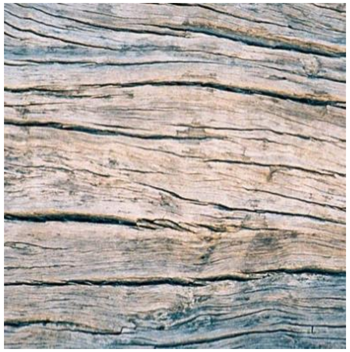
Shading & Material Appearance

Lighting and Material Appearance

- Input for realistic rendering
  - Geometry, Lighting and Materials
- Material appearance
  - Intensity and shape of highlights
  - Glossiness
  - Color
  - Spatial variation, i.e., texture (next Tuesday)



Slide Addy Ngan

Unit Issues - Radiometry

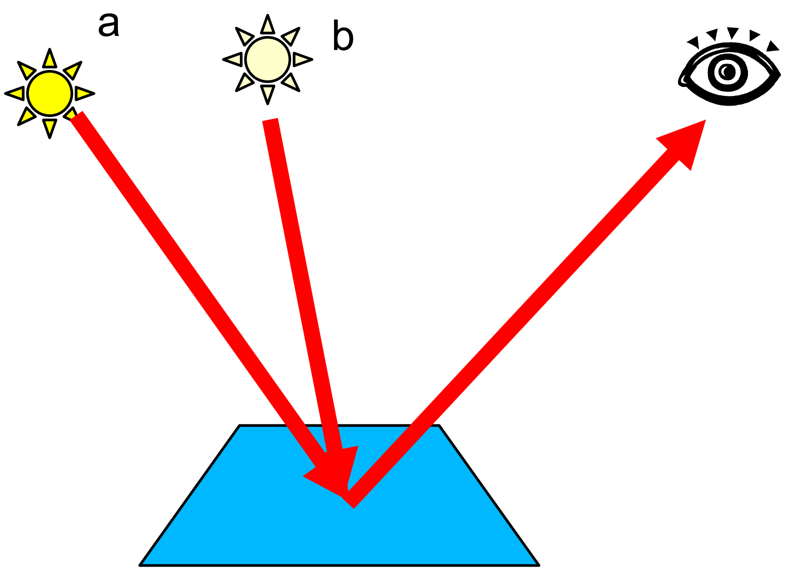
- We will not be too formal in this class
- Issues we will not really care about
  - Directional quantities vs. integrated over all directions
  - Differential terms: per solid angle, per area
  - Power? Intensity? Flux?

- Color
  - All math here is for a single wavelength only; we will perform computations for R, G, B separately
    - Do not panic, that just means
      we will perform every operation three times, that is all

Light Sources

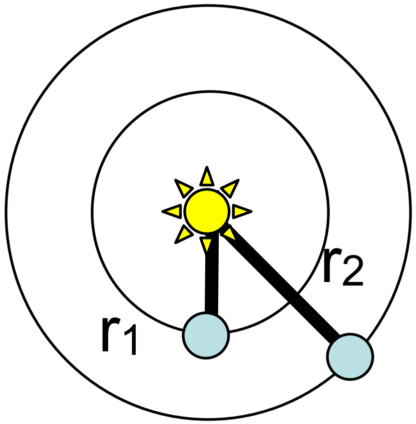
- Today, we only consider point light sources
  - Thus we do not need to care about solid angles
- For multiple light sources, use linearity
  - We can add the solutions for two light sources
    - I(a+b) = I(a) + I(b)
  - We simply multiply the solution when we scale the light intensity
    - I(s a) = s I(a)

Yet again, linearity is our friend!



Intensity as Function of Distance

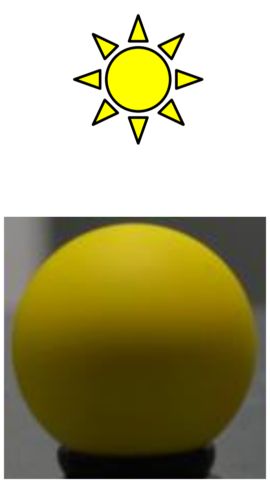
- $1/r^2$ fall-off for isotropic point lights
  - Why? An isotropic point light outputs constant power per solid angle ("into all directions")
  - Must have same power in all concentric spheres
    - Sphere's surface area grows with r^2 => energy obeys $1/r^2$

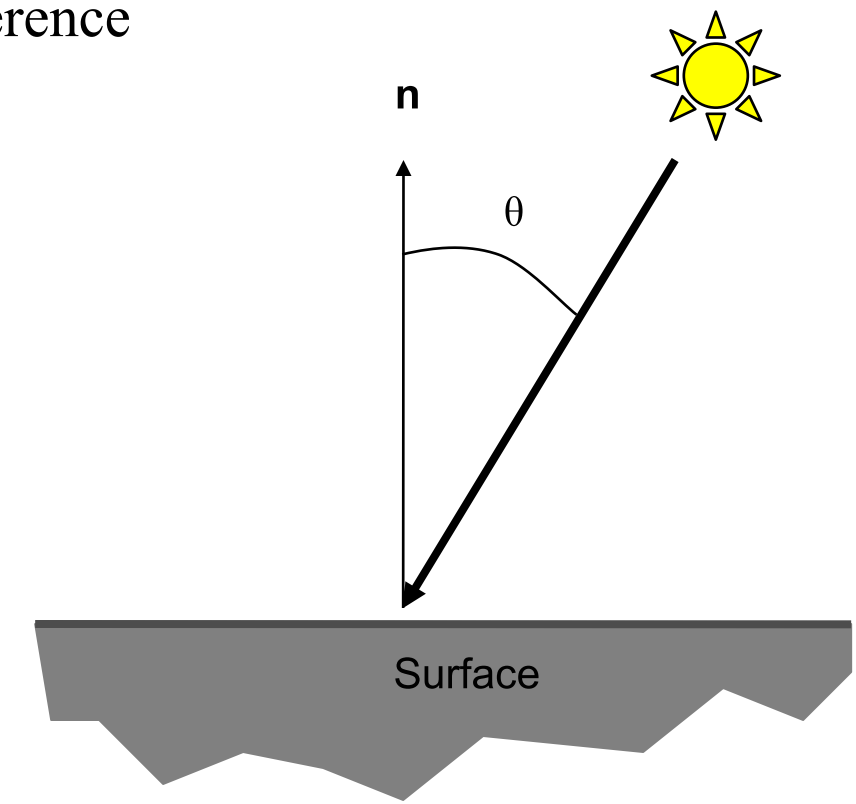


- … but in graphics we often cheat with or ignore this.
  - Why? Ideal point lights are kind of harsh
    - Intensity goes to infinity when you get close – not great!
  - In particular, $1/(ar^2+br+c)$ is popular

Incoming Irradiance

- The amount of light energy received by a surface depends on incoming angle
  - Bigger at normal incidence, even if distance is const.
    - Similar to winter/summer difference
- How exactly?
  - Cos θ law
  - Dot product with normal



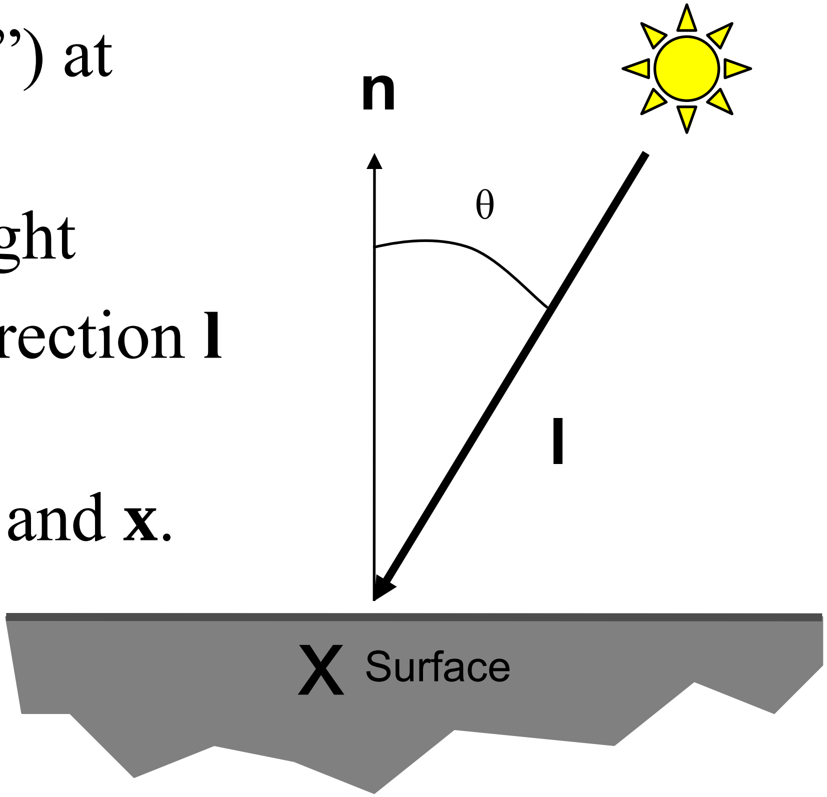


Incoming Irradiance for Pointlights

- Let's combine this with the $1/r^2$ fall-off:

$$I_{\text{in}} = I_{\text{light}} \cos\theta / r^2$$

  - I_{in} is the irradiance ("intensity") at surface point **x**
  - I_{light} is the "intensity" of the light
  - θ is the angle between light direction **l** and surface normal **n**
  - r is the distance between light and **x**.

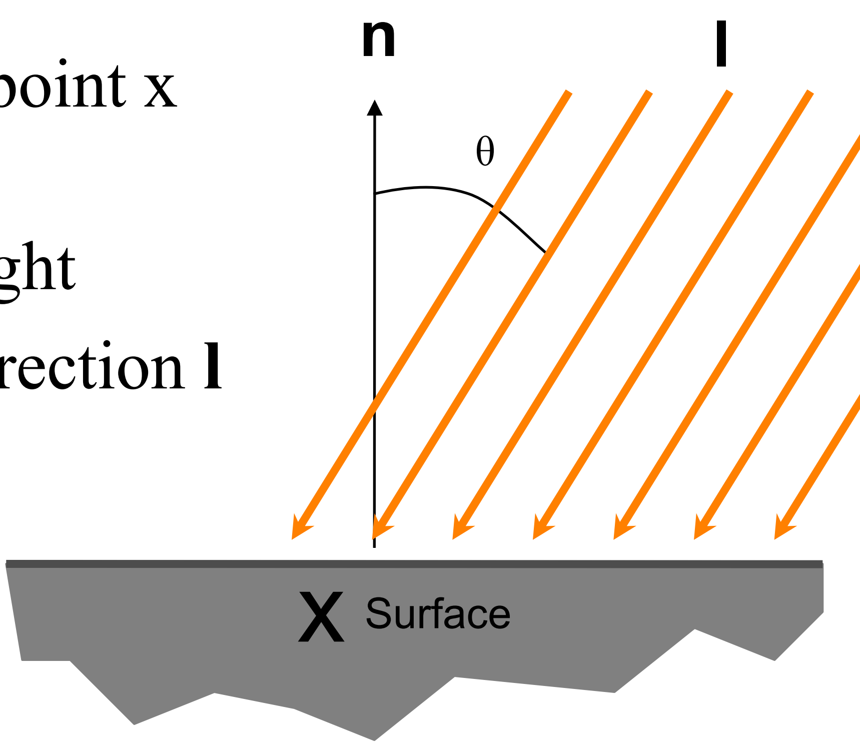


Directional Lights

- "Pointlights that are infinitely far"
  - No falloff, just one direction and one intensity

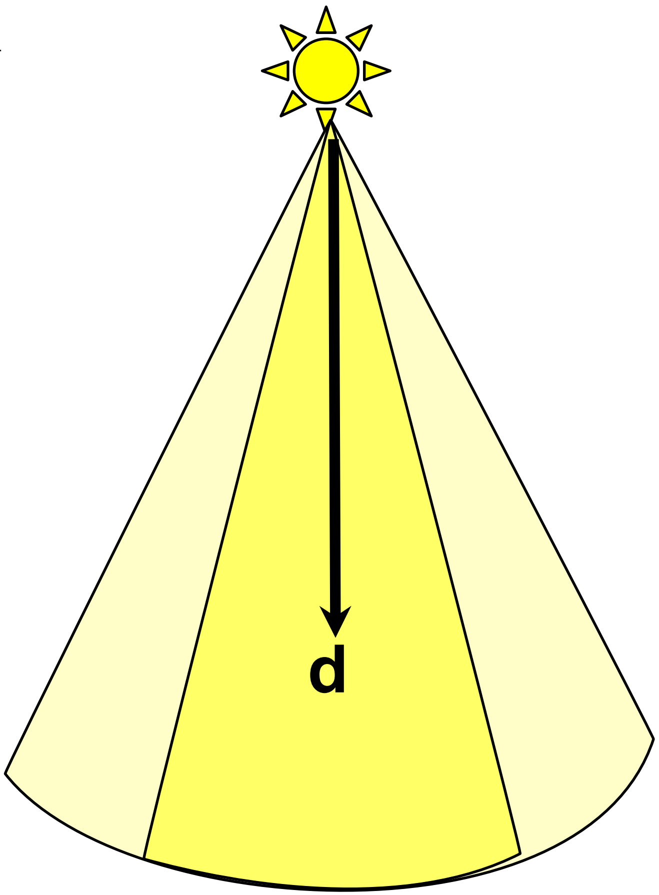
$$I_{\text{in}} = I_{\text{light}} \cos\theta$$

  - I_{in} is the irradiance at surface point x from the directional light
  - I_{light} is the "intensity" of the light
  - θ is the angle between light direction **l** and surface normal **n**
    - Only depends on **n**, not **x**!



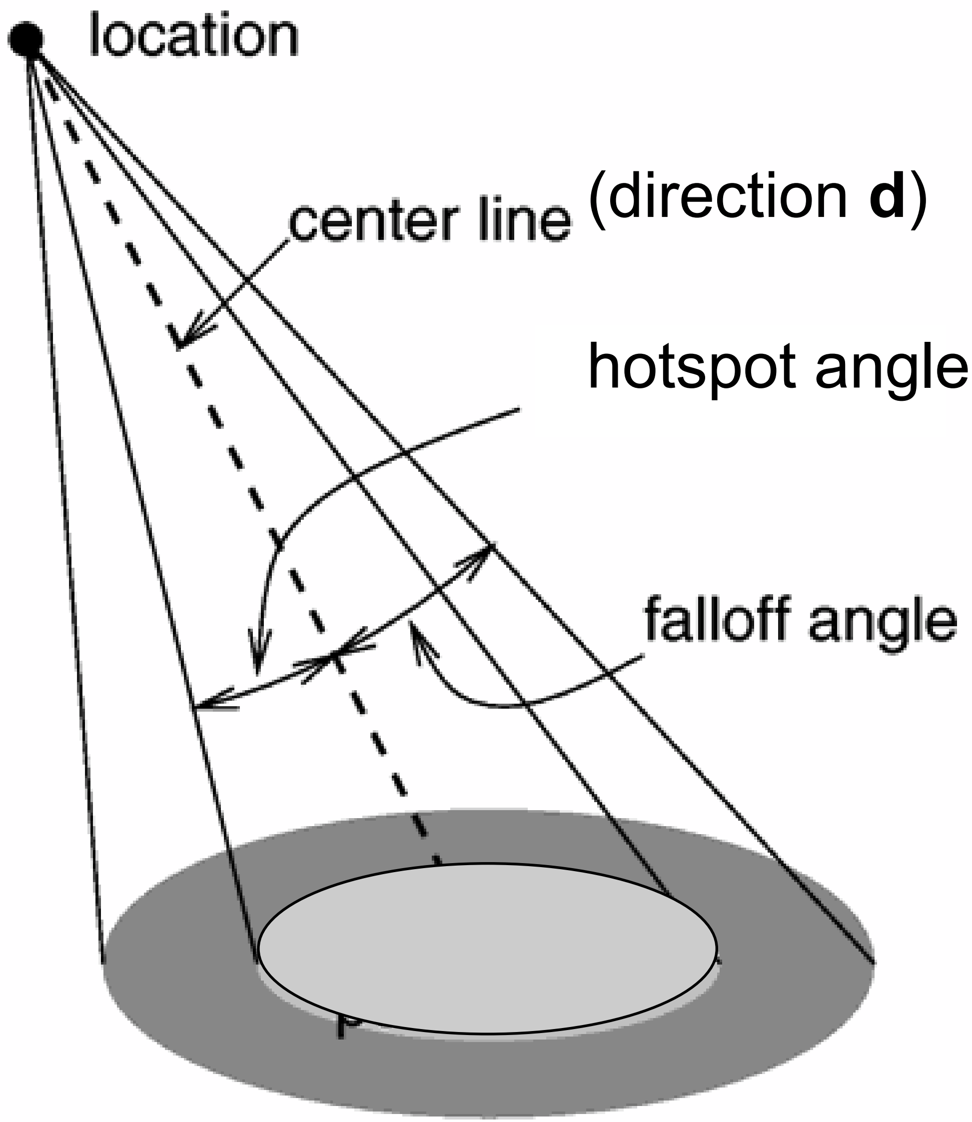
Spotlights

- Pointlights with non-uniform directional emission
- Usually symmetric about a central direction **d**, with angular falloff
  - Often two angles
    - "Hotspot" angle: No attenuation within the central cone
    - "Falloff" angle: Light attenuates from full intensity to zero intensity between the hotspot and falloff angles



- Plus your favorite distance falloff curve

Spotlight Geometry

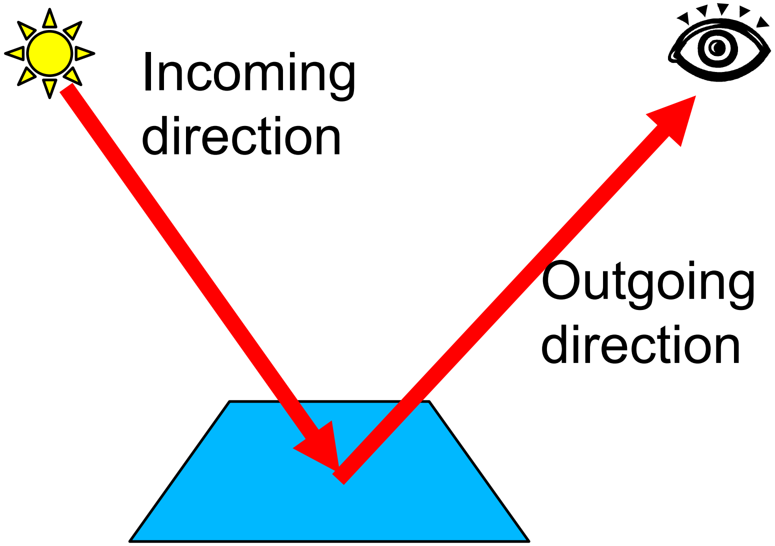


Adapted from
POVRAY documentation

Questions?

