floor

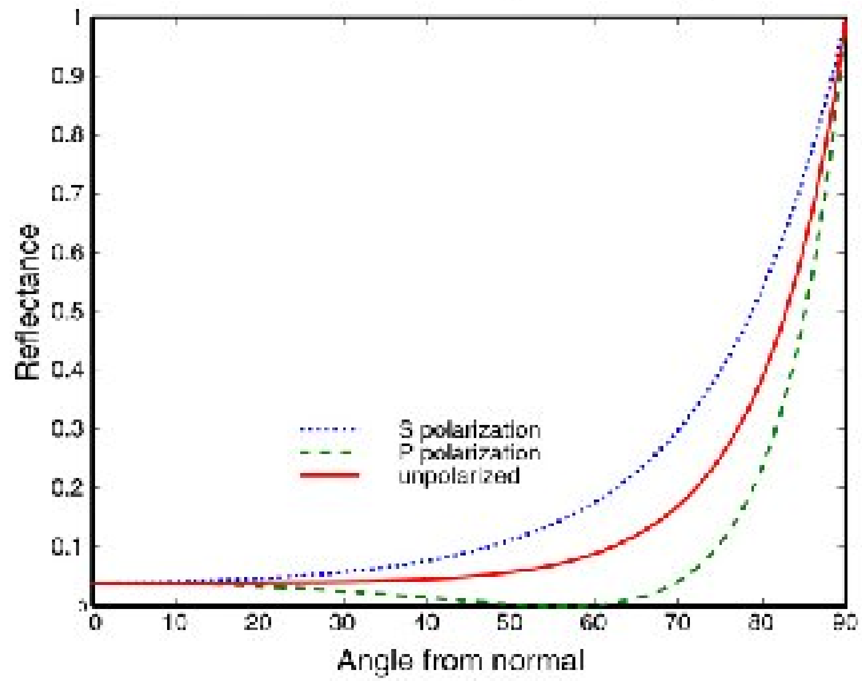
From Lafortune, Foo, Torrance, Greenberg, SIGGRAPH 97

Fresnel Reflectance

Metal (Aluminum)



Dielectric (N=1.5)

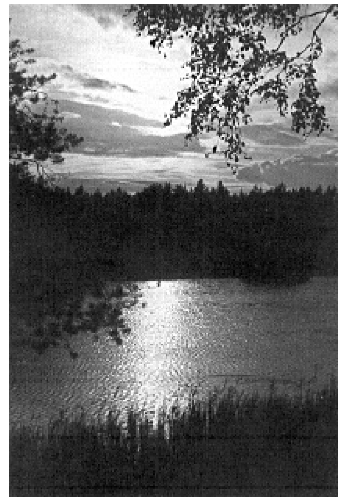


Gold F(0)=0.82
Silver F(0)=0.95

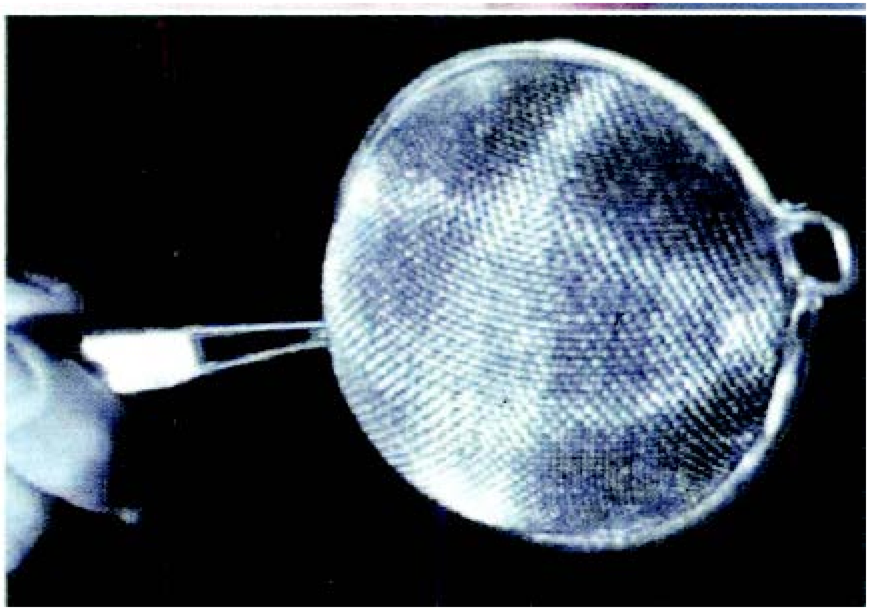
Glass n=1.5 F(0)=0.04
Diamond n=2.4 F(0)=0.15

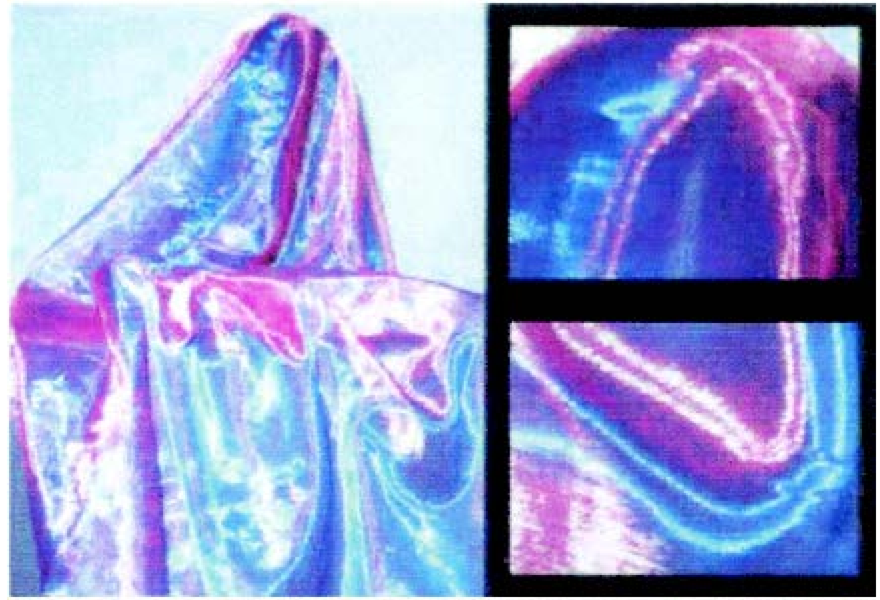
Schlick Approximation $F(\theta) = F(0) + (1 - F(0))(1 - \cos\theta)^5$

