# Computational Photography

Instructor: Sanjeev J. Koppal

MWF

1145am-1235pm

BEN 328

# Acknowledgements

Some slides from

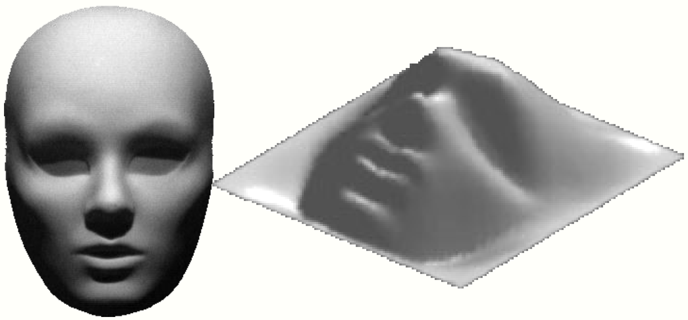
Narasimhan (Carnegie Mellon),

Zickler (Harvard),

and

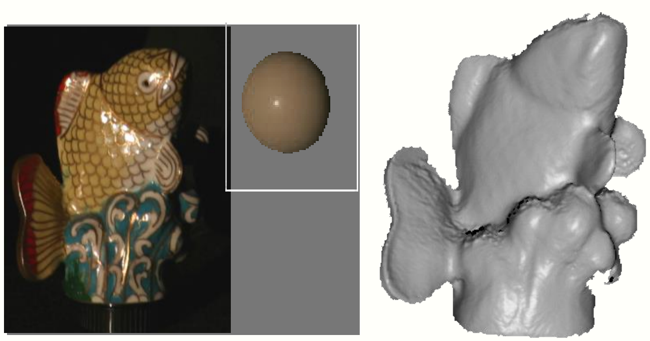
Efros (Berkeley)

# Methods Relying on Surface Reflectance



Shape from Shading

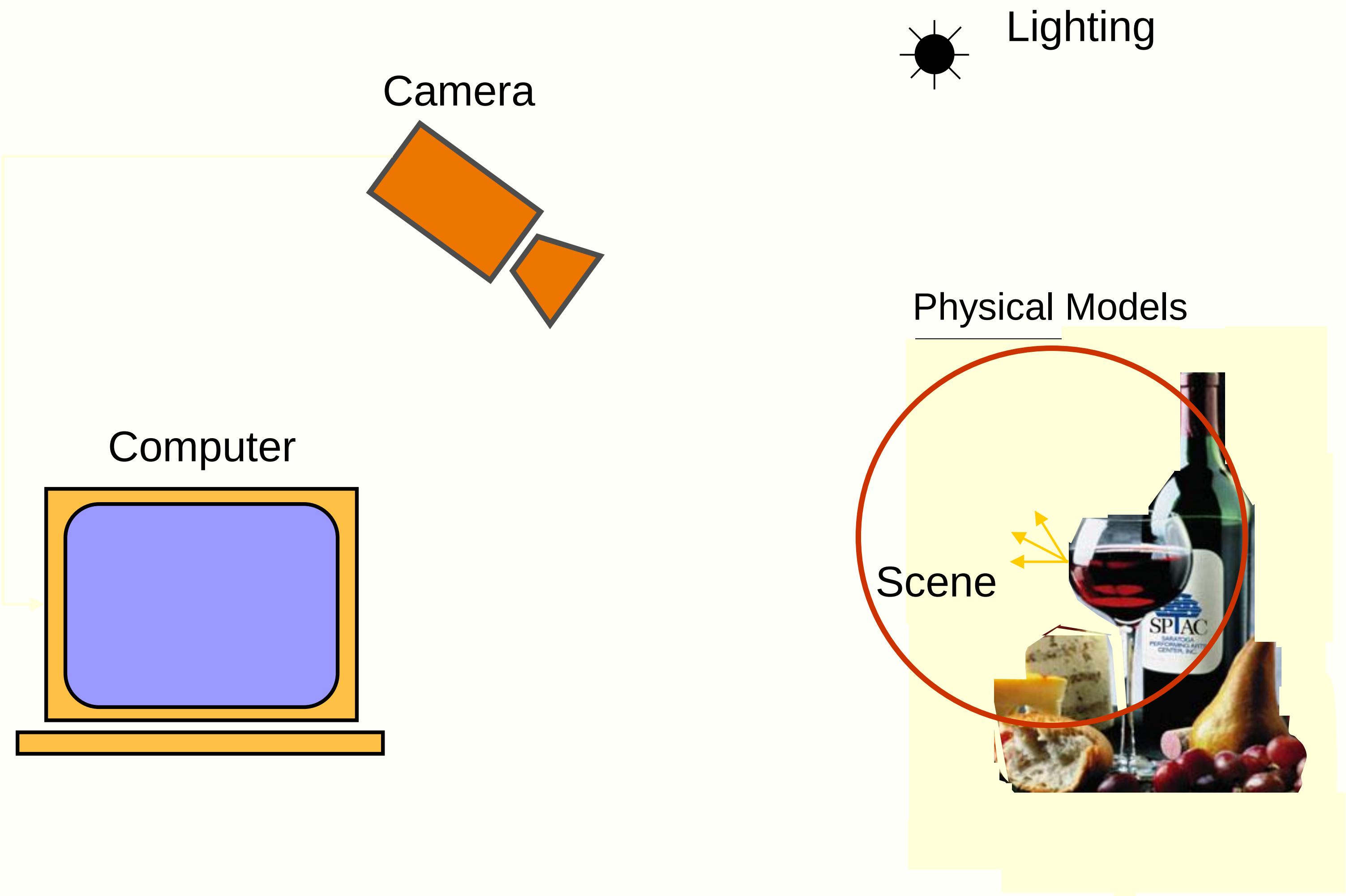

Texture Modeling



Photometric Stereo

Reflection Separation

# Computer Vision: Building Machines that See




We need to understand the relation between
the lighting, surface reflectance and medium and the image of the scene.

# Surface Appearance

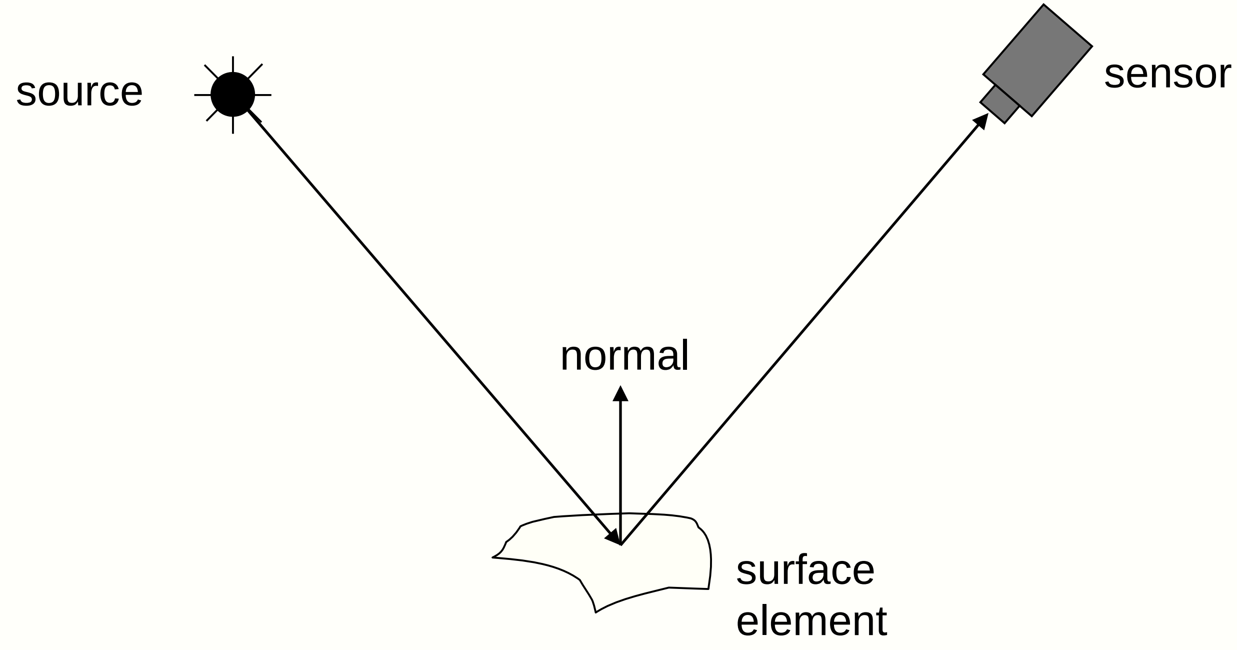
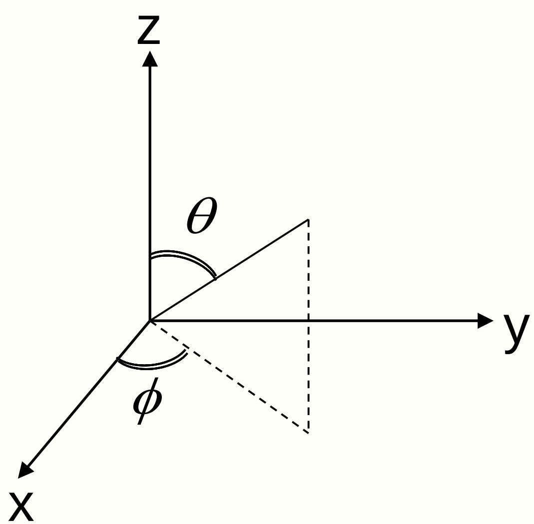
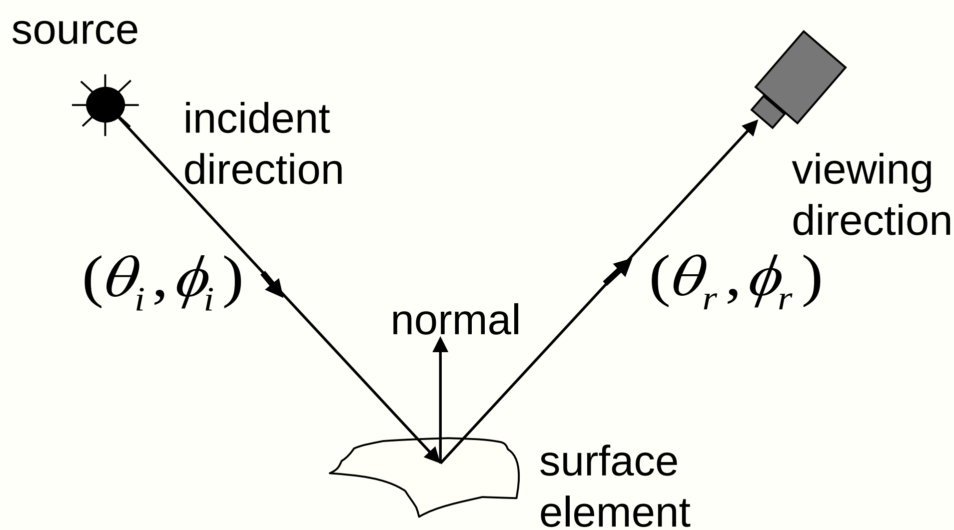



Image intensities = *f* ( normal, surface reflectance, illumination )

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 $(\theta_i, \phi_i)$

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

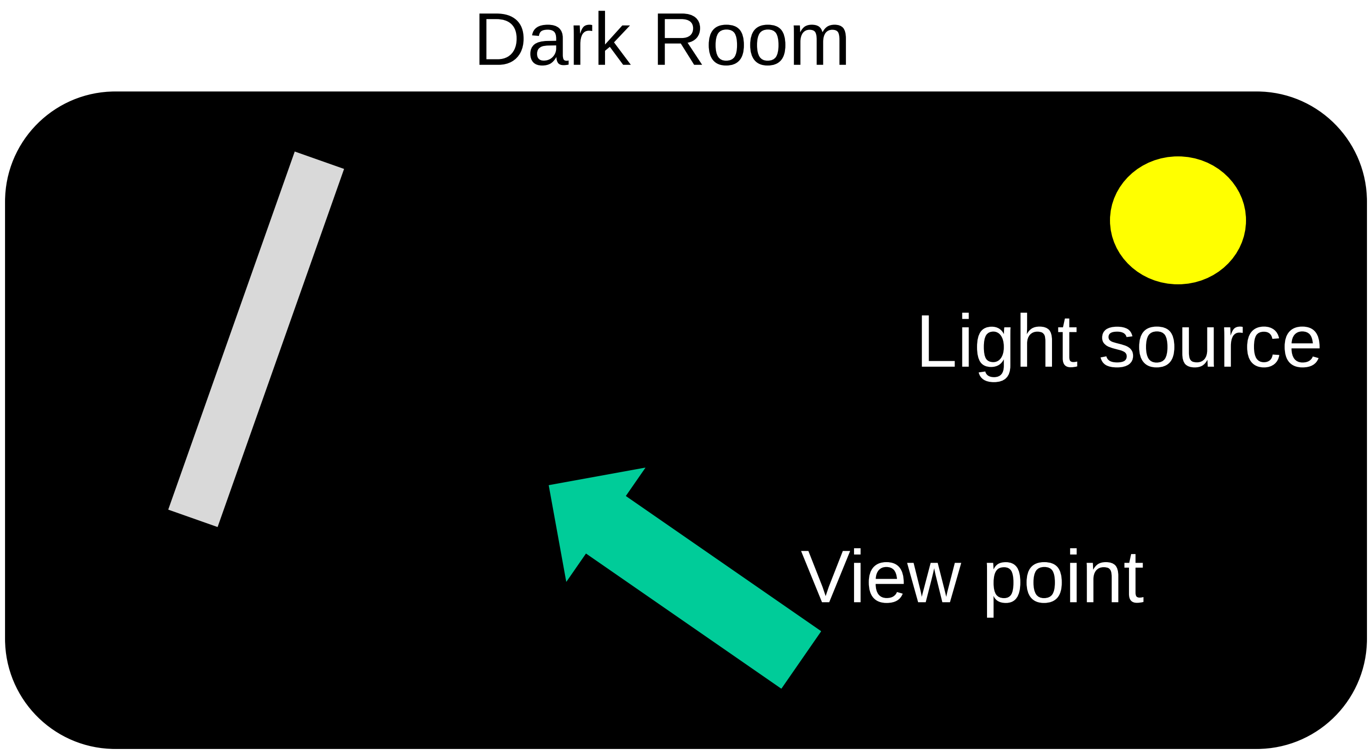
$$\text{BRDF}: f(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{L^{surface}(\theta_r, \phi_r)}{E^{surface}(\theta_i, \phi_i)}$$

