KATEDRA POČÍTAČOVÉ GRAFIKY A INTERAKCE

Light & Shading

Jiří Bittner

Outline

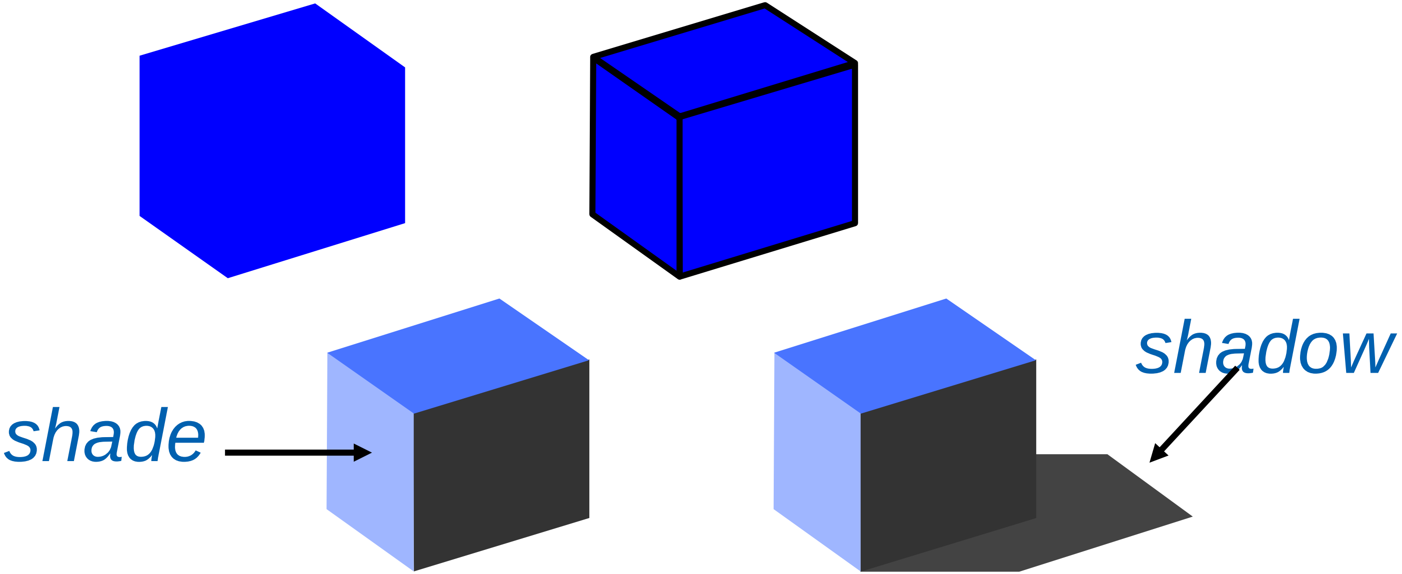
▪ Surface appearance	MPG 10
▪ Radiometry	MPG 10.1
▪ Light sources	MPG 10.6
▪ Surface reflectance models, BRDF	MPG 10.2-10.5
▪ Shading	MPG 10.7

Surface Appearance

- Surface geometry
- Light sources
- Surface reflectance

Illumination Enhances Spatial Cues

- Perception of surfaces
  - Surface shape, structure
- Perception of object positions
  - Shadows, indirect 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)

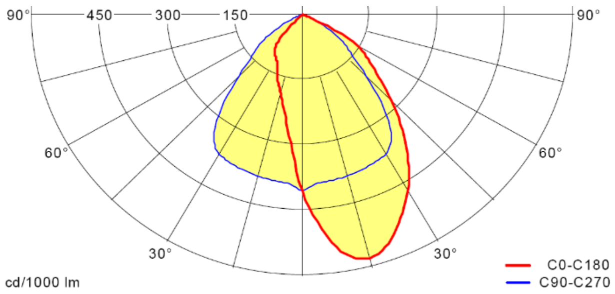
- Irradiance (Intenzita ozáření) E, $[W/m^2]$
  - How many photons per unit area and unit time reach given place

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

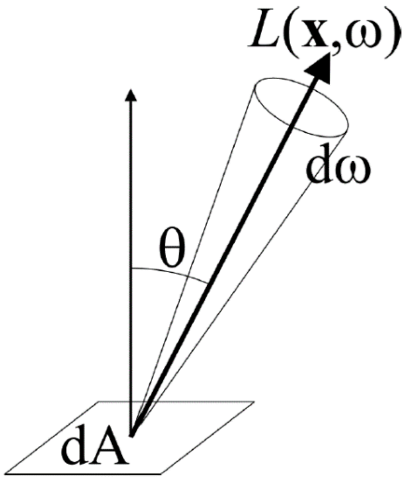


Source: G. Wallner, Geometry of arbitrary light distributions

Radiometry – cont.

- Radiance (Zář)

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



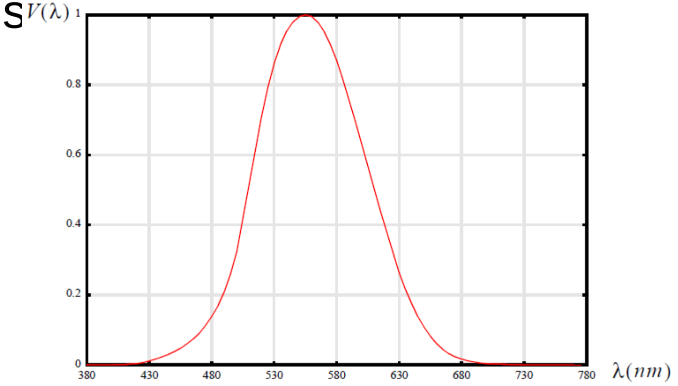
- Camera/eye sensor response is directly **proportional to radiance**
- Other quantities can be obtained by radiance integration