Reflections on water surfaces - Glittering



Split off-specular Reflections in Woven Surfaces



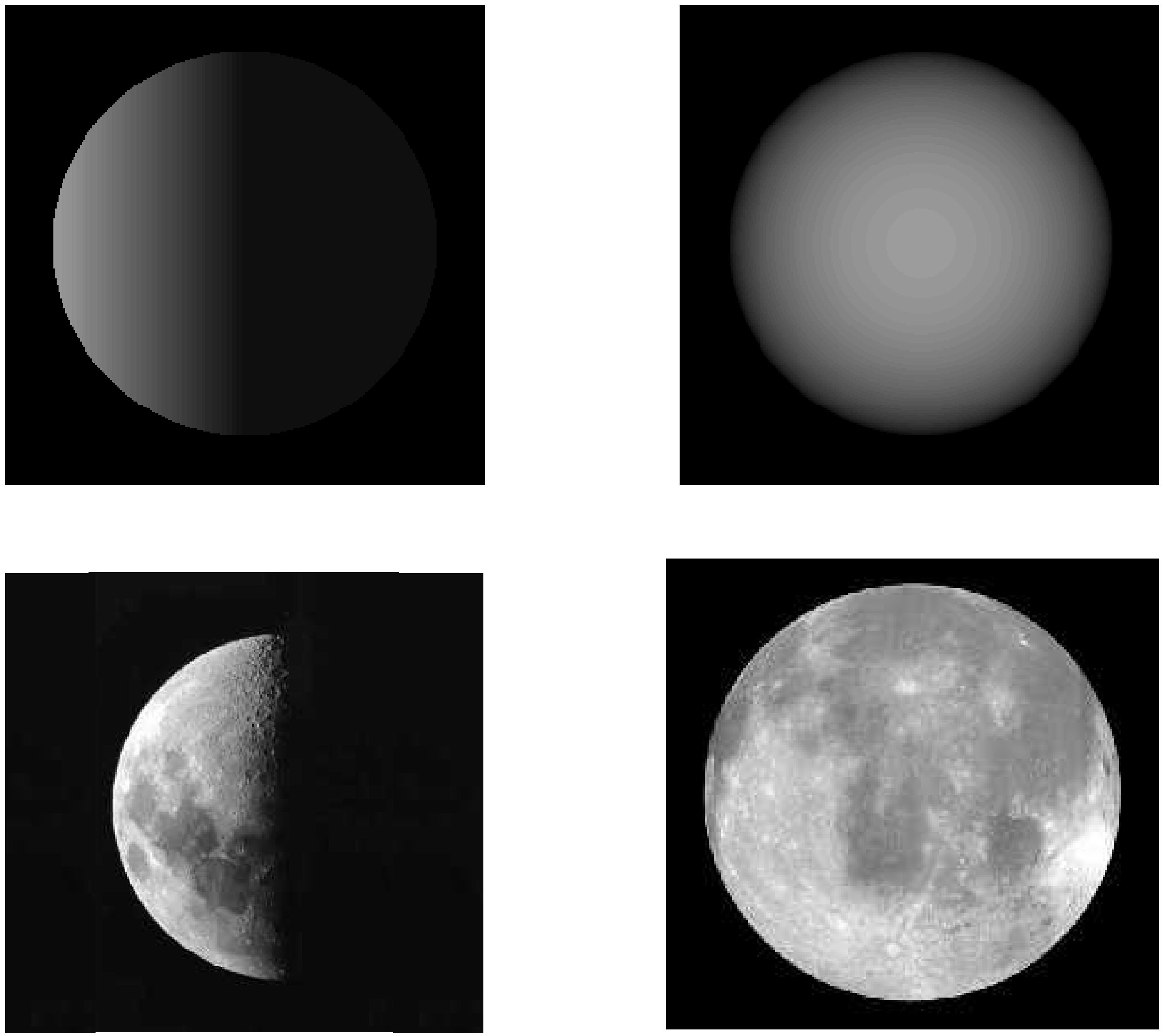


Why does the Full Moon have a flat appearance?

- The moon appears matte (or diffuse)

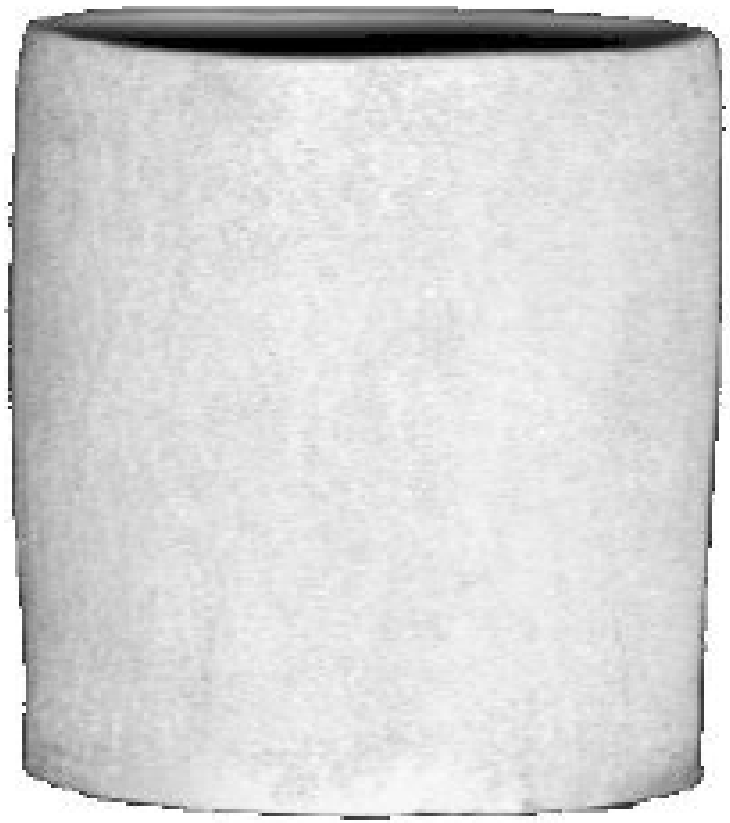
- But still, edges of the moon look bright (not close to zero) when illuminated by earth's radiance.

Why does the Full Moon have a flat appearance?

