KATEDRA POČÍTAČOVÉ GRAFIKY A INTERAKCE

Light & Shading

Jiří Bittner

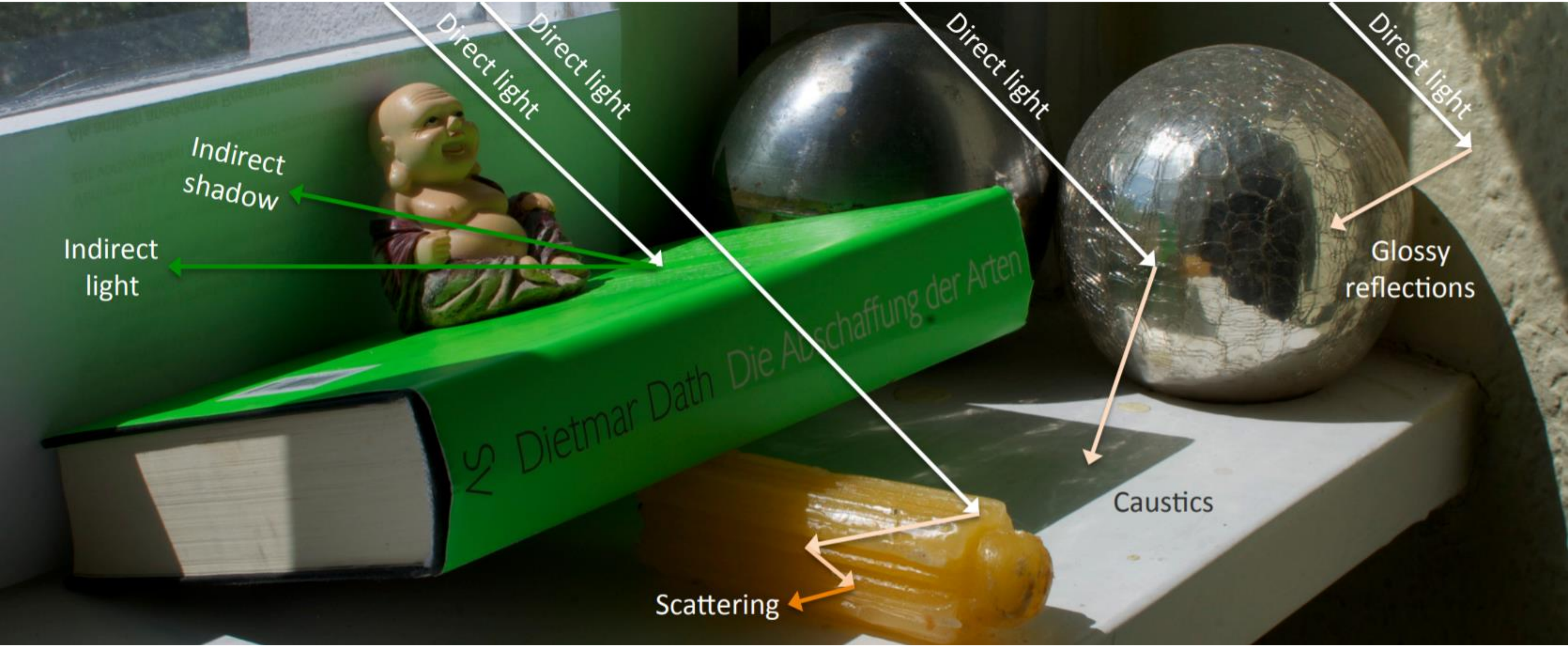
Outline

Surface appearance	MPG 10
Radiometry	MPG 10.1
Light sources	MPG 10.6
Surface reflectance models, BRDF	MPG 10.2-10.5
Shading	MPG 10.7

Surface Appearance

- Surface geometry
- Light sources
- Surface reflectance

Interaction of Light & Scene



Source: Ritschel et al. The State of the Art in Interactive Global Illumination

Light Measurements - Radiometry

- Power, Radiant flux (zářivý tok) P, Φ

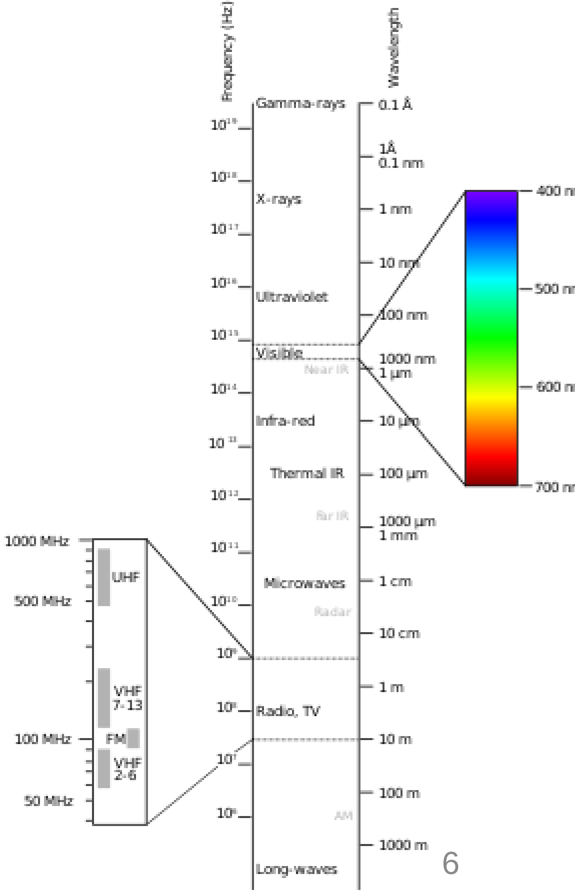
$$\Phi = \frac{\mathrm{dQ}}{\mathrm{dt}} [Js^{-1}, W]$$

  - How fast photons stream through a given place
  - Photon energy (Planck-Einstein relation)

$$E_f = h\,f\ [J]$$

$h = 6.626\ 10^{-34}$ Js   Planck constant

- Example
  - Radiant flux 1W
  - Monochromatic red light 600nm
  - Number of photons / s = 1/(h*c/600E-9) = 3 * 10^{18}



Radiometry – cont.

- Radiosity (Intenzita vyzařování, Radiozita)

$$B(x) = \frac{d\Phi}{dA}\ [W/m^2]$$

  - How many photons per unit area is emitted from a given place in unit of time (power density)

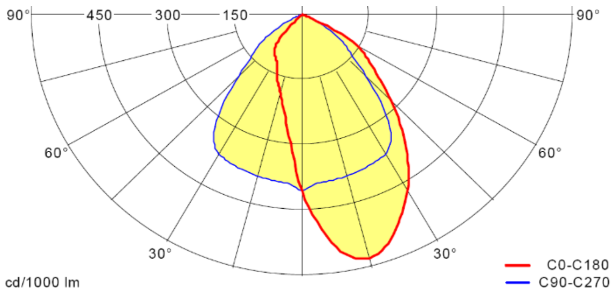
- Irradiance (Intenzita ozáření) E, $[W/m^2]$
  - How many photons per unit area and unit time reach given place

Radiometry – cont.

- Radiant intensity (Zářivost)

$$I(x,\omega) = \frac{d\Phi}{d\omega} \text{ [W/sr]}$$

- How many photons per unit angle is emitted in given direction in unit time
- Emission characteristics
  - IES standards

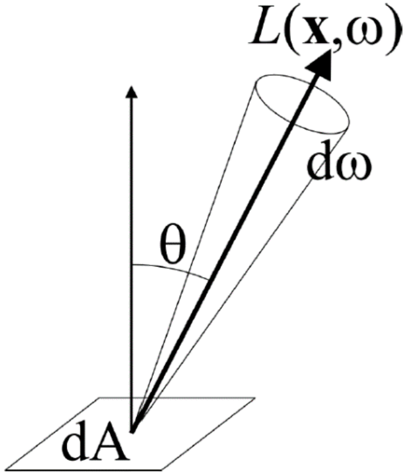


Source: G. Wallner, Geometry of arbitrary light distributions

Radiometry – cont.

- Radiance (Zář)

$$L(x,\omega) = \frac{dE}{d\omega} = \frac{d^2\Phi(x)}{\cos\theta \, dA \, d\omega} \ [Wm^{-2}sr^{-1}]$$

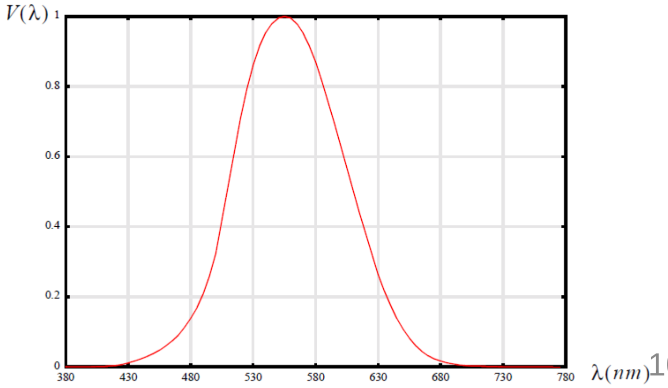


- Camera/eye sensor response is directly **proportional to radiance**
- Other quantities can be obtained by radiance integration

Radiometry vs Photometry

- Radiometry
  - Optical radiation: EM waves 0.01 μm -1mm (ultraviolet to infrared)
  - Radiometric quantities functions of wavelength (spectral flux $[Wm^{-1}]$, spectral radiance $[Wm^{-3}sr^{-1}]$, …)
- Photometry
  - Describes light – EM waves visible by human eye (380-780nm)
  - Radiometric quantities weighted by eye spectral response (CIE luminance function)

$$P = K_m \int_{380nm}^{770nm} V(\lambda)R(\lambda)d\lambda \qquad K_m = 680\text{lumen/watt}$$



