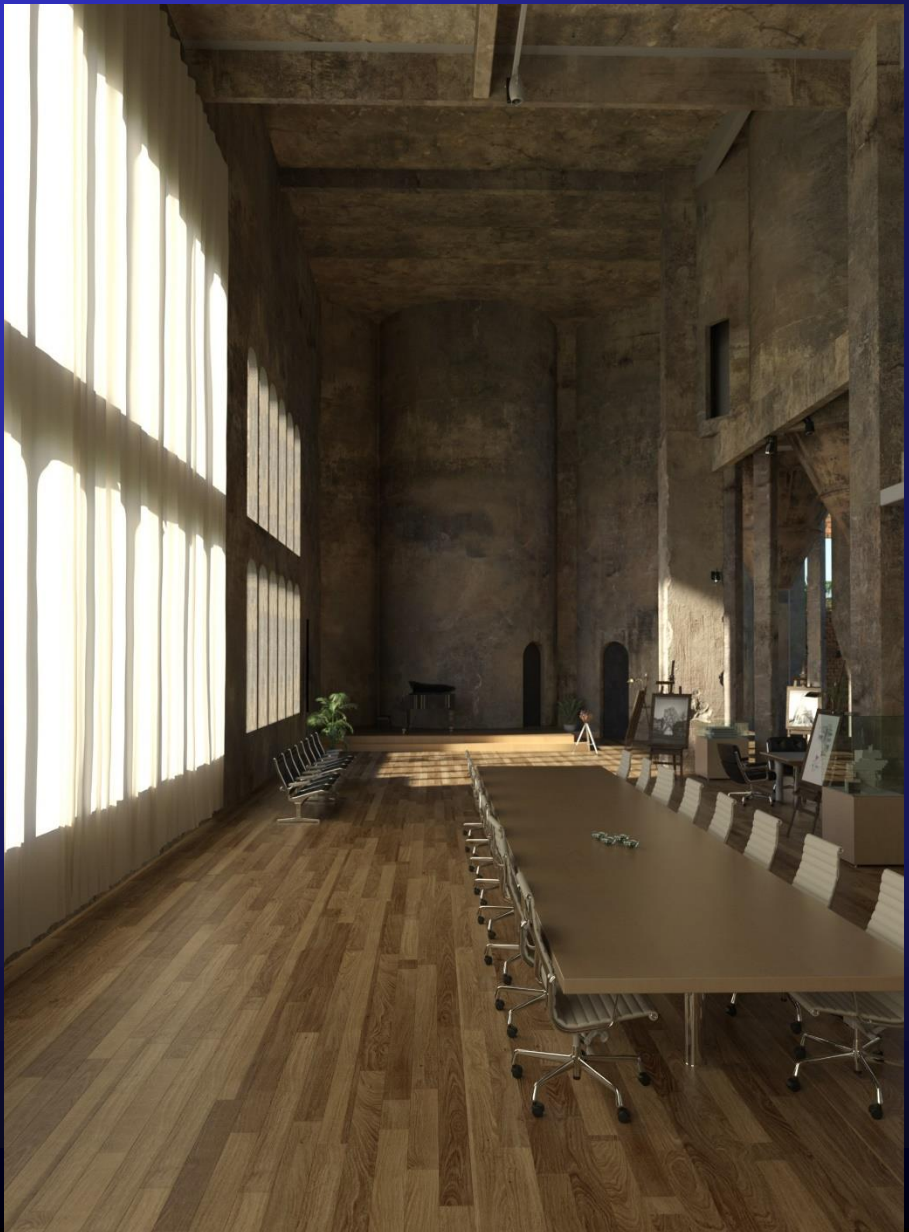
Surface and Material Properties



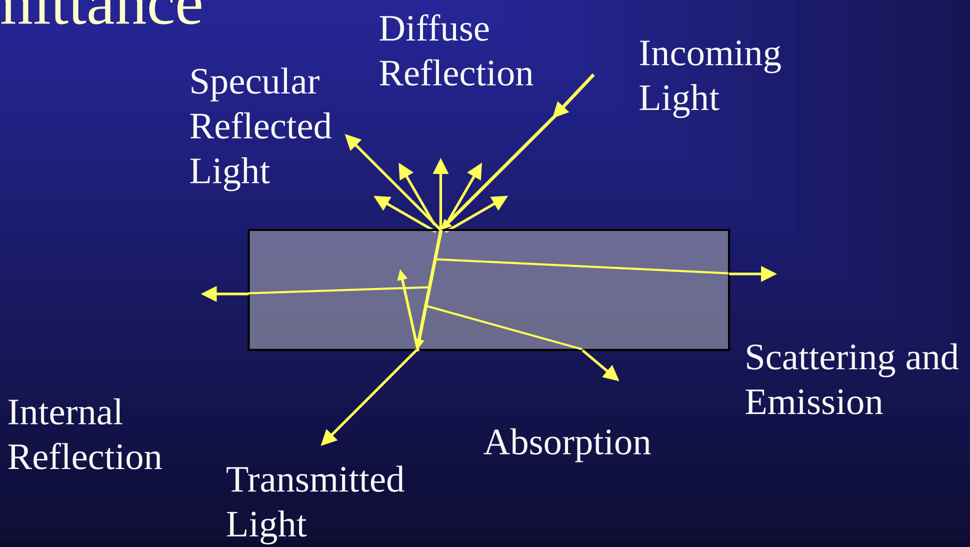
Can you tell Real from Virtual?

- “IKEA revealed that 75% of the photos in its catalog are actually CGI, meaning they've been produced not on a set with real furniture, but at a desk on a computer.” (2014)

http://www.goodhousekeeping.com/home/decorating-ideas/ikea-catalog-cgi

Light & Matter

- Interaction depends on the physical characteristics of the light and its wavelength, as well as the physical composition and characteristics of the matter:
  - Reflection
  - Absorption
  - Transmittance

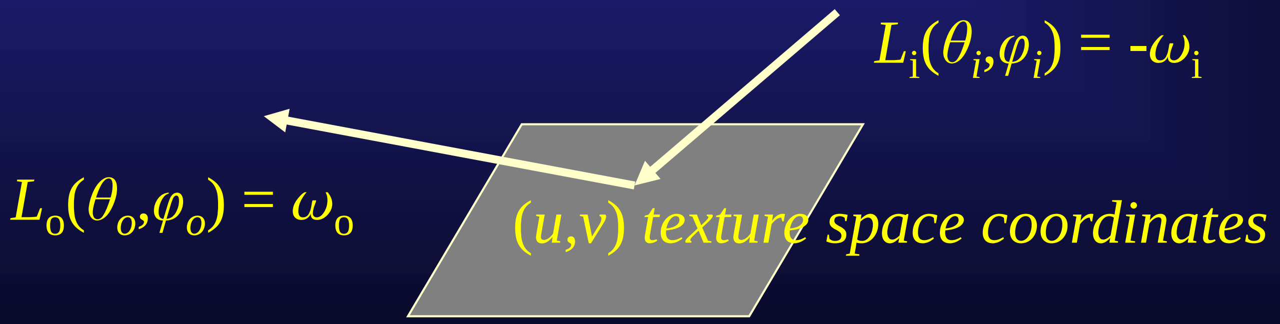


General Material Reflectance Models

- We need to know desired surface reflectance properties at *p*.
- That's what distinguishes one material from another – its BSDF:
  - Bidirectional Scattering Distribution Function
  - Bidirectional Reflectance Distribution Function

$$\mathrm{BRDF}_\lambda\left(\theta_i, \phi_i, \theta_o, \phi_o, u, v\right)$$

  - The BRDF is a function of incoming and outgoing light directions (in spherical coordinates), surface color λ (wavelength), and observed position (u,v) on the surface:

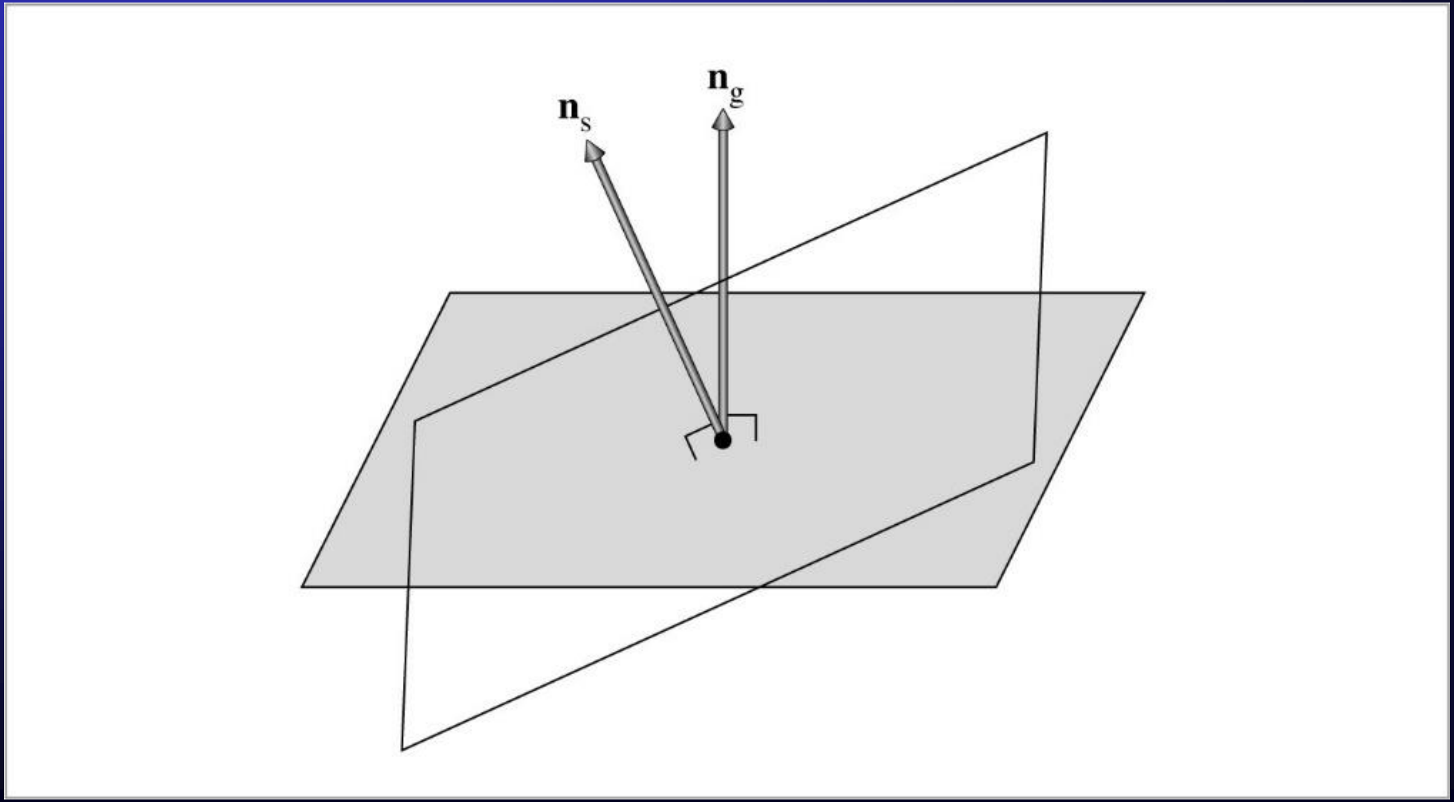


Acronyms

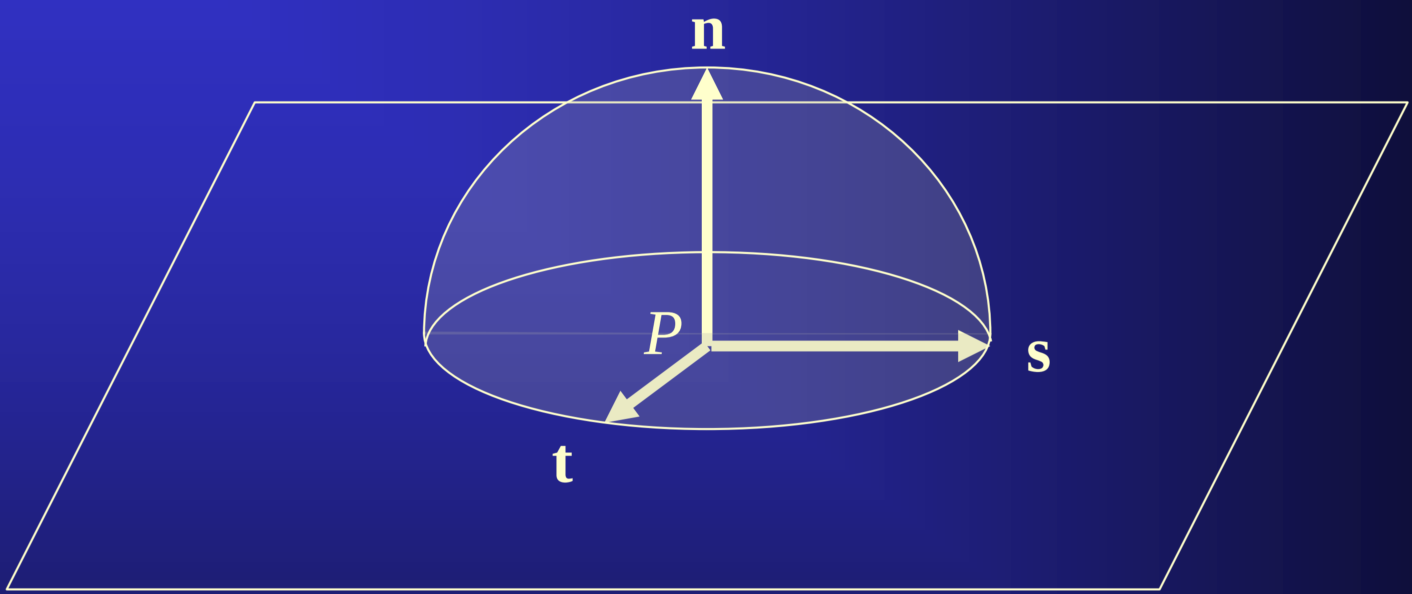
- BSDF – Bidirectional Scattering Distribution Function
- BRDF – Bidirectional Reflectance Distribution Function
- BTDF – Bidirectional Transmission Distribution Function
- BSSRDF – Bidirectional Scattering Surface Reflectance Distribution Function

Surface and Shading Normals

- Geometric normal n_g
- Shading normal (computed) n_s



Reflectance Geometry at a Surface Point Uses the Shading Coordinate System (**stn**)



- Local shading orthonormal coordinate frame **st** on surface with normal **n**.
- Tangent coordinate system:

  P=(0,0,0), **s**→(1,0,0), **t**→(0,1,0), **n**→(0,0,1)
- Unit hemisphere, so all unit length vectors.
- This makes it compatible with **uv** texturing functions.

