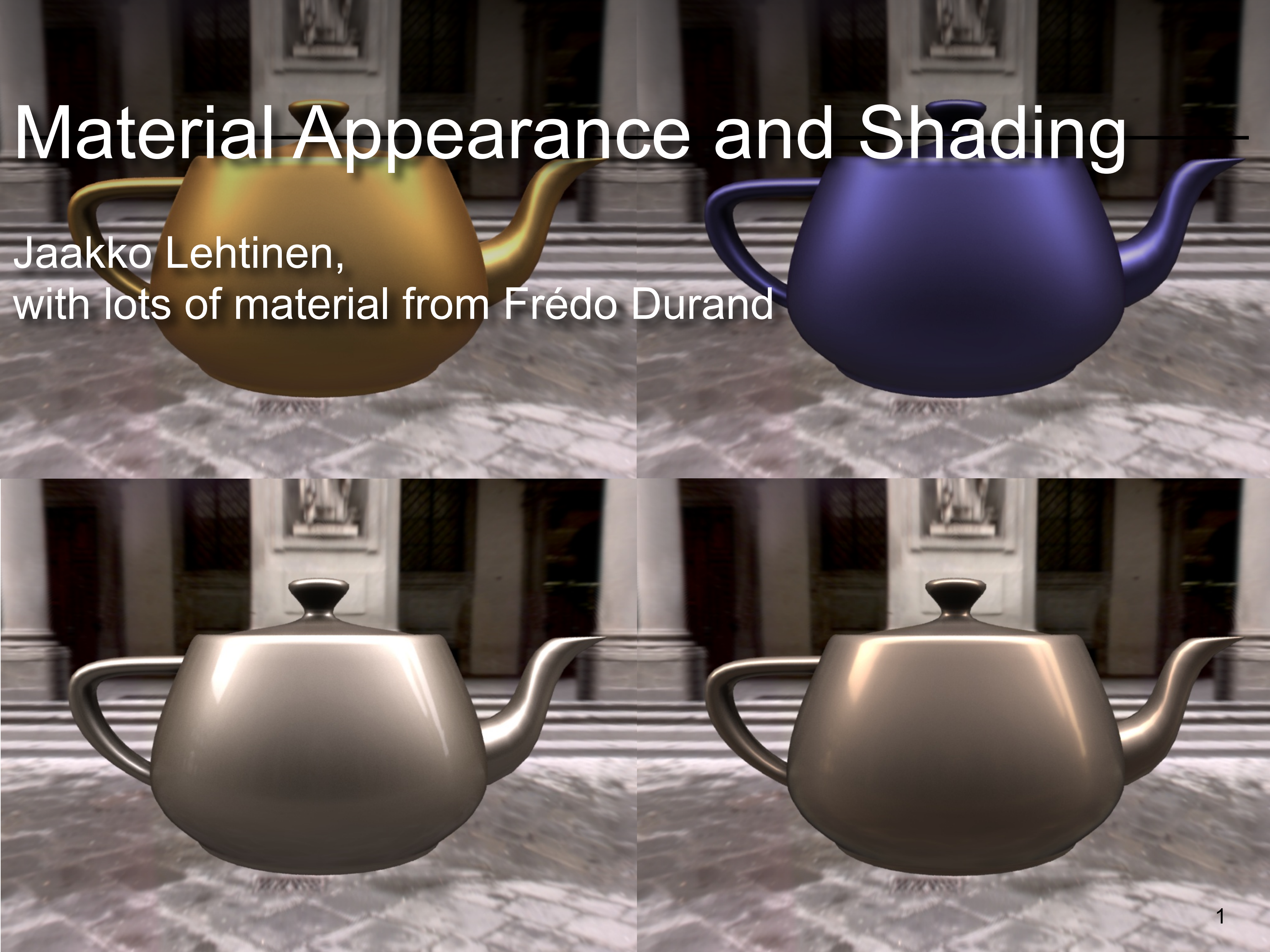
Material Appearance and Shading

Jaakko Lehtinen,
with lots of material from Frédo Durand



In This Video

- Basic physical principles of image formation
- Point light sources
  – Types: Directional, spot
- Quantifying reflection: the BRDF
  – Bidirectional Reflectance Distribution Function
  – Parametric BRDF models: mathematical formulas with interpretable knobs (like “shininess”, etc.)

Images are formed by the interaction of light and matter

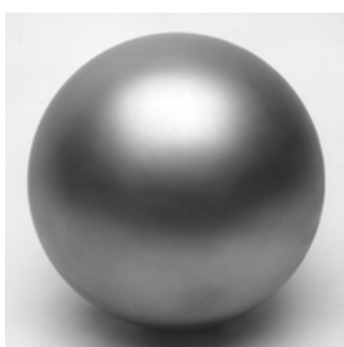
Image Formation

1. Light leaves source
2. Light travels in scene
3. Light either..
   1. reflects off of surface or scatters in participating medium (e.g. smoke) followed by GOTO 2, or
   2. arrives at sensor
      - » Your eye, camera, our virtual camera

- **The way surface reflects light determines its 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 time)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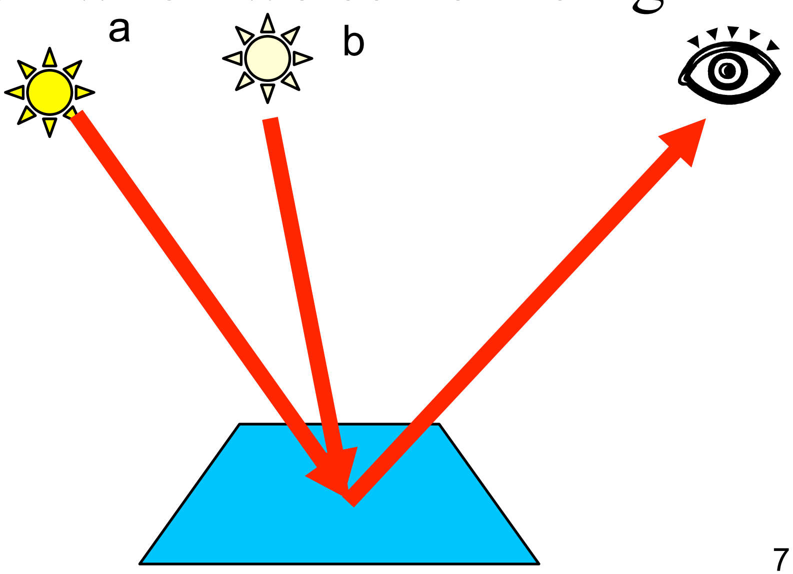
Unit Issues - Radiometry

- We will not be too formal in this class
- Issues we won't 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'll perform computations for R, G, B separately
    - Don't panic, that just means
      we'll perform every operation three times, that's all

Light Sources

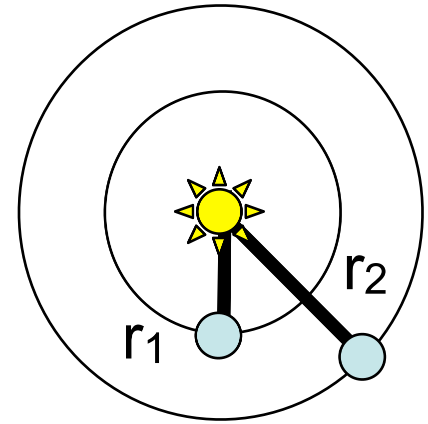
- Today, we only consider point light sources
  - Thus we don't need to care about "solid angles"
- For multiple light sources, use linearity
  - We can add the solutions for two light sources
    - I(a+b) = I(a) + I(b)
  - We simply multiply the solution when we scale the light intensity
    - I(s a) = 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 $1/r^2$



