

# Materials and Surface Appearance

Thanks to Shree Nayar, Ravi Ramamoorthi, Pat Hanrahan

# Surface Appearance

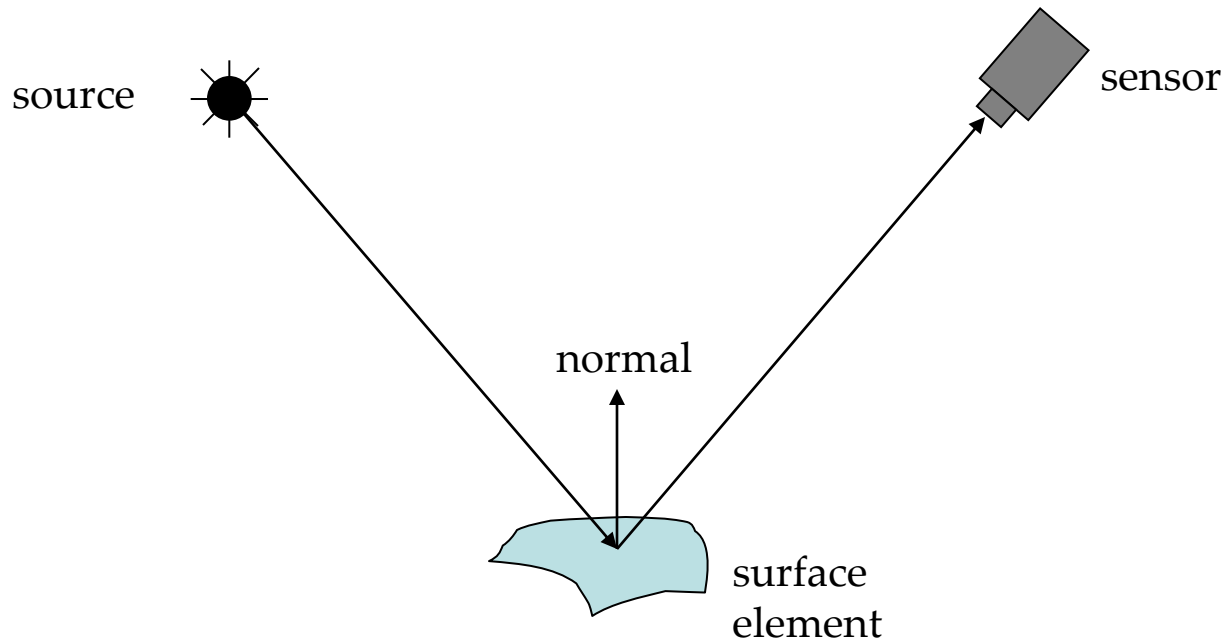
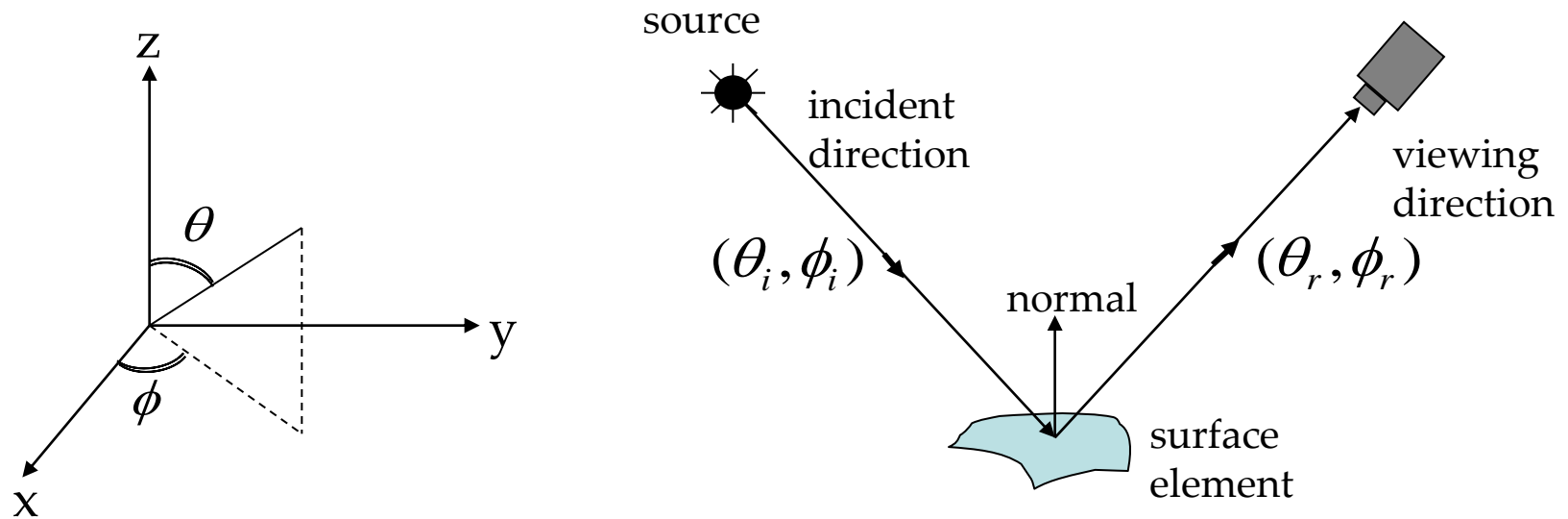


Image intensities =  $f(\text{normal, surface reflectance, illumination})$

Surface Reflection depends on both the viewing and illumination direction.

# BRDF: Bidirectional Reflectance Distribution Function

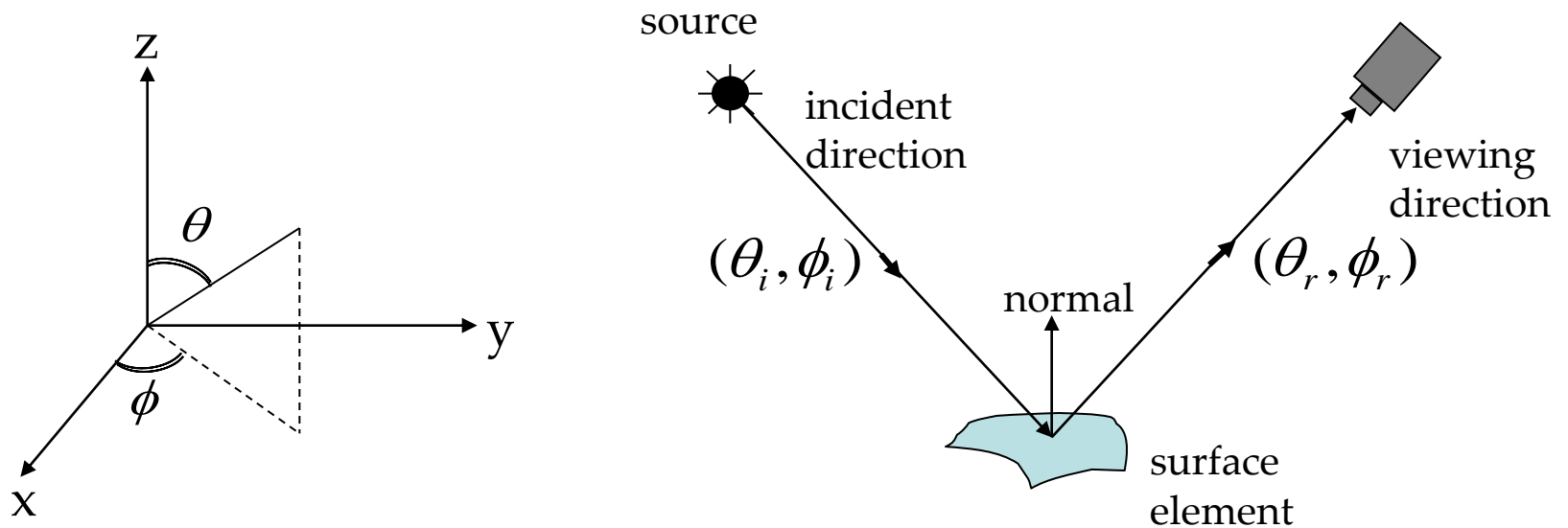


$E^{surface}(\theta_i, \phi_i)$  Irradiance at Surface in direction  $(\theta_i, \phi_i)$

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

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

# Important Properties of BRDFs



- Rotational Symmetry:

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

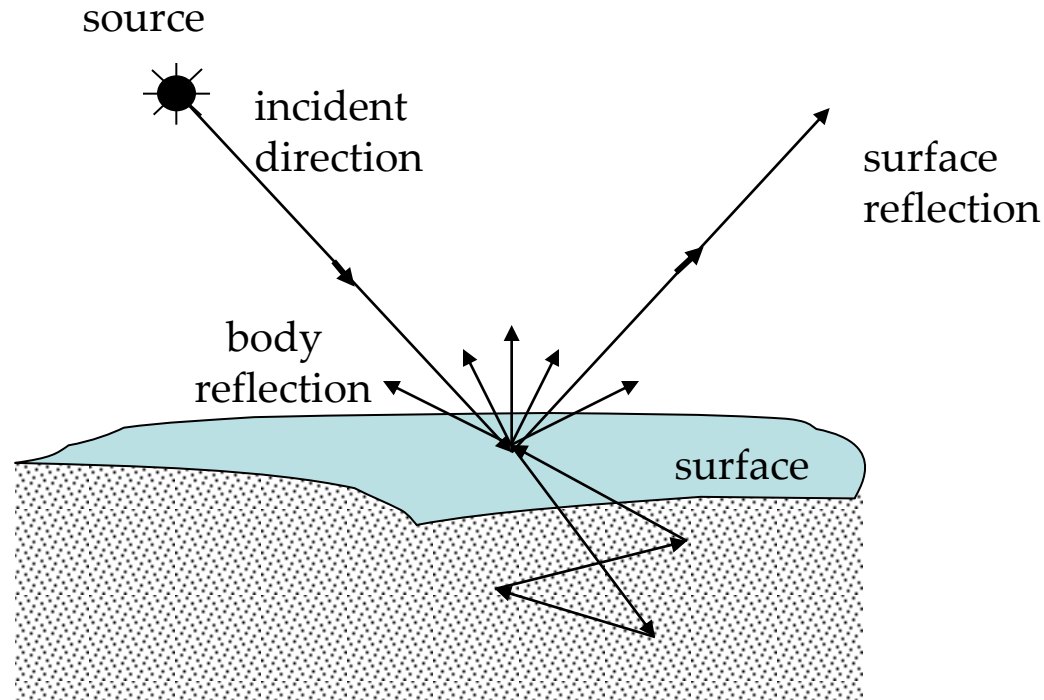
BRDF is only a function of 3 variables :  $f(\theta_i, \theta_r, \phi_i - \phi_r)$

- Helmholtz Reciprocity: (follows from 2<sup>nd</sup> Law of Thermodynamics)