Converting World Coordinates to Shading Coordinates

$$\mathbf{M} = \begin{bmatrix} \mathbf{s}_x & \mathbf{s}_y & \mathbf{s}_z \\ \mathbf{t}_x & \mathbf{t}_y & \mathbf{t}_z \\ \mathbf{n}_x & \mathbf{n}_y & \mathbf{n}_z \end{bmatrix} = \begin{bmatrix} \mathbf{s} \\ \mathbf{t} \\ \mathbf{n} \end{bmatrix}$$

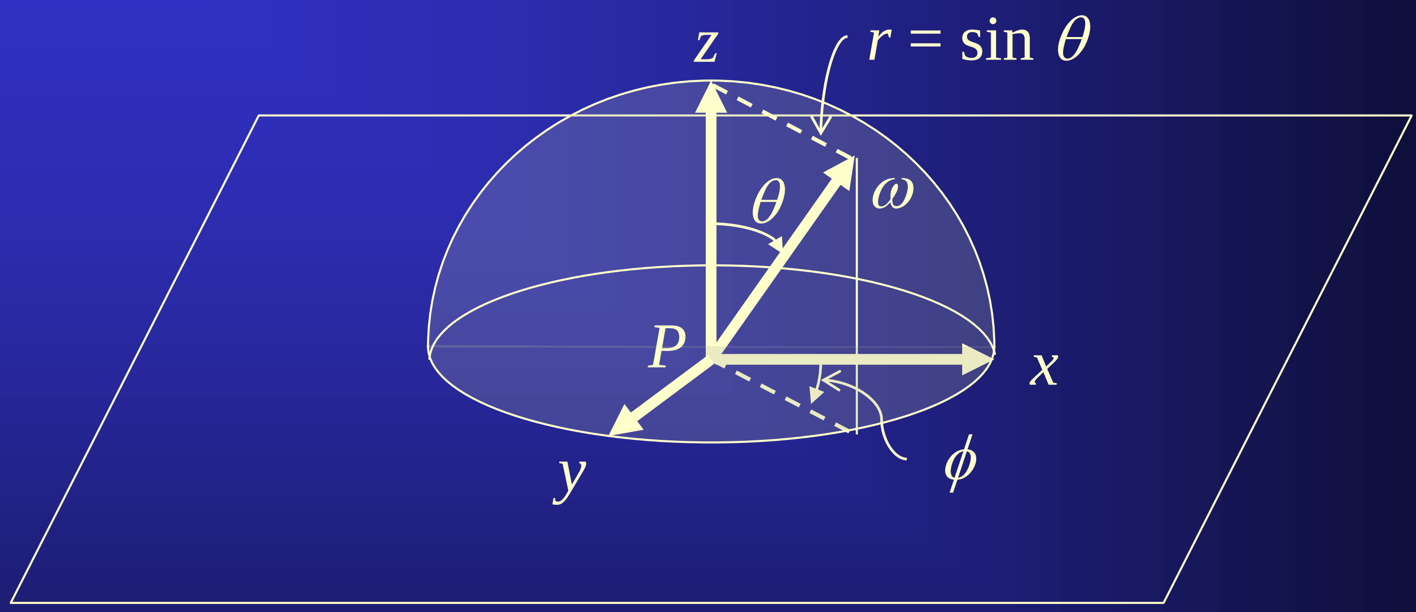
Check:

$$\mathbf{M}\mathbf{n}_{\mathrm{g}} = \left(\mathbf{s}\cdot\mathbf{n}_{\mathrm{g}}, \mathbf{t}\cdot\mathbf{n}_{\mathrm{g}}, \mathbf{n}\cdot\mathbf{n}_{\mathrm{g}}\right) = (0,0,1)$$

Since ***s***, ***t***, and ***n*** are orthonormal unit length vectors and $\mathbf{n} = \mathbf{n}_{\mathrm{g}}$.

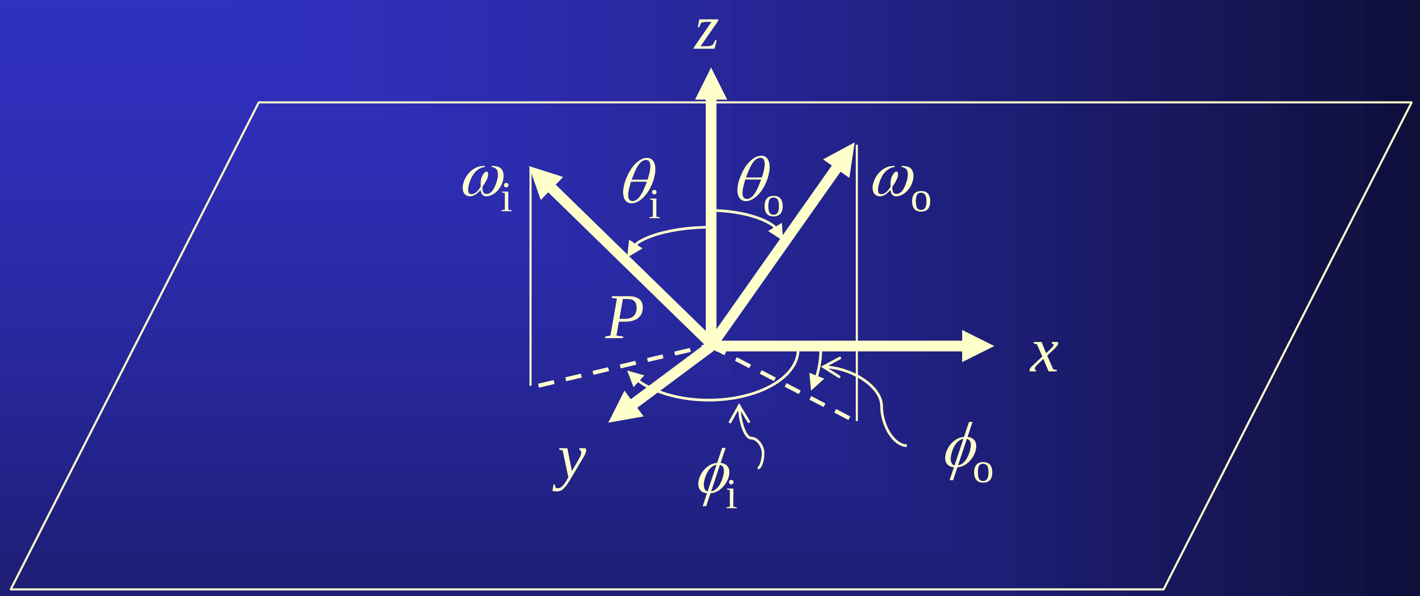
We will often write this shading coordinate system as **x**, **y**, **z** where the transformation is understood.

Converting Between Spherical Directions and 3D Coordinates



- Without loss of generality, we'll just identify $x \leftarrow \mathbf{u}$, $v \leftarrow \mathbf{v}$, $z \leftarrow \mathbf{n}$
- ω is a direction, normalized.
- $\cos\theta = (\mathbf{n} \cdot \omega) = ((0,0,1) \cdot \omega) = \omega_z$
- $\sin\theta = \text{sqrt}\ (1 - \cos^2\theta)$
- $(\omega_x, \omega_y) = (\text{r} \cos\phi, \text{r} \sin\phi)$; but $r = \sin\theta$, so
- $\cos\phi = \omega_x / r = \omega_x / \sin\theta$ and $\sin\phi = \omega_y / r = \omega_y / \sin\theta$

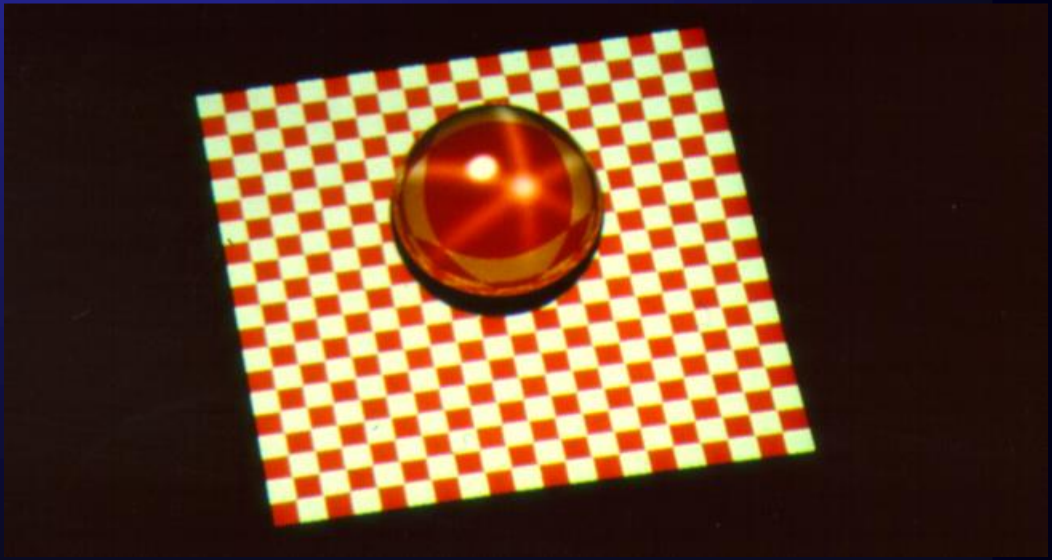
Reflectance Geometry at a Surface Point: Incoming (i) and Outgoing (o) Directions



- Incident ω_i and outgoing ω_o light direction, normalized.
- When ϕ matters, surface reflectance is *anisotropic*.

Classes of BRDFs

- There are two classes of BRDFs:
  - Isotropic BRDFs represent reflectance properties that are invariant with respect to rotation of the surface around the surface normal vector, e.g., smooth plastics.
  - Anisotropic BRDFs exhibit change with respect to rotation of the surface around the surface normal vector: e.g., most real world surfaces.



Properties of BRDFs

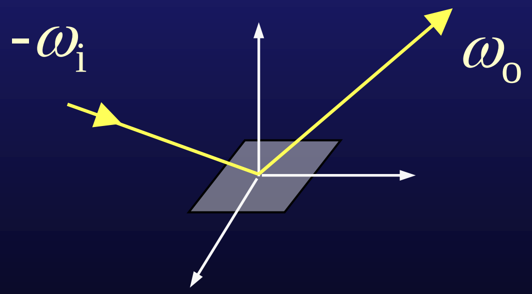
- The important properties of BRDFs are *conservation of energy* and *reciprocity* .
- BRDFs that have these properties are considered to be physically plausible.

Conservation of Energy

light incident at surface =

light reflected + light absorbed + light transmitted

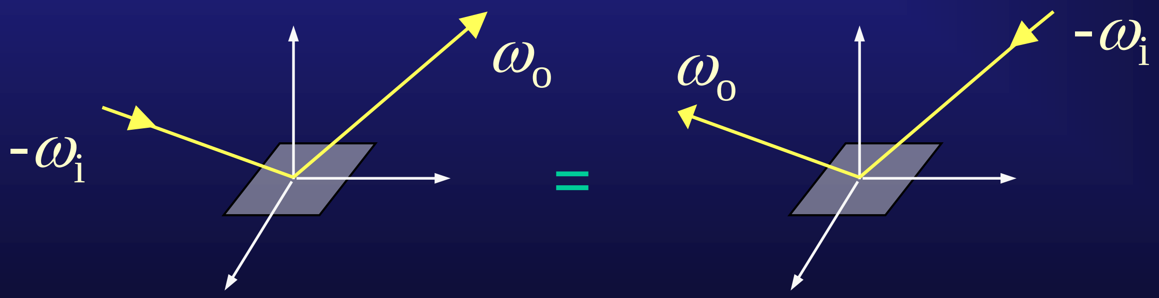
- A BRDF describes how much light is *reflected* when light makes contact with a certain material.
- The other components are modeled by the BSSDF and BTDF terms.



Reciprocity

- If the incoming and outgoing directions are swapped at the same surface point *p*, the value of the BRDF does not change.

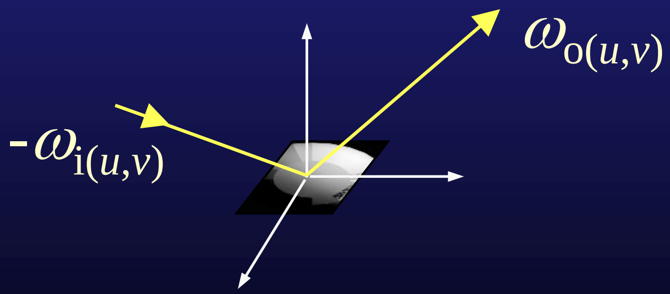
$$\mathrm{BRDF}_\lambda(\theta_i,\phi_i,\theta_o,\phi_o)=\mathrm{BRDF}_\lambda(\theta_o,\phi_o,\theta_i,\phi_i)$$

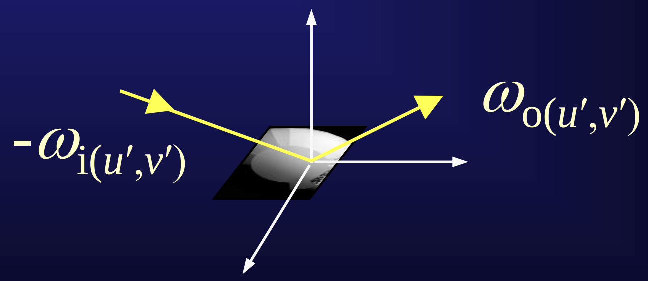


Positional Variance

$$\mathrm{BRDF}_{\lambda}(\theta_i, \phi_i, \theta_o, \phi_o, u, v)$$

- When light interacts differently with different regions of the surface (i. e., varies over *u* and *v*), it is called positional variance.
- Common when using textures.
- Occurs in materials that reflect light with notable surface detail (wood, marble, etc.).



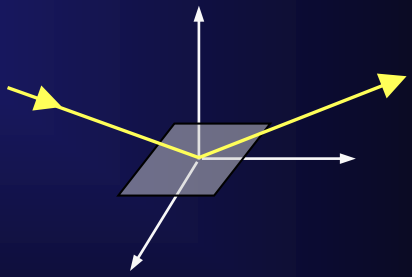


Position-Invariant BRDFs

$$\mathrm{BRDF}_\lambda(\theta_i, \phi_i, \theta_o, \phi_o)$$

- Only valid for homogenous materials: when (*u*,*v*) is not included as a parameter to the function the reflectance properties of the material do not vary with spatial position.
- An isotropic position-invariant BRDF is just three-dimensional:

$$\mathrm{BRDF}_\lambda(\theta_i, \phi_i, \theta_o)$$



- since ϕ_o is just $\phi_i + \pi$

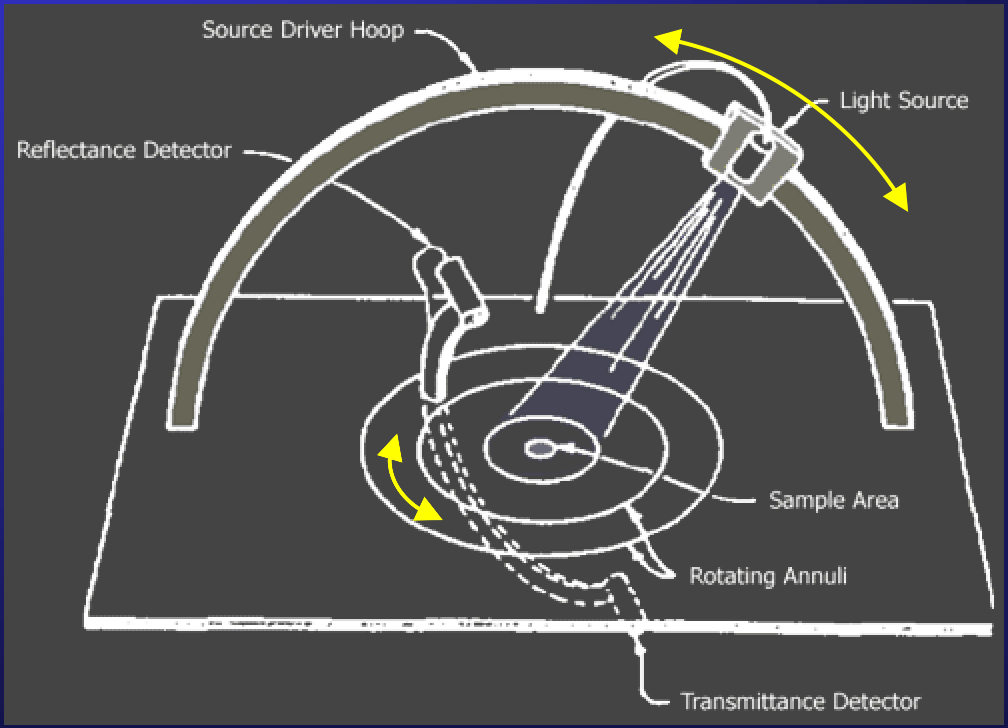
For incoming direction ω_i, outgoing ω_o is just ω_i scaled by (-1,-1,1).

