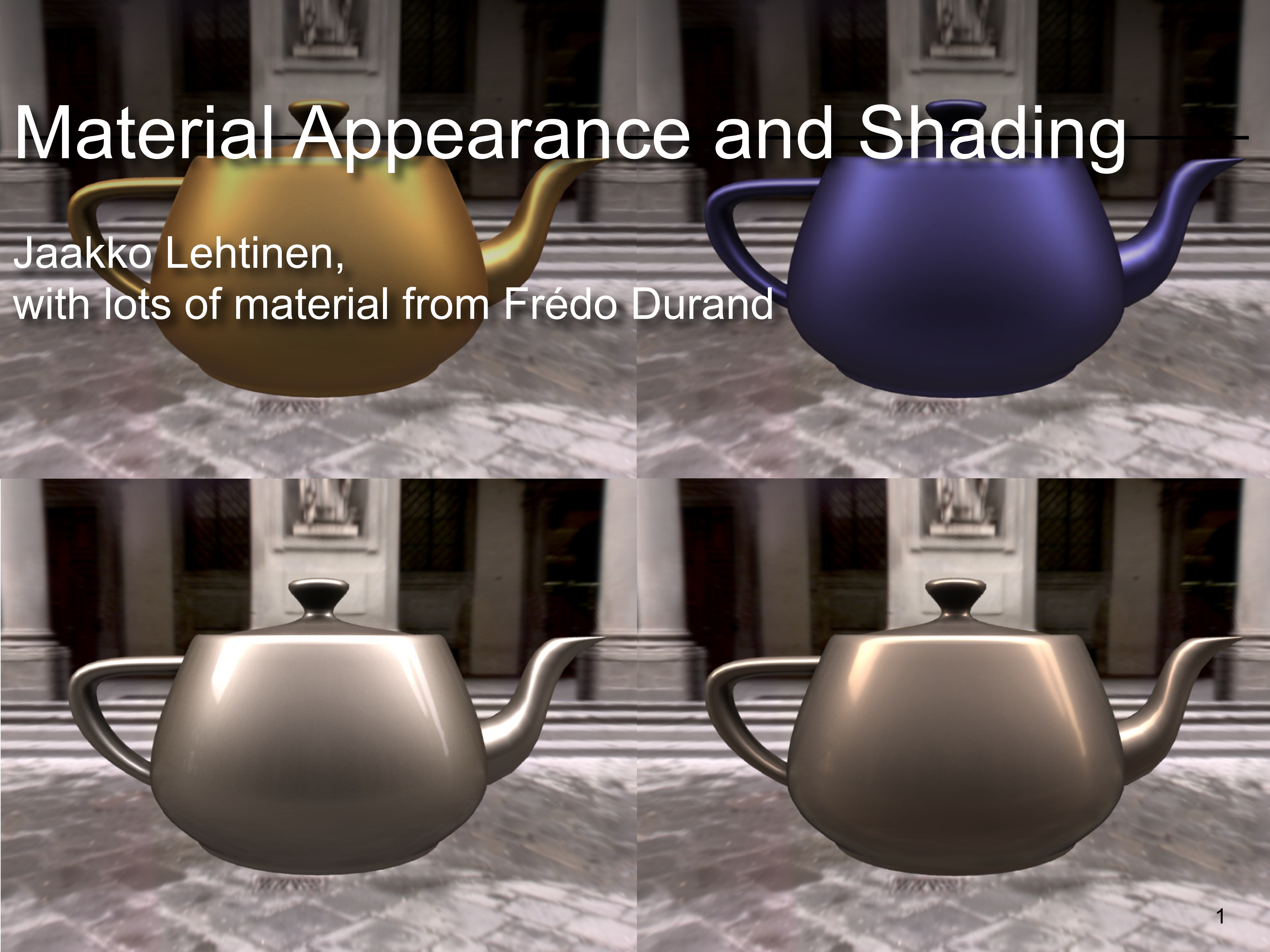
Material Appearance and Shading

Jaakko Lehtinen,
with lots of material from Frédo Durand

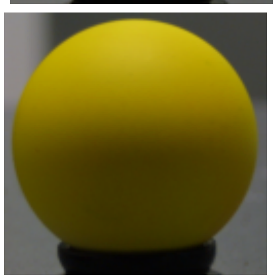


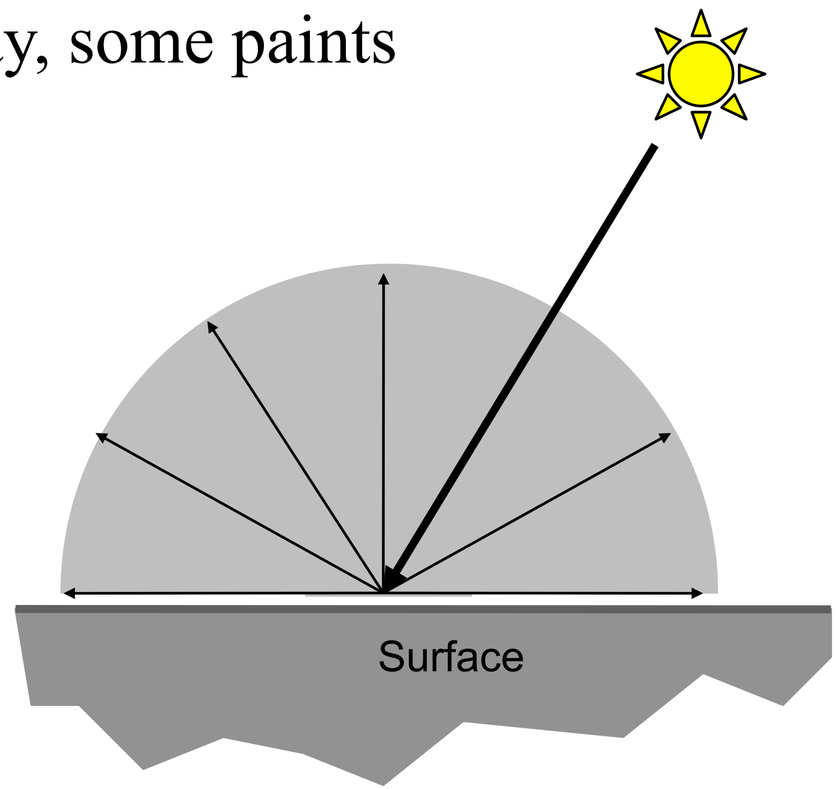
In This Video

- Ideal diffuse reflectance
  - Lambert's cosine law
- Non-diffuse reflection
  - Perfect mirror-like reflection ("specular")
  - Less ideal shiny reflection ("glossy")
  - The specular lobe
  - The Phong specular model and its Blinn-Torrance variant
- Microfacet theory: A way to derive specular models

Ideal Diffuse Reflectance

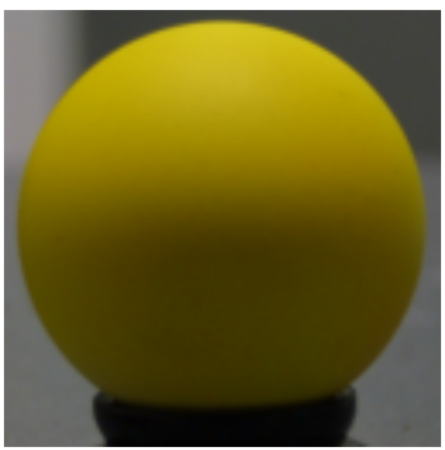
- Assume surface reflects equally in all directions.
- An ideal diffuse surface is, at the microscopic level, a very rough surface.
  – Example: chalk, clay, some paints

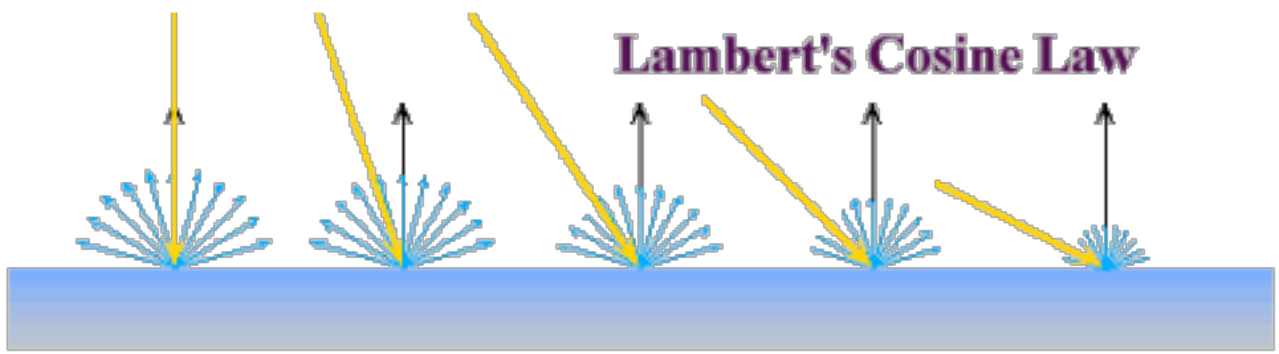




Ideal Diffuse Reflectance

- 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

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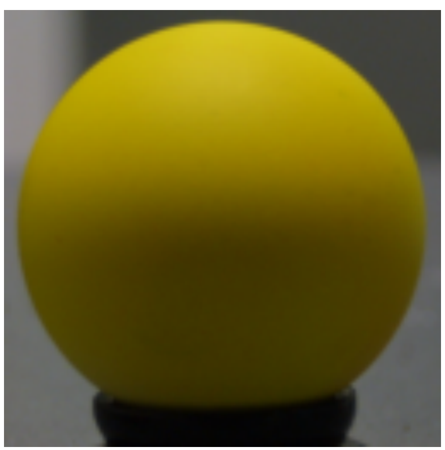
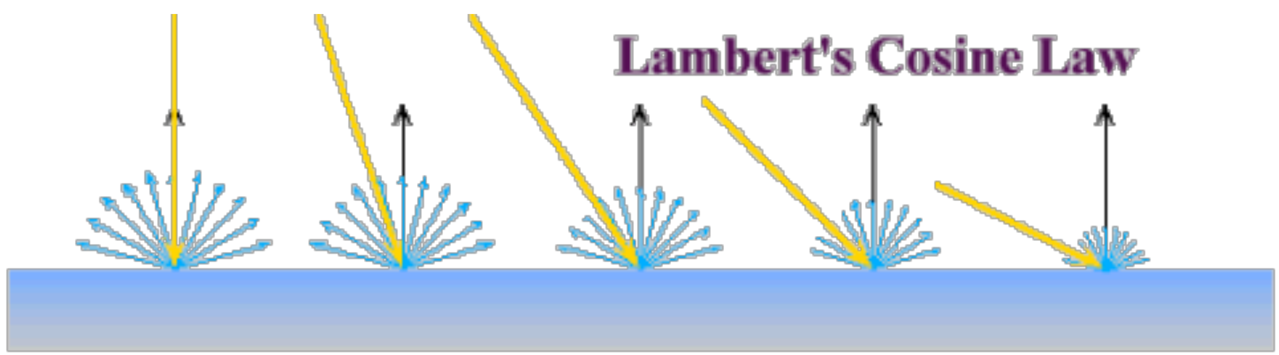
  - The reflected light varies with cosine even if distance to light source is kept constant.

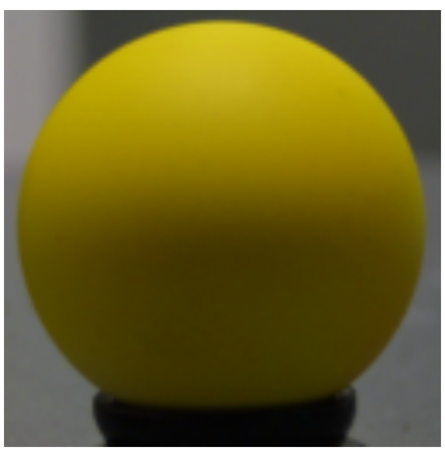
Remembering that incident irradiance depends on cosine, what is the BRDF of an ideally diffuse surface?