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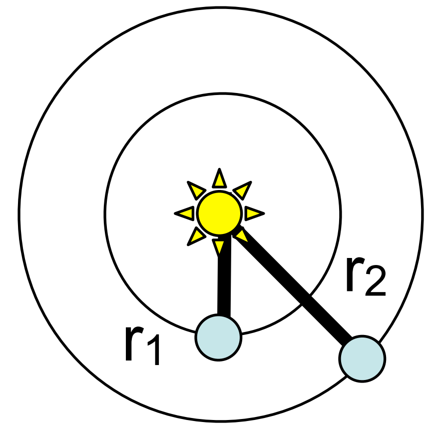
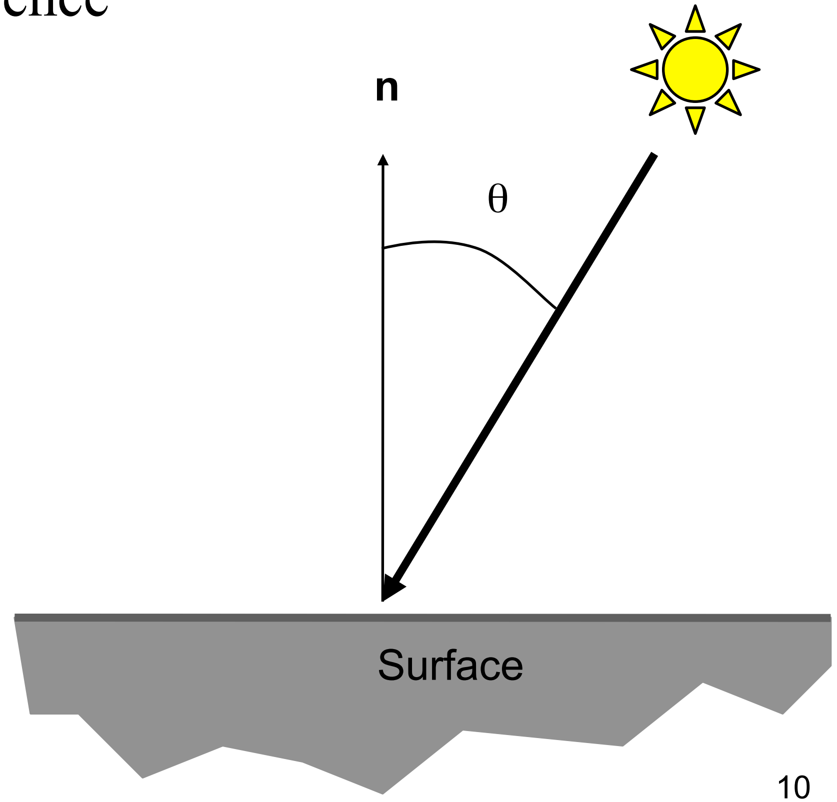


- … but in graphics we often cheat with or ignore this.
  - Why? Ideal point lights are kind of harsh
    - Intensity goes to infinity when you get close – not great!
  - In particular, $1/(ar^2+br+c)$ is popular
  - I'll write $1/r^2$, but take that with a grain of salt

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

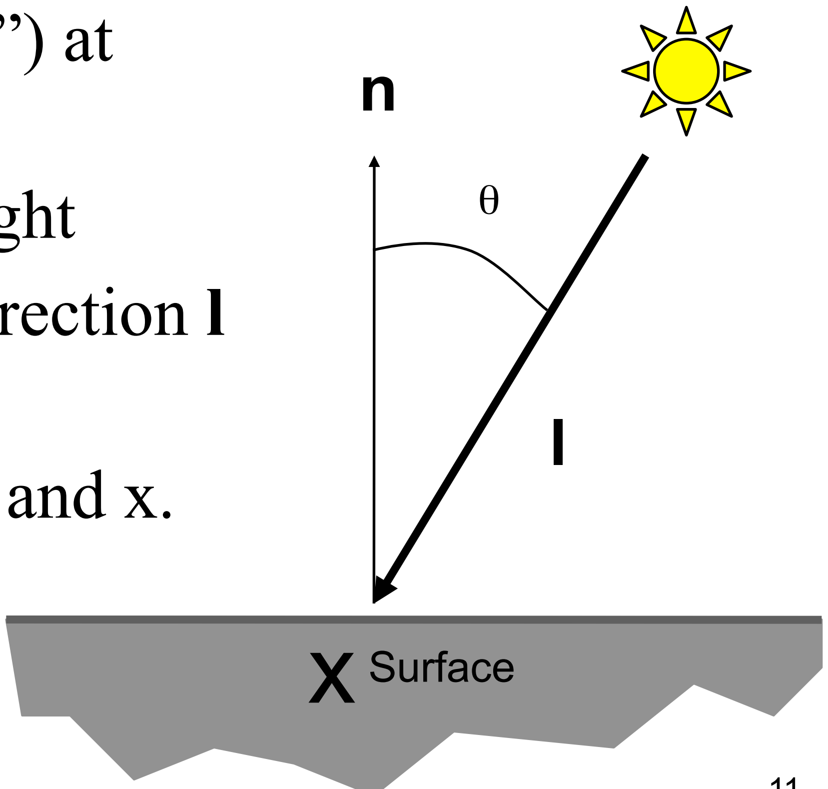


Incoming Irradiance for Pointlights

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

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

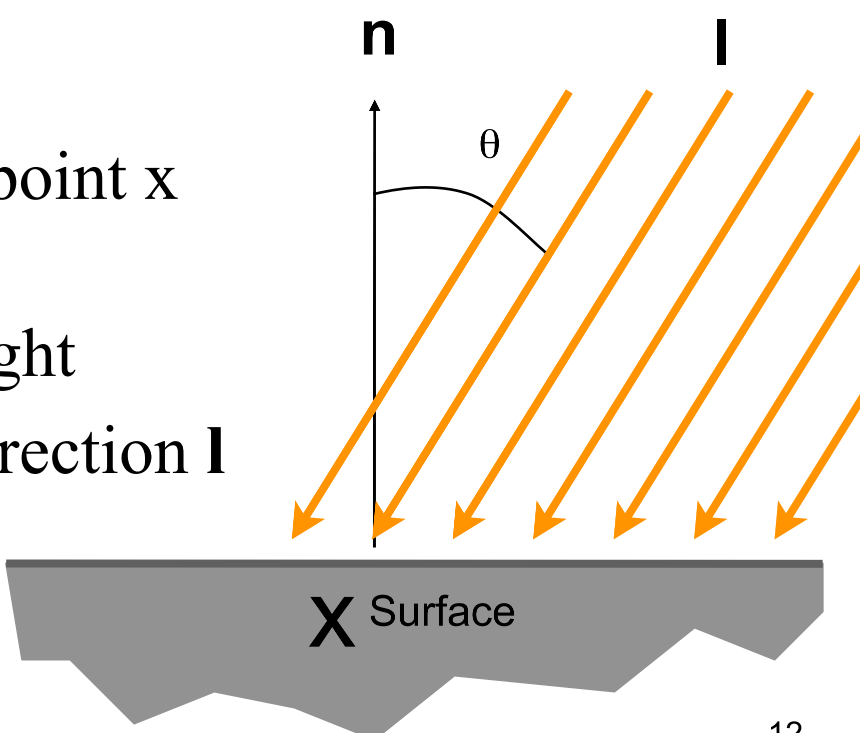
  - I_{in} is the irradiance ("intensity") at surface point x
  - I_{light} is the "intensity" of the light
  - θ is the angle between light direction **l** and surface normal **n**
  - r is the distance between light and x.