Data-Driven (Empirical, Measured) BRDFs of Real Materials

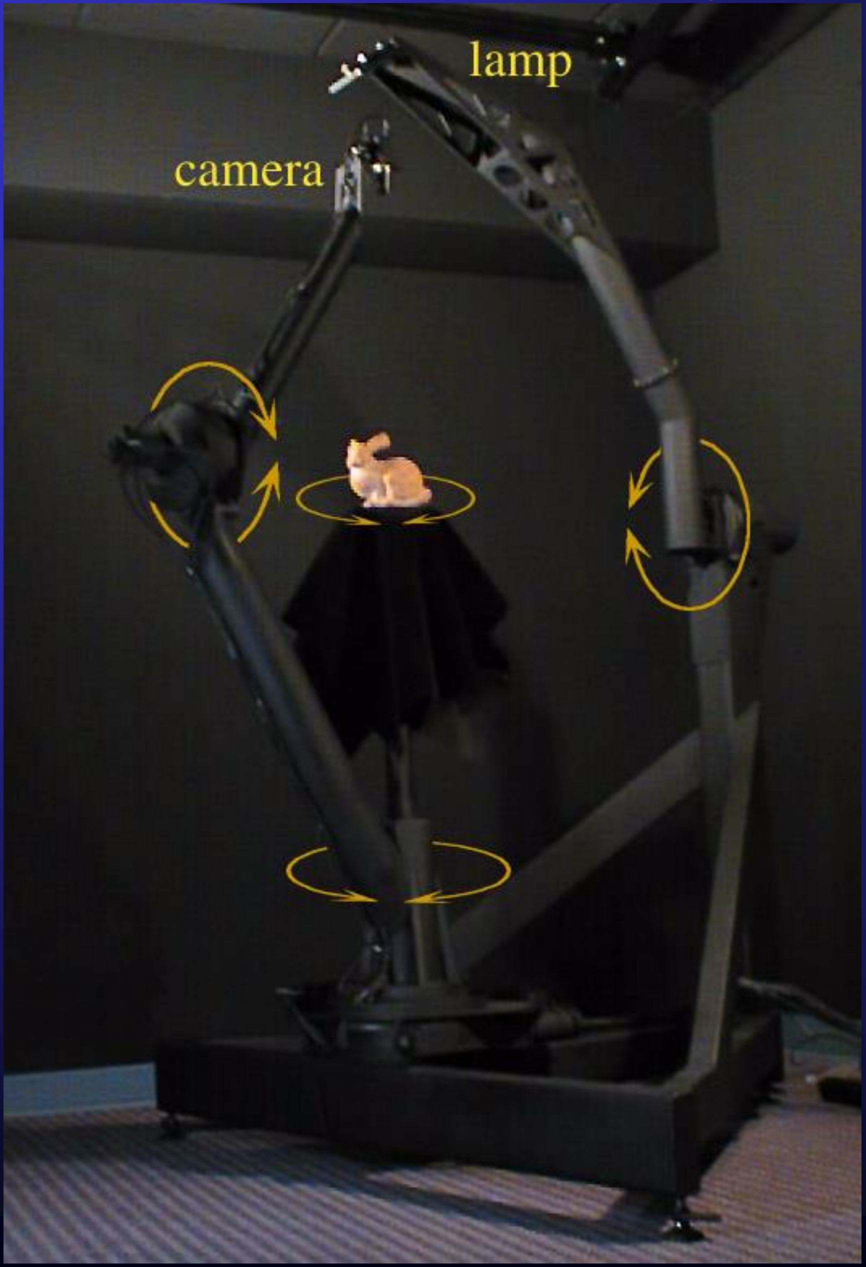
- Dense BRDF measurements on surfaces of 100 different isotropic materials.
- 20M-80M samples/BRDF.
- PCA dimensionality reduction into both linear and nonlinear model spaces.
- Data: http://people.csail.mit.edu/addy/research/ngan05_brdf_supplemental_doc.pdf

Matusik, Pfister, Brand, and McMillan. SIGGRAPH 2002

Greg Ward's Reflectance and Transmittance Gonioreflectometer Apparatus



The Stanford Gantry



Matusik, Pfister, Brand, and McMillan

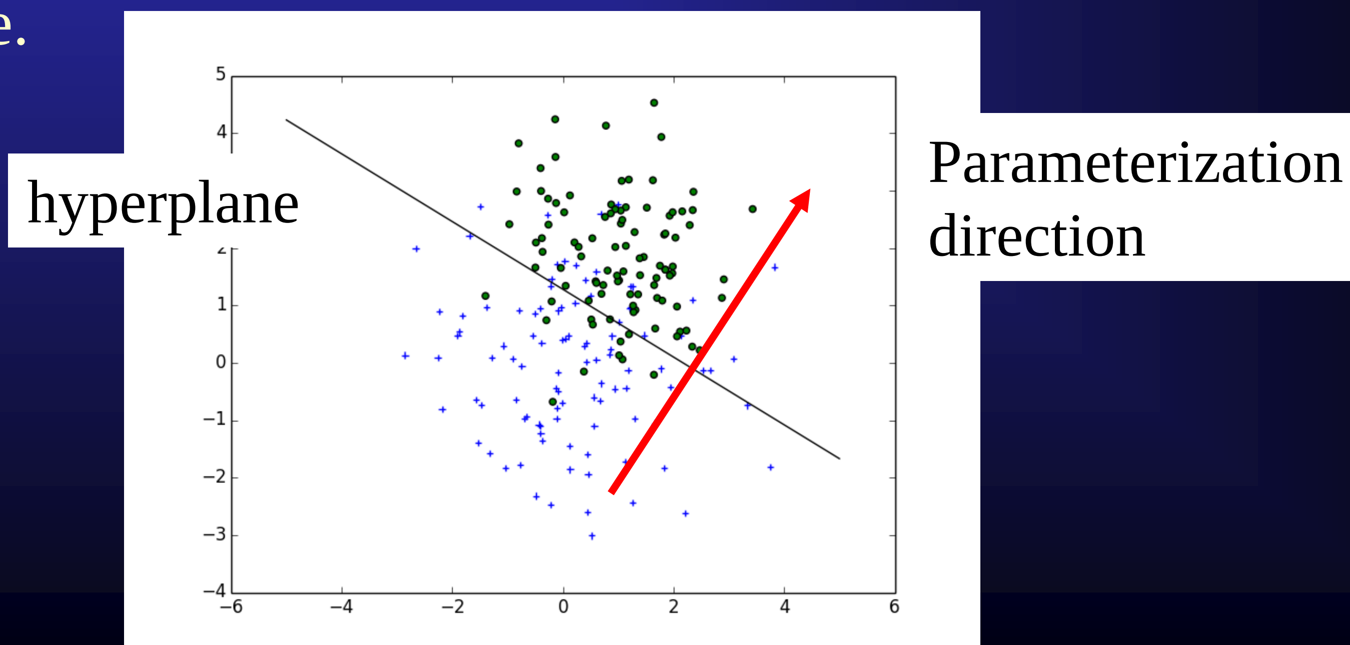
- Simplified gantry for isotropic spherical object BRDF measurement.
- Only need 1 degree of freedom: the light rotates around the sample.

User Navigation in BRDF Space

- Subjects assigned (arbitrary) *traits* to each material:
  - redness, greenness, blueness, specularness, diffuseness, glossiness, metallic-like, plastic-like, roughness, silverness, gold-like, fabric-like, acrylic-like, greasiness, dustiness, rubber-like.
  - With values *possesses*, *not-possesses* or *unclear*.
- Project trait vectors into both linear (45D) and nonlinear (15D) BRDF model spaces.

Parameterizing the Model Spaces

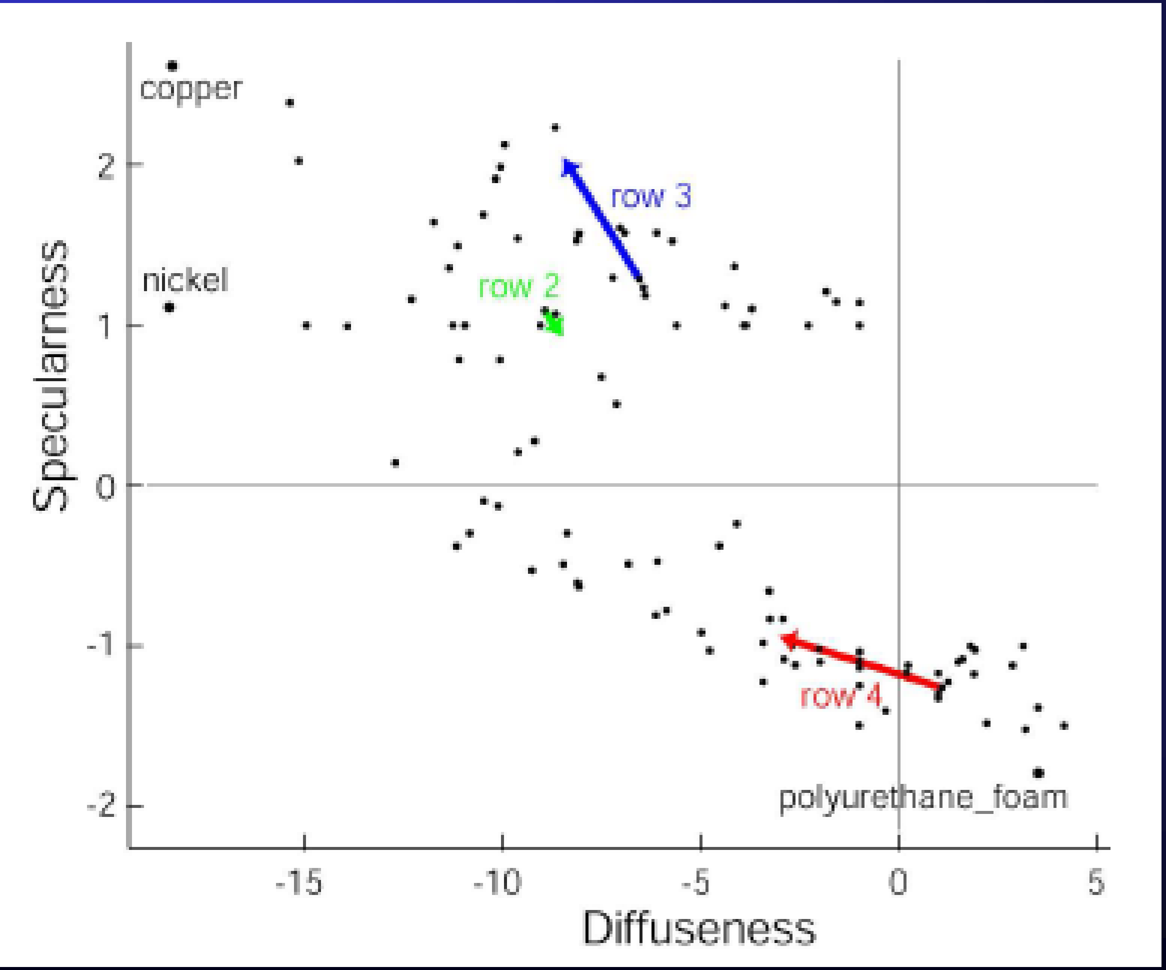
- Used Support Vector Machine(SVM) [Vapnik 1995].
- SVM finds the hyperplane which separates datapoints in one material class from datapoints in a second class.
- The partitioning hyperplane has maximal distance to the closest datapoints (called support vectors) in both material classes.
- The parameterization direction is the (directed) normal to this hyperplane.



Diffuseness *vs*. Specularness

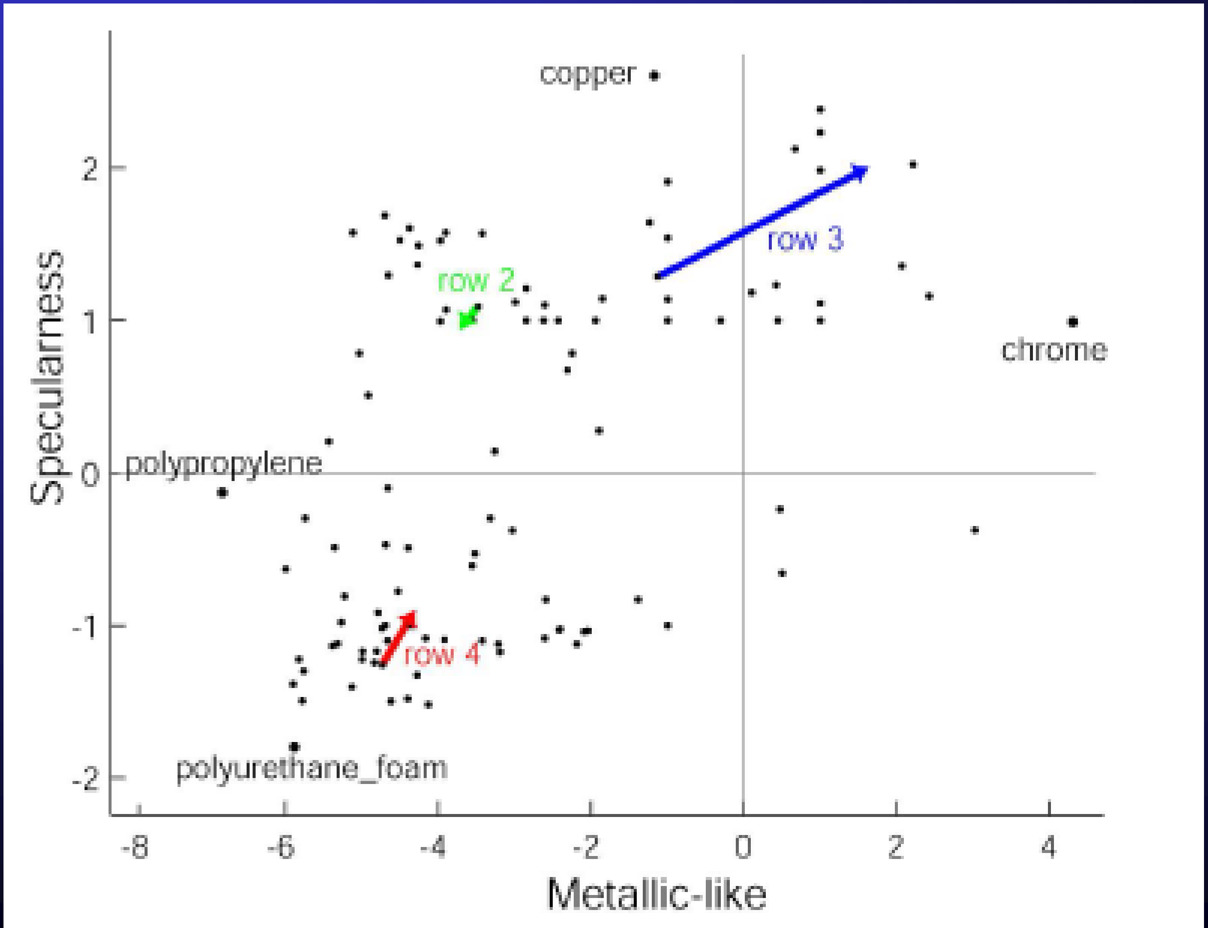
(Red, Green, and Blue vectors represent examples to follow)

Show weak inverse correlation.