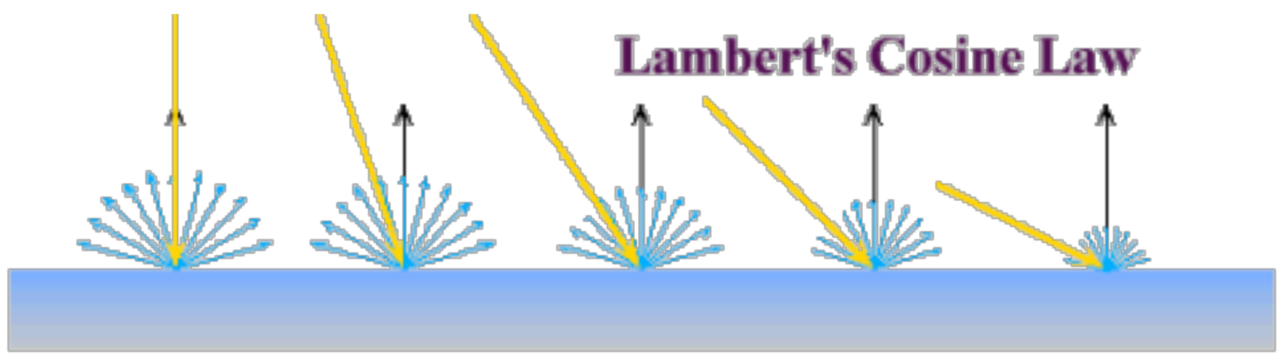




Ideal Diffuse Reflectance

- The ideal diffuse BRDF is a constant: $f_r(\mathbf{l}, \mathbf{v})$ = const.
  - What constant? ρ/π, where ρ is the *albedo*
    - ρ = coefficient between 0 and 1, "what fraction is reflected"
  - Usually just called "diffuse color" k_d





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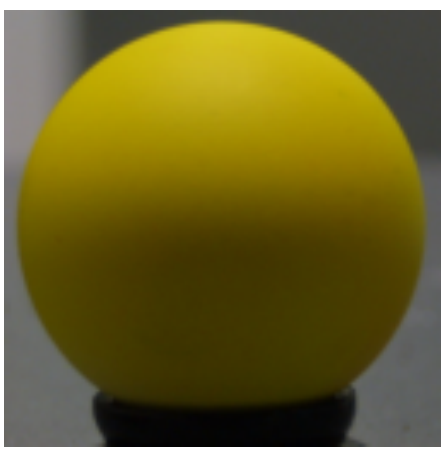
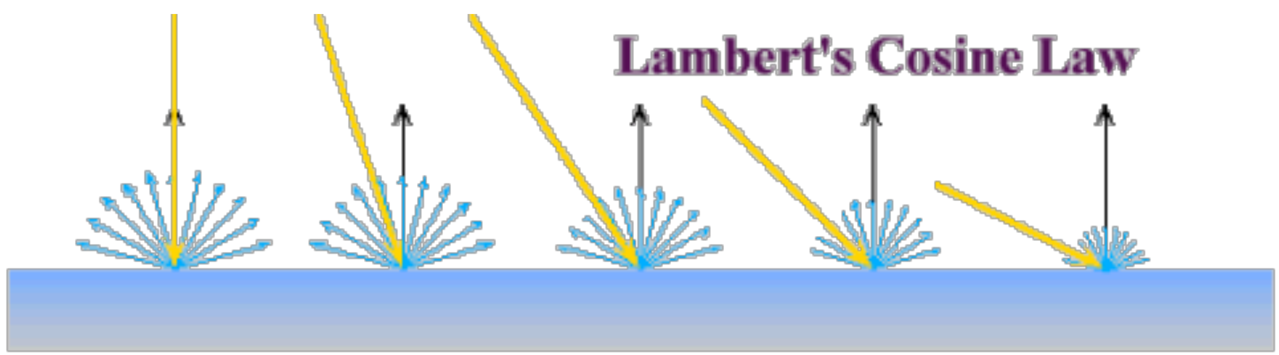
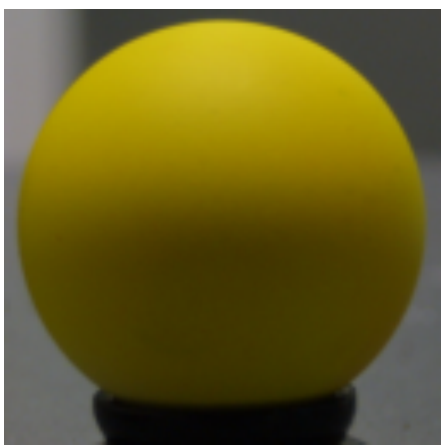
  - (Why the $1/\pi$? You have to take CS-E5520 to find out.)

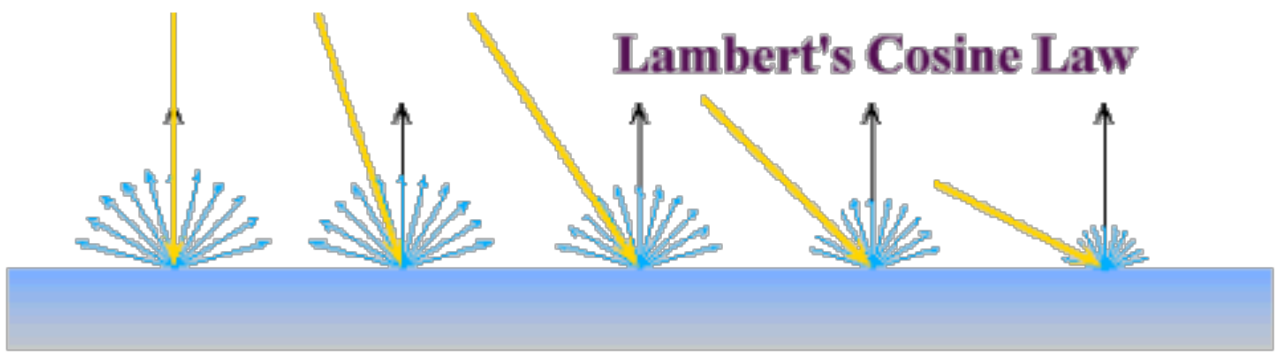




Ideal Diffuse Reflectance

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

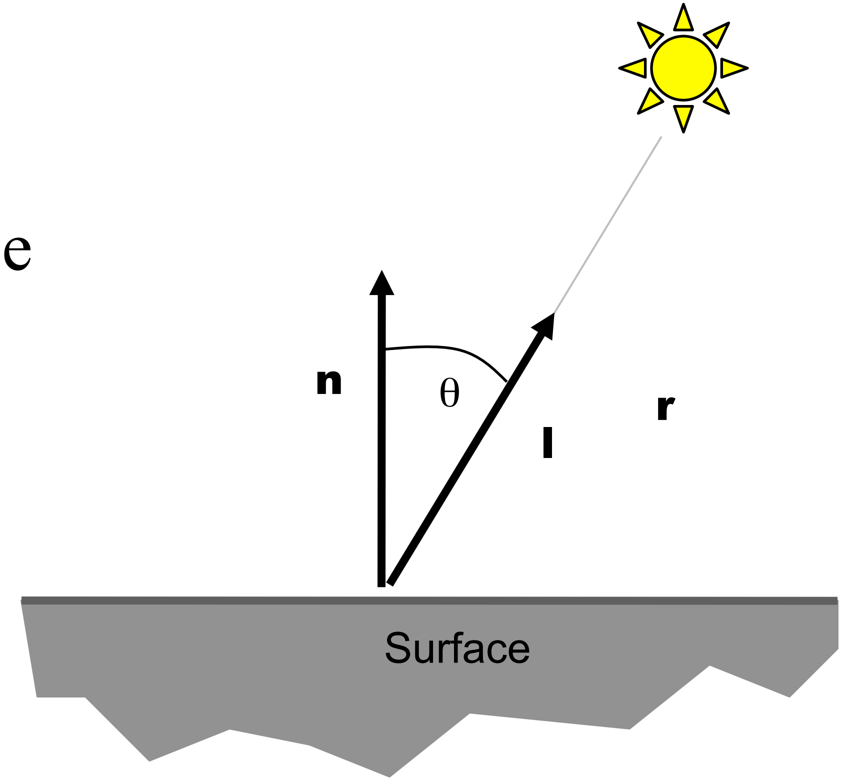




Ideal Diffuse Reflectance Math

- 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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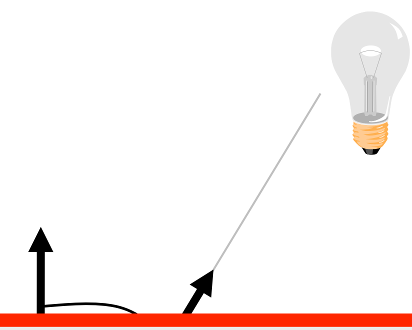
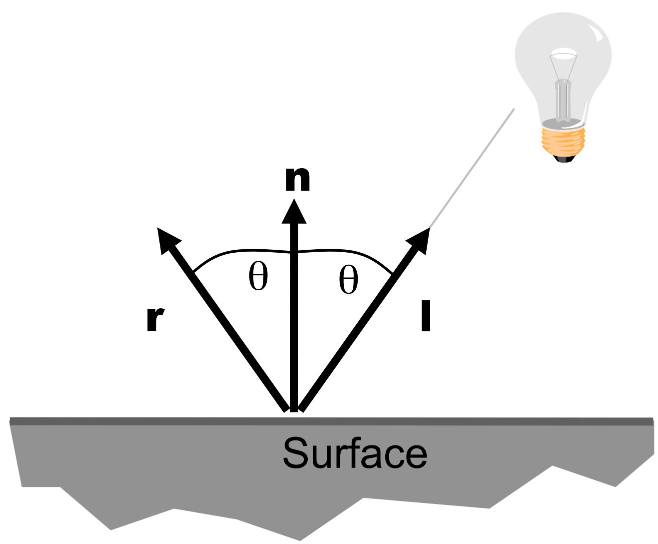


Do not forget to normalize your **n** and **l**!

We don't 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().

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.



Ideal Specular "BRDF"

- Light **only** reflects to the mirror direction
- Corresponding f_r is a "Dirac delta function"

- Not very useful for point lights, only for reflections of other surfaces
  - Why? You can't 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

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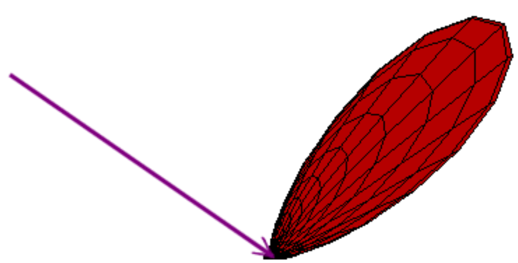
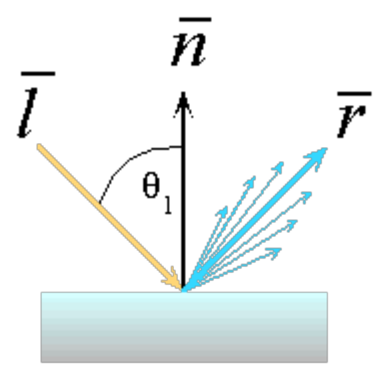
Non-ideal Reflectors

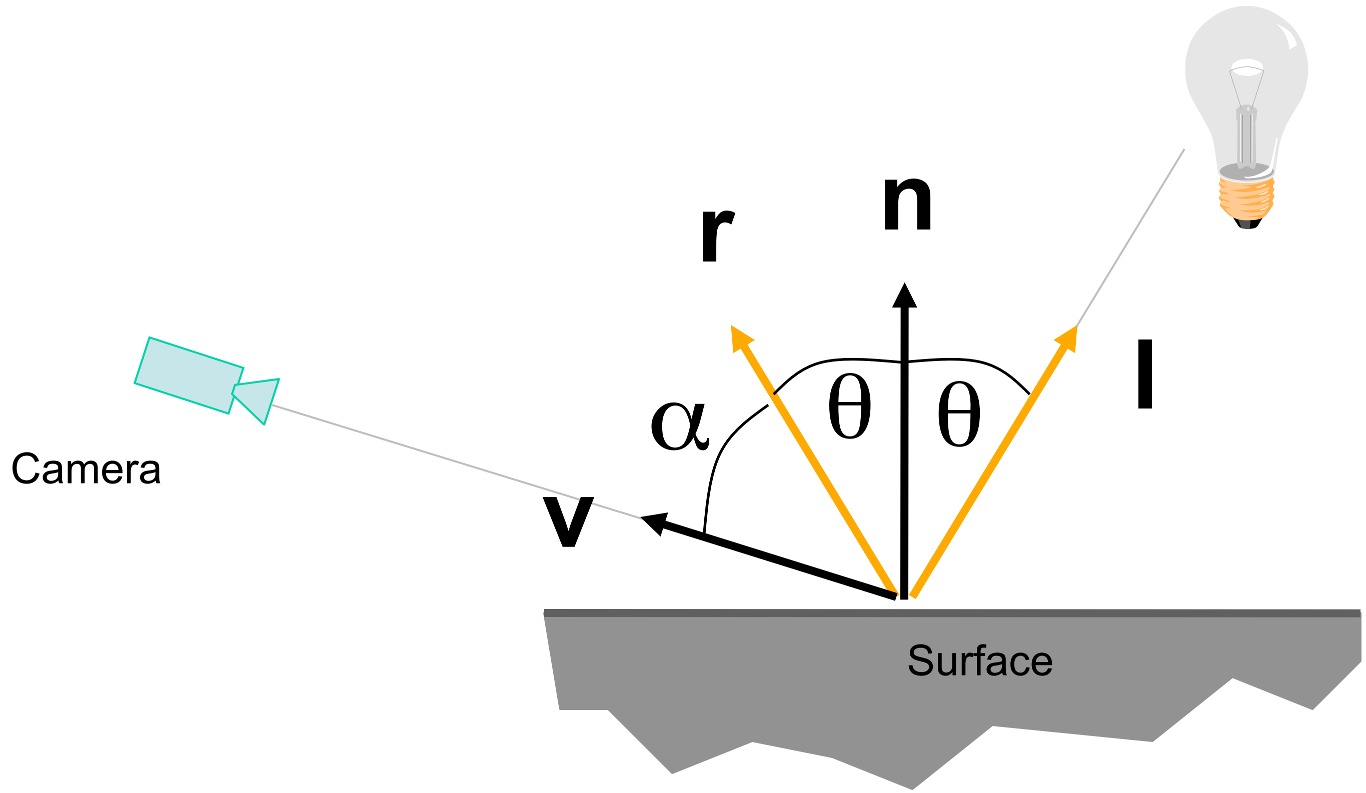
- Simple Empirical Reasoning for Glossy Materials
  - We expect most of the reflected light to travel in the direction of the ideal mirror ray.
  - However, because of microscopic surface variations we might expect some of the light to be reflected just slightly offset from the ideal reflected ray.
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