Zdroj: P. Dutre – Global Illumination Compendium

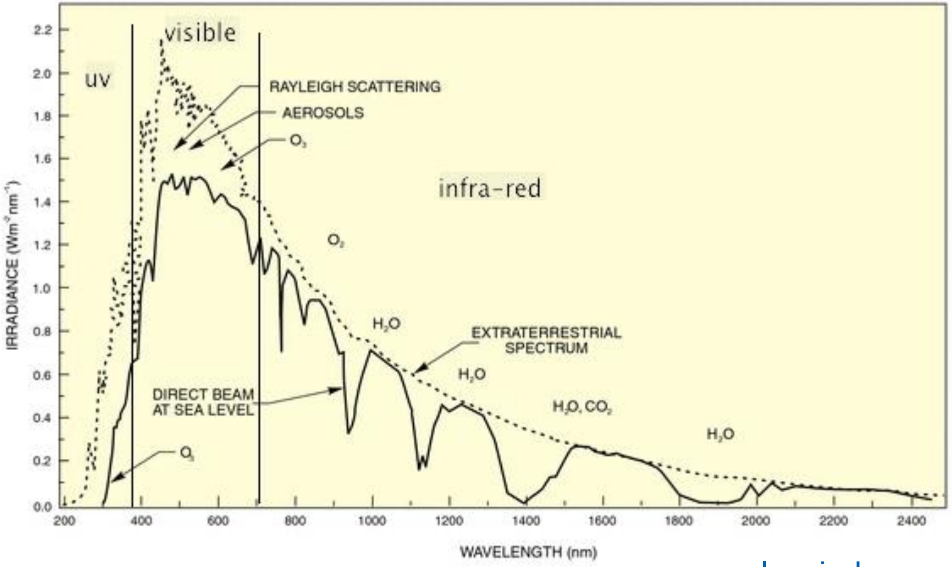
Radiometric & Photometric Quantities

Radiometry			Photometry		
quantity	**symbol**	**unit**	**quantity**	**symbol**	**unit**
radiant flux *zářivý tok*	ϕ	W	luminous flux *světelný tok*	ϕ_v	lm (Lumen)
irradiance *intenzita ozáření*	E	W/m^2	illuminance *osvětlení*	E_v	lx (Lux)
radiant intensity *zářivost*	I	W/sr	luminous intensity *svítivost*	I_v	cd (Candela)
radiance *zář*	L	$Wm^{-2}sr^{-1}$	luminance *jas*	L_v	cd/m^2

Exercise – The Sun

- Radiant flux of the Sun 3.86 10^{26} W
- Distance of Earth from Sun 1.5 10^{11} m
- Irradiance at upper atmosphere layer?

- **1365 W/m²**
  - Solar constant 1362 W/m^2
- 50% infrared light, 40% visible, 10% ultraviolet light
- **546 W/m² visible light**



source:solarwind.com

Exercise – LED Bulb

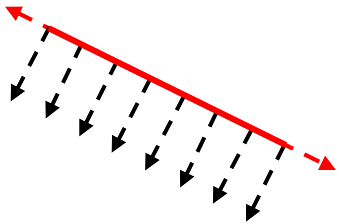
- Luminous flux of 11W LED light bulb $\Phi_v = 1100lm$
- Distance to a table $d = 1.5m$

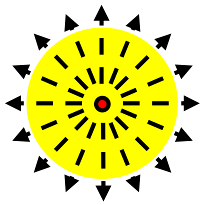
- Direct illuminance at table surface $E_v = \frac{1100lm}{4\pi d^2} = 38.9\ lx$

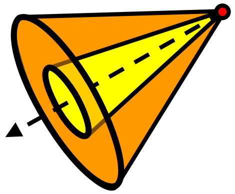
Work Place Type	Recommended illuminance
temporary working place	50 lx
work with important role of sight	100 lx
work requiring with high constract manipulation	300 lx

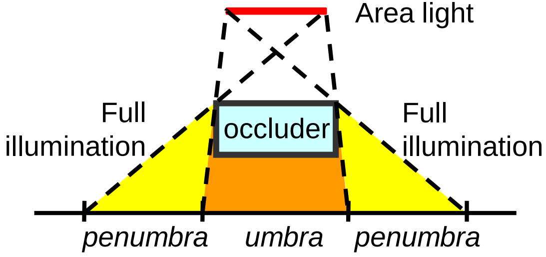
Light Sources

- Directional
  - No origin
  - Constant intensity
- Point
  - Intensity decreases
- Spot lights
- Area
  - Penumbra

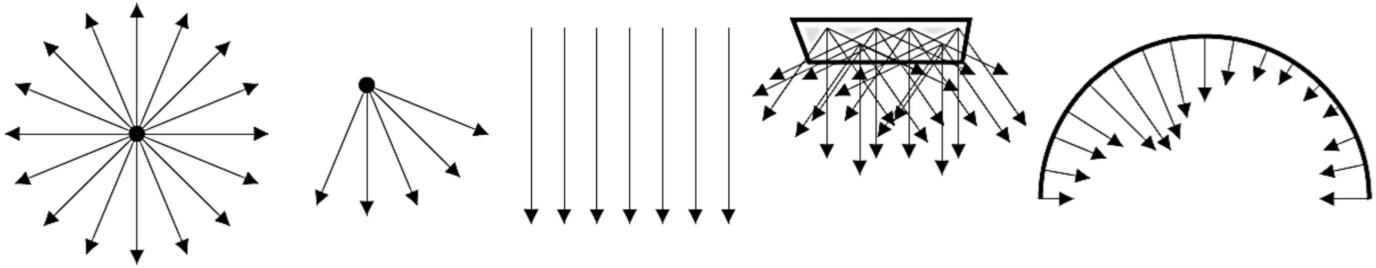




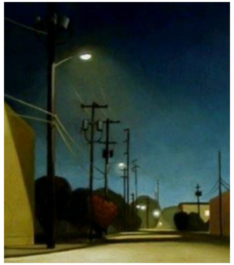
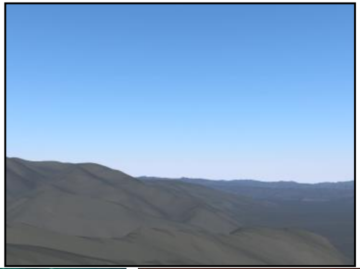


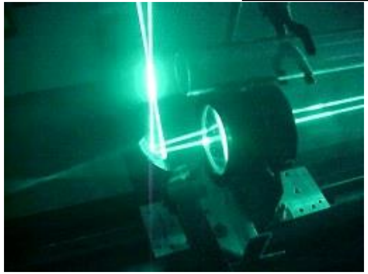


Light Sources - examples



A) Omnidirectional point light B) Spot light C) Directional light D) Area light E) Environment map

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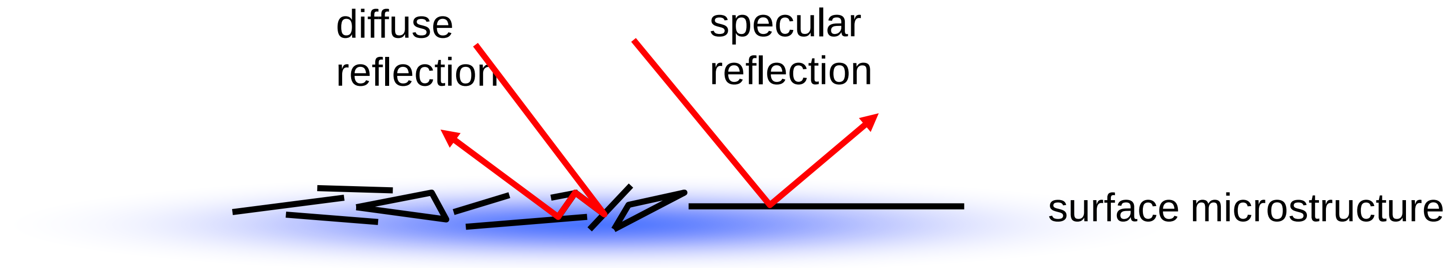
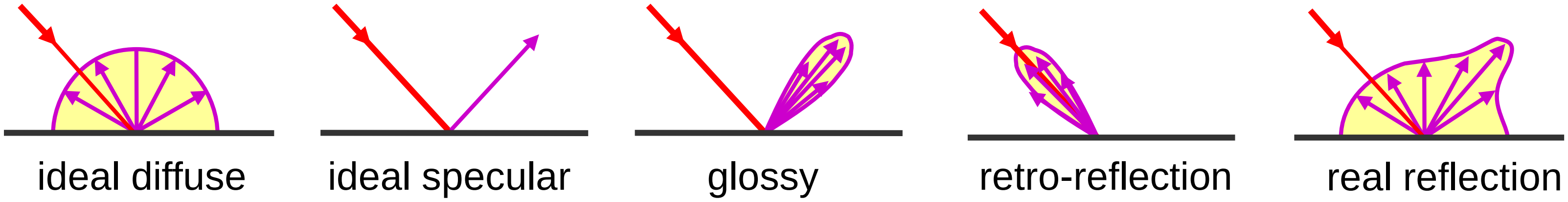
Light Reflection at Surface





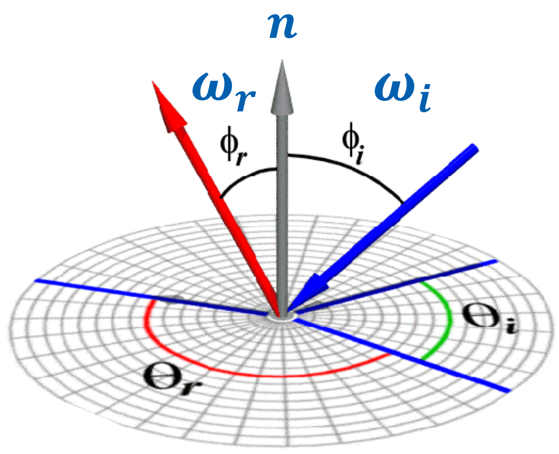
Light reflection at Surface

- BRDF (bidirectional reflection distribution function)

$$f_r(\boldsymbol{\omega}_i, \boldsymbol{\omega}_r) = \frac{dL_r(\boldsymbol{\omega}_r)}{L_i(\boldsymbol{\omega}_i)\cos\phi_i\, d\boldsymbol{\omega}_i}$$

$$f_r(\boldsymbol{\omega}_i, \boldsymbol{\omega}_r) = f_r(\theta_i, \phi_i, \theta_r, \phi_r)$$

$$dL_r(\boldsymbol{\omega}_r) = f_r(\boldsymbol{\omega}_i, \boldsymbol{\omega}_r)\, L_i(\boldsymbol{\omega}_i)\cos\phi_i\, d\boldsymbol{\omega}_i$$