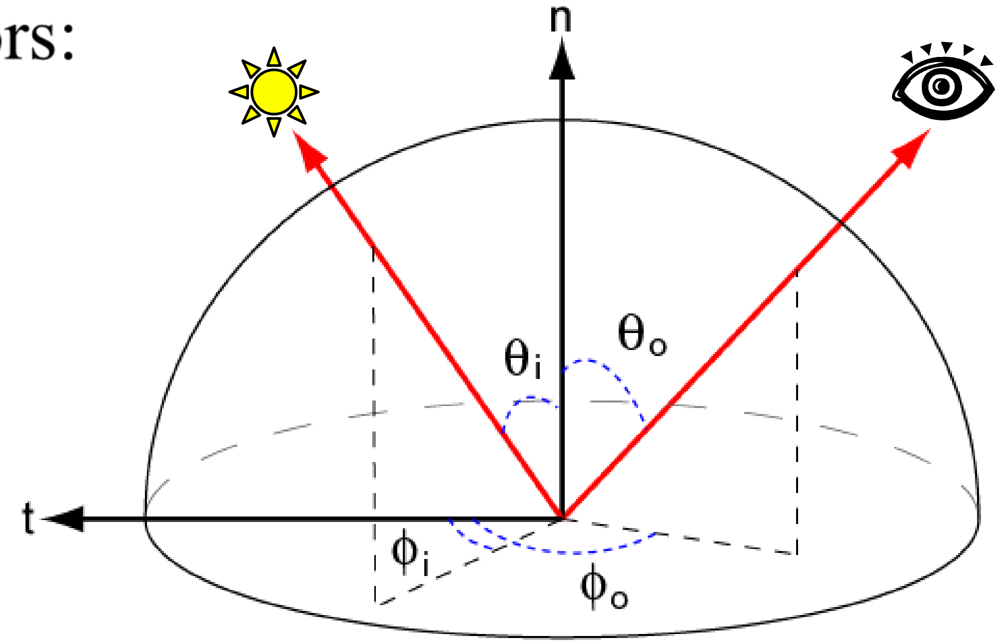
Quantifying Reflection – BRDF

- Bidirectional Reflectance Distribution Function
- Ratio of light coming from one direction that gets reflected in another direction
  - Pure reflection, assumes no light scatters into the material
- Focuses on angular aspects, not spatial variation of the material
- **How many dimensions?**



BRDF f_r

- Bidirectional Reflectance Distribution Function
  - 4D: 2 angles for each direction
  - BRDF = $f_r(\theta_i, \phi_i; \theta_o, \phi_o)$
  - Or just two unit vectors: BRDF = $f_r(\mathbf{l}, \mathbf{v})$
    - $\mathbf{l}$ = light direction
    - $\mathbf{v}$ = view direction



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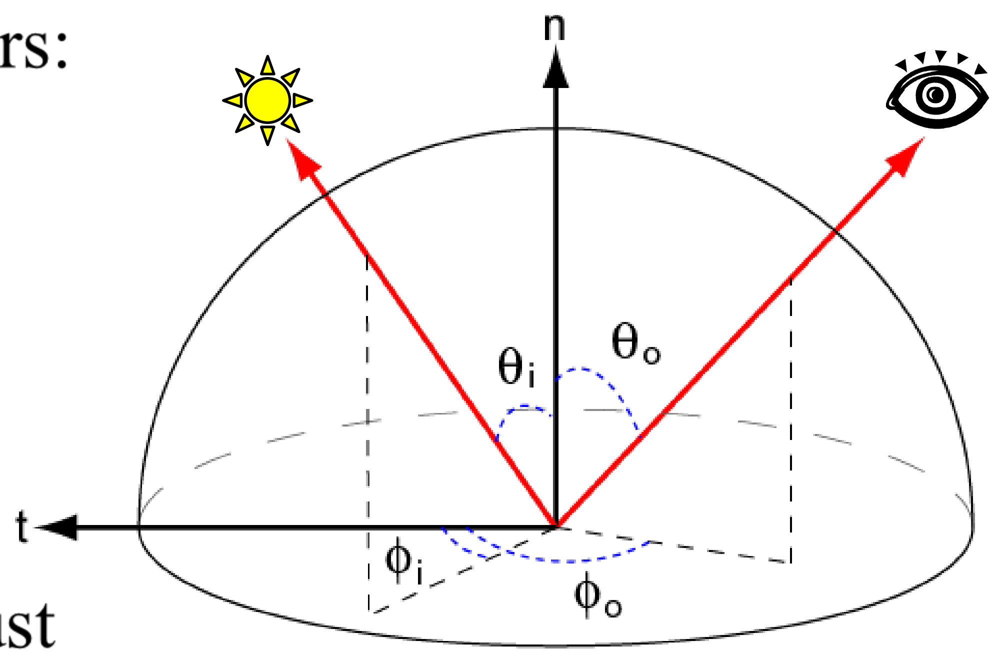
  - Or just two unit vectors: BRDF = $f_r(\mathbf{l}, \mathbf{v})$
    - **l** = light direction
    - **v** = view direction
  - The BRDF is aligned with the surface; the vectors **l** and **v** must be in a local coordinate system

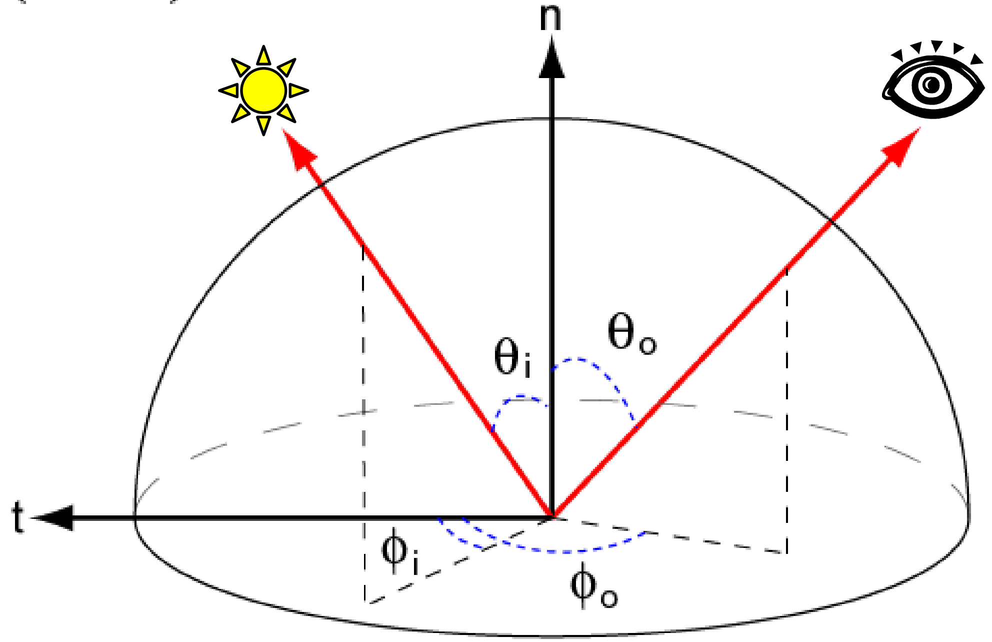


BRDF f_r

- Relates incident irradiance from every direction to outgoing light. How?

l = light direction (incoming)
v = view direction (outgoing)

$$I_{\text{out}}(\boldsymbol{v}) = I_{\text{in}}(\boldsymbol{l})\, f_r(\boldsymbol{v}, \boldsymbol{l})$$



BRDF f_r

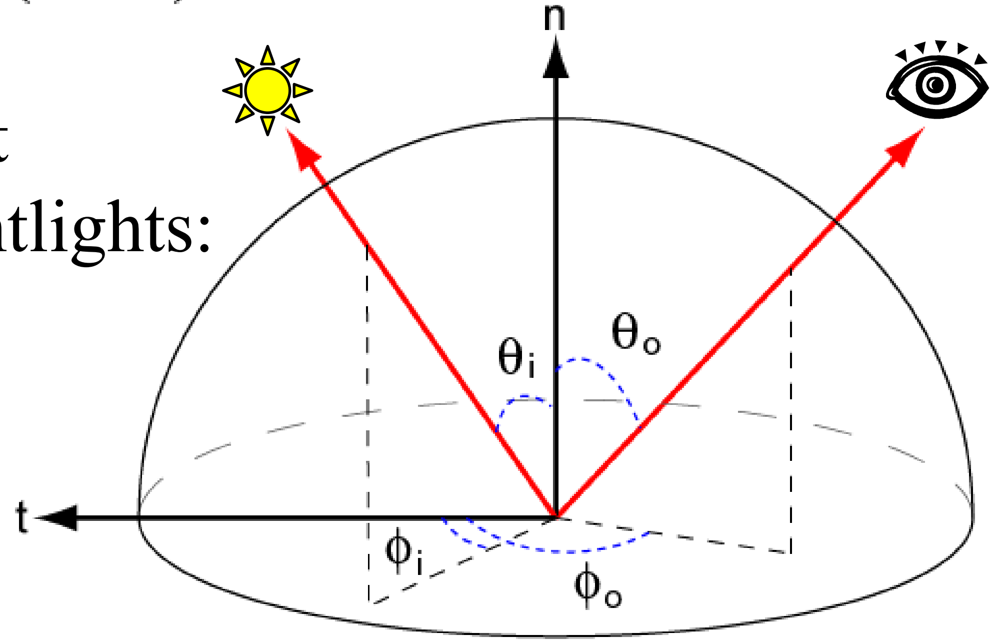
- Relates incident irradiance from every direction to outgoing light. How?

$$I_{\text{out}}(\boldsymbol{v}) = I_{\text{in}}(\boldsymbol{l})\, f_r(\boldsymbol{v}, \boldsymbol{l})$$

- Let's combine with what we know already of pointlights:

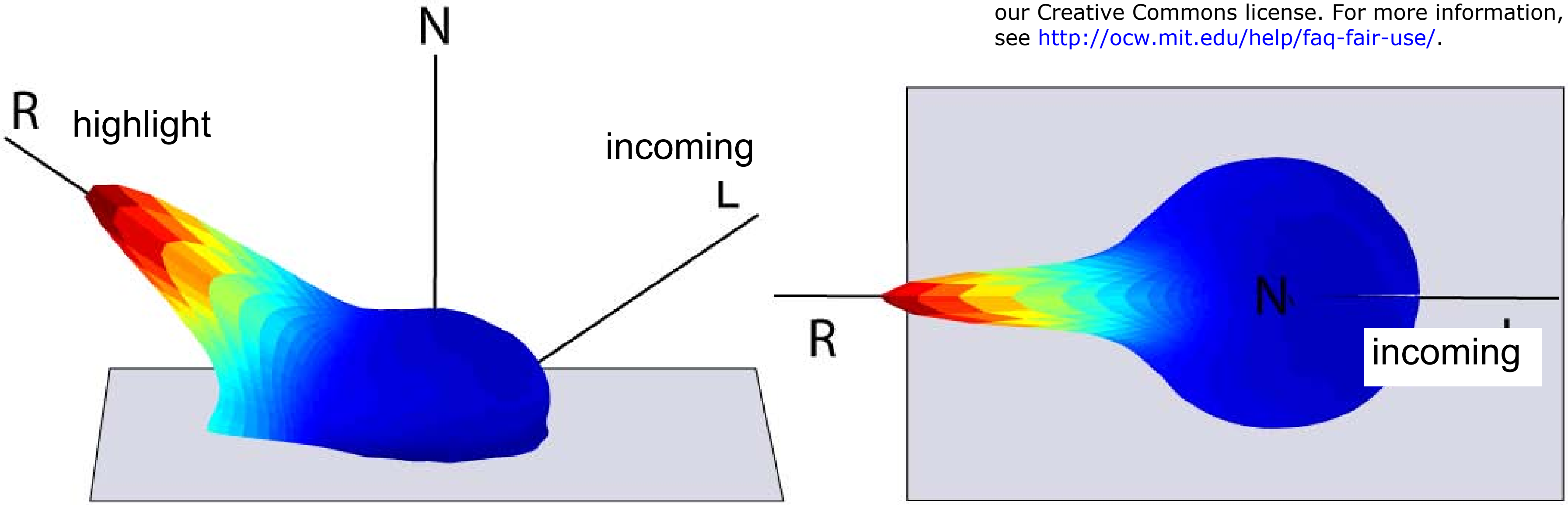
$$I_{\text{out}}(\boldsymbol{v}) = \frac{I_{\text{light}} \cos\theta_i}{r^2} f_r(\boldsymbol{v}, \boldsymbol{l})$$

l = light direction (incoming)
v = view direction (outgoing)



2D Slice at Constant Incidence

- For a fixed incoming direction, view dependence is a 2D spherical function
  - Here a moderate specular component



Example: Plot of "PVC" BRDF at 55° incidence

Demo

Isotropic vs. Anisotropic

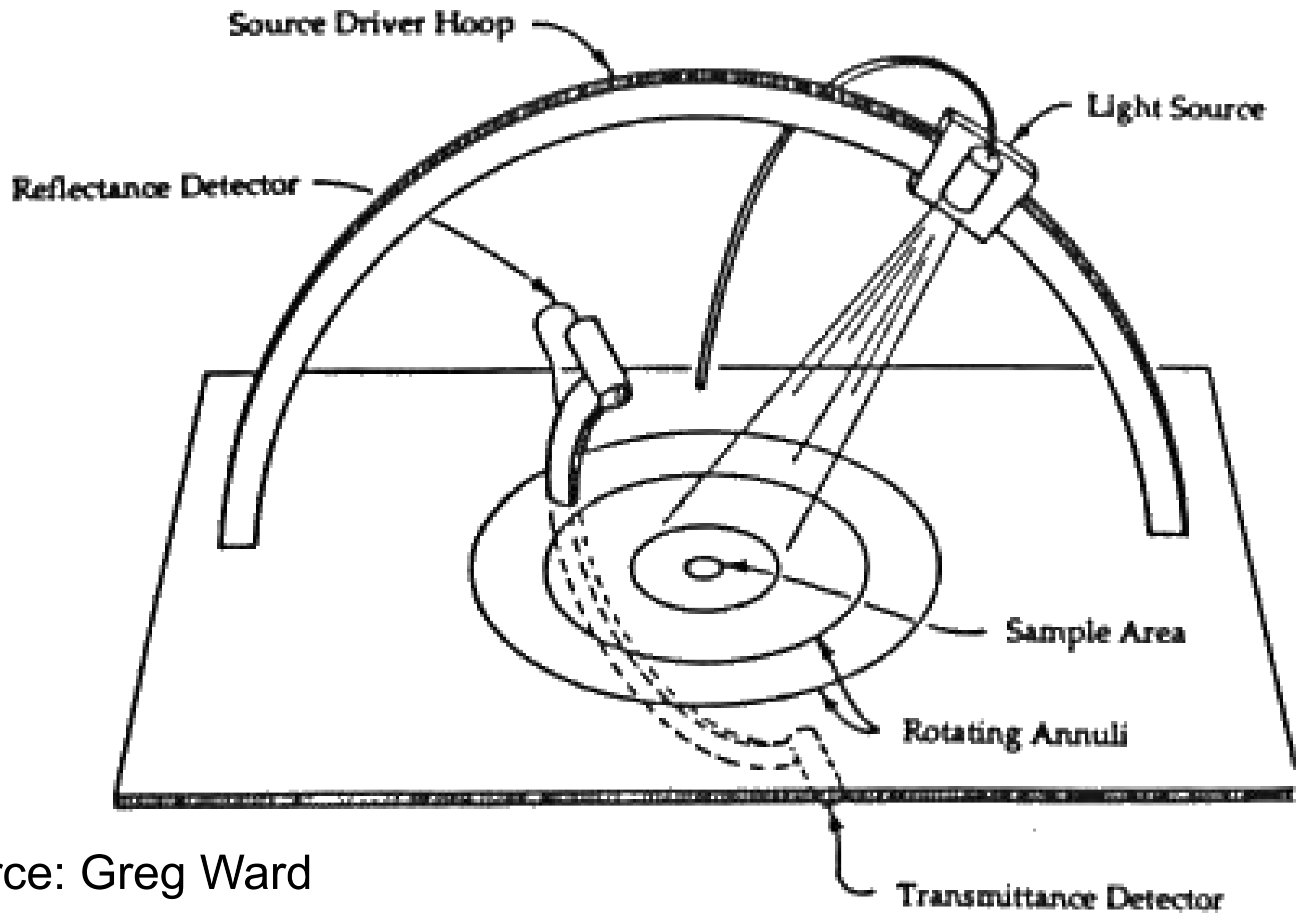
- When keeping **l** and **v** fixed, if rotation of surface around the normal does not change the reflection, the material is called isotropic
- Surfaces with strongly oriented microgeometry elements are anisotropic
- Examples:
  - brushed metals,
  - hair, fur, cloth, velvet

Westin et.al 92

Demo

How do we obtain BRDFs?