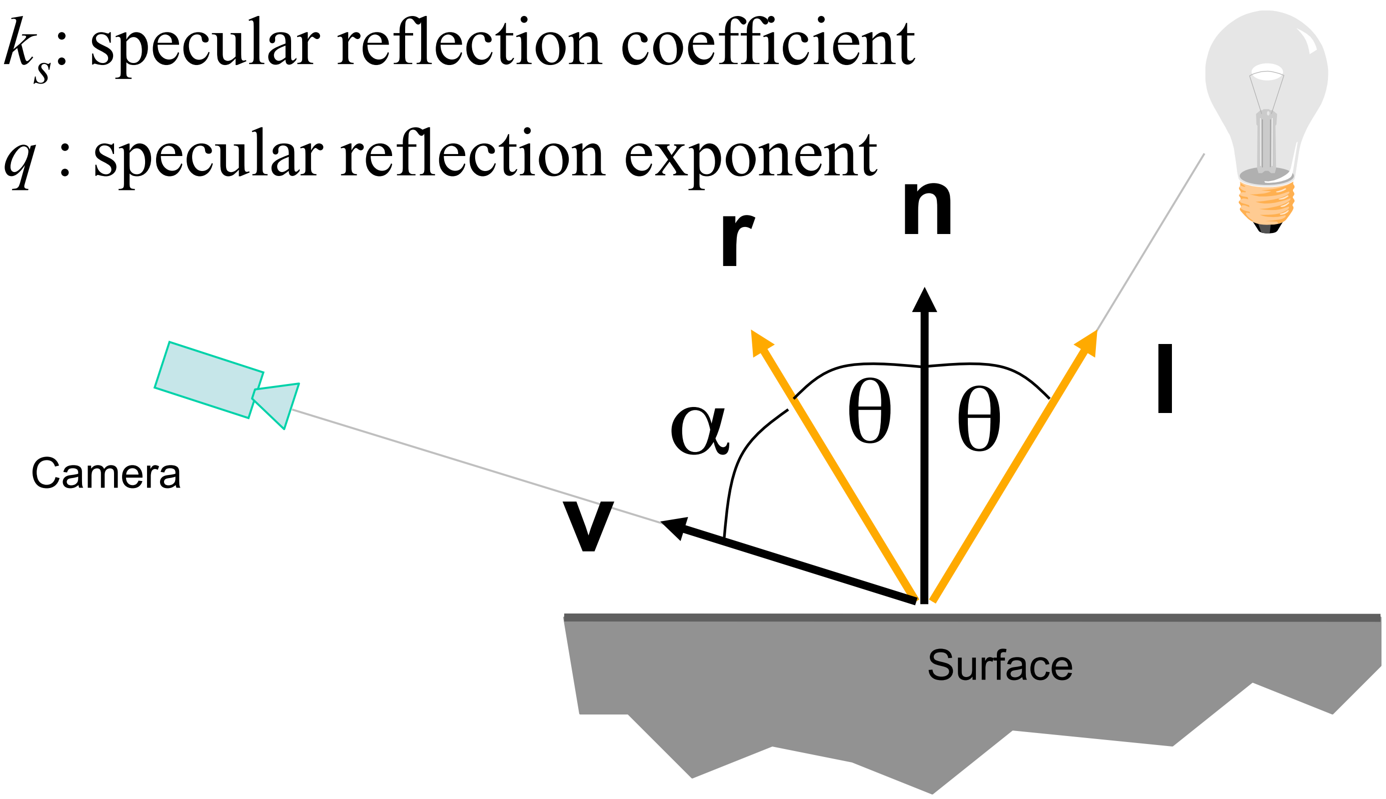
- How much light is reflected?
  - Depends on the angle α between the ideal reflection direction **r** and the viewer direction **v**.



The Phong Specular Model

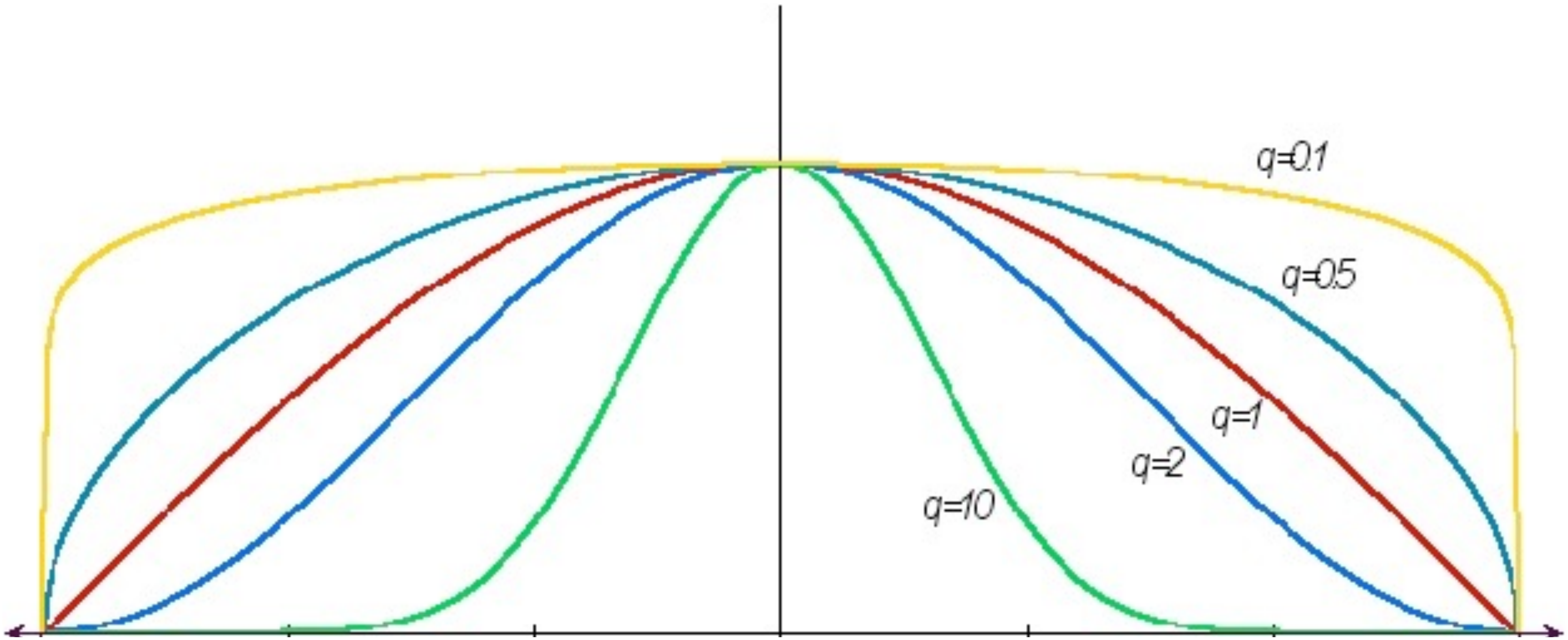
$$L_o = \quad k_s \, (\cos\alpha)^q \, \frac{L_i}{r^2} \quad = k_s \, (\boldsymbol{v} \cdot \boldsymbol{r})^q \, \frac{L_i}{r^2}$$

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



The Phong Model

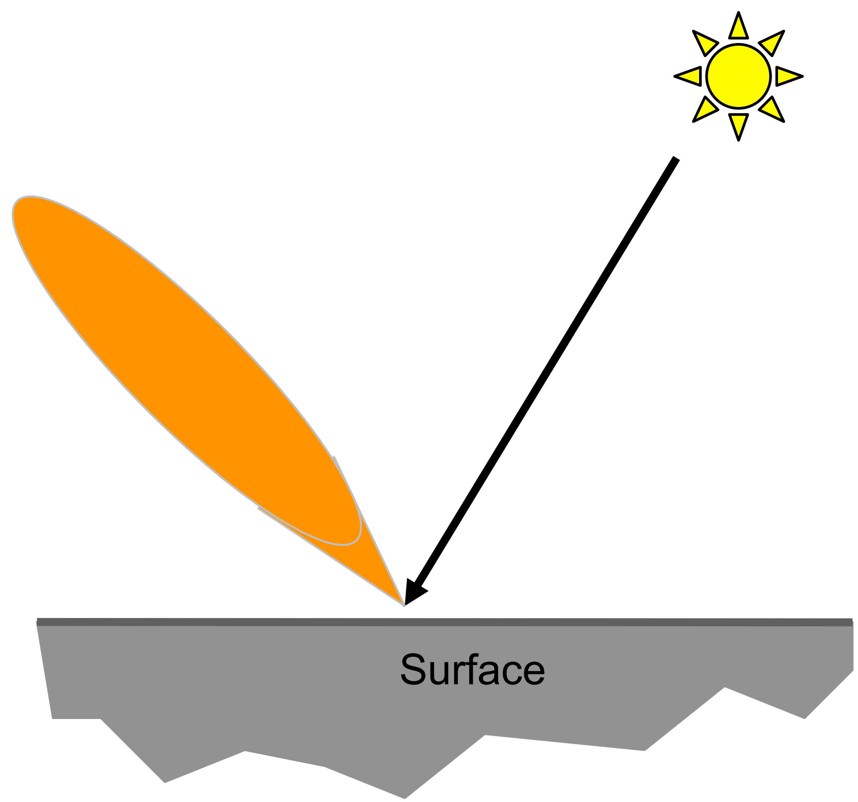
- Effect of the q coefficient



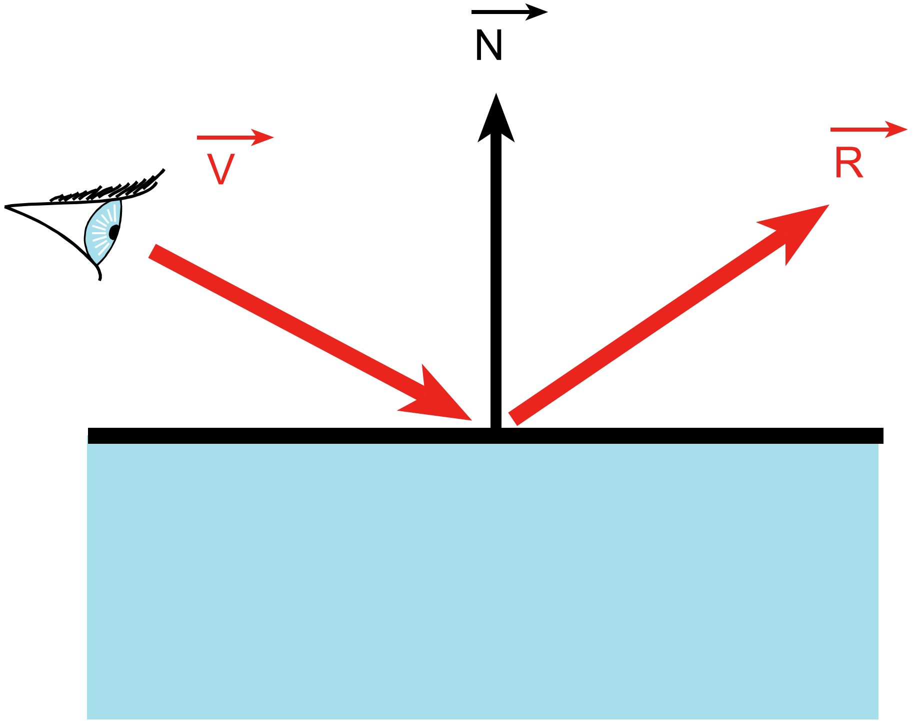
$\alpha = -\pi/2$ $\alpha = 0$ $\alpha = \pi/2$

Terminology: Specular Lobe

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

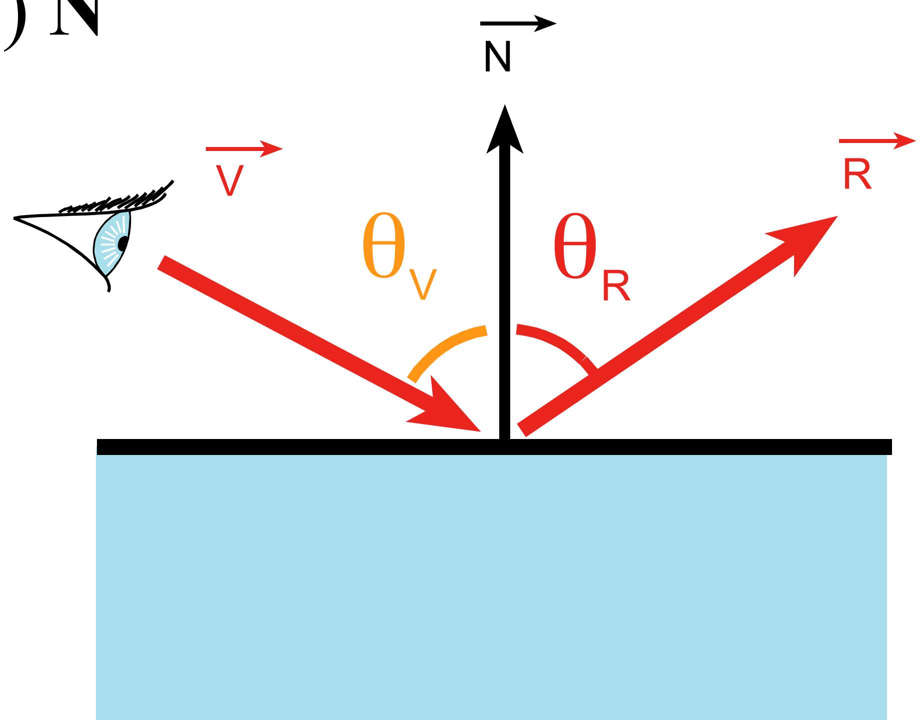


Recap: How to Get Mirror Direction



Recap: How to Get Mirror Direction

- Reflection angle = view angle
  - Normal component is negated
  - Remember particle collisions?
- $\mathbf{R} = \mathbf{V} - 2\,(\mathbf{V} \cdot \mathbf{N})\,\mathbf{N}$