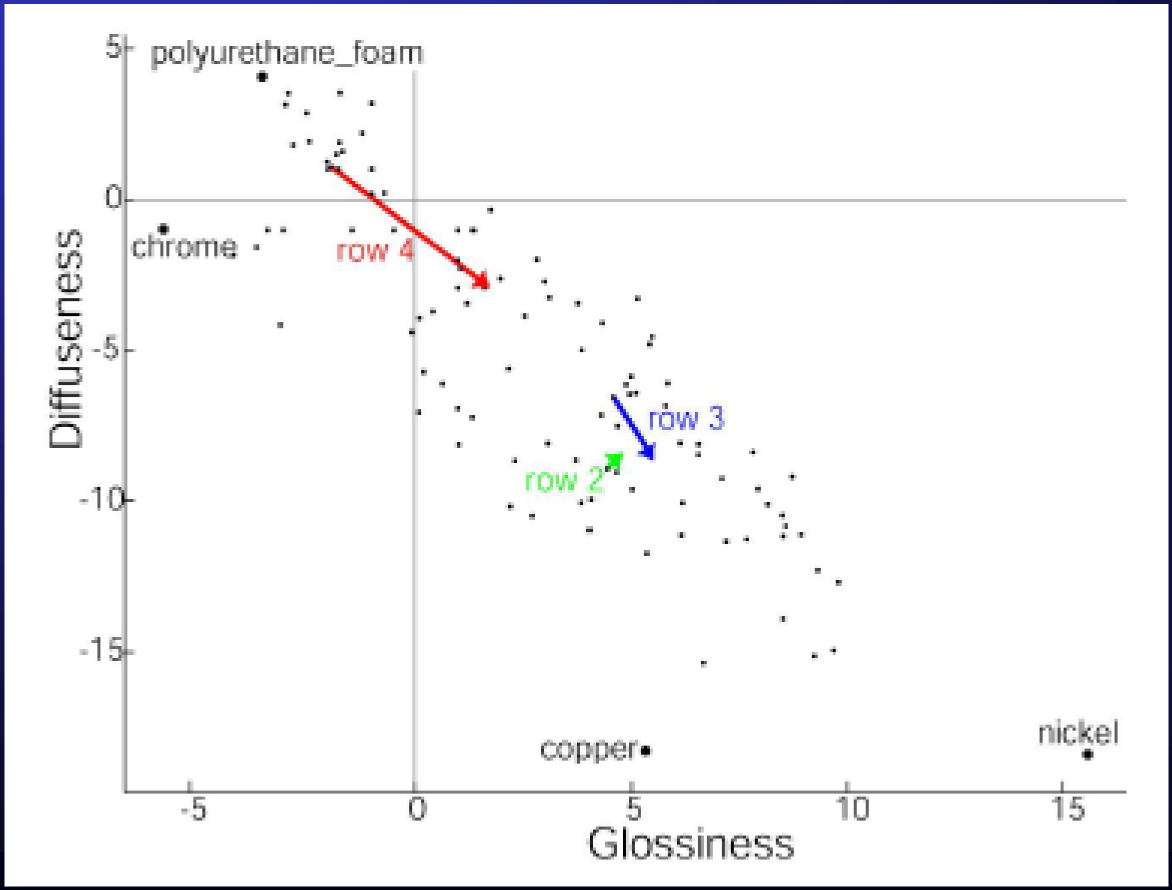
Metallic-like *vs*. Specularness

Show weak correlation.



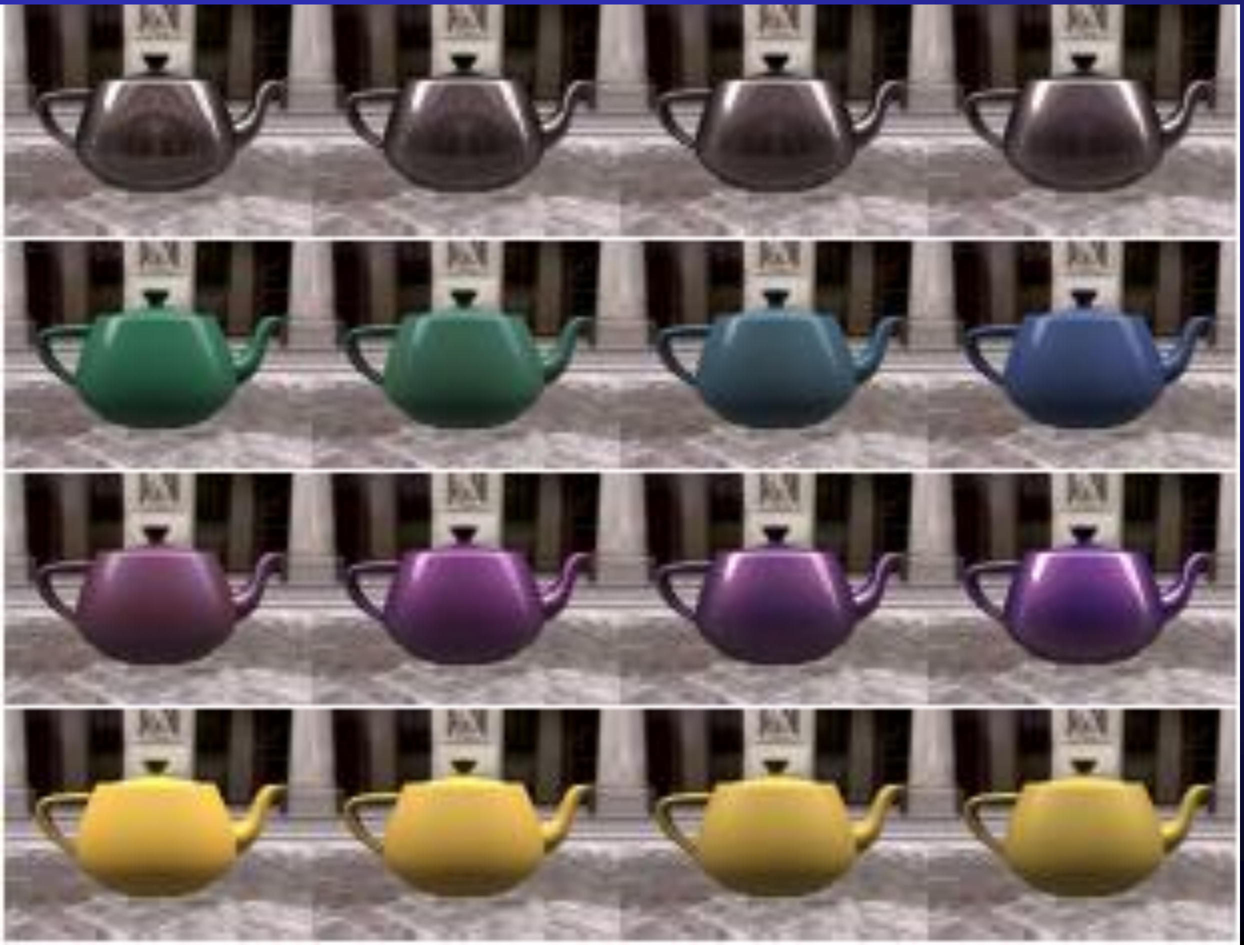
Glossiness *vs.* Diffuseness

Show inverse correlation.



Results of Moving Along Vectors in Illustrated Subspaces

- The red, green and blue vectors in the previous charts show the projections of the BRDF interpolations along single parameters in the non-linear model in rows 2, 3, and 4 in the image below.



Increase *roughness* applied to *Copper* BRDF.

Increase *blueness* applied to the *GreenAcrylic* BRDF.

Apply metallic trait to VioletAcrylic BRDF.

Increase *glossiness* trait to *YellowDiffusePaint* BRDF.

Materials: Based on the NVIDIA Material Definition Language Handbook (mdlhandbook.com)

- Light is reflected, transmitted, or emitted.
- Absorption handled as volumetric effects.

BSDF Combinations and Examples

	Reflection	**Transmission**	**Emission**
Diffuse	plaster; ping-pong ball	frosted plexiglas	red-hot metal
Glossy	brushed aluminum	shower door glass	spotlight; flshlight
Specular	mirror	crystal ball	laser beam

MDL View of a Material

- Material
  - Surface properties of front-facing surfaces
    - Reflection
    - Transmission
    - Emission
  - Surface properties of back-facing surfaces
    - Reflection
    - Transmission
    - Emission
  - Volume properties
  - Geometric properties
  - Shared properties
    - Index of refraction
    - Surface treated as a boundary or a volume

MDL Semantics

- **thin-walled**: distinguishes between boundaries and two-sided objects
- **surface**: defines interactions of light and surface
- **backface**: defines interactions of light with the “back” of a surface
- **ior**: defines the index of refraction for refracting objects
- **volume**: defines the interation of light in a volume
- **geometry**: defines render-time geometric modifications (e. g., displacement maps, cut-outs)

Layered Materials

Jakob, D'Eon, Marschner; Cornell; SIGGRAPH 2014

Subsurface Scattering

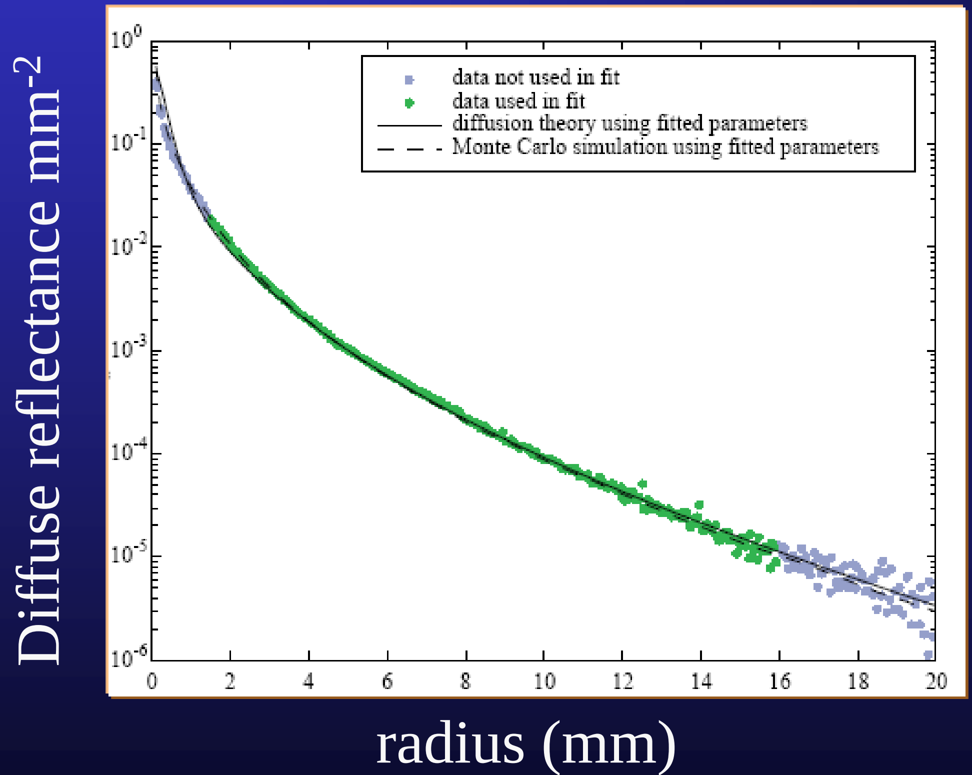
- Marble, skin, milk other materials reflect light after it bounces around material internal to the surface: subsurface scattering.
- Measure scattering empirically from real substance (BSSRDF).

Surface BRDF reflection only Subsurface scattering

Jensen, Marshner Levoy & Hanrahan

Example Empirical Measurements

- From light probe; green wavelength for marble (Jensen *et al.*).
- Fit by exponential, e.g.



Fast Subsurface Scattering Rendering

- Approximate rapid fall-off empirical function with a spike plus a Gaussian blur: $1/(c+\text{radius})^{\text{power}}$

  (where c avoids divide by zero and power ≈ 2).

- Use for diffuse shading only.
- For faces, fall-off is slower in the red channel (subsurface scattering due to blood).

Subsurface Scattering Examples

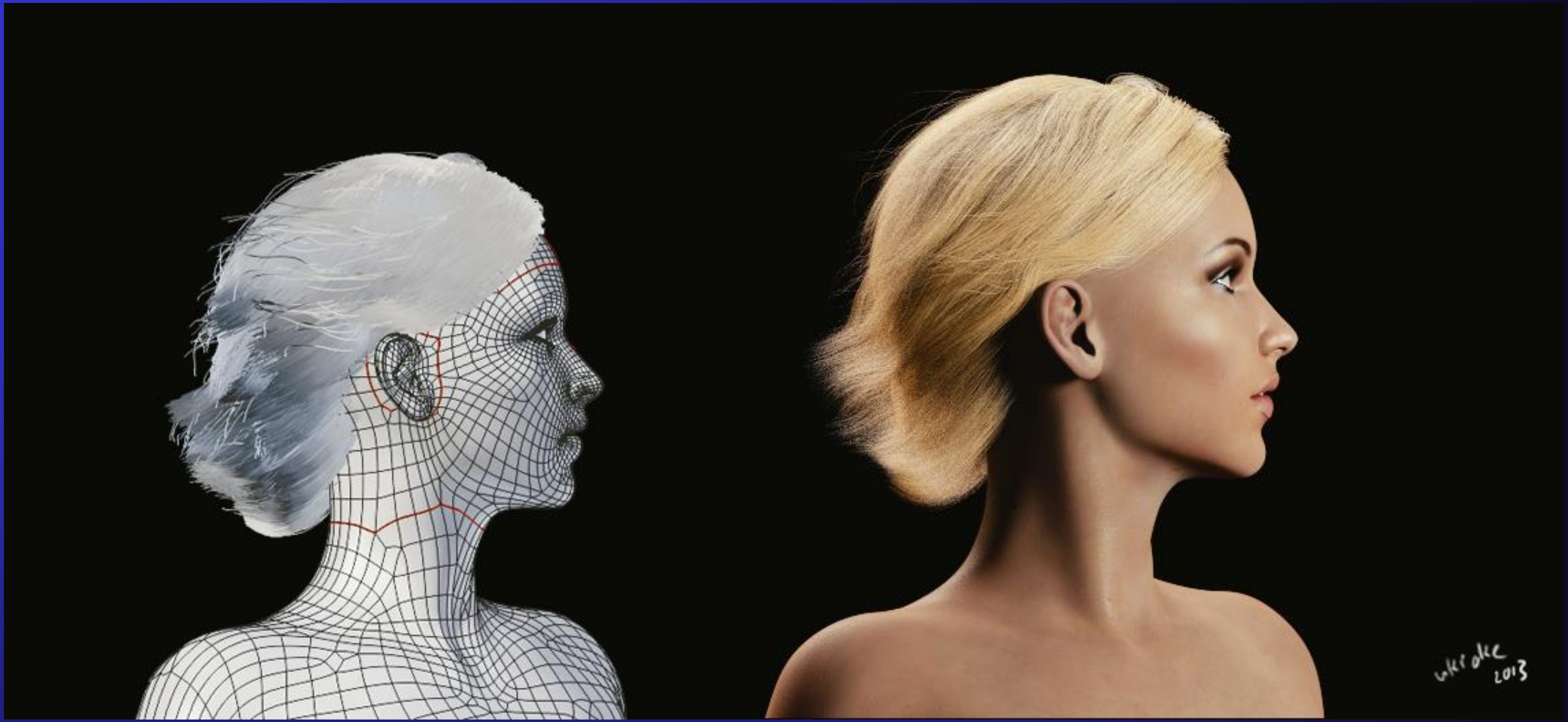
Skin

Skim milk vs. whole milk
(looks like white paint)

Ponytail

Hair close-up

BSSDF for Hair



blenderartists.org

cgcookie.com

Glassy Materials

http://www.3dartistonline.com/news/2014/09/render-glass-objects-in-3ds-max/

BSSDF Used in the Movies

Matrix Reloaded (digital doubles) and also *Lord of the Rings* (Gollum).