Radiometry vs Photometry

- Radiometry
  - 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 s
    (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**	**symb ol**	**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 light, and 10% ultraviolet light
- **546 W/m² visible light**

Exercise – LED Bulb

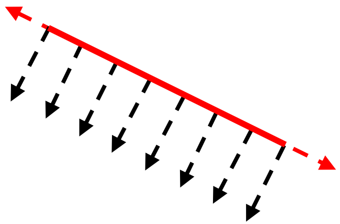
- Luminous flux of 11W LED light bulb $\Phi_v = 1100lm$
- Distance to a table $d = 1.5m$

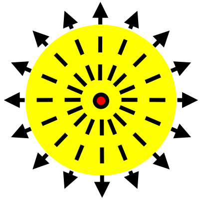
- Direct illuminance at table surface $E_v = \frac{1100lm}{4\pi d^2} = 38.9\ lx$

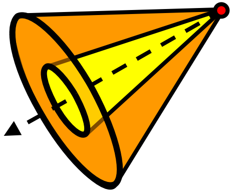
- Radiant flux of LED bulb $\Phi = \frac{1100lm}{680lmW^{-1}} = 1.62\text{W}$
- Irradiance on the table surface $E = \frac{1.62W}{4\pi d^2} = 0.057Wm^{-2}$

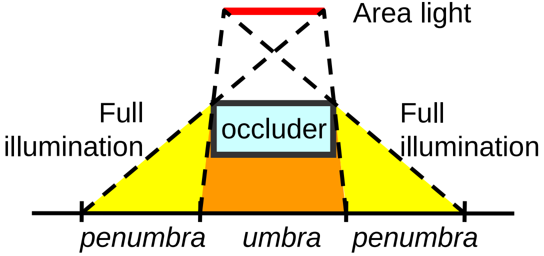
Light Sources

- Directional
  - No origin
  - Constant intesity
- Point
  - Intenzity decreases
- Area
  - Penumbra

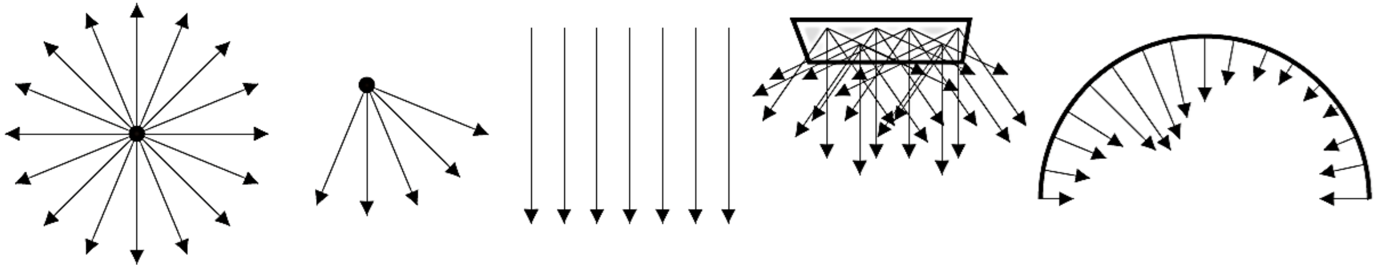




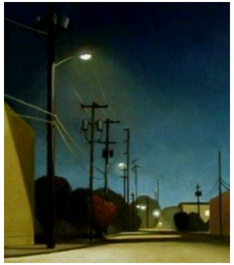


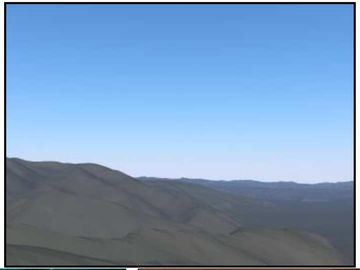


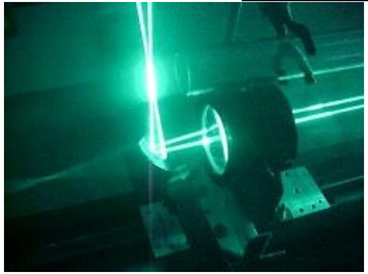
Light Sources - examples



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







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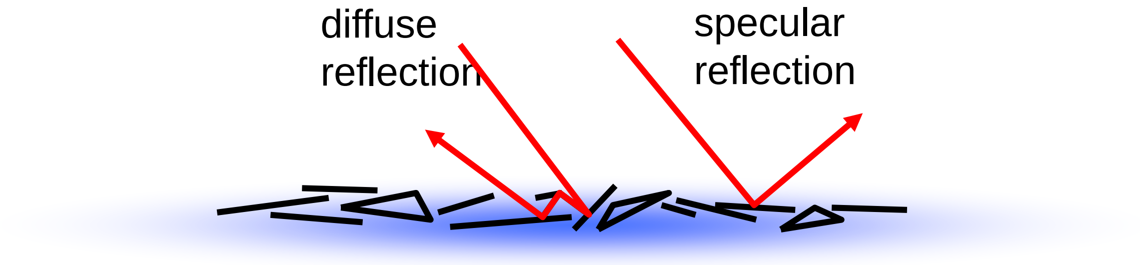
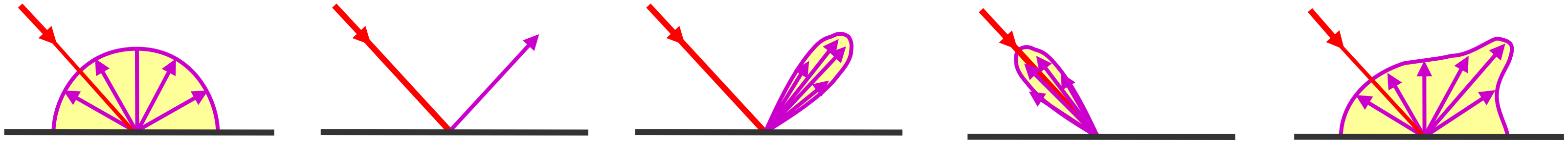
Light Reflection at Surface