Directional Lights

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

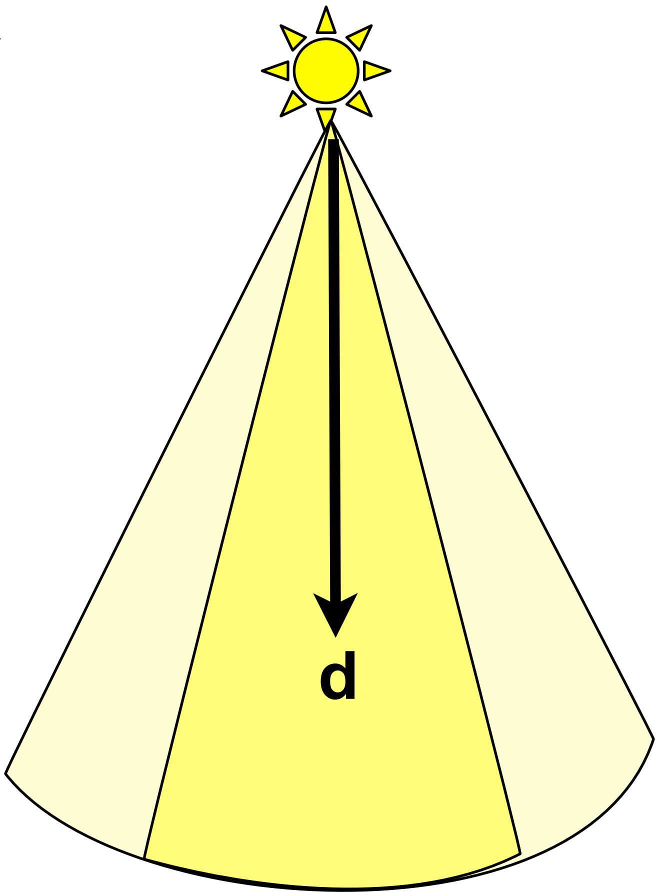
$$I_{\text{in}} = I_{\text{light}} \cos\theta$$



  - 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!

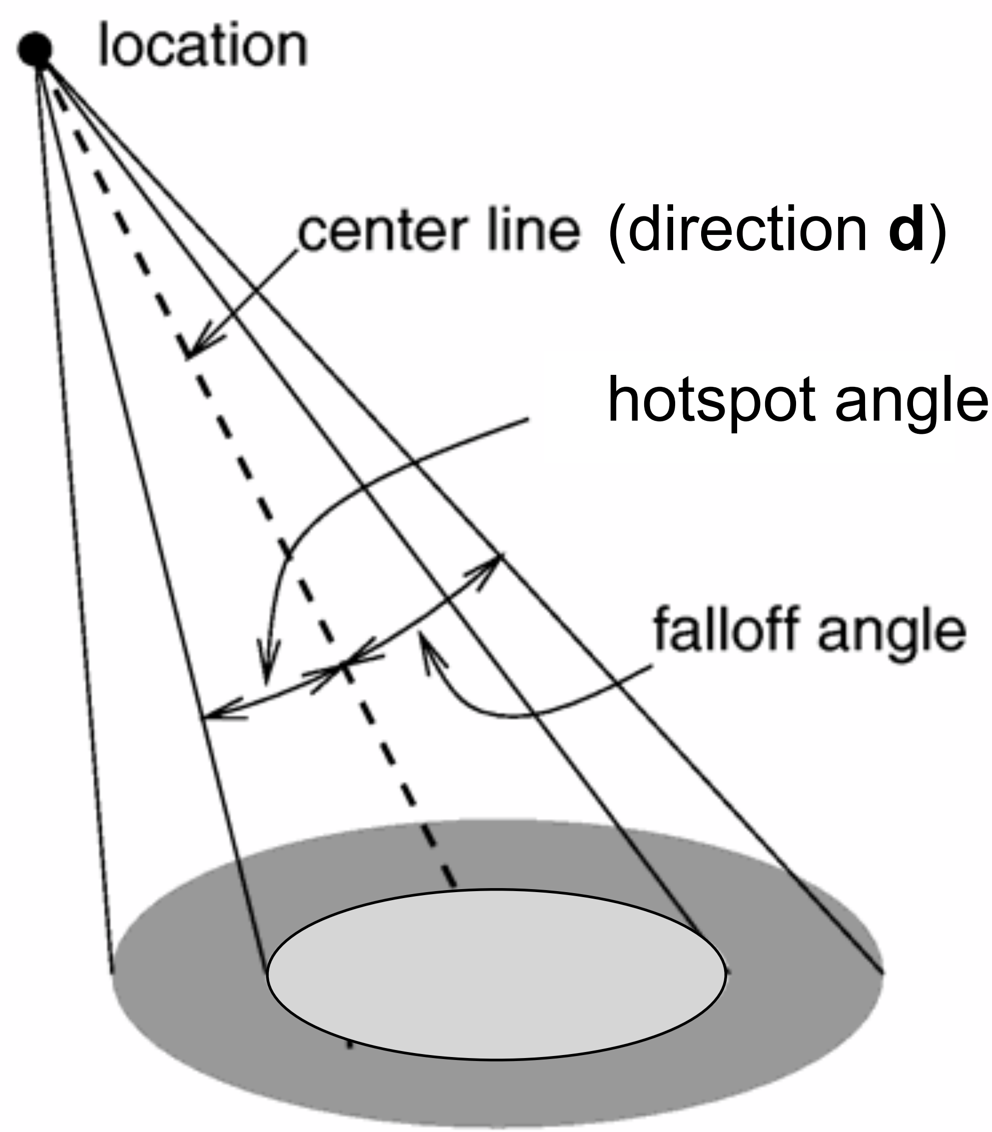
Spotlights

- 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



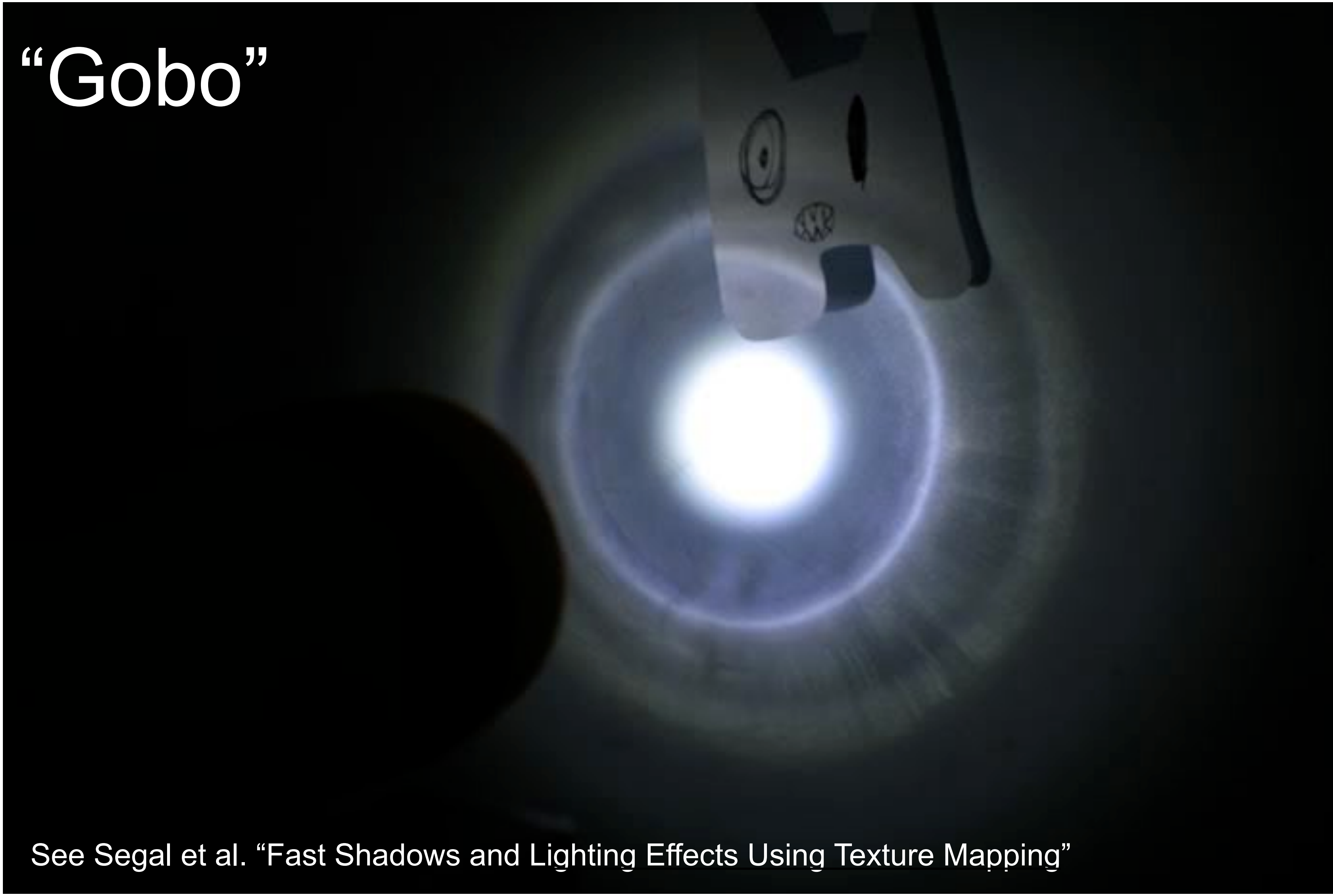
- Plus your favorite distance falloff curve