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

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

# 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

$$\text{Image Intensity} = \text{Body Reflection} + \text{Surface Reflection}$$

# Mechanisms of Surface Reflection

## Body Reflection:

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



## Surface Reflection:

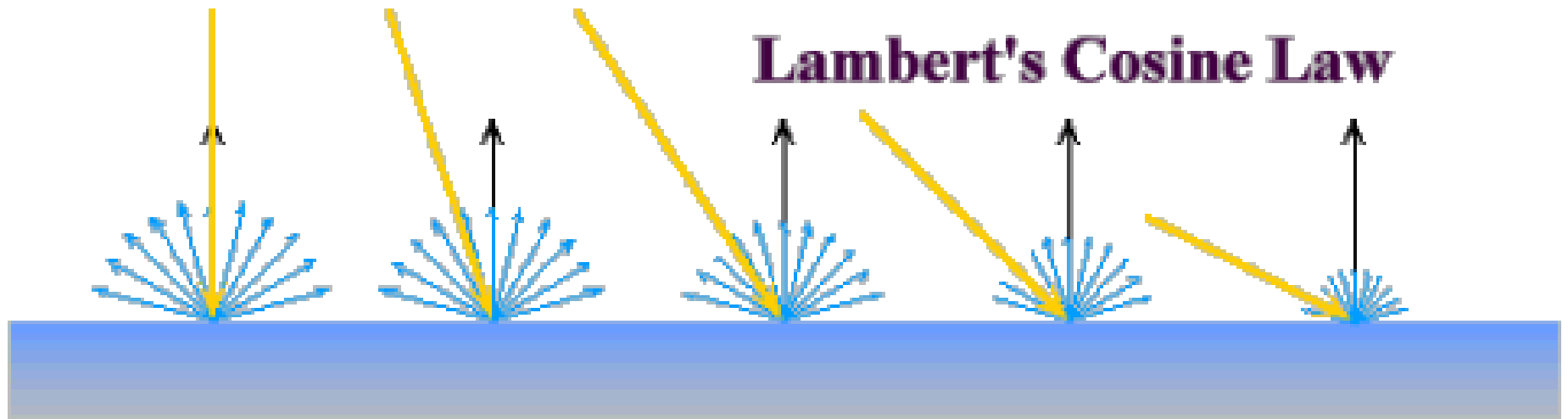
Specular Reflection  
Glossy Appearance  
Highlights  
Dominant for Metals



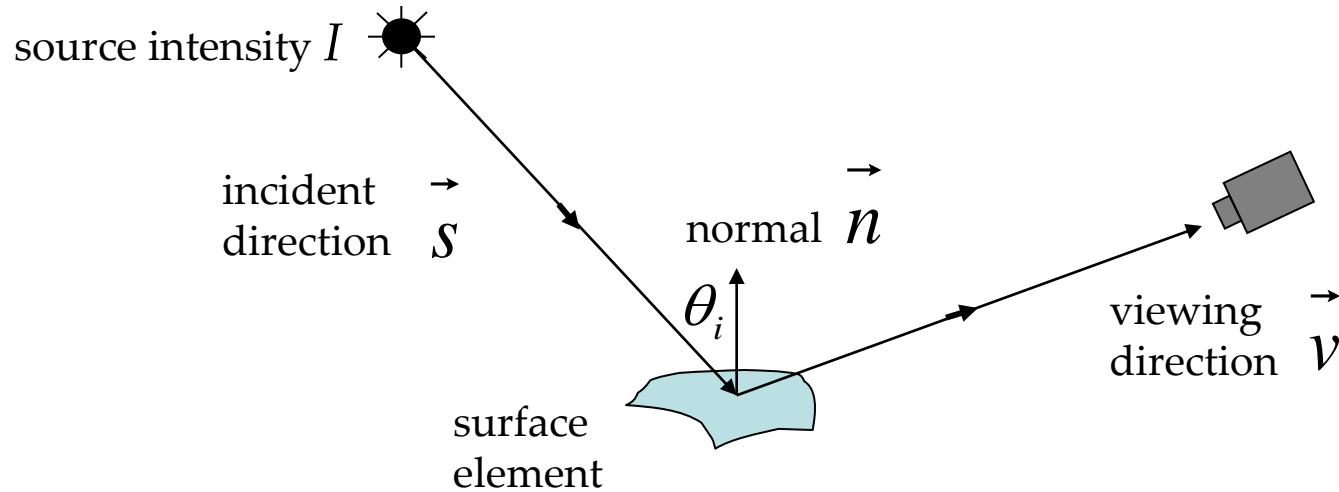
Many materials exhibit both Reflections:



# 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:  $L = \frac{\rho_d}{\pi} I \cos \theta_i = \frac{\rho_d}{\pi} I \vec{n} \cdot \vec{s}$  ↘ source intensity
- Commonly used in Vision and Graphics!



# Rendered Sphere with Lambertian BRDF



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

# White-out Conditions from an Overcast Sky



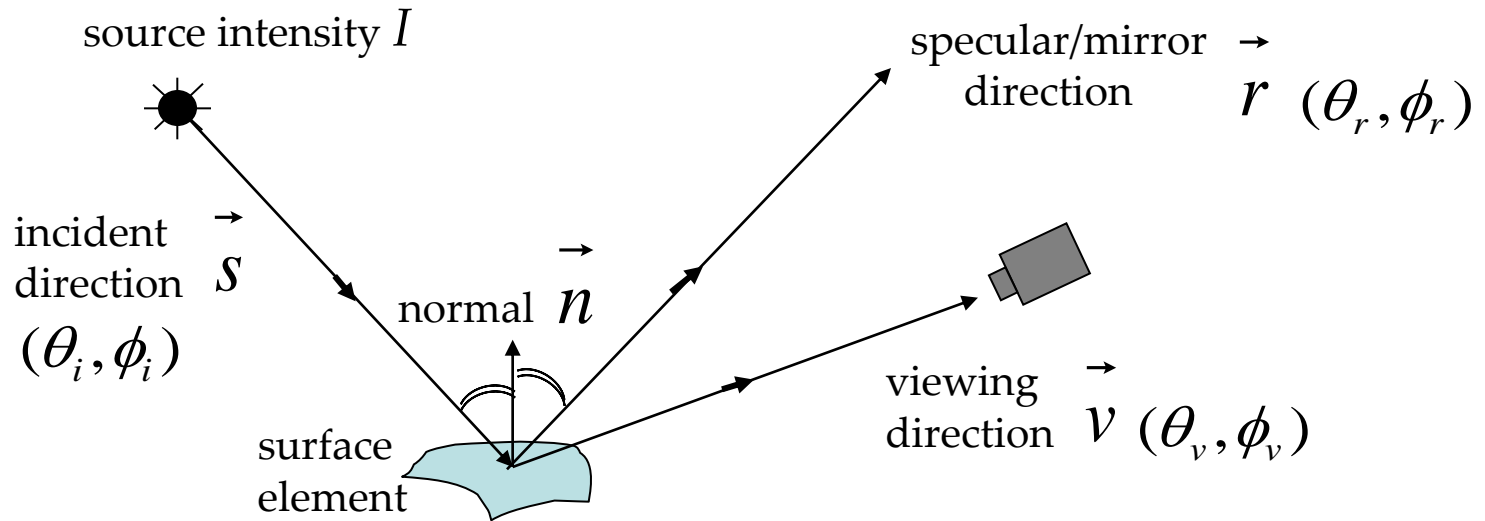
CAN'T perceive the shape of the snow covered terrain!



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 :

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

specular albedo

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

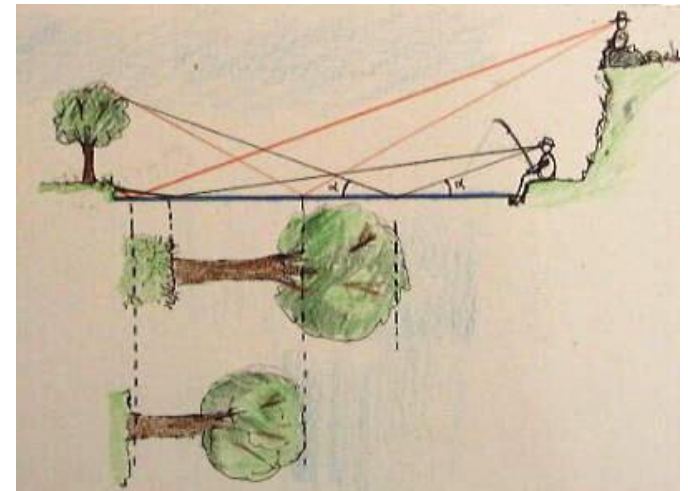
# Specular Reflections in Nature



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

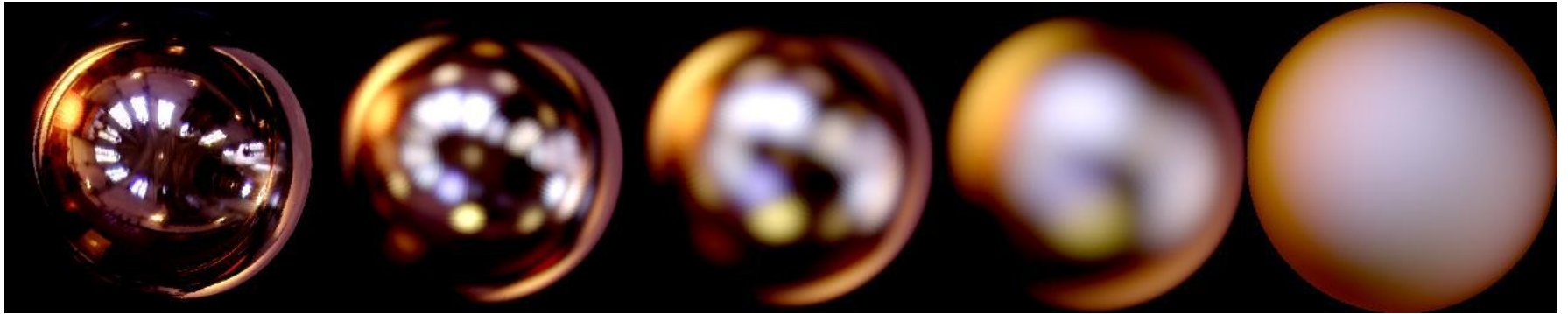
- Delta Function too harsh a BRDF model  
(valid only for highly polished mirrors and metals).
- Many glossy surfaces show broader highlights in addition to mirror reflection.



- Surfaces are not perfectly smooth – they show micro-surface geometry (roughness).
- Example Models : Phong model

Torrance Sparrow model

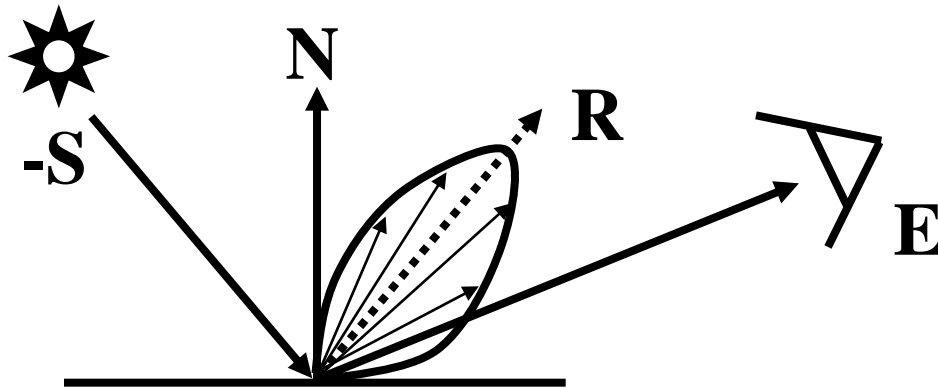
# Blurred Highlights and Surface Roughness



Roughness

# Phong Model: An Empirical Approximation

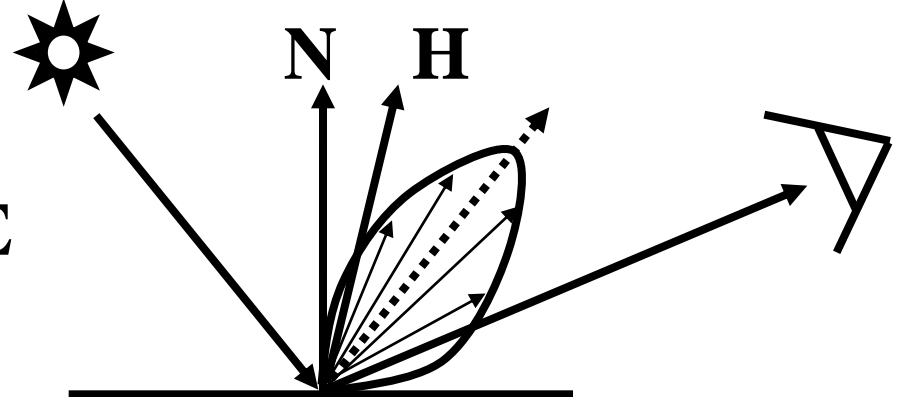
- How to model the angular falloff of highlights:



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

$$R = -S + 2(N \cdot S)N$$

Phong Model



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

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

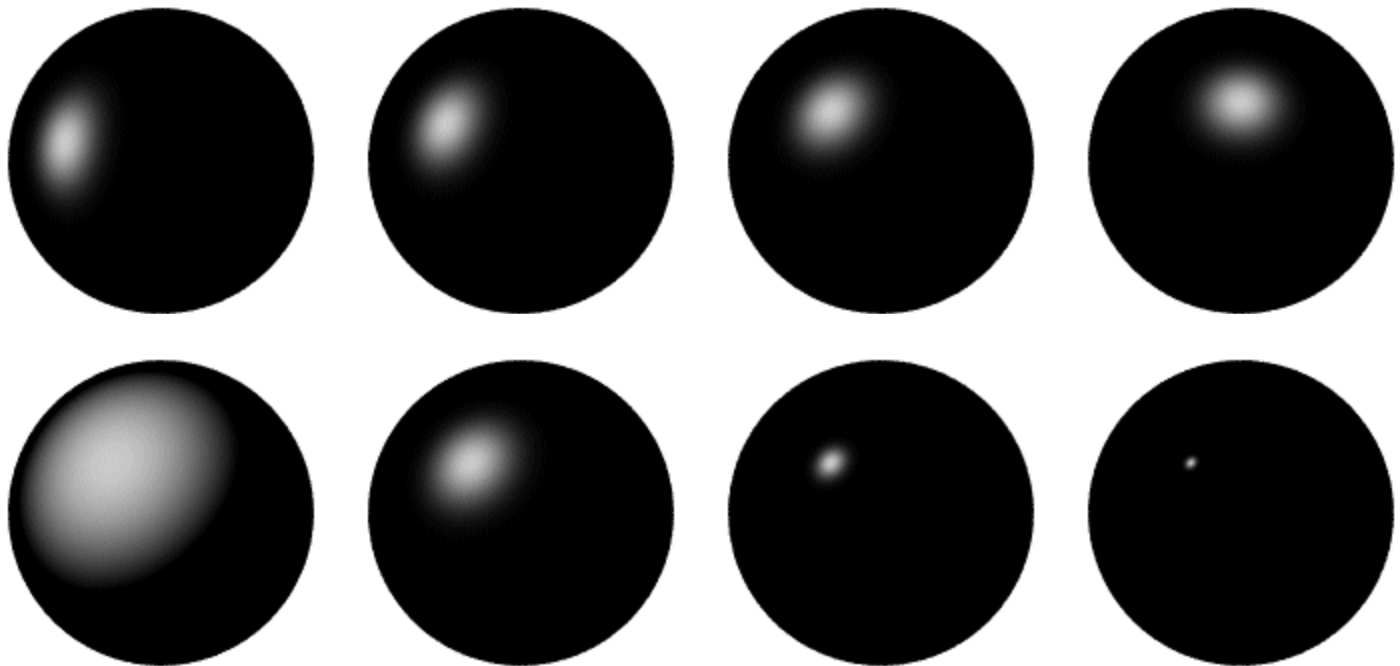
Blinn-Phong Model

- 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

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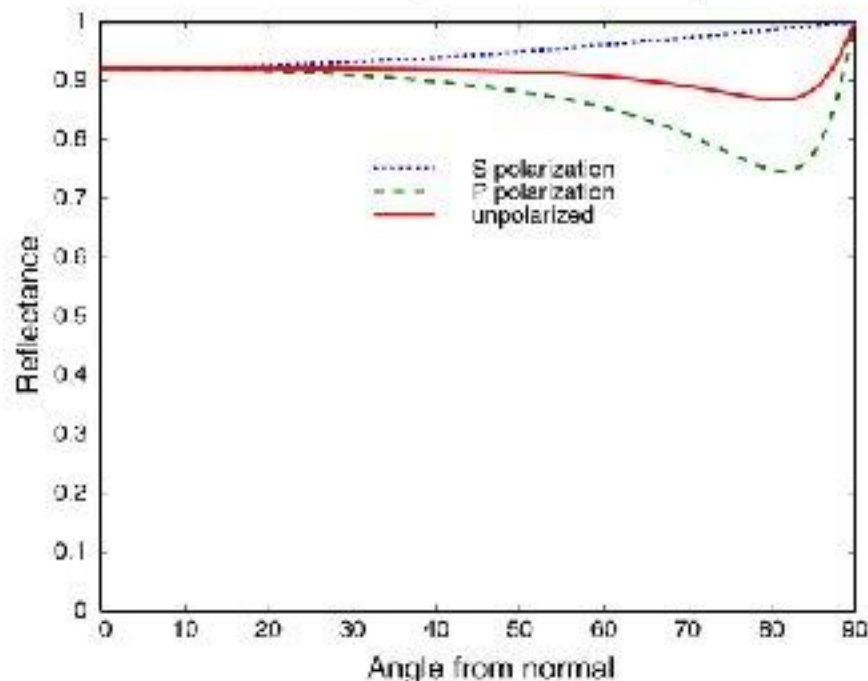
## Reflections from a shiny floor



**From Lafortune, Foo, Torrance, Greenberg, SIGGRAPH 97**

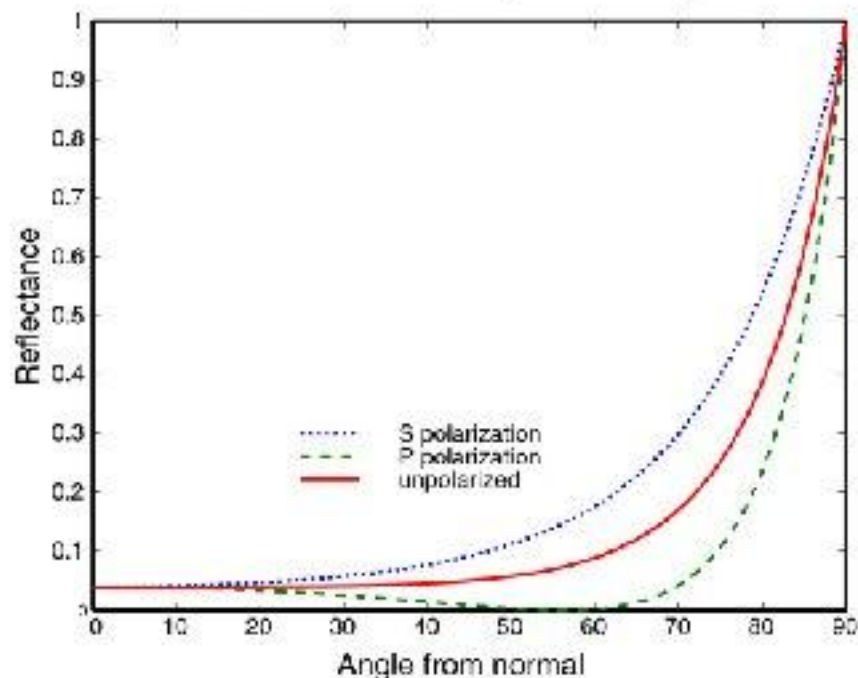
# Fresnel Reflectance

## Metal (Aluminum)



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

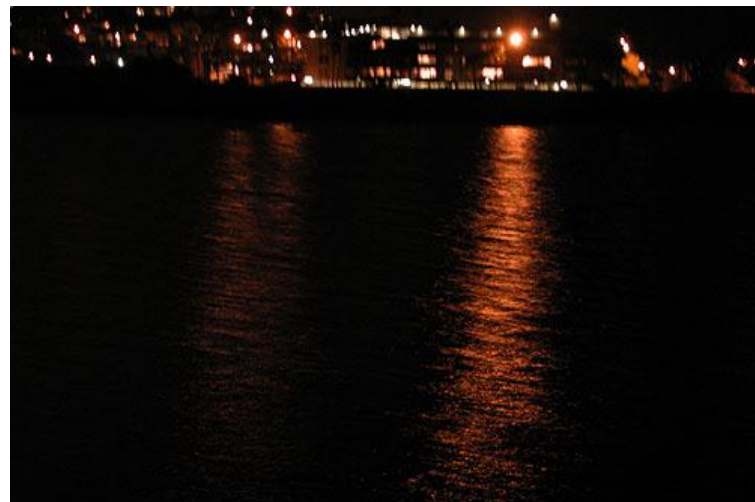
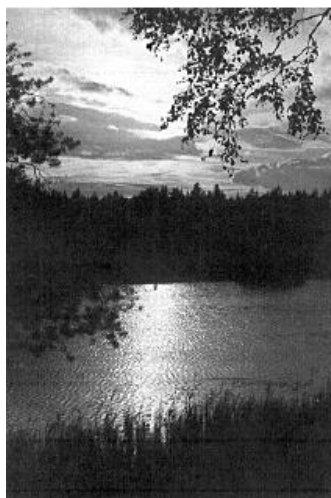
## Dielectric (N=1.5)



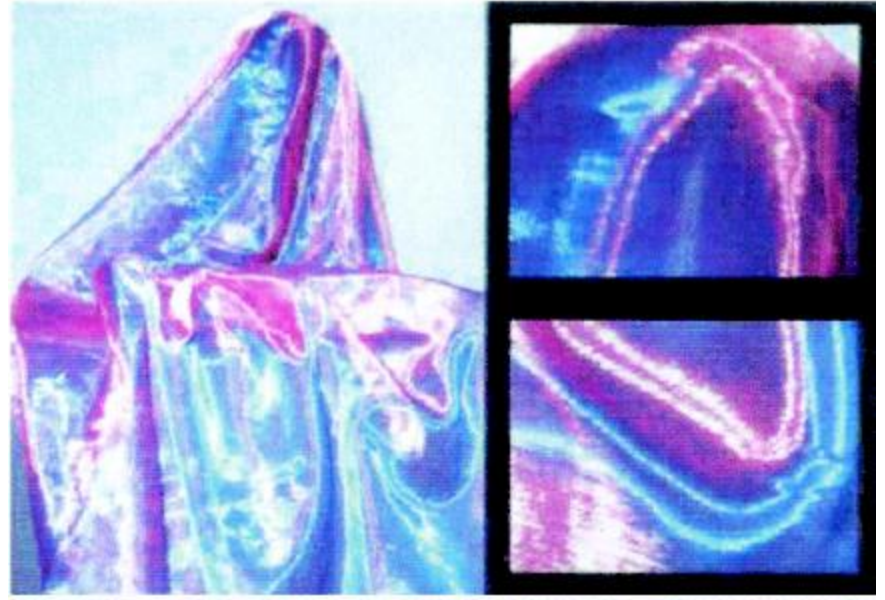
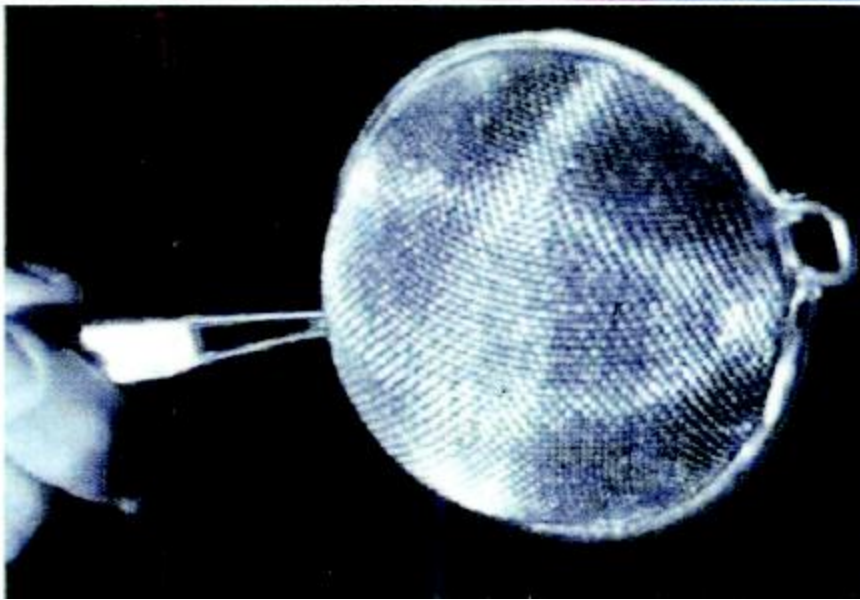
**Glass**  $n=1.5$   $F(0)=0.04$   
**Diamond**  $n=2.4$   $F(0)=0.15$