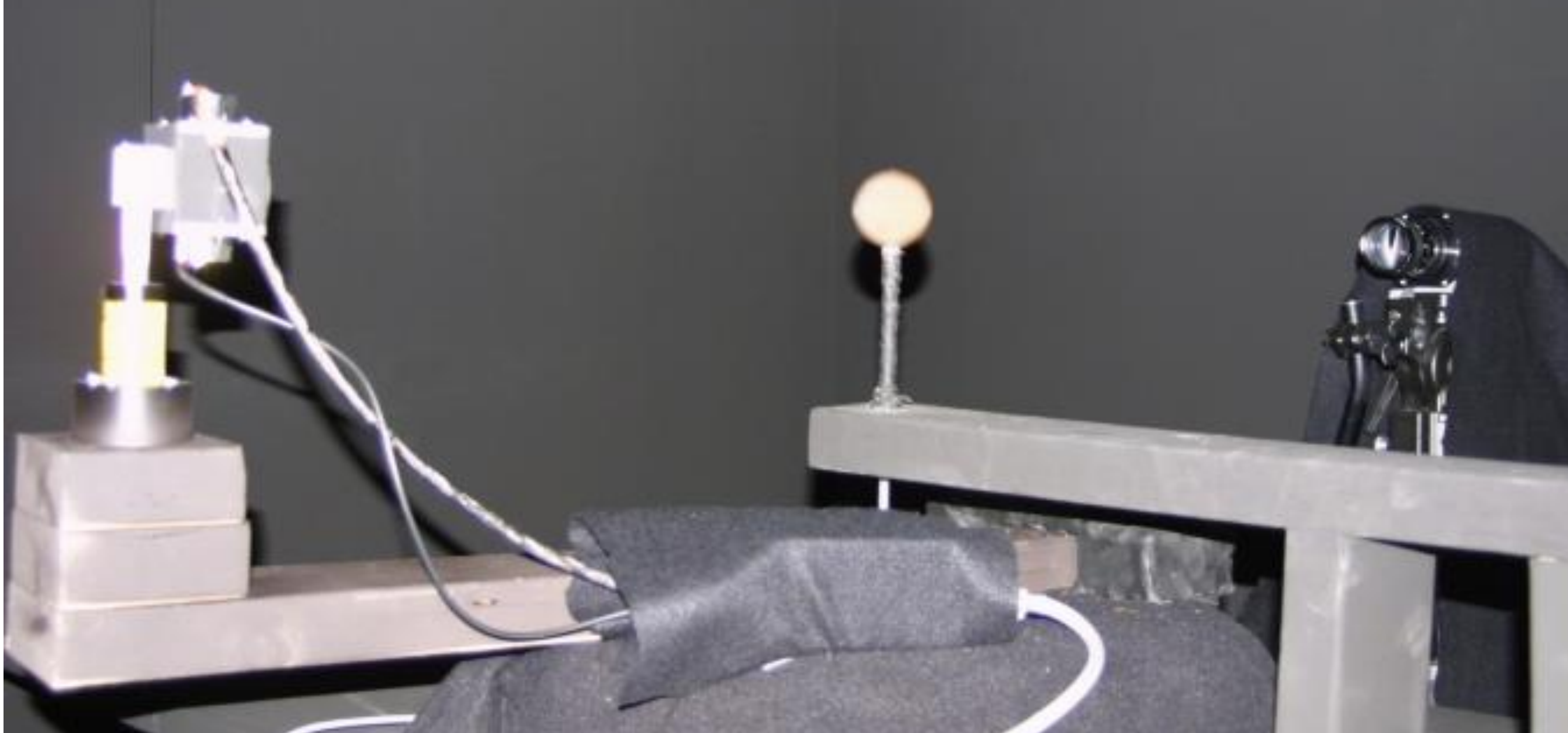
- One possibility: Gonioreflectometer
  - 4 degrees of freedom



Source: Greg Ward

How Do We Obtain BRDFs?

- Another possibility: Take pictures of spheres coated with material, rotate light around a 1D arc
  - This gives 3DOF => isotropic materials only



Matusik et al.

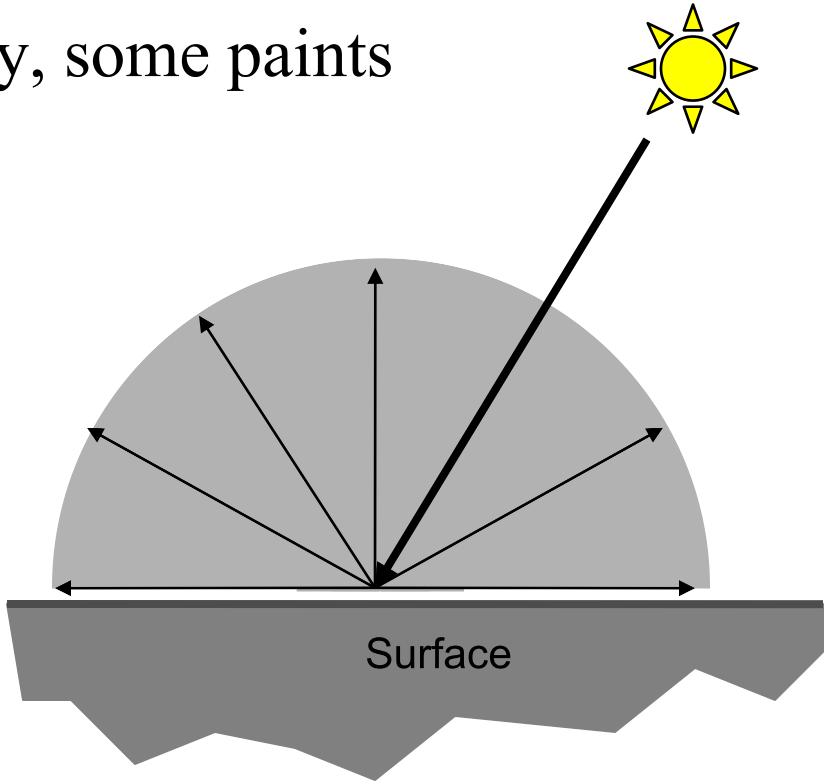
Parametric BRDFs

- BRDFs can be measured from real data
  - But tabulated 4D data is too cumbersome for most uses
- Therefore, parametric BRDF models represent the relationship between incident and outgoing light by some mathematical formula
  - The appearance can then be tuned by setting parameters
    - "Shininess", "anisotropy", etc.
  - Physically-based or Phenomenological
  - They can model with measured data (examples later)
- Popular models: Diffuse, Blinn-Phong, Cook-Torrance, Lafortune, Ward, Oren-Nayar, etc.

Questions?

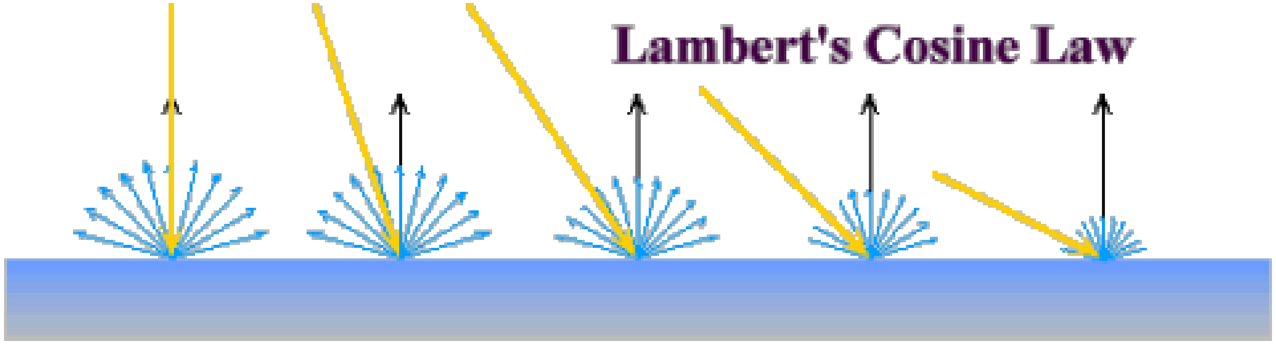
Ideal Diffuse Reflectance

- Assume surface reflects equally in all directions.
- An ideal diffuse surface is, at the microscopic level, a very rough surface.
  - Example: chalk, clay, some paints



Ideal Diffuse Reflectance

- Ideal diffuse reflectors reflect light according to Lambert's cosine law
  - The reflected light varies with cosine even if distance to light source is kept constant



Ideal Diffuse Reflectance

- Ideal diffuse reflectors reflect light according to Lambert's cosine law
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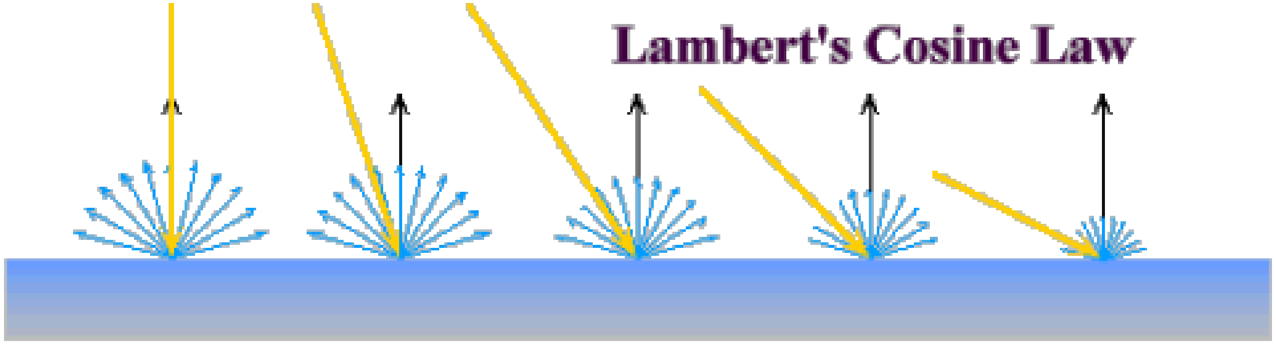
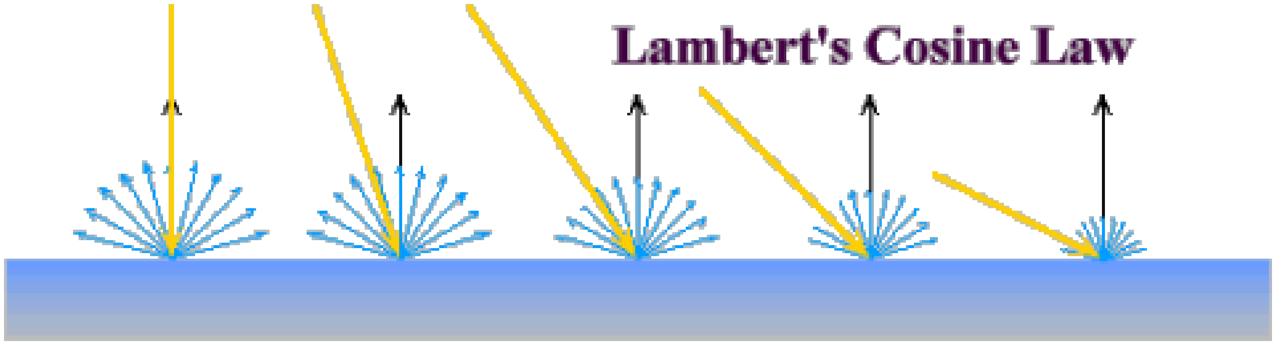
Remembering that incident irradiance depends on cosine, what is the BRDF of an ideally diffuse surface?



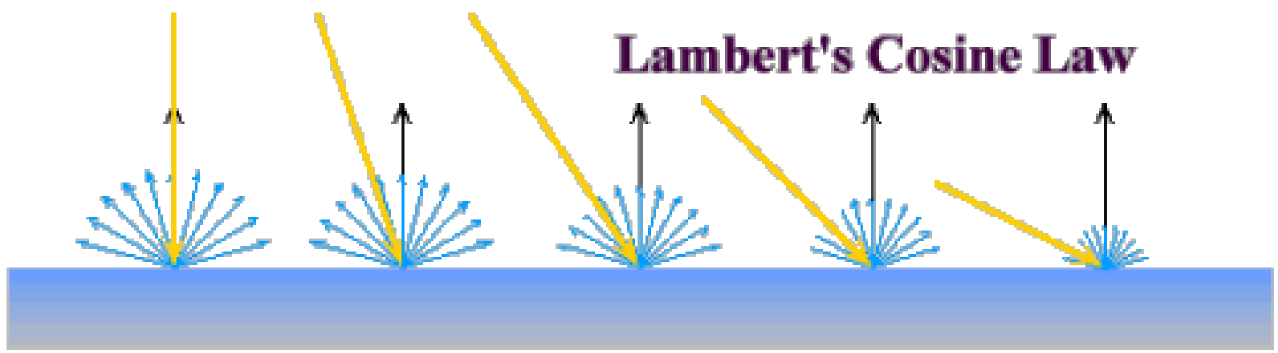
Ideal Diffuse Reflectance

- The ideal diffuse BRDF is a constant $f_r(\mathbf{l}, \mathbf{v})$ = const.
  - What constant ρ/π, where ρ is the *albedo*
    - Coefficient between 0 and 1 that says what fraction is reflected
  - Usually just called "diffuse color" k_d
  - You have already implemented this by taking dot products with the normal and multiplying by the "color"!



Ideal Diffuse Reflectance

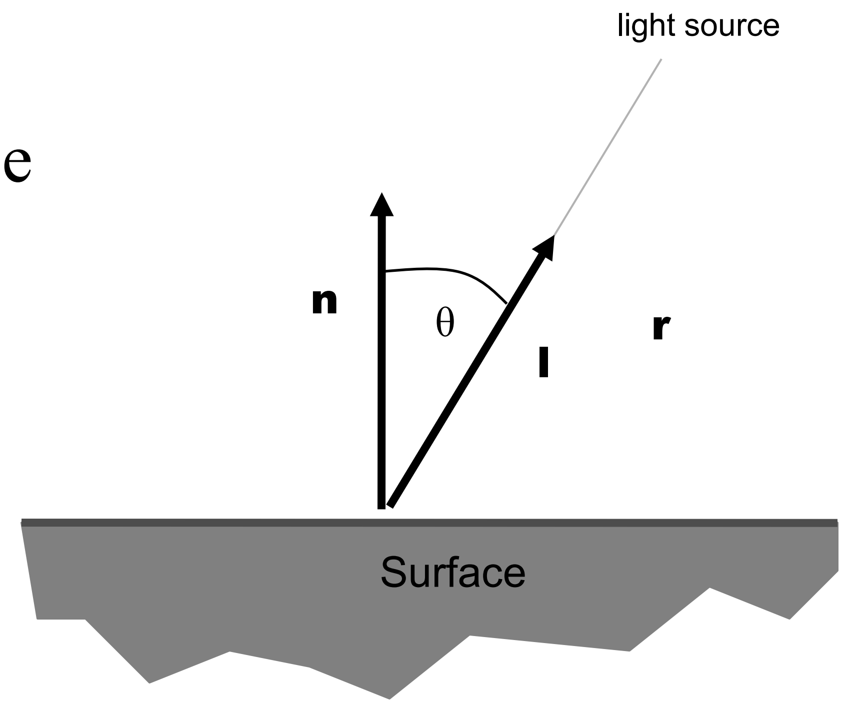
- This is the simplest possible parametric BRDF
  - One parameter: k_d
    - (One for each RGB channel)



Ideal Diffuse Reflectance Math

- Single Point Light Source
  - k_d: diffuse coefficient (color)
  - **n**: Surface normal.
  - **l**: Light direction.
  - L_i: Light intensity
  - r: Distance to source
  - L_o: Shaded color

$$L_o = k_d \max(0, \boldsymbol{n} \cdot \boldsymbol{l}) \frac{L_i}{r^2}$$



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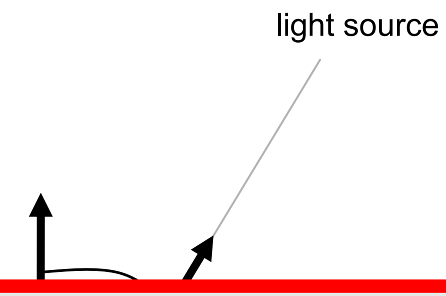


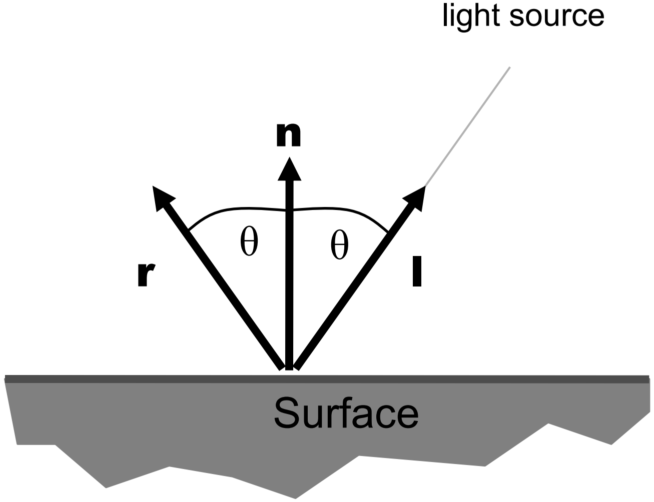
We do not want light from below the surface! From now on we always assume (on this lecture) that **dot products are clamped to zero** and skip writing out the max().