Spotlight Geometry



Adapted from
POVRAY documentation

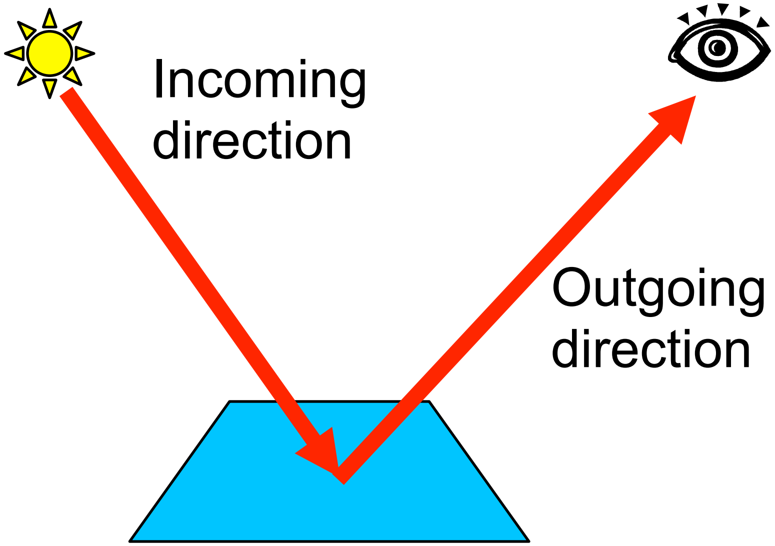
“Gobo”



See Segal et al. “Fast Shadows and Lighting Effects Using Texture Mapping”

Quantifying Reflection – BRDF

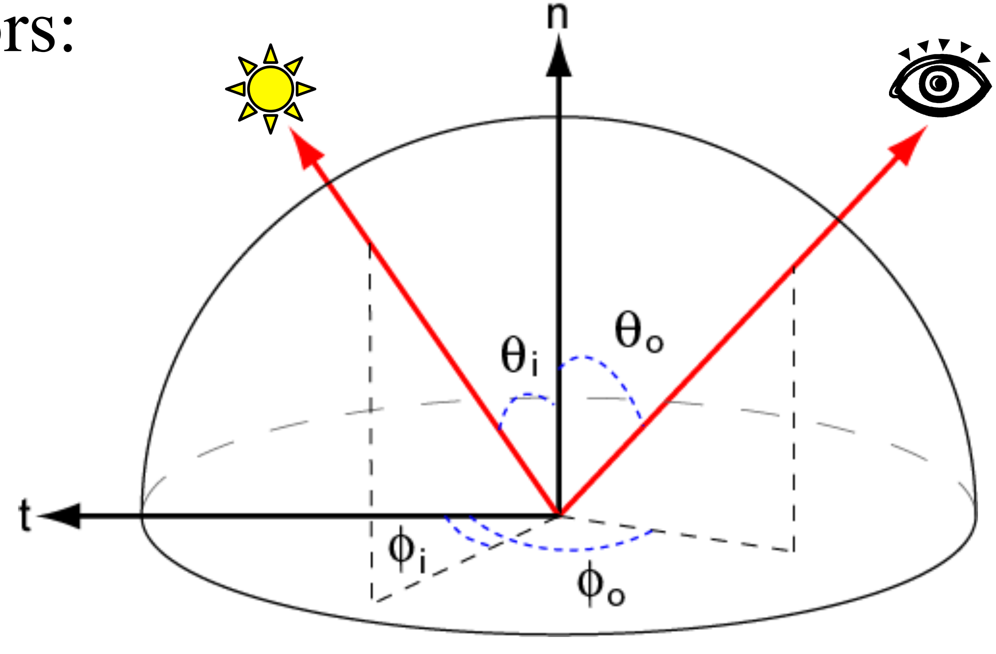
- Bidirectional Reflectance Distribution Function
- Ratio of light coming from one direction that gets reflected in another direction
  - Pure reflection, assumes no light scatters into the material



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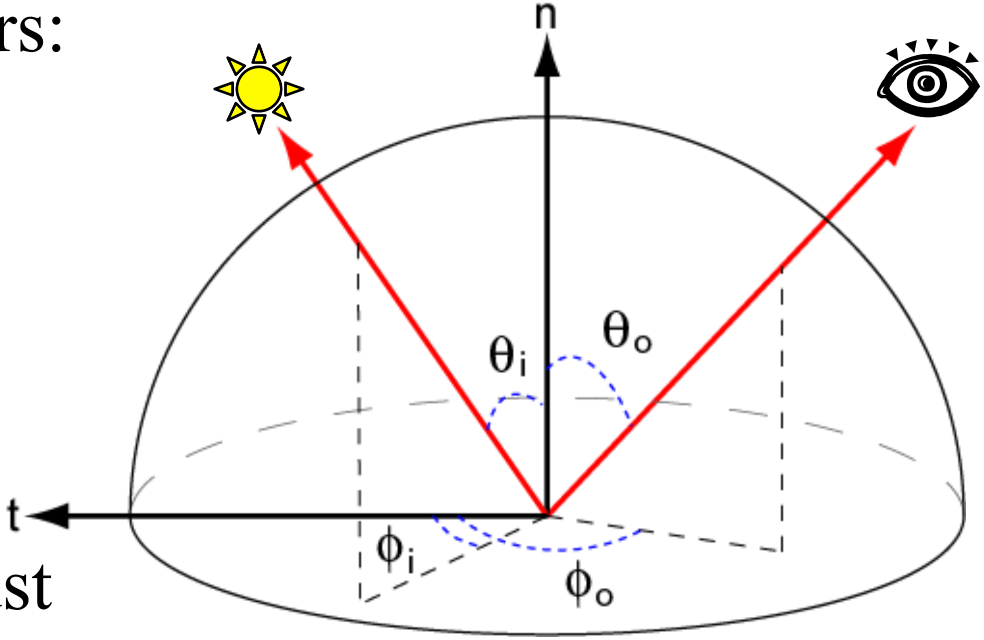
  - Or just two unit vectors: BRDF = $f_r(\mathbf{l}, \mathbf{v})$
    - $\mathbf{l}$ = light direction
    - $\mathbf{v}$ = view direction
  - The BRDF is aligned with the surface; the vectors **l** and **v** must be in a local coordinate system