ideal diffuse

(surface color dominates)

ideal specular

(light color dominates)

glossy

retro-reflection

real reflection

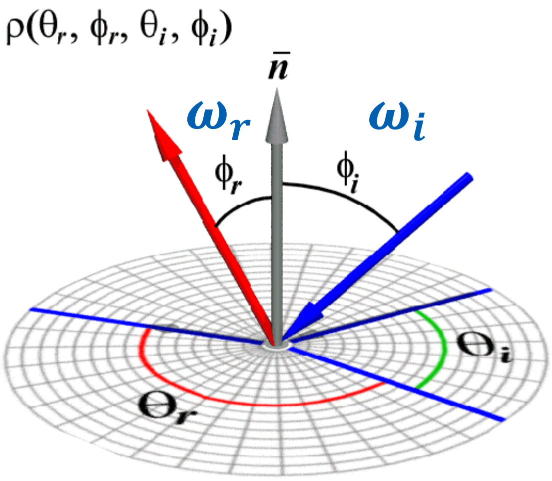
Light reflection at Surface

- BRDF (bidirectional reflection distribution function)

$$f_r(\omega_i, \omega_r) = \frac{dL_r(\omega_r)}{L_i(\omega_i)\cos\Phi_i\, d\omega_i}$$

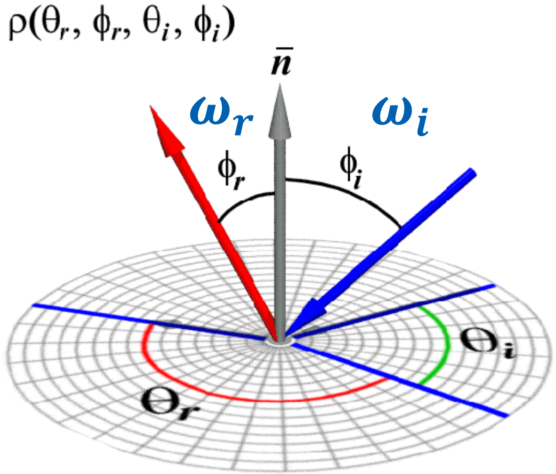
$$dL_r(\omega_r) = f_r(\omega_i, \omega_r)\, L_i(\omega_i)\cos\Phi_i\, d\omega_i$$

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



Reflection equation / Rendering equation

BRDF properties



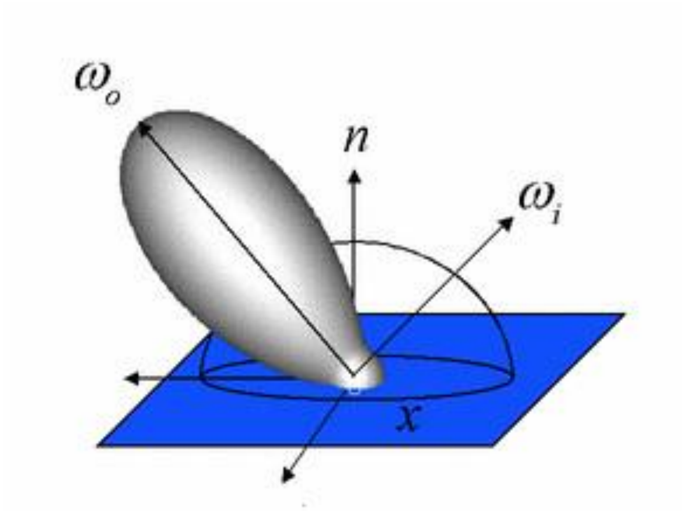
$$\int_{\Omega} f_r(\omega_i, \omega_r)\, \cos \Phi_i \, d\omega_i \leq 1$$