Real vs. CG

Capturing BRDFs *in situ*

- Zányi, Schroer, Mudge, Chalmers: “Lighting and Byzantine Glass Tesserae”
- Gold, silver, and glass mosaic pieces.
- Reflectance properties measured photographically from multiple light and camera positions.
- Stored a 6D polynomial “texture”.
- Mosaic appearance under different lighting directions:

Cloth Appearance and Simulation

https://3dnews.files.wordpress.com/2008/09/clothfx.jpg

Brittany Binler

Textiles: Geometry and Reflectance Both Needed

http://www.cs.cornell.edu/~arbree/images/scarf.png

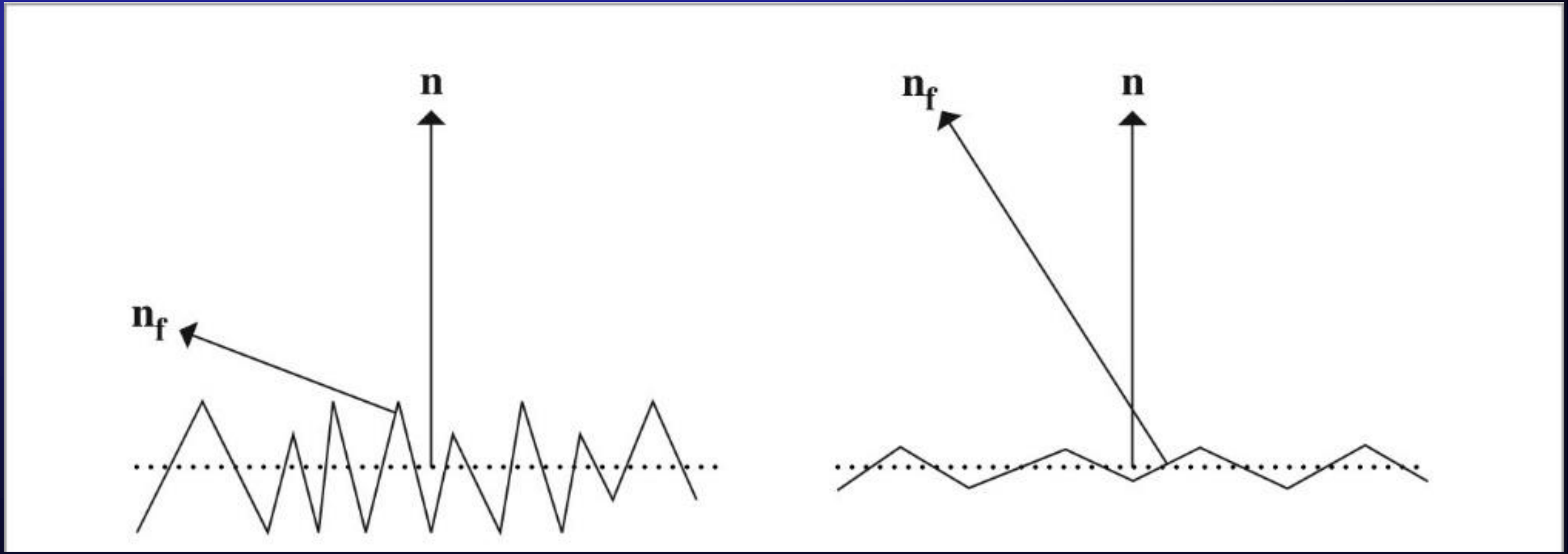
Microfacets: Statistical Model of Surface Reflectance Properties Without Using "Tiny Polygons"

- How would you create a 3D model of a very rough yet reflective surface, e.g., sandpaper?
- Surface is a statistical collection of randomly-oriented "microfacets"; these microfacets are not explicitly modeled as polygons, but act like miniature surfaces with their own reflectance properties (e. g., mirror or diffuse).

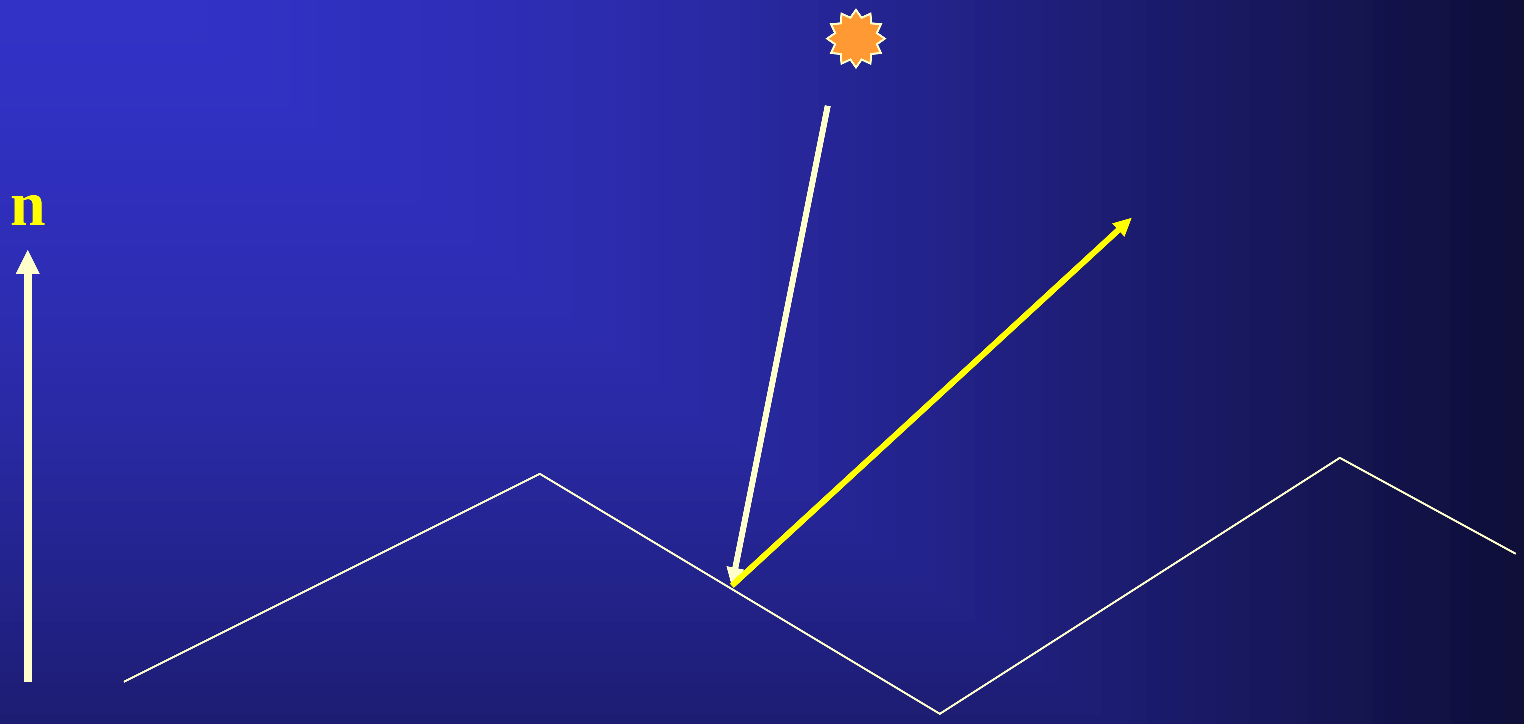
Microfacet Paradigm

- Microfacets trade actual geometry for a statistical description!
- Describe the distribution of microfacet normal $\mathbf{n}_f$ relative to the geometric normal $\mathbf{n}$.
- Roughness represented by more variance.