# Participation

*What is the BRDF of a mirror?*

# Participation

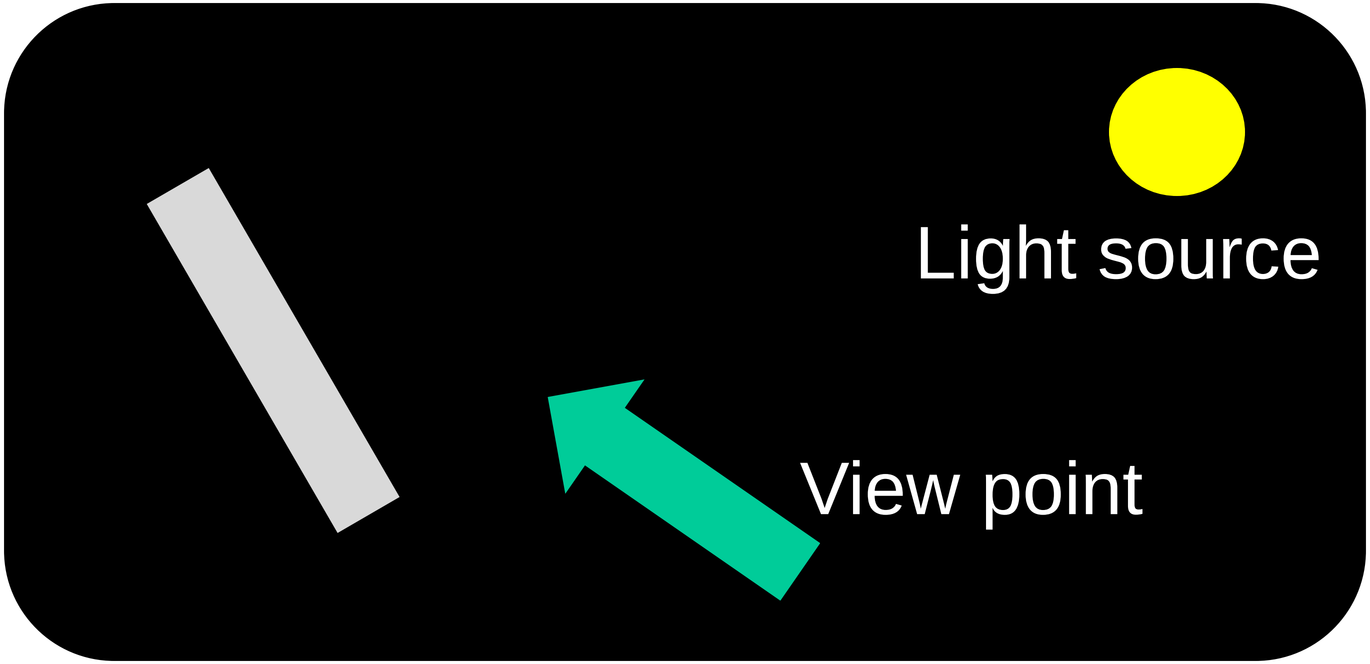
*What do we see?*



# Participation

*Now?*

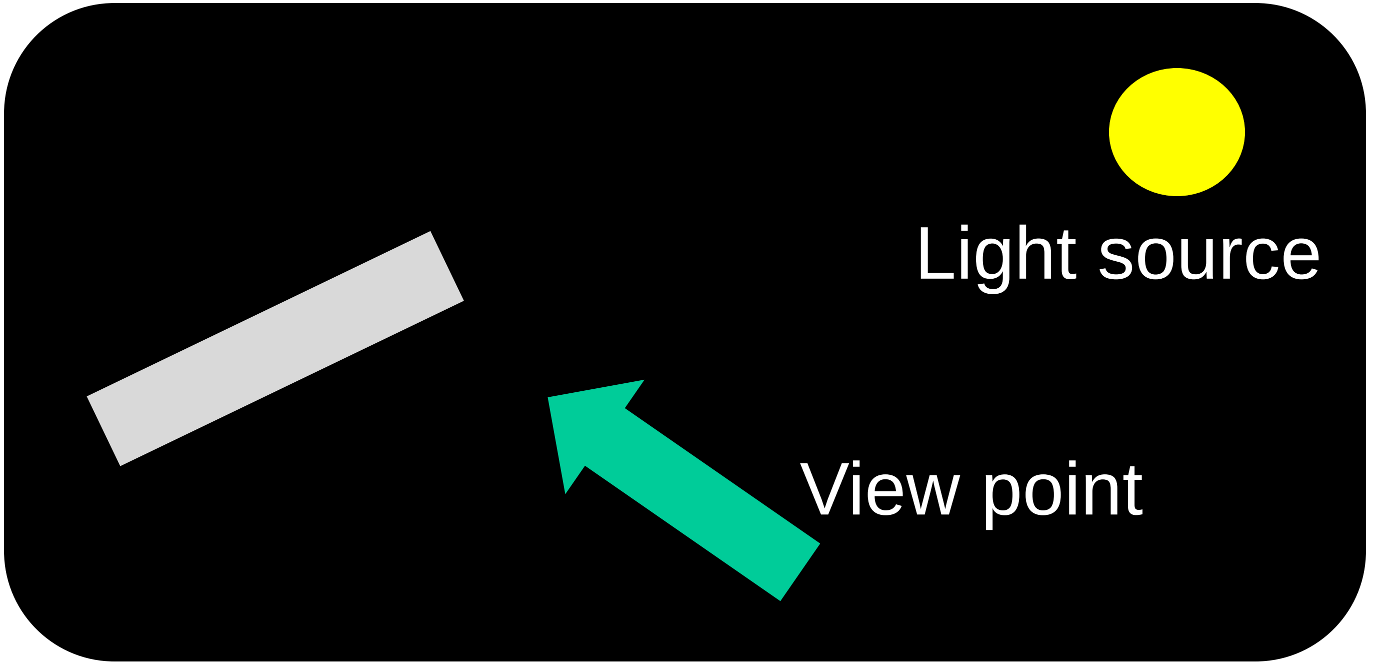
Dark Room



# Participation

*Now?*

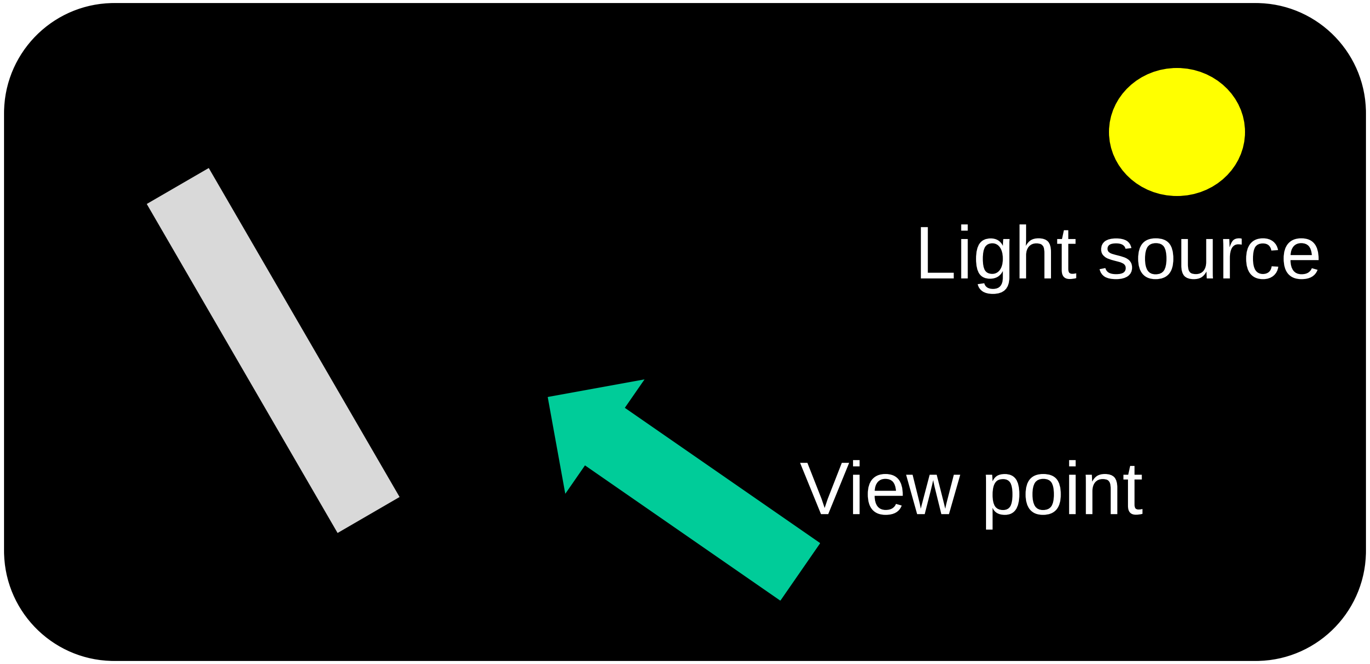
Dark Room



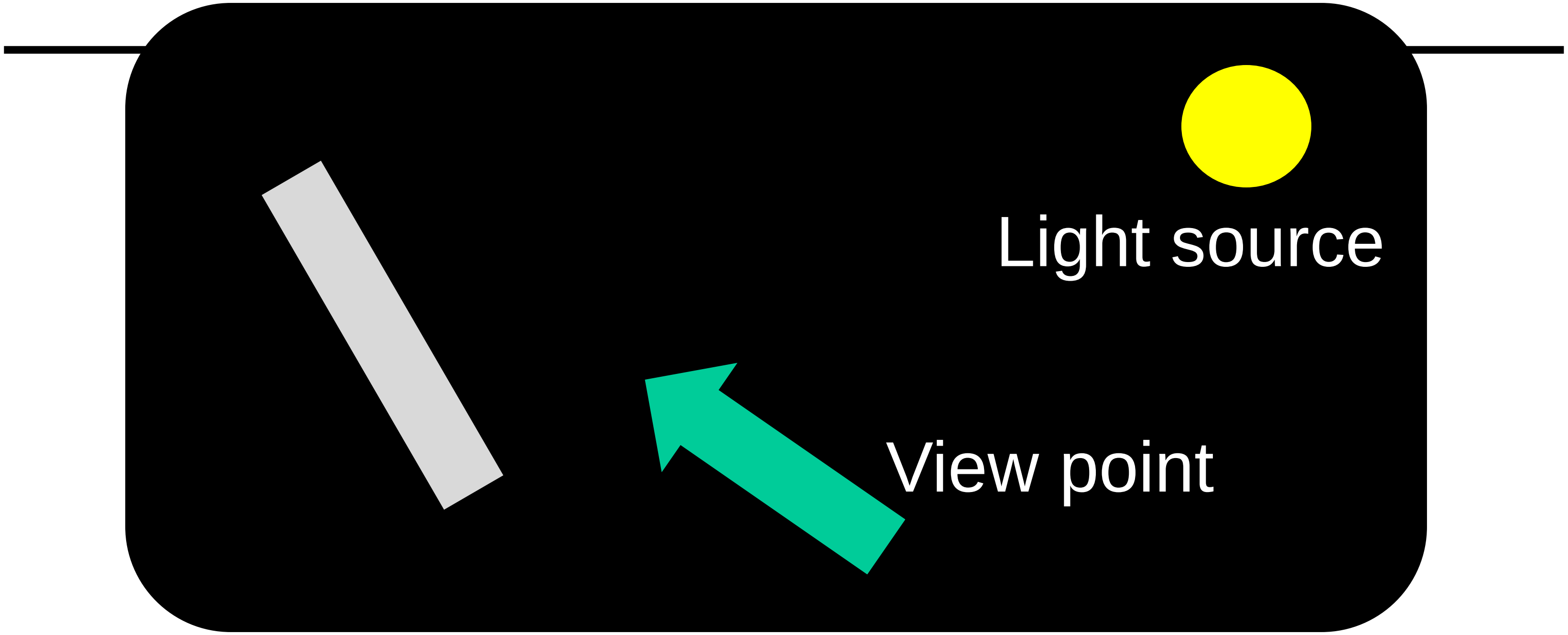
# Participation

*Over angle?*

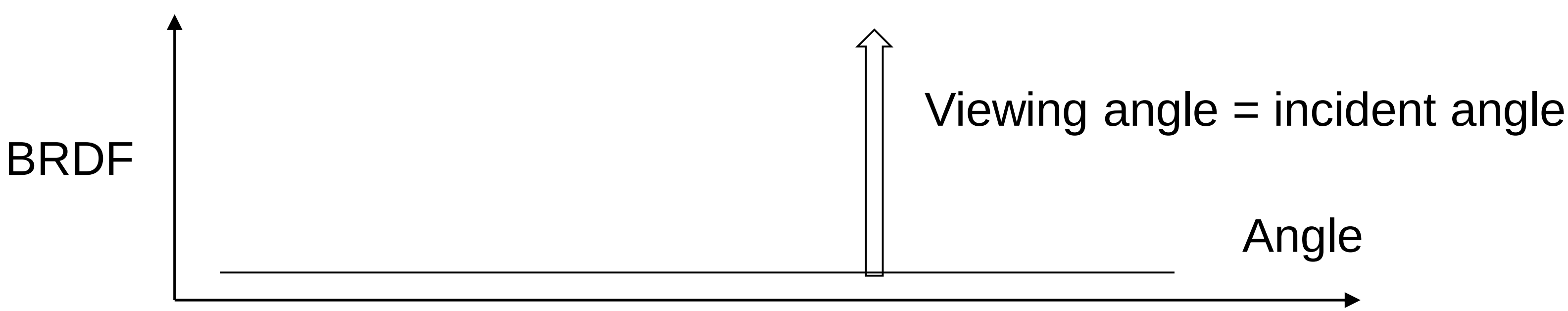
Dark Room



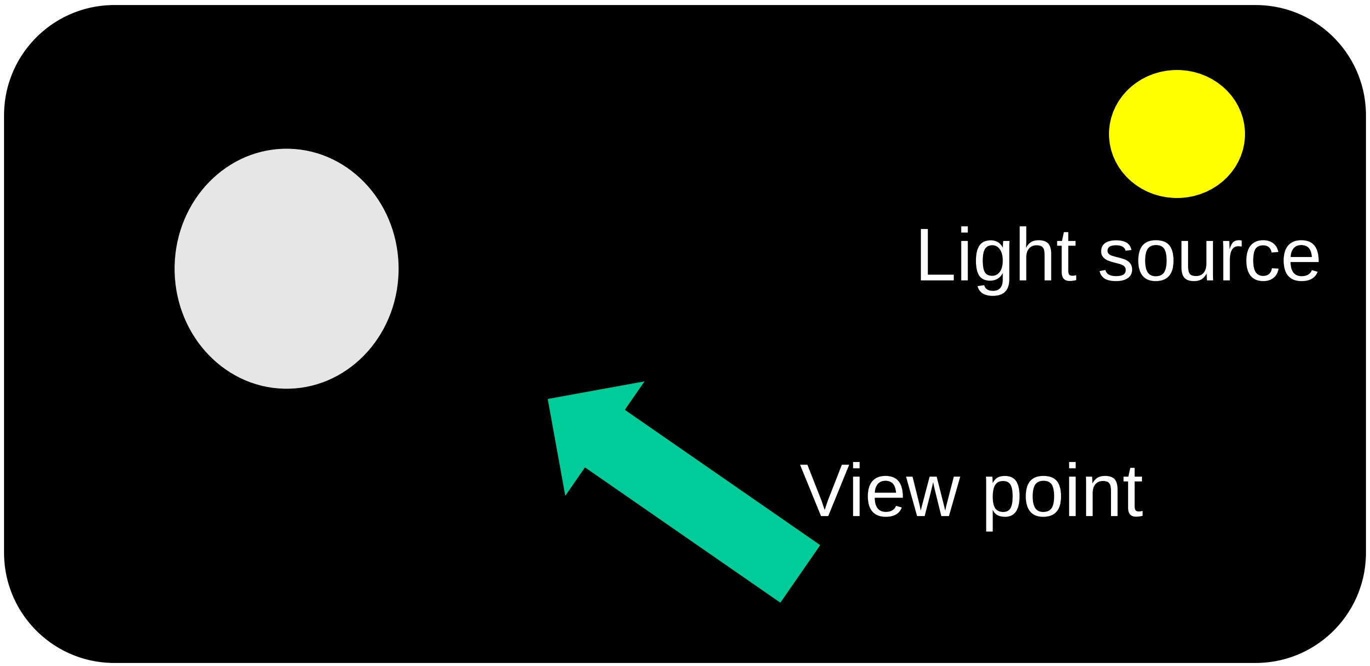
# Dark Room



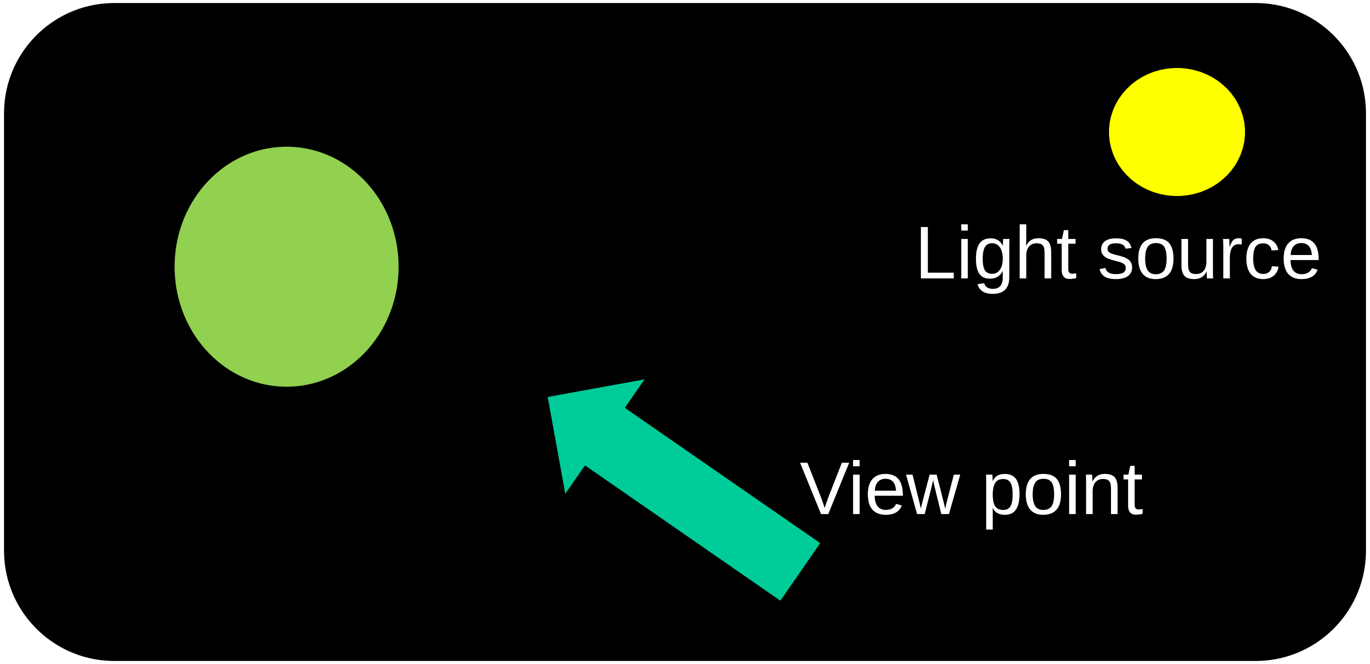

$$\text{BRDF}: f(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{L^{surface}(\theta_r, \phi_r)}{E^{surface}(\theta_i, \phi_i)}$$



# The reflectance of a mirror sphere?

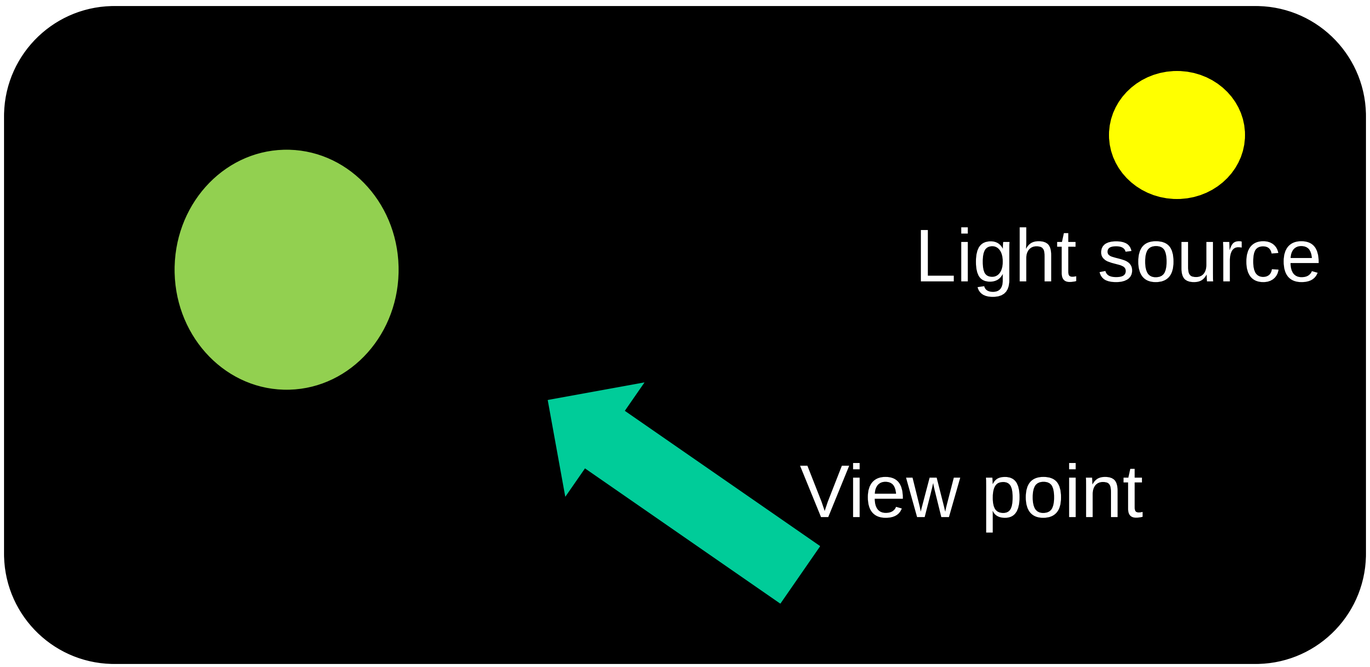


# What if I change the color of the sphere?

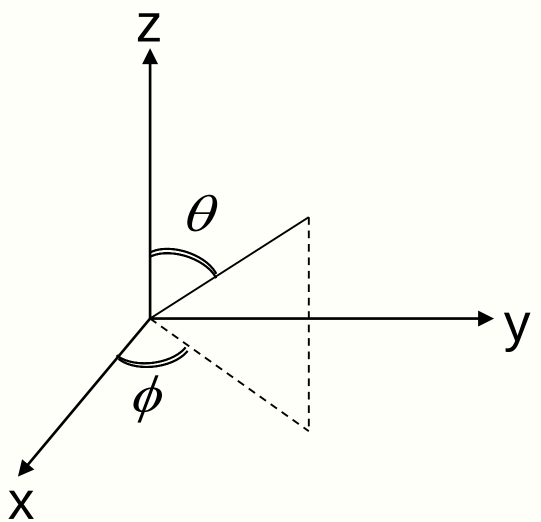


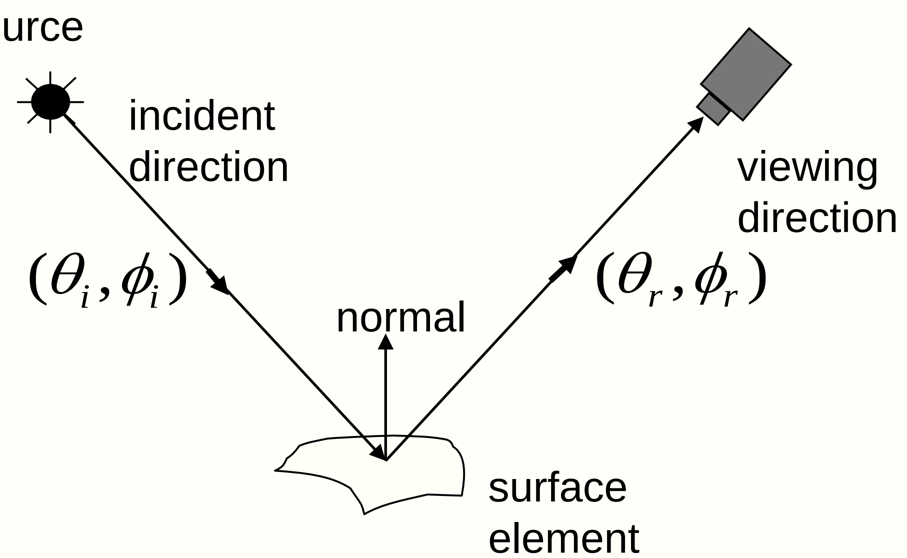
# Colored metal

# What if I change the color of the sphere?



# Important Properties of BRDFs




- Rotational Symmetry:

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

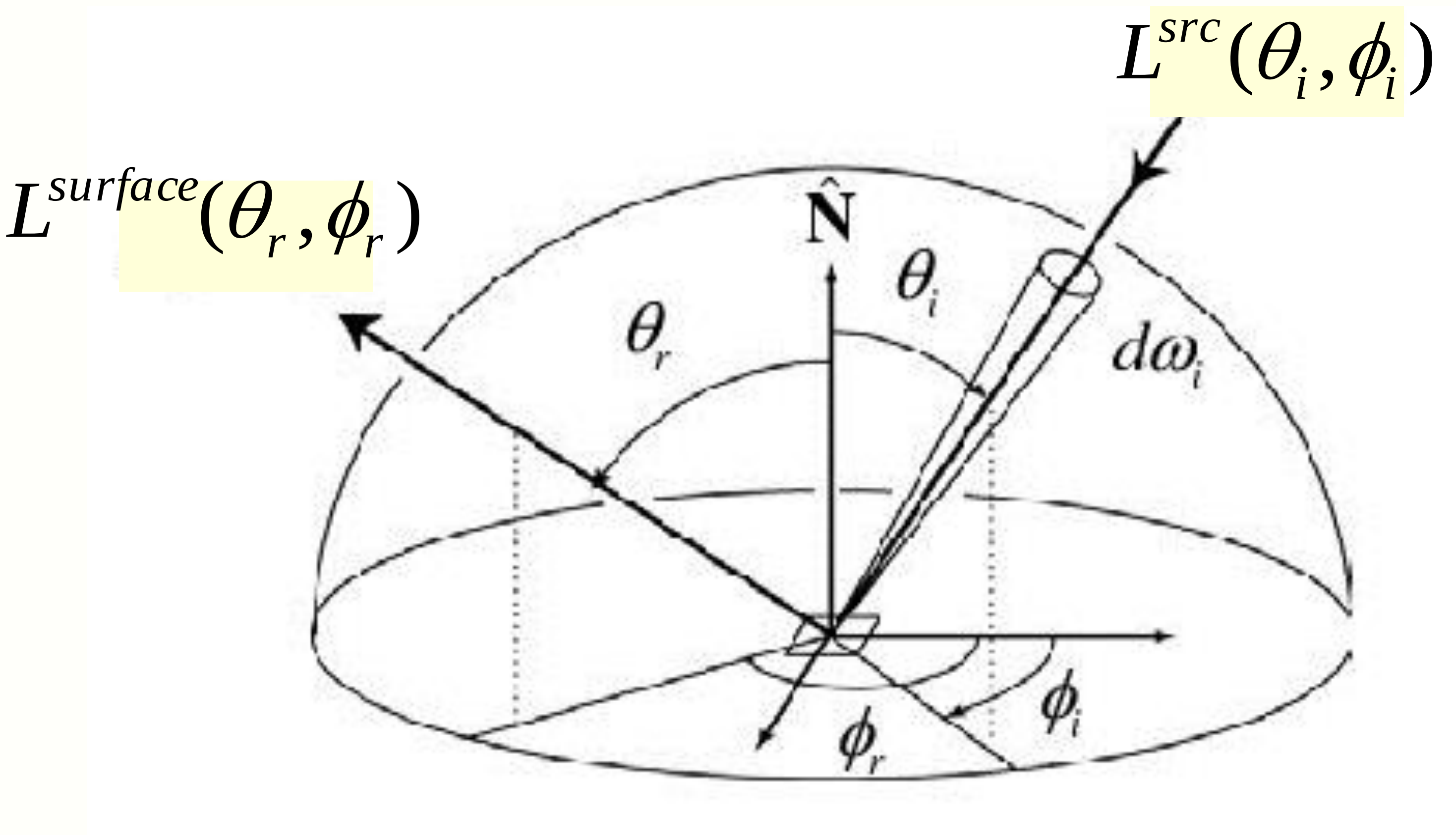
BRDF is only a function of 3 variables : $f(\theta_i, \theta_r, \phi_i - \phi_r)$

- Helmholtz Reciprocity: (follows from $2^{nd}$ Law of Thermodynamics)

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

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

# Derivation of the Scene Radiance Equation




From the definition of BRDF:

$$L^{surface}(\theta_r, \phi_r) \quad = \quad E^{surface}(\theta_i, \phi_i)\, f(\theta_i, \phi_i; \theta_r, \phi_r)$$

# Derivation of the Scene Radiance Equation – Important!

From the definition of BRDF:

$$L^{surface}(\theta_r, \phi_r) = \underline{E^{surface}(\theta_i, \phi_i)}\, f(\theta_i, \phi_i; \theta_r, \phi_r)$$

Write Surface Irradiance in terms of Source Radiance:

$$L^{surface}(\theta_r, \phi_r) = \underline{L^{src}(\theta_i, \phi_i)}\, f(\theta_i, \phi_i; \theta_r, \phi_r)\, \underline{\cos\theta_i d\omega_i}$$

# Participation

*Why the cosine term?*

# Participation

*Foreshortening*

# Derivation of the Scene Radiance Equation – Important!

From the definition of BRDF:

$$L^{surface}(\theta_r,\phi_r) \quad = \quad \underline{E^{surface}(\theta_i,\phi_i)}\, f(\theta_i,\phi_i;\theta_r,\phi_r)$$

Write Surface Irradiance in terms of Source Radiance:

$$L^{surface}(\theta_r,\phi_r) \quad = \quad \underline{L^{src}(\theta_i,\phi_i)}\, f(\theta_i,\phi_i;\theta_r,\phi_r)\, \underline{\cos\theta_i d\omega_i}$$

Integrate over entire hemisphere of possible source directions:

$$L^{surface}(\theta_r,\phi_r) \quad = \quad \int_{2\pi} L^{src}(\theta_i,\phi_i)\, f(\theta_i,\phi_i;\theta_r,\phi_r)\cos\theta_i\ \underline{d\omega_i}$$

Convert from solid angle to theta-phi representation:

$$L^{surface}(\theta_r,\phi_r) \quad = \quad \int_{-\pi}^{\pi}\int_{0}^{\pi/2} L^{src}(\theta_i,\phi_i)\, f(\theta_i,\phi_i;\theta_r,\phi_r)\cos\theta_i\ \underline{\sin\theta_i d\theta_i d\phi_i}$$

# Lesson 1

Reflectance depends on surface normals, and involves lots of angles.