**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



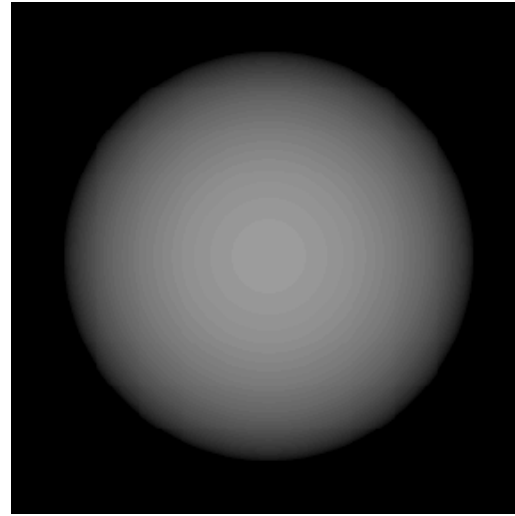
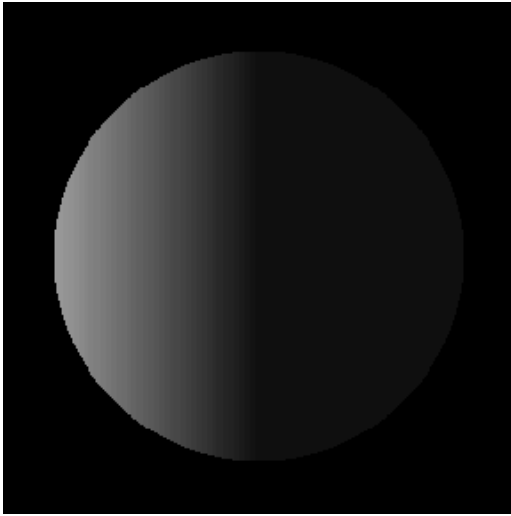
# Why does the Full Moon have a flat appearance?



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



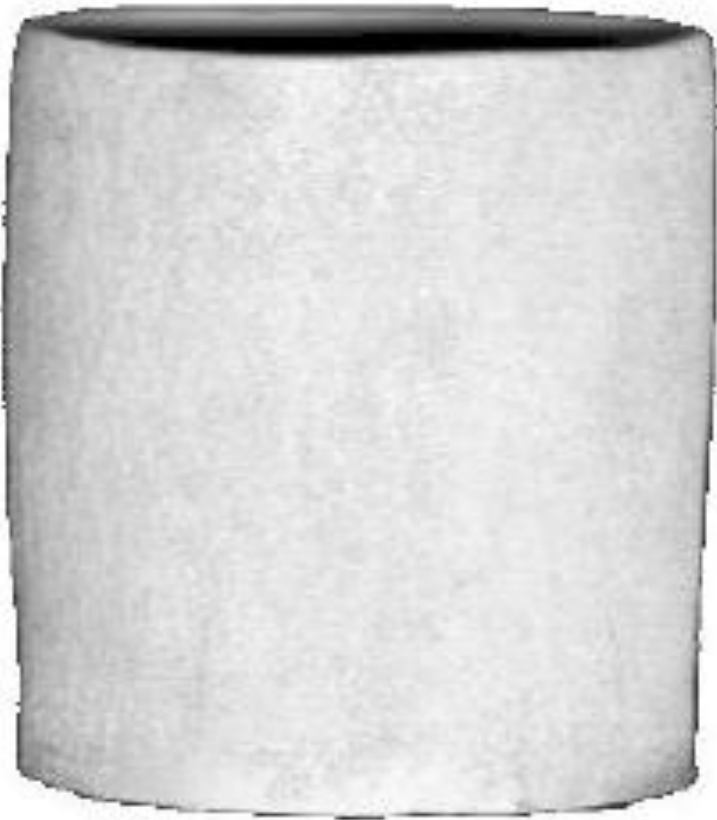
Why does the Full Moon have a flat appearance?



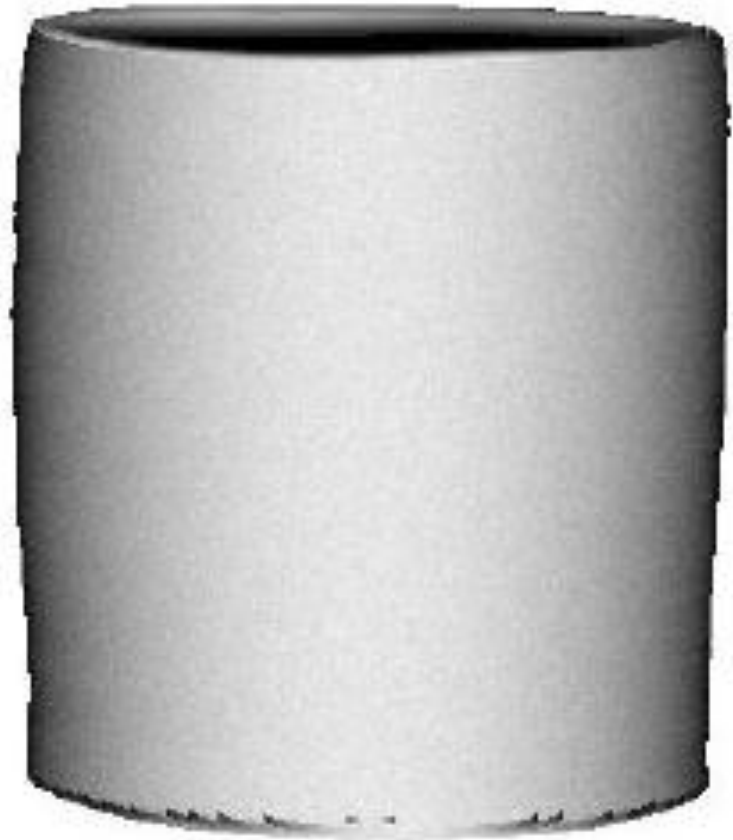
Lambertian Spheres and Moon Photos illuminated similarly



# Surface Roughness Causes Flat Appearance



Actual Vase



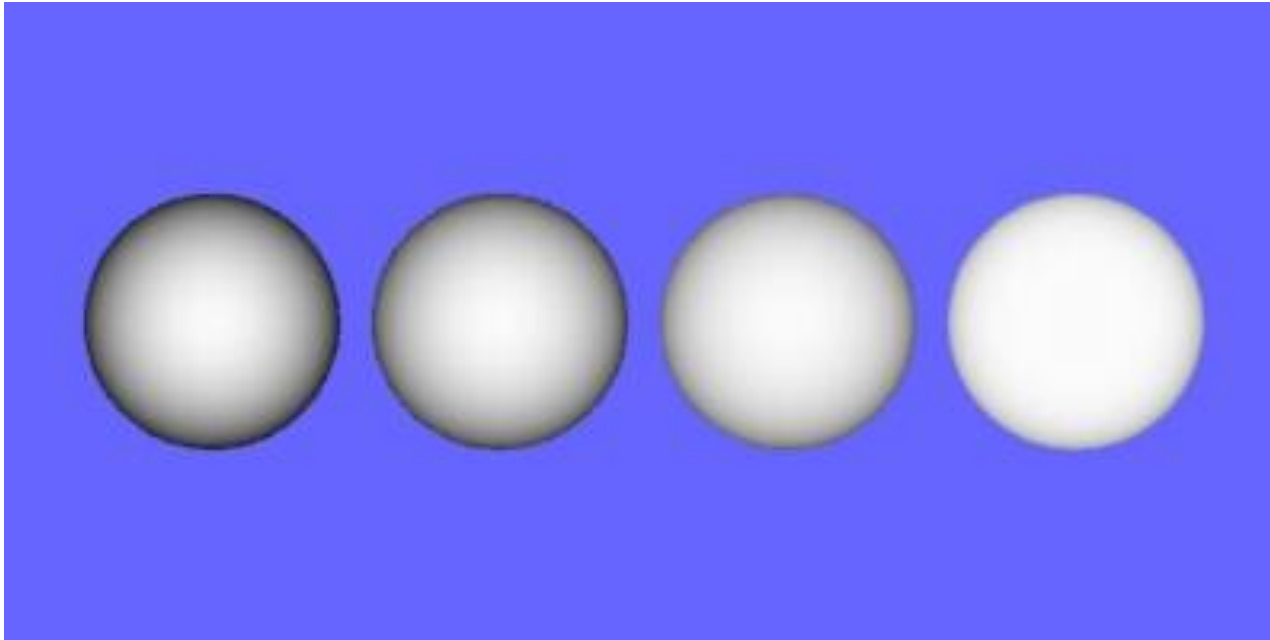
Lambertian Vase

# Rendered Sphere with Lambertian BRDF



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# Surface Roughness Causes Flat Appearance



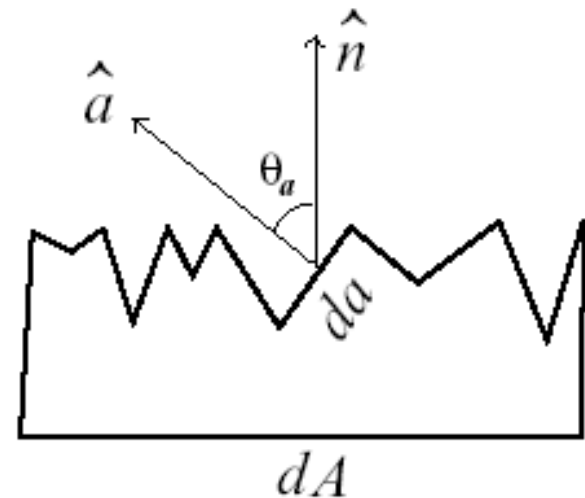
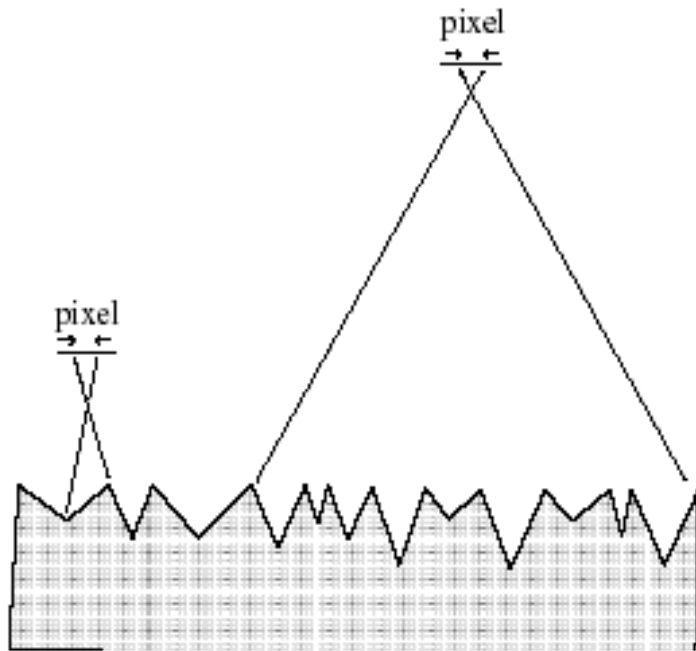
Increasing surface roughness 

Lambertian model

Valid for only SMOOTH MATTE surfaces.