Do not forget to normalize your **n** and **l**!

Questions?

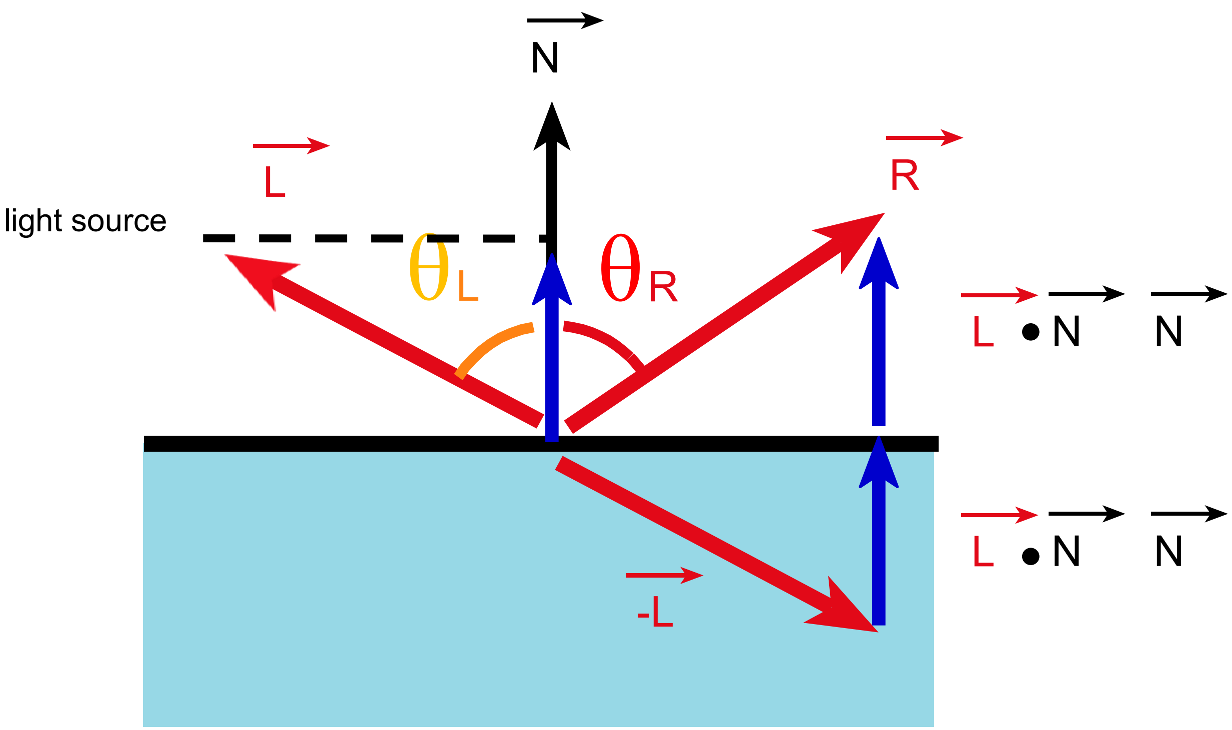
Ideal Specular Reflectance

- Reflection is only at mirror angle
- View dependent
  - Microscopic surface elements are usually oriented in the same direction as the surface itself.
  - Examples: mirrors, highly polished metals.



Recap: How to Get Mirror Direction

- Reflection angle = light angle
  - Both **R & L** have to lie on one plane
- $\mathbf{R} = -\mathbf{L} + 2\,(\mathbf{L} \cdot \mathbf{N})\,\mathbf{N}$



Ideal Specular BRDF

- Light **only** reflects to the mirror direction
- A Dirac delta multiplied by a specular coefficient k_s

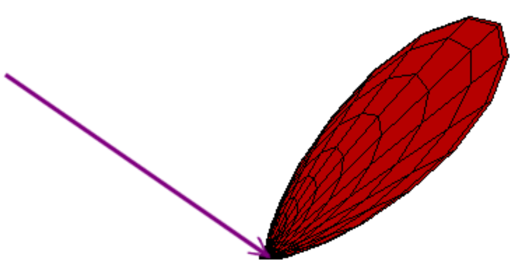
- Not very useful for point lights, only for reflections of other surfaces
  – Why? You cannot really see a mirror reflection of an infinitely small light!

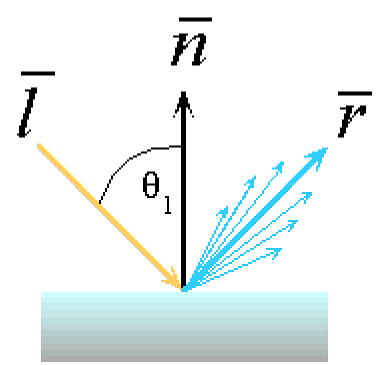
Non-ideal Reflectors

- Real glossy materials usually deviate significantly from ideal mirror reflectors
  - Highlight is blurry
- They are not ideal diffuse surfaces either …

Non-ideal Reflectors

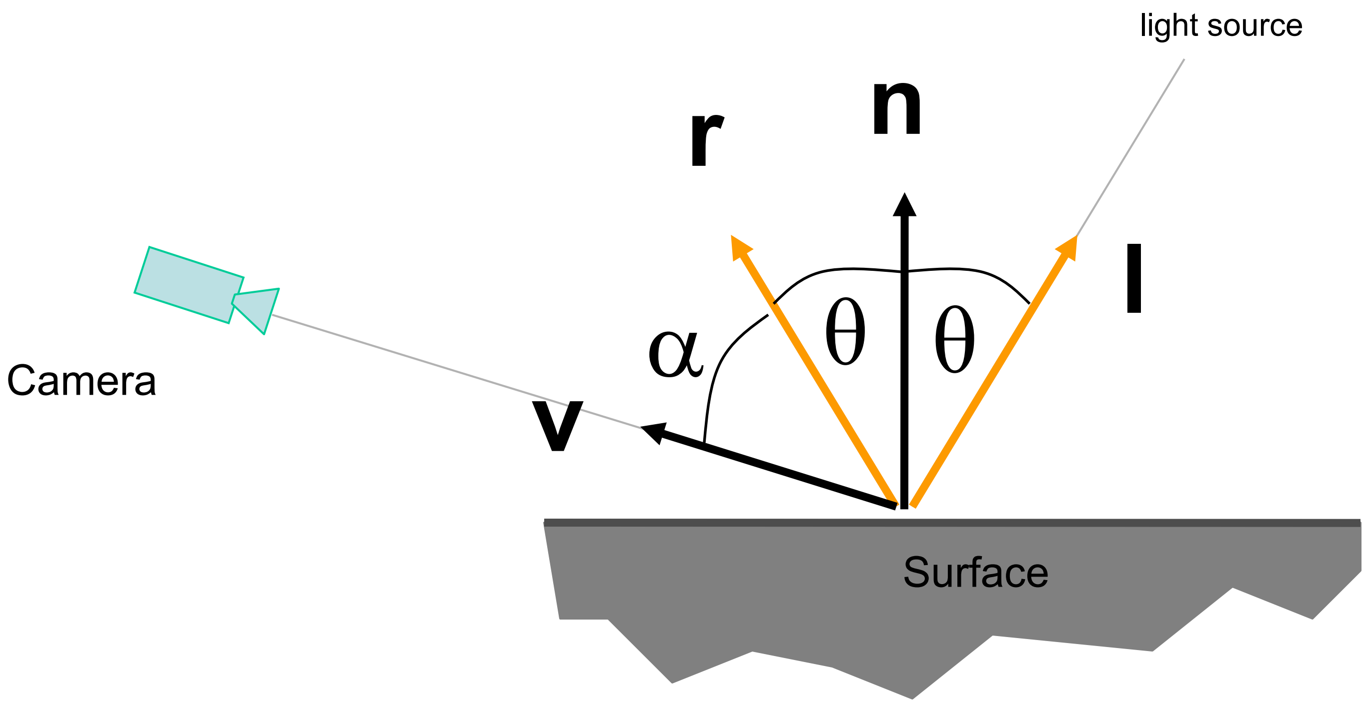
- Simple Empirical Reasoning for Glossy Materials
  - We expect most of the reflected light to travel in the direction of the ideal mirror ray.
  - However, because of microscopic surface variations we might expect some of the light to be reflected just slightly offset from the ideal reflected ray.
  - As we move farther and farther, in the angular sense, from the reflected ray, we expect to see less light reflected.





The Phong Specular Model

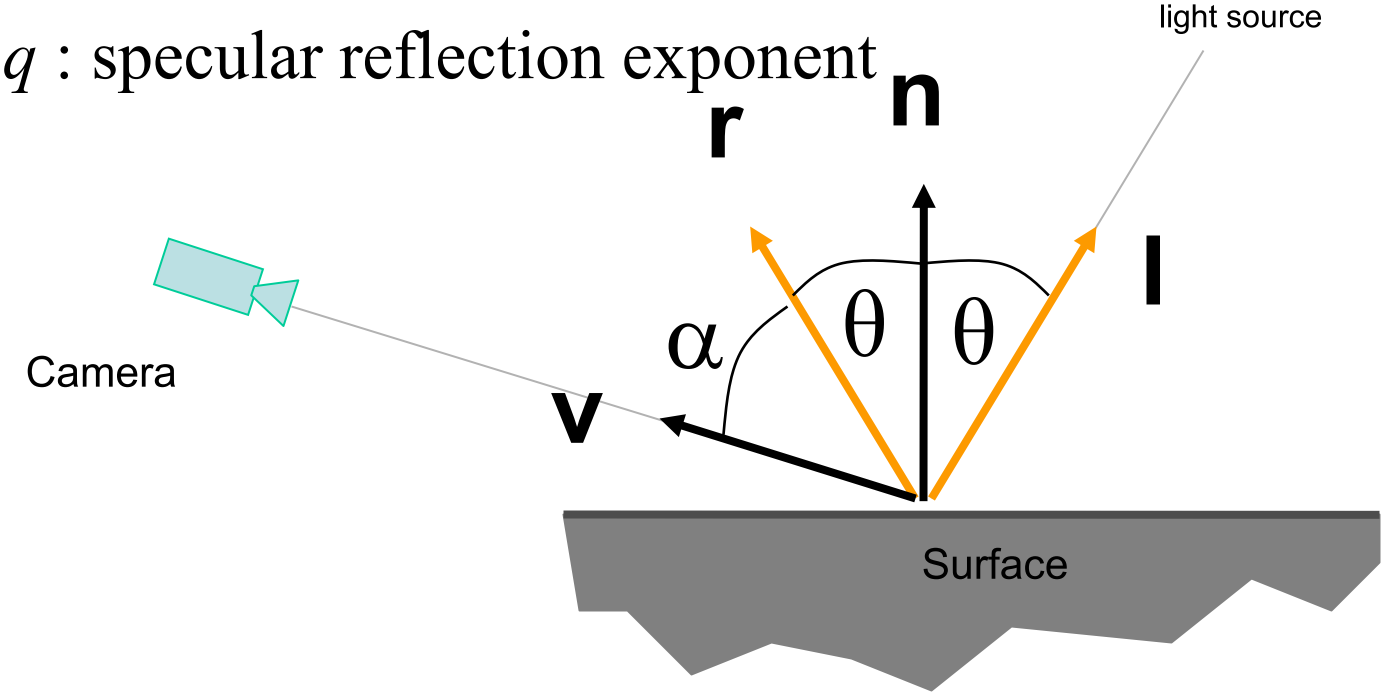
- How much light is reflected?
  - Depends on the angle α between the ideal reflection direction **r** and the viewer direction **v**.



The Phong Specular Model

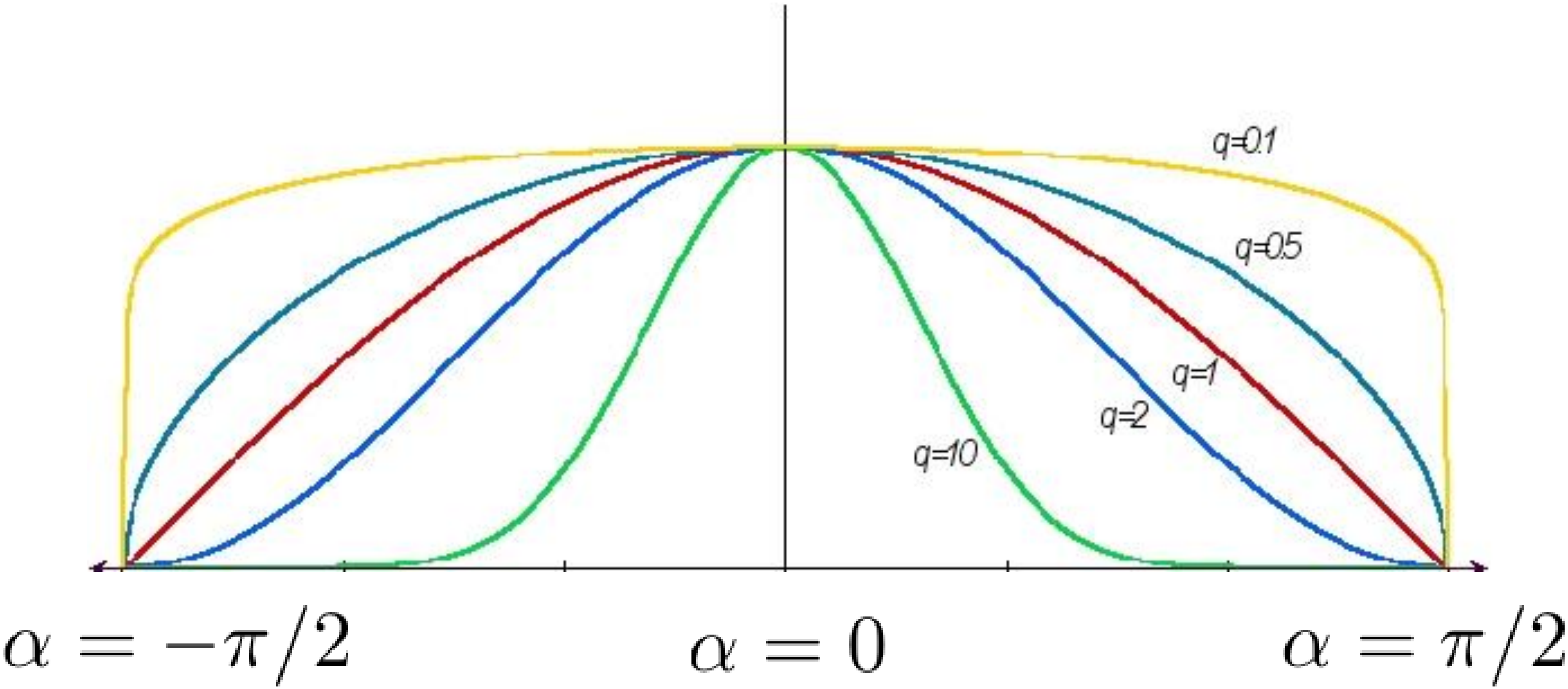
$$L_o = \quad k_s \, (\cos\alpha)^q \, \frac{L_i}{r^2} \quad = k_s \, (\boldsymbol{v} \cdot \boldsymbol{r})^q \, \frac{L_i}{r^2}$$

- Parameters
  - k_s: specular reflection coefficient
  - q : specular reflection exponent