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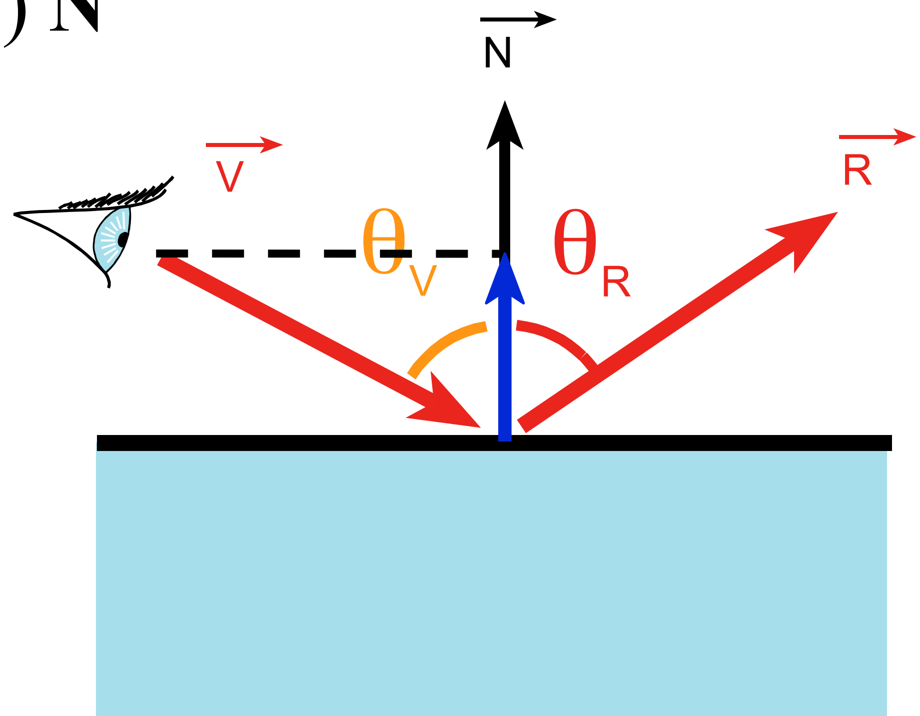

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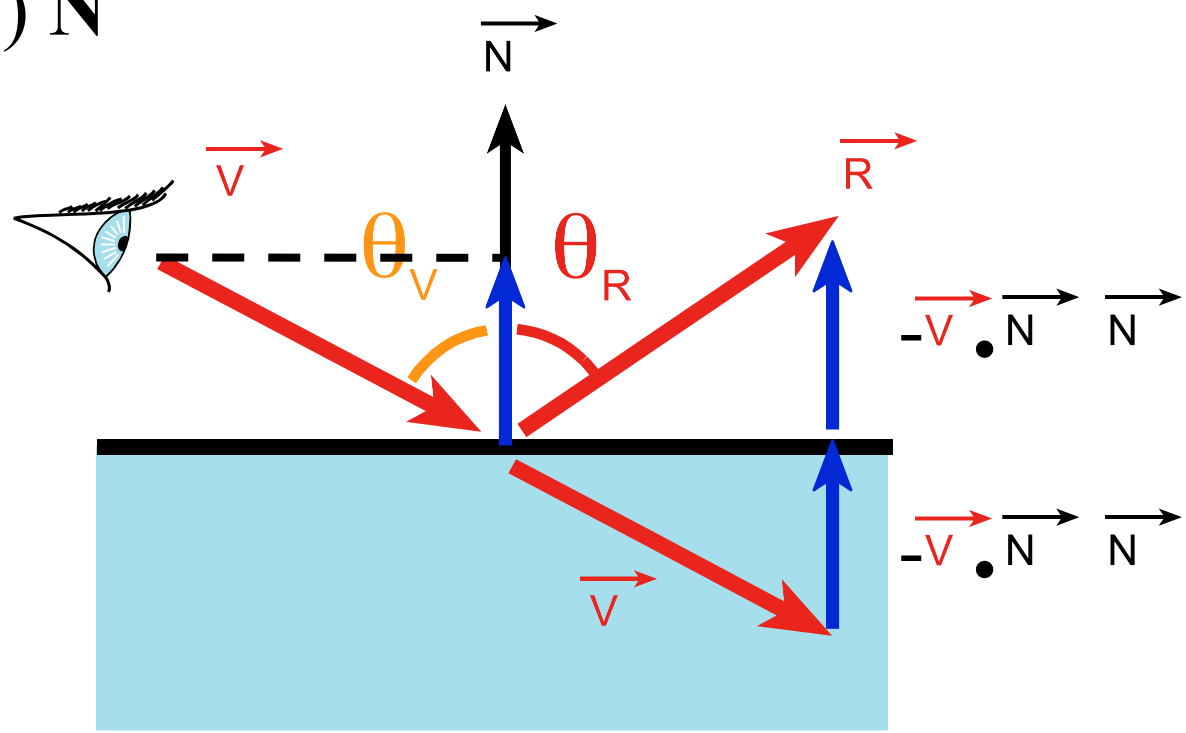
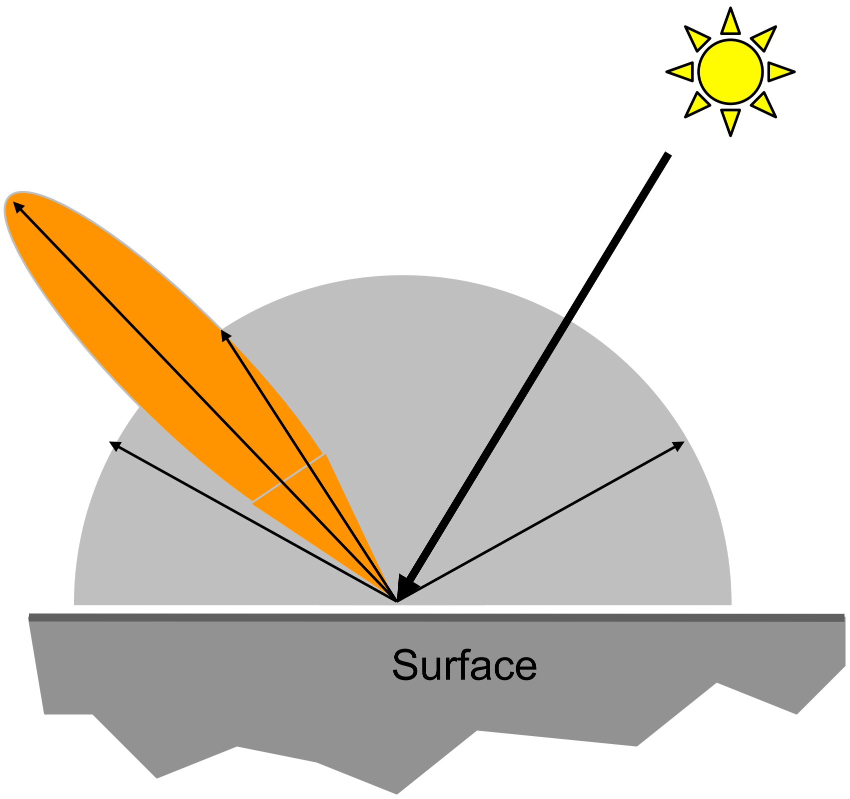


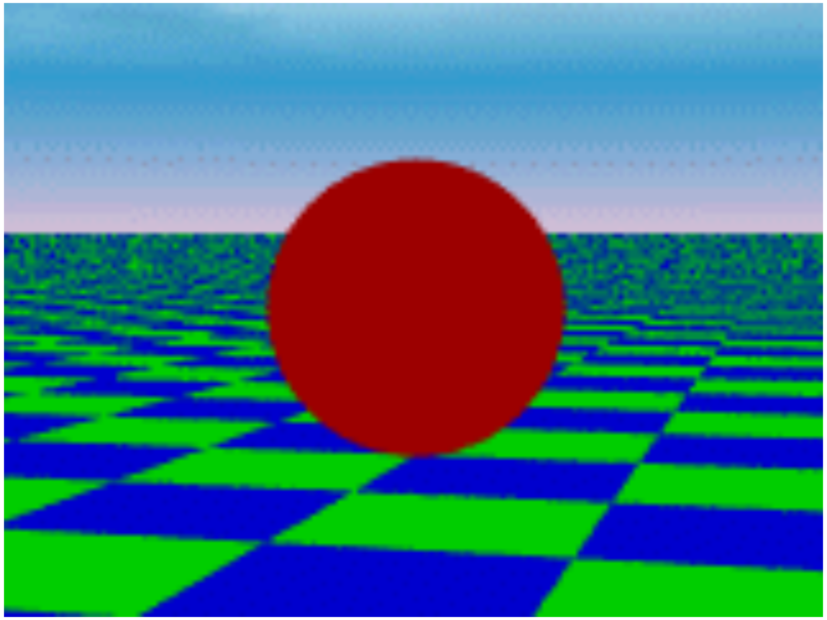
The Complete Phong Model

- Sum of three components:
  ideal diffuse reflection +
  specular reflection +
  "ambient".



Ambient Illumination

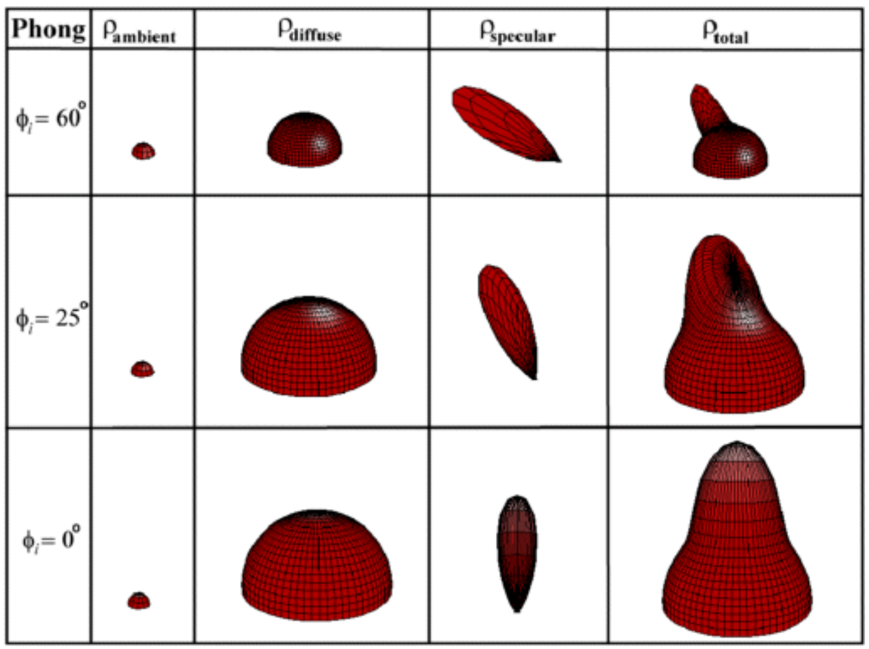
- Represents the reflection of all indirect illumination.
- This is a total hack!
- Avoids the complexity of indirect ("global") illumination



Putting It All Together

- Phong Illumination Model

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



Putting It All Together

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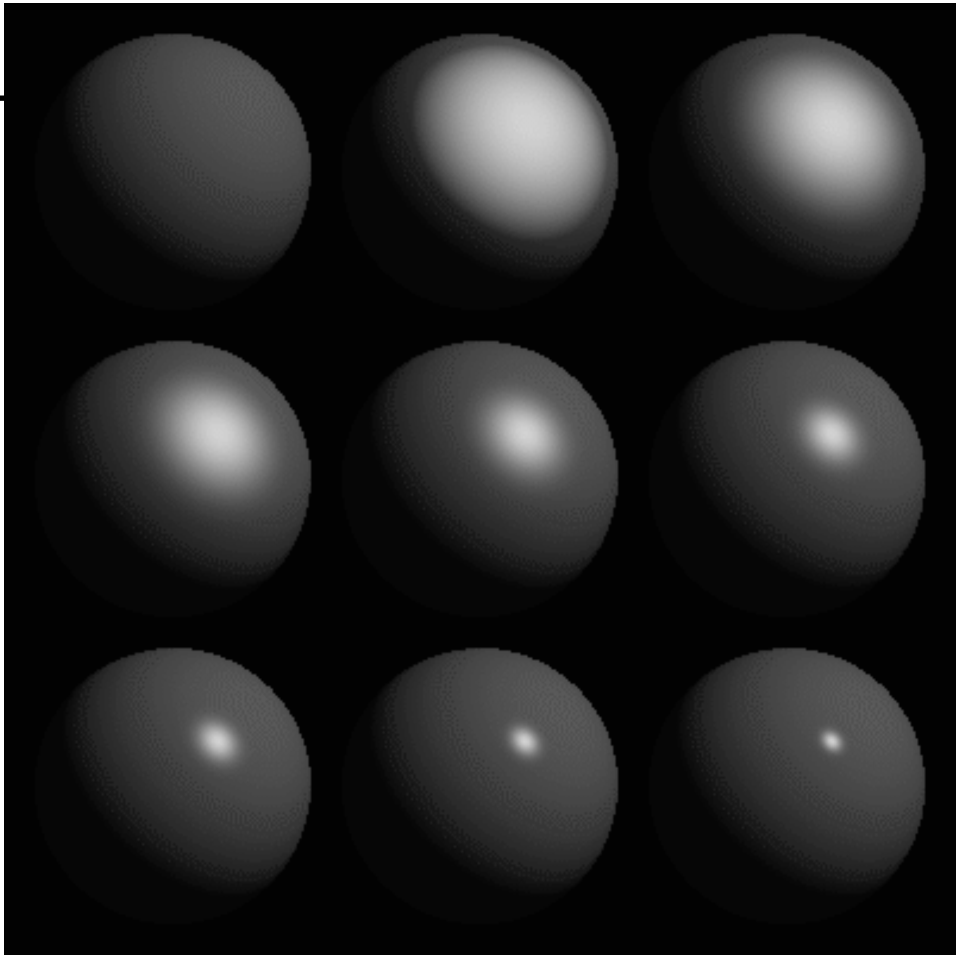
$$L_o = k_a k_d + \left[k_d(\mathbf{n}\cdot\mathbf{l}) + k_s(\mathbf{v}\cdot\mathbf{r})^q\right] \frac{L_i}{r^2}$$

- Is it physically based?
  - No, does not even conserve energy, may well reflect more energy than what goes in
  - Furthermore, it doesn't 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.