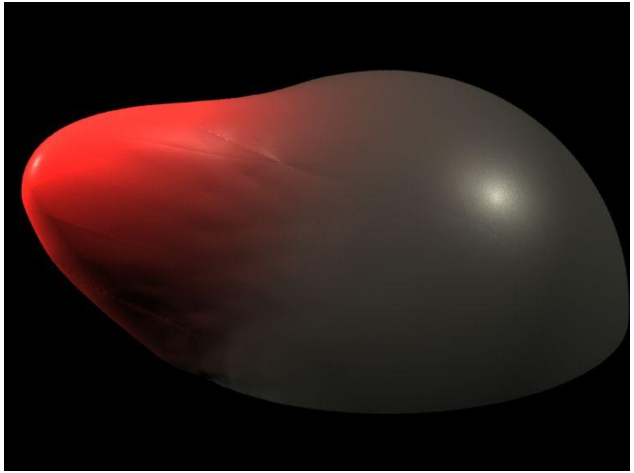
Energy conservation

$$f_r(\omega_i, \omega_r) = f_r(\omega_r, \omega_i)$$

Helmholtz reciprocity

BRDF Visualization



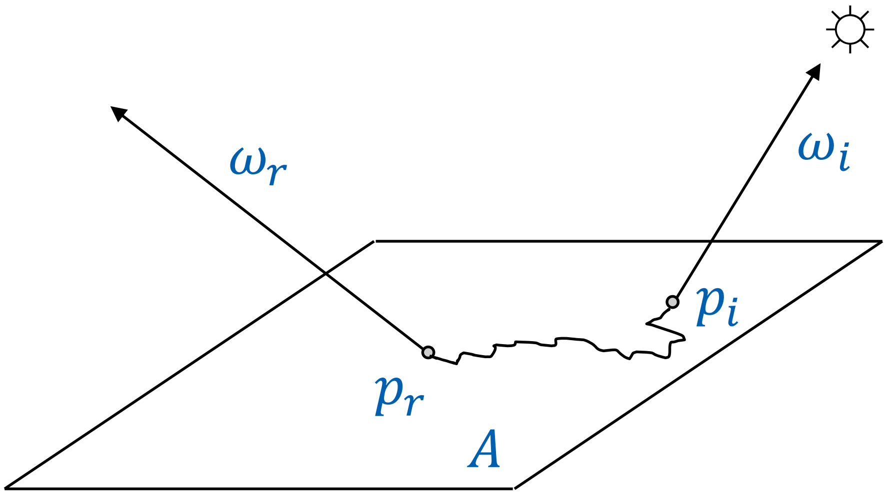


Other Scattering Models

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

BSSRDF

- Bidirectional subsurface scattering reflectance distribution function



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

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

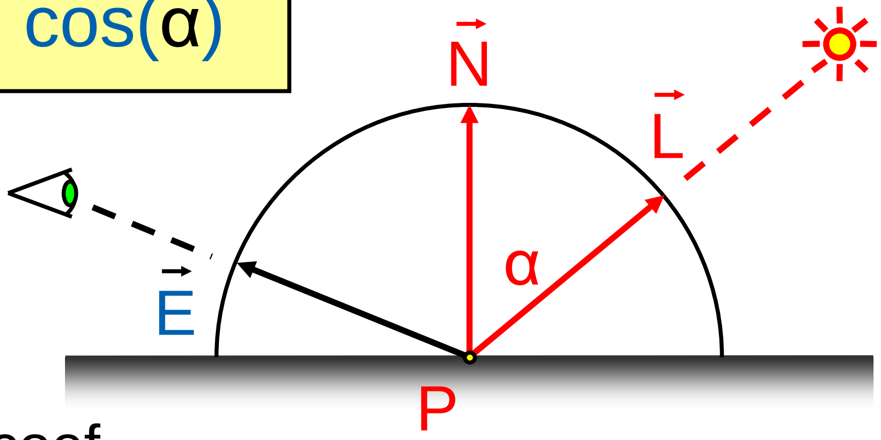
$$I_A = C_A \cdot (C_D \cdot k_A)$$

- 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

$$I_D = C_L \,.\, C_D \,.\, k_D \,.\, \cos(\alpha)$$



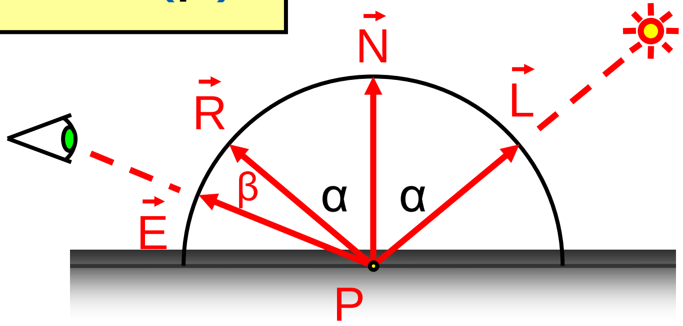
- C_L light color
- C_D surface color
- $k_D \in \langle 0,1 \rangle$ Diffuse reflection coef.
- $\cos(\alpha)$ = dot product of L and N