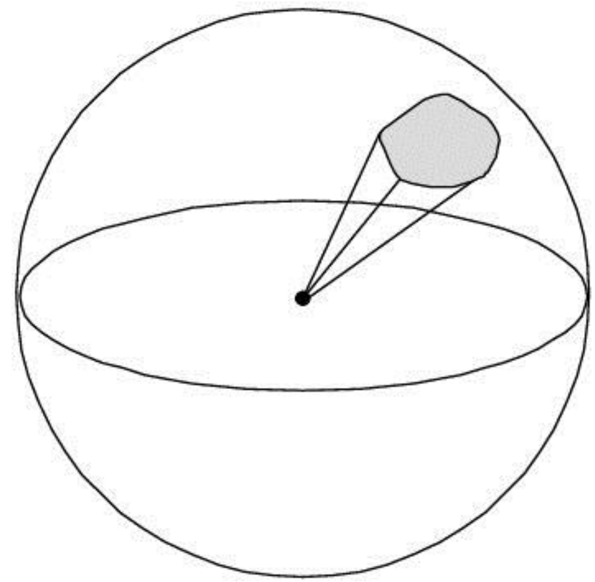
# Angles and Solid Angles

- **Angle** $\theta = \frac{l}{r}$

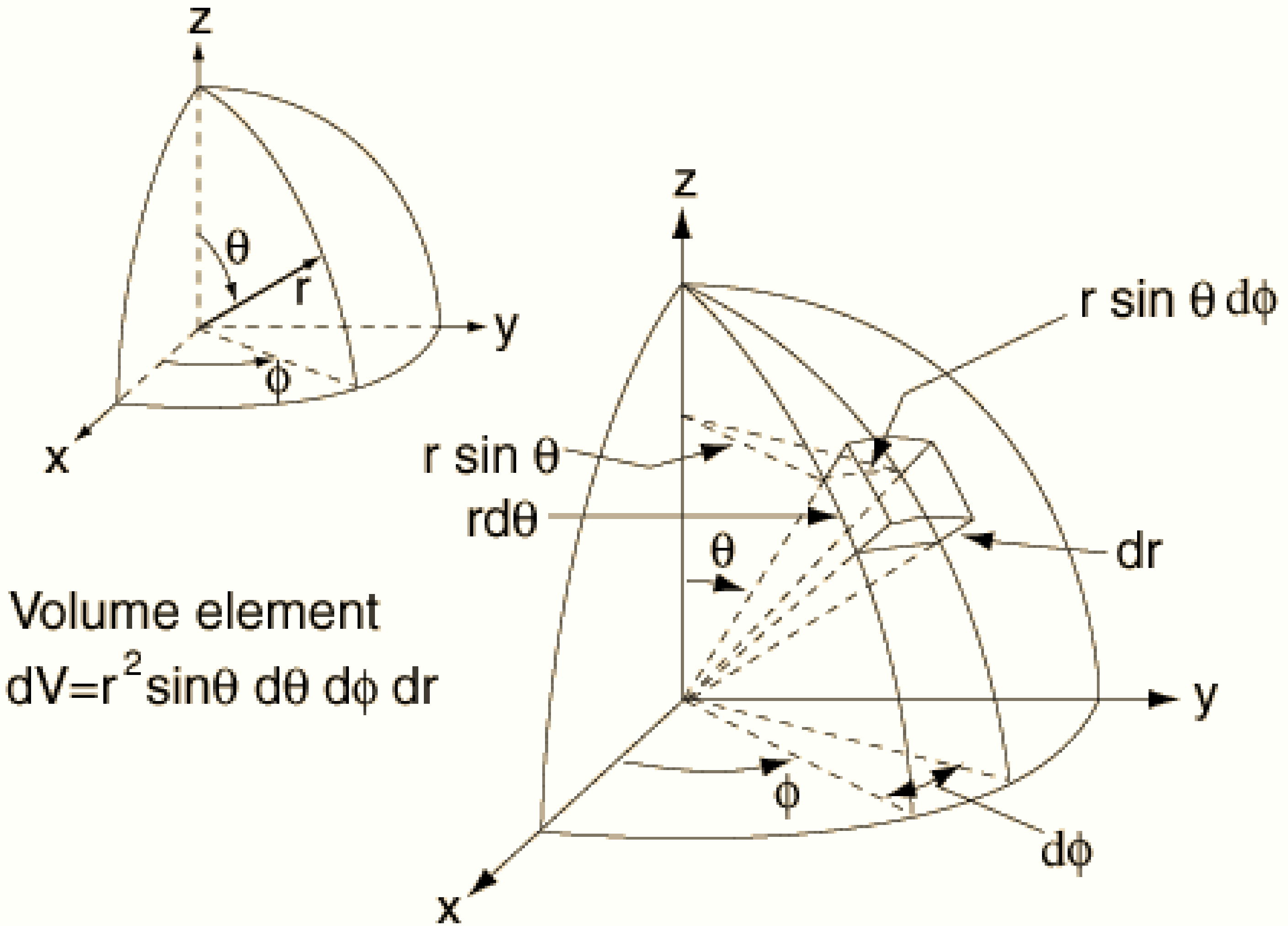
  $\Rightarrow$ **circle has $2\pi$ radians**

- **Solid angle** $\Omega = \frac{A}{R^2}$

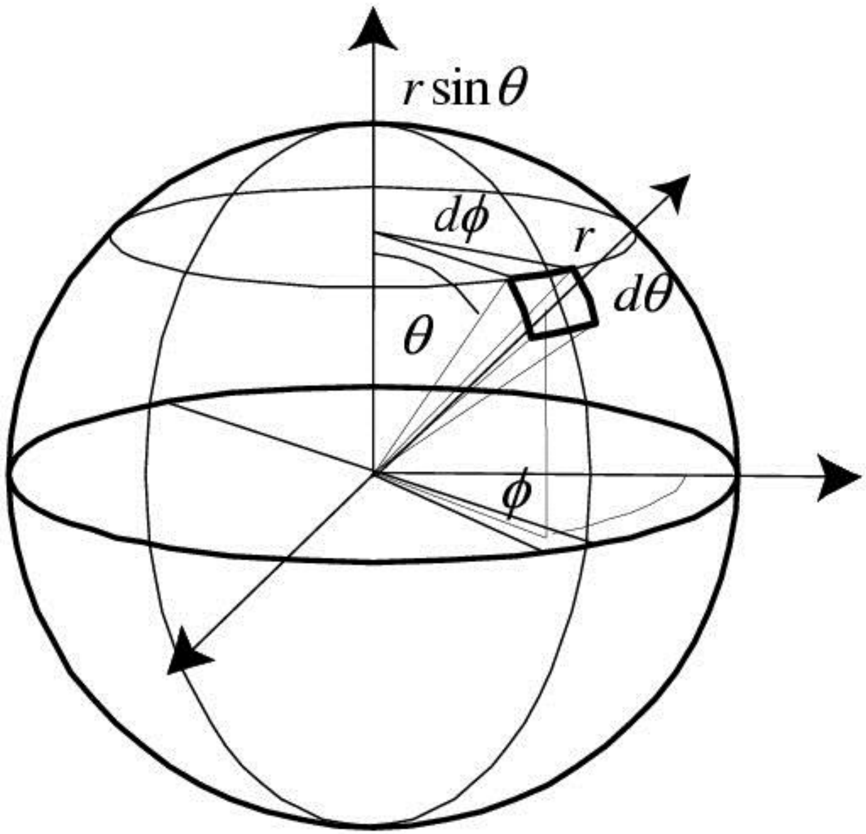
  $\Rightarrow$ **sphere has $4\pi$ steradians**



# Differential Solid Angle and Spherical Polar Coordinates



# Differential Solid Angles

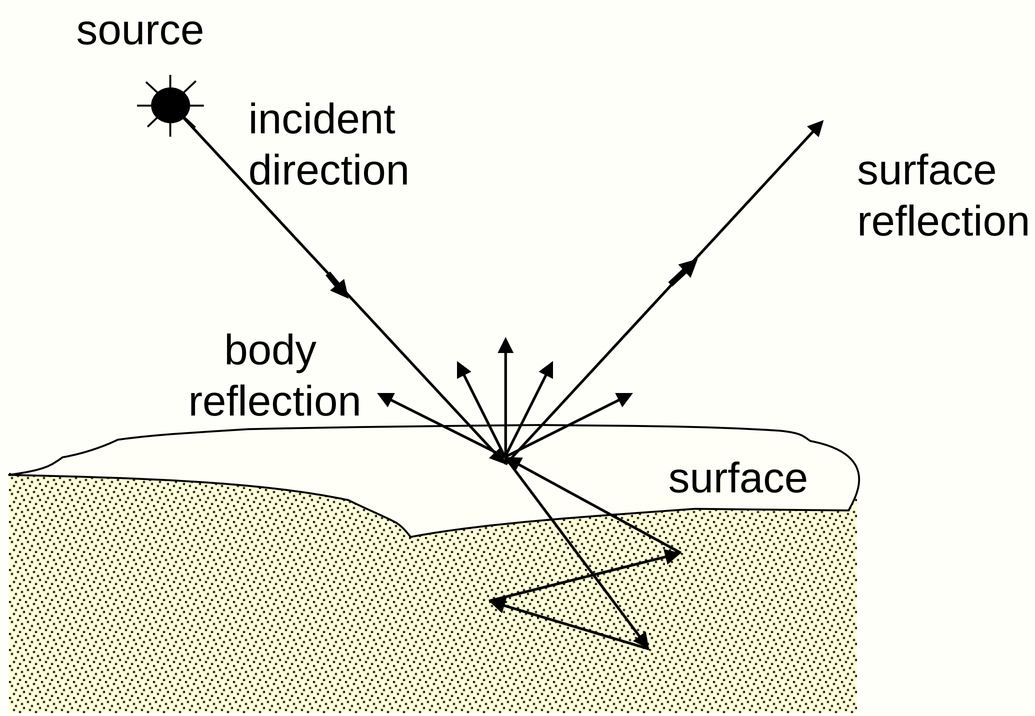



$$dA = (r\,d\theta)(r\sin\theta\,d\phi) = r^2\sin\theta\,d\theta\,d\phi$$

$$d\omega = \frac{dA}{r^2} = \sin\theta\,d\theta\,d\phi$$

$$S = \int_0^{\pi}\int_0^{2\pi} \sin\theta\,d\theta\,d\phi = 4\pi$$

# Mechanisms of Reflection




Body Reflection:

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

Surface Reflection:

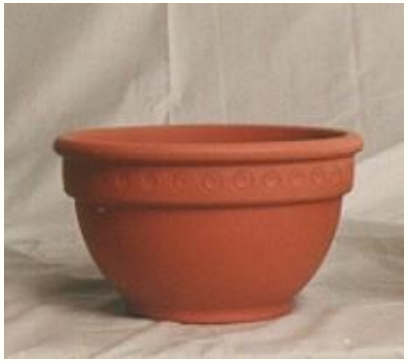
Specular Reflection
Glossy Appearance
Highlights
Dominant for Metals

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:

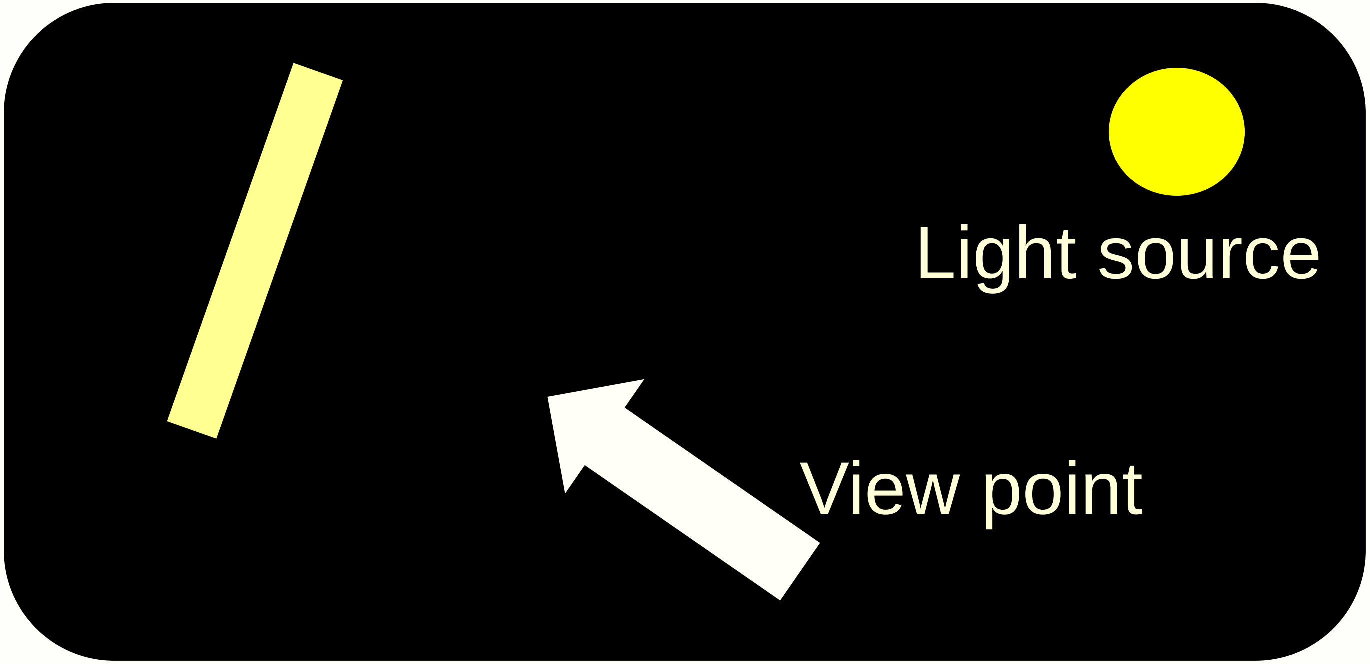

# Participation

*What is the BRDF of a slab of chalk?*

# Participation

*What do we see?*

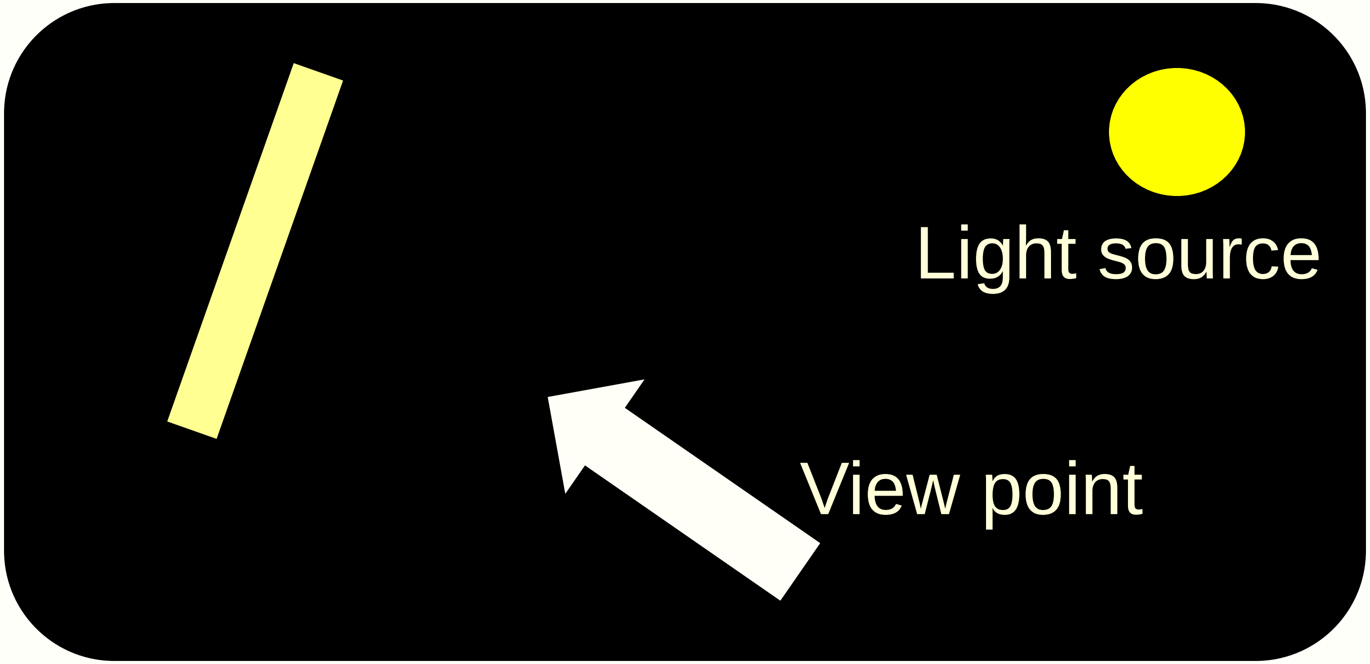
Dark Room



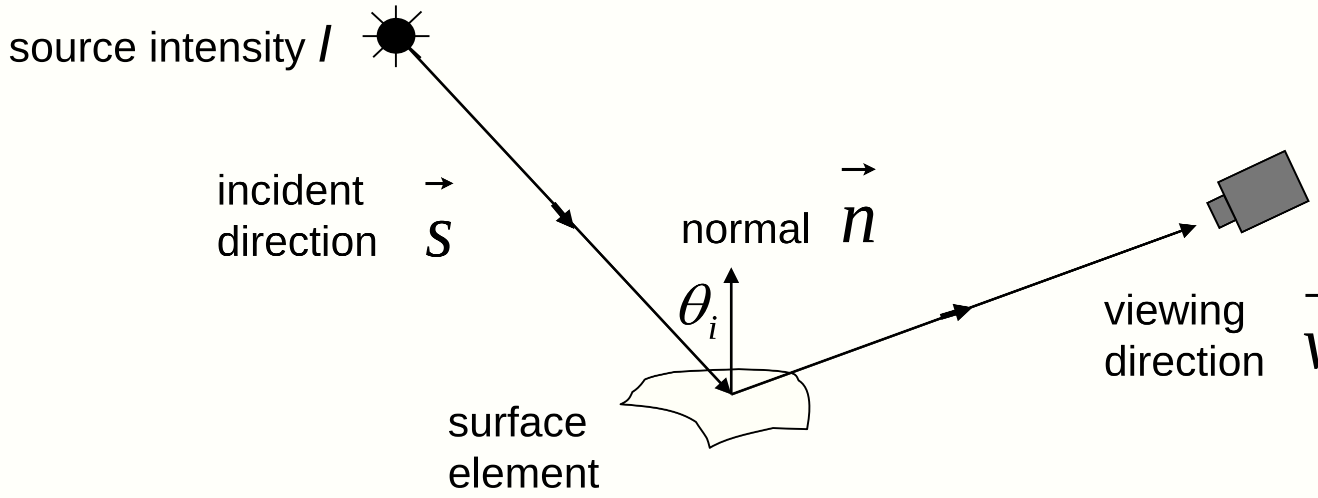
# Participation

*What do we see?*

Dark Room

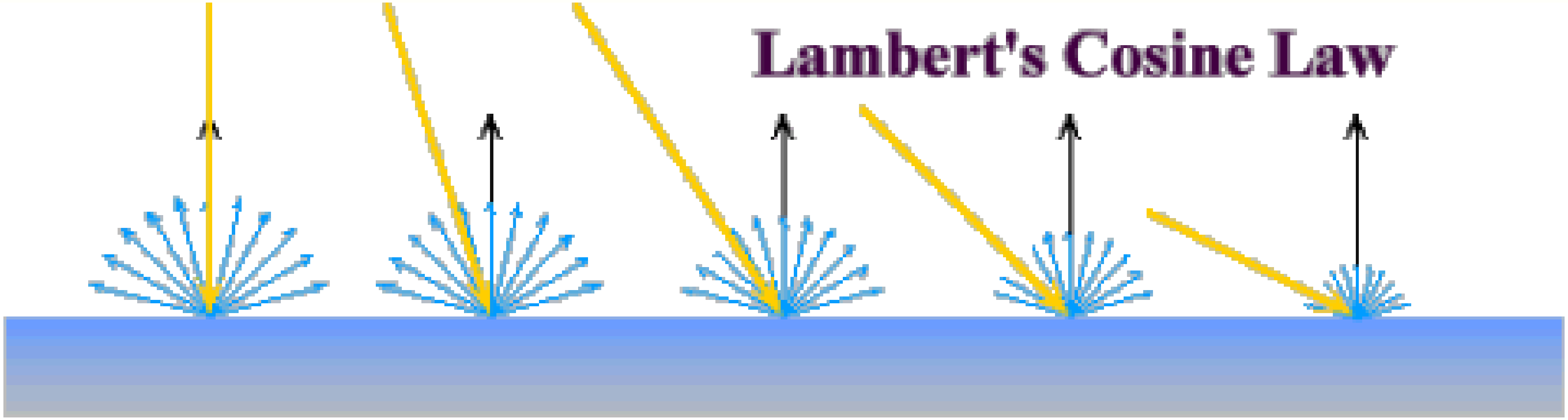


# Diffuse Reflection and Lambertian BRDF




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

# Diffuse Reflection and Lambertian BRDF



# Lesson 2

Diffuse reflectance is easy to compute.
A lot of vision is trying to “filter” images into a diffuse image.