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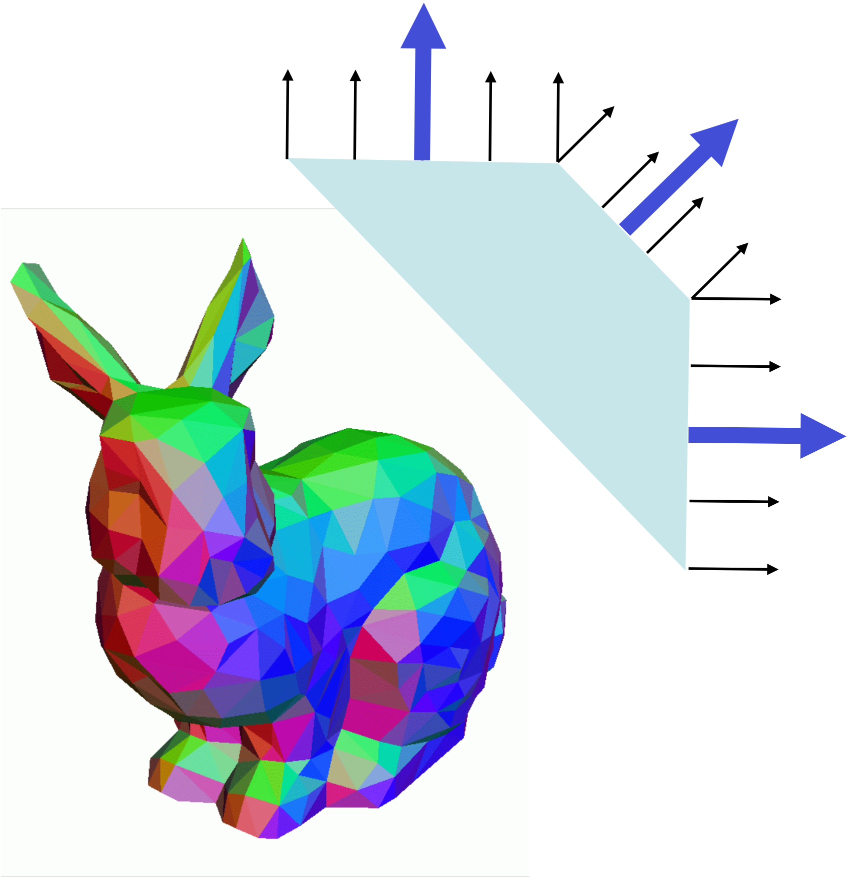
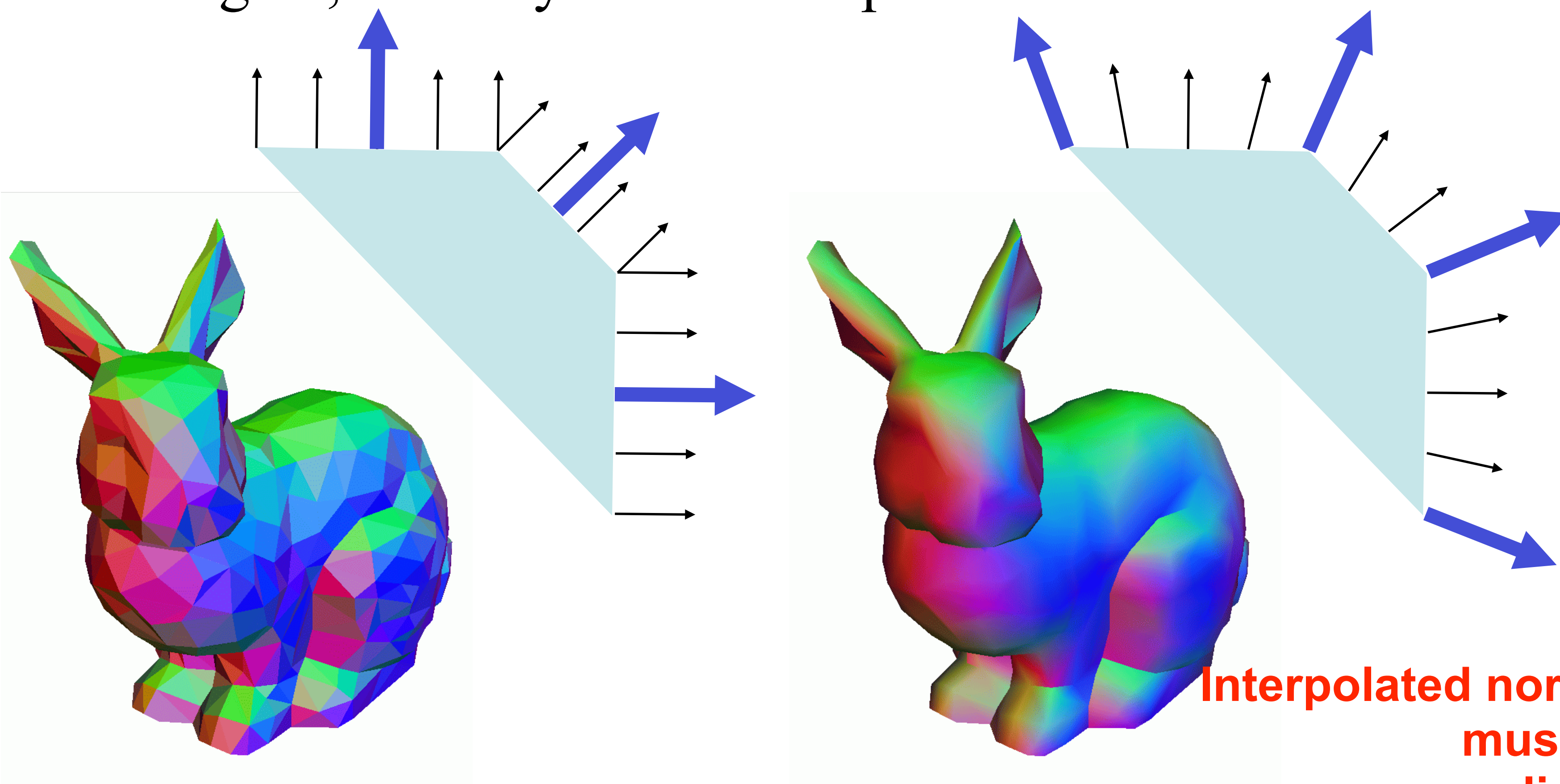
Phong Normal Interpolation (Not Phong *Shading*)



Phong Normal Interpolation (Not Phong *Shading*)

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



Interpolated normal must be renormalized!

What About Color?

- Diffuse coefficients:
  - $k_{d\text{-}red}$, $k_{d\text{-}green}$, $k_{d\text{-}blue}$
- Specular coefficients:
  - $k_{s\text{-}red}$, $k_{s\text{-}green}$, $k_{s\text{-}blue}$
- Specular exponent:

  q

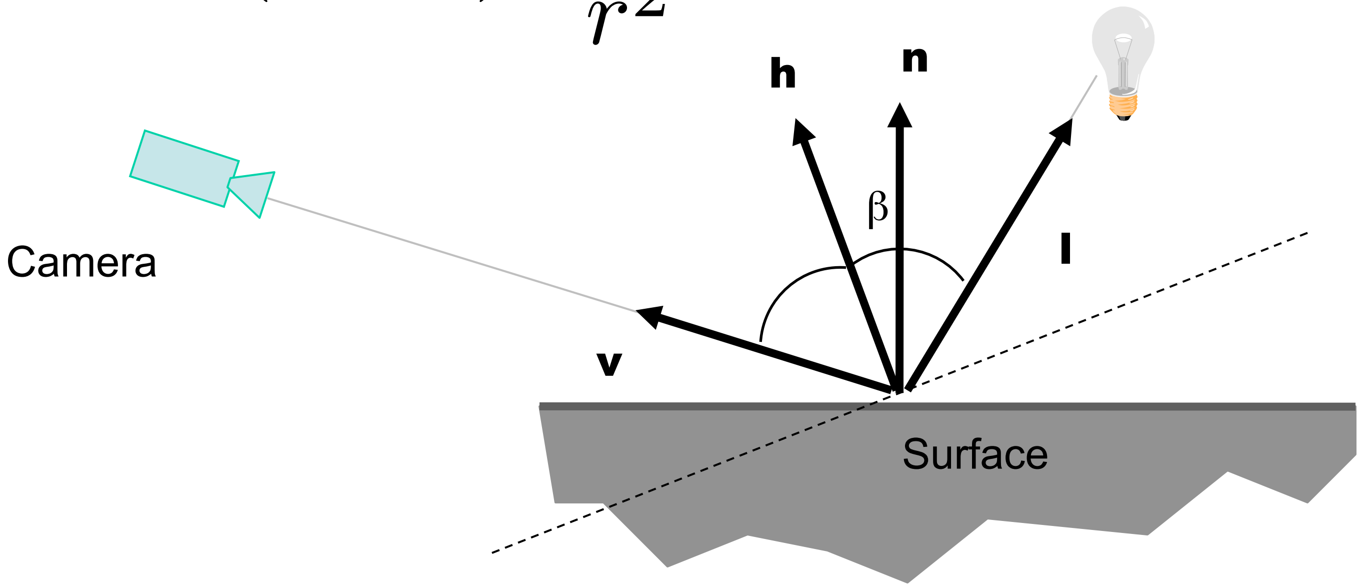
Blinn-Torrance Variation of Phong

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

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

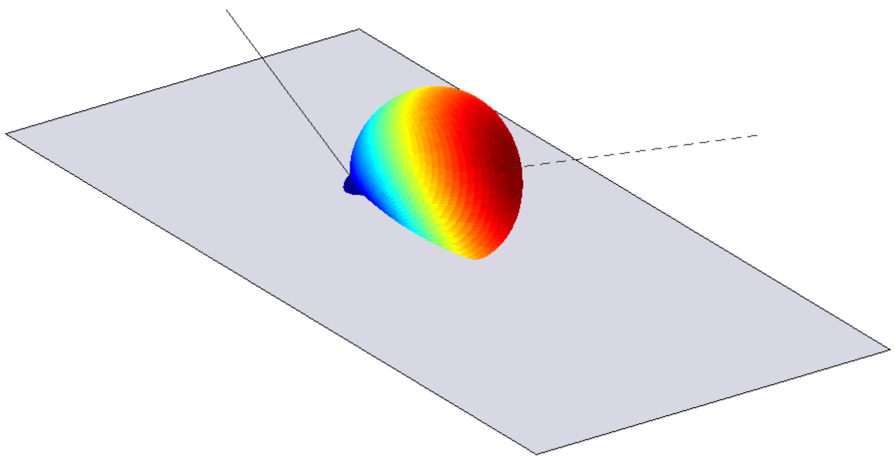
$$= k_s (\boldsymbol{n} \cdot \boldsymbol{h})^q \frac{L_i}{r^2}$$