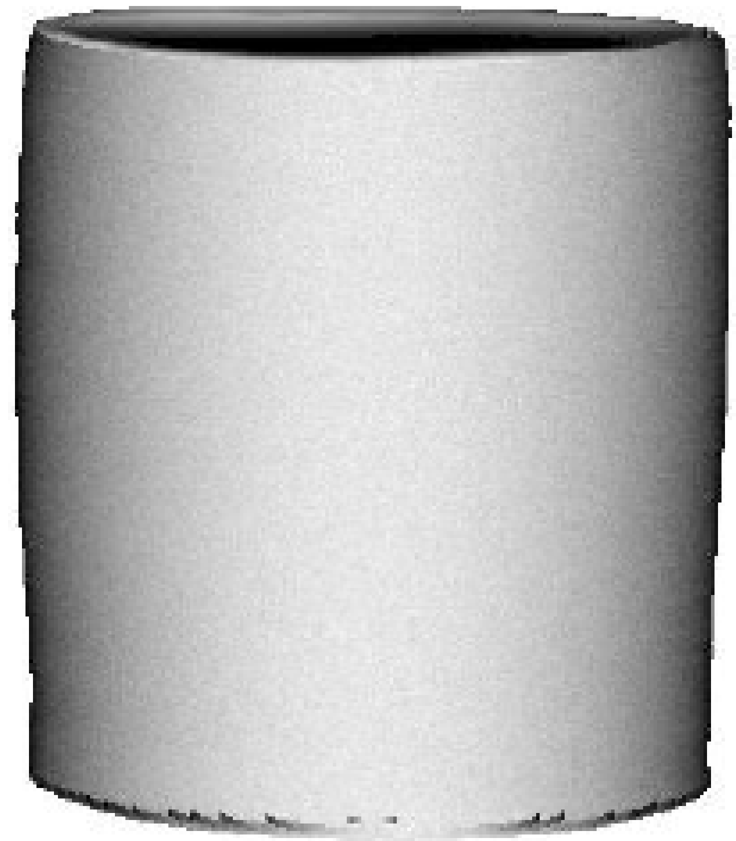


Lambertian Spheres and Moon Photos illuminated similarly

Surface Roughness Causes Flat Appearance

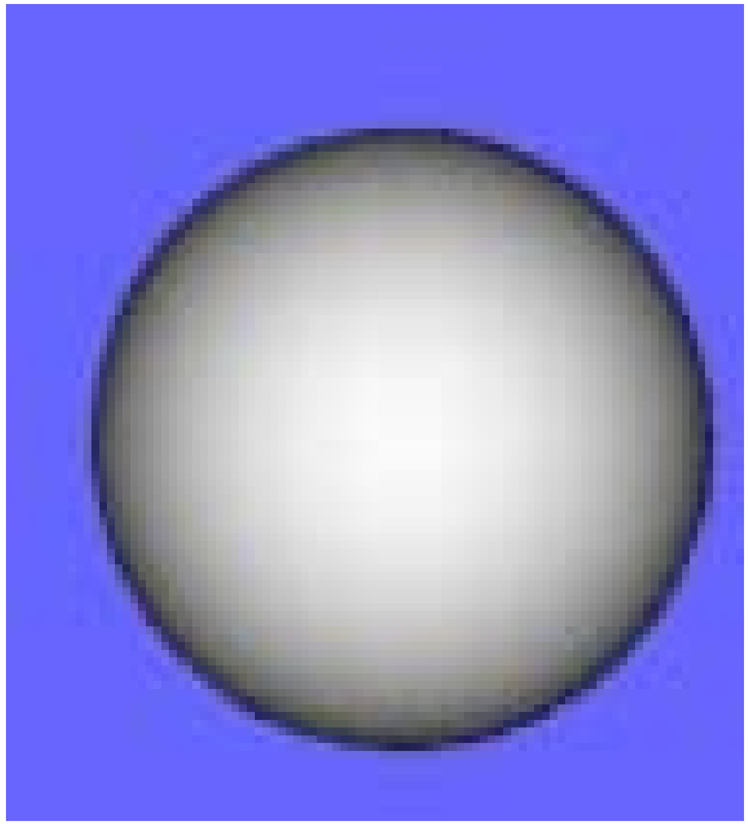


Actual Vase



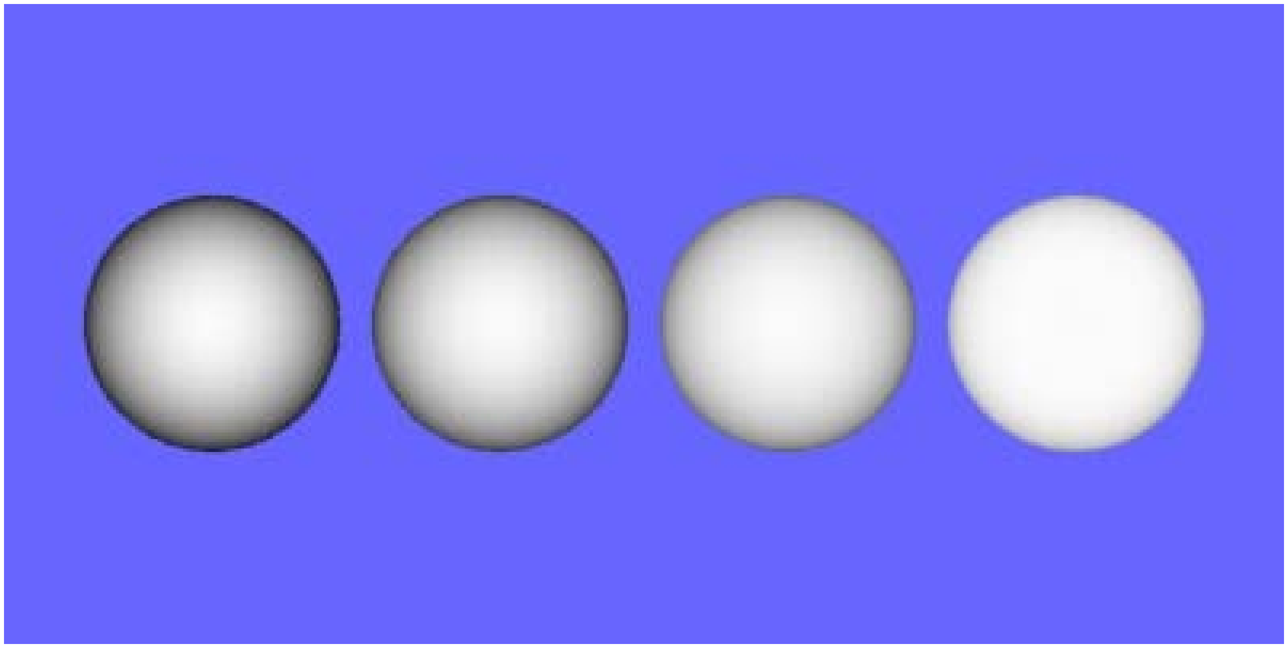
Lambertian Vase

Rendered Sphere with Lambertian BRDF



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

Surface Roughness Causes Flat Appearance



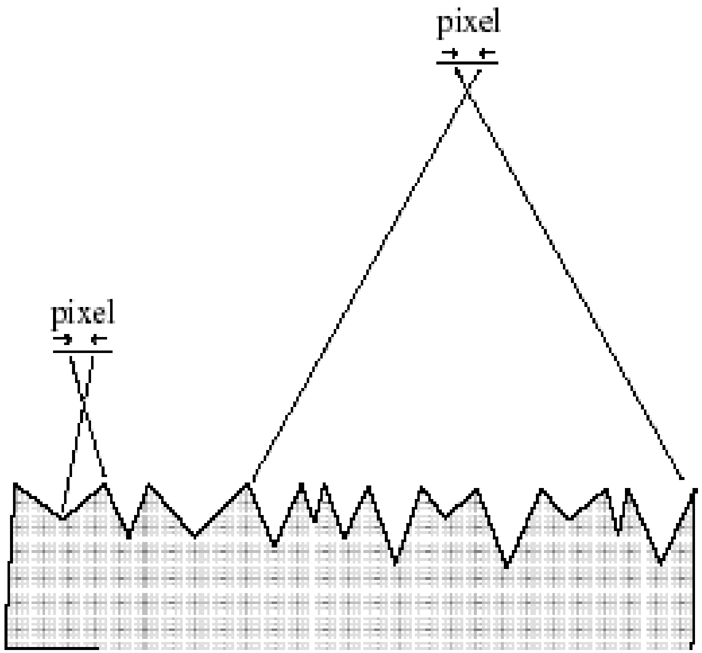
Increasing surface roughness →

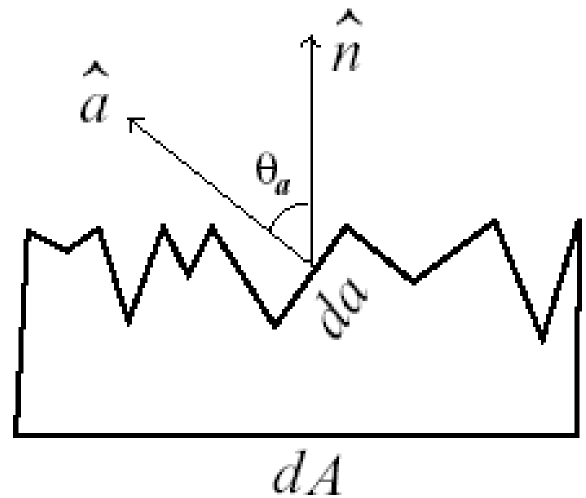
Lambertian model

Valid for only SMOOTH MATTE surfaces.

Bad for ROUGH MATTE surfaces.

Modeling Rough Surfaces - Microfacets



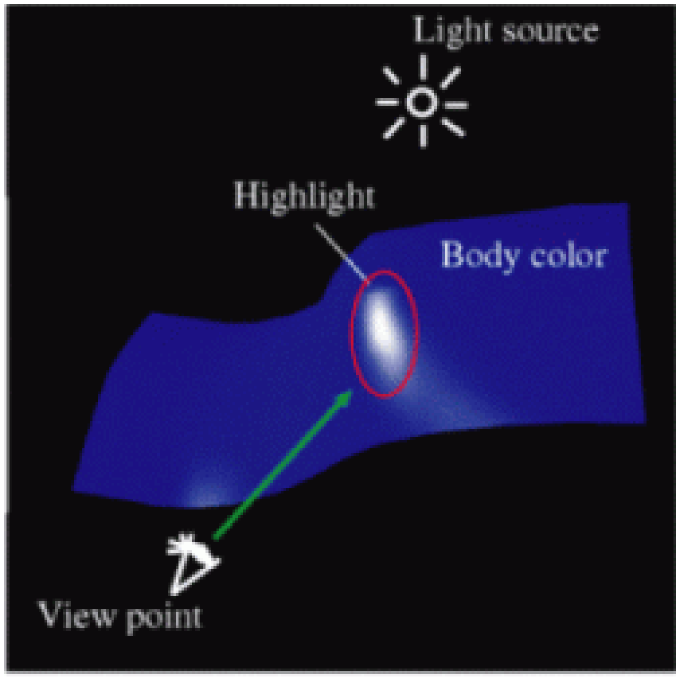


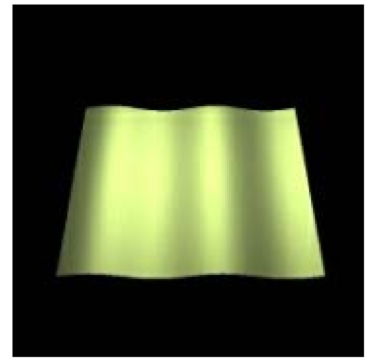
- Roughness simulated by Symmetric V-groves at Microscopic level.
- Distribution on the slopes of the V-grove faces are modeled.
- Each microfacet assumed to behave like a **perfect lambertian surface.**

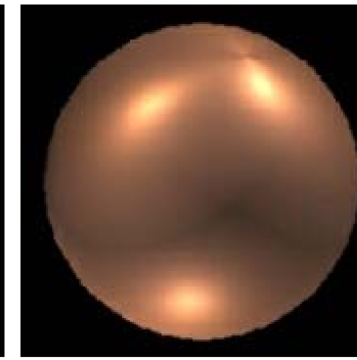
A Simple Reflection Model - Dichromatic Reflection

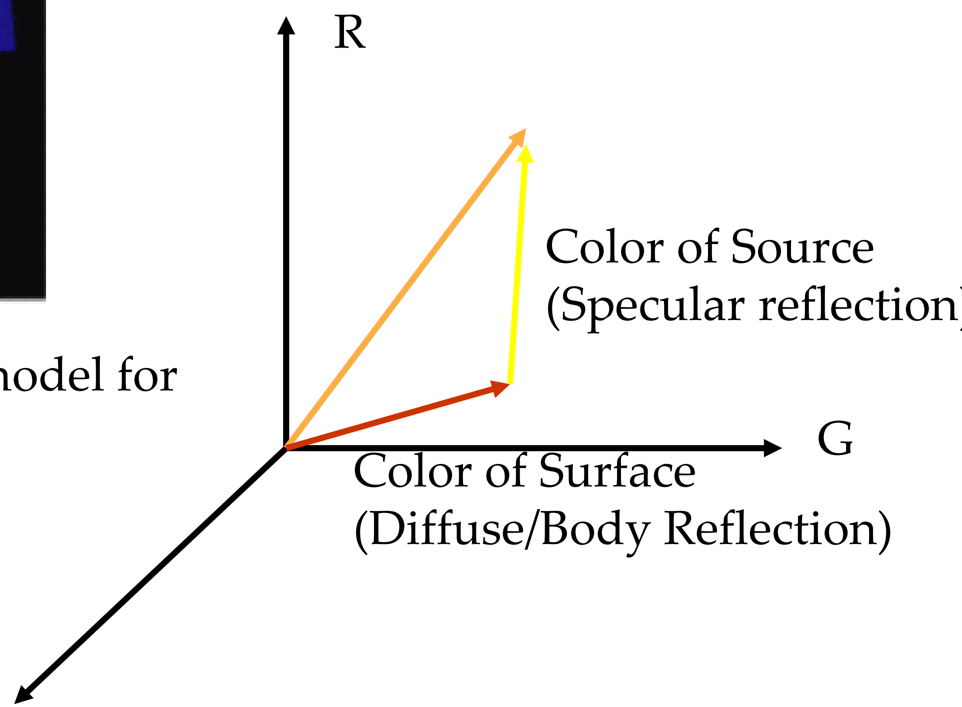
Observed Image Color = a x Body Color + b x Specular Reflection Color

Klinker-Shafer-Kanade 1988









Does not specify any specific model for
Diffuse/specular reflection

Measuring BRDFs

Why bother modeling BRDFs?