# 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!!

# Participation

*Why can we perceive shape in the last picture?*

# Diffuse Reflection from Uniform Sky

$$L^{surface}(\theta_r,\phi_r) \quad = \quad \int_{-\pi}^{\pi}\int_{0}^{\pi/2} L^{src}(\theta_i,\phi_i)\, f(\theta_i,\phi_i;\theta_r,\phi_r)\cos\theta_i\,\sin\theta_i\, d\theta_i\, d\phi_i$$

- Assume Lambertian Surface with Albedo = 1 (no absorption)

$$f(\theta_i,\phi_i;\theta_r,\phi_r) = \frac{1}{\pi}$$

- Assume Sky radiance is constant

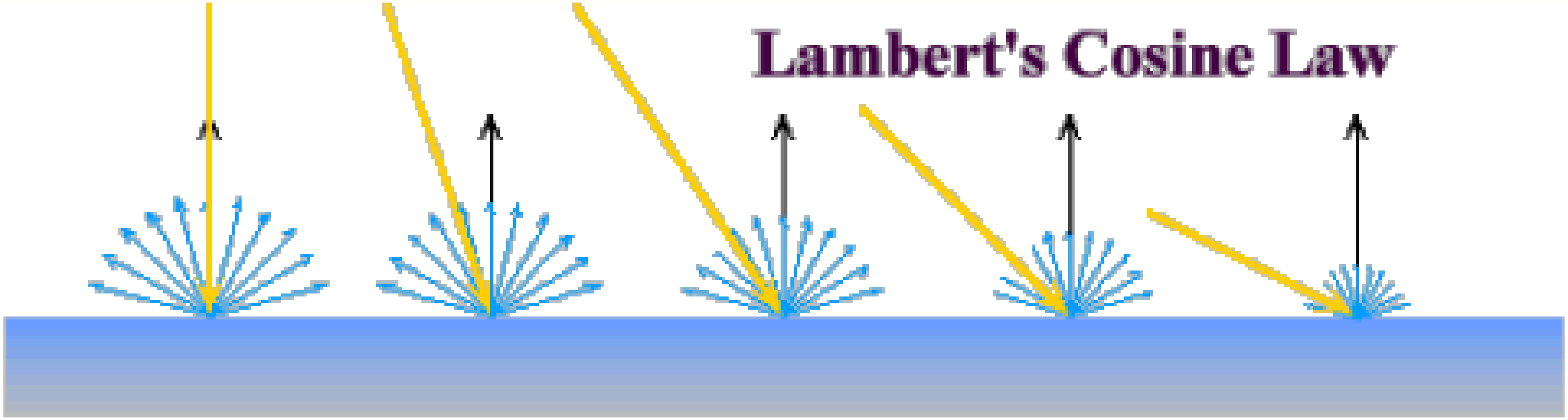
$$L^{src}(\theta_i,\phi_i) = L^{sky}$$

- Substituting in above Equation:

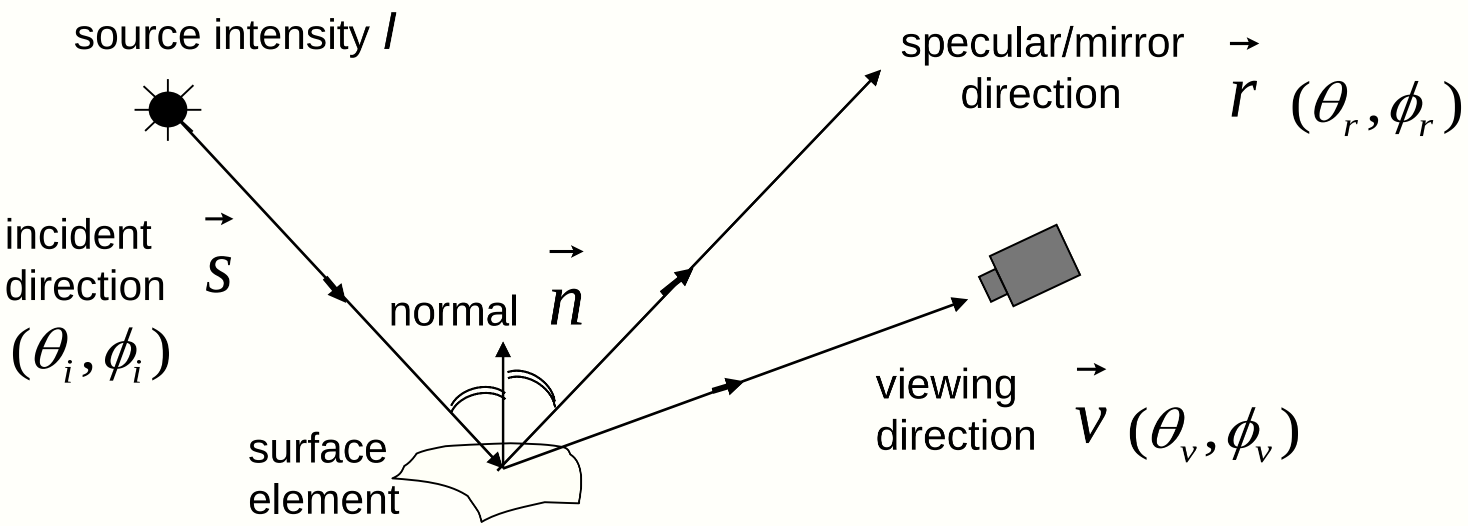
$$\boxed{L^{surface}(\theta_r,\phi_r) \quad = \quad L^{sky}}$$

Radiance of any patch is the same as Sky radiance !! (white-out condition)

# Diffuse Reflection and Lambertian BRDF



# Specular Reflection and Mirror BRDF




- Very smooth surface.

- All incident light energy reflected in a SINGLE direction. (only when $\vec{v} = \vec{r}$)

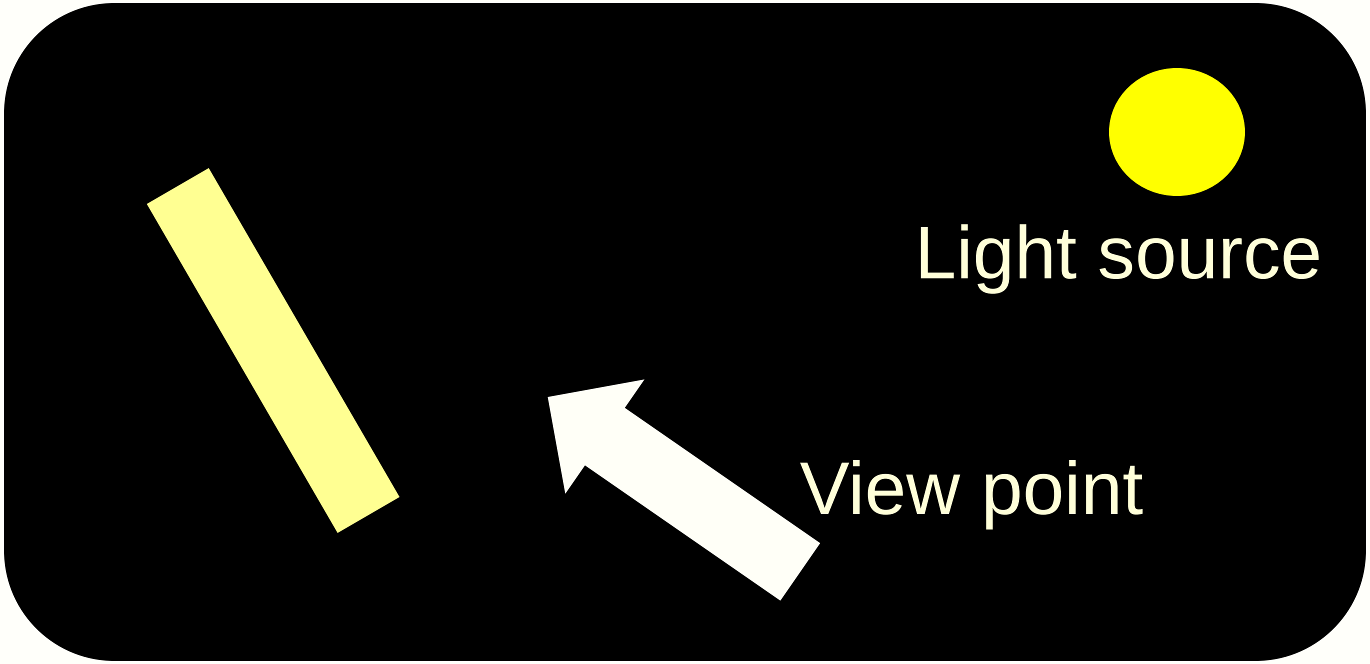
- Mirror BRDF is simply a double-delta function :

specular albedo

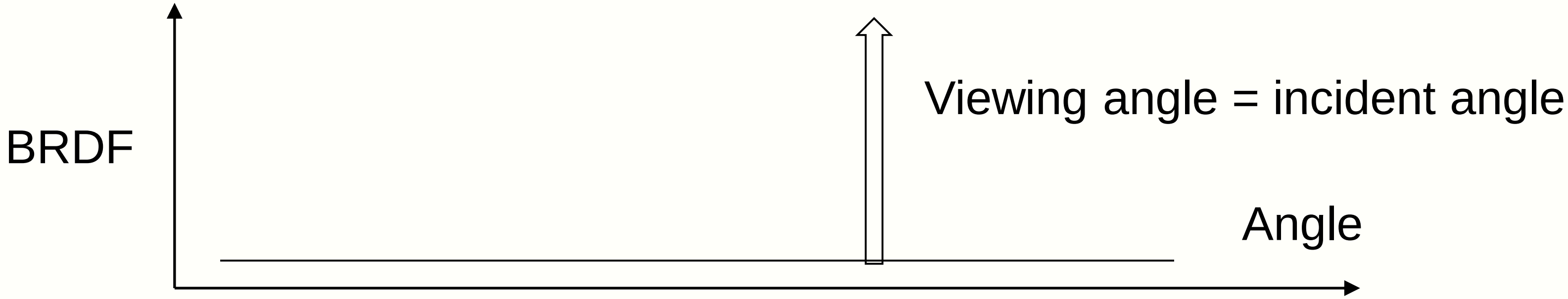
$$f(\theta_i, \phi_i; \theta_v, \phi_v) = \rho_s\ \delta(\theta_i - \theta_v)\ \delta(\phi_i + \pi - \phi_v)$$

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

# Remember the Dark Room example




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



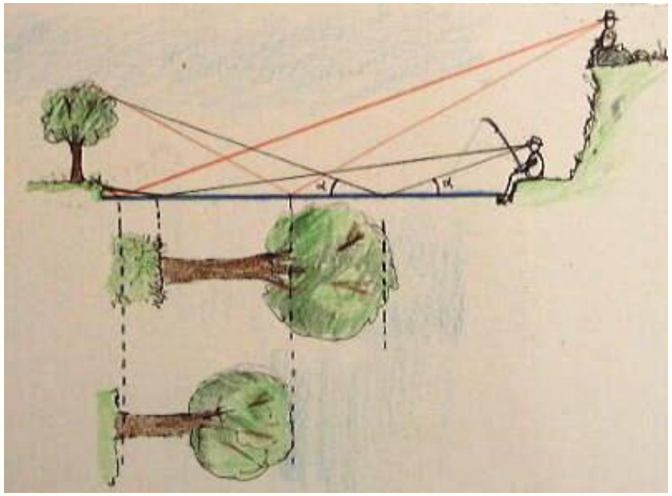
# Specular Reflections in Nature



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

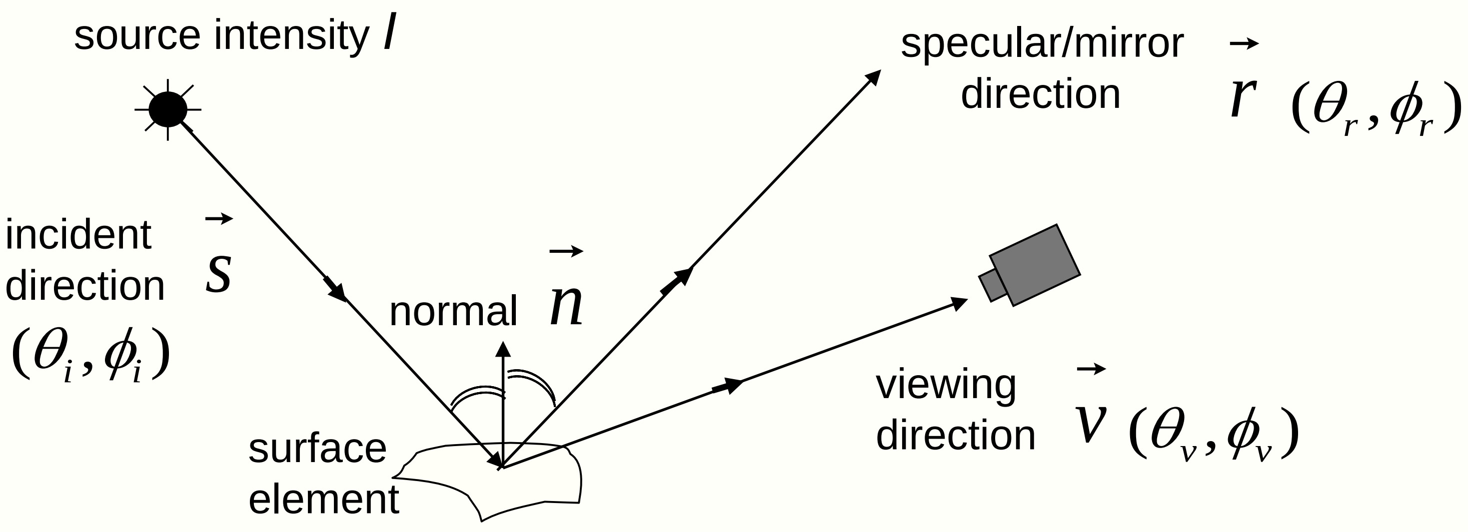
 

The reflections of bright objects have better perceived contrast.

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

# More advanced BRDFs
# (micro facets)

# Specular Reflection and Mirror BRDF - RECAP




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

# Glossy Surfaces

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

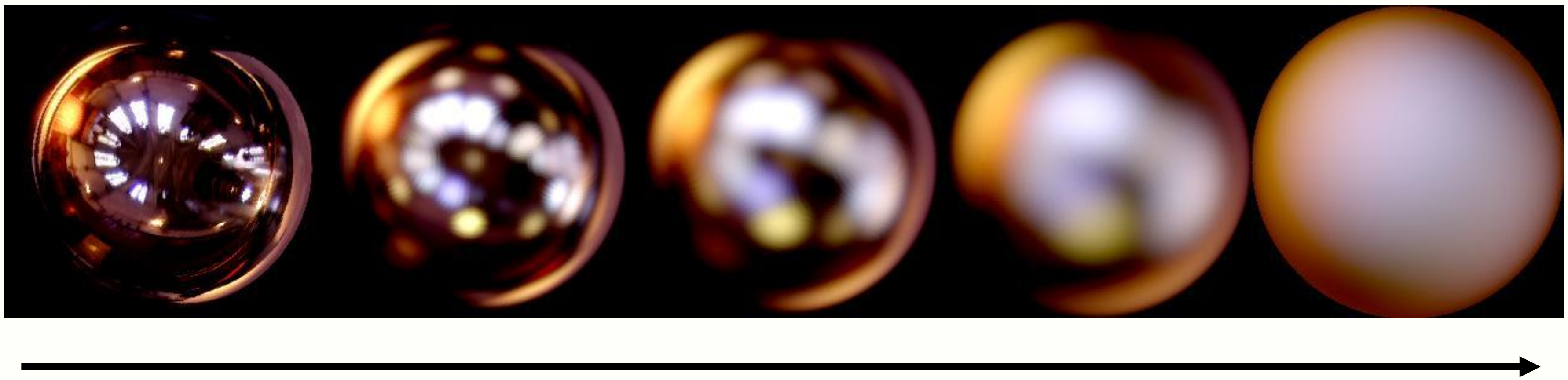
• Many glossy surfaces show broader highlights in addition to mirror reflection.

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

• Example Models : Phong model

Torrance Sparrow model

# Blurred Highlights and Surface Roughness



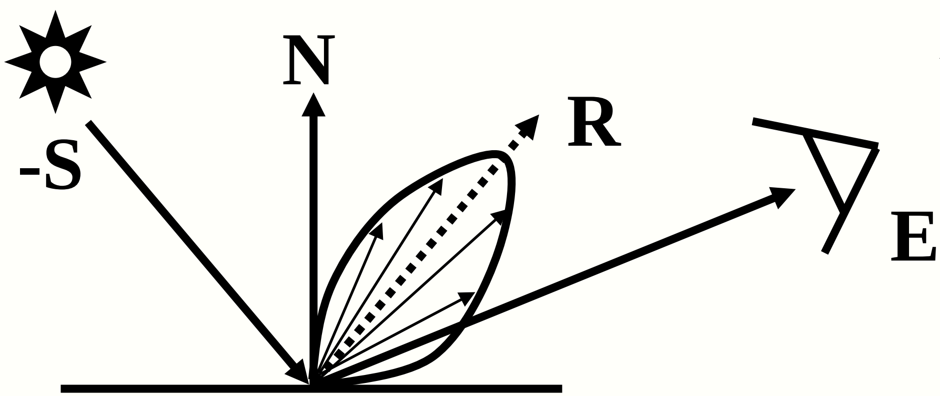
Roughness

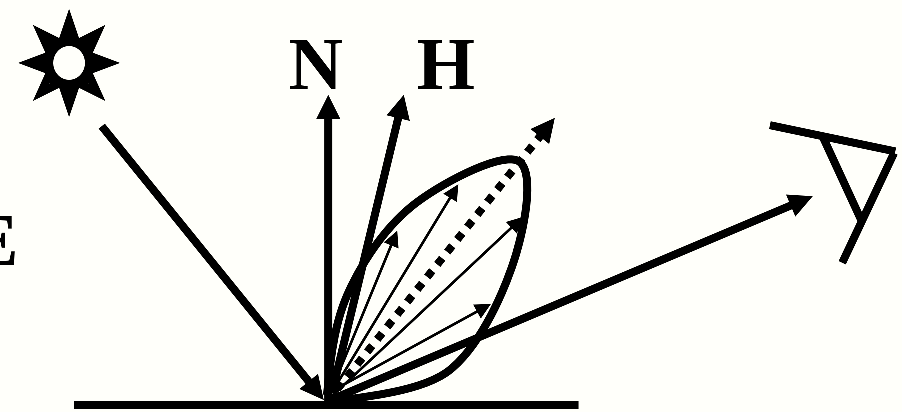
# Participation

*Does this remind you of anything?*

# 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

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

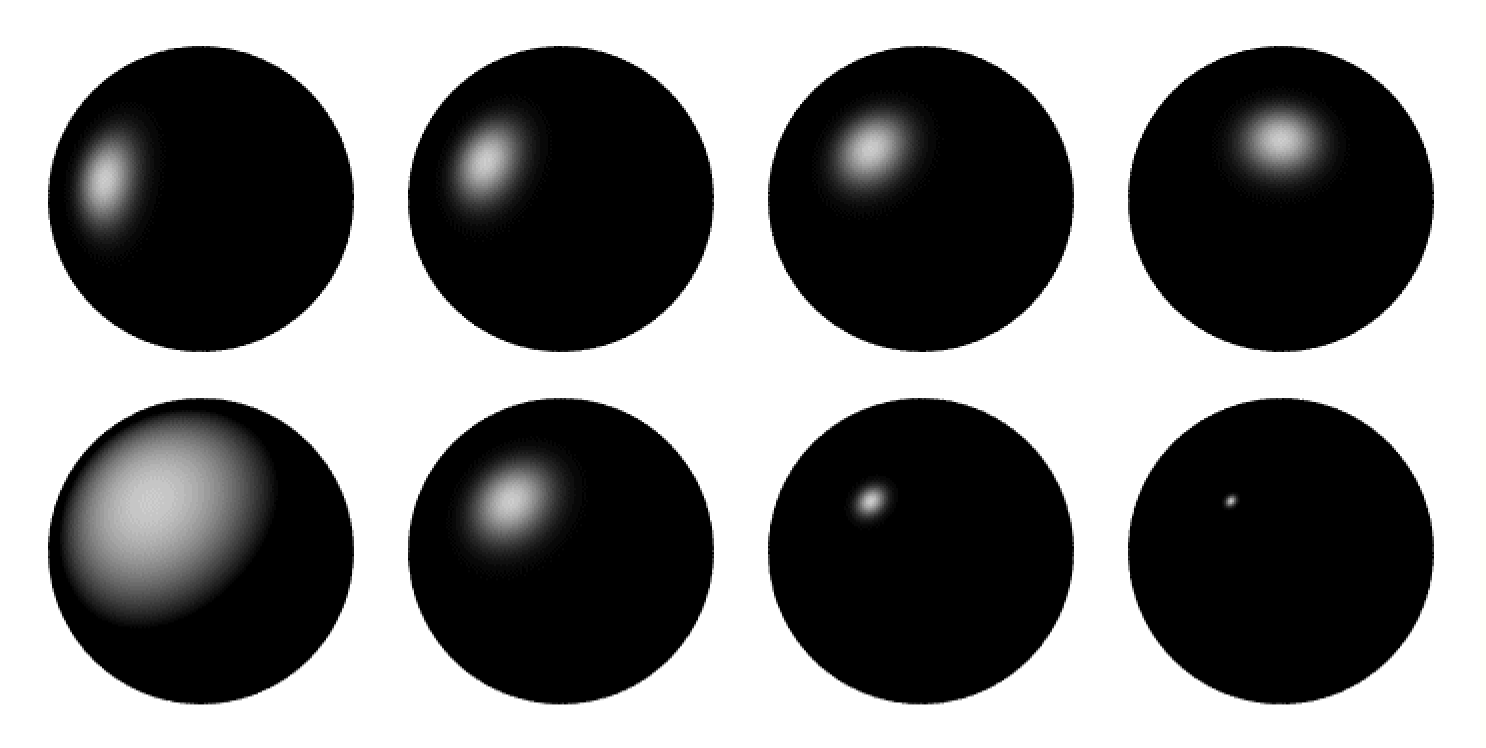
$$H = (E+S)/2$$

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:



# Participation

*Why are the spheres so dark?*

# 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

# Torrance-Sparrow Model – Main Points

•Physically Based Model for Surface Reflection.