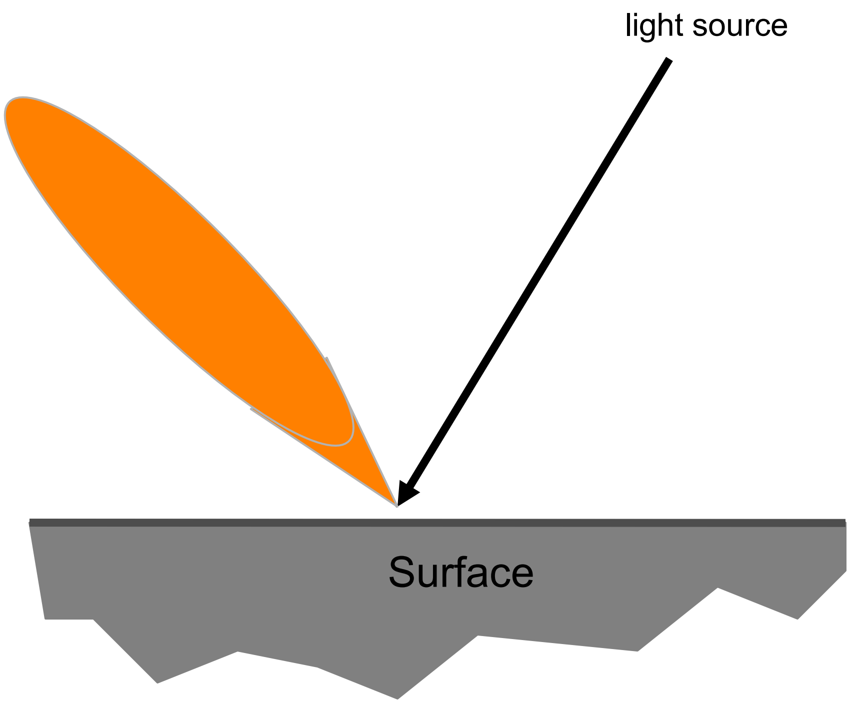
The Phong Model

- Effect of q – the specular reflection exponent



Terminology: Specular Lobe

- The specular reflection distribution is usually called a “lobe”
  - For Phong, its shape is $(\boldsymbol{r} \cdot \boldsymbol{v})^q$



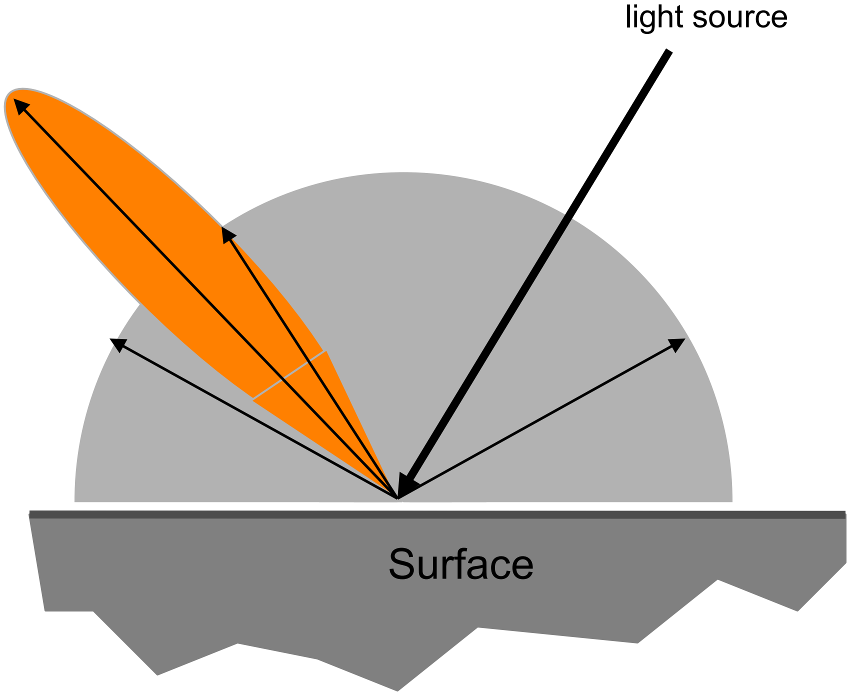
The Complete Phong Model

- Sum of three components:

  ideal diffuse reflection +

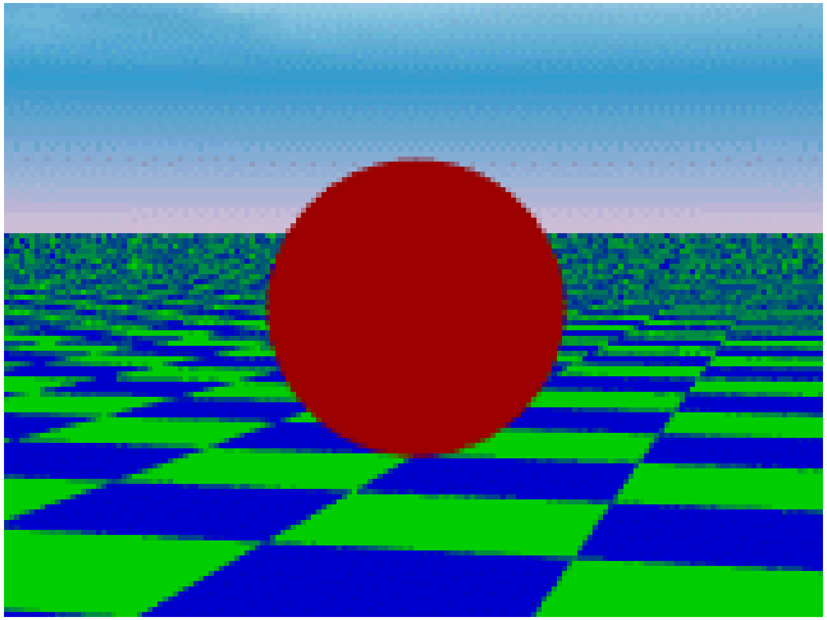
  specular reflection +

  "ambient".



Ambient Illumination

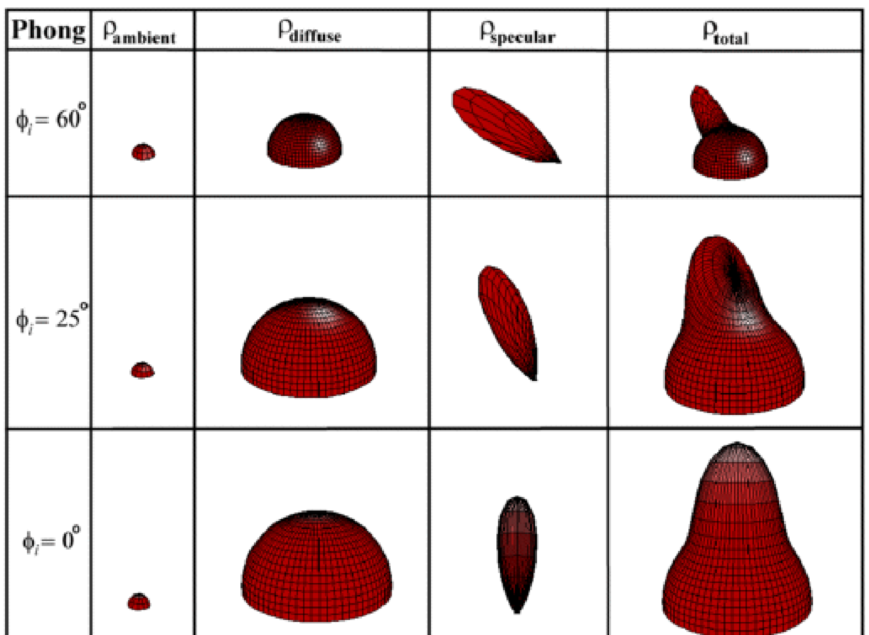
- Represents the reflection of all indirect illumination.
- This is a total hack!
- Avoids the complexity of indirect ("global") illumination



Putting It All Together

- Phong Illumination Model

$$L_o = \left[k_a + k_d \left(\boldsymbol{n} \cdot \boldsymbol{l} \right) + k_s \left(\boldsymbol{v} \cdot \boldsymbol{r} \right)^q \right] \frac{L_i}{r^2}$$



Putting It All Together

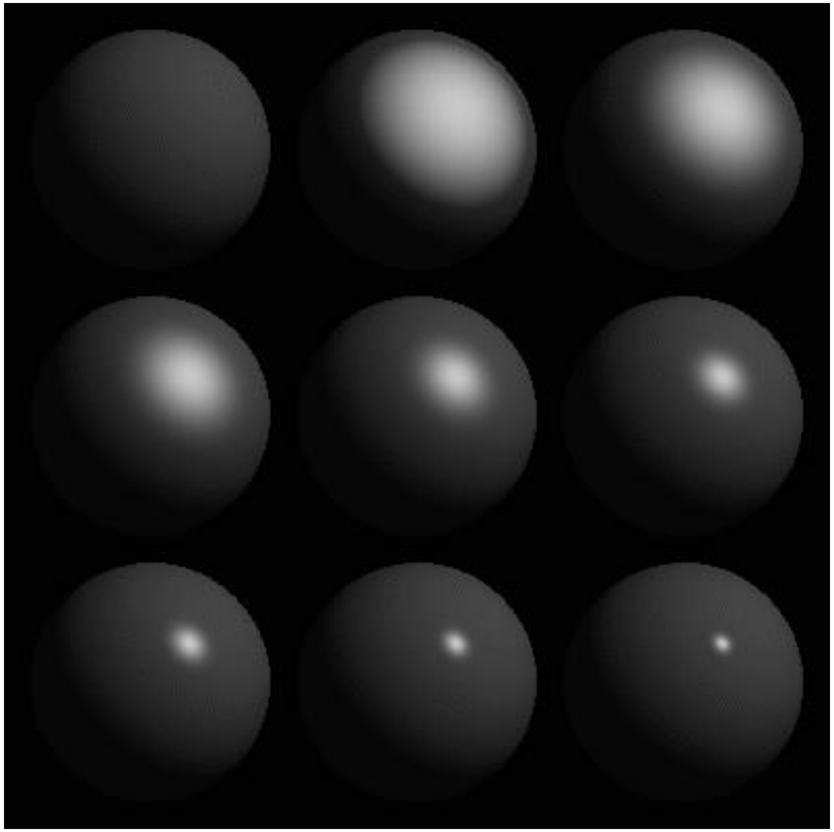
- Phong Illumination Model

$$L_o = \left[k_a + k_d\,(\boldsymbol{n}\cdot\boldsymbol{l}) + k_s\,(\boldsymbol{v}\cdot\boldsymbol{r})^q\right]\frac{L_i}{r^2}$$

- Is it physically based?
  - No, does not even conserve energy,
    may well reflect more energy than what goes in
  - Furthermore, it does not even conform to the BRDF model directly (we are taking the proper cosine for diffuse, but not for specular)
  - And ambient was a total hack

Phong Examples

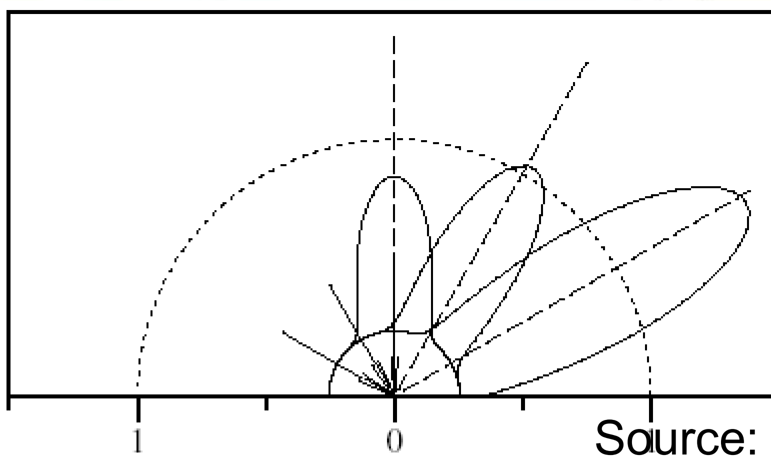
- The spheres illustrate specular reflections as the direction of the light source and the exponent q (amount of shininess) is varied.



$$L_o = \left[k_a + k_d\,(\boldsymbol{n}\cdot\boldsymbol{l}) + k_s\,(\boldsymbol{v}\cdot\boldsymbol{r})^q\right]\frac{L_i}{r^2}$$

Fresnel Reflection

- Increasing specularity near grazing angles.
  - Most BRDF models account for this.



Source: Lafortune et al. 97

Questions?

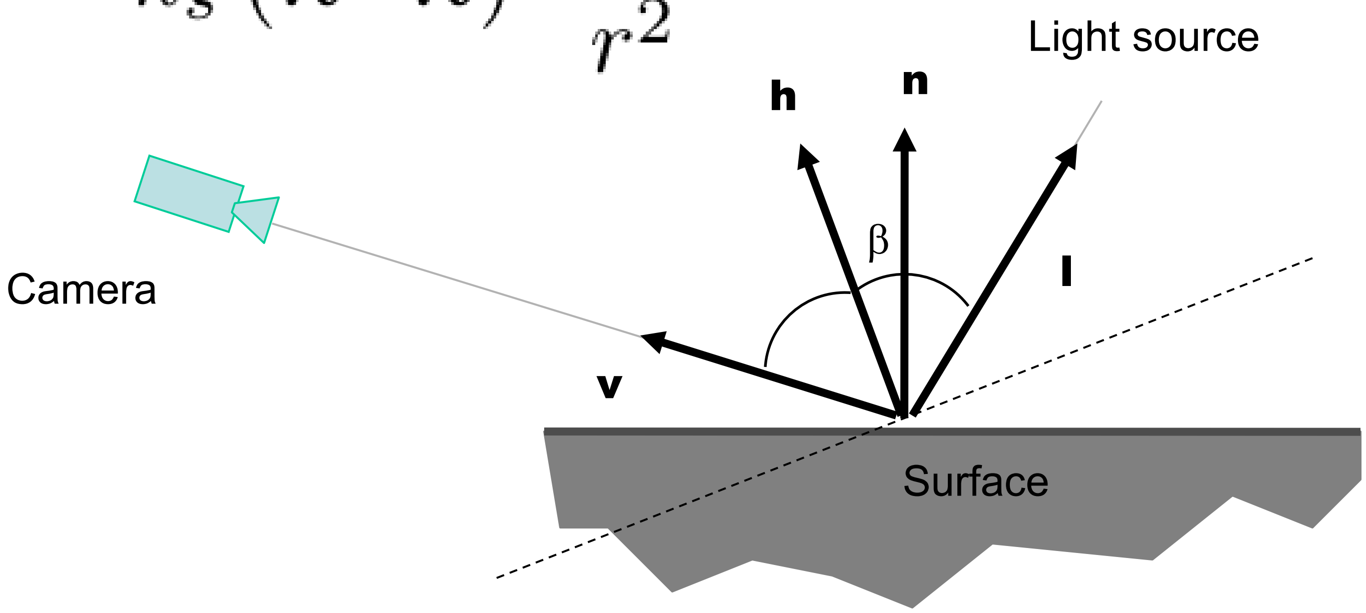
Blinn-Torrance Variation of Phong

- Uses the "halfway vector" **h** between **l** and **v**.

$$L_o = k_s \cos(\beta)^q \frac{L_i}{r^2}$$

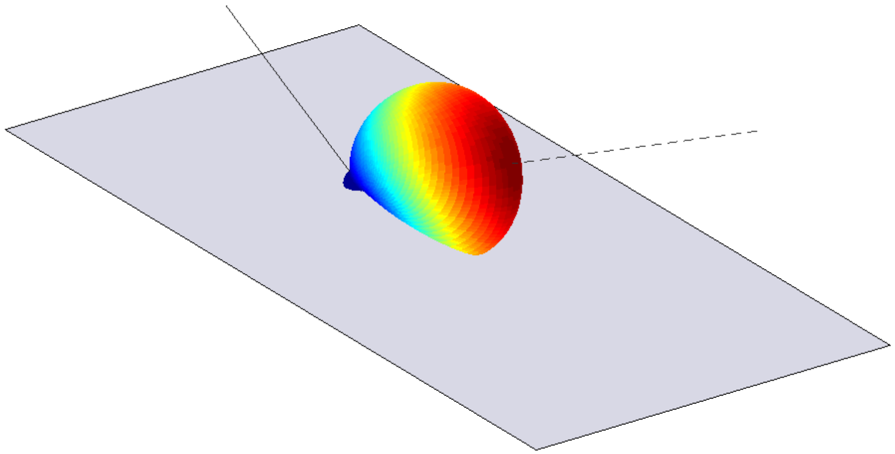
$$= k_s (\boldsymbol{n} \cdot \boldsymbol{h})^q \frac{L_i}{r^2}$$

$$\boldsymbol{h} = \frac{\boldsymbol{l} + \boldsymbol{v}}{\|\boldsymbol{l} + \boldsymbol{v}\|}$$