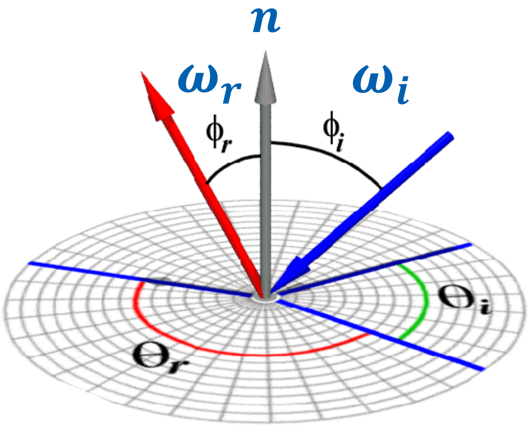


$$L_r(\boldsymbol{\omega}_r) = \int_\Omega f_r(\boldsymbol{\omega}_i, \boldsymbol{\omega}_r)\, L_i(\boldsymbol{\omega}_i)\cos\phi_i\, d\boldsymbol{\omega}_i$$

Reflection equation / Rendering equation

BRDF properties

$$f_r(\boldsymbol{\omega}_i, \boldsymbol{\omega}_r) = f_r(\theta_i, \phi_i, \theta_r, \phi_r)$$



$$\int_{\Omega} f_r(\boldsymbol{\omega}_i, \boldsymbol{\omega}_r) \cos\phi_i \, d\boldsymbol{\omega}_i \leq 1$$

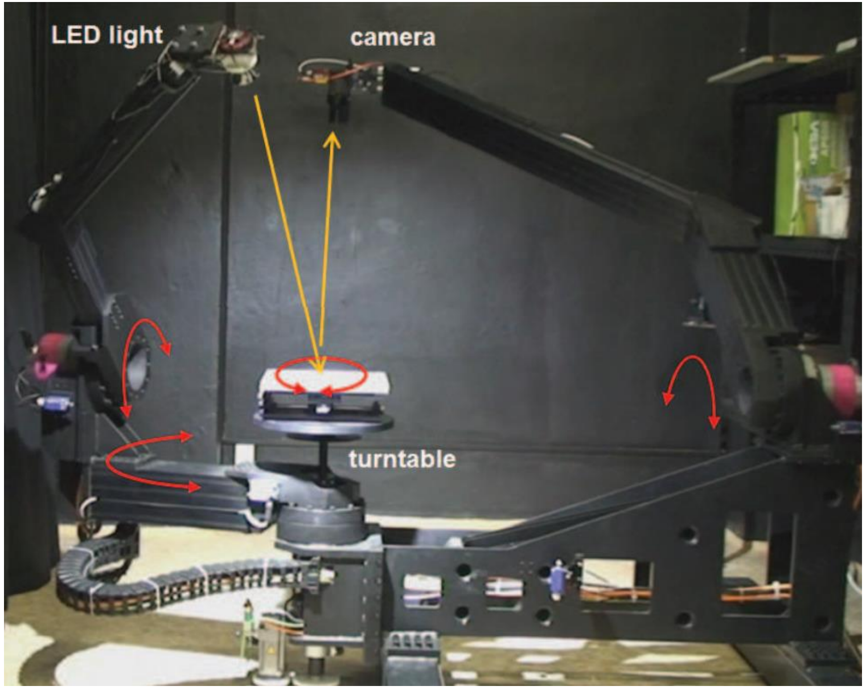
Energy conservation

$$f_r(\boldsymbol{\omega}_i, \boldsymbol{\omega}_r) = f_r(\boldsymbol{\omega}_r, \boldsymbol{\omega}_i)$$

Helmholtz reciprocity

Measuring BRDF

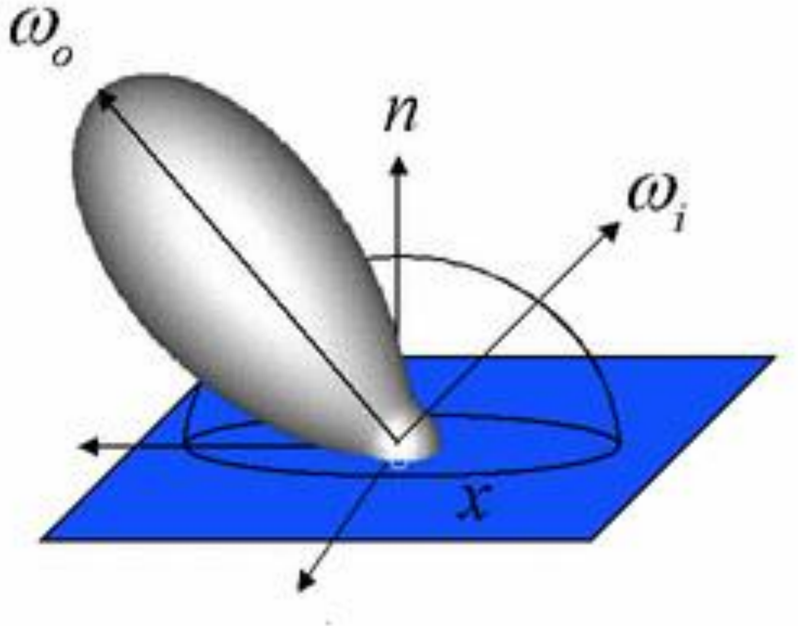
Goniometer



Goniometer (UTIA)

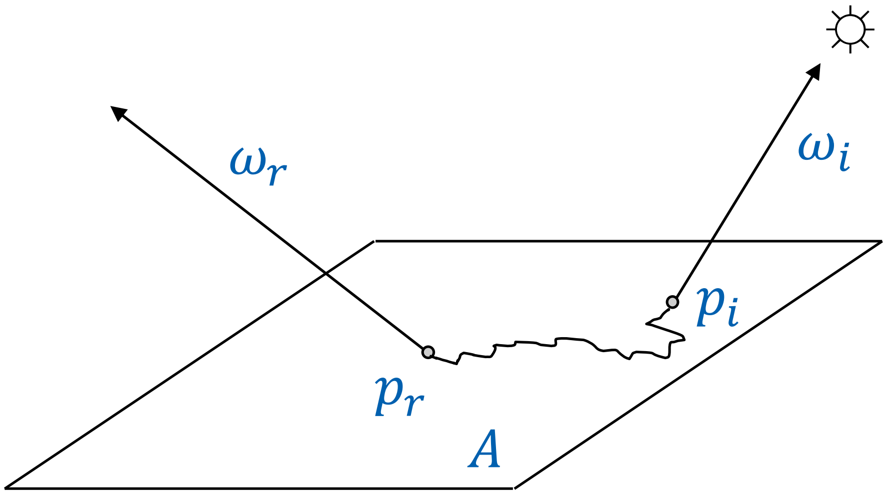
Lightdrum (DCGI)

BRDF Visualization



BSSRDF

- Bidirectional subsurface scattering reflectance distribution function



$$L_r(\omega_r) = \int_A \int_\Omega s_r(p_i, \omega_i, p_r, \omega_r)\, L_i(\omega_i) \cos\phi_i \, d\omega_i$$

Other Scattering Models

- BTDF - bidirectional transmittance dist. function
- BSDF- bidirectional scattering distribution function
  - BRDF + BTDF
- SVBRDF – spatially varying BRDF
- BTF – bidirectional texture function

Scattering Models

- Reflection/Shading/Lighting/Illumination model
  - Modeling BSDF / BRDF
- Scattering model determines surfaces appearance
  - light reflection / refraction

1. Empirical
   - Blinn, Phong, Mineart, …
2. Physically based
   - Cook-Torrance, Torrance-Sparrow, …
3. Measured BRDF data

Empirical Scattering Models

- Simple mathematical formula
- Easy and fast to evaluate
- Intuitive control

Phong Illumination Model

- Bui-Tuong Phong, disertation 1973
- Local illumination model
  - Not a physically plausible BRDF model
- Surface color composed of:
  - Ambient light I_A
  - Diffuse reflection I_D
  - Specular reflection I_S
- $I = I_A + I_D + I_S$
- Color computed by components (r, g, b)

Ambient Component

- Omnidirectional illumination (light noise)
  - Mimics global illumination (much simplified!)
  - Constant for the whole scene

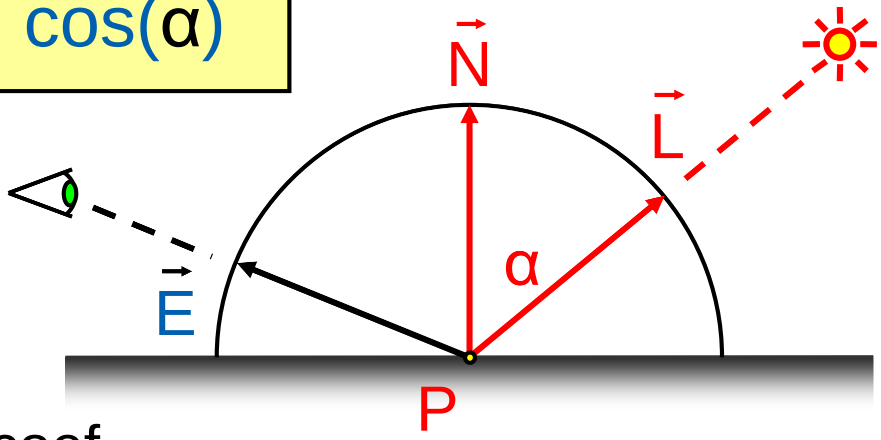
$$I_A = C_A \cdot C_D \cdot k_A$$

- C_A – color of ambient light
- C_D –surface color (as for diffuse component)
- $k_A \in \langle 0,1 \rangle$ − ambient reflection coefficient