Rough surface Smoother surface



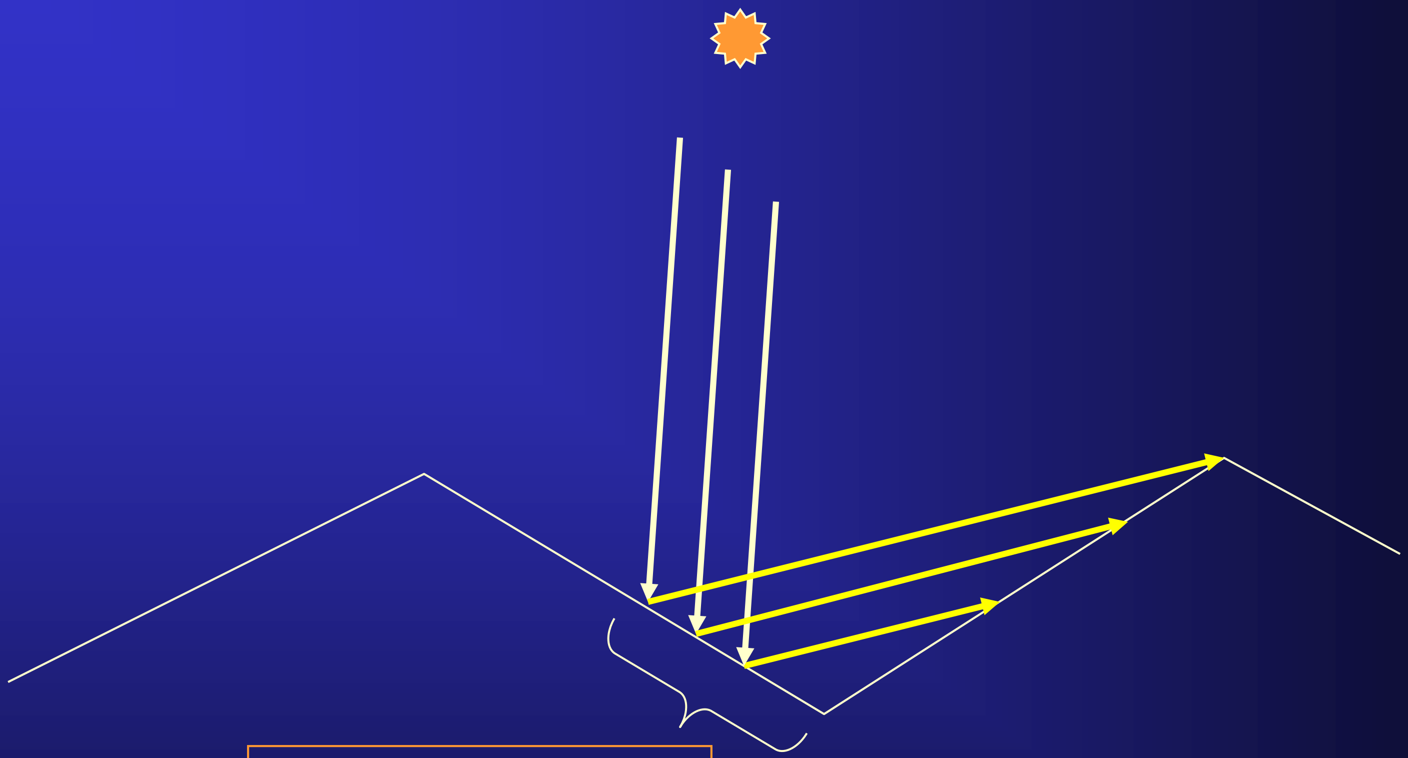
Microfacets and Light



Actual
surface
normal

Simple reflectance

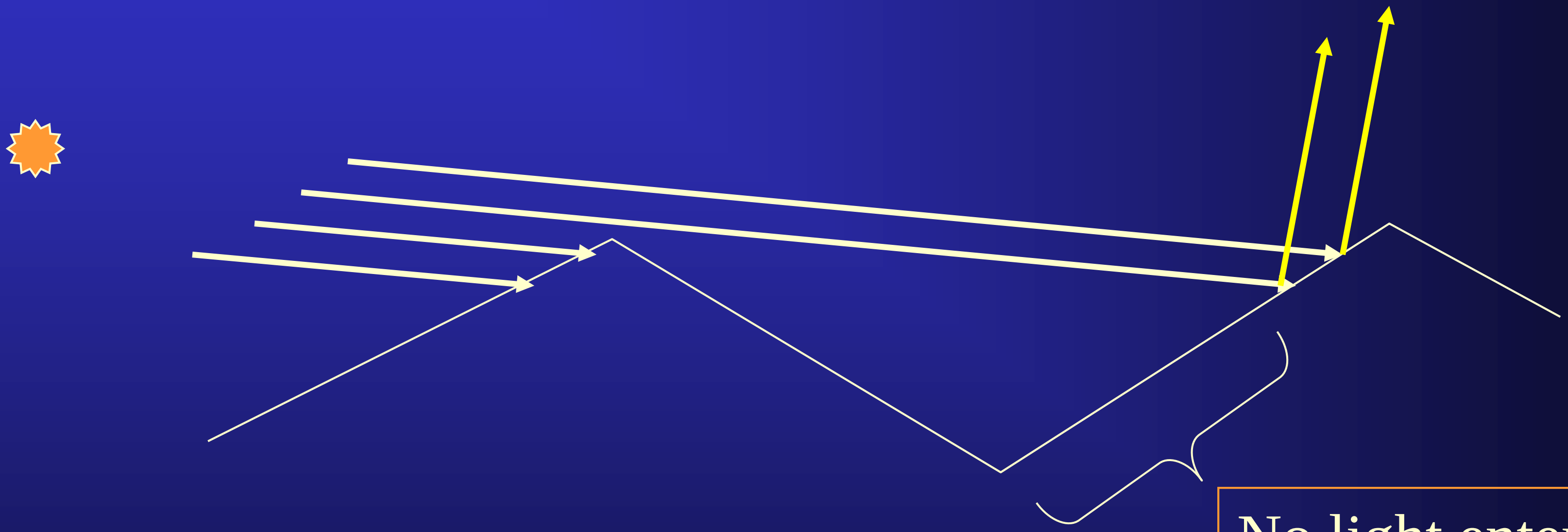
Microfacet Masking



No light escapes

Some reflected light is blocked

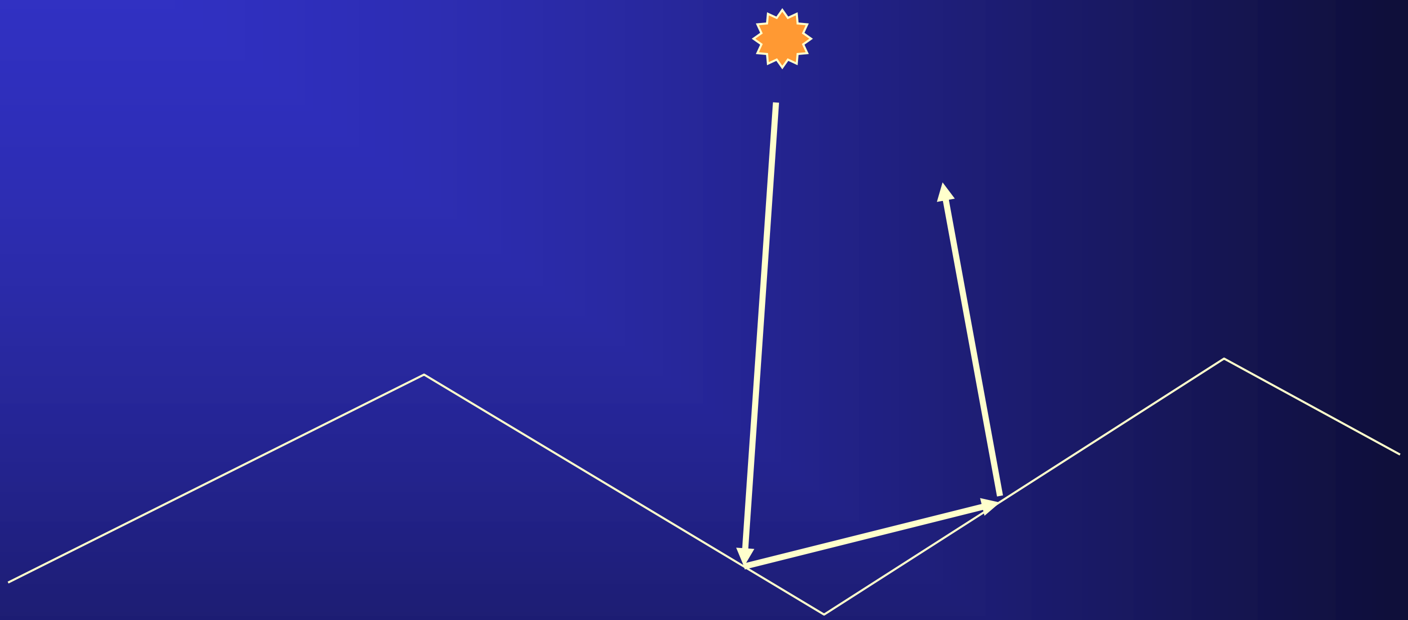
Microfacet Shadowing



No light enters

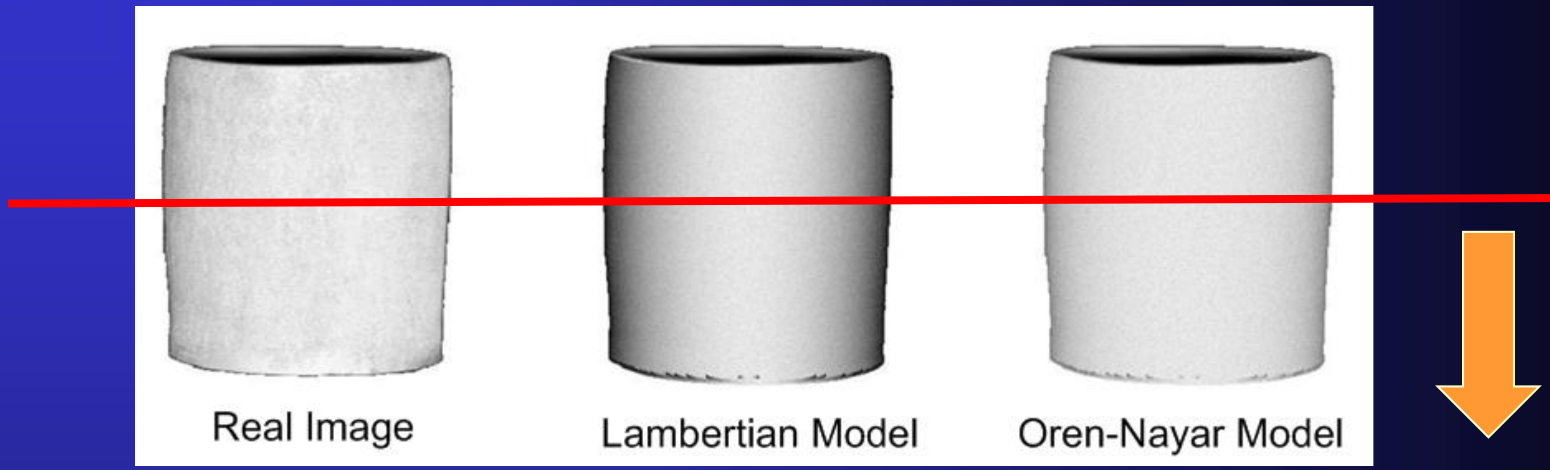
Some incident light is blocked

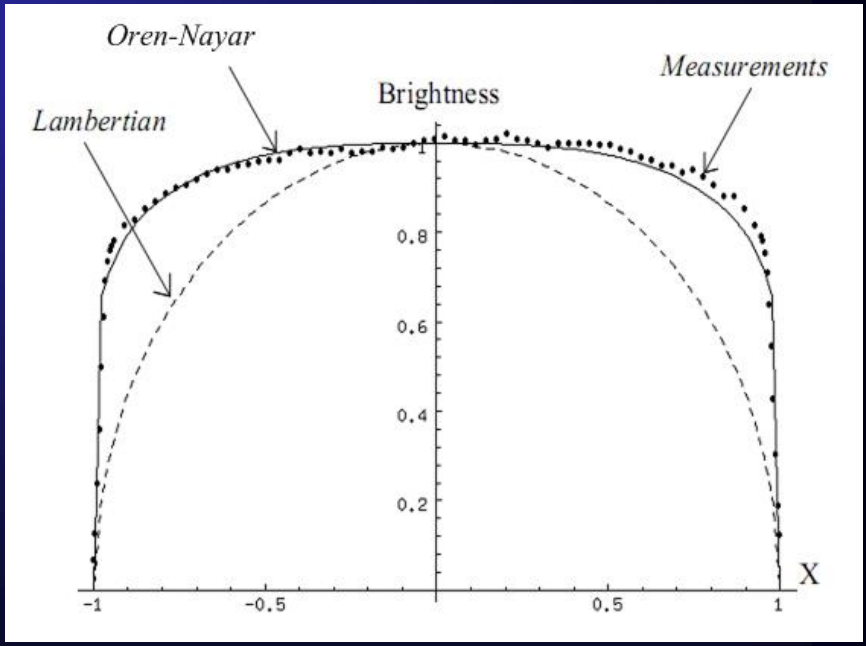
Microfacet Interreflection



Light bounces among microfacets before exiting to viewer

Comparison — from Oren and Nayar



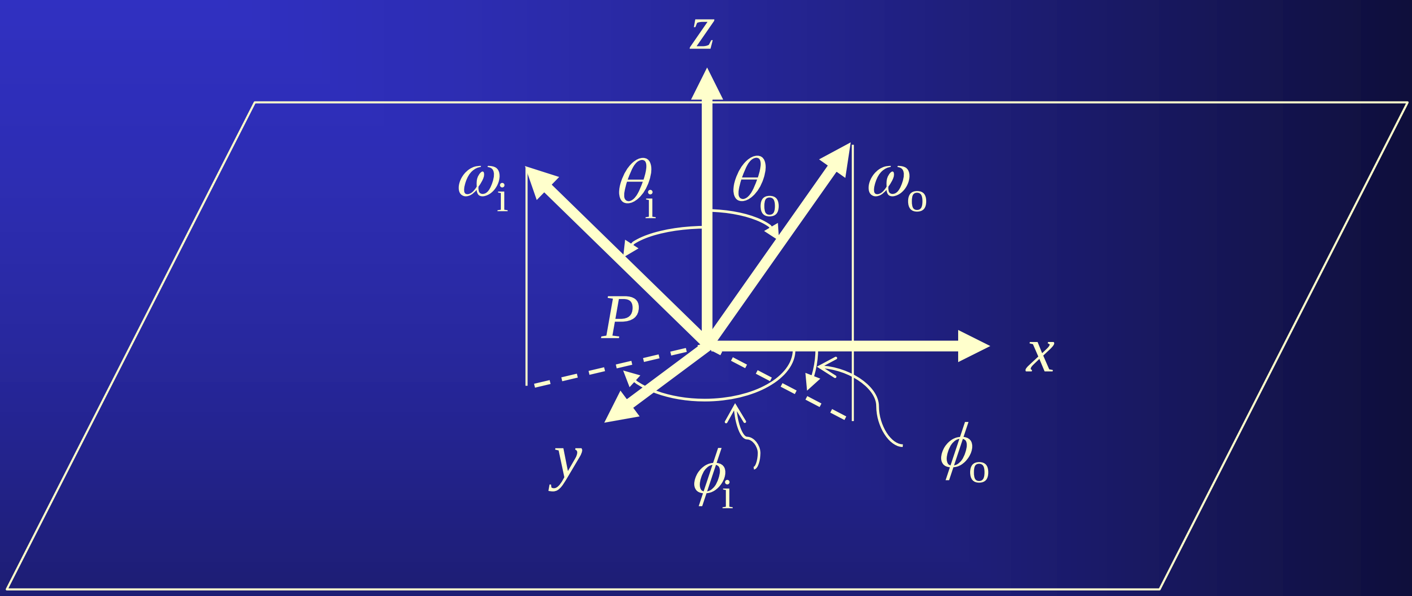


- Matte clay vase test.
- http://www.cs.columbia.edu/CAVE//projects/oren/, GPL, https://commons.wikimedia.org/w/index.php?curid=9000088

Oren-Nayar Model for Diffuse Reflection

- Describe rough surfaces by V-shaped microfacets.
- All microfacets are perfect diffuse reflectors.
- Use a spherical normal distribution with mean 0 and a single parameter σ, the standard deviation of the microfacet orientation angle from the surface normal.
- With the V-shape assumption, interreflection between “grooves” can be accounted for by considering only the neighboring microfacets.

Recall: Reflectance Geometry at a Surface Point



- Incident ω_i and outgoing ω_o light direction, normalized.

Oren-Nayar “V-groove” BRDF

- For surface color R, σ in radians, an approximation to the BRDF f:

$$f(\omega_i, \omega_o) = \frac{R}{\pi}\left(\mathrm{A} + \mathrm{B}\max\left(0, \cos(\varphi_i - \varphi_o)\right)\sin\alpha \tan\beta\right)$$

$$\mathrm{A} = 1 - \frac{\sigma^2}{2(\sigma^2 + 0.57)} \dagger$$

$$\mathrm{B} = \frac{0.45\,\sigma^2}{\sigma^2 + 0.09}$$

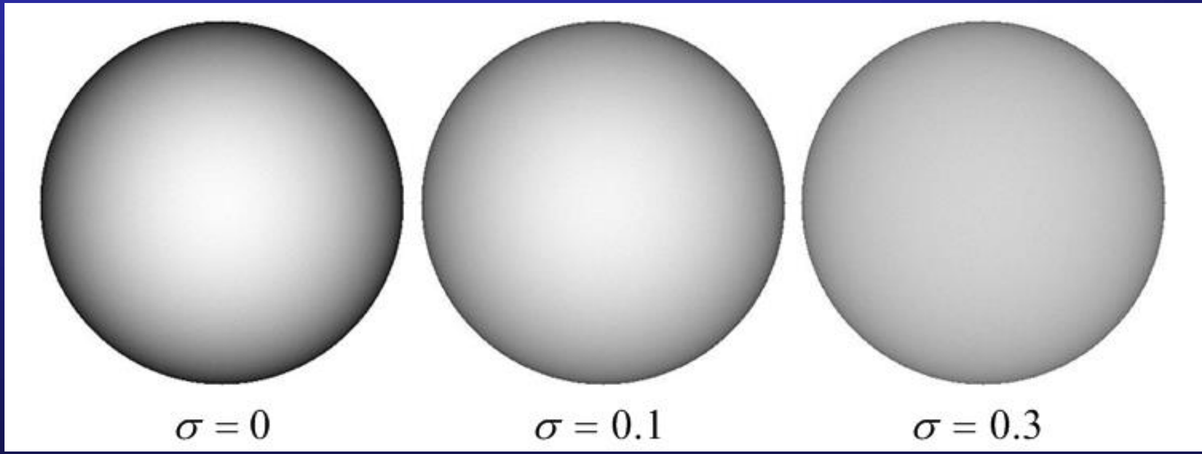
$$\alpha = \max\left(\theta_i, \theta_o\right)$$

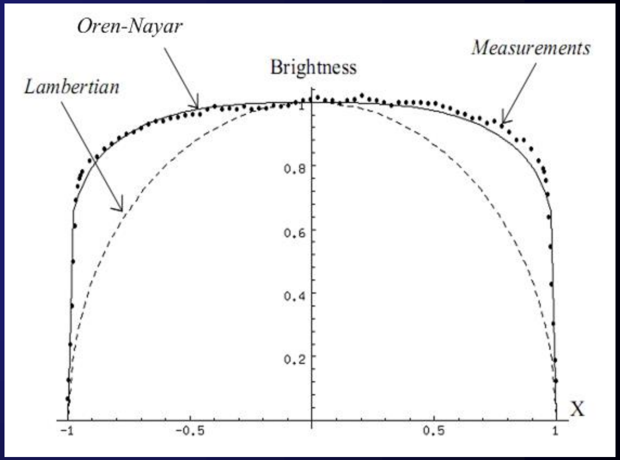
$$\beta = \min\left(\theta_i, \theta_o\right)$$

† Suggested modification of 0.33 to 0.57 in http://ruh.li/GraphicsOrenNayar.html to account for removed interreflection terms.

Varying σ

- When $\sigma = 0$ the model reduces to pure Lambertian diffuse. (No microfacet normal deviates from the geometric normal.)
- Increasing roughness sharpens the silhouette light transitions.