Specular Component

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

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

- specular color C_S

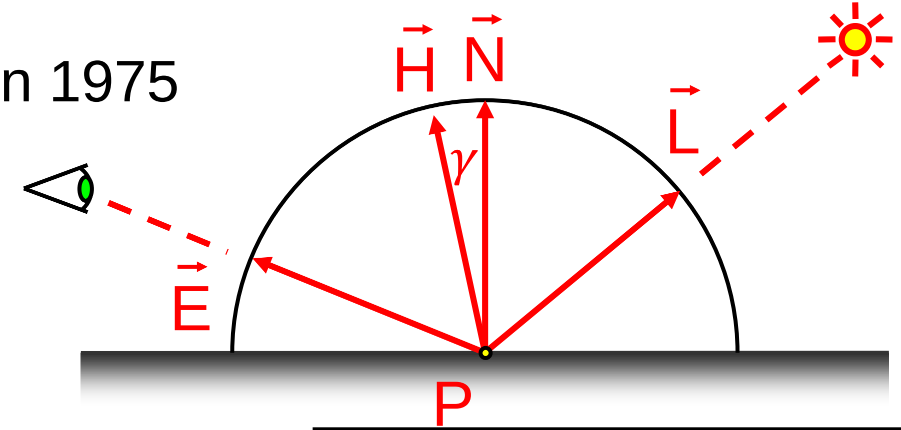


R = 2(LN)N-L

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

Blinn-Phong Illumination Model

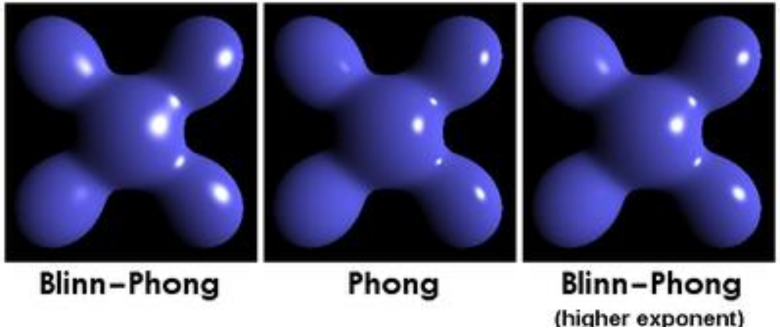
- Jim Blinn 1975



$H = (L+E)/2$

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

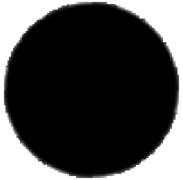
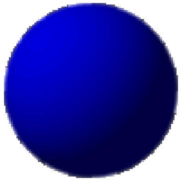
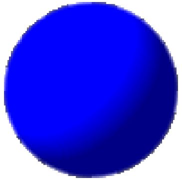
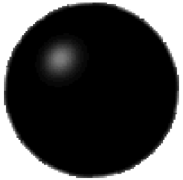
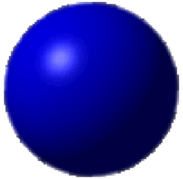
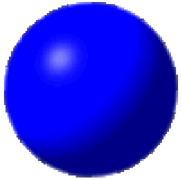
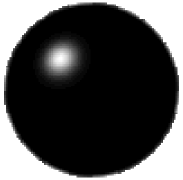
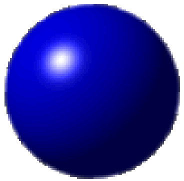
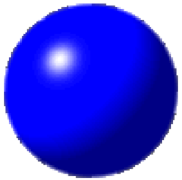
OpenGL / DirectX



Use 4x higher h than Phong!

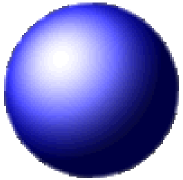
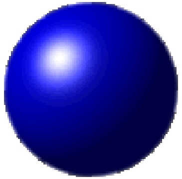
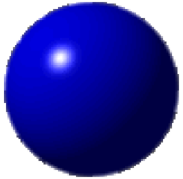
https://seblagarde.wordpress.com/2012/03/29/relationship-between-phong-and-blinn-lighting-model/

Examples - Phong

k_S \ k_D	0.0	0.5	1.0
0.0			
0.5			
1.0			

$k_A = 0.0$, $h = 50$

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

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

- Practical setting of Phong model

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

Physically Plausible Phong Model

- [Lafortune & Willems 1994]

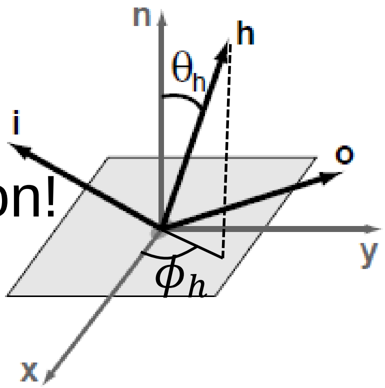
$$f_r(\omega_i, \omega_r) = \frac{k_d}{\pi} + \frac{k_s(n+2)}{2\pi} \cos^n \alpha$$

$$k_s + k_d \leq 1$$

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

Ward BRDF

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



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

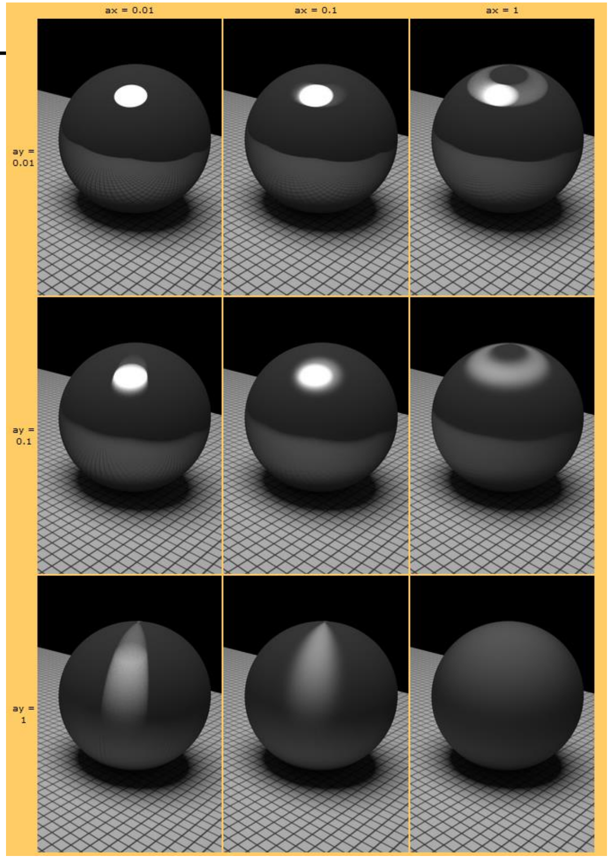
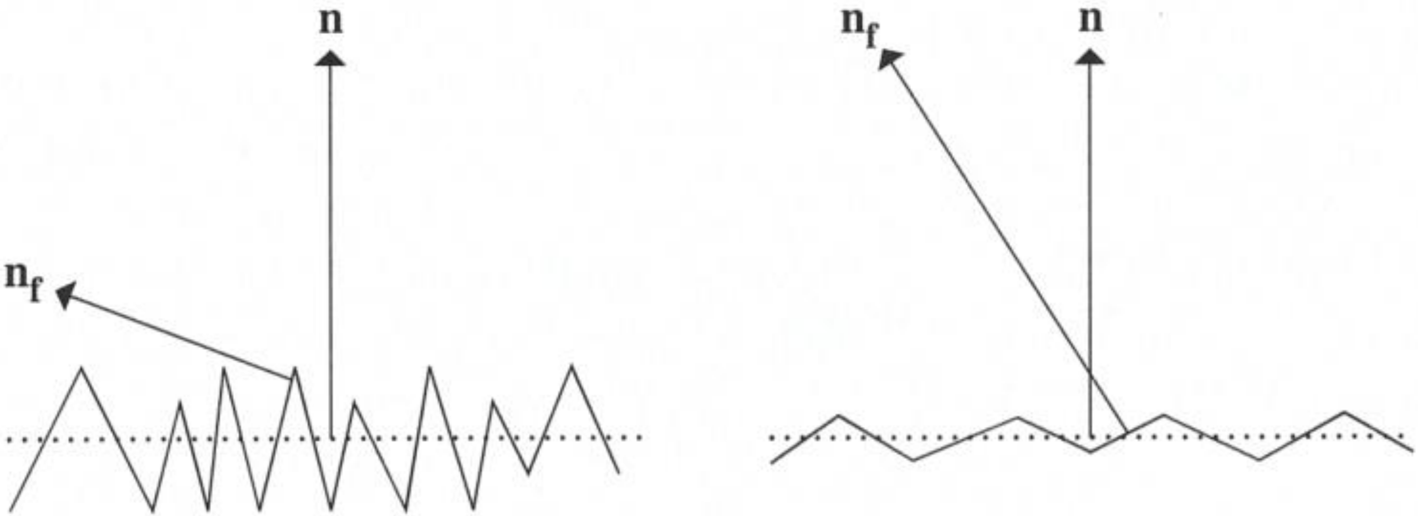