Diffuse Component

- Ideally matte object
- Depends on angle between L and N

$$I_D = C_L \cdot C_D \cdot k_D \cdot \cos(\alpha)$$



- C_L light color
- C_D surface color

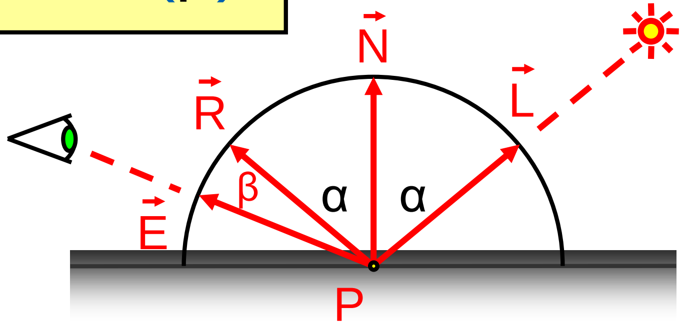
- $k_D \in \langle 0,1 \rangle$ Diffuse reflection coef.
- cos(α) = dot product of L and N

Specular Component

- Ideally specular object
- Depends on angle between E and R

$$I_S = C_L \cdot C_S \cdot k_S \cdot \cos^h(\beta)$$

- specular color C_S

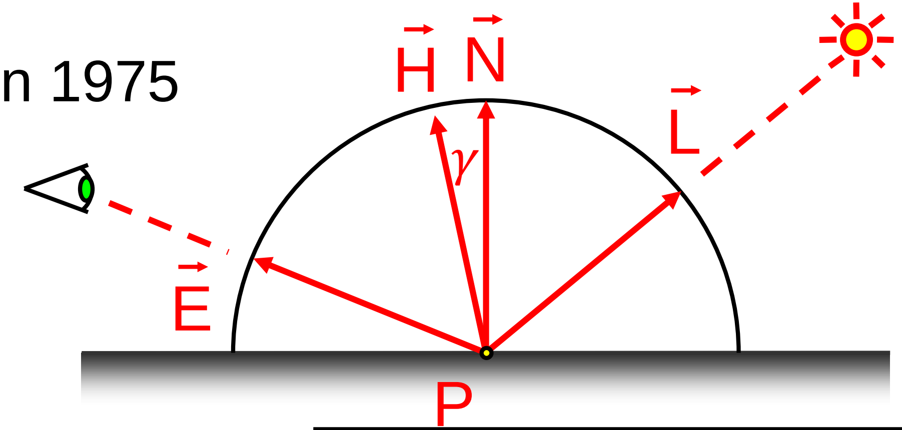


R = 2(LN)N-L

- $k_S \in \langle 0,1 \rangle$
- $h \in \langle 1, \infty \rangle$, shininess (ostrost odrazu)
- $\cos(\beta)$ = dot product of E and R

Blinn-Phong Illumination Model

- Jim Blinn 1975

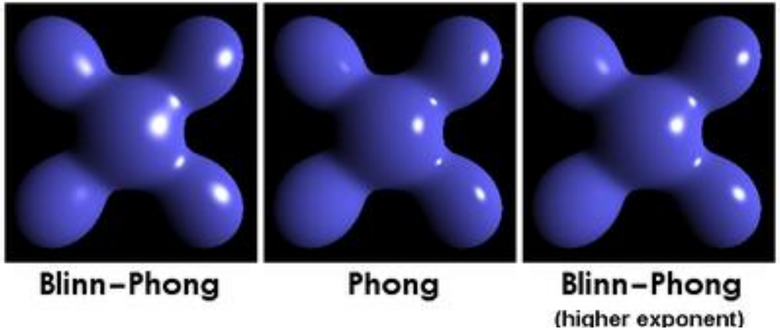


H = (L+E)/2

$$I_S = C_L \,.\, C_S \,.\, k_S \,.\, \cos^h(\gamma)$$

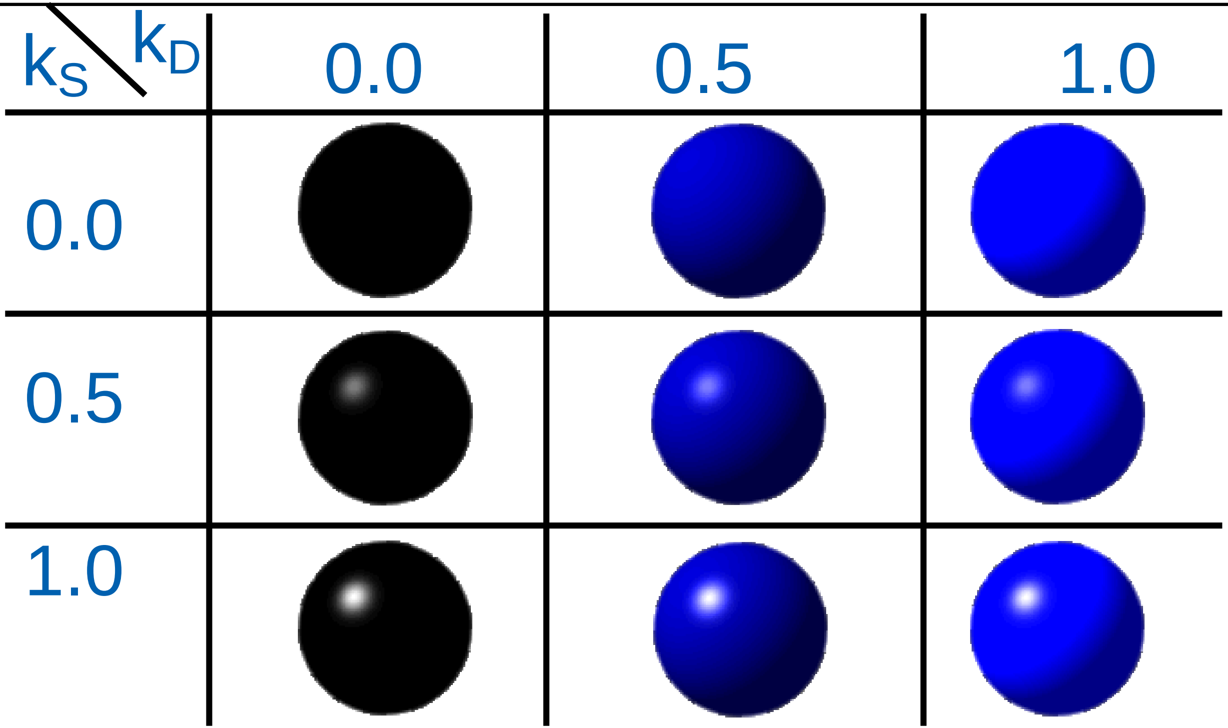
OpenGL / DirectX

Use 4x higher h than Phong!



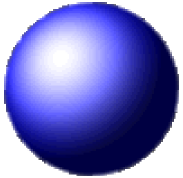
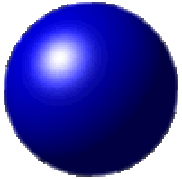
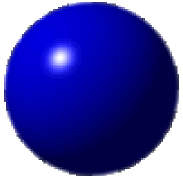
https://seblagarde.wordpress.com/2012/03/29/relationship-between-phong-and-blinn-lighting-model/

Examples - Phong



$k_A = 0.0, h = 50$

Shininess - Phong

	10	20	100
h			

$k_A = 0.0$
$k_D = 0.5$
$k_S = 1$

Blinn-Phong Model Summary

- More light sources L_i

$$I = I_A + \sum_i (I_D + I_S)$$

- Practical setting of Phong model

$$k_A + k_D + k_S \leq 1$$

Physically Plausible Phong Model

- [Lafortune & Willems 1994]

$$f_r(\omega_i, \omega_r) = \frac{k_d}{\pi} + \frac{k_s(n+2)}{2\pi}\cos^n \alpha$$

$$k_s + k_d \leq 1$$

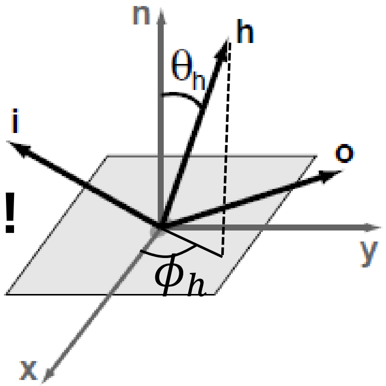
- Helmholtz reciprocity & Energy conservation
  - Use in physically correct renderer !

$$L_r(\omega_r) = \int_\Omega f_r(\omega_i, \omega_r)\, L_i(\omega_i) \cos\phi_i \, d\omega_i$$

Ward BRDF

- Empirical (as Phong, Blinn)
  - Good to fit measured data
- **Anisotropic specular reflection!**
  - Gaussians
- Params
  - $k_d, k_s, \alpha_x, \alpha_y$

$$f_r = \frac{k_d}{\pi} + k_s \frac{e^{-\tan^2\theta_h\left(\frac{\cos^2\phi_h}{\alpha_x}+\frac{\sin^2\phi_h}{\alpha_y}\right)}}{4\pi\alpha_x\alpha_y\sqrt{cos\theta_i cos\theta_o}}$$