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

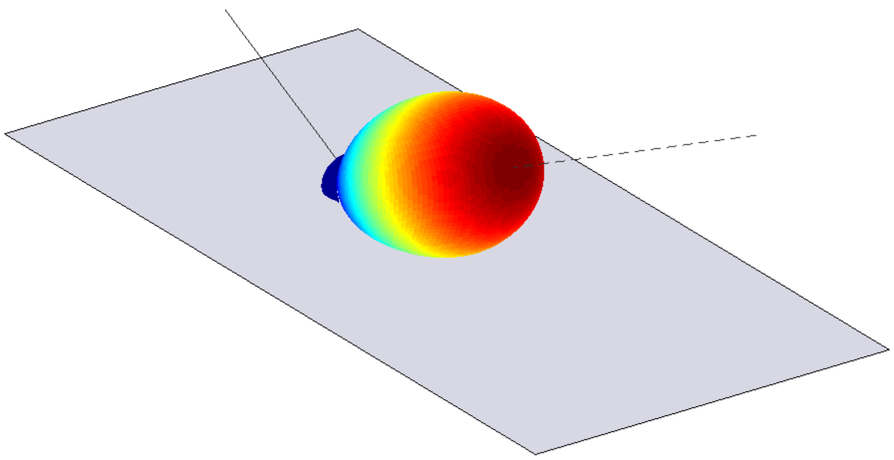


Lobe Comparison

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



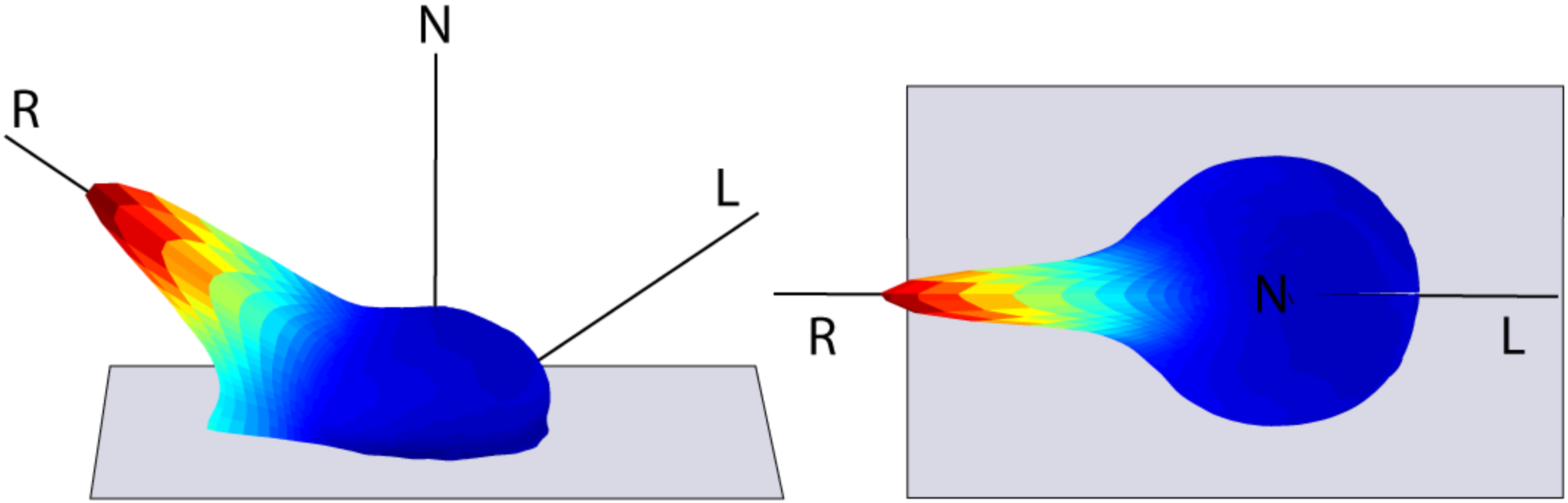
Half vector lobe



Mirror lobe

Half Vector Lobe is Better

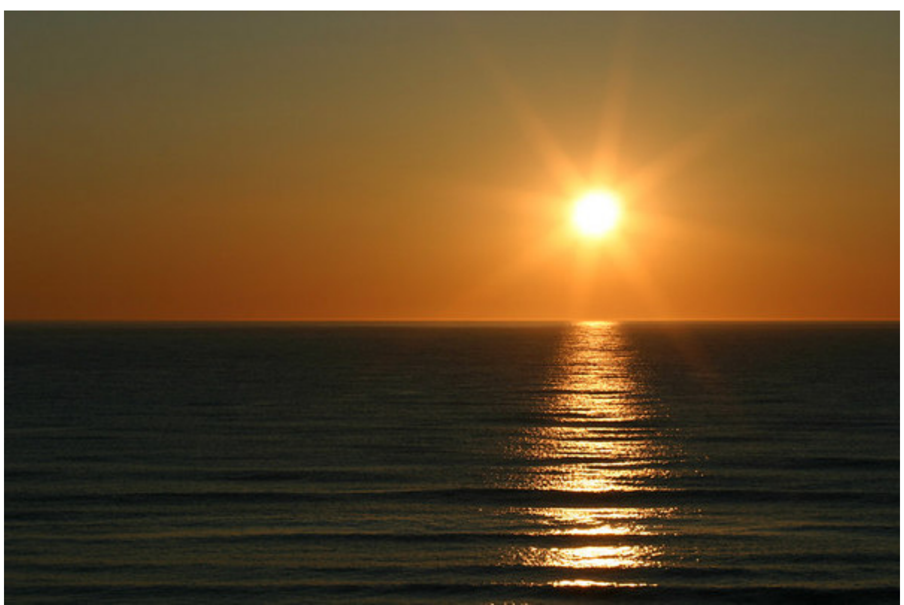
- More consistent with what is observed in measurements (Ngan, Matusik, Durand 2005)



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

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

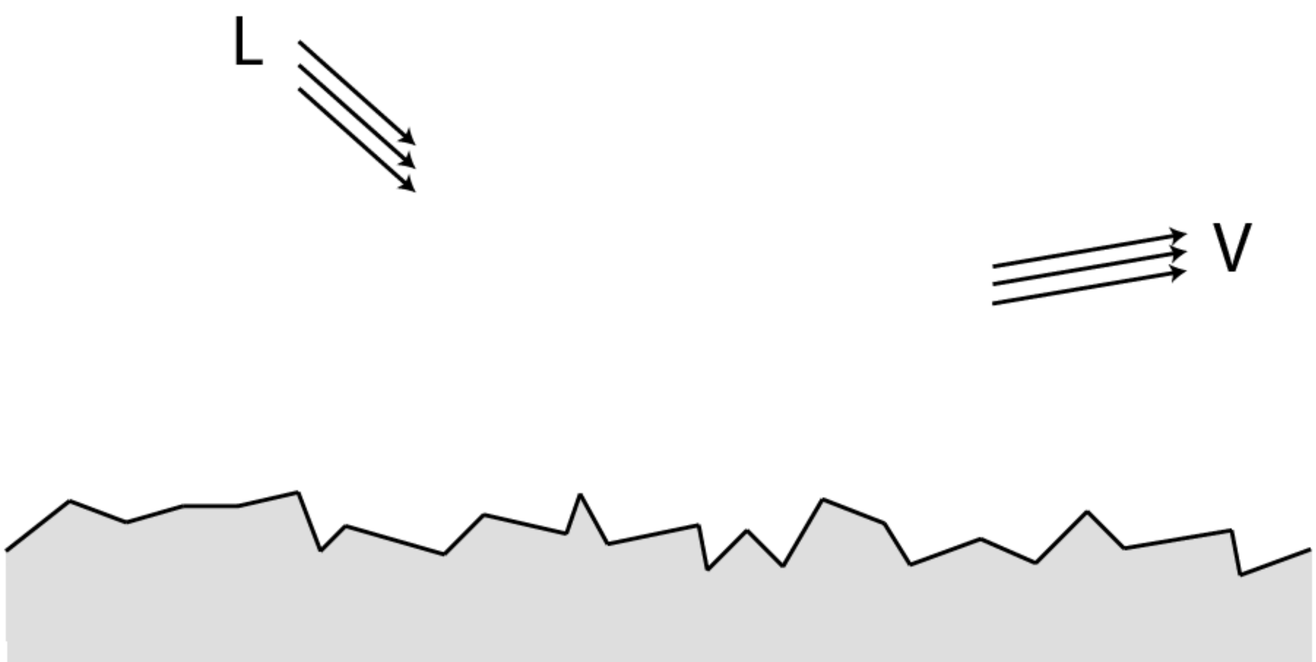


Microfacet Theory

- 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



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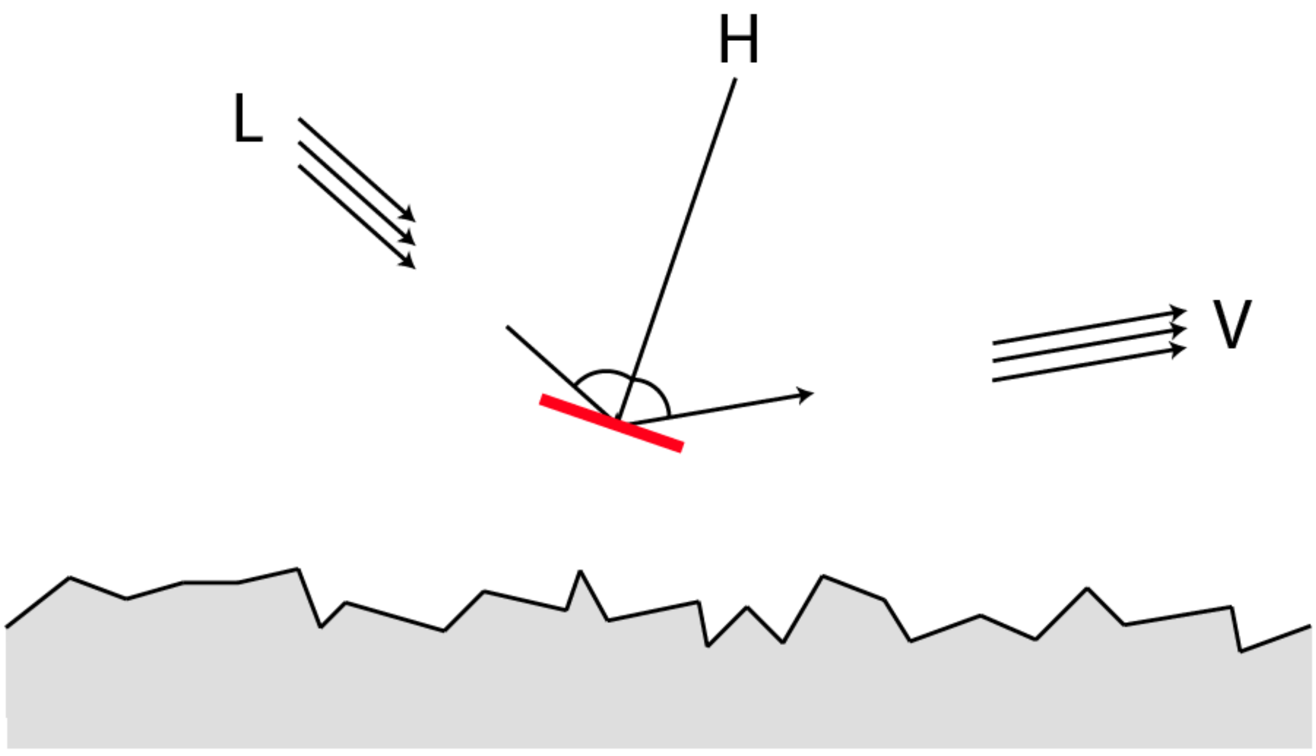

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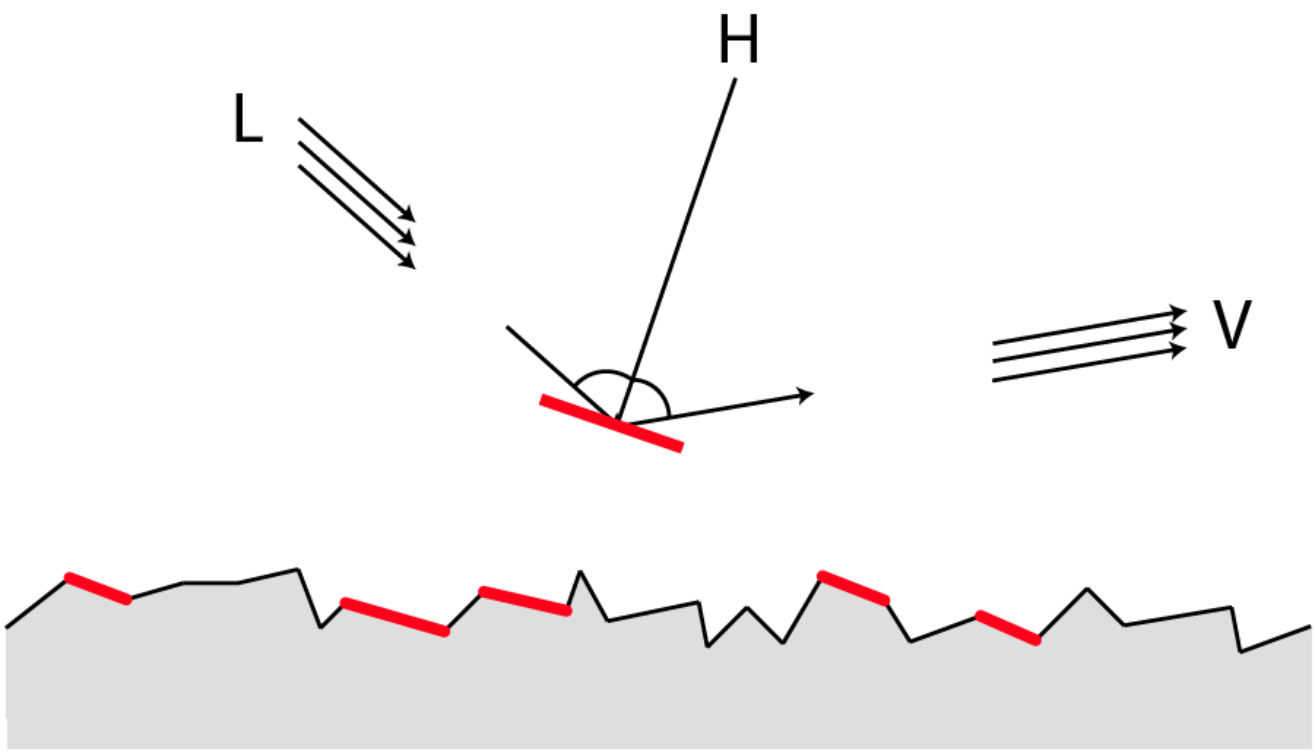