Bad for ROUGH MATTE surfaces.

# Modeling Rough Surfaces - Microfacets

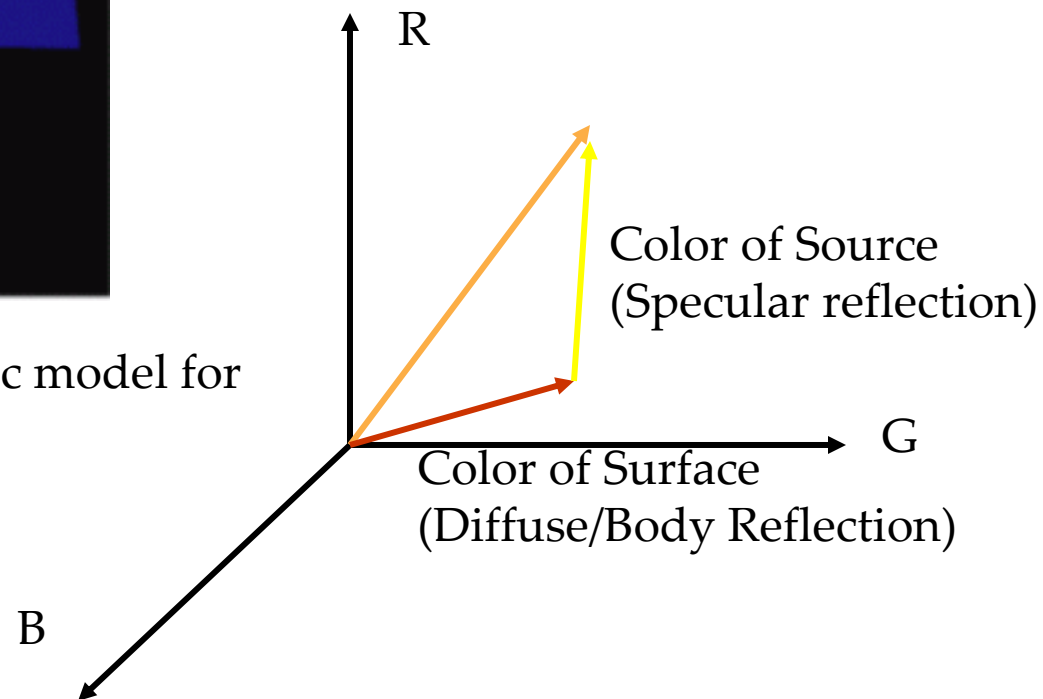
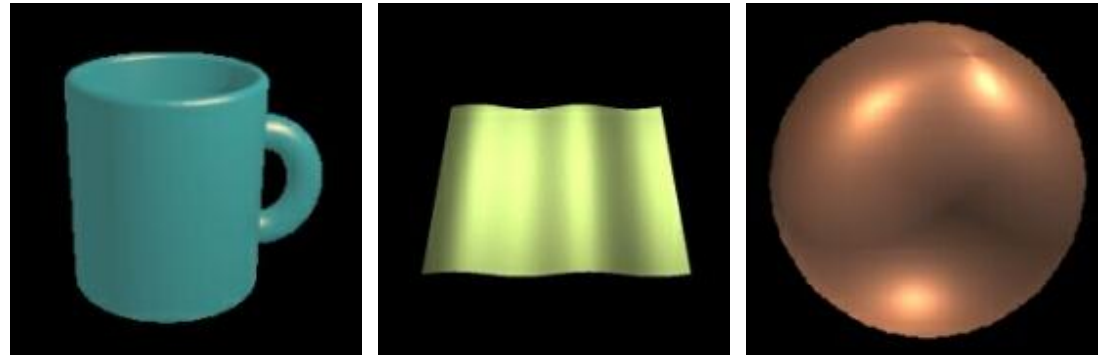
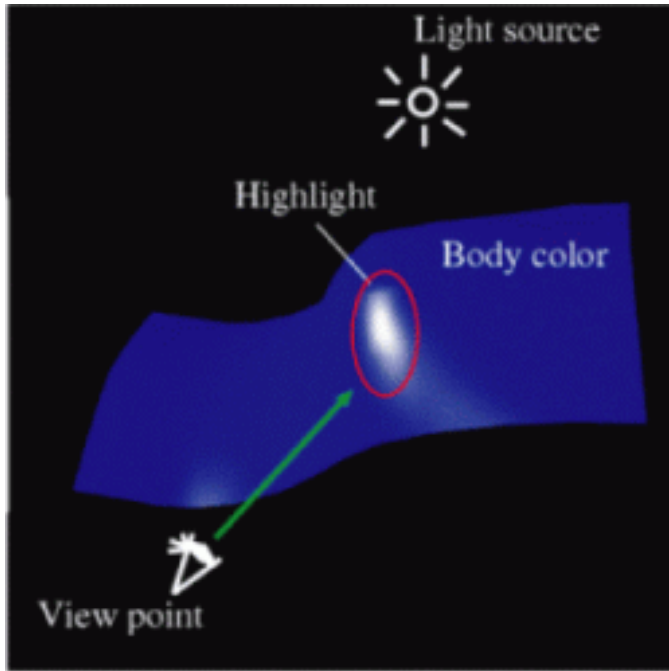


- Roughness simulated by Symmetric V-groves at Microscopic level.
- Distribution on the slopes of the V-grove faces are modeled.
- Each microfacet assumed to behave like a **perfect lambertian surface**.

# A Simple Reflection Model - Dichromatic Reflection

$$\text{Observed Image Color} = a \times \text{Body Color} + b \times \text{Specular Reflection Color}$$

Klinker-Shafer-Kanade 1988



Does not specify any specific model for Diffuse/specular reflection

# Measuring BRDFs

Why bother modeling BRDFs?

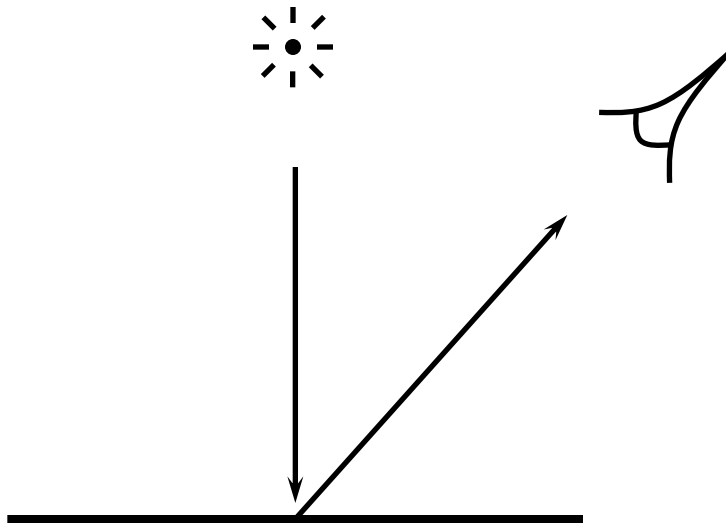
Why not directly measure BRDFs?