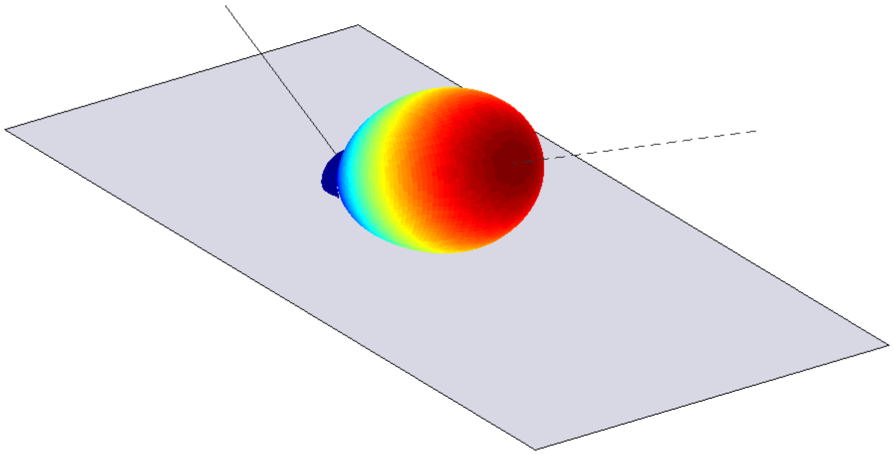


Lobe Comparison

- Half vector lobe
  - Gradually narrower when approaching grazing
- Mirror lobe
  - Always circular



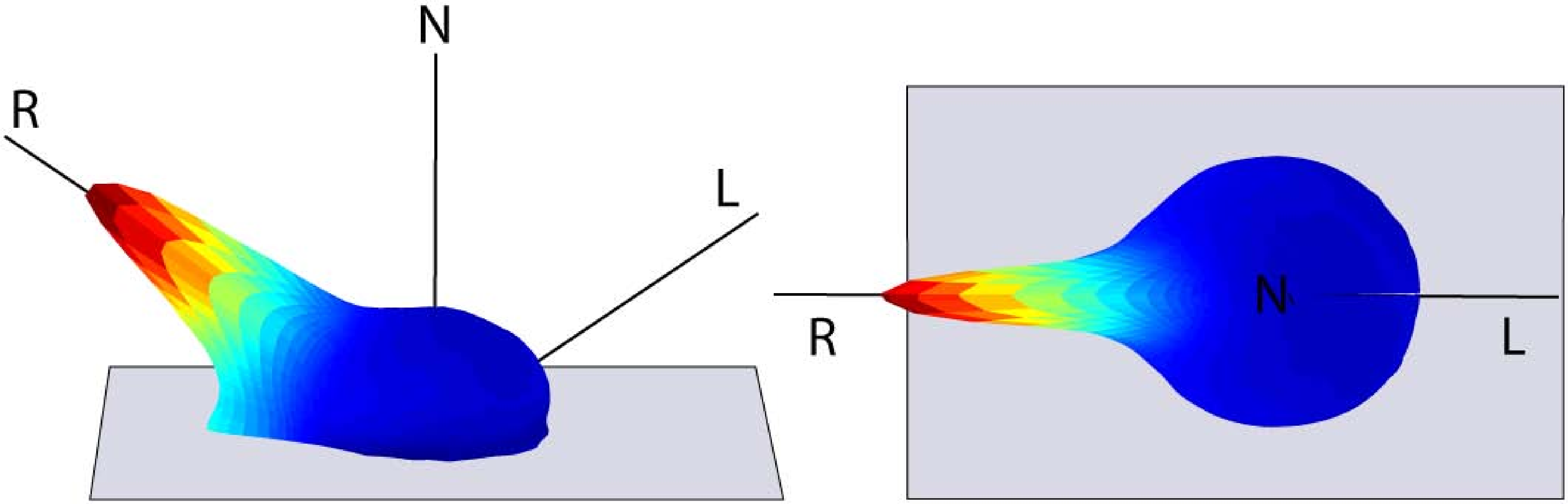
Half vector lobe



Mirror lobe

Half Vector Lobe is Better

- More consistent with what is observed in measurements (Ngan, Matusik, Durand 2005)



Courtesy of Mitsubishi Electric Researh Laboratories, Inc. Used with permission.

Example: Plot of “PVC” BRDF at 55° incidence

Questions?

Microfacet Theory

- Example
  - Think of water surface as lots of tiny mirrors (microfacets)
  - “Bright” pixels are
    - Microfacets aligned with the vector between sun and eye
    - But not the ones in shadow
    - And not the ones that are occluded

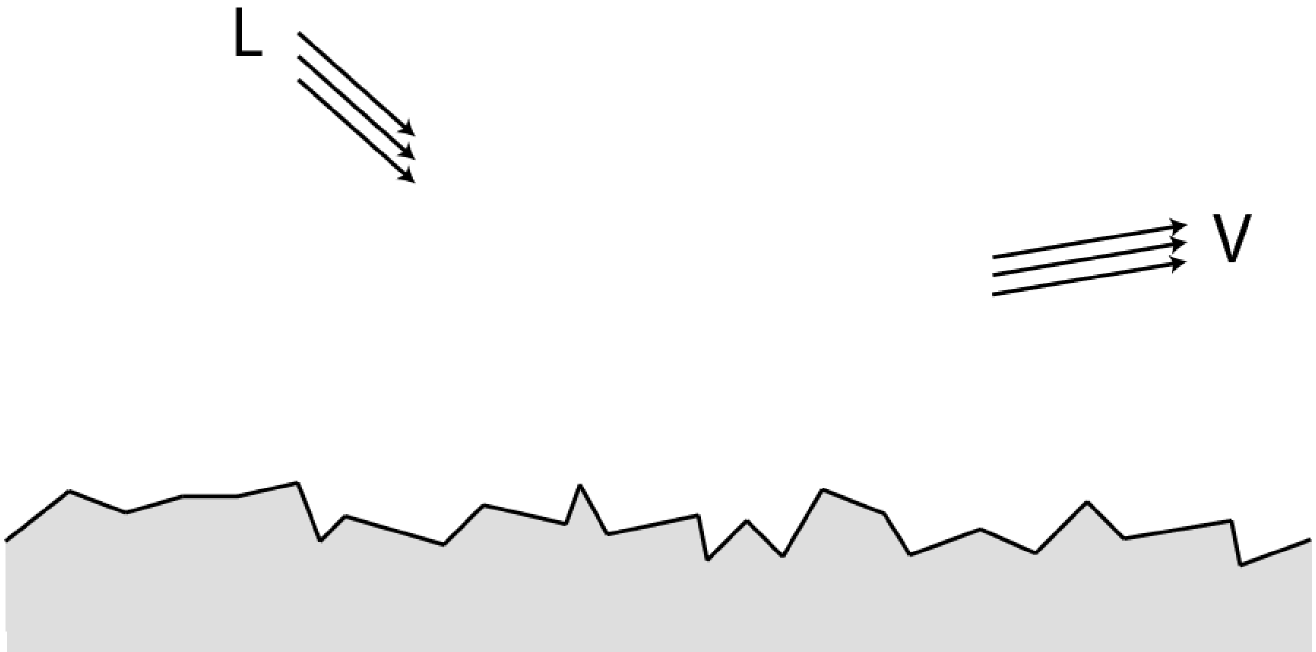
Image of sunset removed due to copyright restrictions.

Microfacet Theory

- Model surface by tiny mirrors [Torrance & Sparrow 1967]

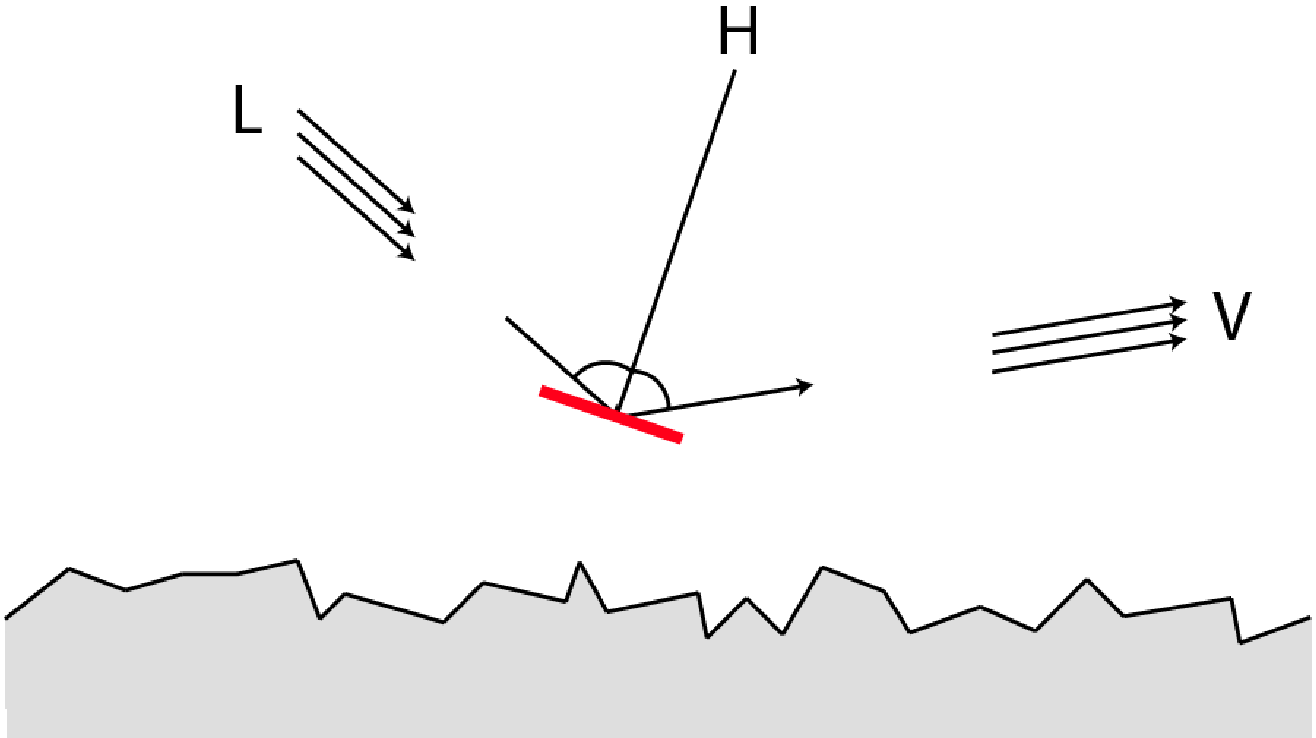
Microfacet Theory

- Value of BRDF at (L,V) is a product of
  - number of mirrors oriented halfway between L and V



Microfacet Theory

- Value of BRDF at (L,V) is a product of
  - number of mirrors oriented halfway between L and V



Microfacet Theory

- Value of BRDF at (L,V) is a product of
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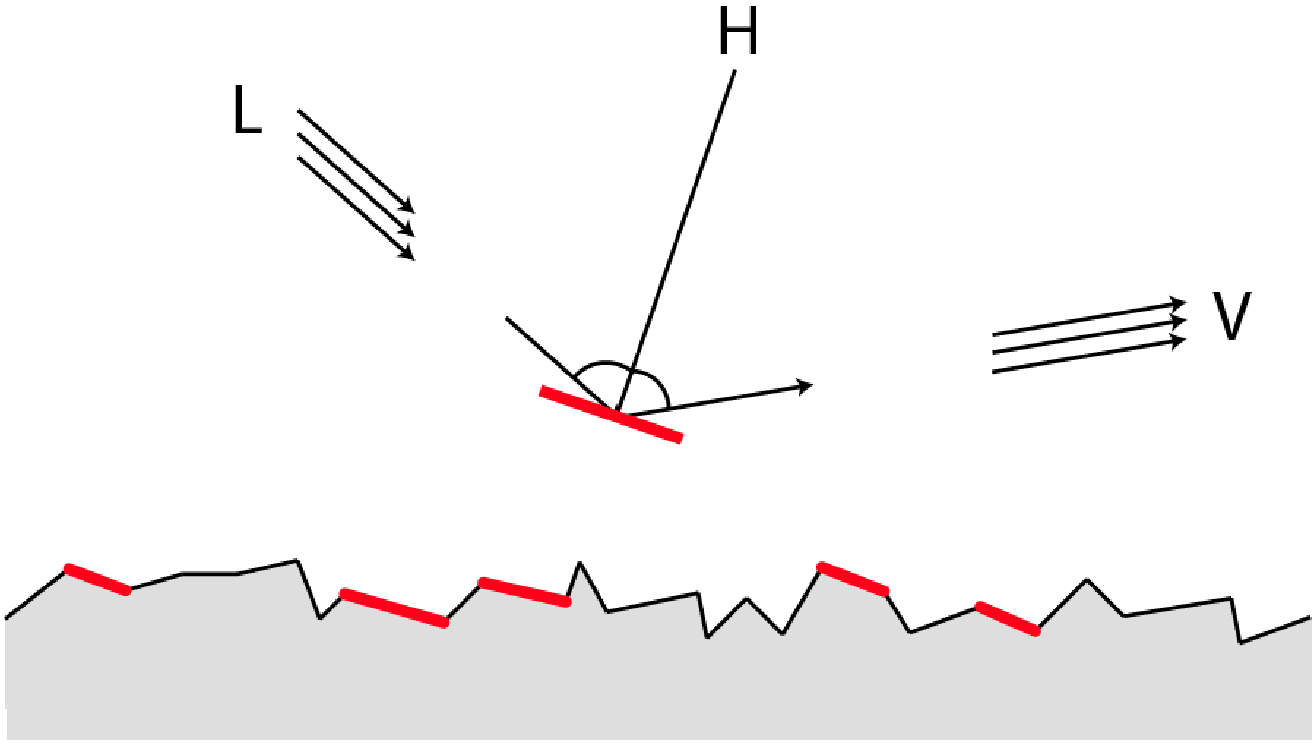
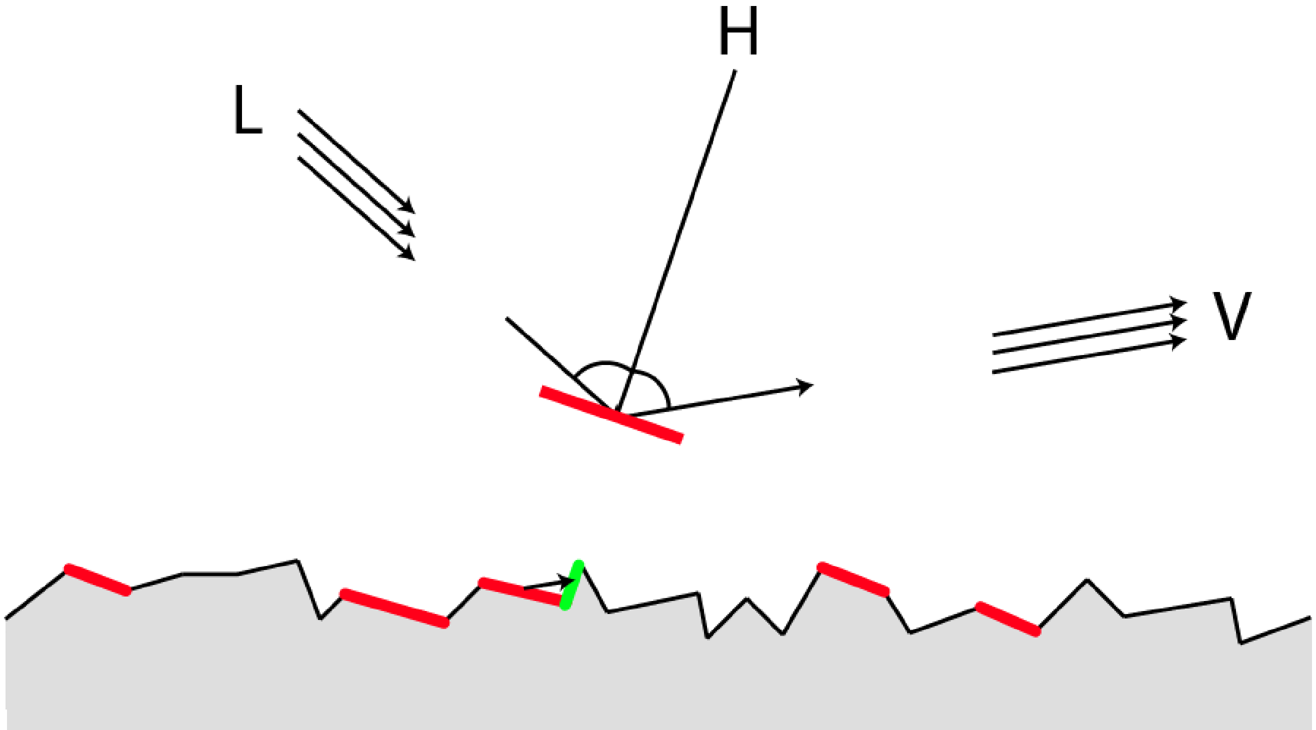