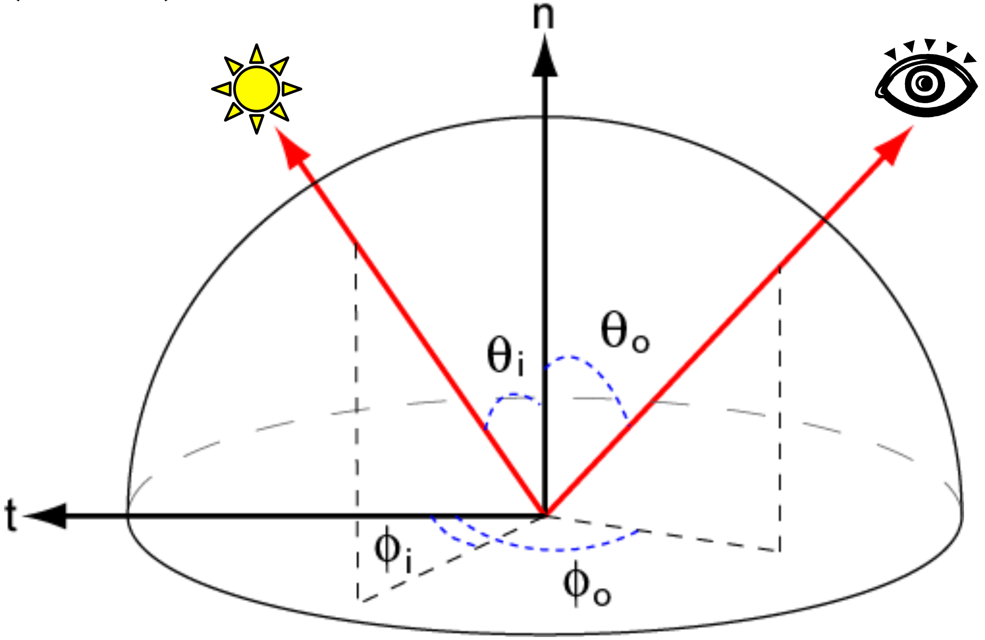


BRDF f_r

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

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

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



BRDF f_r

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

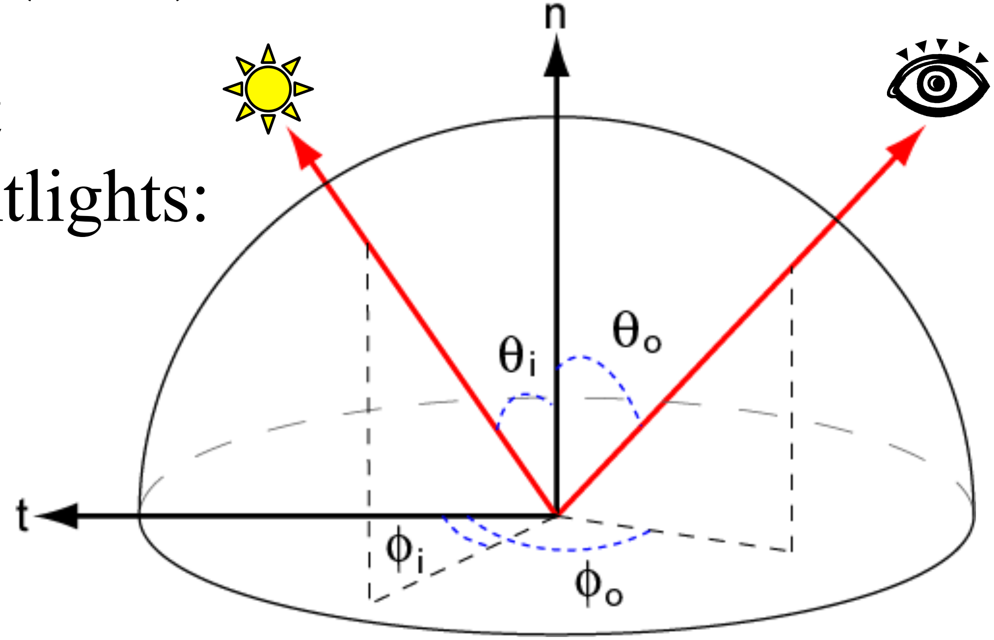
$$I_{\text{out}}(\boldsymbol{v}) = I_{\text{in}}(\boldsymbol{l})\, f_r(\boldsymbol{v}, \boldsymbol{l})$$

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

$$I_{\text{out}}(\boldsymbol{v}) =$$

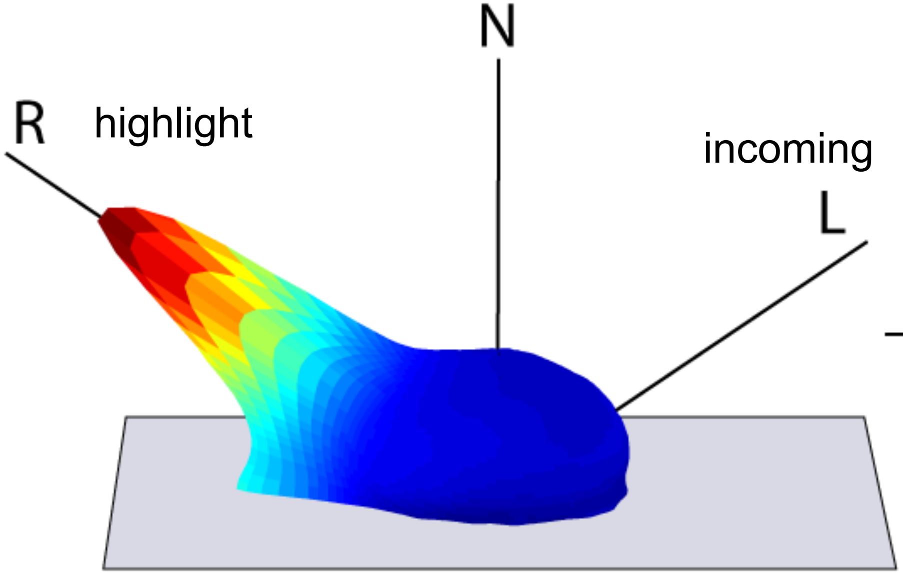
$$\frac{I_{\text{light}} \cos\theta_i}{r^2} f_r(\boldsymbol{v}, \boldsymbol{l})$$

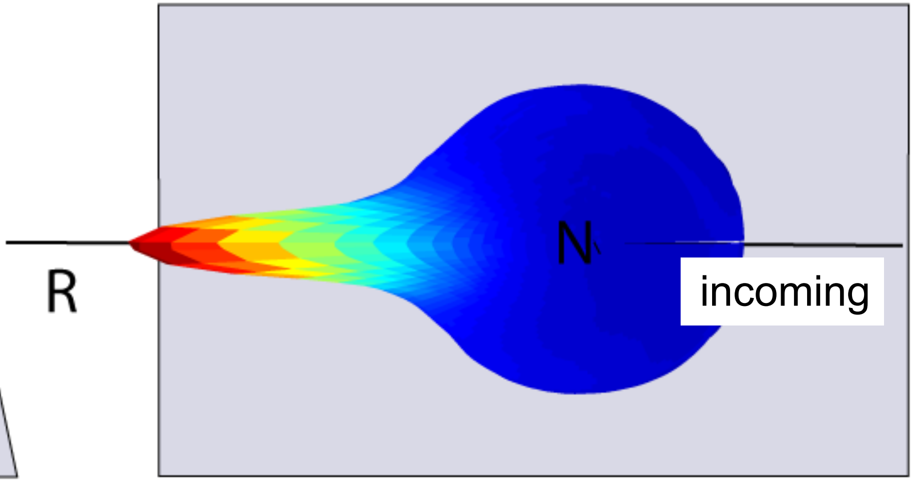
l = light direction (incoming)
v = view direction (outgoing)