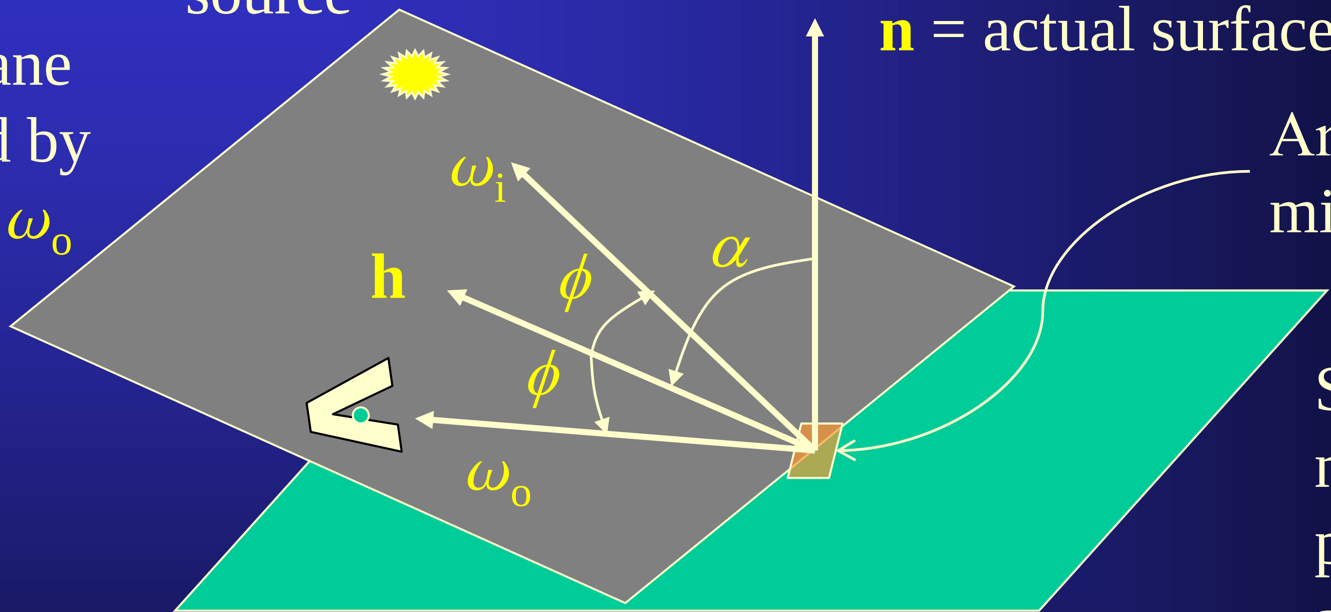


https://commons.wikimedia.org/w/index.php?curid=24465892

What about *Specular* Microfacets?

- The [perfect] specular component arises from microfacets that are oriented in the direction **h**: the “half-vector” bisecting the pair of rays from a point to the light and the eye.
- So if the eye is looking at a point on the surface, we compute from a probability distribution whether we “see” the light reflected in a specular microfacet with normal **h**.

Microfacet Geometry for a Surface



ω_i is unit vector to light source.

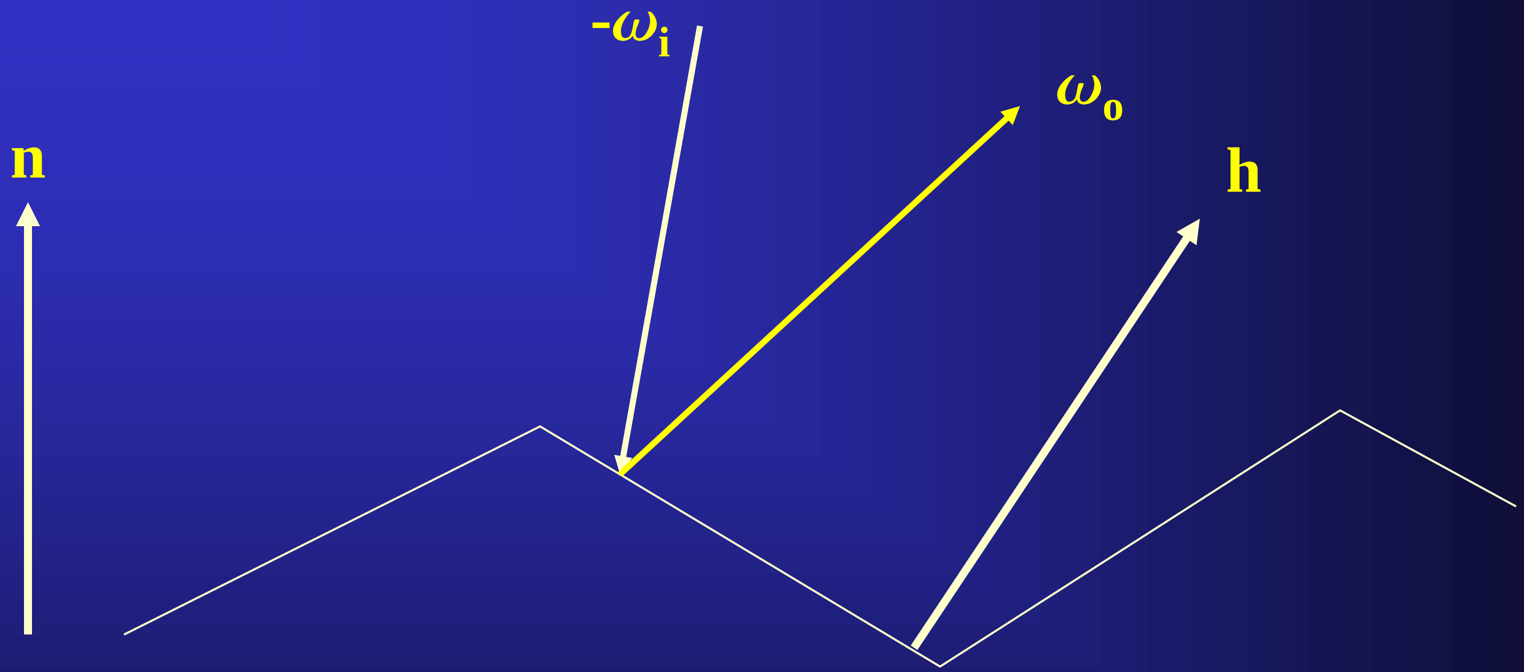
ω_o is unit direction to eye.

P is plane formed by ω_i and ω_o.

$\mathbf{h}$ (in P) is then unit normal to (imaginary) microfacet.

α is angle between $\mathbf{n}$ and $\mathbf{h}$.

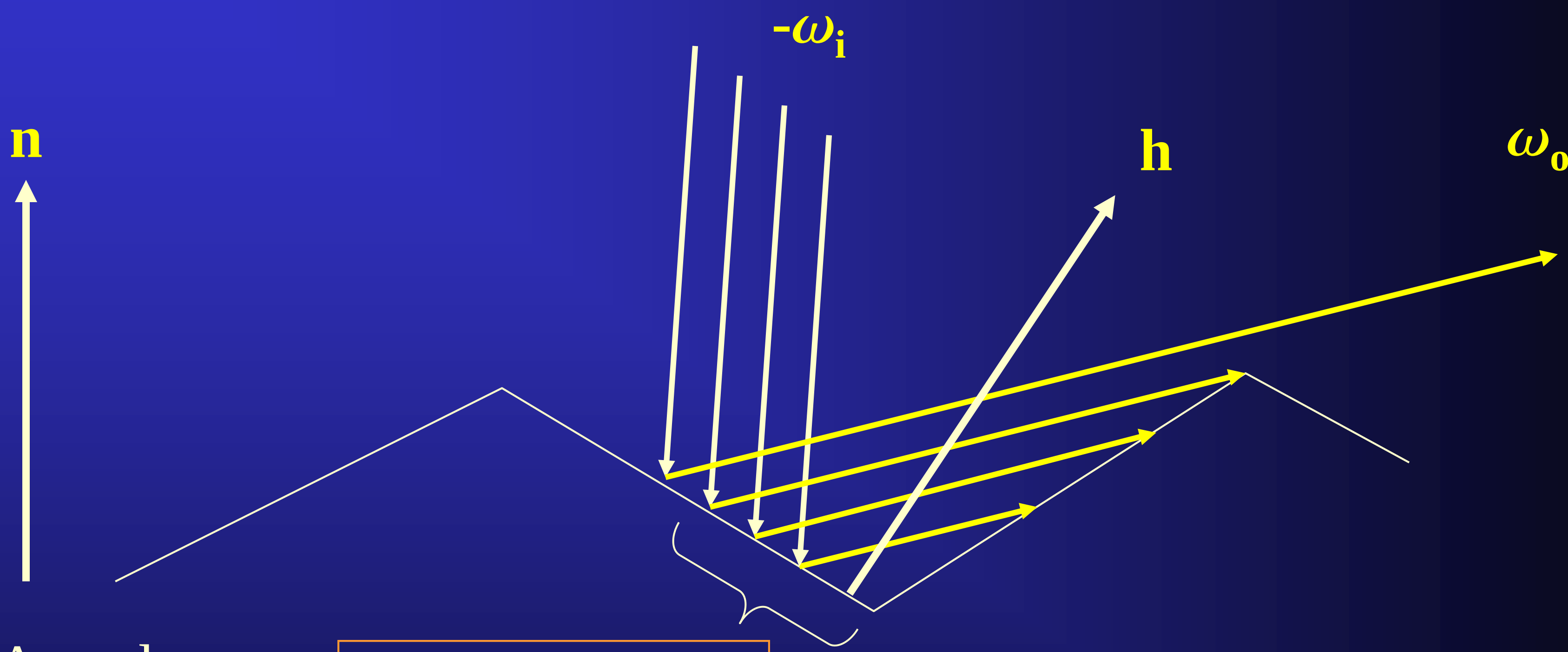
Microfacet Shadowing and Masking (G)



Actual surface normal

No interference with microfacets:
$G_1 = 1$

Microfacet Masking

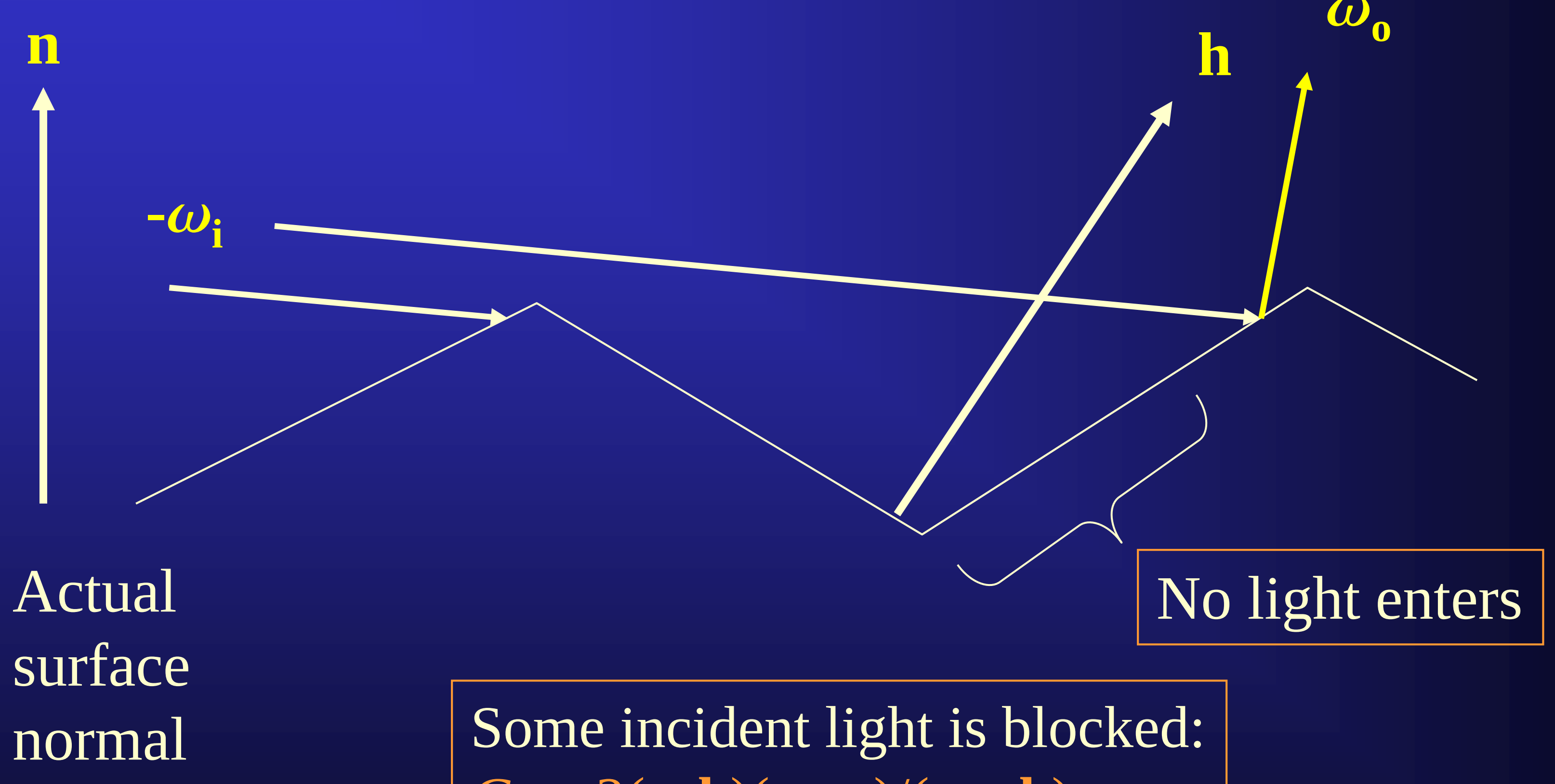


Actual surface normal

No light escapes

Some reflected light is blocked:
$G_2 = 2(\mathbf{n}\cdot\mathrm{h})(\mathbf{n}\cdot\omega_o)/(\omega_o\cdot\mathbf{h})$

Microfacet Shadowing



Some incident light is blocked:
$G_3 = 2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\omega_i)/(\omega_o \cdot\mathbf{h})$

Summary: $G = \min(G_1, G_2, G_3)$

Torrance-Sparrow Model for *Specular* Microfacets

$$f_r(\mathrm{p}, \omega_o, \omega_i) = \frac{D(\omega_h)G(\omega_o, \omega_i)F(\omega_o)}{4\cos\theta_o \cos\theta_i}$$

$D(\omega_h)$ = probability that a microfacet has orientation **h** :

$(0 \leq D(\omega_h) \leq 1)$: (0 rough; 1 smooth)

G = fraction of light not shadowed or masked $(0 \leq G \leq 1)$:

deep grooves (more attenuation) -- no grooves (flat)