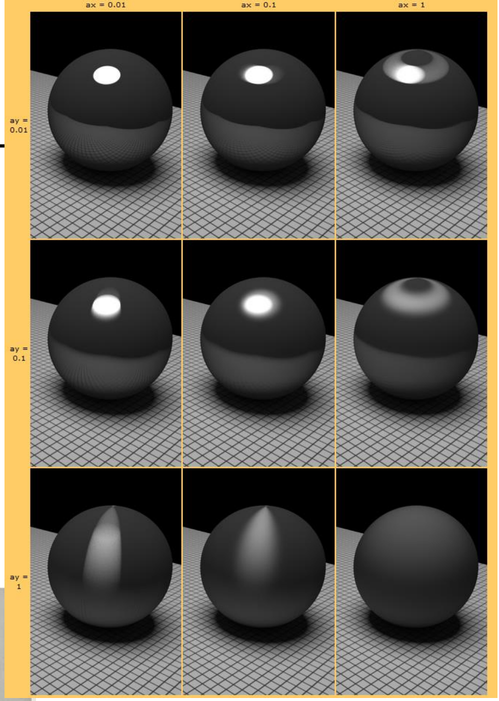
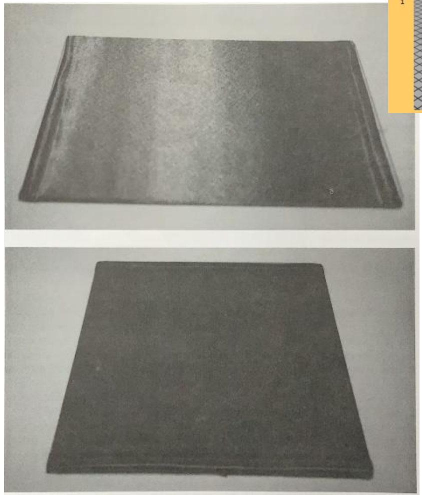


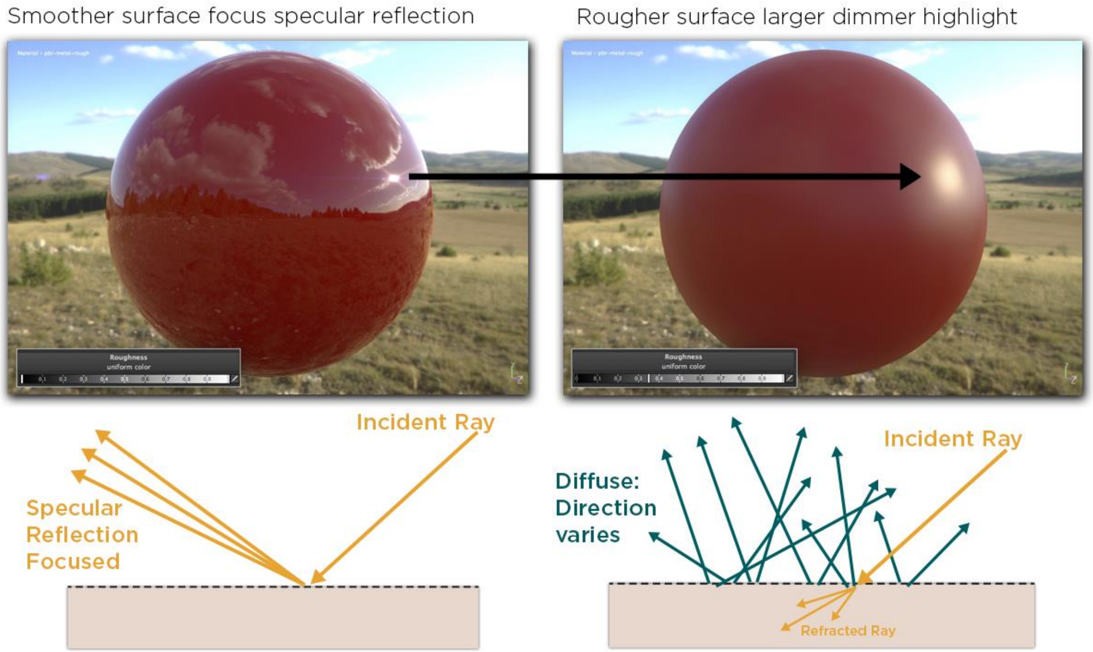
Image: Chia-Kai Liang



Photos of satin fabric (Jeffrey McConnel)

Physically Based Models

- Microfacet distribution – “V” grooves
- Normal distribution (D)
- Shadowing-masking (G)
- Fresnel term (F)

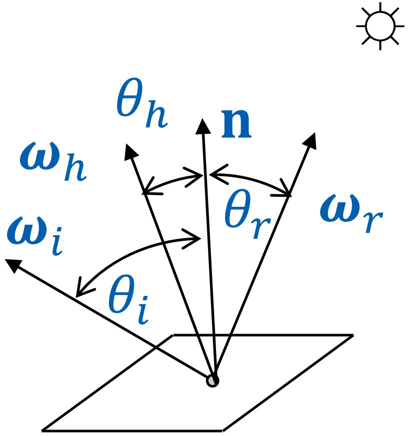


Source: PBR Guide by Allegorithmic.

Microfacet models

- Normal distribution (D), Fresnel term (F), shadowing-masking (G)
- Cook-Torrance BRDF for specular surfaces
- Specular microfacets

$$f_r(\boldsymbol{\omega}_i, \boldsymbol{\omega}_r) = \frac{D(\boldsymbol{\omega}_h)F(\boldsymbol{\omega}_h, \boldsymbol{\omega}_i)G(\boldsymbol{\omega}_i, \boldsymbol{\omega}_r)}{4\cos\theta_i \cos\theta_r}$$



$\boldsymbol{\omega}_h$ … *half vector*

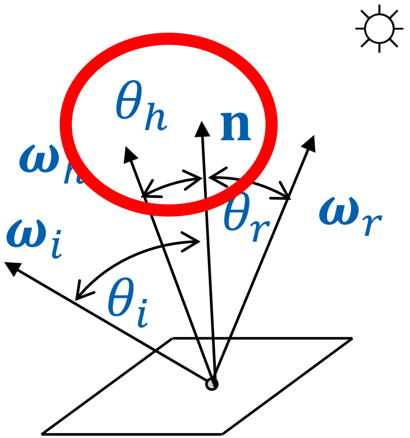
$$\boldsymbol{\omega}_h = \frac{(\boldsymbol{\omega}_i + \boldsymbol{\omega}_r)}{||\boldsymbol{\omega}_i + \boldsymbol{\omega}_r||}$$

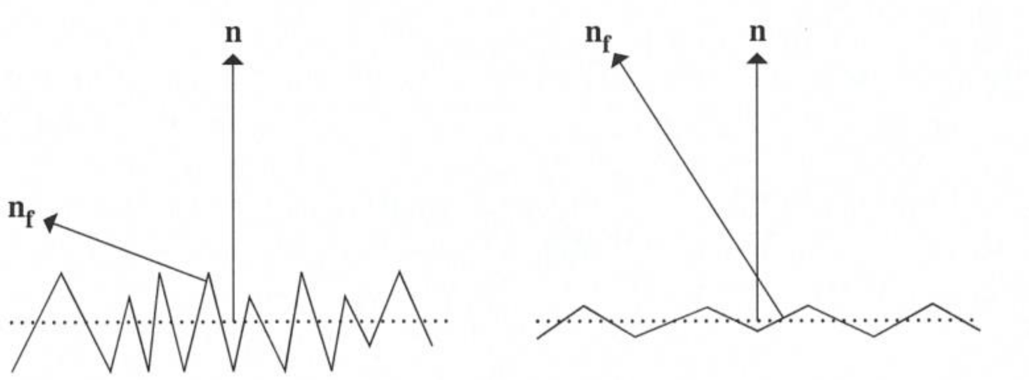
Cook & Torrance: A reflectance model for computer graphics, TOG 1982.

Microfacet models - Normal distribution (D)

- Microfacet distribution – “V” grooves
  - Model surface roughness

angle between half vector and surface normal





$\boldsymbol{\omega}_h$ … *half vector*

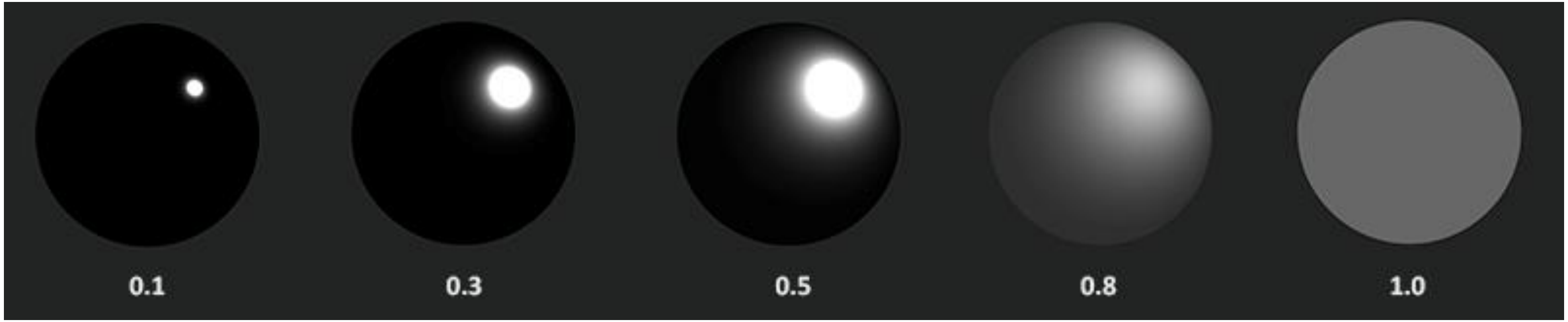
$$\boldsymbol{\omega}_h = \frac{(\boldsymbol{\omega}_i + \boldsymbol{\omega}_r)}{||\boldsymbol{\omega}_i + \boldsymbol{\omega}_r||}$$

$$D(\boldsymbol{\omega}_h) = \frac{e^{(-(tan\,\theta_h/\alpha)^2)}}{\pi\alpha^2\cos^4\theta_h}$$

α roughness

Beckmann distribution

Microfacet models - Normal distribution (D)