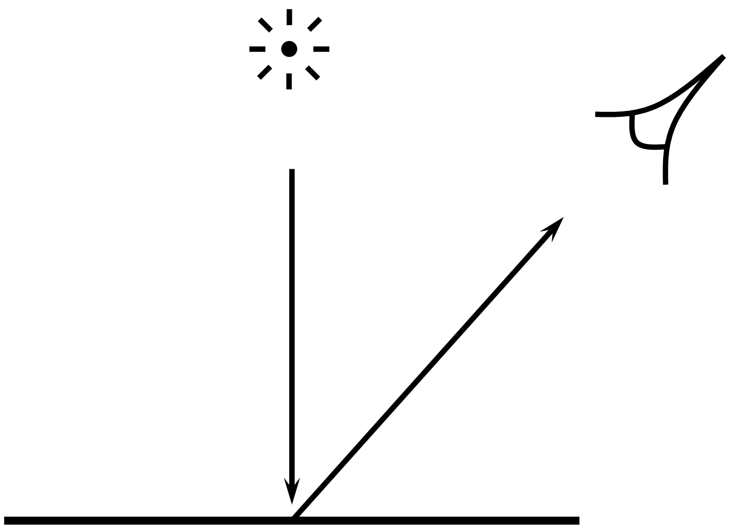
Why not directly measure BRDFs?

- True knowledge of surface properties
- Accurate models for graphics

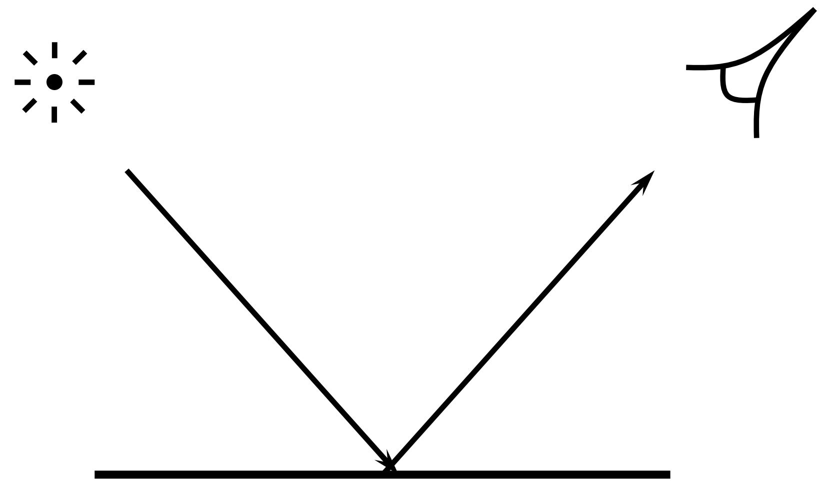
Measuring BRDFs

- A full BRDF is 4-dimensional
- Simpler measurements (0D/1D/2D/3D) often useful
- Lets start with simplest and get more complex

Measuring Reflectance



0º/45º
Diffuse Measurement



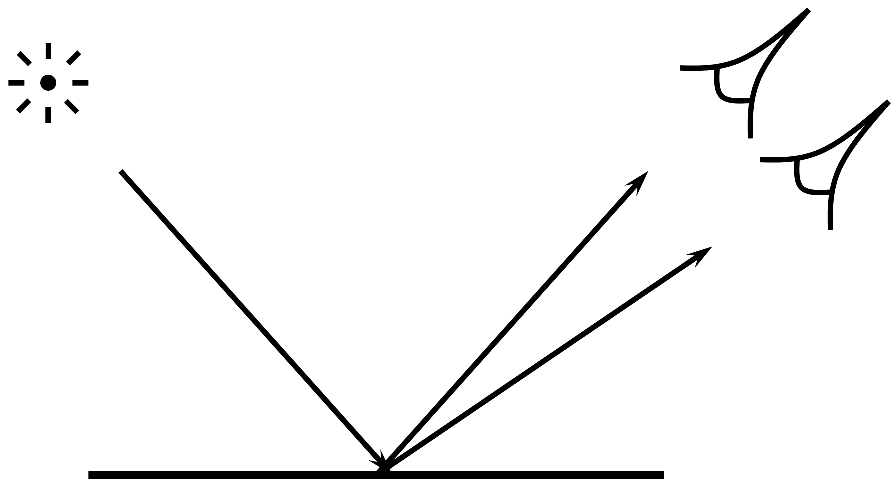
45º/45º
Specular Measurement

Gloss Measurements

- Standardized for applications such as paint manufacturing
- Example: “contrast gloss” is essentially ratio of specular to diffuse
- “Sheen” is specular measurement at 85°