•Based on Geometric Optics.

•Explains off-specular lobe (wider highlights).

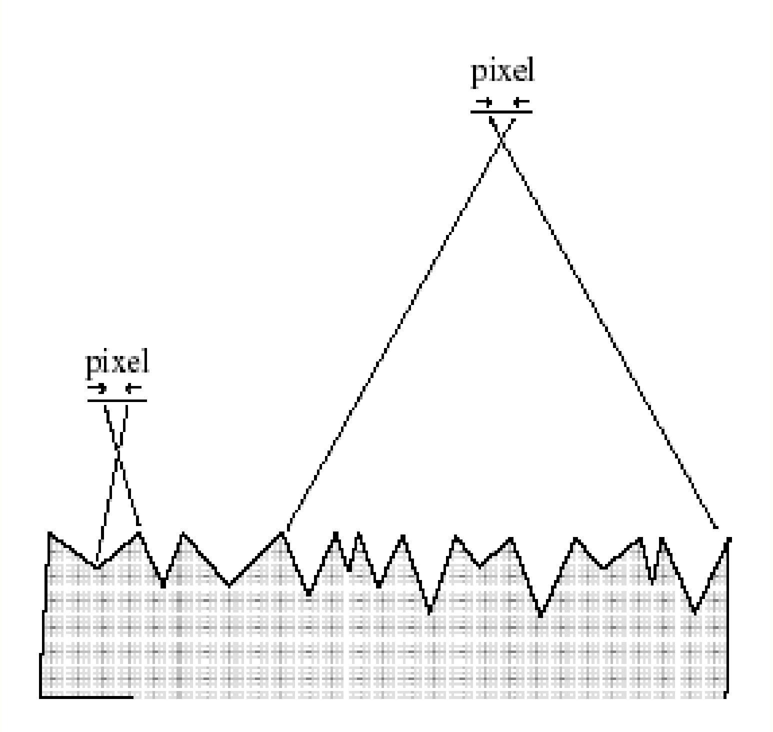
•Works for only rough surfaces.

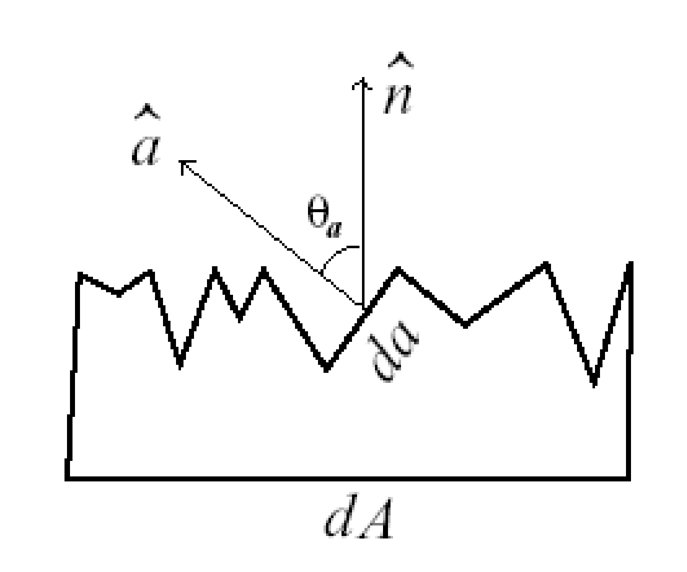
•For very smooth surfaces, electromagnetic nature of light must be used

Beckmann-Spizzichinno model.

Beyond the scope of this course.

# 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 mirror.

# Torrance-Sparrow BRDF – Different Factors

Fresnel term:
allows for
wavelength
dependency

Geometric Attenuation:
reduces the output based on the amount of shadowing or masking that occurs.

$$f = \frac{F(\theta_i)G(\omega_i, \omega_r)D(\theta_h)}{4\cos(\theta_i)\cos(\theta_r)}$$

Distribution:
distribution function determines what percentage of microfacets are oriented to reflect in the viewer direction.

How much of the macroscopic surface is visible to the light source

How much of the macroscopic surface is visible to the viewer

# Torrance-Sparrow BRDF – Different Factors

Fresnel term:
allows for
wavelength
dependency

Geometric Attenuation:
reduces the output based on the amount of shadowing or masking that occurs.

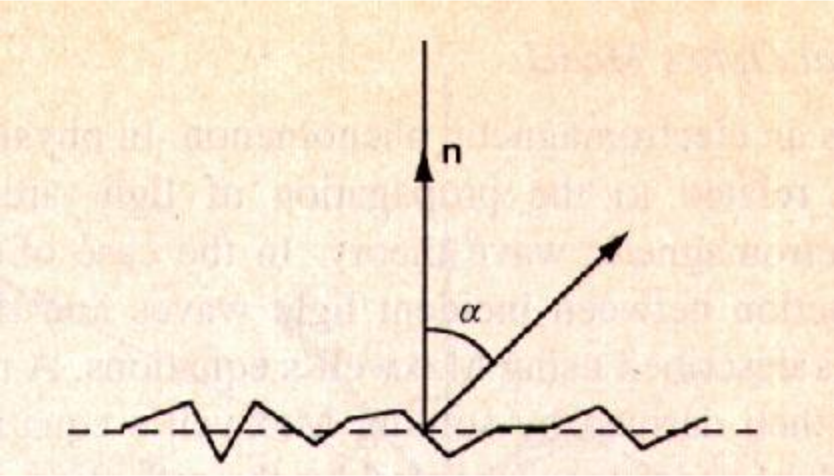
$$f = \frac{F(\theta_i)G(\omega_i, \omega_r)D(\theta_h)}{4\cos(\theta_i)\cos(\theta_r)}$$

Distribution:
distribution function determines what percentage of microfacets are oriented to reflect in the viewer direction.

How much of the macroscopic surface is visible to the light source

How much of the macroscopic surface is visible to the viewer

# Slope Distribution Model




- Model the distribution of slopes as Gaussian.
- Mean is Zero, Variance represents ROUGHNESS.

$$\rho_\alpha(\alpha) = \frac{1}{\sqrt{2\pi\sigma_\alpha}} e^{-\frac{\alpha^2}{2\sigma_\alpha{}^2}} .$$

# Torrance-Sparrow BRDF – Different Factors

Fresnel term:
allows for
wavelength
dependency

Geometric Attenuation:
reduces the output based on the amount of shadowing or masking that occurs.

$$f = \frac{F(\theta_i)G(\omega_i, \omega_r)D(\theta_h)}{4\cos(\theta_i)\cos(\theta_r)}$$

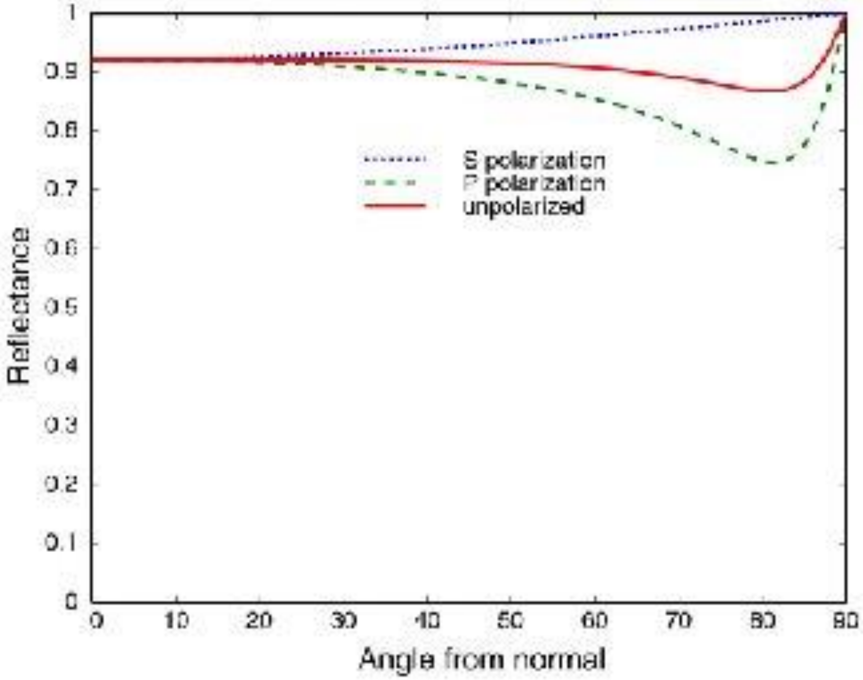
Distribution:
distribution function determines what percentage of microfacets are oriented to reflect in the viewer direction.

How much of the macroscopic surface is visible to the light source

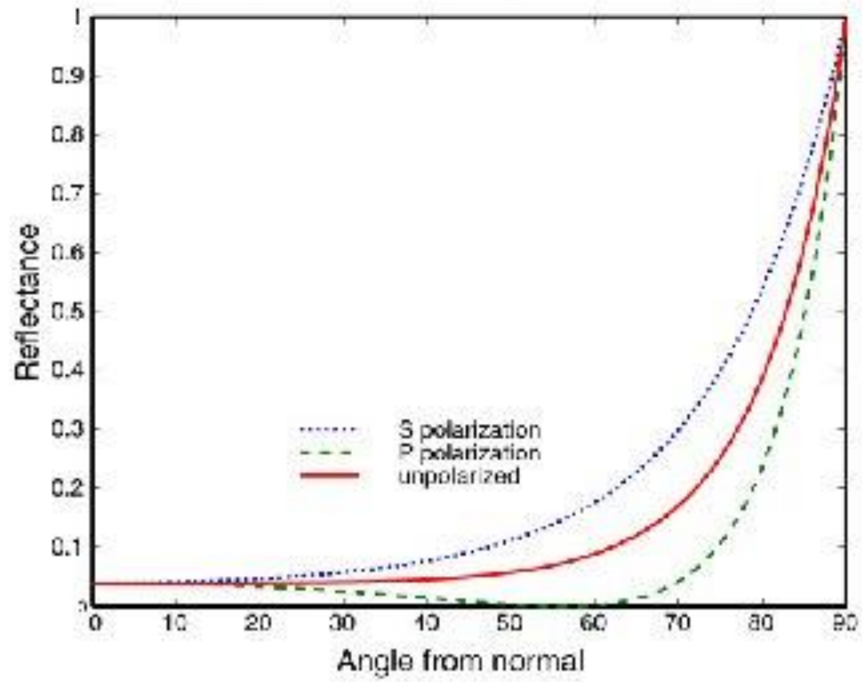
How much of the macroscopic surface is visible to the viewer

# 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** $F(\theta) = F(0) + (1 - F(0))(1 - \cos\theta)^5$

# Experiment

## Reflections from a shiny floor


From Lafortune, Foo, Torrance, Greenberg, SIGGRAPH 97

# Lesson 3

The effect of Fresnel reflectance increases greatly at grazing angles.

# Torrance-Sparrow BRDF – Different Factors

Fresnel term:
allows for
wavelength
dependency

Geometric Attenuation:
reduces the output based on the
amount of shadowing or masking
that occurs.

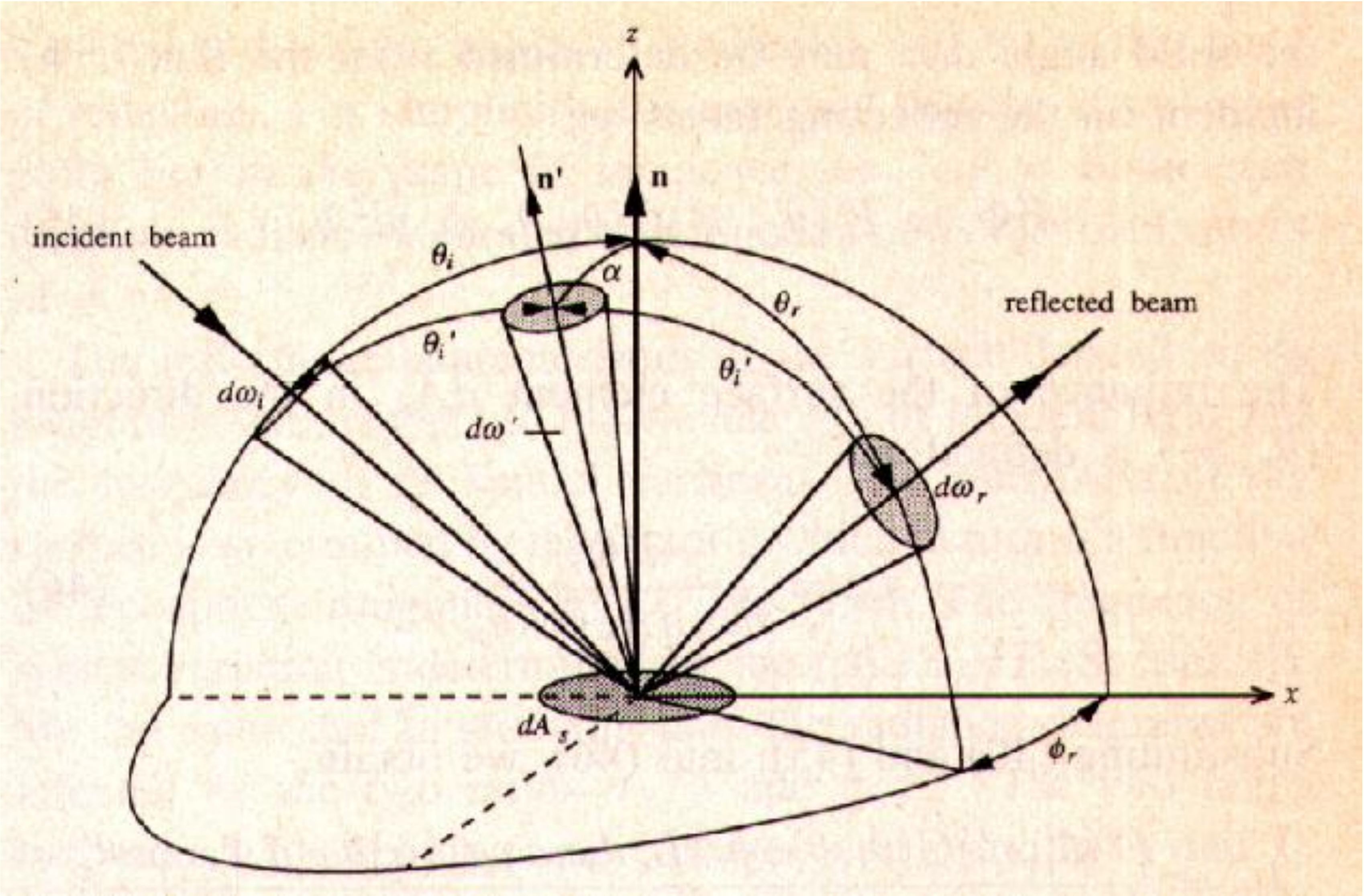
$$f = \frac{F(\theta_i)G(\omega_i, \omega_r)D(\theta_h)}{4\cos(\theta_i)\cos(\theta_r)}$$

Distribution:
distribution function
determines what
percentage of
microfacets are
oriented to reflect
in the viewer
direction.

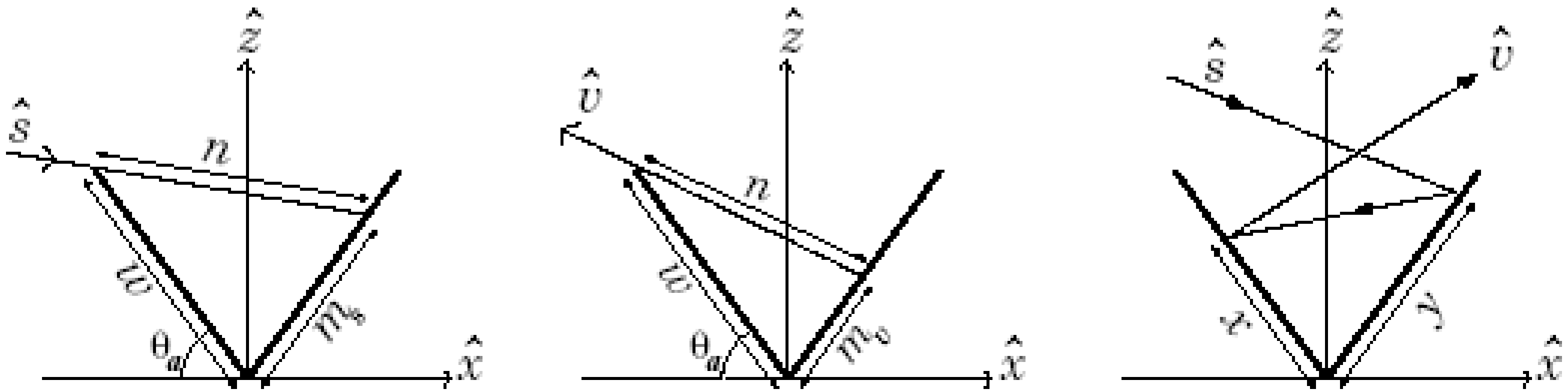
How much of the
macroscopic
surface is visible
to the light source

How much of
the macroscopic
surface is visible
to the viewer

# Coordinate System needed to derive T-S model



# Geometric Attenuation Factor

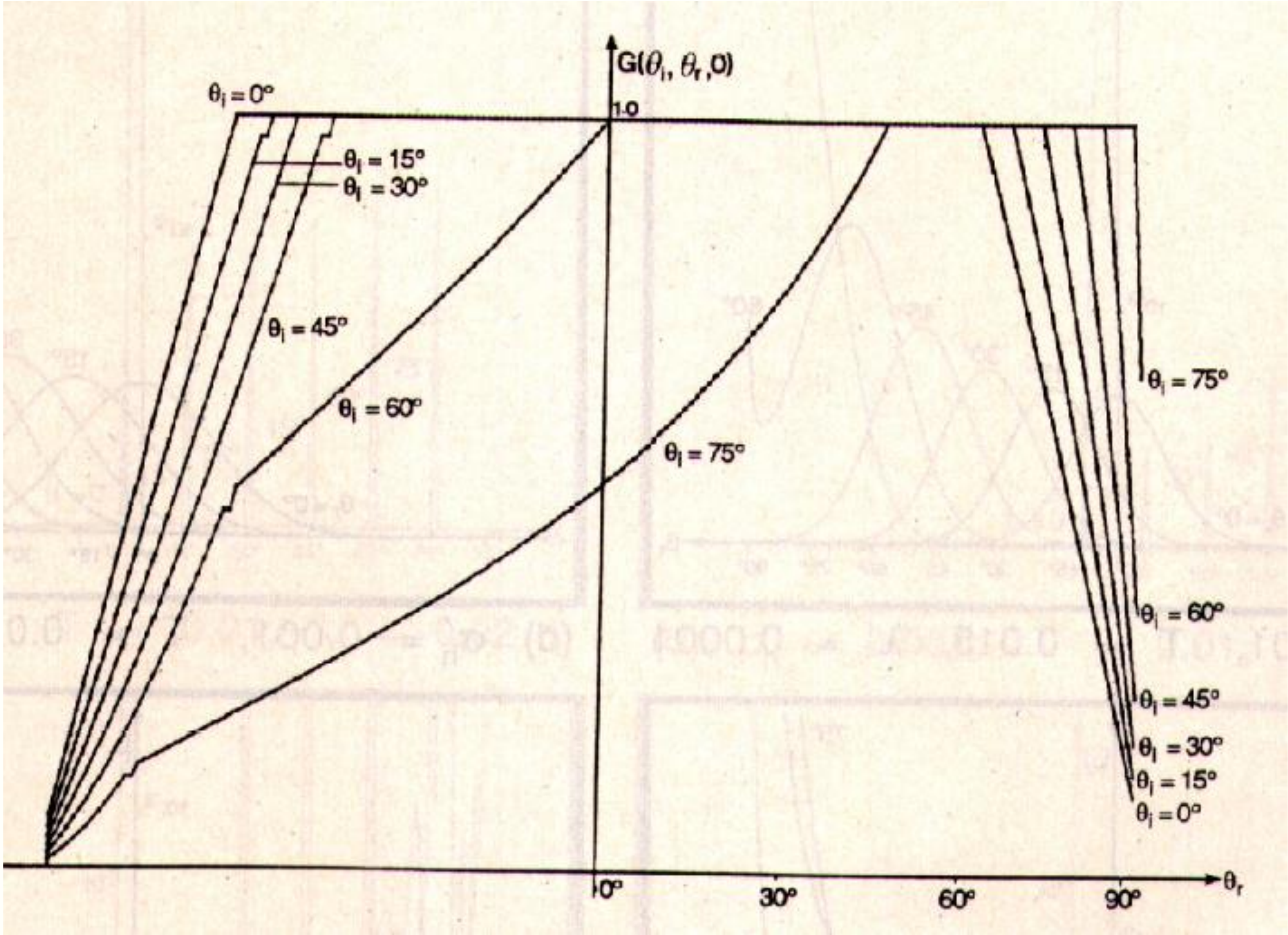


(a) Shadowing (b) Masking (c) Interreflection

$$G(\theta_i, \theta_r, \phi_r) = \min\left(1, \frac{2\cos\alpha\cos\theta_r}{\cos\theta_i'}, \frac{2\cos\alpha\cos\theta_i}{\cos\theta_i'}\right).$$

- No interreflections taken into account in above function.
- Derivation found in 1967 JOSA paper (read if interested).