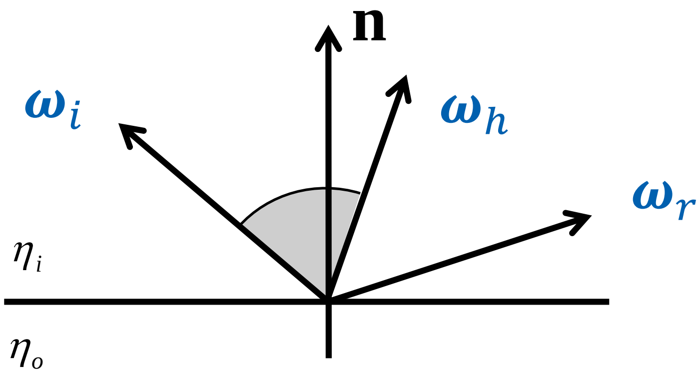


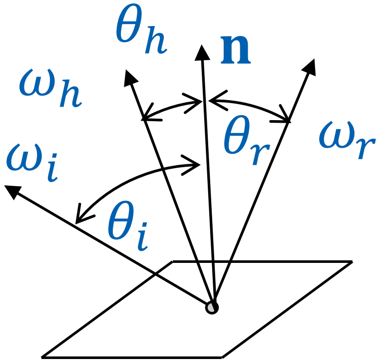
α roughness

Image source: https://learnopengl.com/PBR/Theory

Microfacet models - Fresnel term (F)

- reflection / transmission on media interface





characteristic specular color at normal incidence

$$F(\boldsymbol{\omega}_h, \boldsymbol{\omega}_i) = F_0 + (1 - F_0)(1 - \boldsymbol{\omega}_h \boldsymbol{\omega}_i)^5,$$

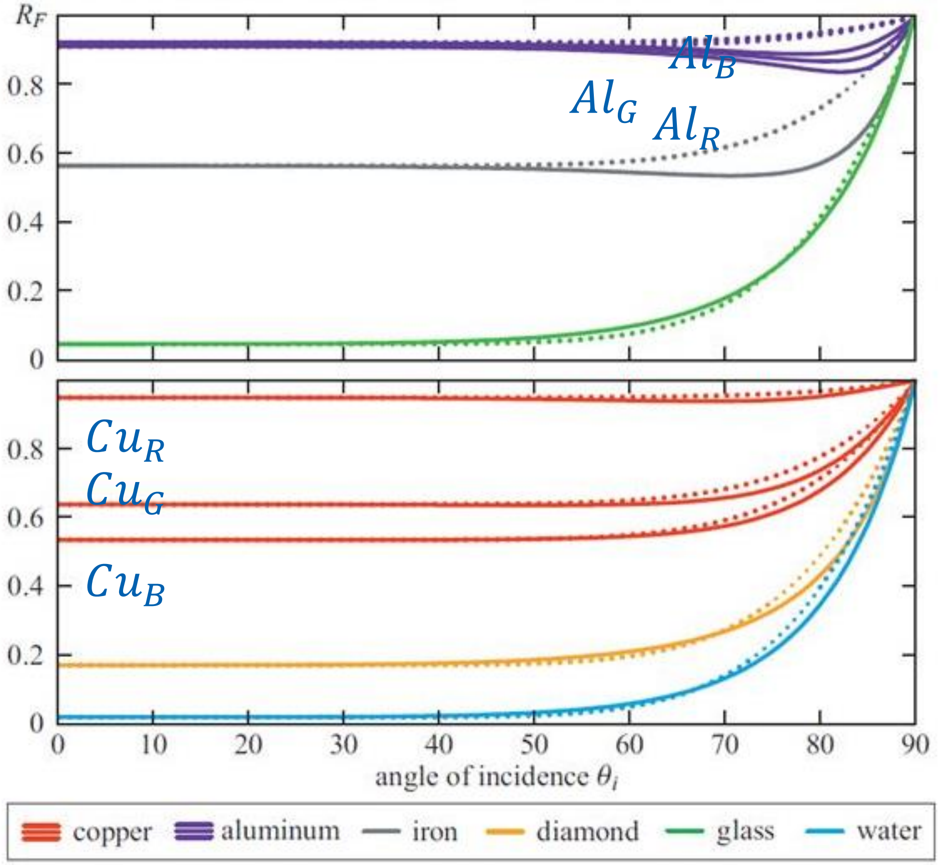
Schlick's approximation

$$F_0 = \left(\frac{\eta_1 - \eta_2}{\eta_1 + \eta_2}\right)^2$$

Examples

solid = Fresnel
dotted = Schlick

F



Source: Möller et al. RTR 3ed.

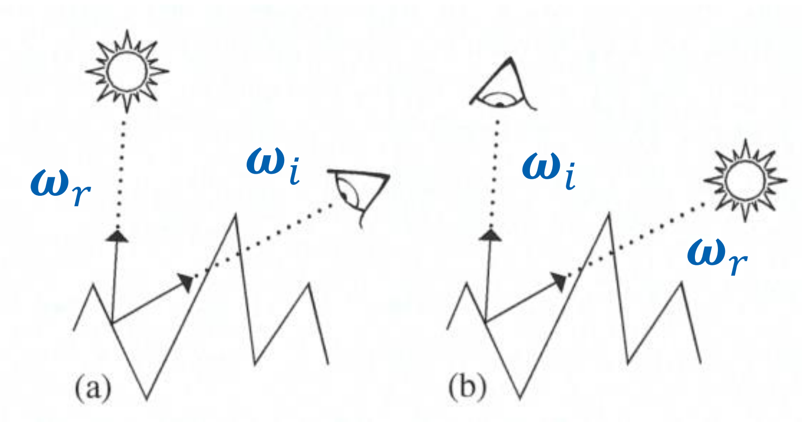
Fresnel term – F_0 examples

Dielectric	Linear	Texture	Color	Notes
Water	0.02	39		
Living tissue	0.02–0.04	39–56		Watery tissues are toward the lower bound, dry ones are higher
Skin	0.028	47		
Eyes	0.025	44		Dry cornea (tears have a similar value to water)
Hair	0.046	61		
Teeth	0.058	68		
Fabric	0.04–0.056	56–67		Polyester highest, most others under 0.05
Stone	0.035–0.056	53–67		Values for the minerals most often found in stone
Plastics, glass	0.04–0.05	56–63		Not including crystal glass
Crystal glass	0.05–0.07	63–75		
Gems	0.05–0.08	63–80		Not including diamonds and diamond simulants
Diamond-like	0.13–0.2	101–124		Diamonds and diamond simulants (e.g., cubic zirconia, moissanite)

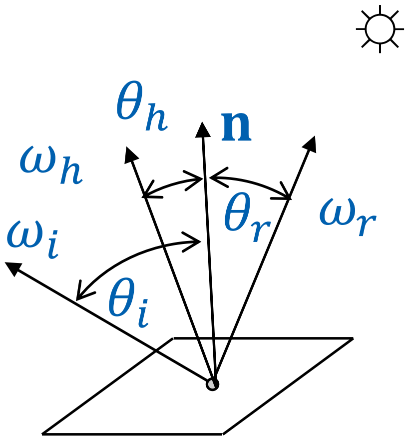
Metal	Linear	Texture	Color
Titanium	0.542,0.497,0.449	194,187,179	
Chromium	0.549,0.556,0.554	196,197,196	
Iron	0.562,0.565,0.578	198,198,200	
Nickel	0.660,0.609,0.526	212,205,192	
Platinum	0.673,0.637,0.585	214,209,201	
Copper	0.955,0.638,0.538	250,209,194	
Palladium	0.733,0.697,0.652	222,217,211	
Mercury	0.781,0.780,0.778	229,228,228	
Brass (C260)	0.910,0.778,0.423	245,228,174	
Zinc	0.664,0.824,0.850	213,234,237	
Gold	1.000,0.782,0.344	255,229,158	
Aluminum	0.913,0.922,0.924	245,246,246	
Silver	0.972,0.960,0.915	252,250,245	

source: Real-Time Rendering 3rd edition

Microfacet models - Shadowing-masking (G)



masking shadowing



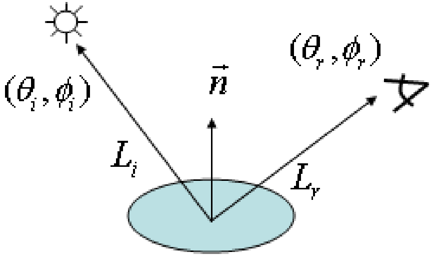
masking shadowing

$$G(\boldsymbol{\omega}_i, \boldsymbol{\omega}_r) = \min\left(1, \frac{2\cos\theta_h \cos\theta_r}{\boldsymbol{\omega}_r \boldsymbol{\omega}_h}, \frac{2\cos\theta_h \cos\theta_i}{\boldsymbol{\omega}_r \boldsymbol{\omega}_h}\right)$$

Cook Torrance

Oren-Nayar BRDF for diffuse surfaces

- Diffuse microfacets
  - Functional approximation to analytic solution for rough surf.