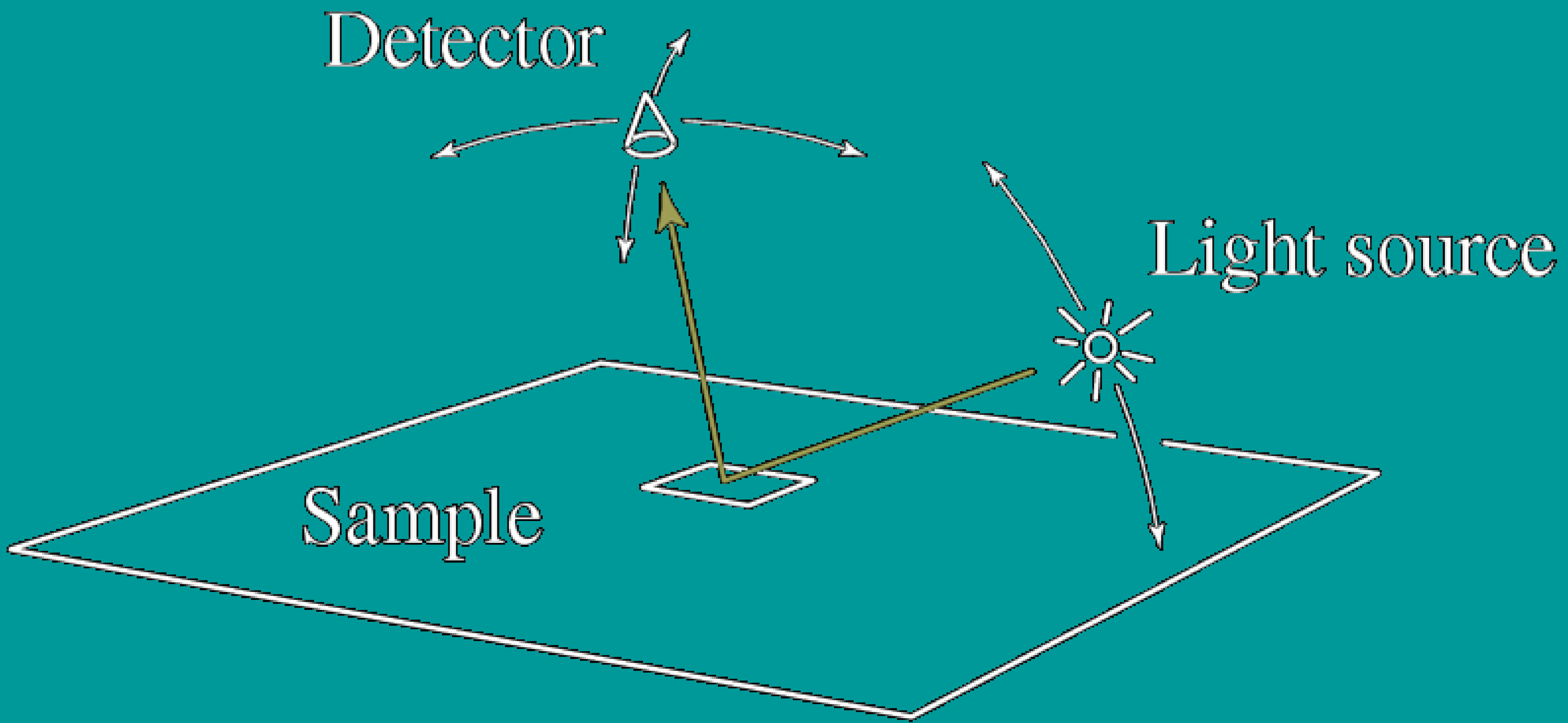
Gloss Measurements

- “Haze” and “distinctness of image” are measurements of width of specular peak



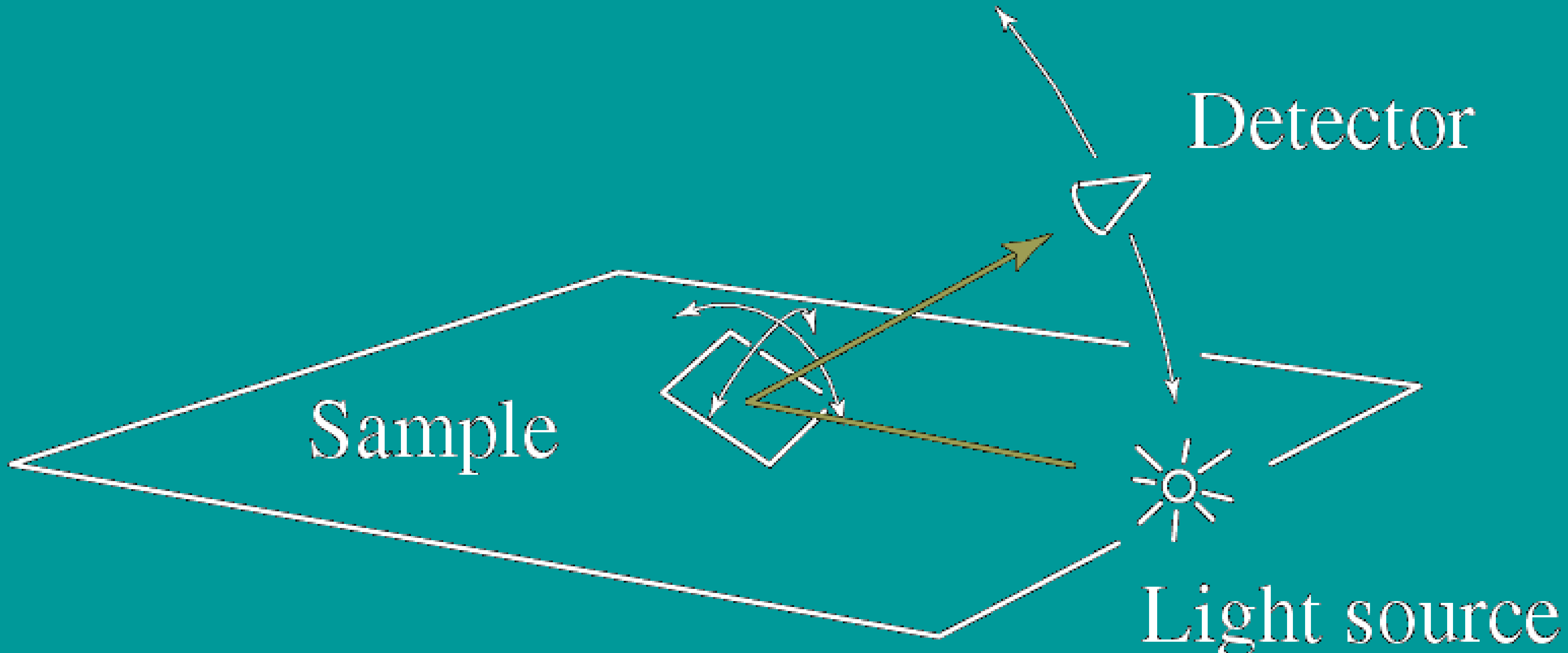
Gonioreflectometers

- Three degrees of freedom spread among light source, detector, and/or sample



Gonioreflectometers

- Three degrees of freedom spread among light source, detector, and/or sample



Gonioreflectometers

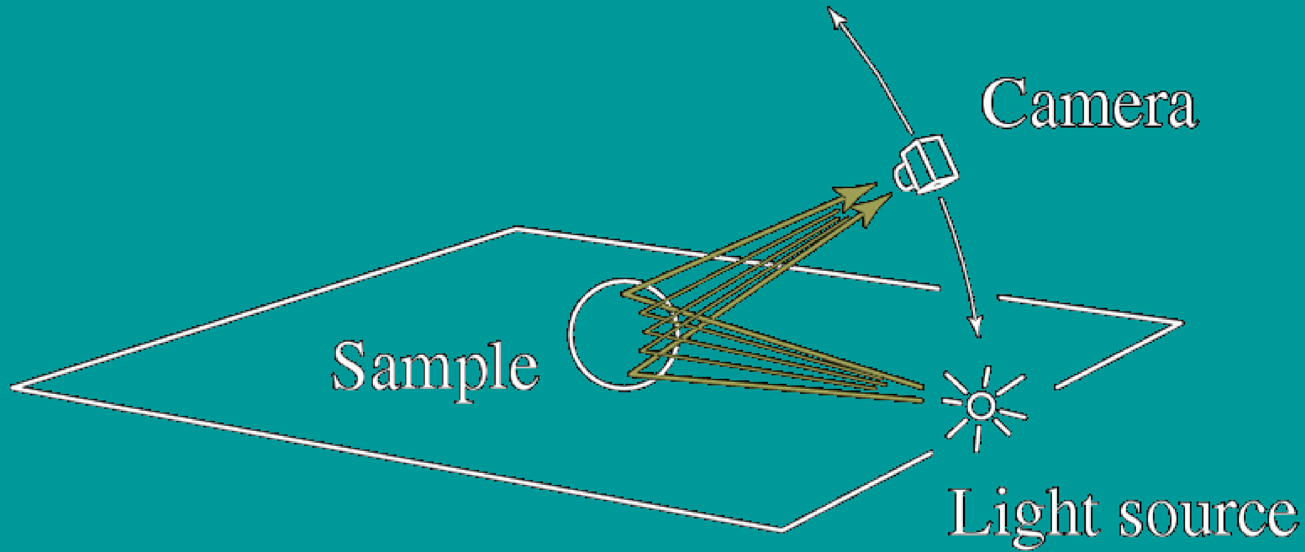
- Can add fourth degree of freedom to measure anisotropic BRDFs

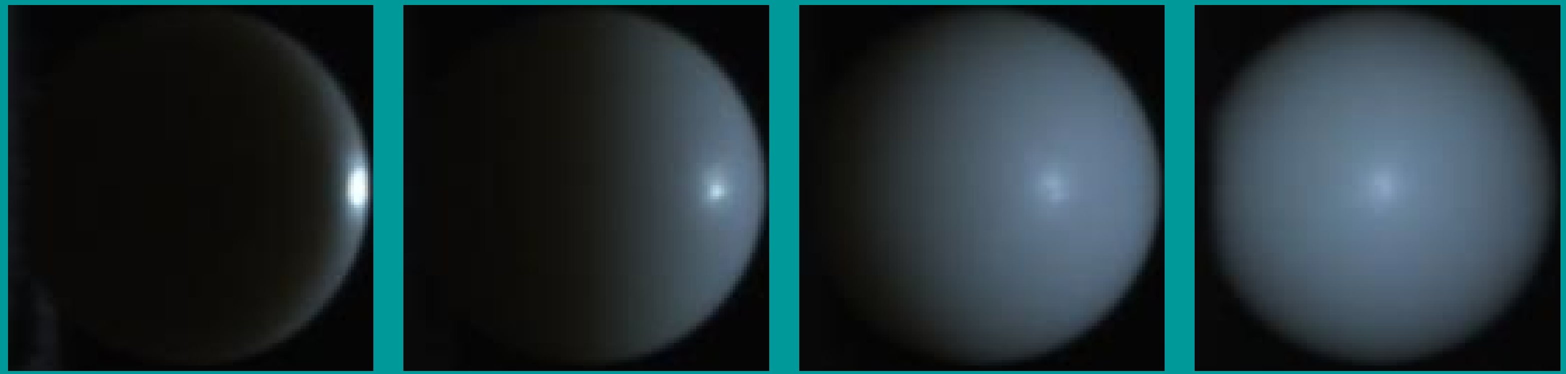
Image-Based BRDF Measurement

- Reduce acquisition time by obtaining larger (e.g. 2-D) slices of BRDF at once
- Idea: Camera can acquire 2D image
- Requires mapping of angles of light to camera pixels

Image-Based BRDF Measurement

- For uniform BRDF, capture 2-D slice corresponding to variations in normals (Marschner et al)



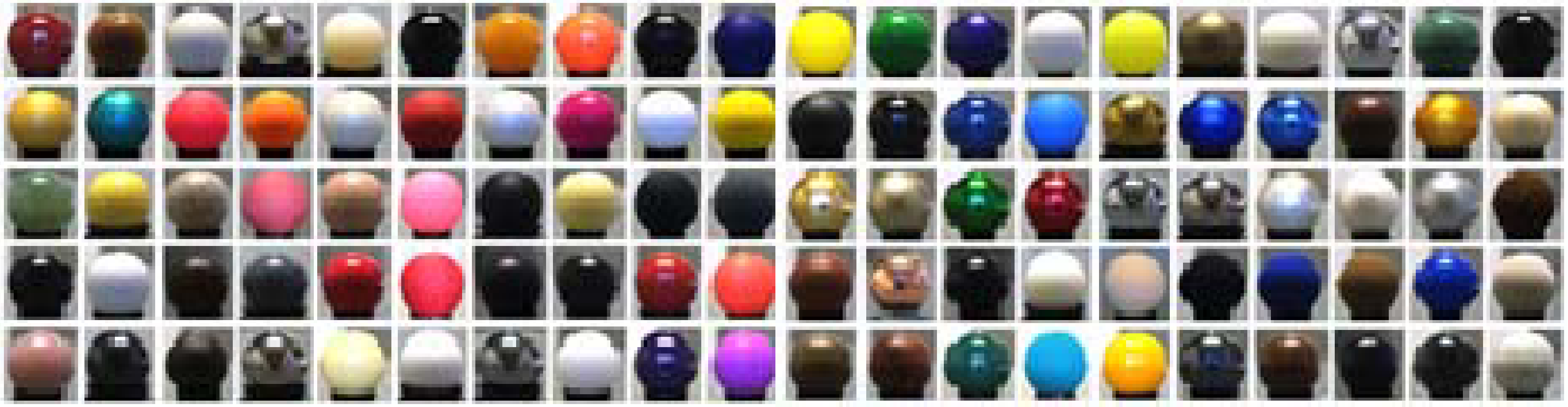


Measurement

- Light Source
  - Hamamatsu SQ Xenon lamp
    - Stable emission output
    - Continuous and relatively constant radiation spectrum