Microfacet Theory

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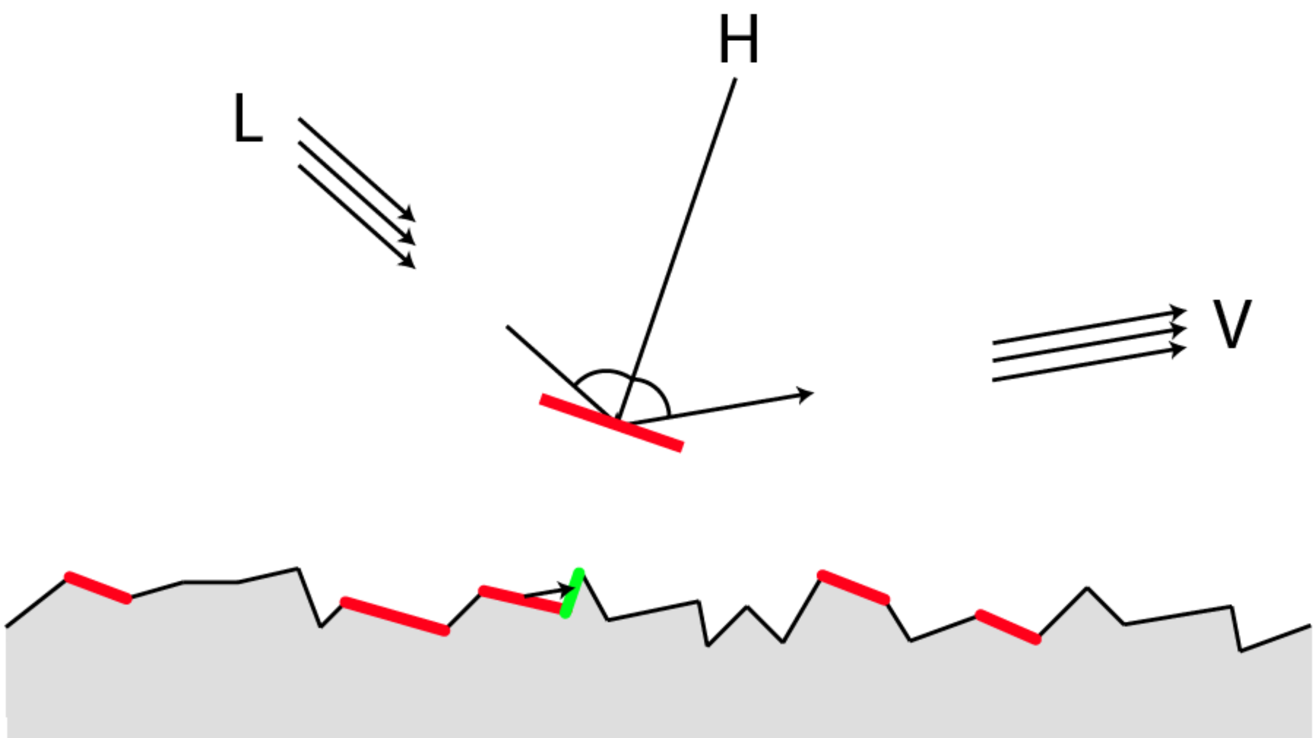
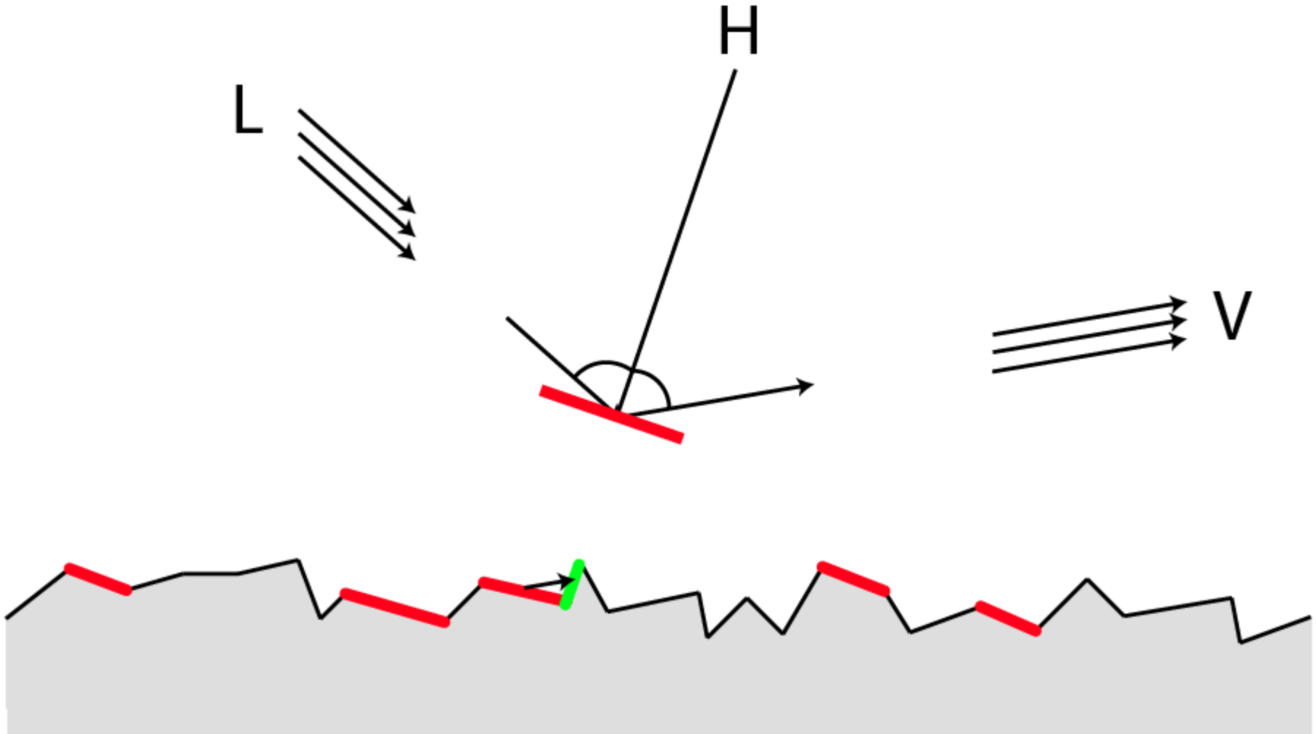


Microfacet Theory

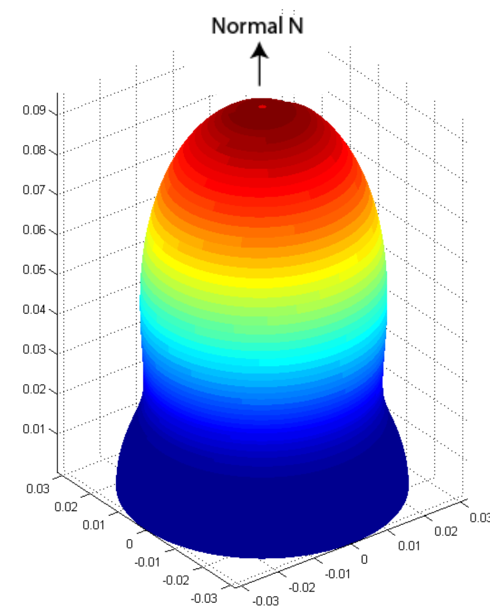
- Value of BRDF at (L,V) is a product of
  - number of mirrors oriented halfway between L and V
  - ratio of the un(shadowed/masked) mirrors
  - Fresnel coefficient



Microfacet Theory-based Models

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

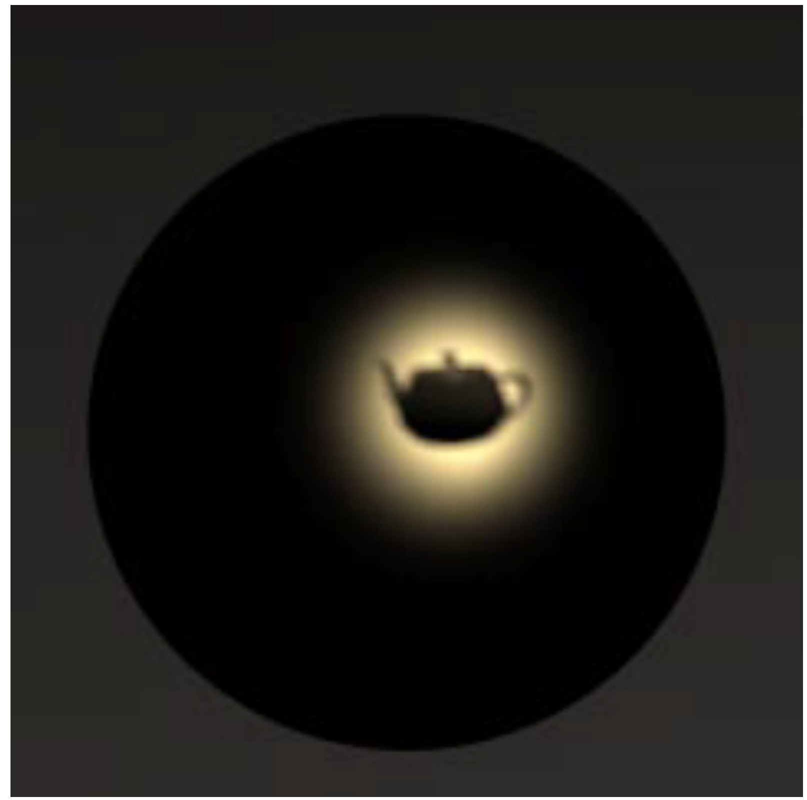
- Model the distribution p(H) of microfacet normals
  - Also, statistical models for shadows and masking



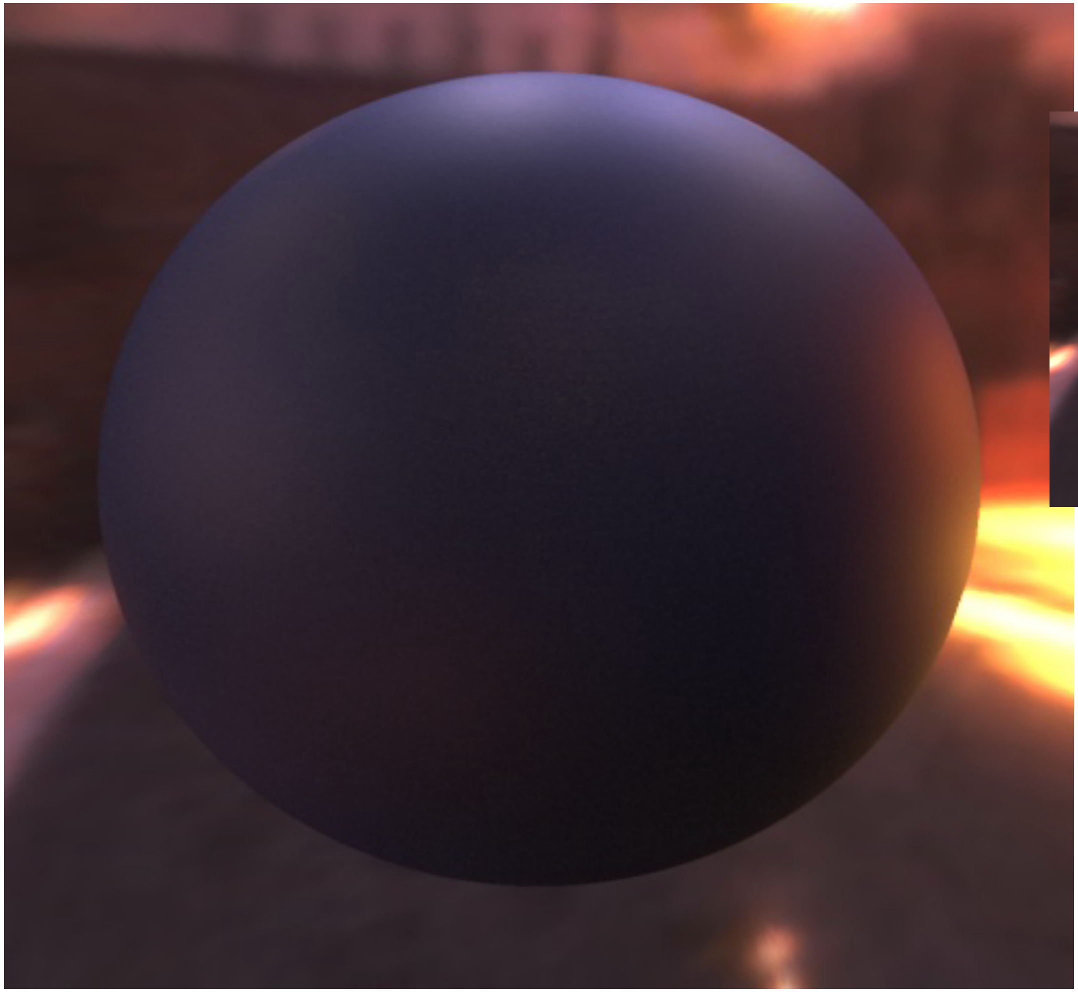
spherical plot of a Gaussian-like p(H)

Questions?

- "Designer BRDFs" by Ashikhmin et al.



BRDF Examples from Ngan et al.