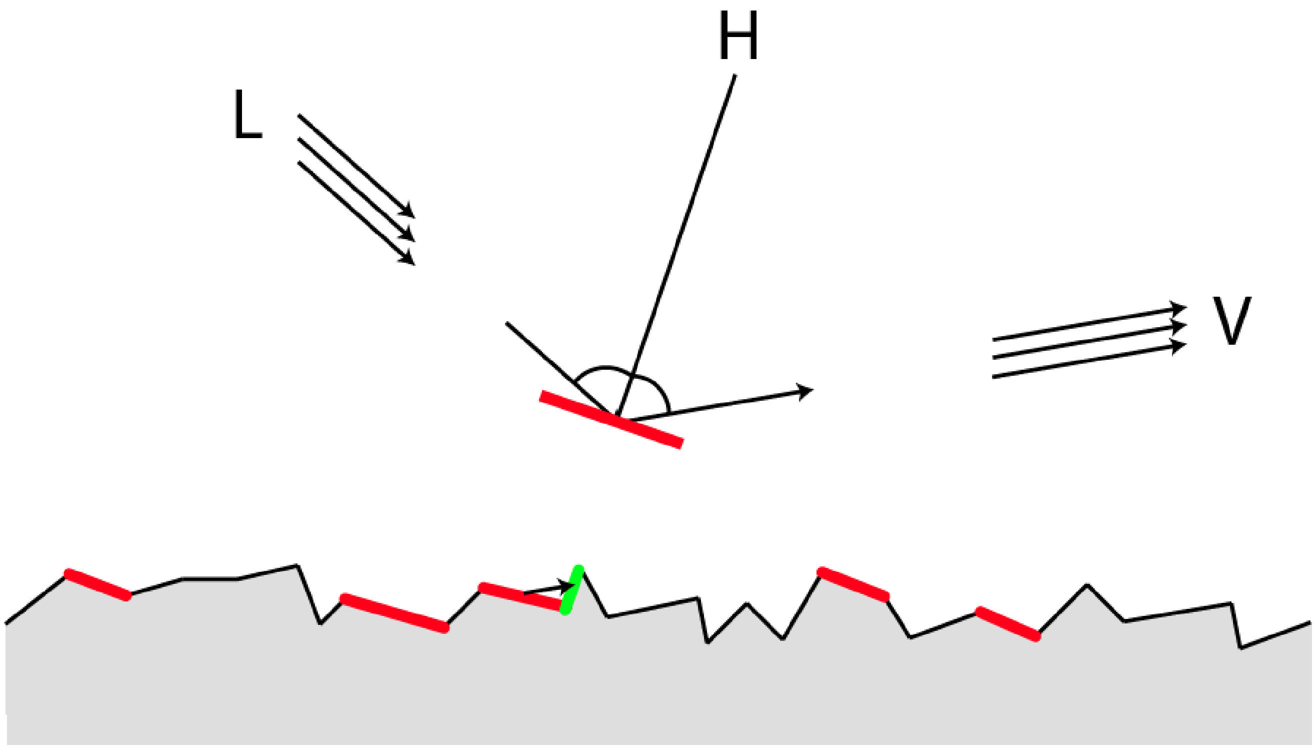
Microfacet Theory

- Value of BRDF at (L,V) is a product of
  - number of mirrors oriented halfway between L and V
  - ratio of the un(shadowed/masked) mirrors



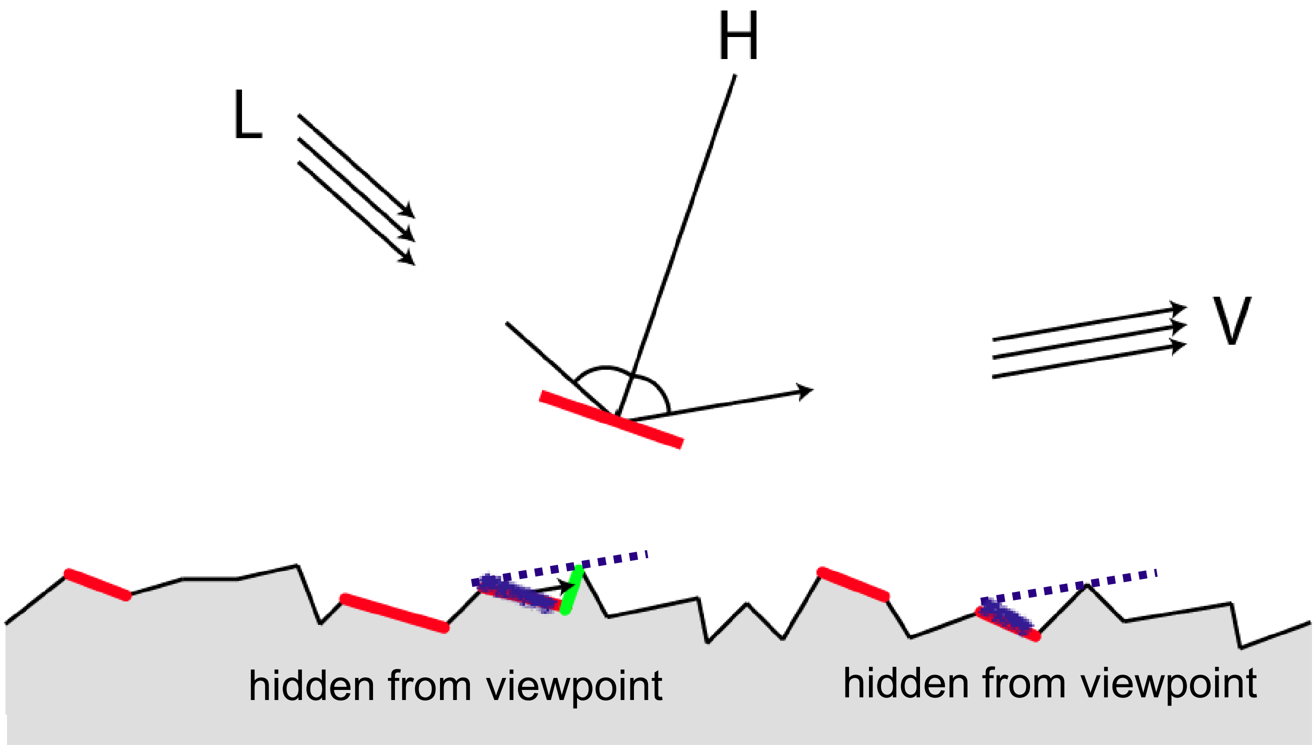
Microfacet Theory

- Value of BRDF at (L,V) is a product of
  - number of mirrors oriented halfway between L and V
  - ratio of the un(shadowed/masked) mirrors
  - Fresnel coefficient



Shadowing and Masking

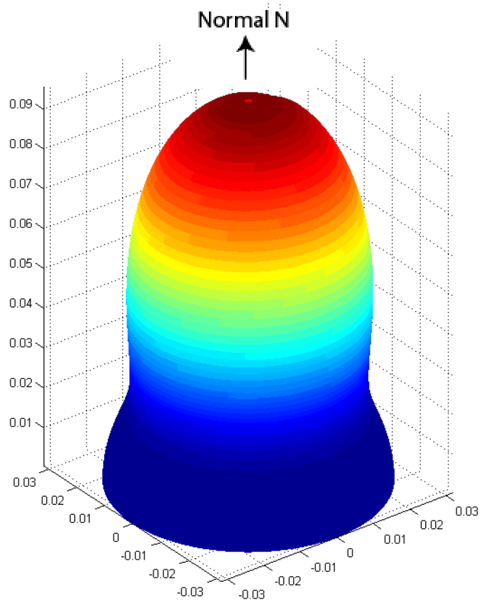
- Some facets are hidden from viewpoint
- Some are hidden from the light



Microfacet Theory-based Models

- Develop BRDF models by imposing simplifications [Torrance-Sparrow 67], [Blinn 77], [Cook-Torrance 81], [Ashikhmin et al. 2000]

- Model the distribution p(H) of microfacet normals
  - Also, statistical models for shadows and masking



spherical plot of a Gaussian-like p(H)

Full Cook-Torrance Lobe

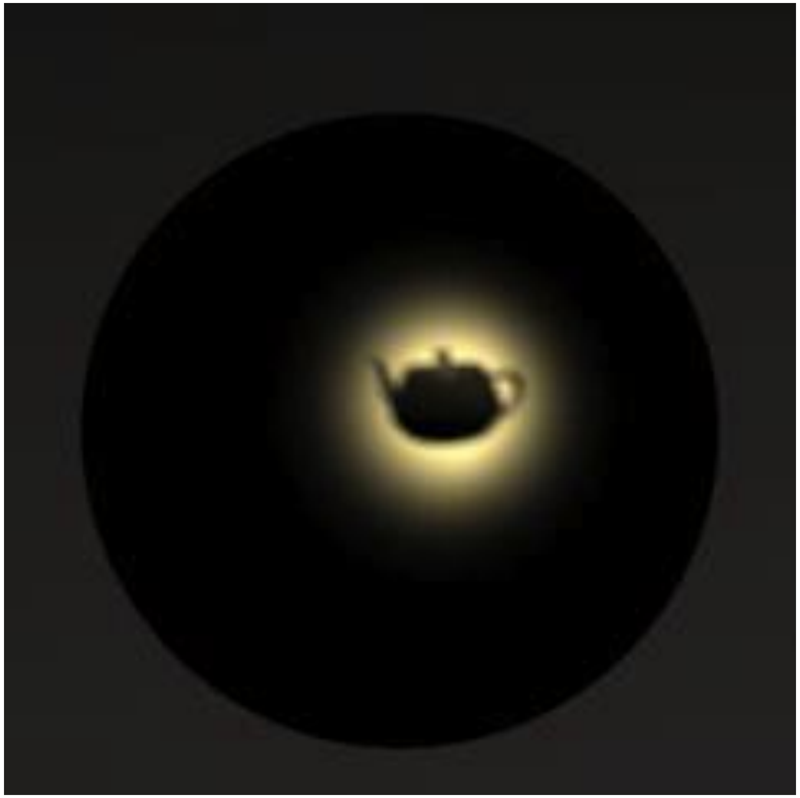
- ρ_s is the specular coefficient (3 numbers RGB)
- D is the microfacet distribution
  - δ is the angle between the half vector H and the normal N
  - m defines the roughness (width of lobe)
- G is the shadowing and masking term
- Need to add a diffuse term

$$K = \frac{\rho_s}{\pi} \frac{DG}{(N \cdot L)(N \cdot V)} Fresnel(F_0, V \cdot H)$$

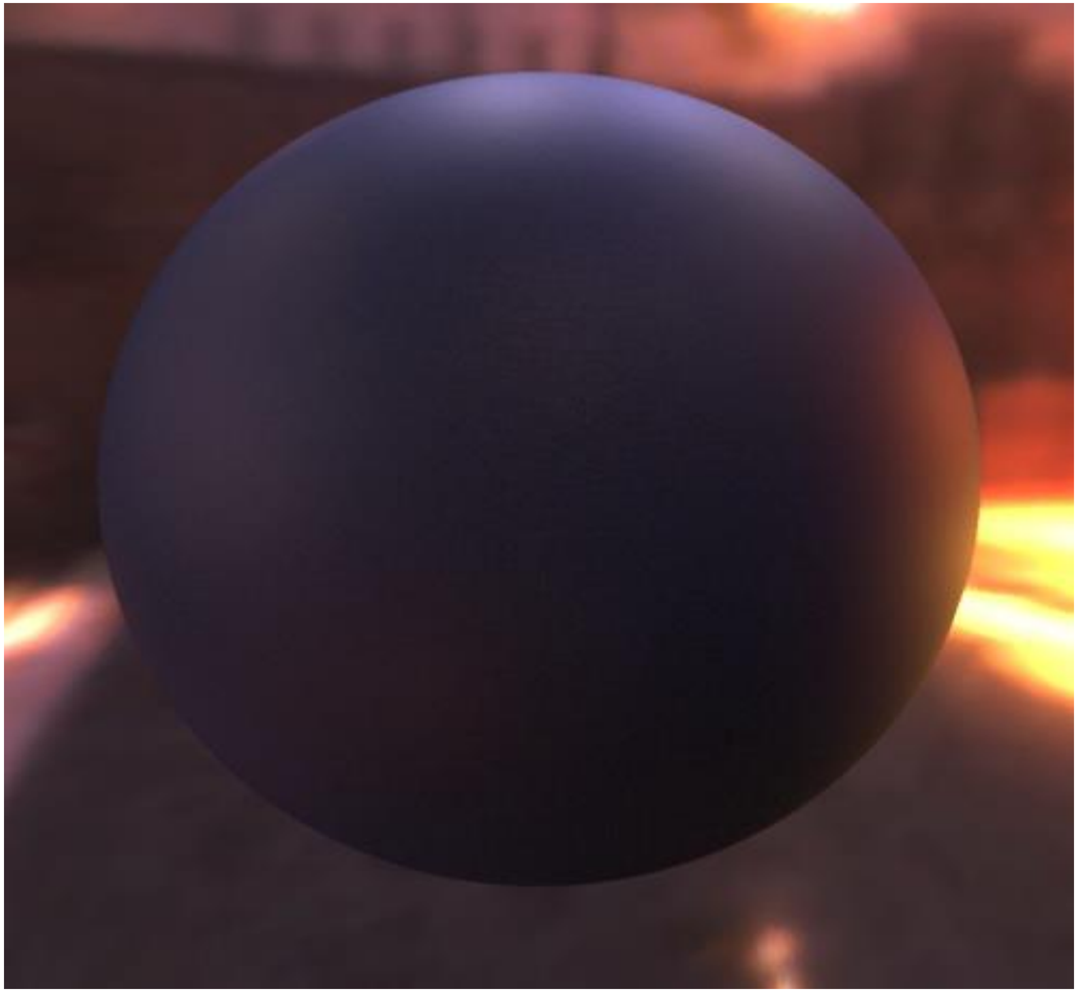
where $G = min\{1, \frac{2(N \cdot H)(N \cdot V)}{(V \cdot H)}, \frac{2(N \cdot H)(N \cdot L)}{(V \cdot H)}\}$ and $D = \frac{1}{m^2 \cos^4 \delta} e^{-[(tan\delta)/m]^2}$

Questions?

- “Designer BRDFs” by Ashikhmin et al.



BRDF Examples from Ngan et al.