# Geometric Attenuation Factor

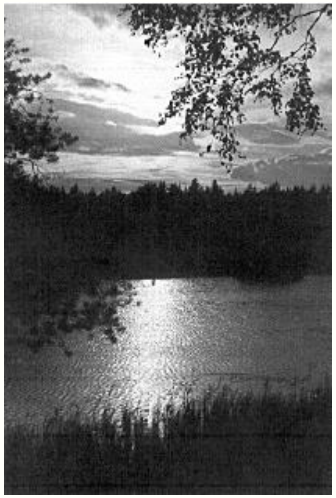


# Torrance Sparrow Model - Final Expression

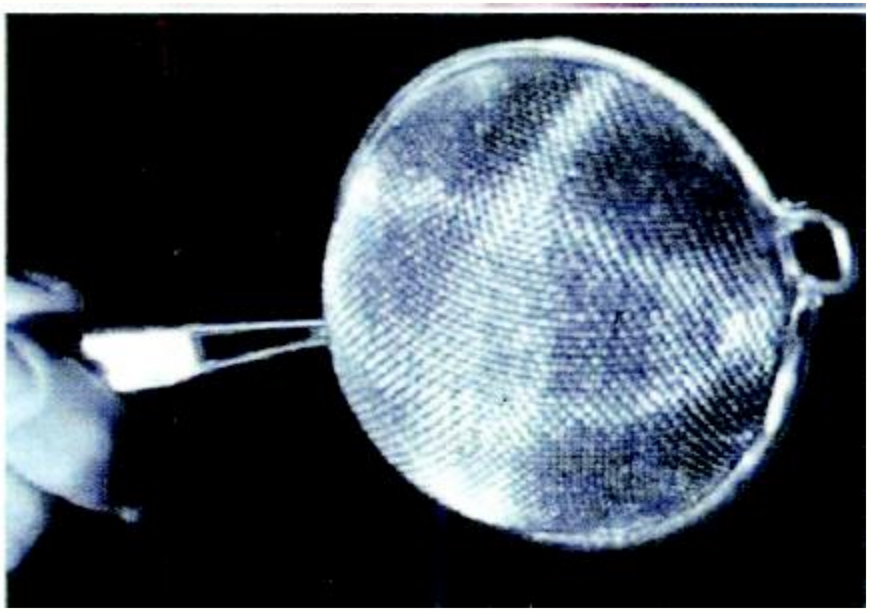
$$L_r = \kappa_{\text{spec}} \frac{L_i d\omega_i}{\cos\theta_r} e^{-\frac{\alpha^2}{2\sigma_\alpha{}^2}}$$

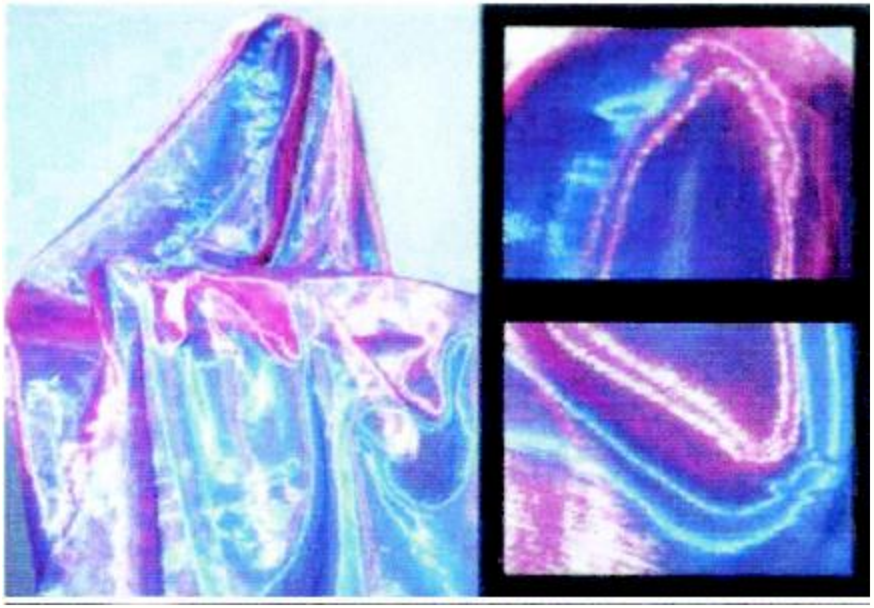
$$\kappa_{\text{spec}} = \frac{c a_f F'(\theta_i', \eta') G(\theta_i, \theta_r, \phi_r)}{4}.$$

# Reflections on water surfaces - Glittering



# Split off-specular Reflections in Woven Surfaces





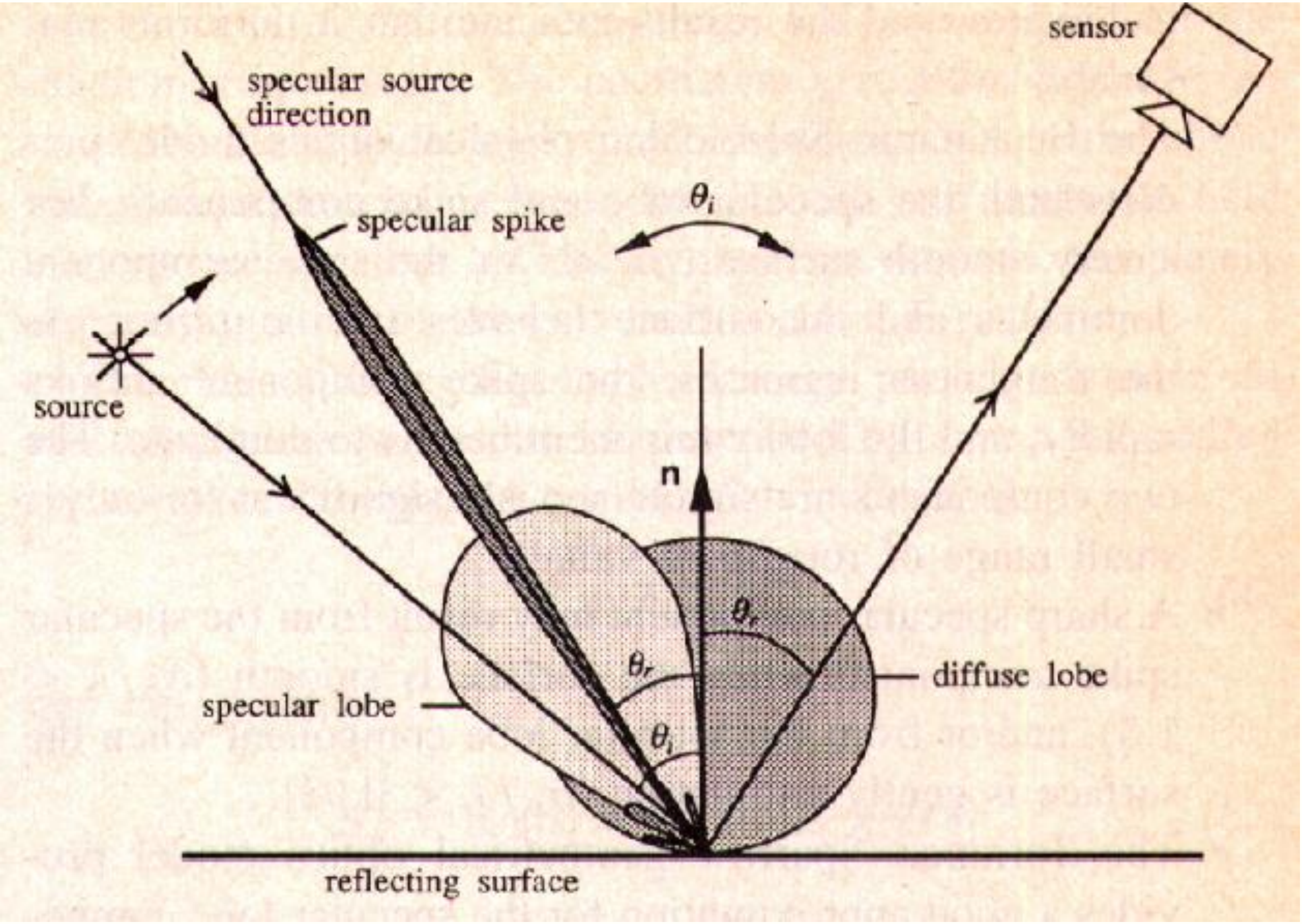
# Lesson 4

Many scenes do not have diffuse reflectance and cannot be easily made diffuse.

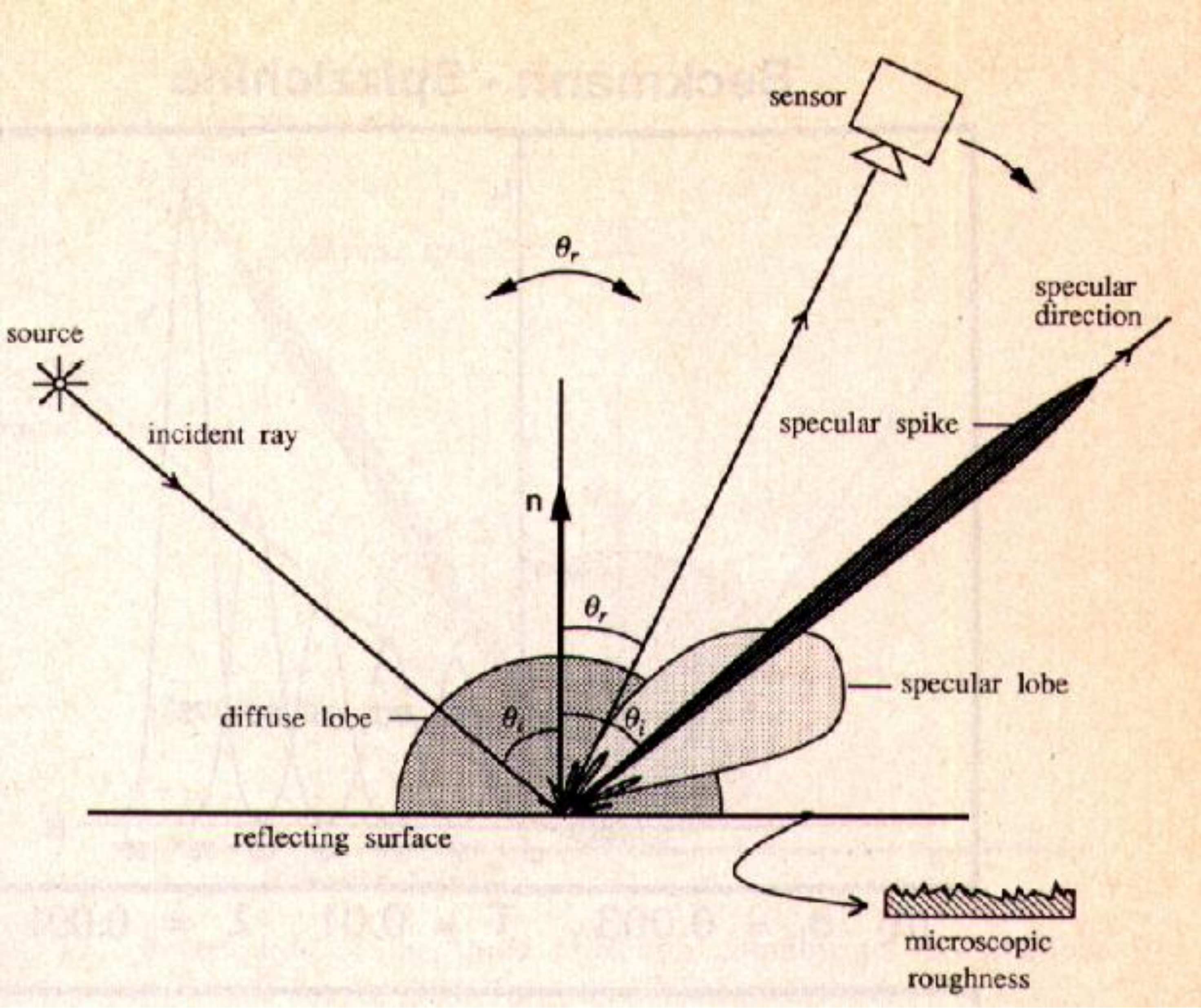
So we need to do more work.

Add a diffuse component to the TS model

# Components of Surface Reflection – Moving Light Source



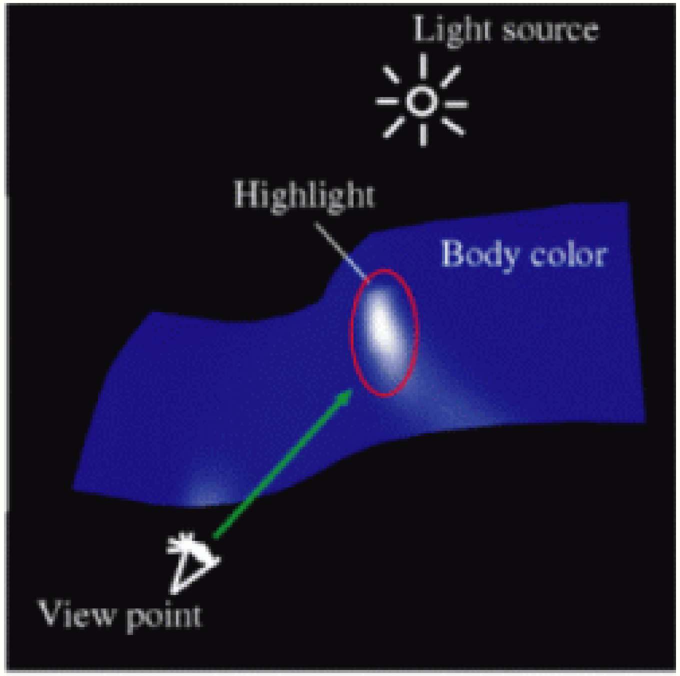
# Components of Surface Reflection – Moving Camera

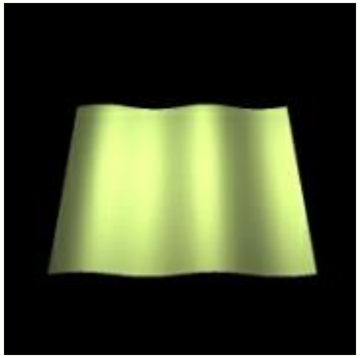


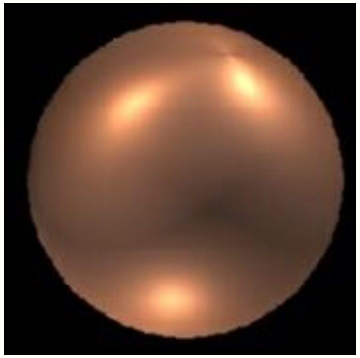
# A Simple Reflection Model - Dichromatic Reflection

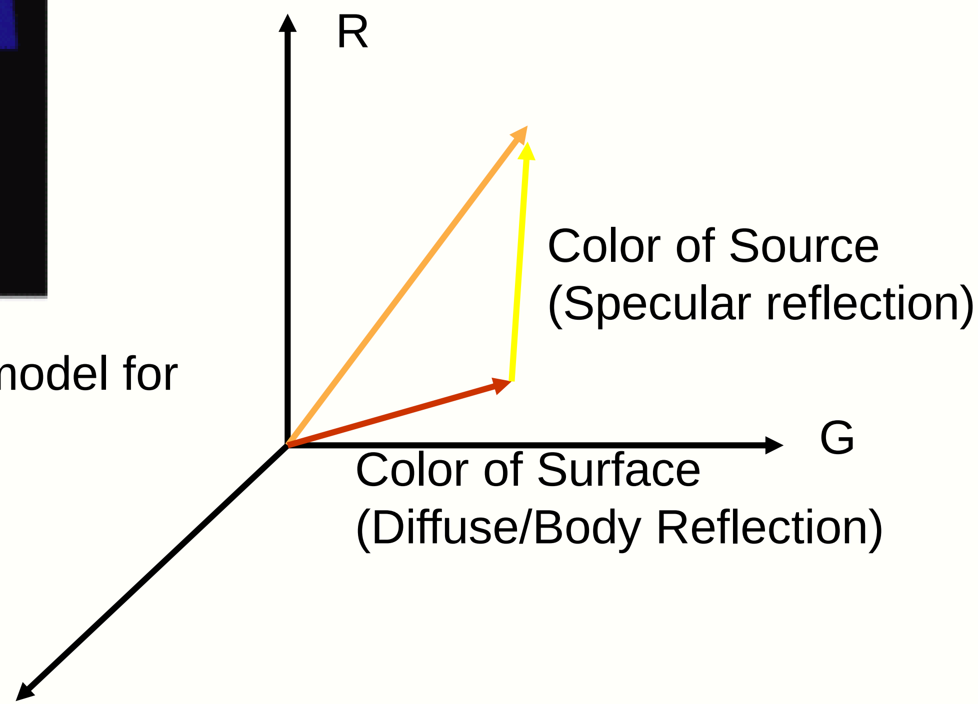
Observed Image Color = a x Body Color + b x Specular Reflection Color

Klinker-Shafer-Kanade 1988



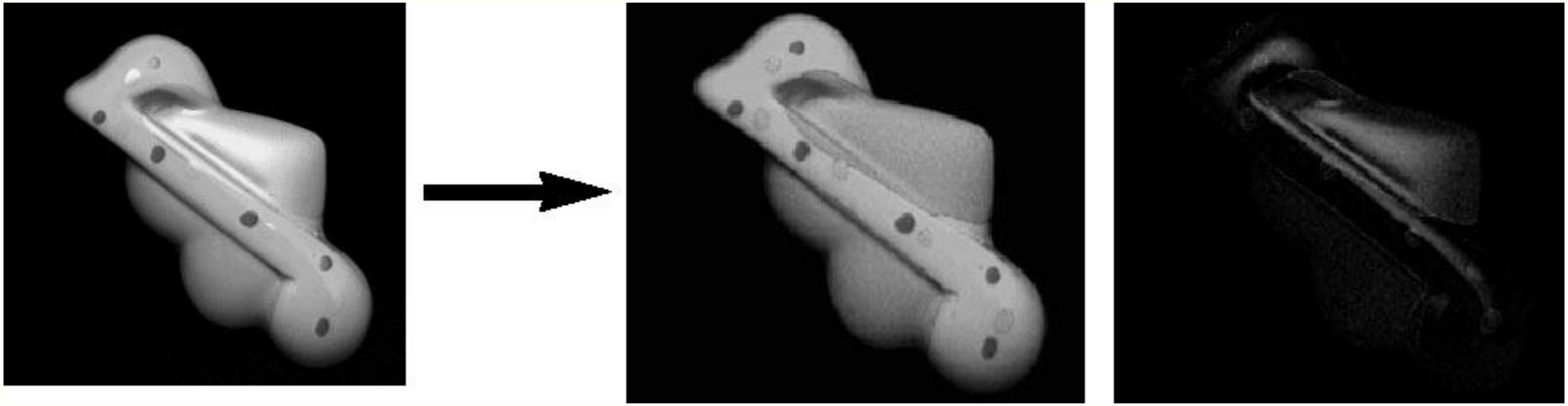


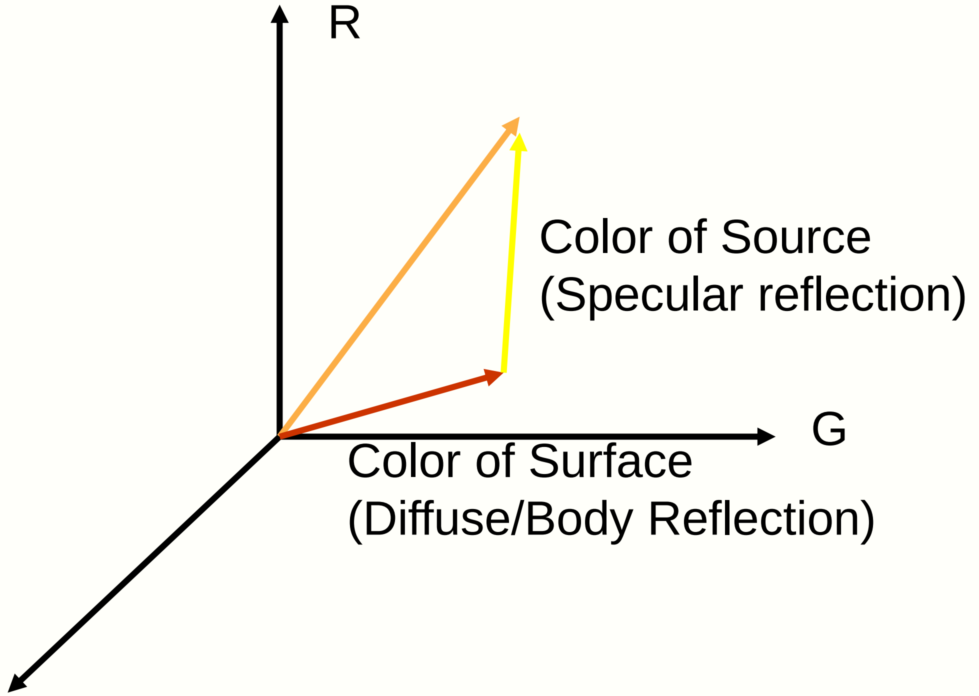



Does not specify any specific model for Diffuse/specular reflection

# Separating Diffuse and Specular Reflections

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

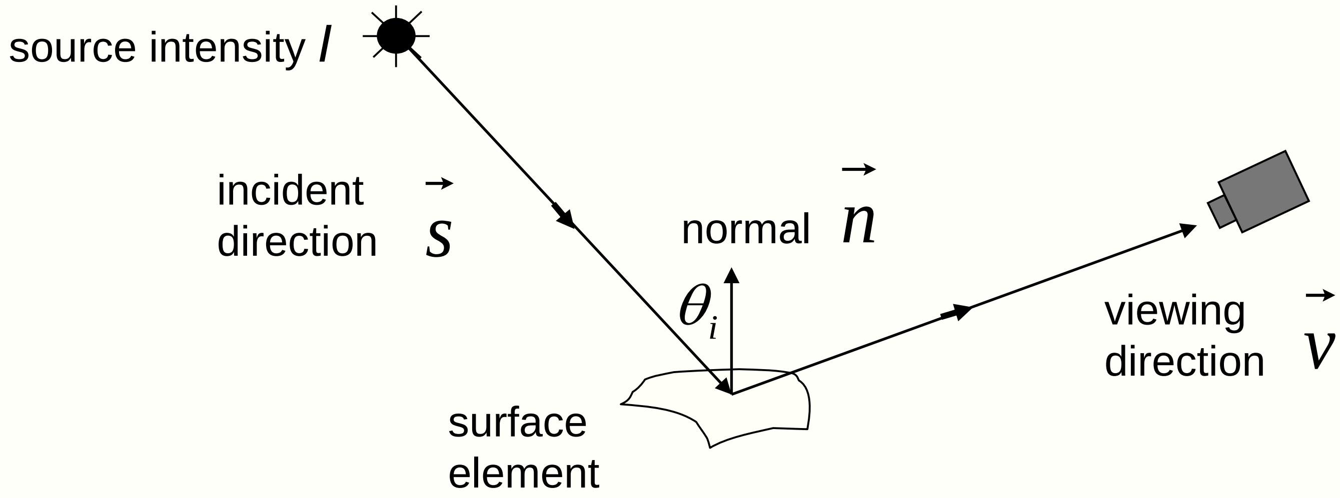




We looked at rough specular things, and we added diffuse stuff to them.