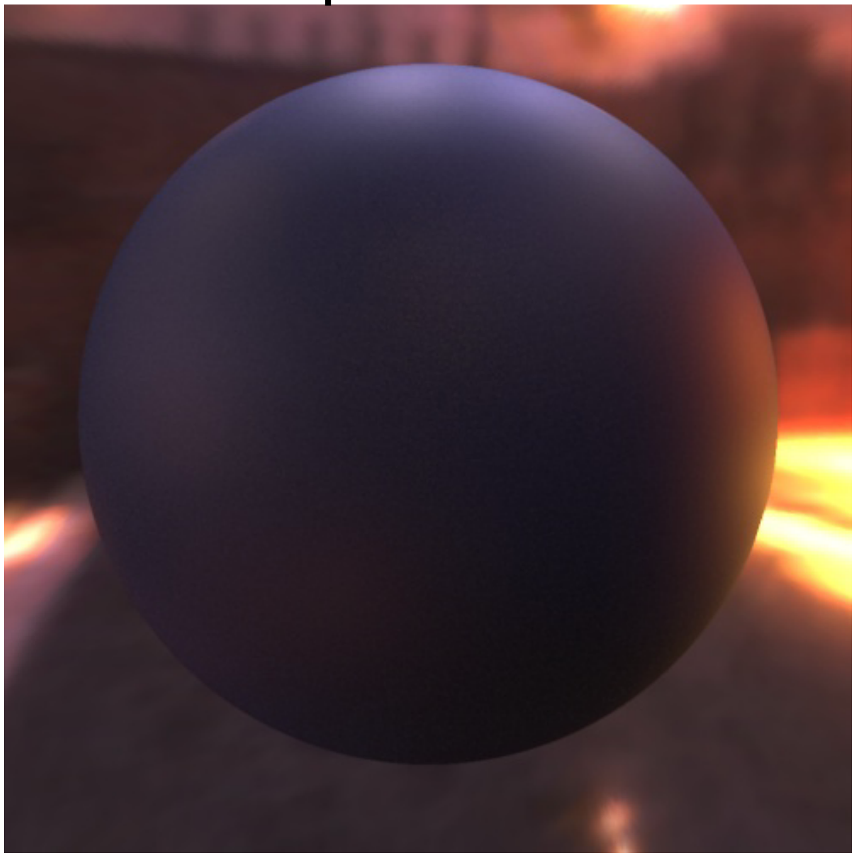


Lighting

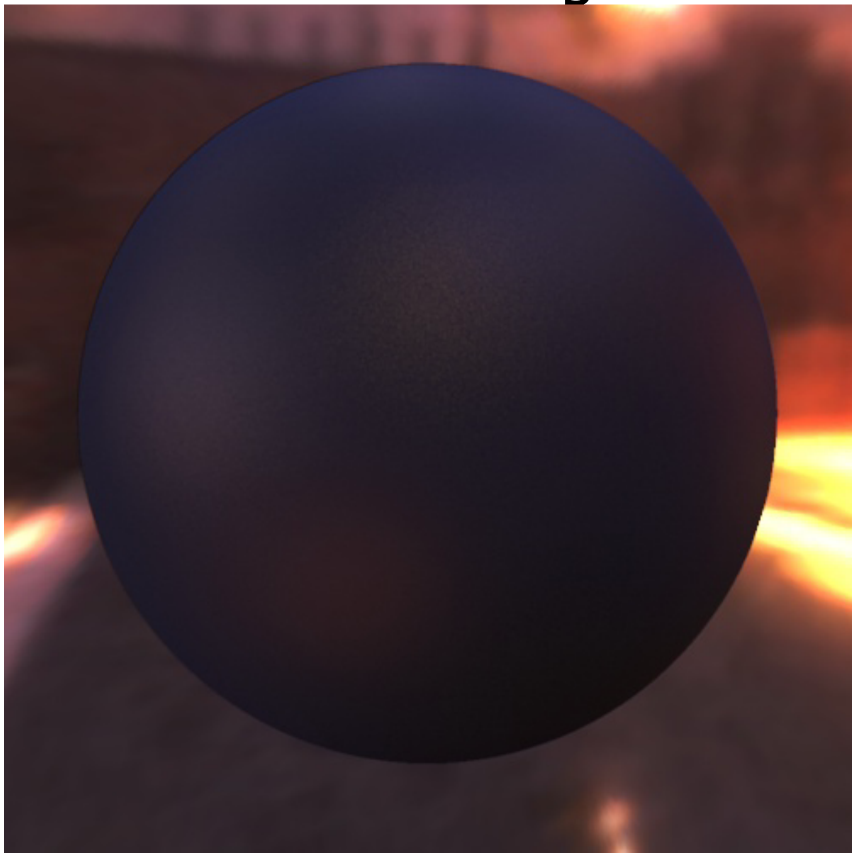
Material – Dark blue paint

Dark blue paint

Acquired data



Blinn-Phong



Finding the BRDF model parameters that best reproduce the real material

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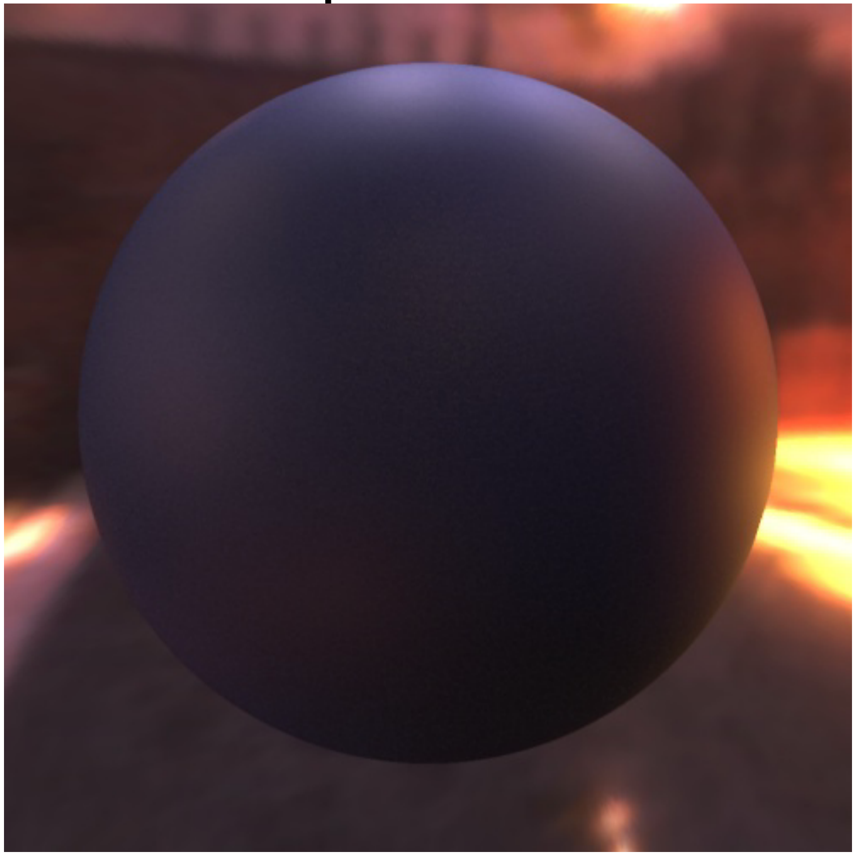
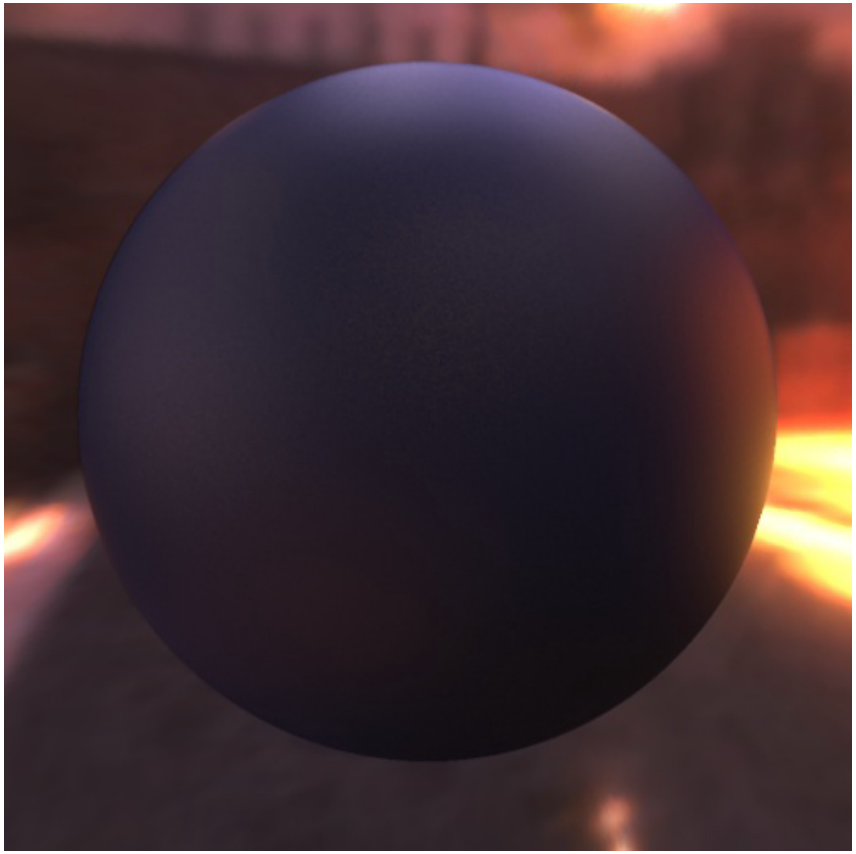


Cook-Torrance



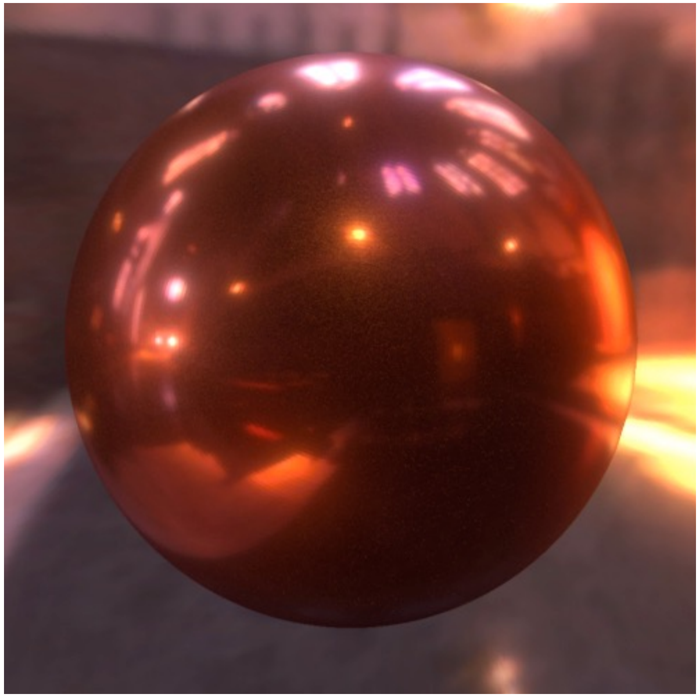
Finding the BRDF model parameters that best reproduce the real material

Material – Dark blue paint

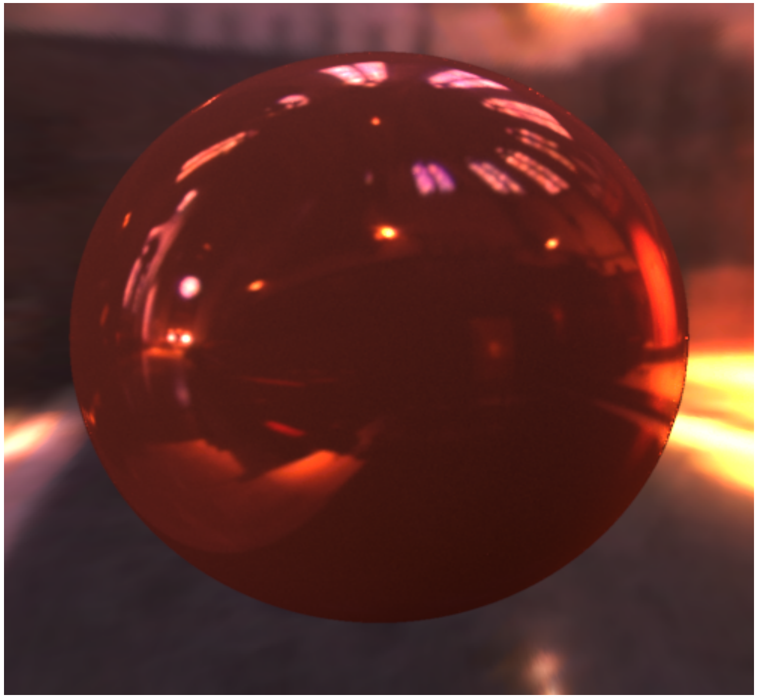
Observations

- Some materials impossible to represent with a single lobe

Acquired data



Cook-Torrance

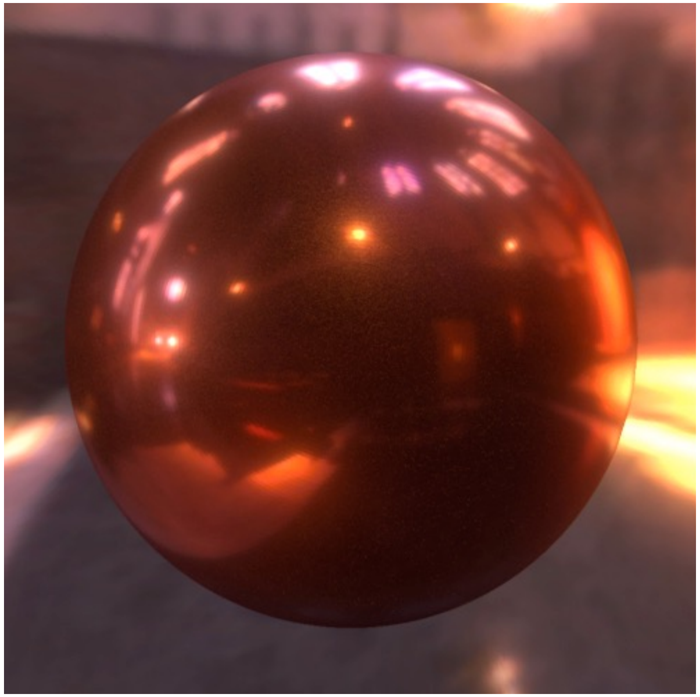


Material – Red Christmas Ball

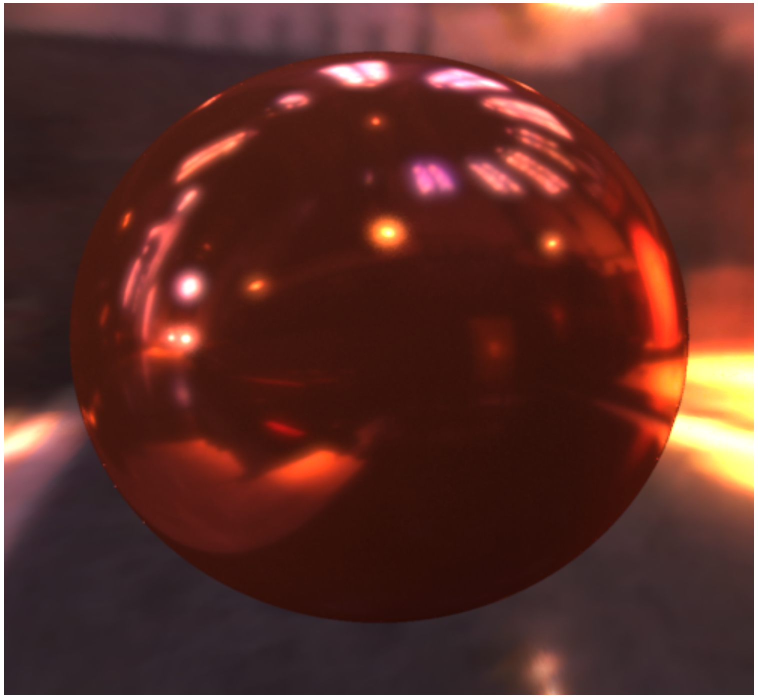
Adding a second lobe

- Some materials impossible to represent with a single lobe

Acquired data



Cook-Torrance 2 lobes



Material – Red Christmas Ball