Image: Chia-Kai Liang

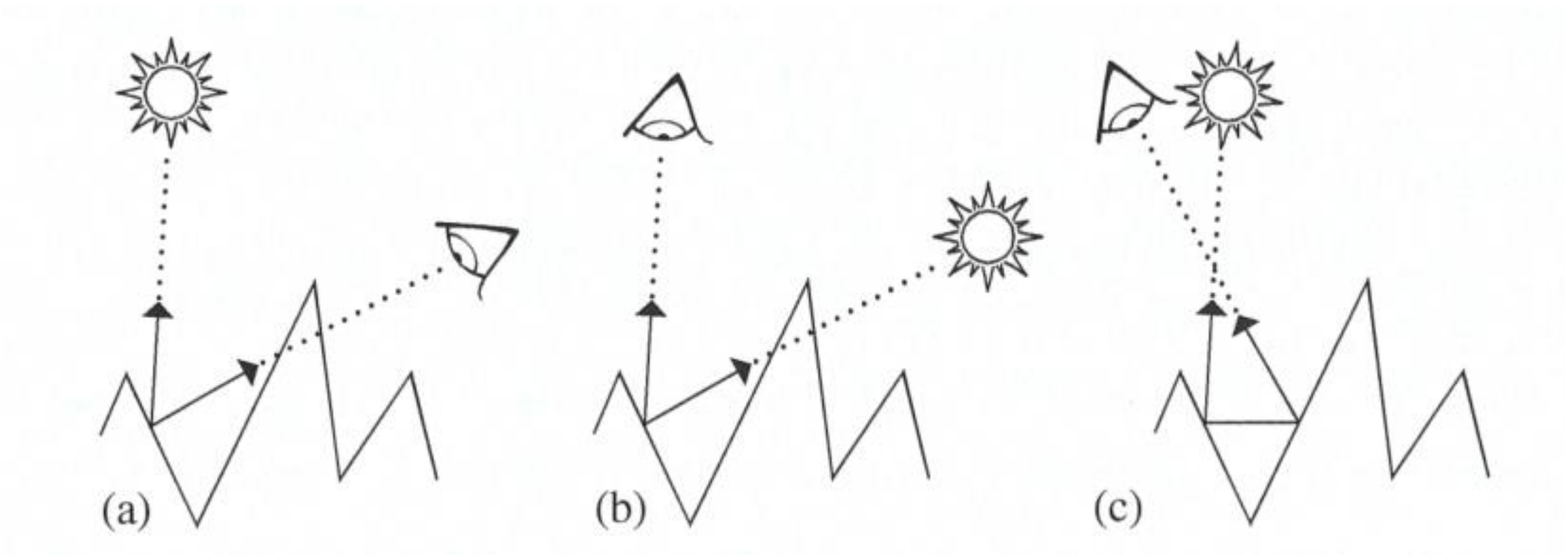
Physically Based Models

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



Microfacet models

- Normal distribution (D), shadowing-masking (G), Fresnel term (F)

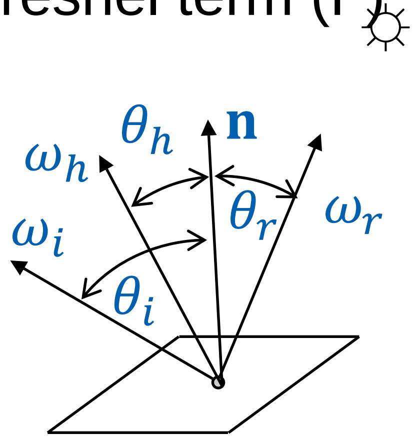


masking shadowing interreflection

Cook-Torrance BRDF for specular surfaces

- Specular microfacets
- Normal distribution (D), shadowing-masking (G), Fresnel term (F)

$$f_r(\omega_i, \omega_r) = \frac{D(\omega_h)\, G(\omega_i, \omega_r) F(\omega_r)}{4 \cos \omega_i \cos \omega_r}$$



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

α roughness

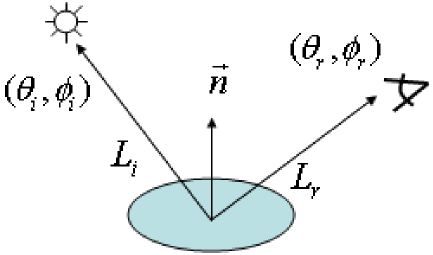
$$G = \min(1, \frac{2 \cos \theta_h \cos \theta_r}{\omega_r h}, \frac{2 \cos \theta_h \cos \theta_i}{\omega_r h})$$

$$F = F_0 + (1 - F_0)(1 - \cos(\theta))^5, F_0 = \left(\frac{\eta_1 - \eta_2}{\eta_1 + \eta_2}\right)^2$$