- True knowledge of surface properties
- Accurate models for graphics

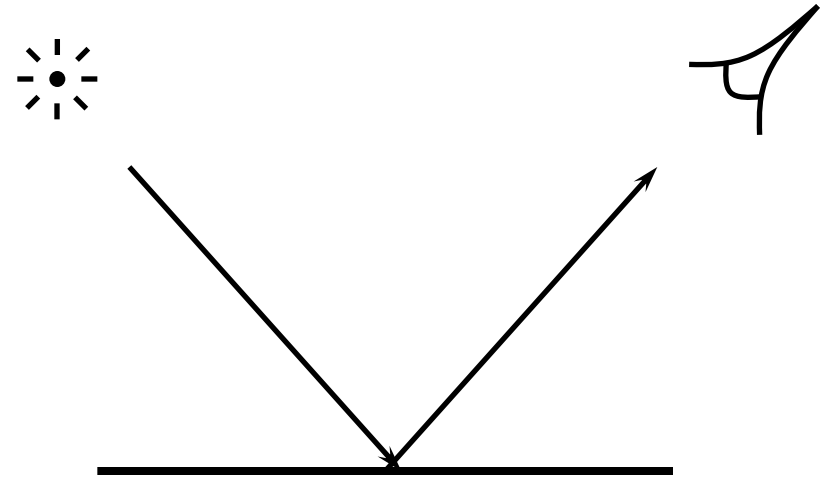
# Measuring BRDFs

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

# Measuring Reflectance



$0^\circ/45^\circ$   
Diffuse Measurement



$45^\circ/45^\circ$   
Specular Measurement

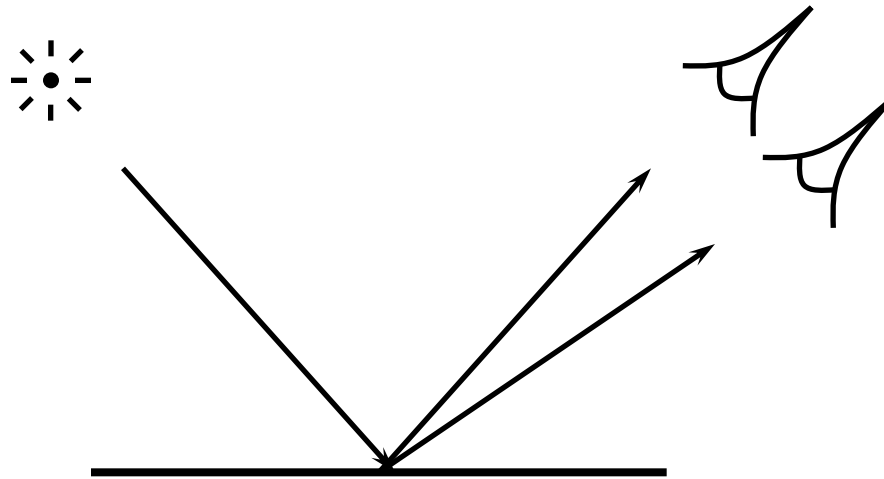


# Gloss Measurements

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

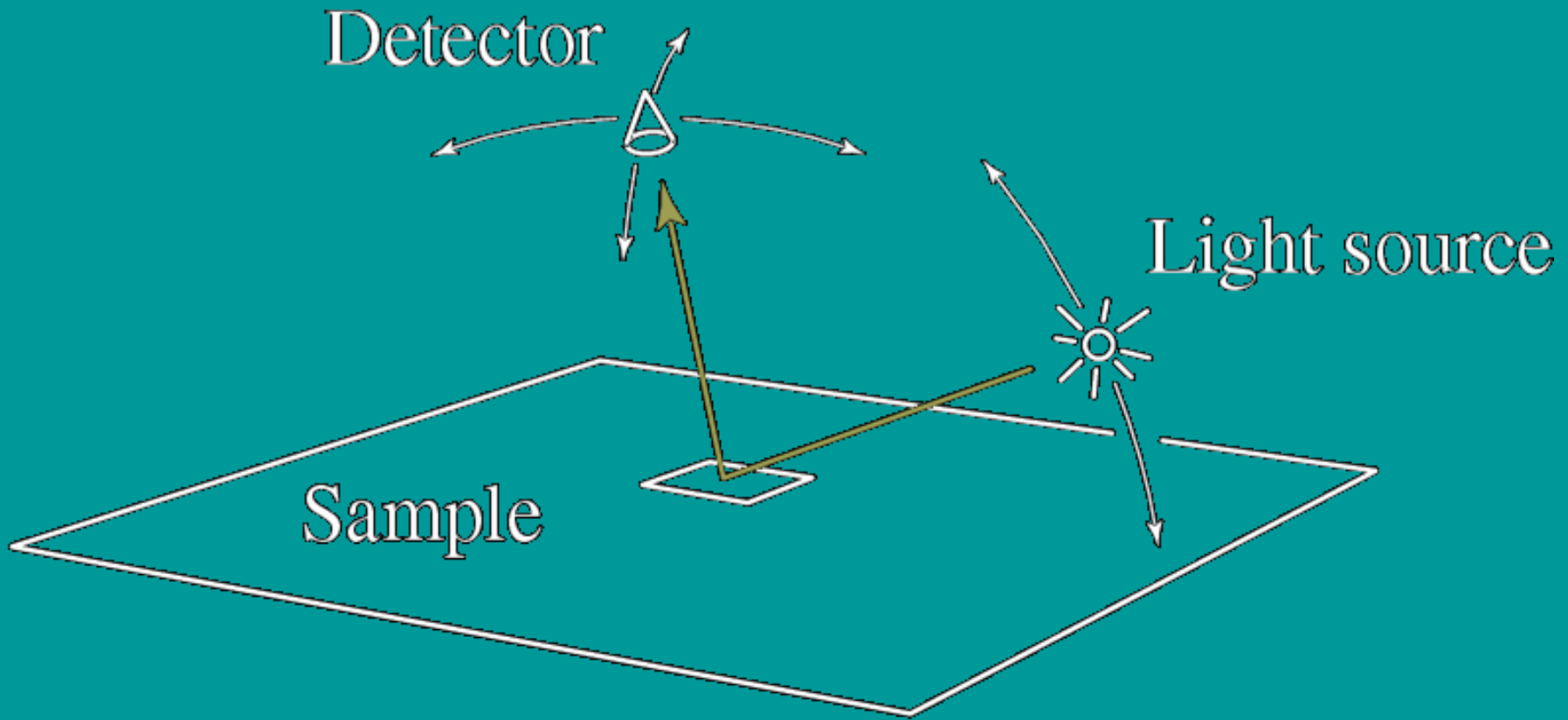
# Gloss Measurements

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



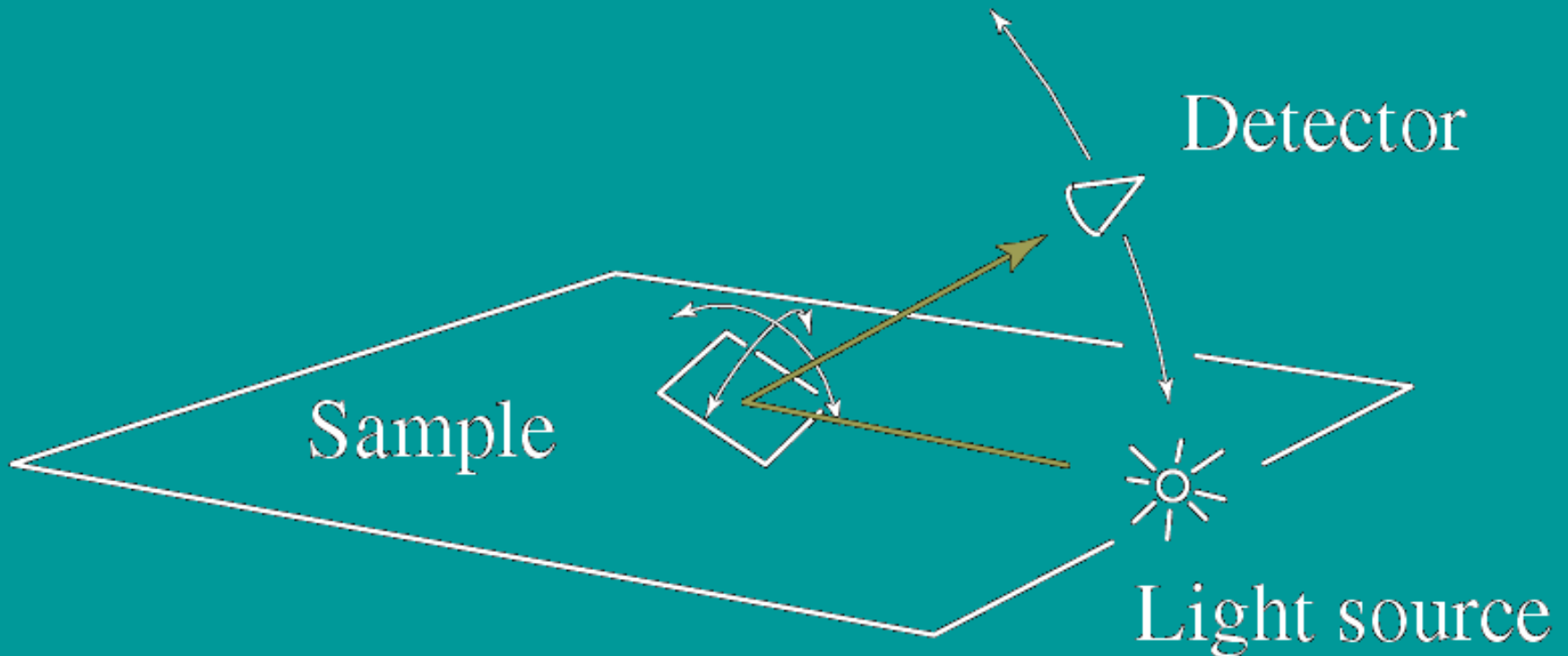
# Gonioreflectometers

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



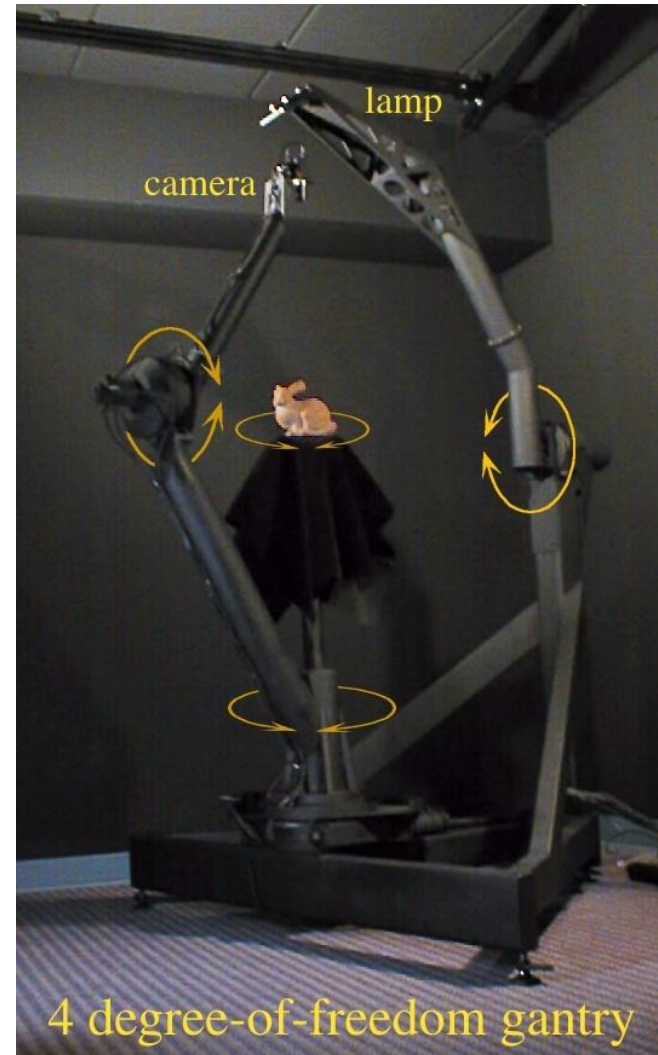
# Gonioreflectometers

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



# Gonioreflectometers

- Can add fourth degree of freedom to measure anisotropic BRDFs

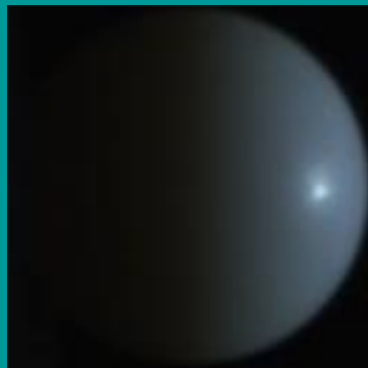
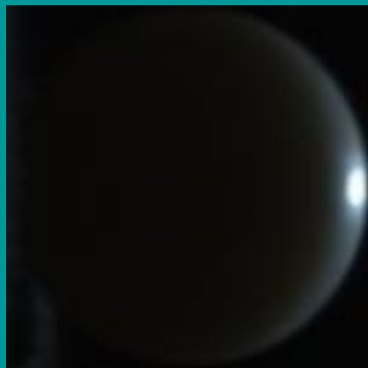
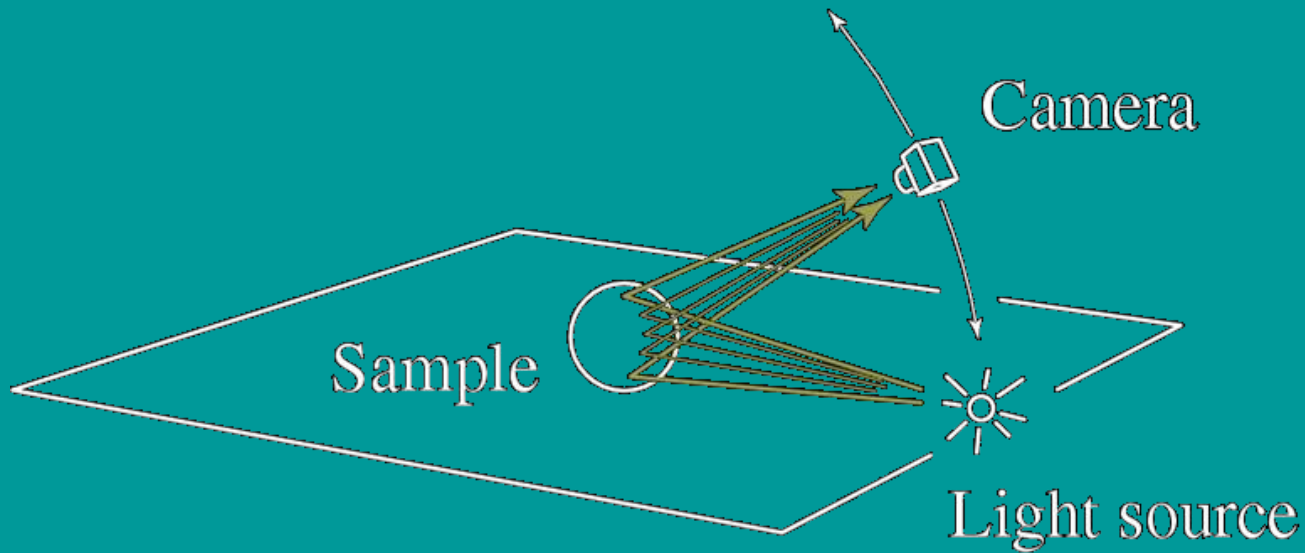


# Image-Based BRDF Measurement

- 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)





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# Measurement

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







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# Measurement

- 20-80 million reflectance measurements per material
- Each tabulated BRDF entails  $90 \times 90 \times 180 \times 3 = 4,374,000$  measurement bins





SIGGRAPH2005

# Rendering from Tabulated BRDFs

- These BRDFs are immediately useful
- Direct renderings from measurements



Nickel

Hematite

Gold Paint

Pink Felt


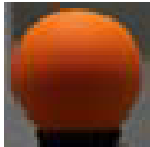


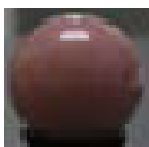


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# Linear Combinations of BRDFs (LCB)