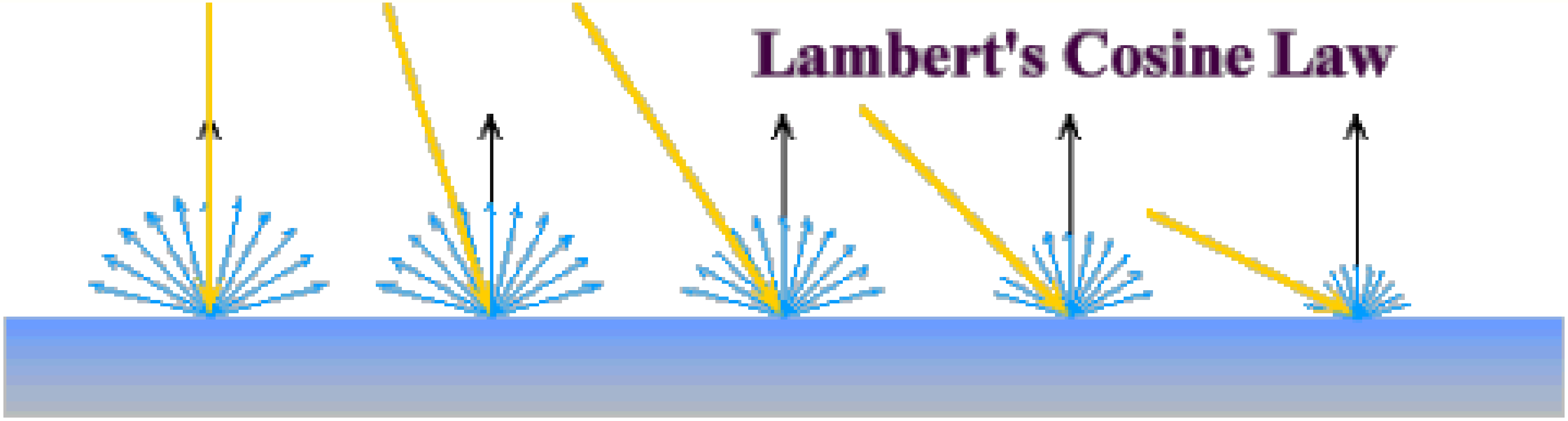
What about rough diffuse things?

# Diffuse Reflection and Lambertian BRDF - Recap




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

# Diffuse Reflection and Lambertian BRDF - Recap




Radiance decreases with increase in angle between surface normal and source

# Rendered Sphere with Lambertian BRDF

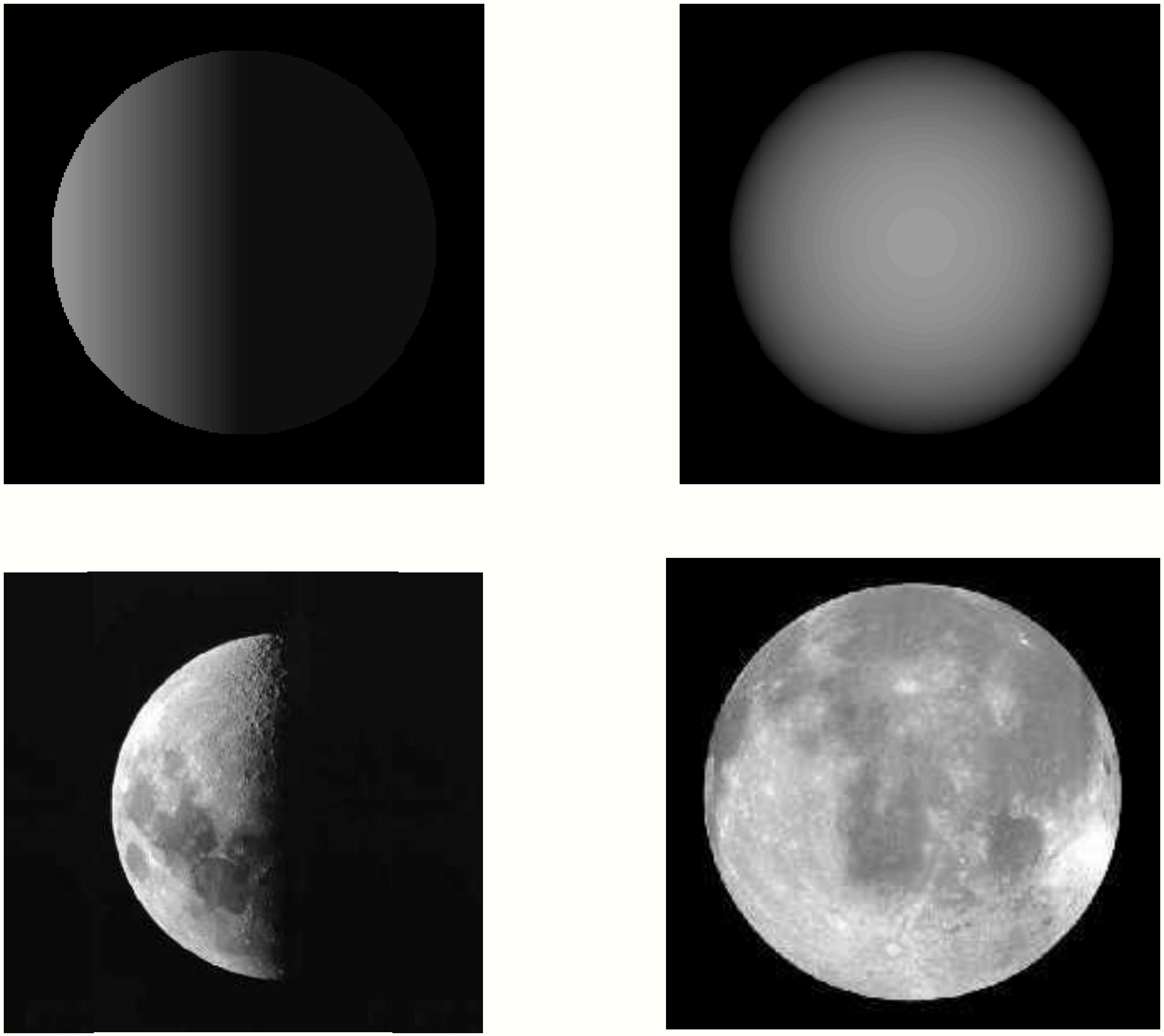
- Edges are dark (N.S = 0) when lit head-on
- See shading effects clearly.

# Why does the Full Moon have a flat appearance?

• The moon appears matte (or diffuse)

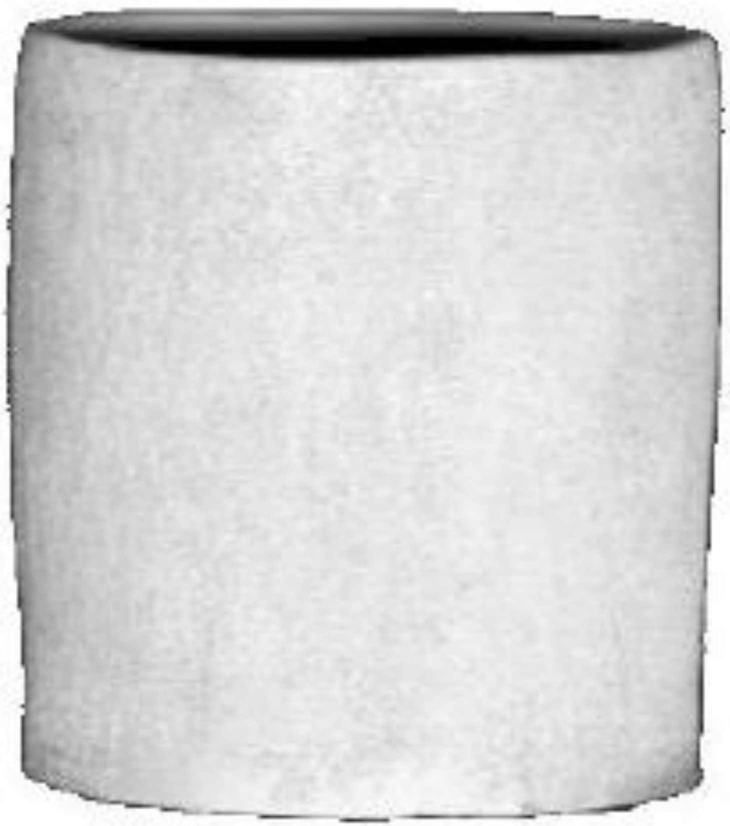
• But still, edges of the moon look bright (not close to zero) when illuminated by earth's radiance.

# Why does the Full Moon have a flat appearance?



Lambertian Spheres and Moon Photos illuminated similarly

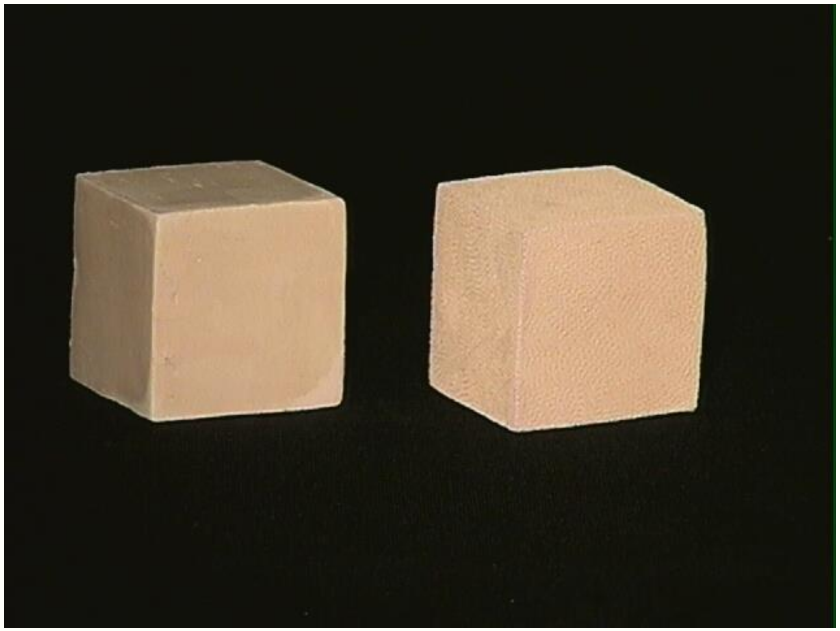
# Surface Roughness Causes Flat Appearance

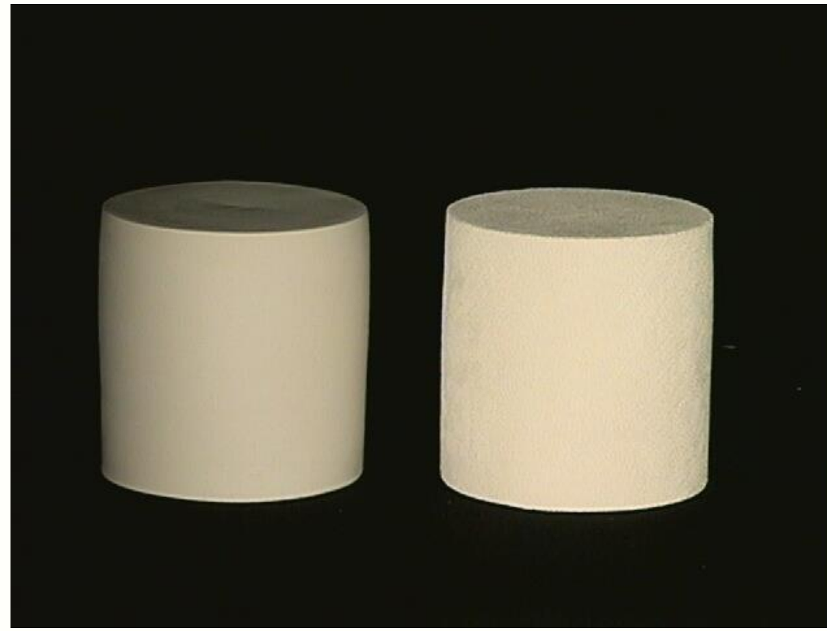


Actual Vase

Lambertian Vase

# Surface Roughness Causes Flat Appearance – More Examples

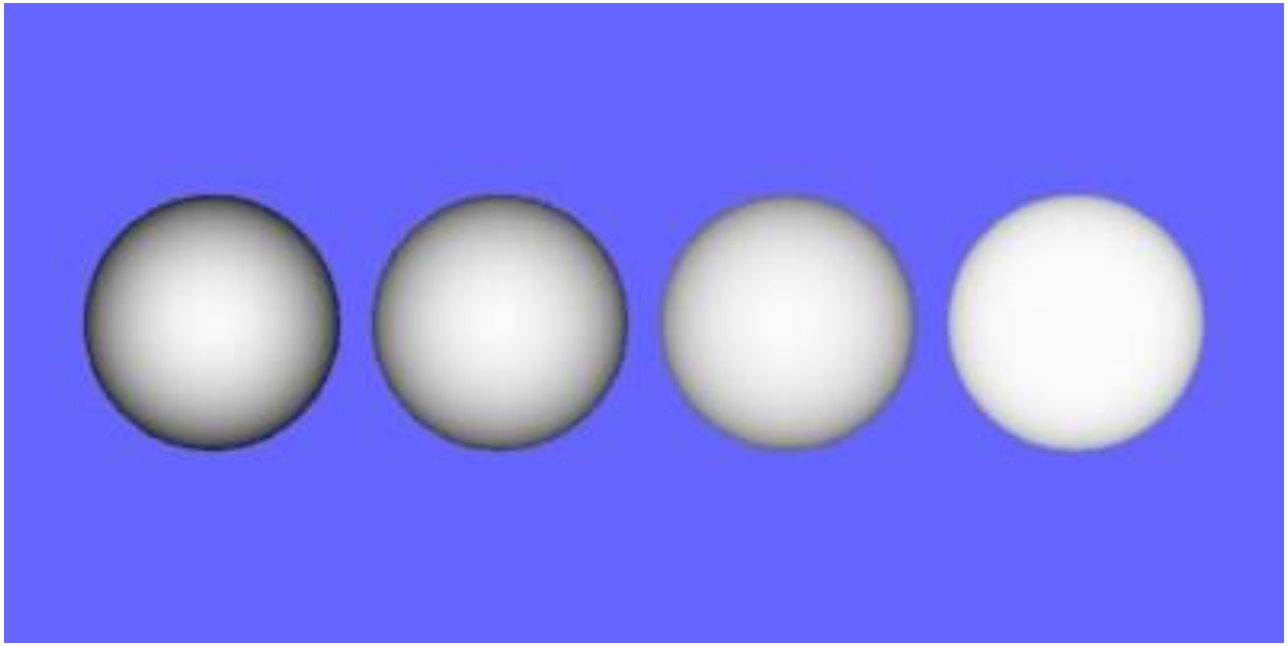




# Lesson 5

Local reflectance properties can create surprising global effects.

# Surface Roughness Causes Flat Appearance



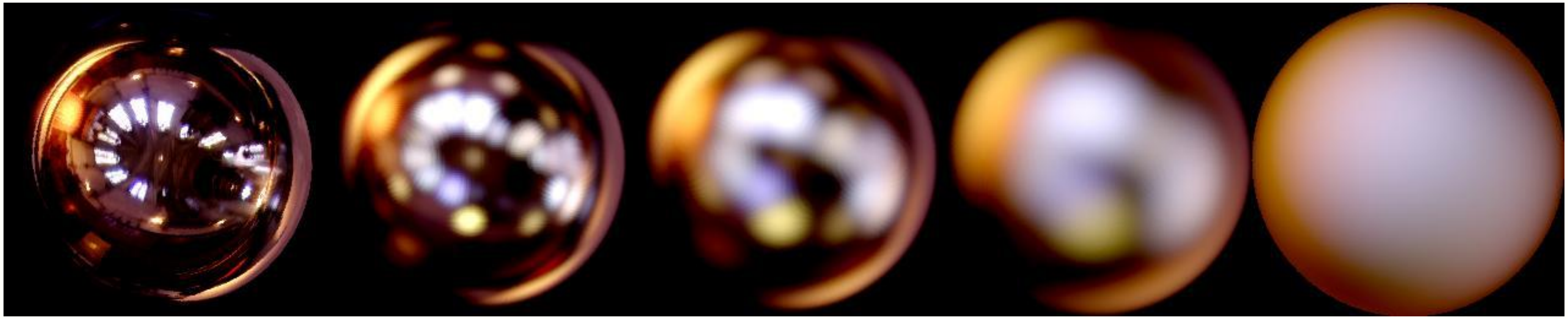
Increasing surface roughness →

Lambertian model

Valid for only SMOOTH MATTE surfaces.

Bad for ROUGH MATTE surfaces.

# Blurred Highlights and Surface Roughness - RECAP



Roughness

# Oren-Nayar Model – Main Points

•Physically Based Model for Diffuse Reflection.

•Based on Geometric Optics.

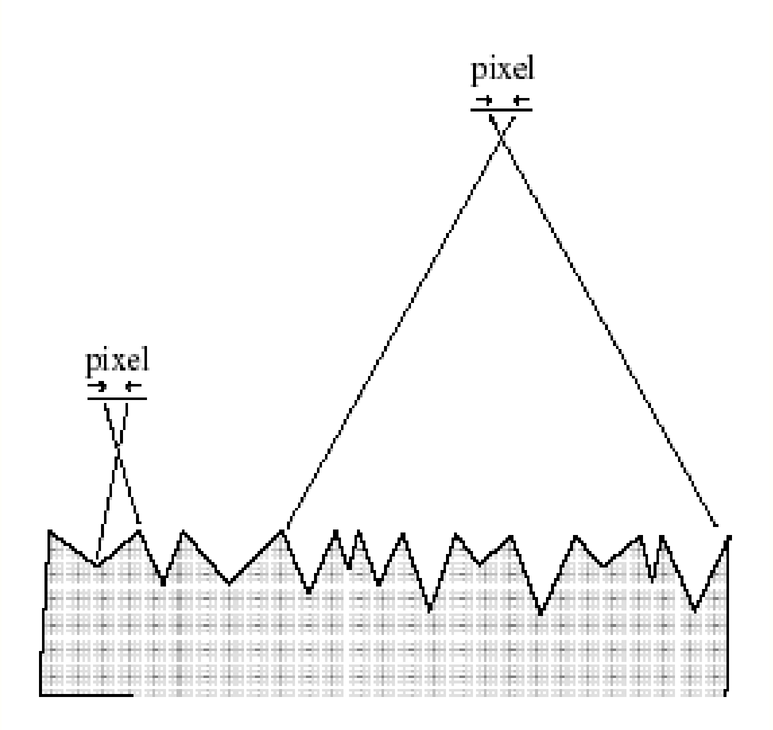
•Explains view dependent appearance in Matte Surfaces

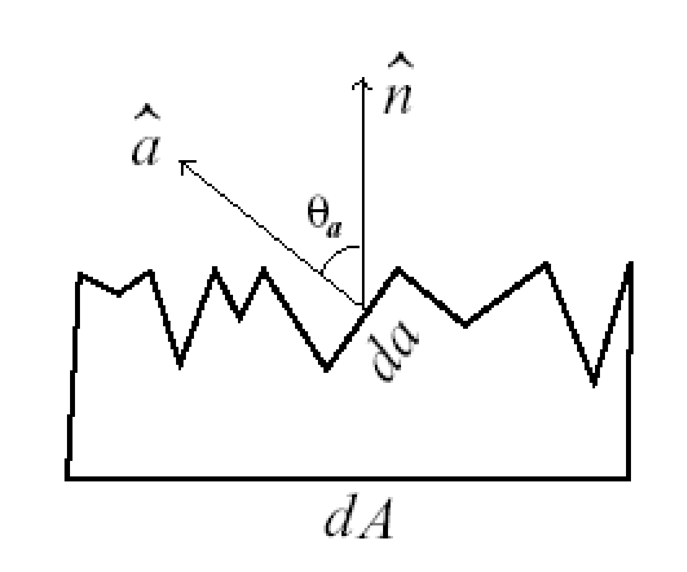
•Take into account partial interreflections.

•Roughness represented like in Torrance-Sparrow Model

•Lambertian model is simply an extreme case with roughness equal to zero.