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

Oren-Nayar BRDF for diffuse surfaces

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



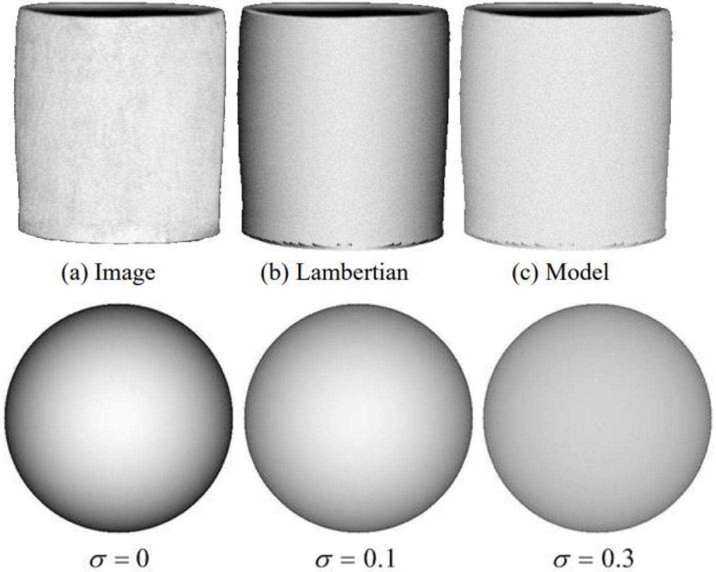
$$f_r(\omega_i, \omega_r) = \frac{\rho}{\pi}(A + (B \max[0, \cos(\phi_i - \phi_r)] \sin\alpha \tan\beta))$$