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

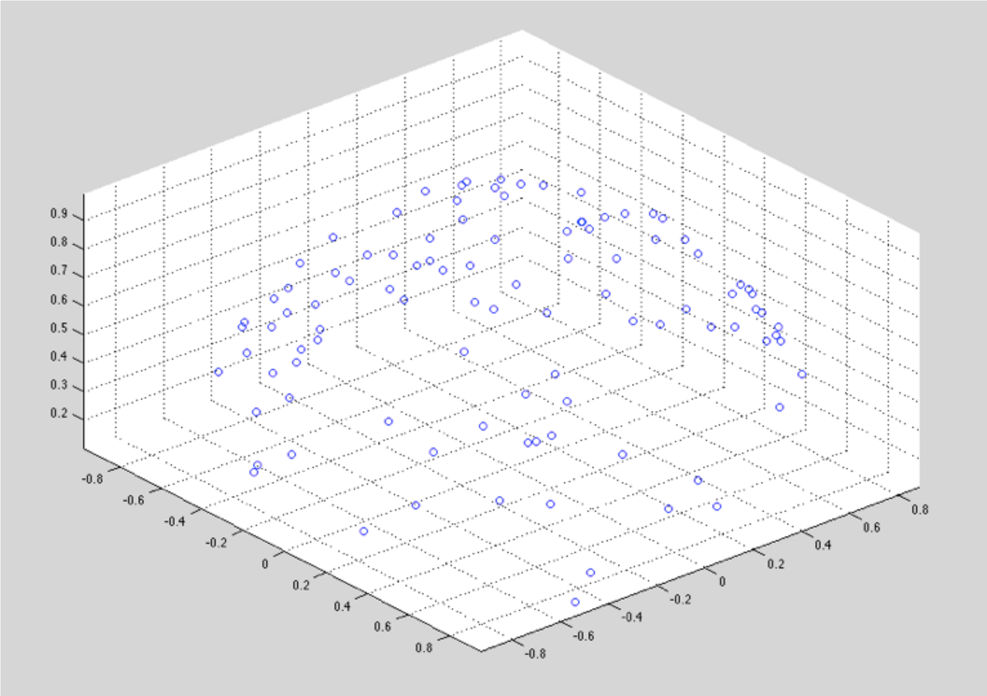
Isotropic vs. Anisotropic

- When keeping **l** and **v** fixed, if rotation of surface around the normal doesn't 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

Parametric BRDFs

- BRDFs can be measured from real data
  - But tabulated 4D data is too cumbersome for most uses
  - Why? Let’s see what happens if we use, say, 100 directions for both incident and outgoing directions (not a lot!)



Parametric BRDFs

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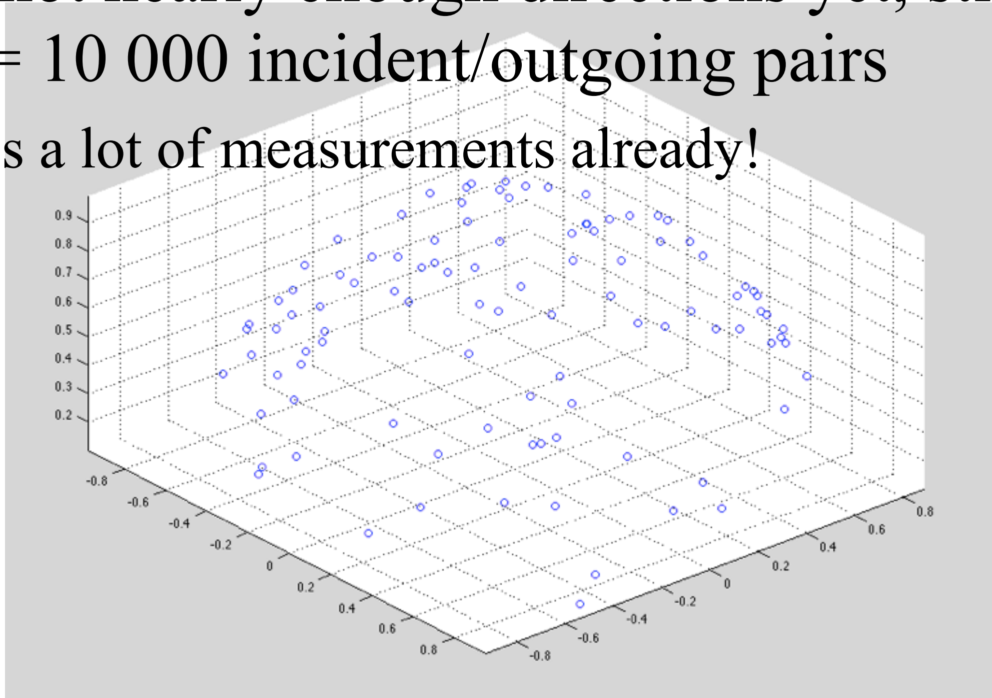
  - But tabulated 4D data is too cumbersome for most uses
  - Why? Let's see what happens if we use, say, 100 directions for both incident and outgoing directions (not a lot!)
  - This is not nearly enough directions yet, still 100^2 = 10 000 incident/outgoing pairs
    - That's a lot of measurements already!



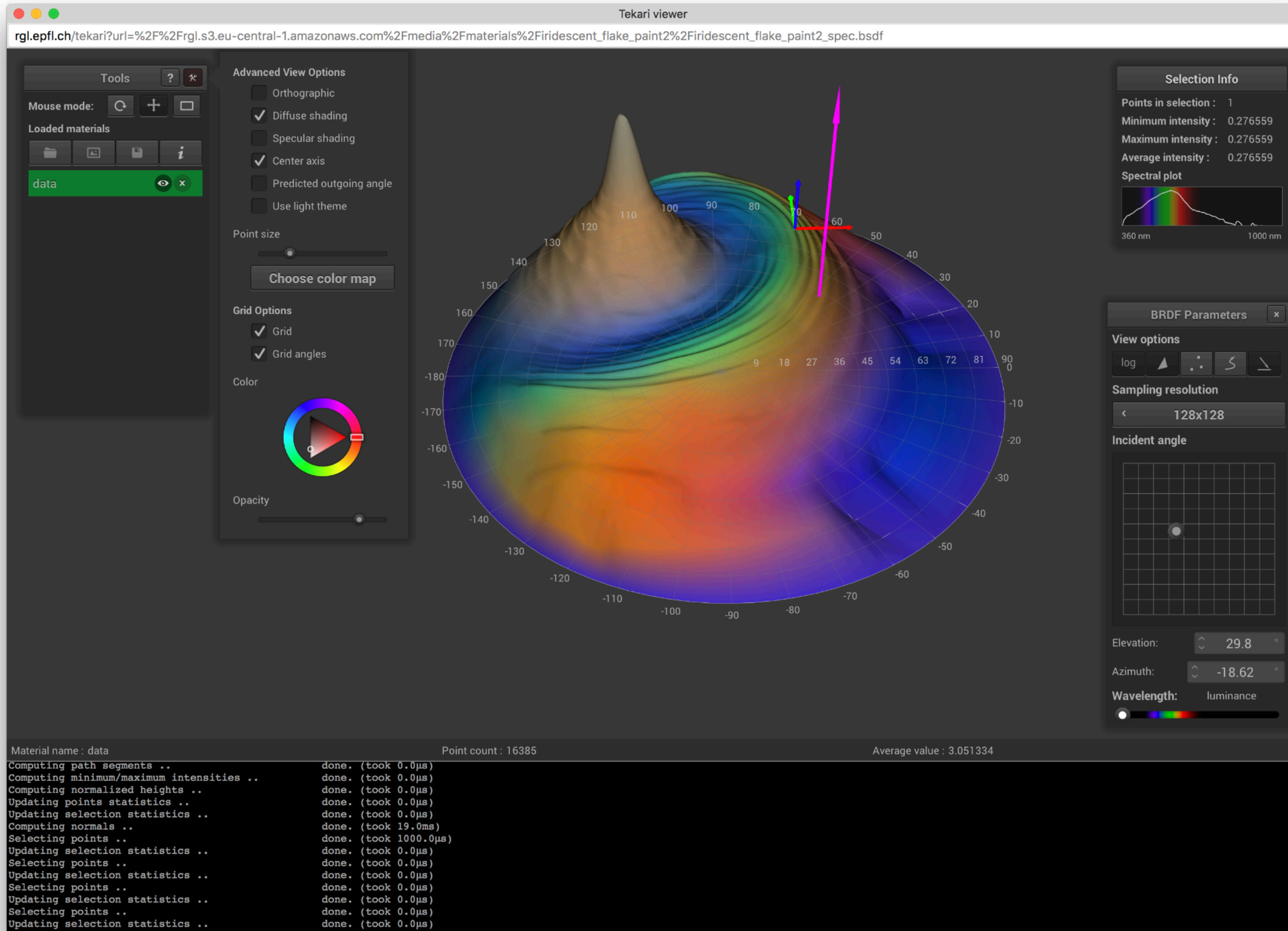
Can be done smarter (of course!)