Measurement

- 20-80 million reflectance measurements per material
- Each tabulated BRDF entails 90x90x180x3=4,374,000 measurement bins



Rendering from Tabulated BRDFs

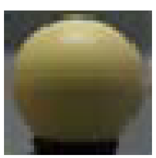
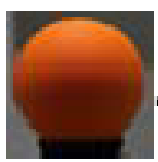
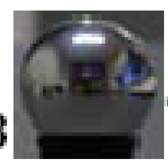
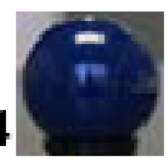
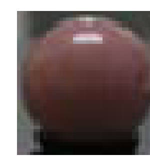
- These BRDFs are immediately useful
- Direct renderings from measurements

Nickel   Hematite   Gold Paint   Pink Felt

Linear Combinations of BRDFs (LCB)

SIGGRAPH2005

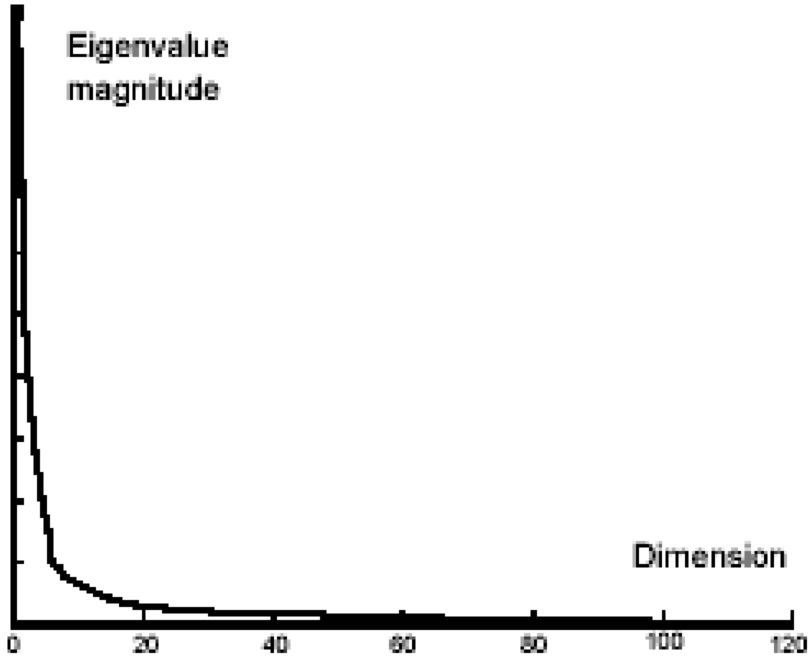
- Can we find a linear combination of our existing BRDFs that match any new one?
- Requires only estimating 100 coefficients for source BRDFs
- Compute a set of 800 constraints that allow estimating these 100 coefficients robustly

α_1  $+ \alpha_2$  $+ \alpha_3$  $+ \alpha_4$  $+ \ldots =$ 

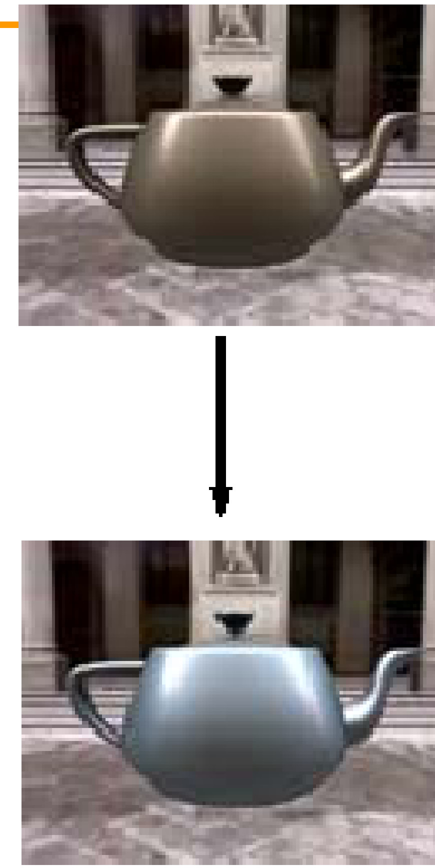
Linear Analysis (PCA)

SIGGRAPH2005

- Find optimal linear basis for our data set
- 45 components needed to reduce residue to under measurement error



Navigation Results



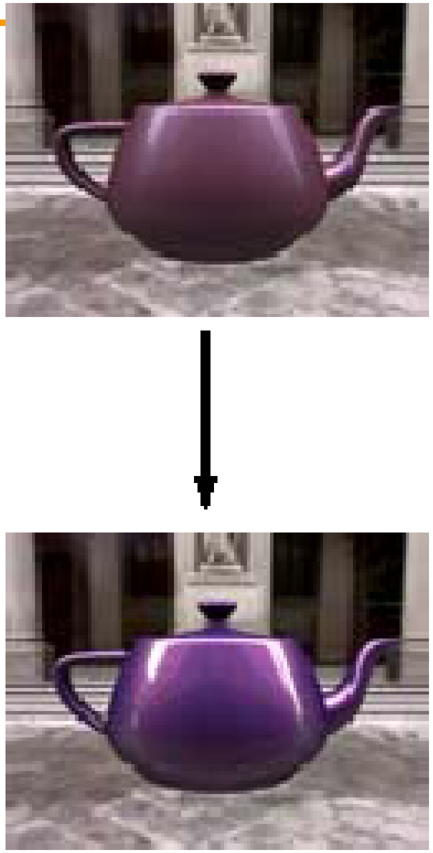
Adding Silver Trait

Navigation Results

SIGGRAPH2005

Adding Specular Trait

Navigation Results



Adding Metallic Trait

Representing Physical Processes

SIGGRAPH2005

Steel Oxidation

Next Step in the Appearance Food Chain

Textures

Spatially Varying BRDFs
Bi-Directional Texture Distribution Functions (BTF)

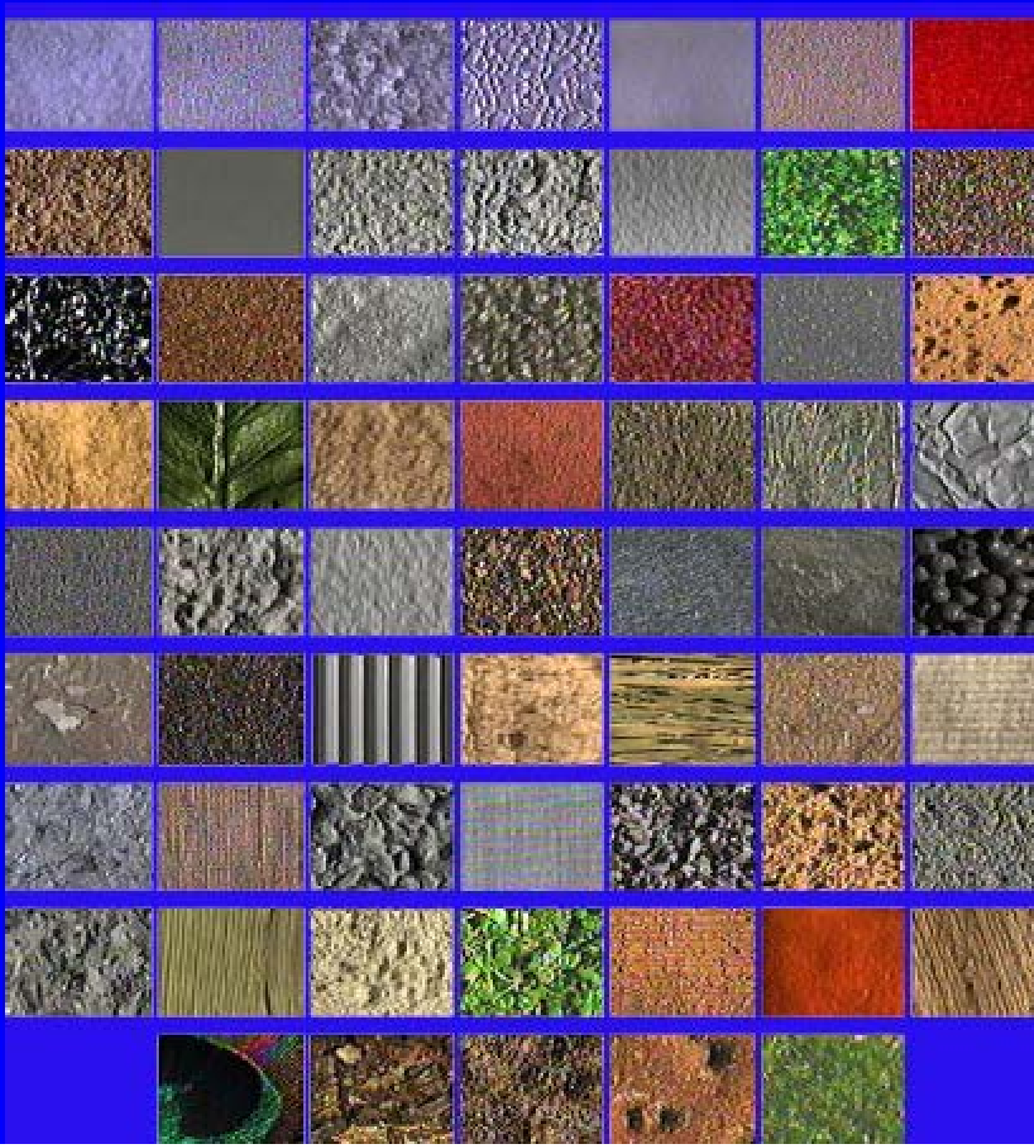
CURET Database – [Dana, Nayar 96]