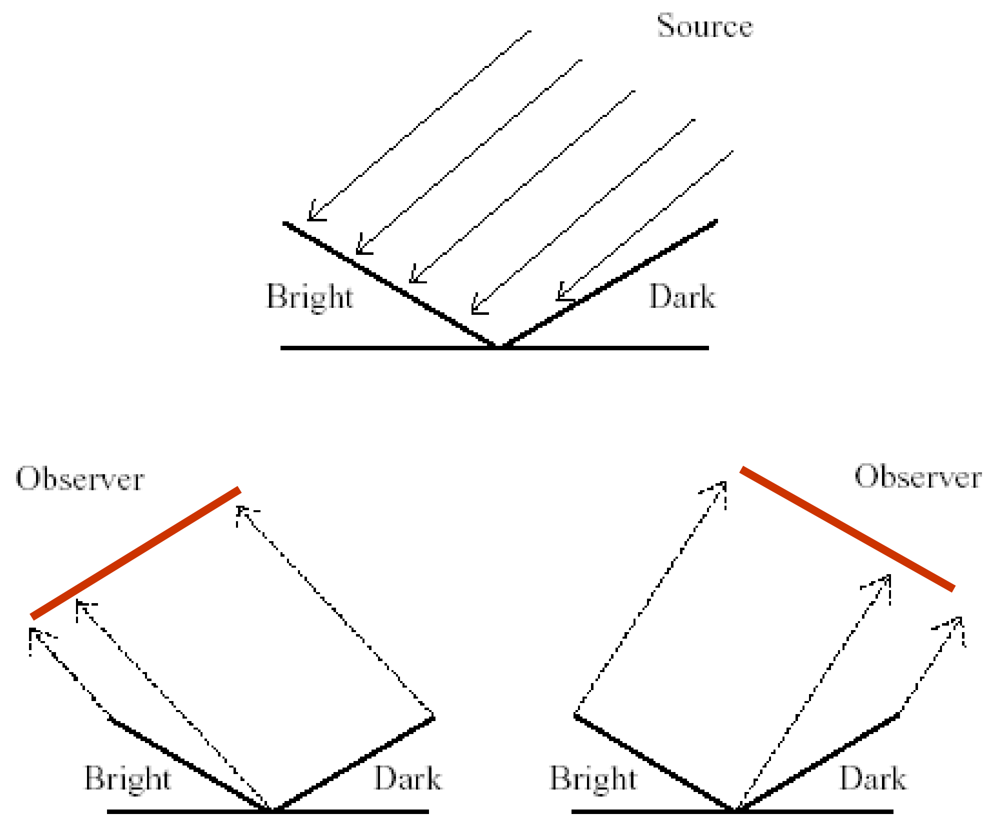
# Modeling Rough Surfaces - Microfacets




- 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.**

# View Dependence of Matte Surfaces - Key Observation




- Overall brightness increases as the angle between the source and viewing direction decreases. WHY?

- Pixels have finite areas. As the viewing direction changes, different mixes between dark and bright are added up to give pixel brightness.

# Torrance-Sparrow BRDF – Different Factors (RECAP)

Fresnel term:
allows for
wavelength
dependency

Geometric Attenuation:
reduces the output based on the amount of shadowing or masking that occurs.

$$f = \frac{F(\theta_i)G(\omega_i, \omega_r)D(\theta_h)}{4\cos(\theta_i)\cos(\theta_r)}$$

Distribution:
distribution function determines what percentage of microfacets are oriented to reflect in the viewer direction.

How much of the macroscopic surface is visible to the light source

How much of the macroscopic surface is visible to the viewer

# Oren-Nayar Model – Different Factors

~~Fresnel term: allows for wavelength dependency~~

Geometric Attenuation: reduces the output based on the amount of shadowing or masking that occurs.

$$f = \frac{\cancel{F(\theta_i)}G(\omega_i, \omega_r)D(\theta_h)}{4\cos(\theta_i)\cancel{\cos(\theta_r)}}$$

~~Distribution: distribution function determines what percentage of microfacets are oriented to reflect in the viewer direction.~~

How much of the macroscopic surface is visible to the light source

~~How much of the macroscopic surface is visible to the viewer~~

# Oren-Nayar Model – Different Factors

~~Fresnel term: allows for wavelength dependency~~

Geometric Attenuation: reduces the output based on the amount of shadowing or masking that occurs.

$$f = \frac{\cancel{F(\theta_i)}\,G(\omega_i,\omega_r)\,D(\theta_h)}{4\cos(\theta_i)\,\cancel{\cos(\theta_r)}}$$

Distribution: distribution function determines what fraction of the surface area do the facets of the same orientation cover?

How much of the macroscopic surface is visible to the light source

~~How much of the macroscopic surface is visible to the viewer~~

# Oren-Nayar Model – Different Factors

~~Fresnel term: allows for wavelength dependency~~

Geometric Attenuation: reduces the output based on the amount of shadowing or masking that occurs.

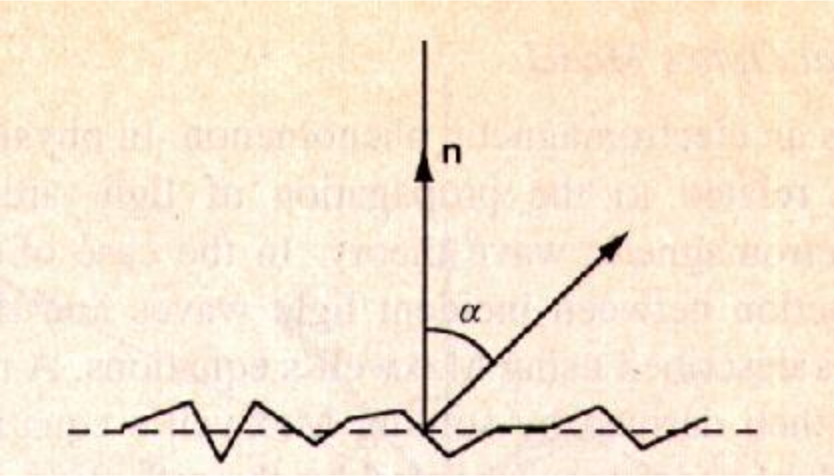
$$f = \frac{\cancel{F(\theta_i)}G(\omega_i,\omega_r)D(\theta_h)}{4\cos(\theta_i)\cancel{\cos(\theta_r)}}$$

Distribution: distribution function determines what fraction of the surface area do the facets of the same orientation cover?

How much of the macroscopic surface is visible to the light source

~~How much of the macroscopic surface is visible to the viewer~~

# Slope Distribution Model




- Model the distribution of slopes as Gaussian.
- Mean is Zero, Variance represents ROUGHNESS.

$$\rho_\alpha(\alpha) = \frac{1}{\sqrt{2\pi\sigma_\alpha}} e^{-\frac{\alpha^2}{2\sigma_\alpha{}^2}} .$$

# Oren-Nayar Model – Different Factors

~~Fresnel term: allows for wavelength dependency~~

Geometric Attenuation: reduces the output based on the amount of shadowing or masking that occurs.

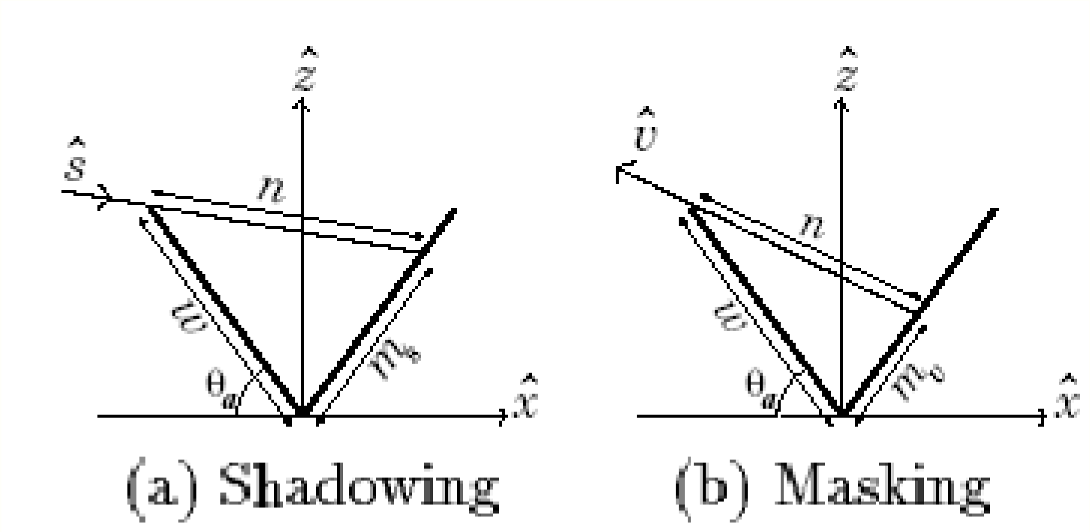
$$f = \frac{\cancel{F(\theta_i)}\,G(\omega_i, \omega_r)\,D(\theta_h)}{4\cos(\theta_i)\,\cancel{\cos(\theta_r)}}$$

Distribution: distribution function determines what fraction of the surface area do the facets of the same orientation cover?

How much of the macroscopic surface is visible to the light source

~~How much of the macroscopic surface is visible to the viewer~~

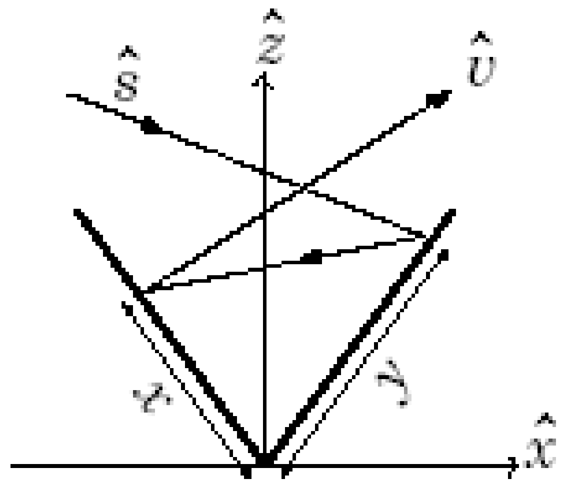
# TS Geometric Attenuation Factor - RECAP




$$G(\theta_i, \theta_r, \phi_r) = \min\left(1,\ \frac{2\cos\alpha\cos\theta_r}{\cos\theta_i'},\ \frac{2\cos\alpha\cos\theta_i}{\cos\theta_i'}\right).$$

- No interreflections taken into account in above function.
- Derivation found in 1967 JOSA paper (read if interested).

# Oren-Nayar Model – Different Factors (contd.)




(c) Interreflection

- Take into account two light bounces (reflections).
- Hard to solve analytically, so they find a functional approximation.

# Oren-Nayar Model – Final Expression

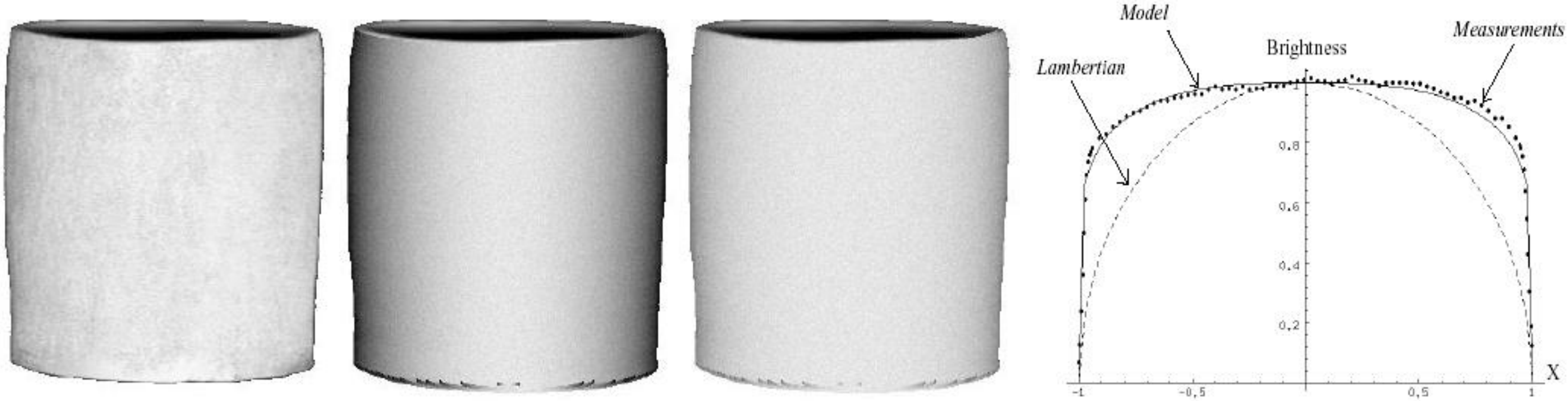
$$\boxed{L(\theta_r, \theta_i; \phi_r - \phi_i; \rho, \sigma) \;=\; \frac{\rho}{\pi} E_0 \cos\theta_i (A + B\,Max\left[0, \cos(\phi_r - \phi_i)\right] \sin\alpha \tan\beta),}$$

$$A \;=\; 1.0 - 0.5 \frac{\sigma^2}{\sigma^2 + 0.33}, \qquad \alpha = Max(\theta_r, \theta_i)$$

$$B \;=\; 0.45 \frac{\sigma^2}{\sigma^2 + 0.09}, \qquad \beta = Min(\theta_r, \theta_i).$$

Lambertian model is simply an extreme case with roughness equal to zero.

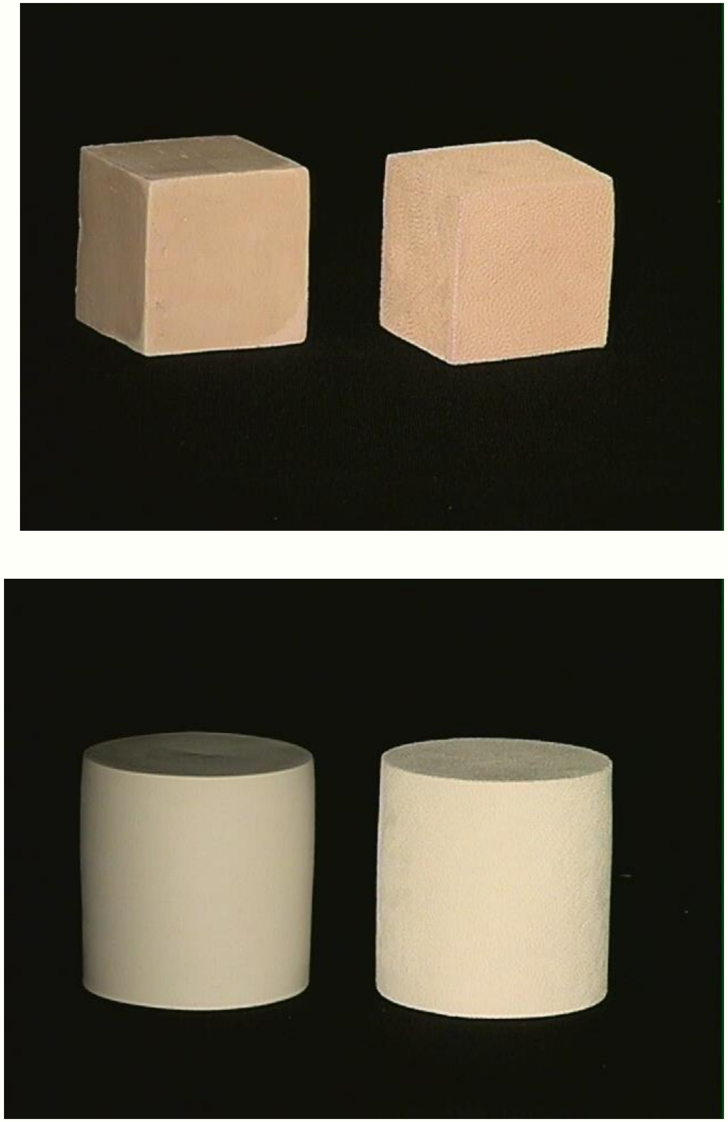
# Comparison to Ground Truth



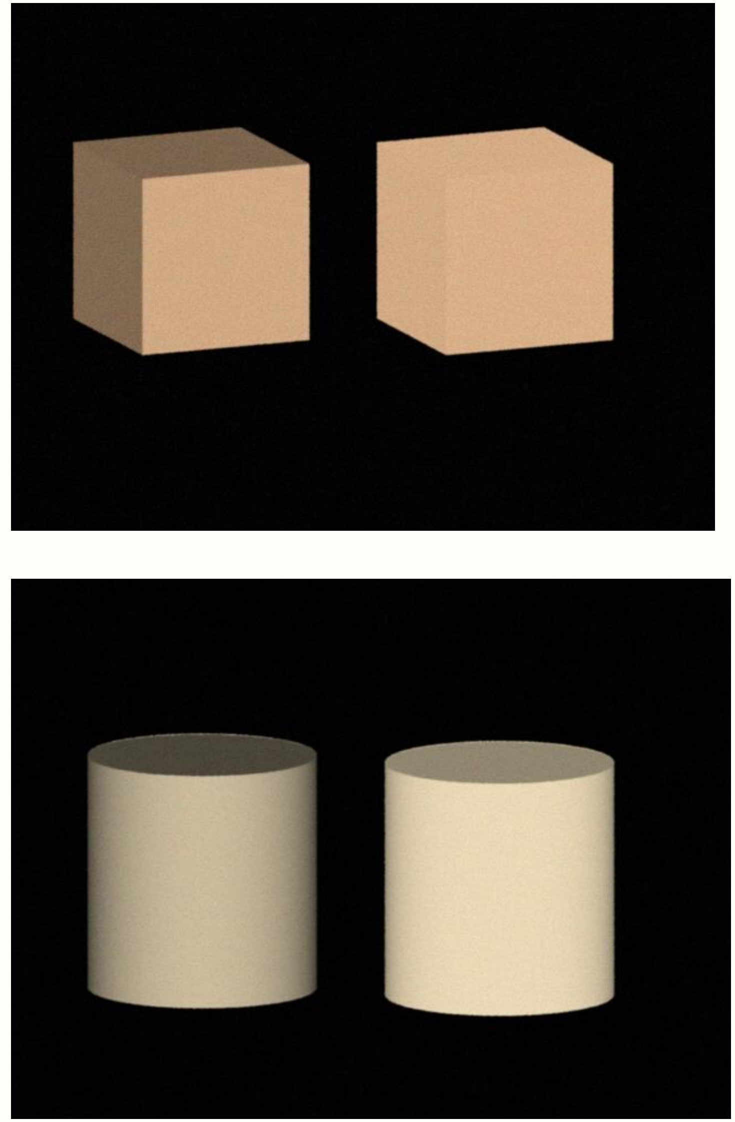

(a) Image (b) Lambertian (c) Model (d)

**Fig. 7.** (a-c) Real image of a cylindrical clay vase compared with images rendered using the Lambertian and proposed models. Illumination is from the direction $\theta_i = 0°$. (d) Comparison between image brightness along the cross-sections of the three vases.

# Comparison to Ground Truth



Real Objects



Renderings

# Summary of Surfaces and BRDFs

Smooth → Rough

Specular ↓ Diffuse

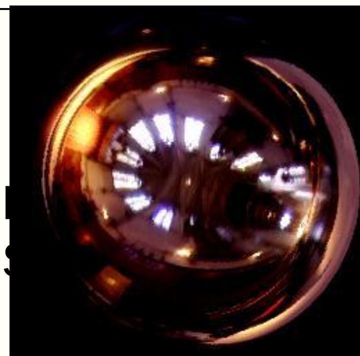
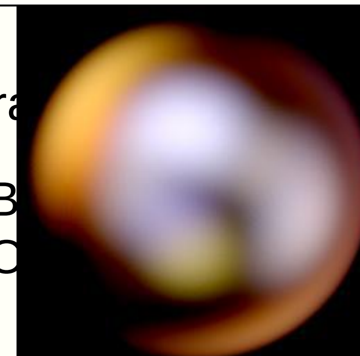
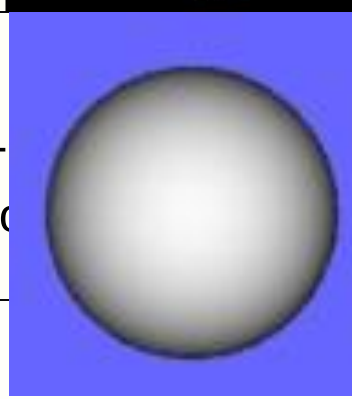
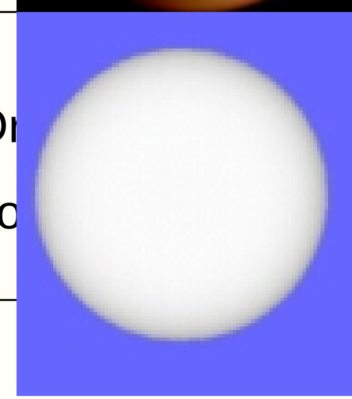
| | Smooth | Rough |
|---|---|---|
| Specular | Mirror BRDF<br><br>Delta Function<br>Speck of reflection | Torrance-Sparrow BRDF<br><br>Broader Highlights<br>Off-specular lobe |
| Diffuse | Lambertian BRDF<br><br>No view dependence | Oren-Nayar BRDF<br><br>Models view dependence |

Many surfaces may be rough and show both diffuse and surface reflection.

# Summary of Surfaces and BRDFs

Smooth → Rough

Specular ↓ Diffuse

| | Smooth | Rough |
|---|---|---|
| Specular | I<br>S  n | Torra  RDF<br>B s<br>C |
| Diffuse | L  t<br>N ce | Or <br>Mo dence |

Many surfaces may be rough and show both diffuse and surface reflection.

# Thank you

Lesson summary:

1. Reflectance depends on surface normals, and involves lots of angles.

2. Diffuse reflectance is easy to compute.
A lot of vision is trying to “filter” images into a diffuse image.

3. The effect of Fresnel reflectance
increases greatly at grazing angles.

4. Many scenes do not have diffuse reflectance and cannot be easily made diffuse. So algorithms need to model the reflectance.

5. Local reflectance properties can create surprising global effects.