An Adaptive Parameterization for Efficient Material Acquisition and Rendering

Jonathan Dupuy — Unity Technologies
Wenzel Jakob — EPFL

In *Transactions on Graphics (Proceedings of SIGGRAPH Asia 2018)*

See their cool visualizer!

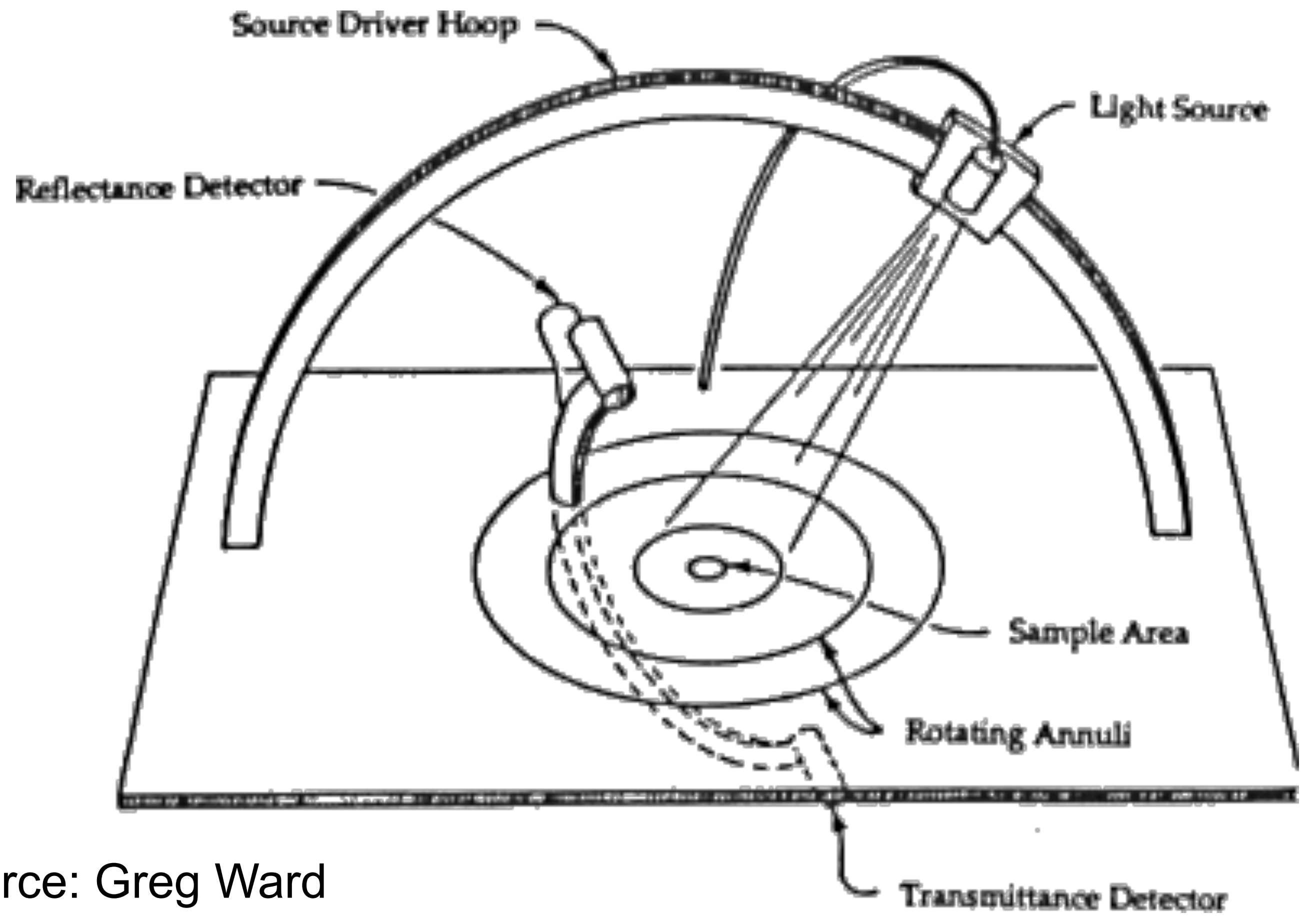


Parametric BRDFs

- 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.
  - Many ways of coming up with these
  - Can models with measured data (examples later)
- Popular models: Diffuse, Blinn-Phong, Cook-Torrance, Lafortune, Ward, Oren-Nayar, etc.

How do we obtain BRDFs?