BRDF vs. BTF

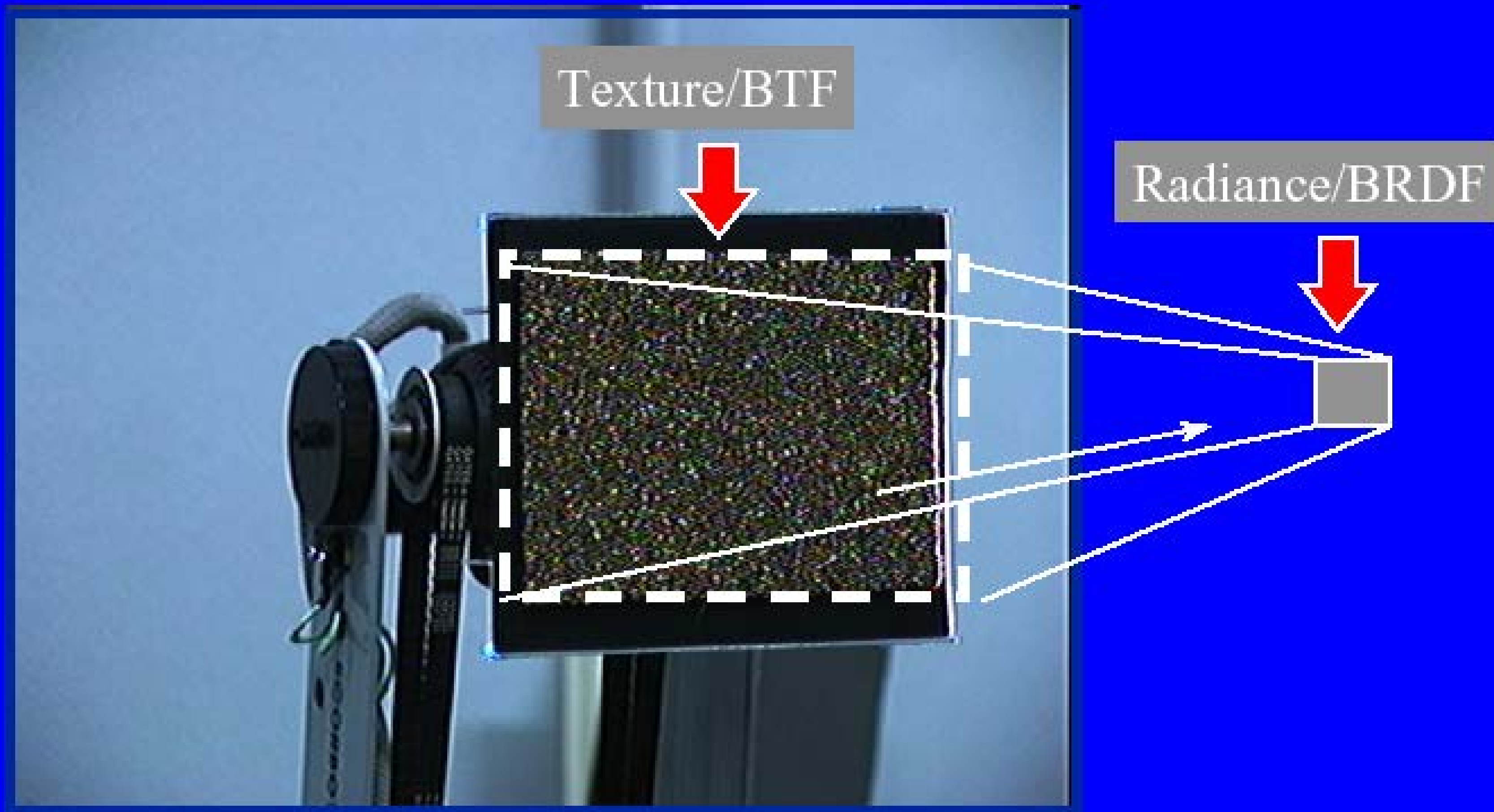
Samples for Measurements

<u>61 samples:</u>

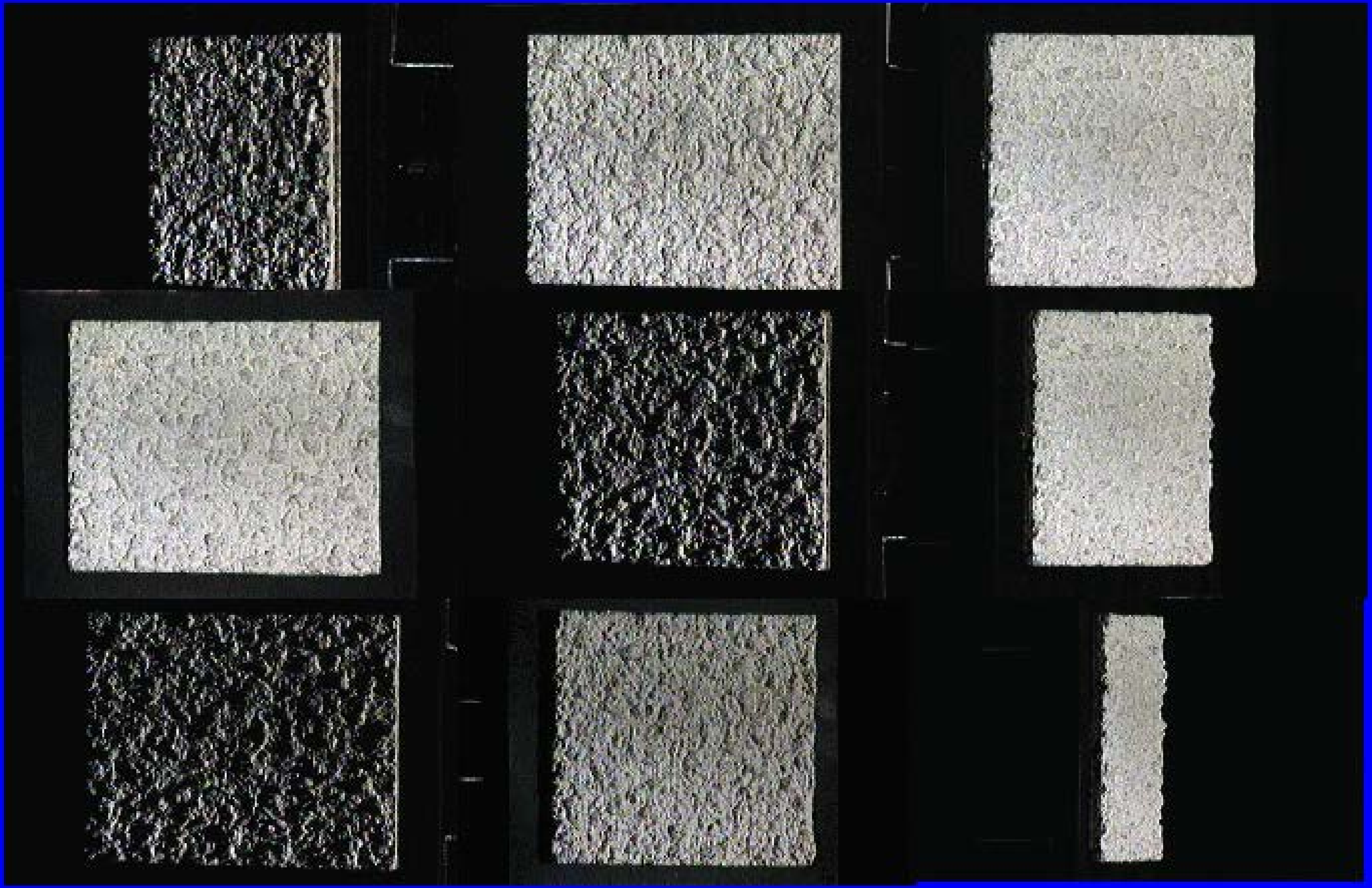
- *specular* (foil, artificial grass)
- *diffuse* (brick, plaster)
- *natural* (fur, moss)
- *man-made* (velvet, leather)
- *isotropic* (bread, concrete)
- *anisotropic* (corn husk, wood)