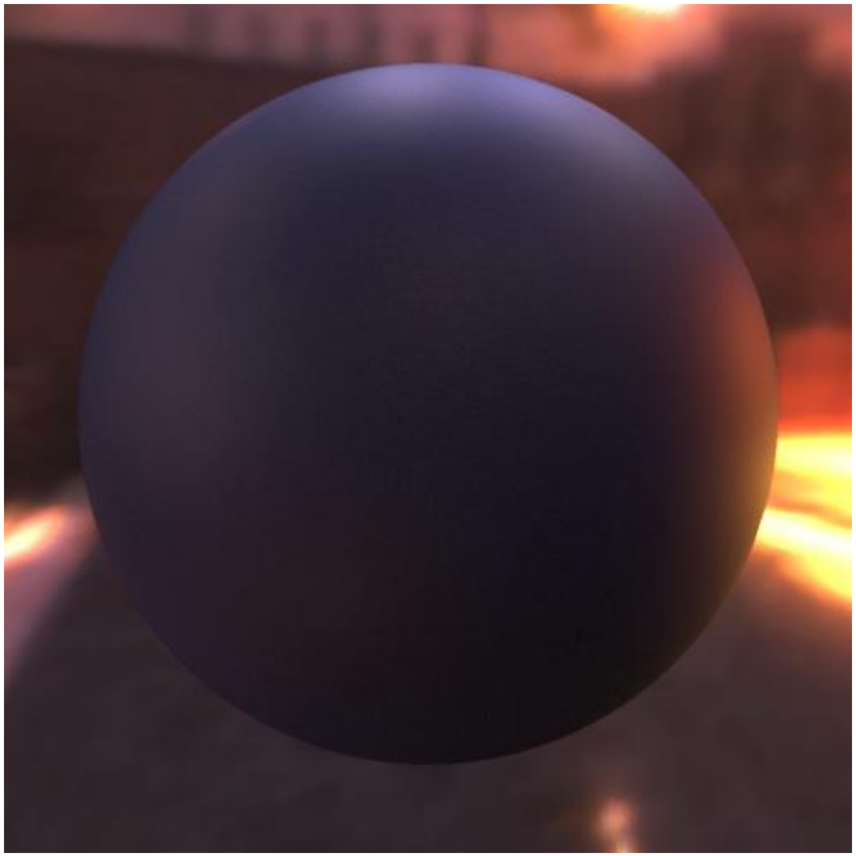


Material – Dark blue paint

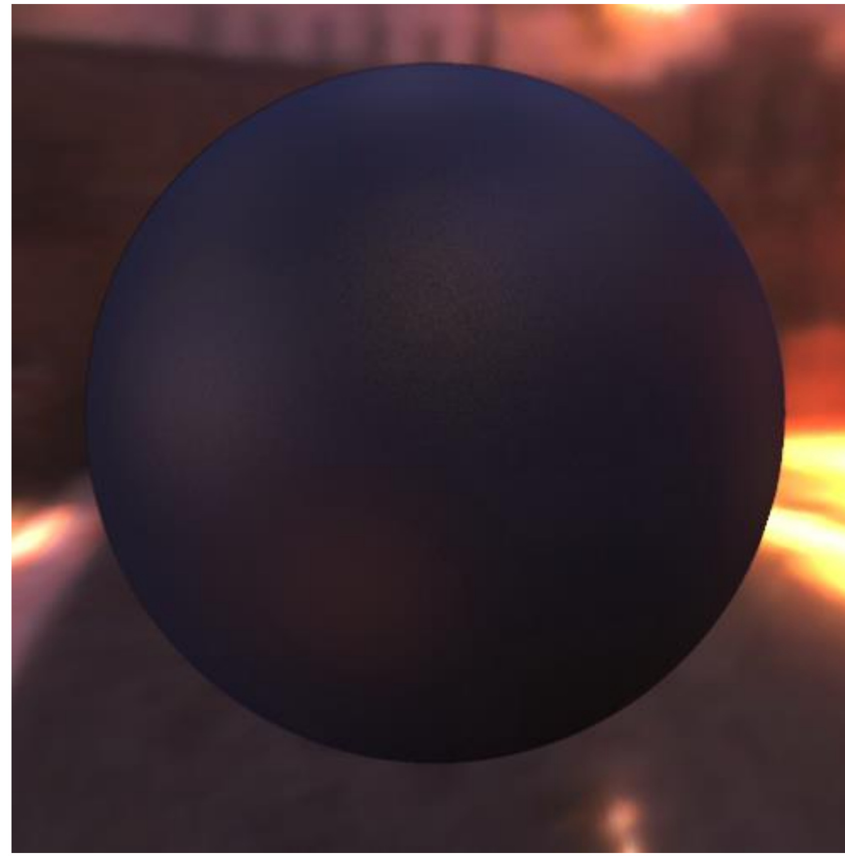
Lighting

Dark Blue Paint

Acquired data



Blinn-Phong

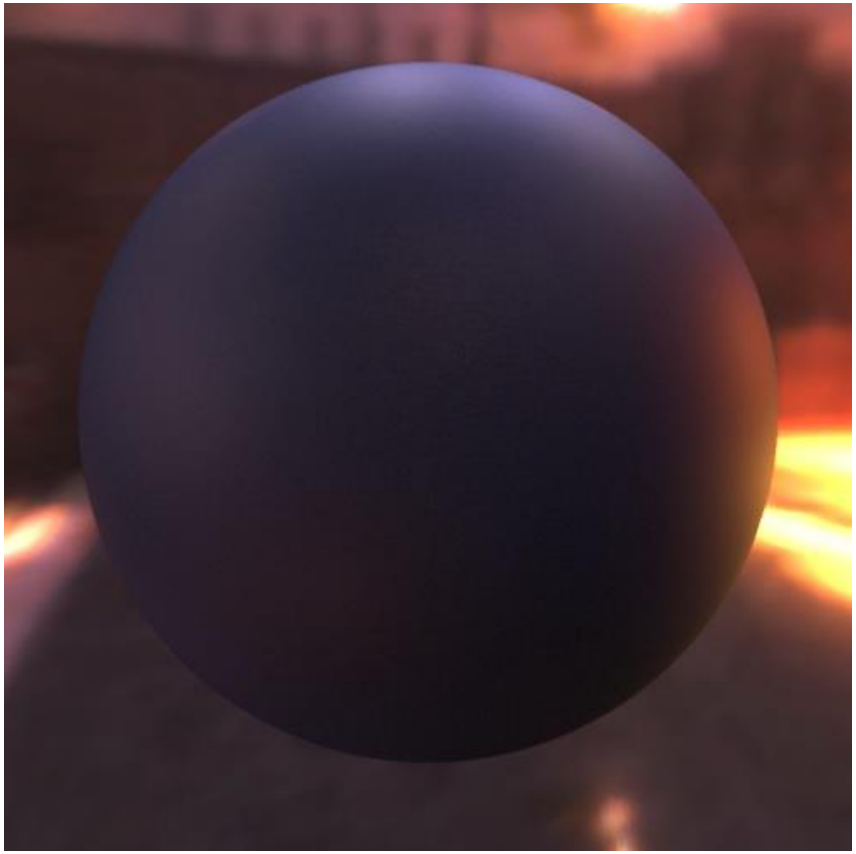


Finding the BRDF model parameters that best reproduce the real material

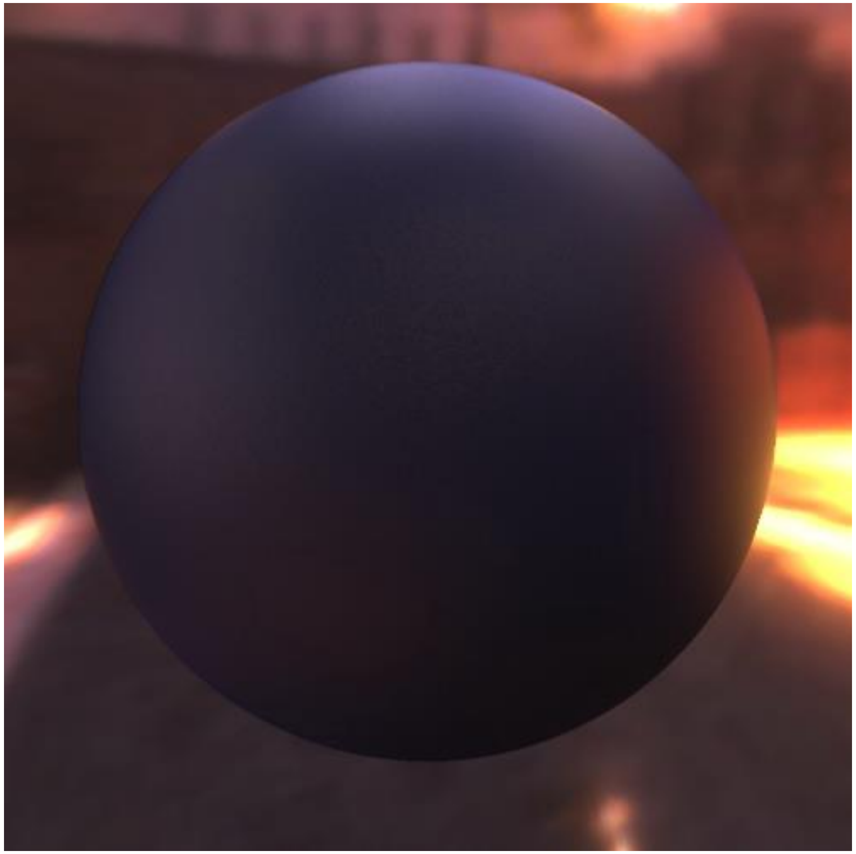
Material – Dark blue paint

Dark Blue Paint

Acquired data



Cook-Torrance



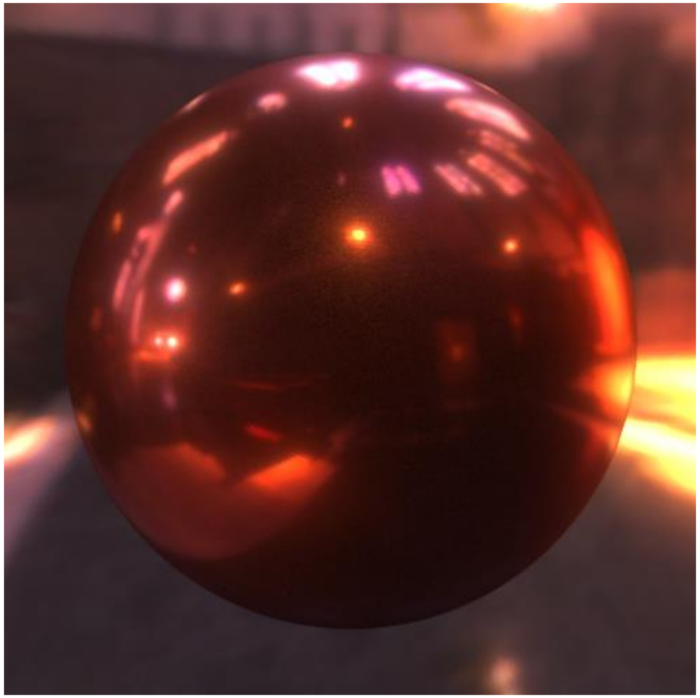
Finding the BRDF model parameters that best reproduce the real material

Material – Dark blue paint

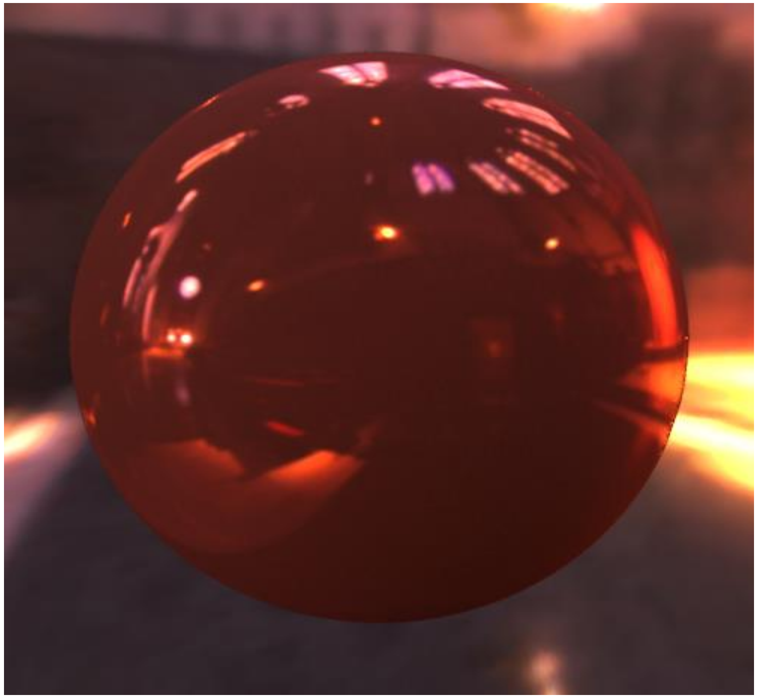
Observations

- Some materials impossible to represent with a single lobe

Acquired data



Cook-Torrance

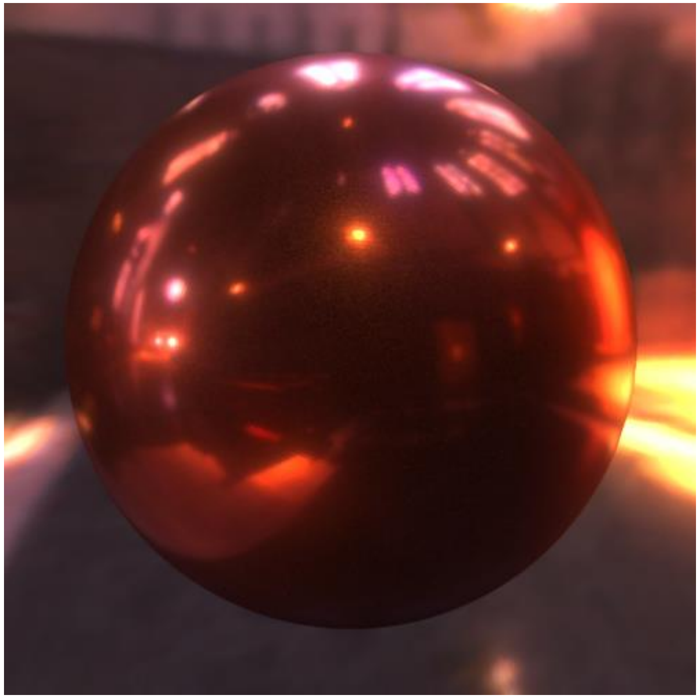


Material – Red Christmas Ball

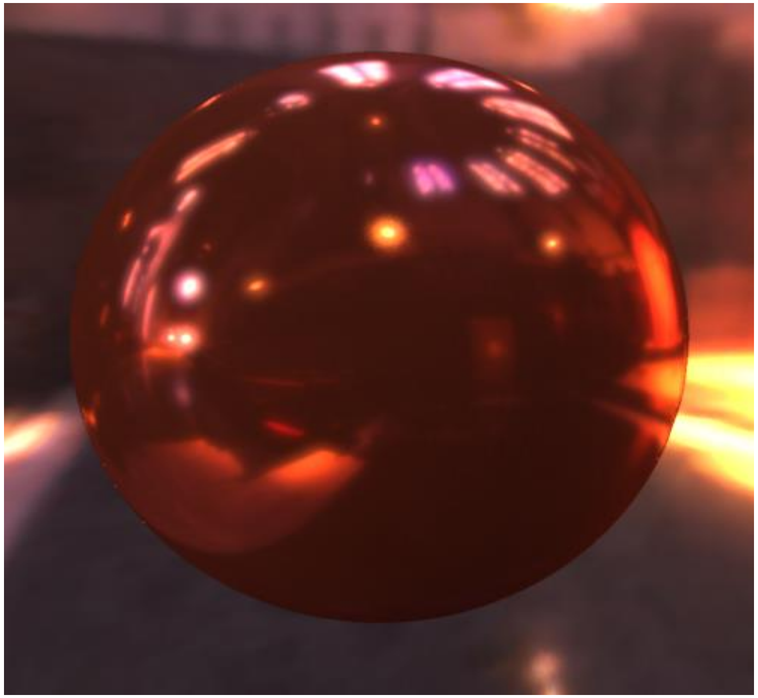
Adding a Second Lobe

- Some materials impossible to represent with a single lobe

Acquired data



Cook-Torrance 2 lobes



Material – Red Christmas Ball

Image-Based Acquisition

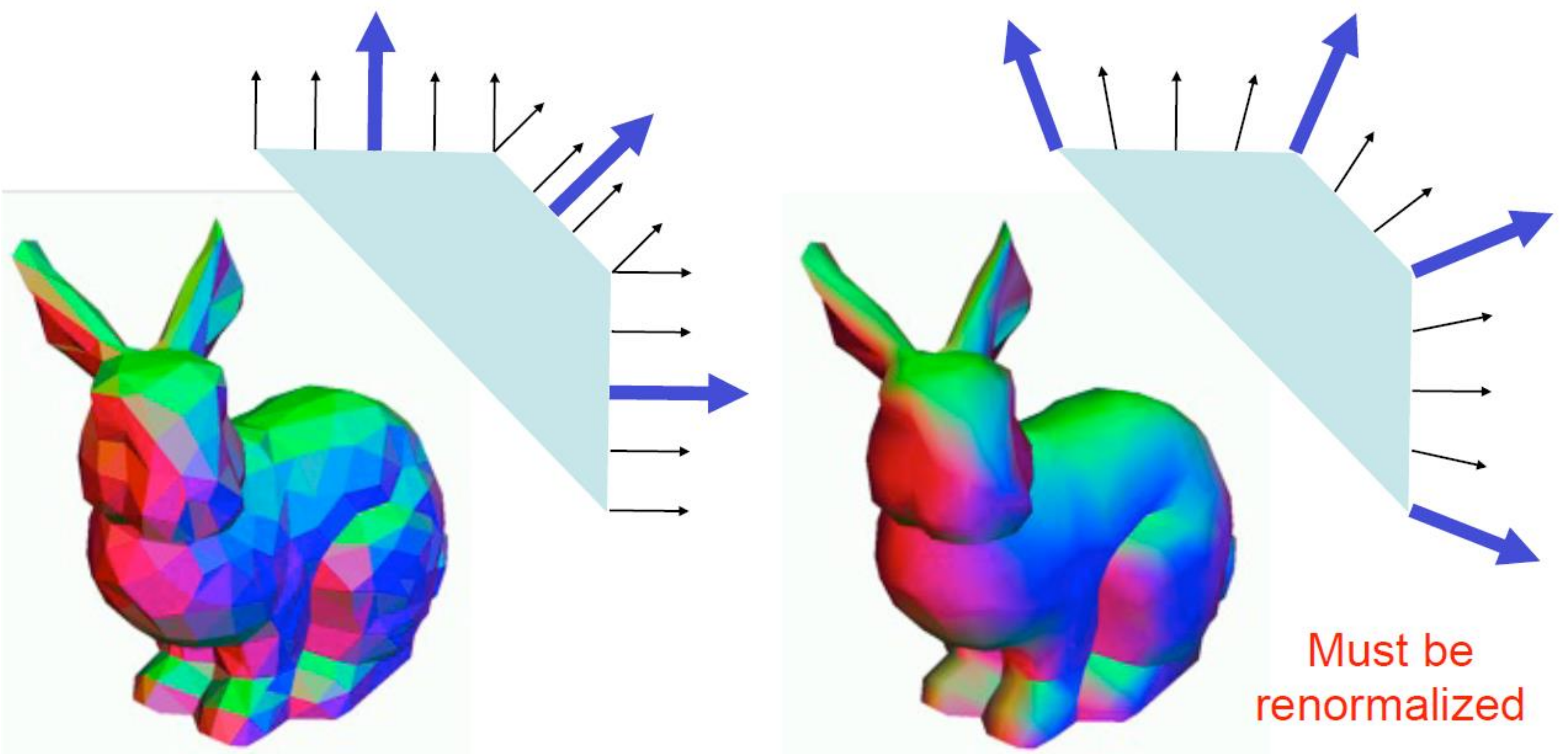
- A Data-Driven Reflectance Model, SIGGRAPH 2003
  - The data is available http://people.csail.mit.edu/wojciech/BRDFDatabase/

Questions?

T. Weyrich et al., Fabricating Microgeometry for Custom Surface Reflectance, SIGGRAPH 2009

Phong Normal Interpolation (Not Phong *Shading*)

- Interpolate the average vertex normals across the face and use this in shading computations
  - Again, use barycentric interpolation!



That’s All for Today!

Images from the movie, “The Matrix,” removed due to copyright restrictions.

Spatial Variation

- All materials seen so far are the same everywhere
  - In other words, we are assuming the BRDF is independent of the surface point x
  - No real reason to make that assumption
  - More next time

6.837 Computer Graphics
Fall 2012