F = Fresnel reflection $(0 \leq F(\phi, \eta, \lambda) \leq 1)$: where

η = index of refraction of surface

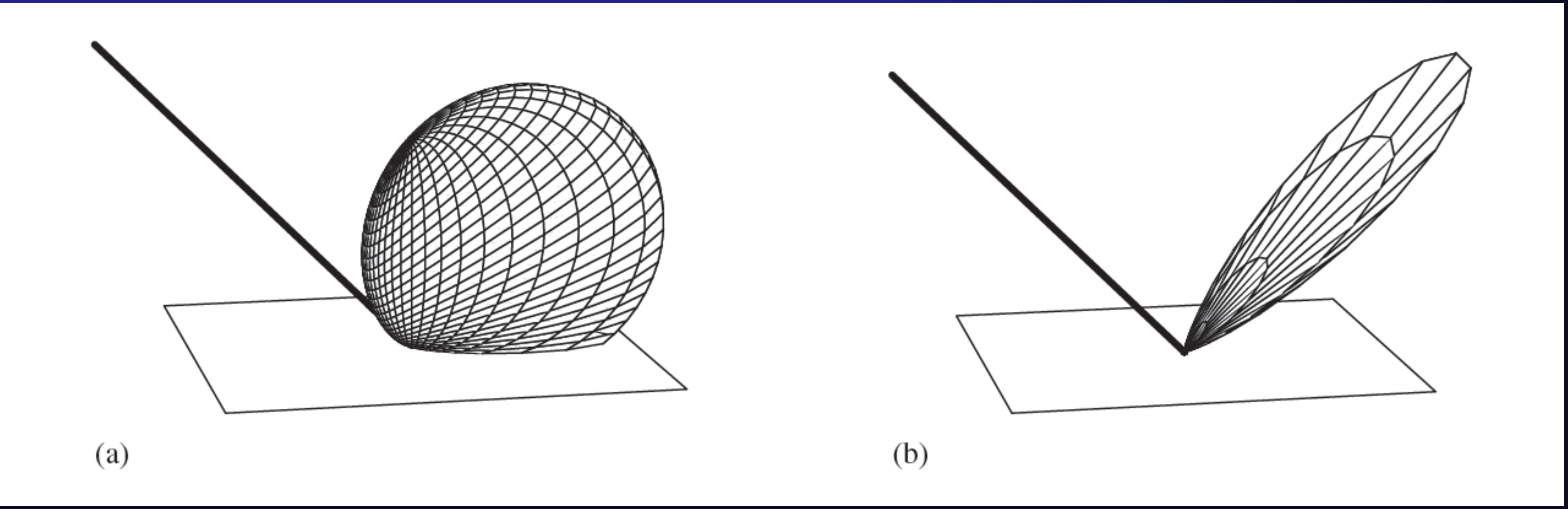
λ = wavelength of incident light

(some light may be absorbed by surface)

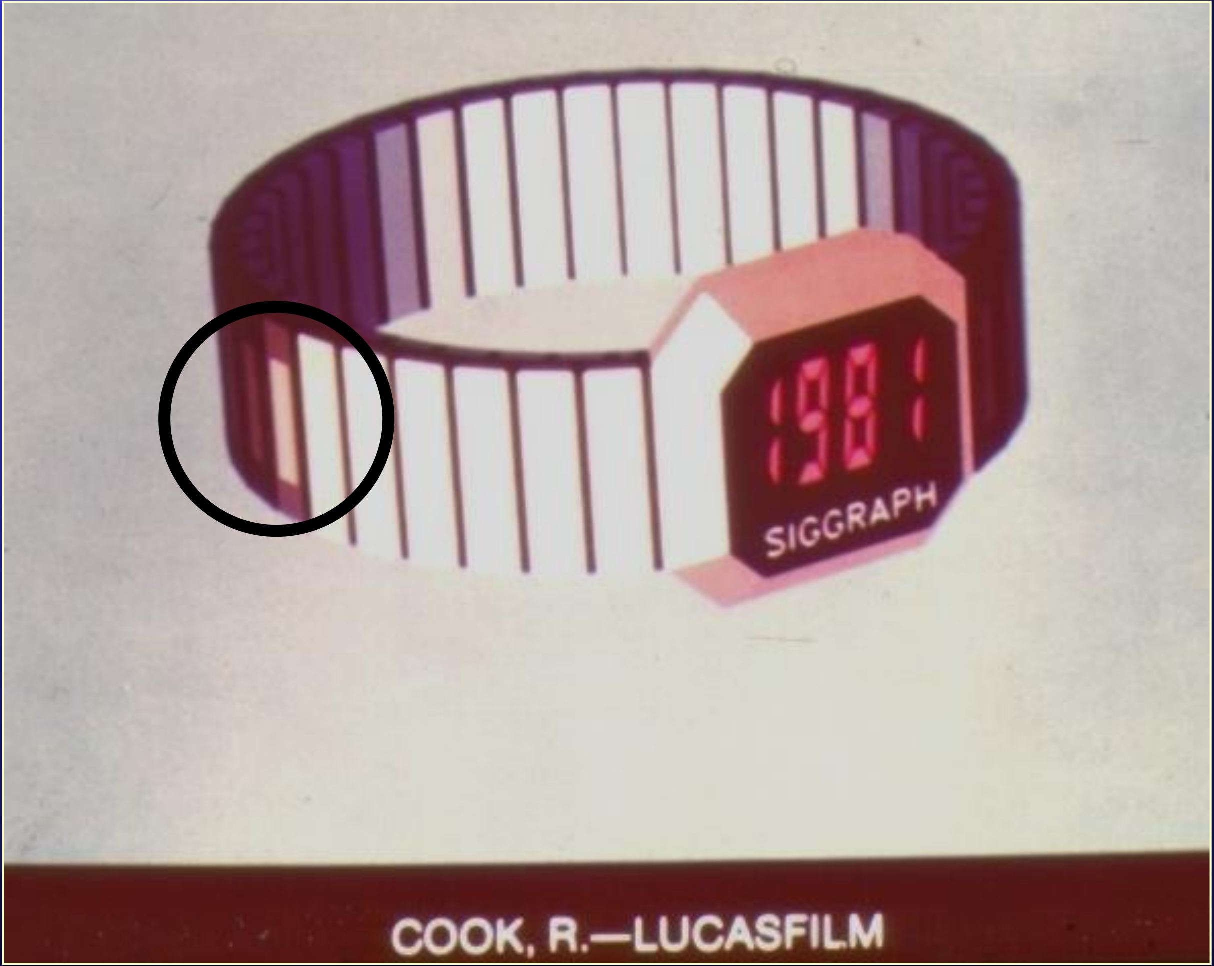
Specular Reflectance Function (D)

- Blinn-Phong: $D(\omega_{\mathrm{h}}) = \dfrac{e+2}{2\pi}(\omega_{\mathrm{h}} \cdot \mathbf{n})^{e}$
- Larger e means specular microfacet is more likely oriented close to the geometric normal **n**.

e = 4.0 (rough) e = 20.0 (smoother)



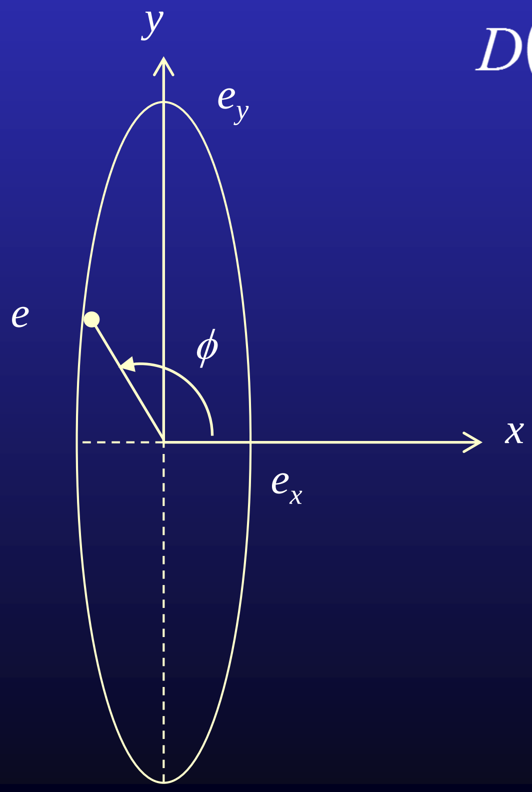
Surface Roughness

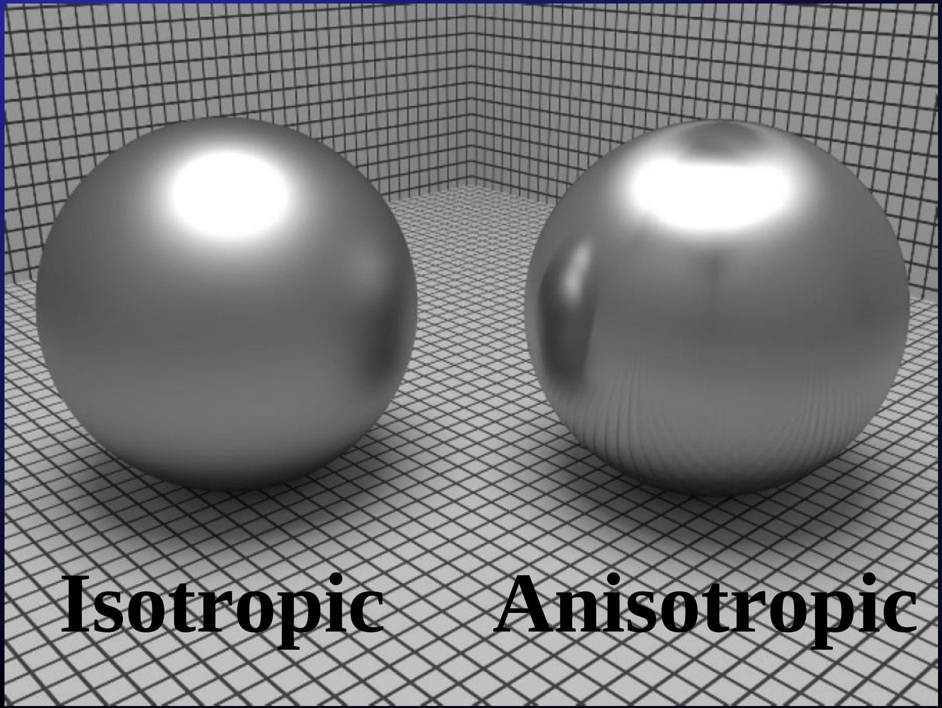


Anisotropic Variance

- Ashikhmin and Shirley's model: Anisotropic microfacet distribution replaces isotropic parameter e by two parameters e_x and e_y which are the Blinn-Phong exponents (magnitudes) of long/short axis of an ellipse:

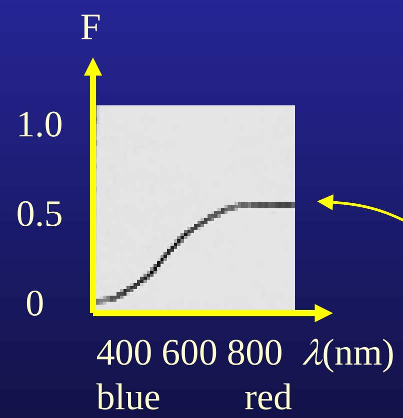
$$D(\omega_h) = \frac{\sqrt{(e_x+2)(e_y+2)}}{2\pi} (\omega_h \cdot \mathbf{n})^{e_x \cos^2\phi + e_y \sin^2\phi}$$

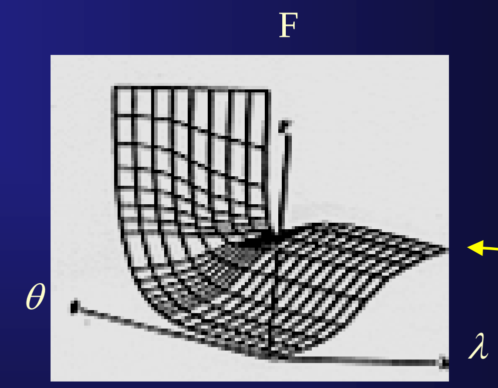




Reflectance Depends on Wavelength of Light (F)

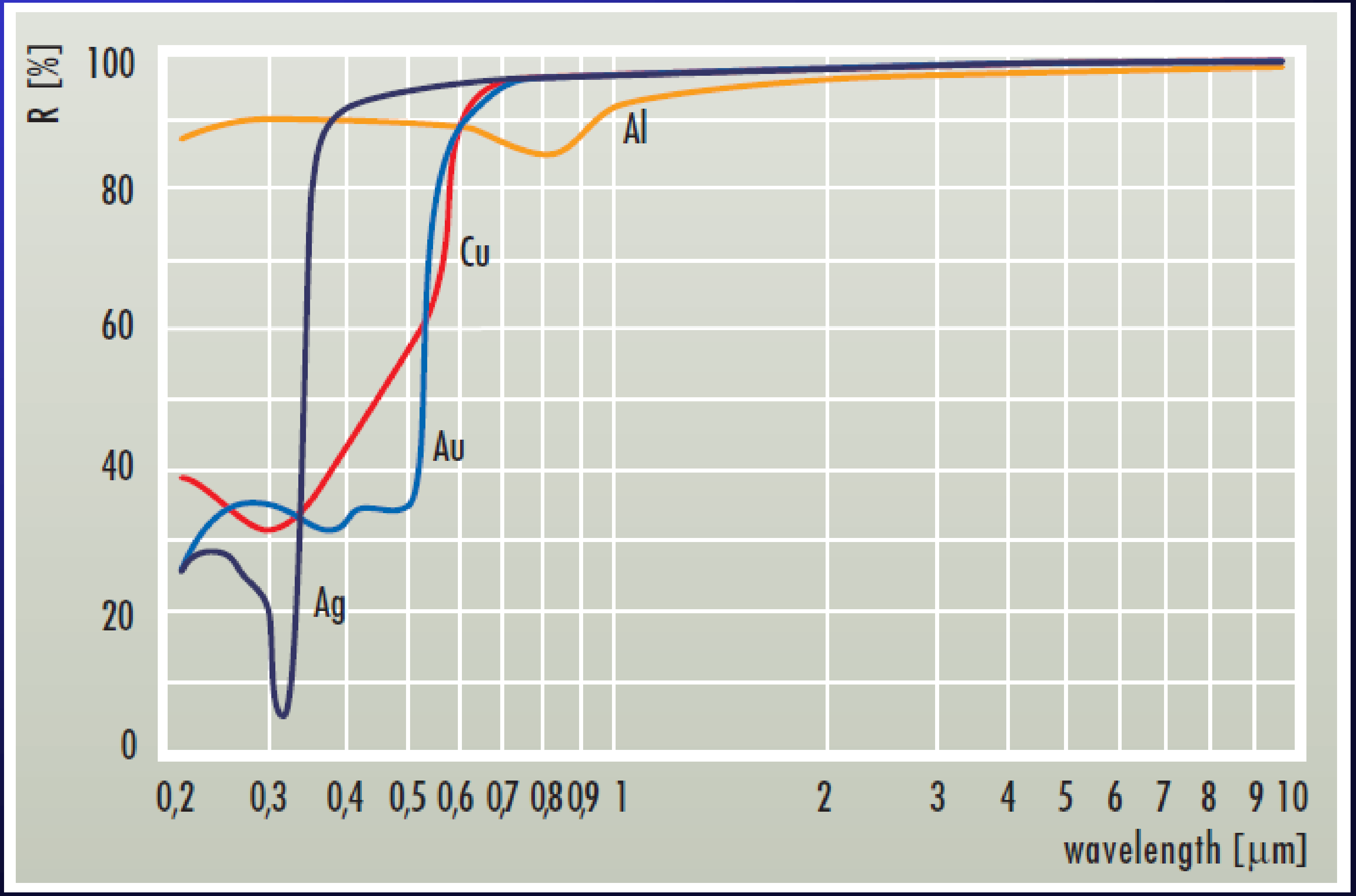
- Fresnel term F is a function of surface index of refraction and wavelength of incident light.
- Computed by multiple passes for several wavelength samples (or RGB colors), then summed.





Reflectance of bronze at normal incidence ($\theta = 0$)
and as a function of incidence angle θ and wavelength λ.

Example Metal Reflectance Functions by Wavelength



Blue Red

Varying Material Properties (Cook's Jars)