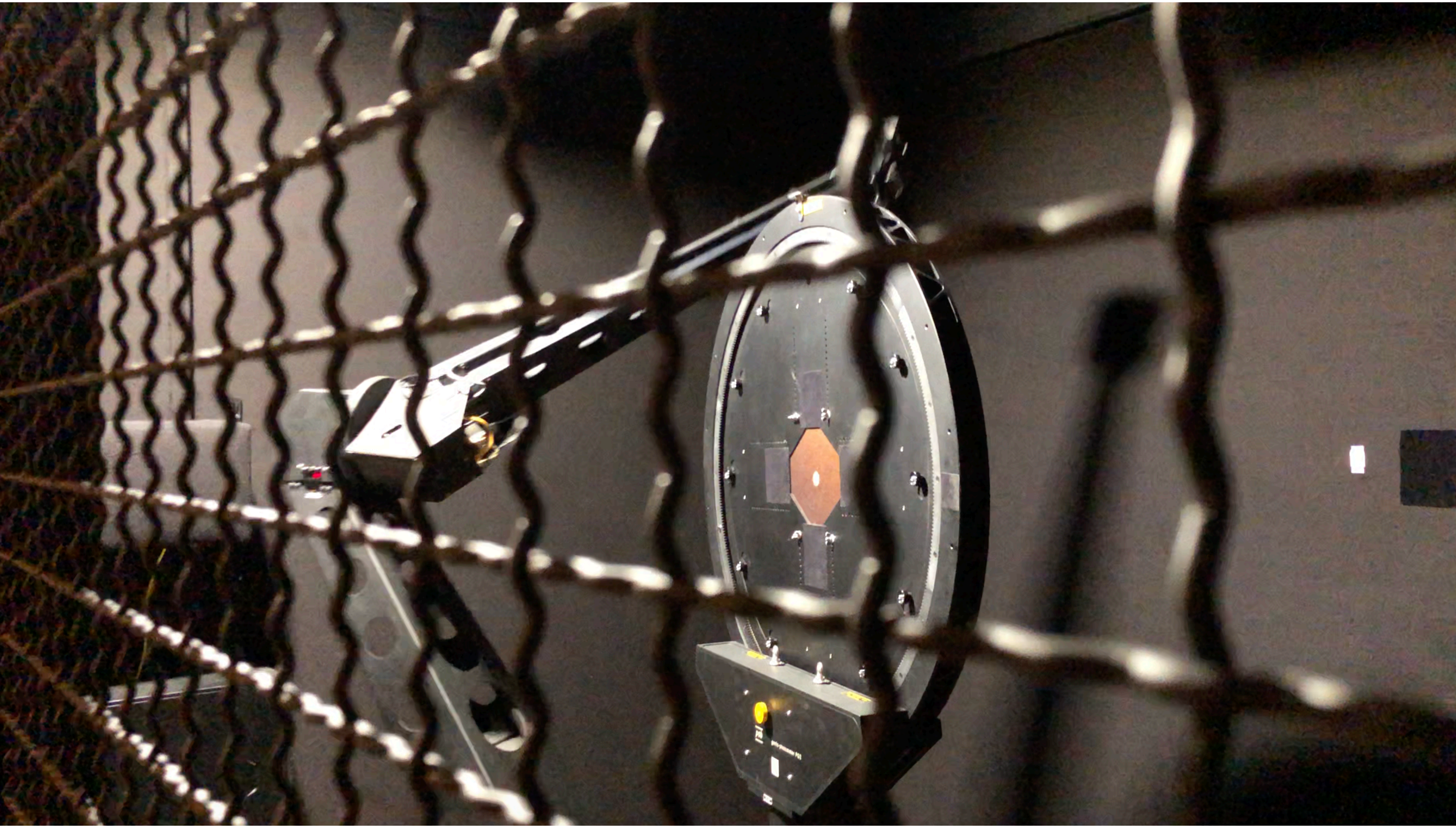
- One possibility: Gonioreflectometer
  - 4 degrees of freedom



Source: Greg Ward

Modern take (Wenzel Jakob, EPFL)

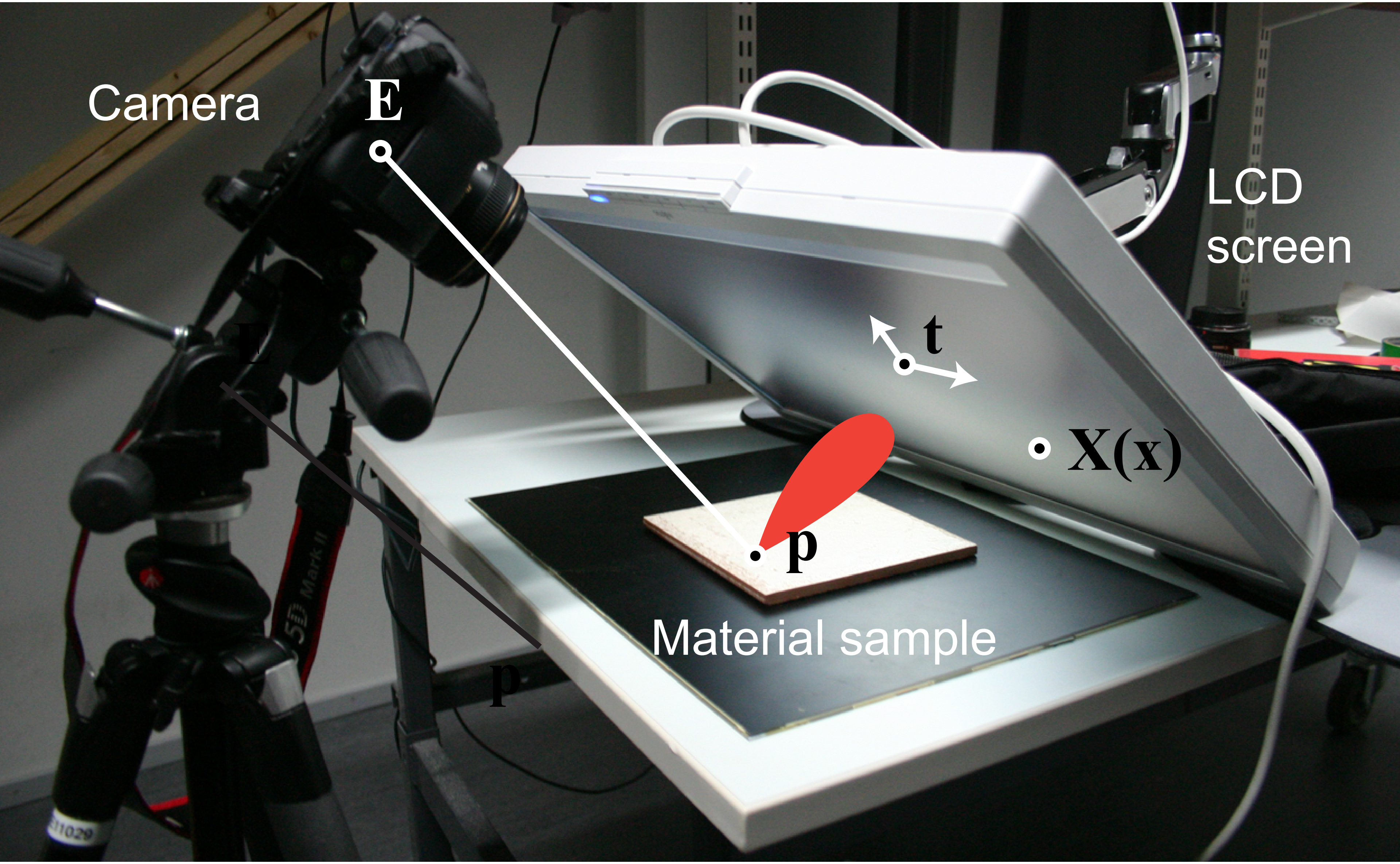
Video



How do we obtain BRDFs?

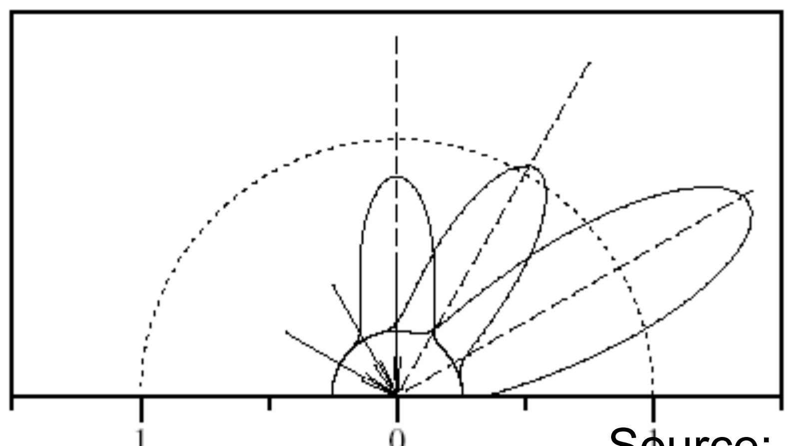
Matusik et al.

Aittala, Weyrich, Lehtinen 2013



Fresnel Reflection

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



Source: Lafortune et al. 97