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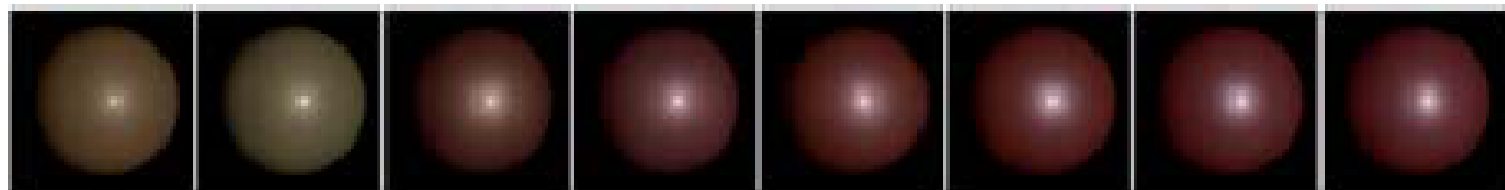
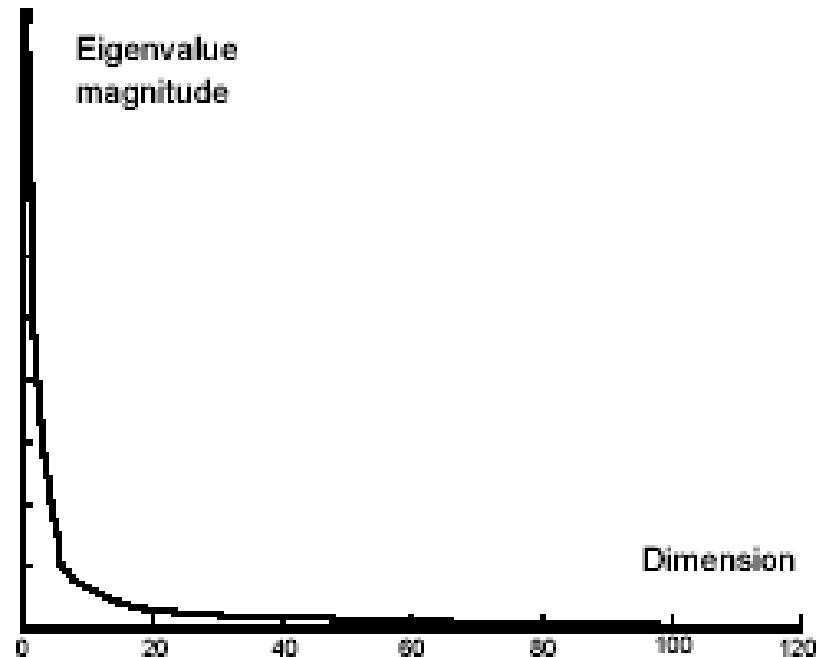
- Can we find a linear combination of our existing BRDFs that match any new one?
- Requires only estimating 100 coefficients for source BRDFs
- Compute a set of 800 constraints that allow estimating these 100 coefficients robustly

$$\alpha_1 \text{  + \alpha_2 \text{  + \alpha_3 \text{  + \alpha_4 \text{  + \dots = \text{ $$



# Linear Analysis (PCA)

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



mean

5

10

20

30

45

60

all



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# Navigation Results



Adding Silver Trait



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# Navigation Results



Adding Specular Trait

# Navigation Results



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Adding Metallic Trait

# Representing Physical Processes



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Steel Oxidation



# Next Step in the Appearance Food Chain

## Textures

Spatially Varying BRDFs

Bi-Directional Texture Distribution Functions (BTF)

CURET Database – [Dana, Nayar 96]