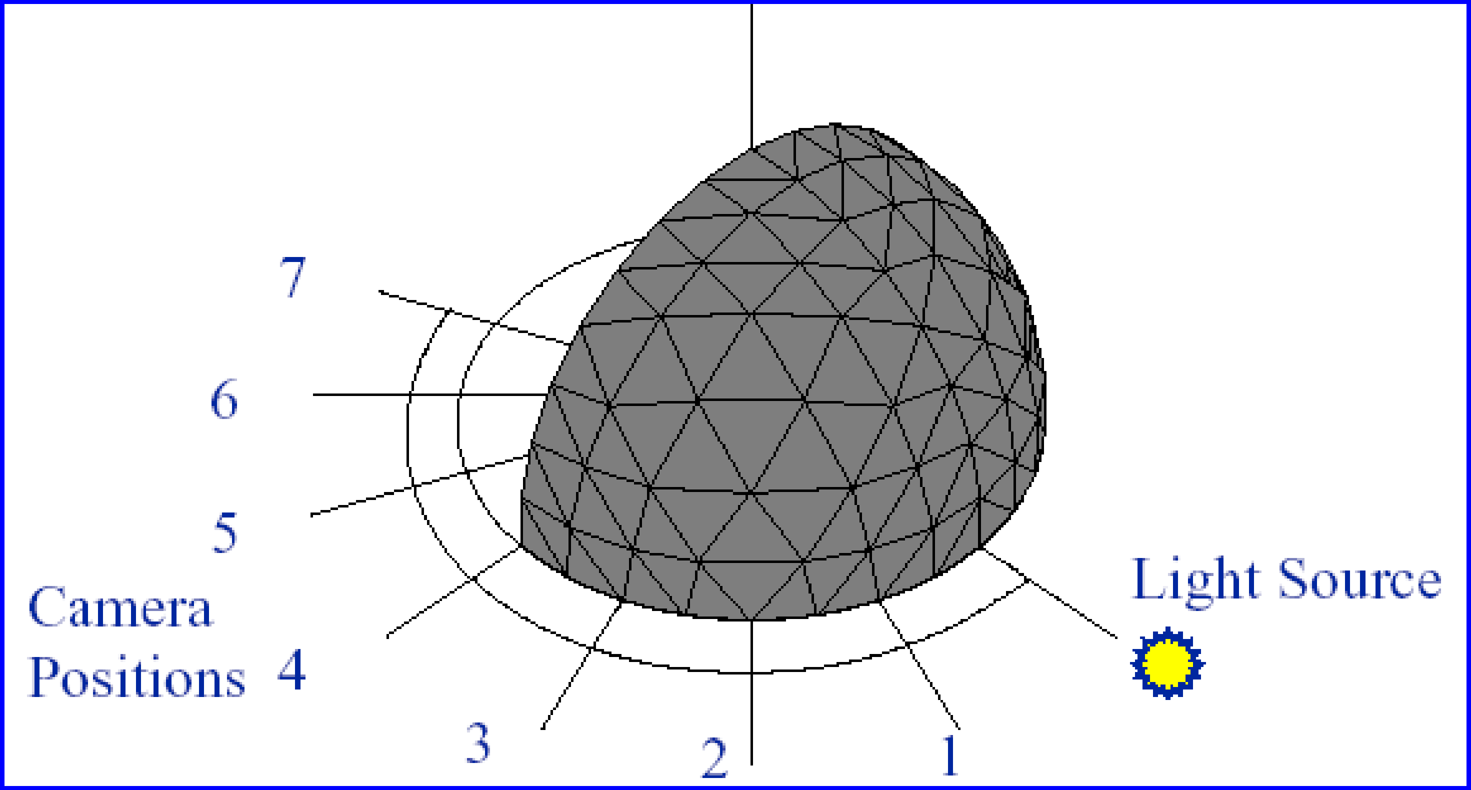
Measurement Methods



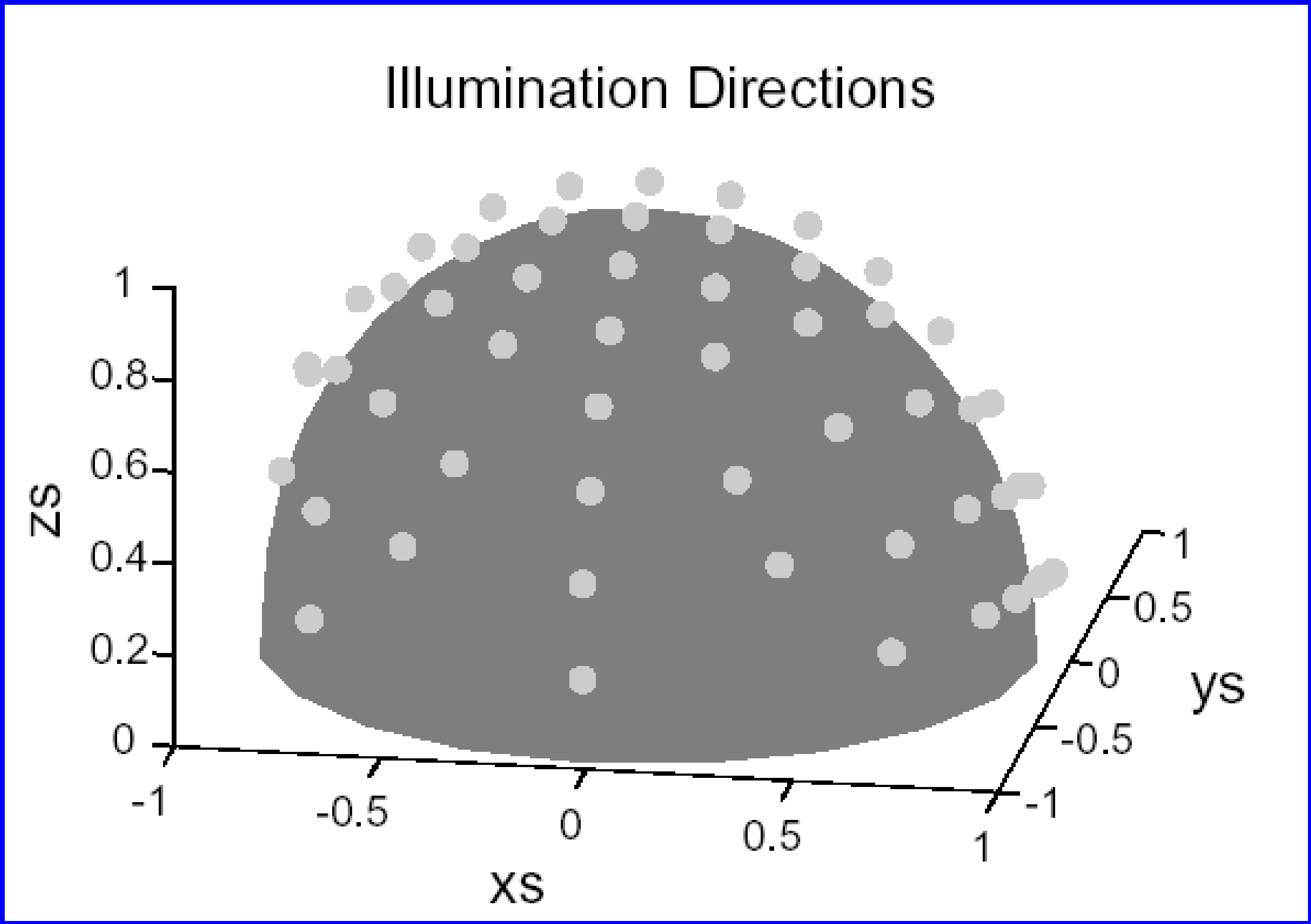
Example images



Measurement Methods

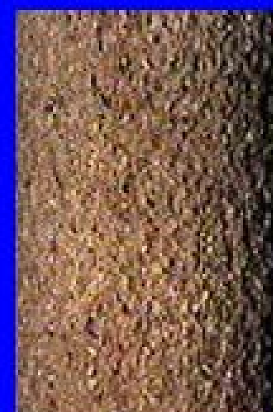


Measurement Methods



Texture-mapping using BTF

standard
texture-mapping



texture-mapping
with the BTF

Texture-mapping using BTF

standard
texture-mapping

texture-mapping
with the BTF

Materials Change with Time