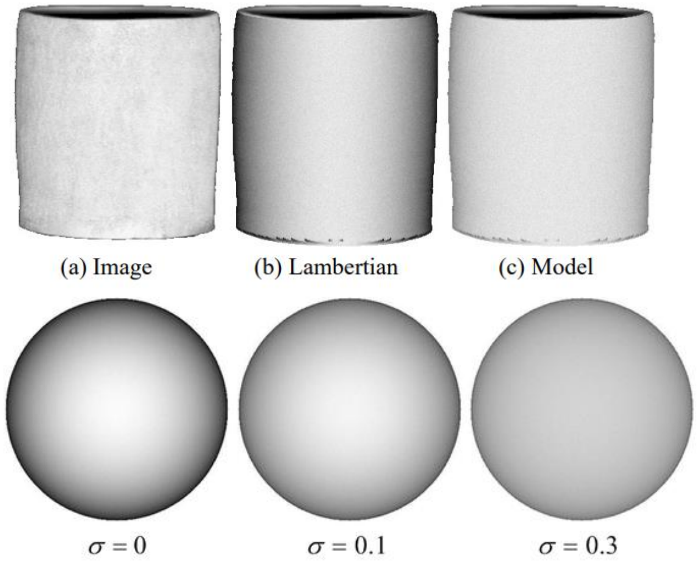
$$f_r(\omega_i, \omega_r) = \frac{\rho}{\pi}(A + (B \max[0, \cos(\phi_i - \phi_r)] \sin\alpha \tan\beta))$$

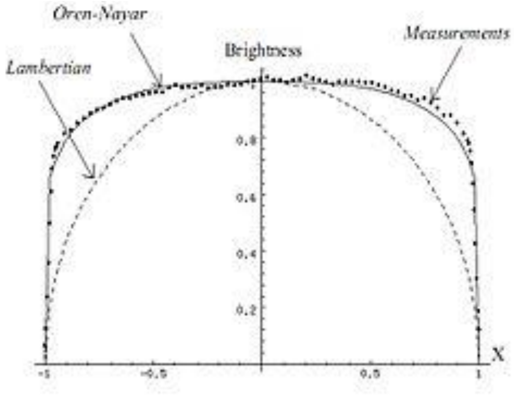
$$A = 1 - 0.5\frac{\sigma^2}{\sigma^2 + 0.33}$$

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

$$\alpha = \max(\theta_i, \theta_r)$$

$$\beta = \min(\theta_i, \theta_r)$$





M. Oren and S.K. Nayar, "Generalization of Lambert's Reflectance Model". SIGGRAPH. pp.239-246, Jul, 1994

Current “PBR” BRDF models

- Disney model (Brent Burley. Physically-Based Shading at Disney. 2012)
  - Cook-Torrance BRDF for specular reflection
  - Oren-Nayar BRDF for diffuse reflection
- GGX Distribution for D (and G) terms
  - Walter et al. Microfacet Models for Refraction through Rough Surfaces
  - https://www.cs.cornell.edu/~srm/publications/EGSR07-btdf.pdf
- Blending using “metalness / metallic” parameter
  - 0: diffuse + specular reflection using wavelength independent (“white”) base reflectivity F_0 ~ [0.04, 0.04, 0.04] (holds for most dielectrics)
  - 1: only specular reflection using albedo as base reflectivity F_0
- SIGGRAPH 14 Course: Physically Based Shading in Theory and Practice
  - https://blog.selfshadow.com/publications/s2014-shading-course/

Example 1 - Unity PBR Shader

```
//Example from Built-in shader at https://unity3d.com/get-unity/download/archive


#define unity_ColorSpaceDielectricSpec half4(0.04, 0.04, 0.04, 1.0 - 0.04) // standard dielectric reflectivity coef at incident angle (= 4%)


inline FragmentCommonData MetallicSetup (float4 i_tex)
{
    half2 metallicGloss = MetallicGloss(i_tex.xy);
    half metallic = metallicGloss.x;
    half smoothness = metallicGloss.y; // this is 1 minus the square root of real roughness m.

    half oneMinusReflectivity;
    half3 specColor;
    half3 diffColor = DiffuseAndSpecularFromMetallic (Albedo(i_tex), metallic, /*out*/ specColor, /*out*/ oneMinusReflectivity);

    FragmentCommonData o = (FragmentCommonData)0;
    o.diffColor = diffColor;
    o.specColor = specColor;
    o.oneMinusReflectivity = oneMinusReflectivity;
    o.smoothness = smoothness;
    return o;
}

inline half3 DiffuseAndSpecularFromMetallic (half3 albedo, half metallic, out half3 specColor, out half oneMinusReflectivity)
{
    specColor = lerp (unity_ColorSpaceDielectricSpec.rgb, albedo, metallic);
    oneMinusReflectivity = OneMinusReflectivityFromMetallic(metallic);
    return albedo * oneMinusReflectivity;
}
```

Example 2 – PBRT V3 materials

- https://github.com/mmp/pbrt-v3/tree/master/src/materials

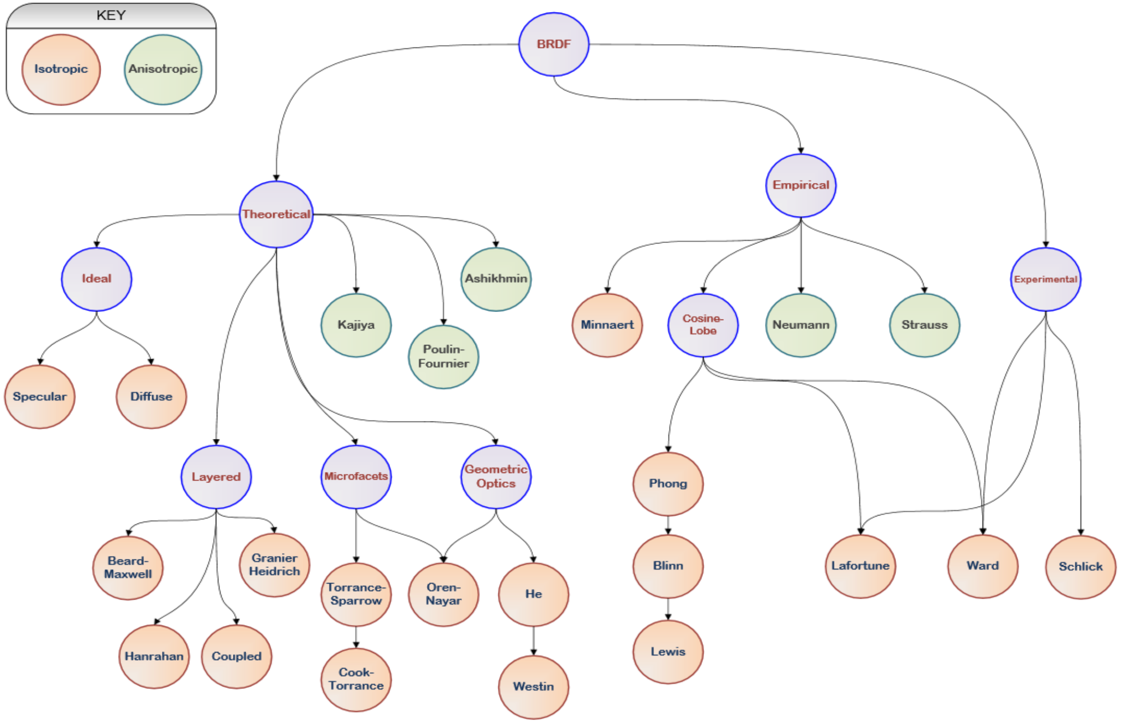
master pbrt-v3 / src / materials / Go to file

rgirish28 and **mmp** Correct importance sampling as per d'Eon paper c65c588 on Dec 13, 2019 History

..

disney.cpp	Fix DisneyMaterial microfacet model	3 years ago
disney.h	Removed unused baseColor texture (#205)	4 years ago
fourier.cpp	Merge pull request #99 from syoyo/bswap-fix	6 years ago
fourier.h	Add namespace pbrt.	6 years ago
glass.cpp	Standardize on "eta" for specifying IOR in materials.	6 years ago
glass.h	Add namespace pbrt.	6 years ago
hair.cpp	Correct importance sampling as per d'Eon paper	3 years ago
hair.h	Add missing degrees->radians conversion for Hair alpha parameter.	6 years ago
kdsubsurface.cpp	Fix default for KdSubsurfaceMaterial "mfp" parameter.	6 years ago
kdsubsurface.h	Add namespace pbrt.	6 years ago
matte.cpp	Add namespace pbrt.	6 years ago
matte.h	Add namespace pbrt.	6 years ago
metal.cpp	Add namespace pbrt.	6 years ago
metal.h	Add namespace pbrt.	6 years ago
mirror.cpp	Add namespace pbrt.	6 years ago

BRDF Models - Overview



Rosana Montes, Carlos Ureña. An Overview of BRDF Models.

Scattering Models - Timeline

- Minnaert (1941)
- Torrance-Sparrow (1967)
- Phong (1975)
- Cook-Torrance (1981)
- Strauss (1990)
- Ward (1992)
- Hanrahan and Kreuger (1993)
- Blinn-Phong (1994)
- Oren-Nayar (1994)
- Phong physical (1994)
- Schlick (1994)
- Lafortune (1997)
- Shirley-Hu-Smits-Lafortune (1997)
- Neumann-Neumann-Kalos (1999)
- Neumann (1999)
- Ashikhmin-Shirley (2000)
- Kelemen-Kalos (2001)
- Beard-Maxwell (2002)
- Ward-Dür (2006)
- Kurt-Kalos-Krivanek (2010)
- Moroder-Dür (2010)
- …

BRDF Models

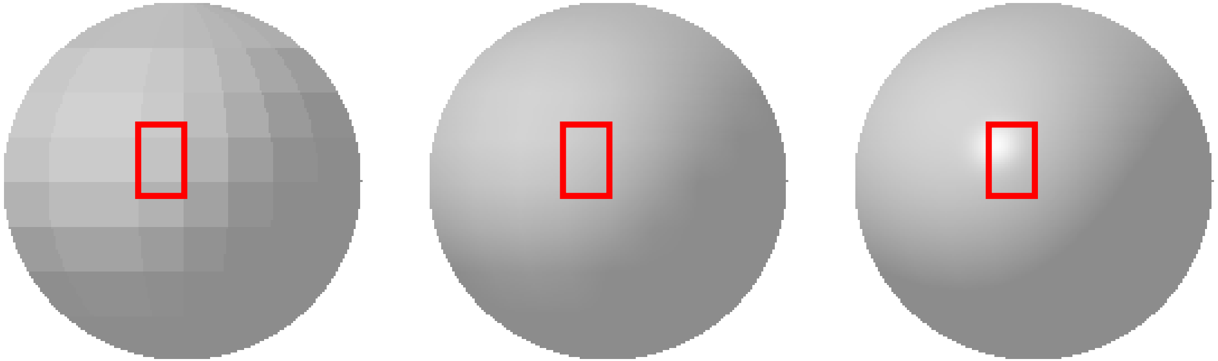
- DEMO

Outline

- Surface appearance — MPG 10
- Radiometry — MPG 10.1
- Light sources — MPG 10.6
- Surface reflectance models, BRDF — MPG 10.2-10.5
- Shading — MPG 10.7