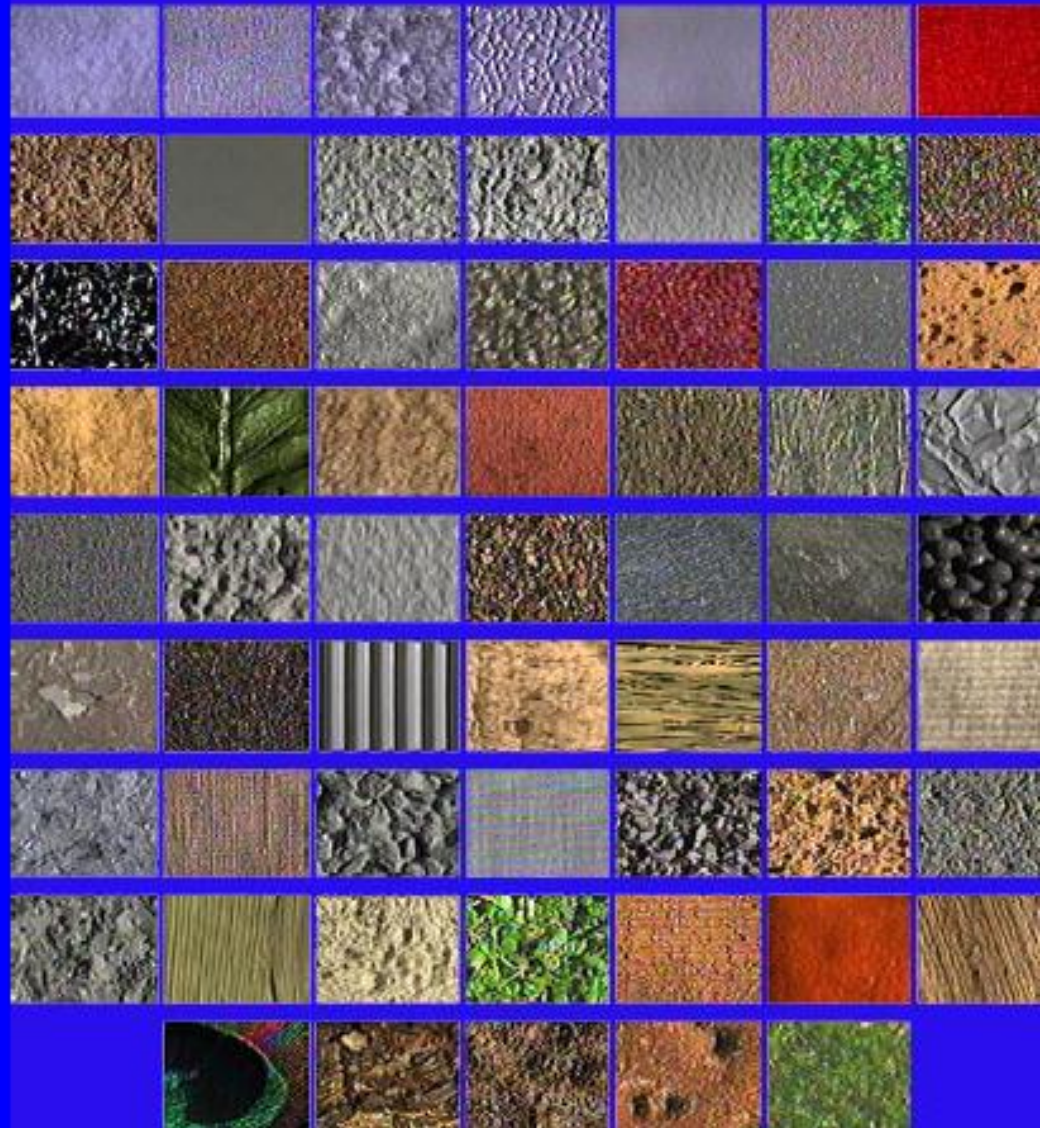
# BRDF vs. BTF



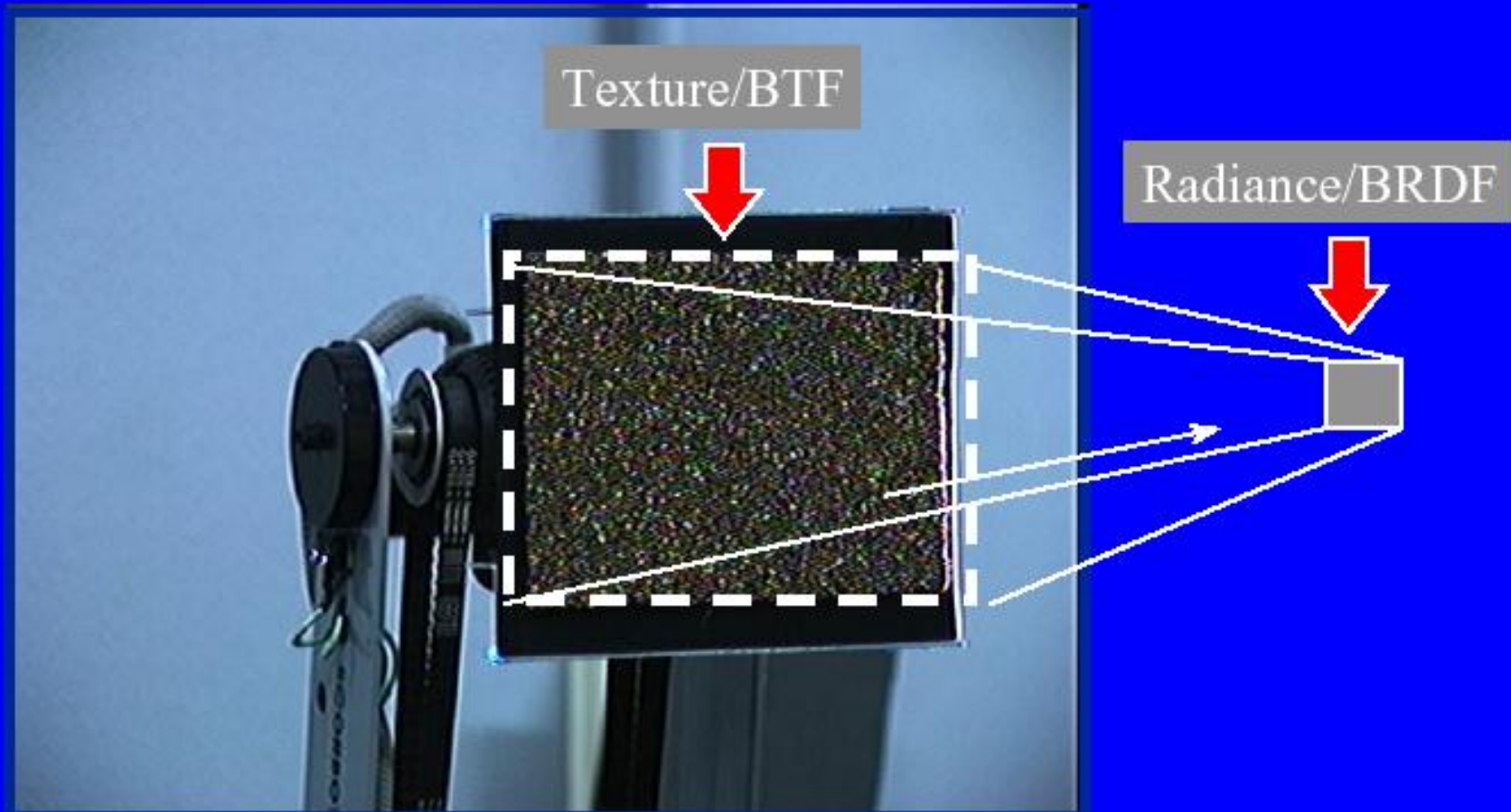
# Samples for Measurements

## 61 samples:

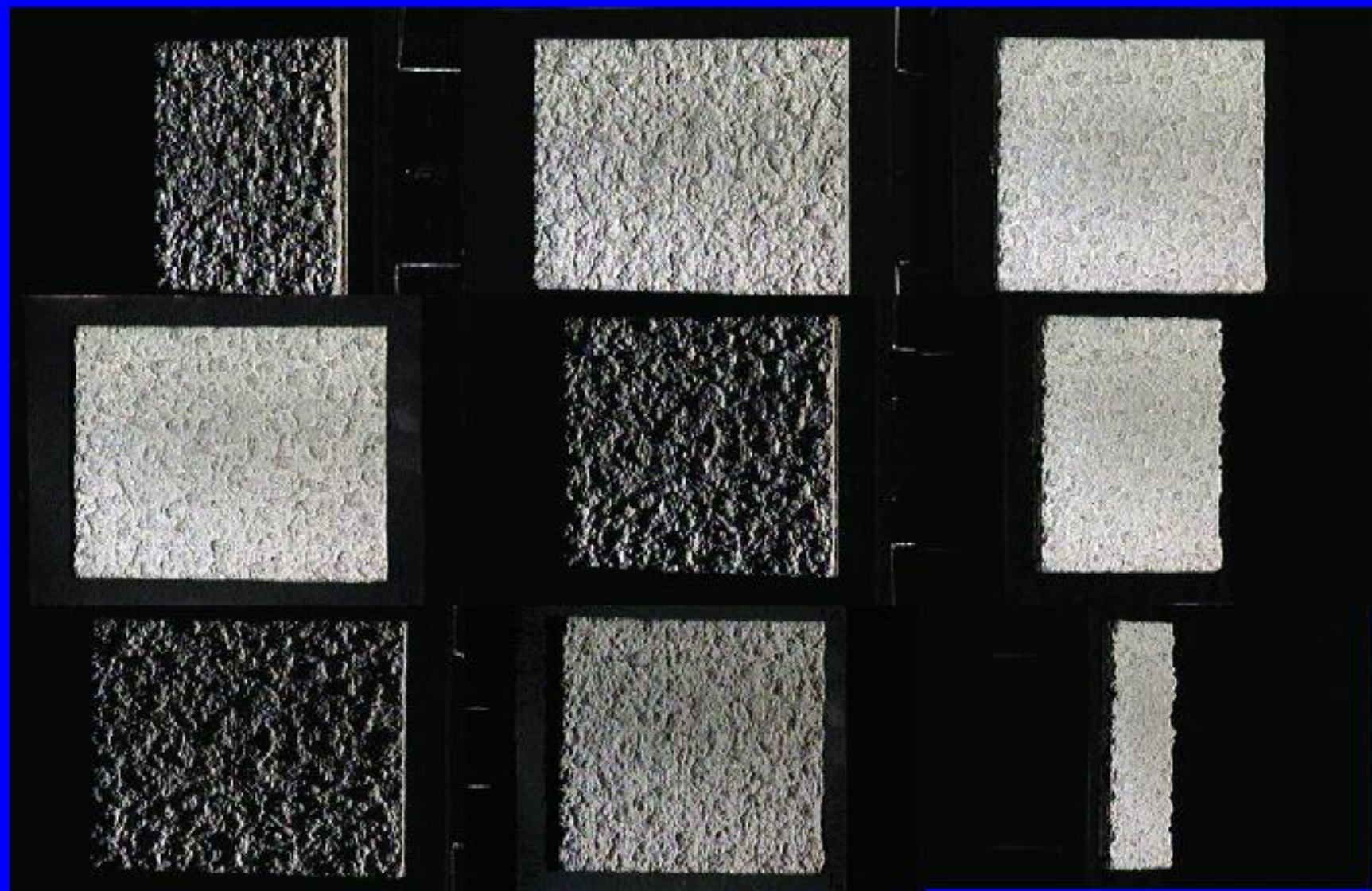
- *specular* (foil, artificial grass)
- *diffuse* (brick, plaster)
- *natural* (fur, moss)
- *man-made* (velvet, leather)
- *isotropic* (bread, concrete)
- *anisotropic* (corn husk, wood)



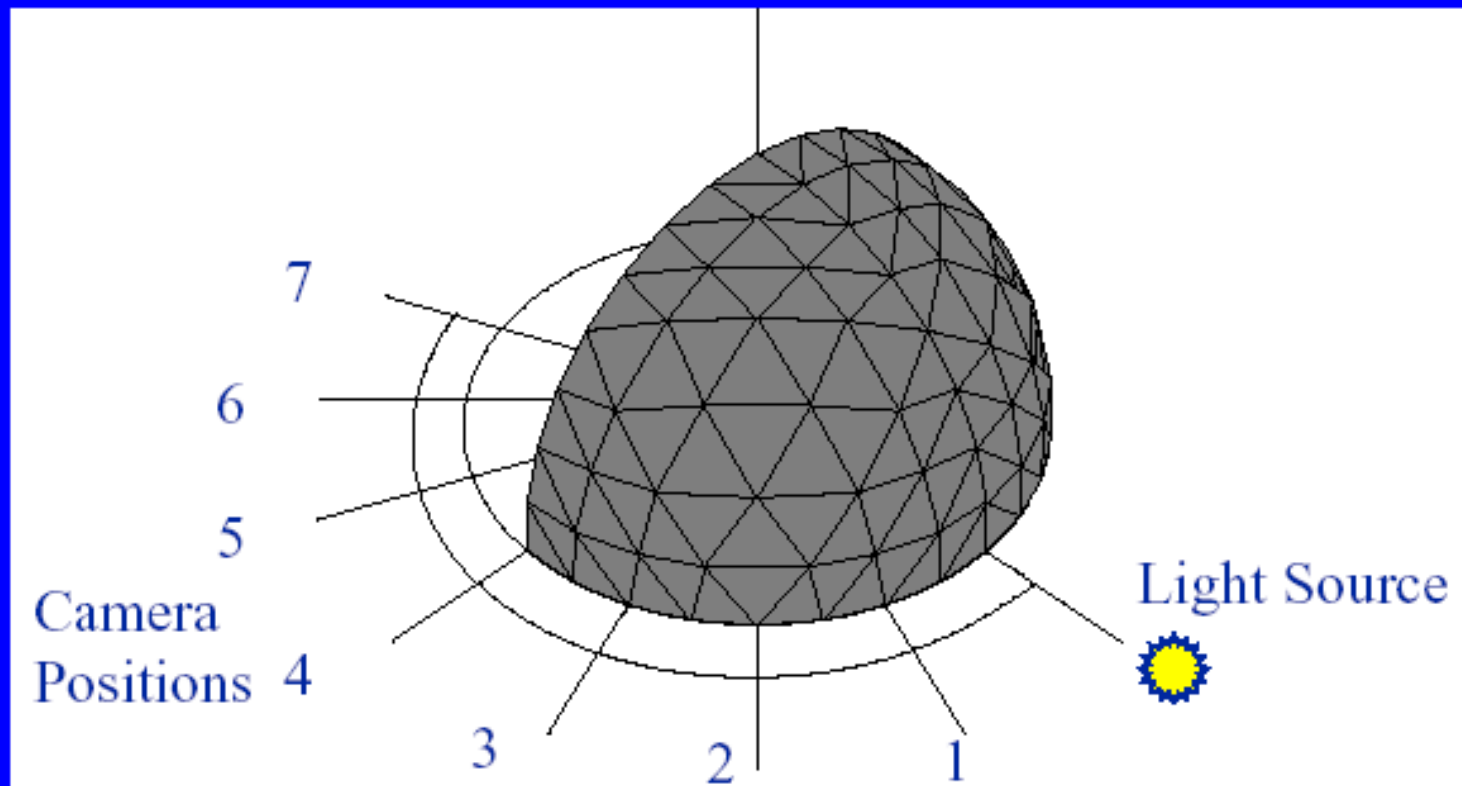
# Measurement Methods



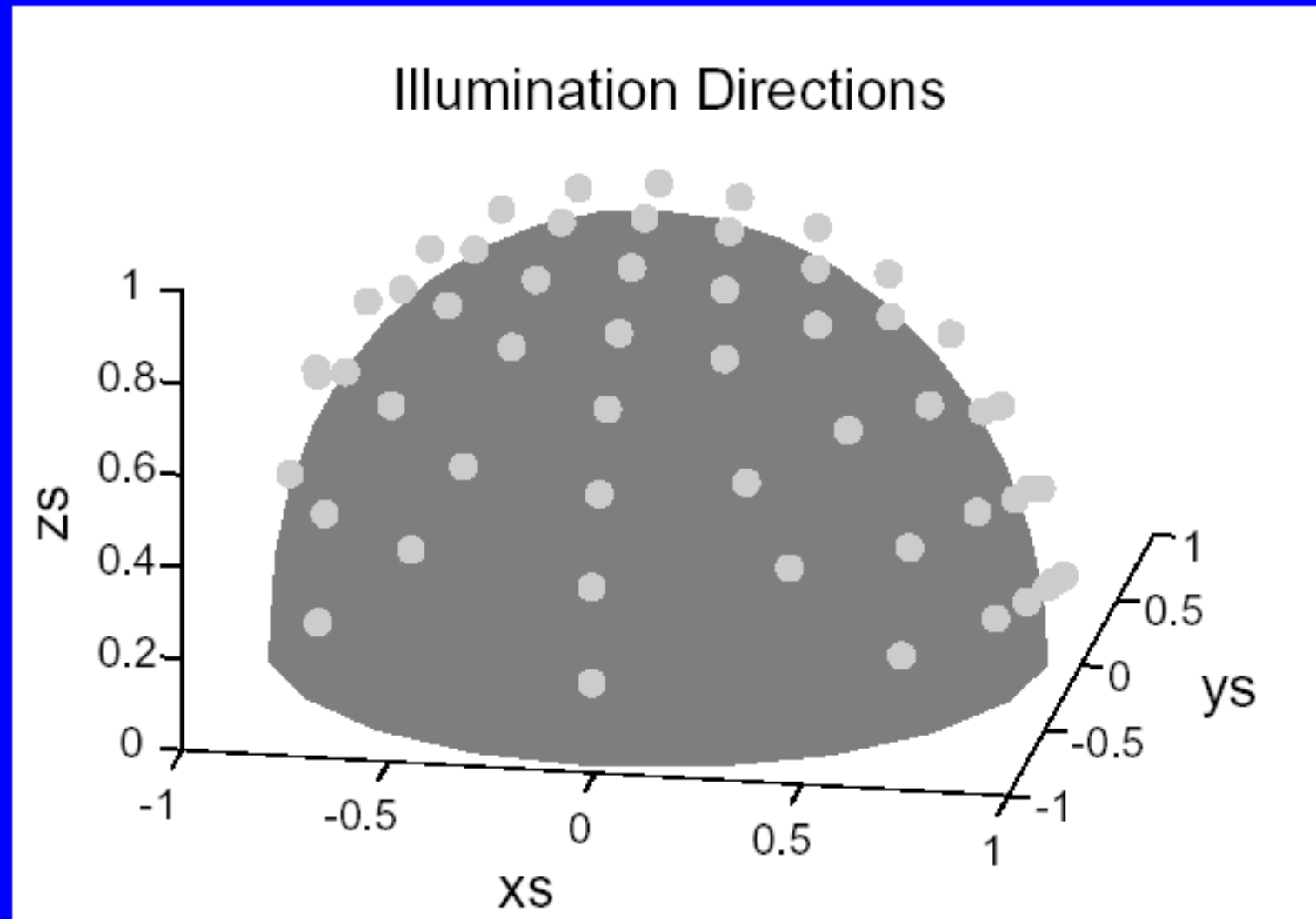
# Example images



# Measurement Methods



# Measurement Methods



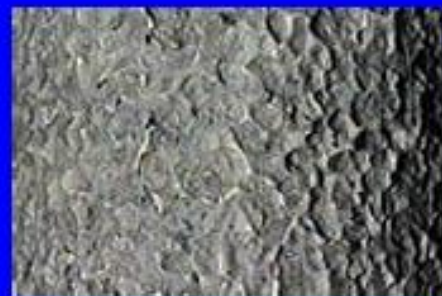
# Texture-mapping using BTF



standard  
texture-mapping



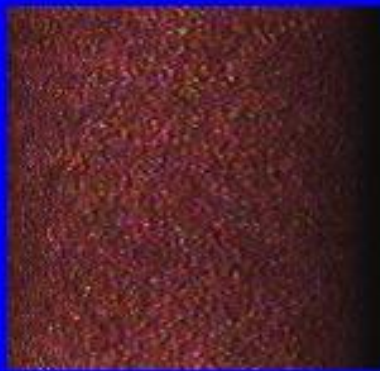
texture-mapping  
with the BTF





# Texture-mapping using BTF

standard  
texture-mapping



texture-mapping  
with the BTF

# Materials Change with Time

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