Shading in Rasterization

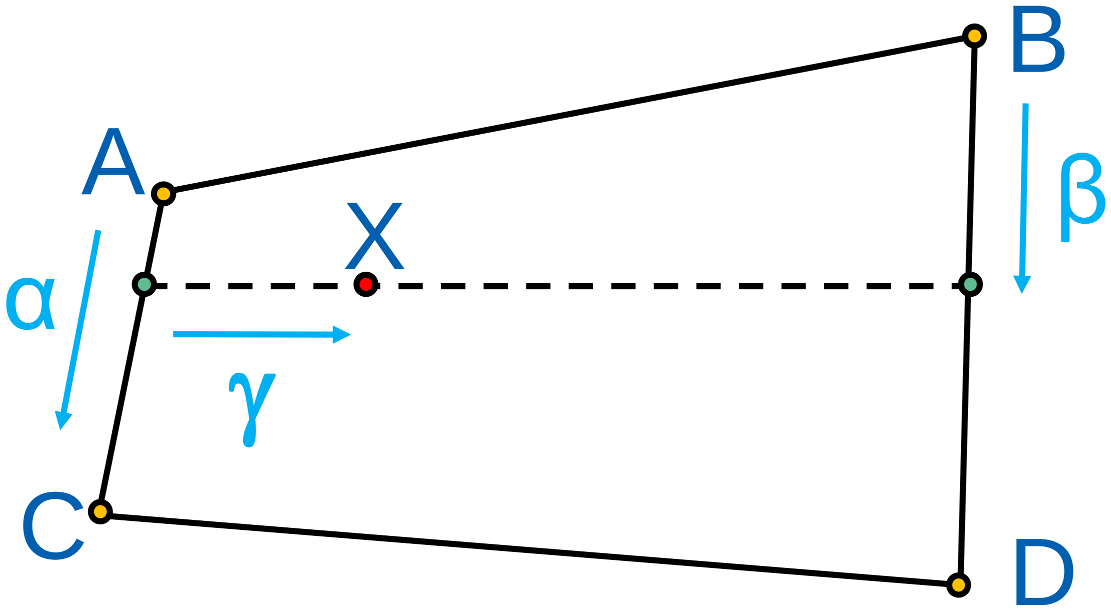
- Determining colors / shades of all patch points
  - Constant color
  - Interpolation of colors from vertices
  - Interpolation of normals from vertices



Smooth Shading

- Gouraud interpolation of color
  - Good for diffuse surfaces
  - Illumination model computed apriori
  - Simple HW support
- Phong interpolation of normals
  - More realistic for glossy surfaces
  - Illumination model computed for all surface points
  - Slower

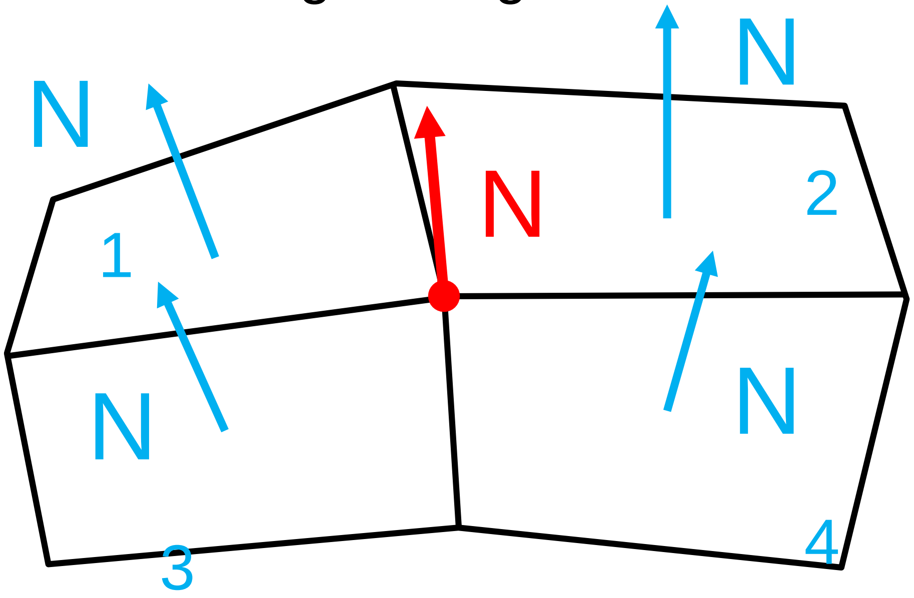
Principle of Bilinear Interpolation



$$f_X = (1-\gamma).[(1-\alpha).f_A + \alpha.f_C] + \gamma.[(1-\beta).f_B + \beta.f_D]$$

Computing Vertex Normals

- Analytically (from surface definition)
- From normals of neighboring faces:

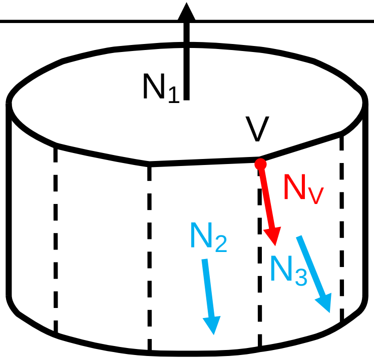


$$N = (N_1+N_2+N_3+N_4)/4$$

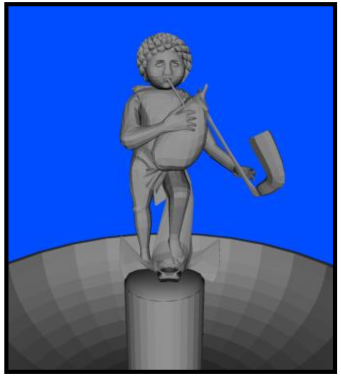
Real and Auxiliary Edges

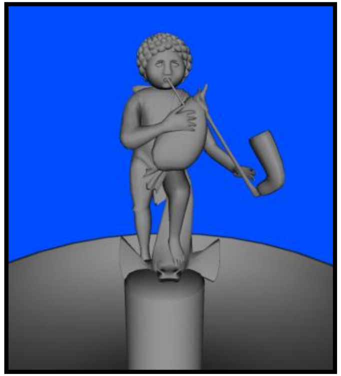
a) Stored in model:

$$N_V = (N_2+N_3)/2$$



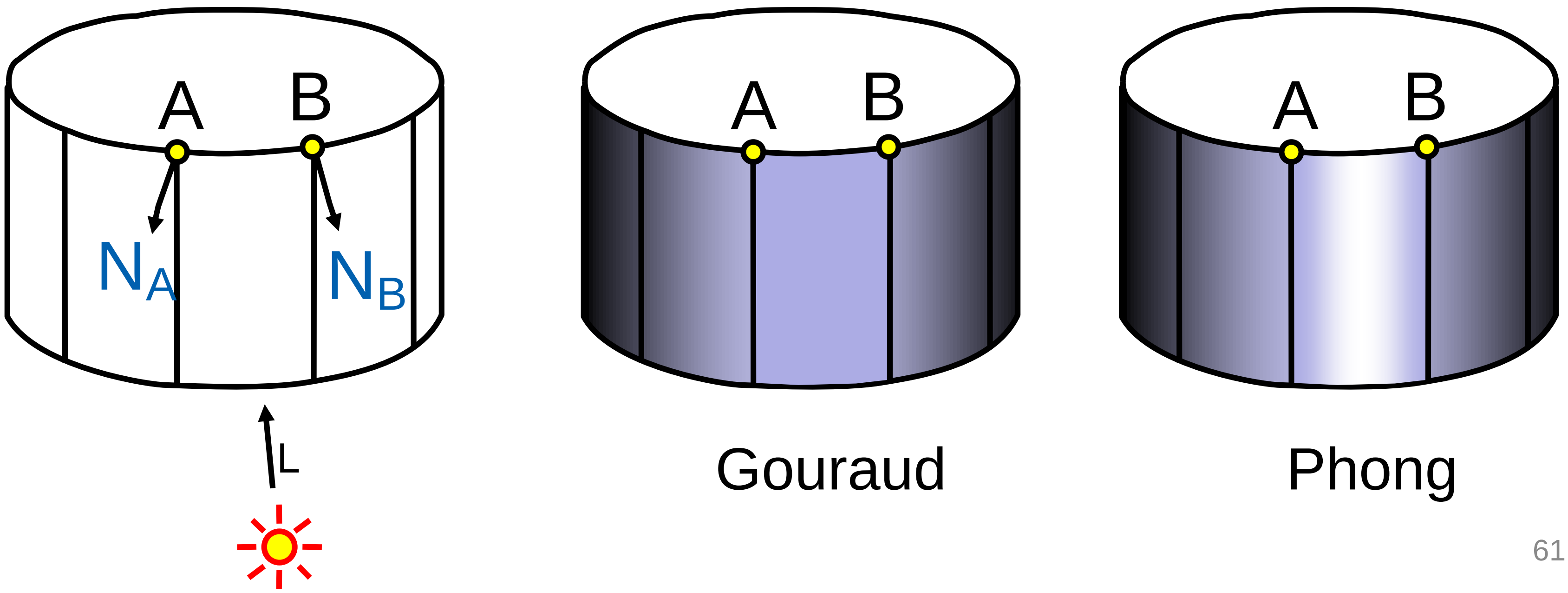
b) *Computed using crease angle*





Gouraud versus Phong Shading

- Gouraud does not capture maximal reflection
- Gouraud not invariant to rotation – temporal artifacts



Outline

▪ Surface appearance	MPG 10
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KATEDRA POČÍTAČOVÉ GRAFIKY A INTERAKCE

Questions?