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

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

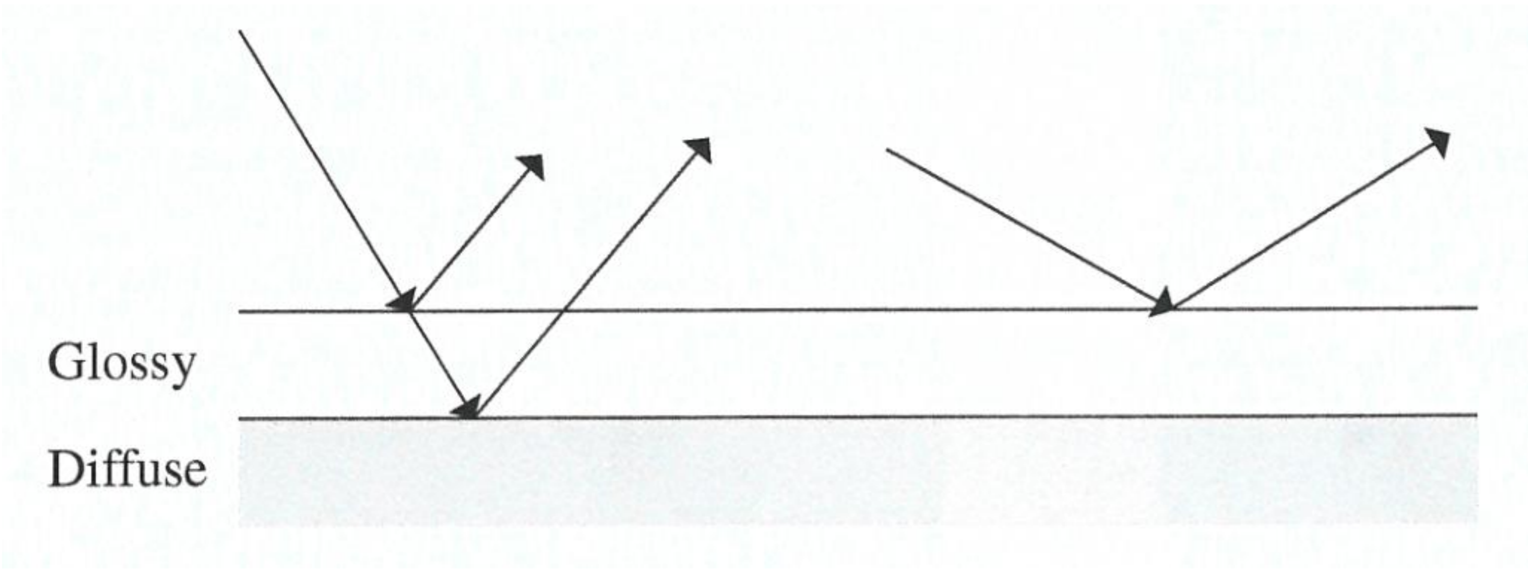
$$\alpha = \max(\theta_i, \theta_r)$$

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



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

Layered models

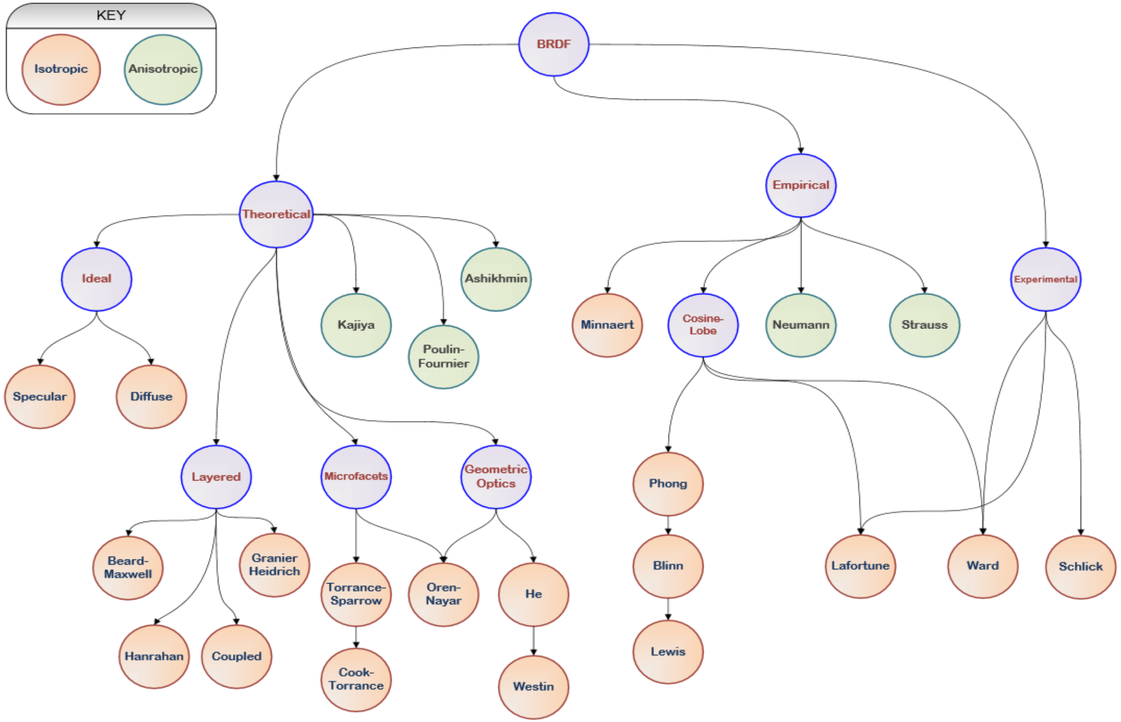


[Ashikhmin and Shirley 2002]

Current “PBR” models

- 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
  - 1 only specular reflection using albedo as base reflectivity F_0
- SIGGRAPH 2014 Course: Physically Based Shading in Theory and Practice
  - https://blog.selfshadow.com/publications/s2014-shading-course/

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)
- …

Illumination Models

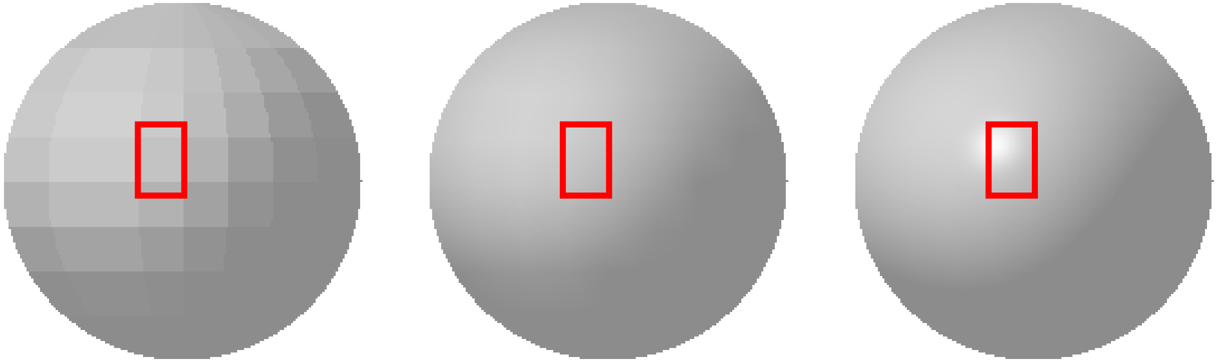
- DEMO

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

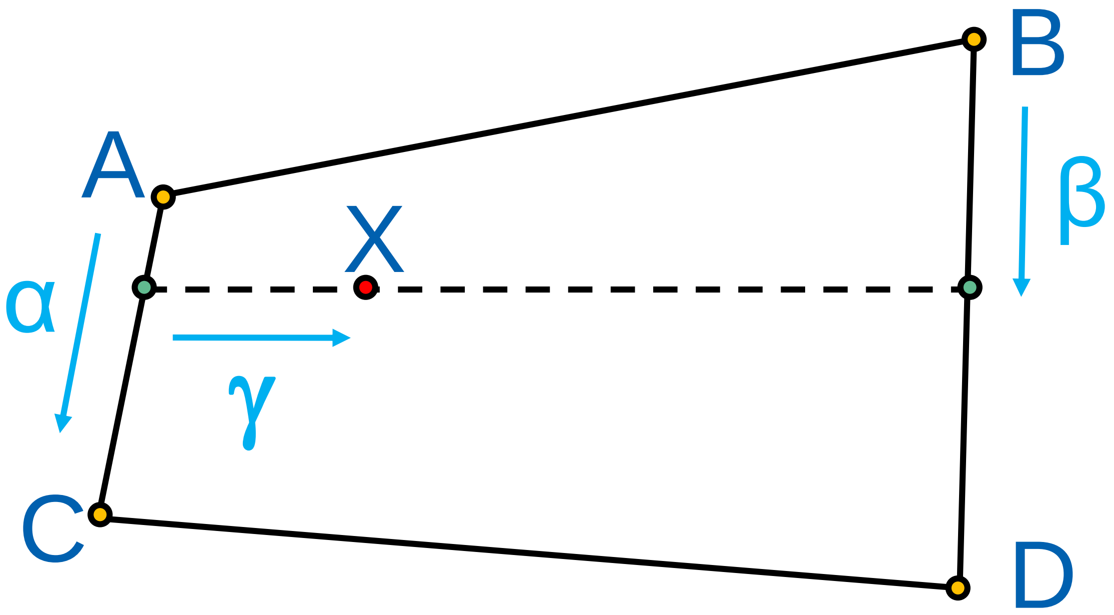
- Determining colors / shades of all patch points
  - Constant color
  - Interpolation of colors from vertices
  - Interpolation of normals from vertices



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

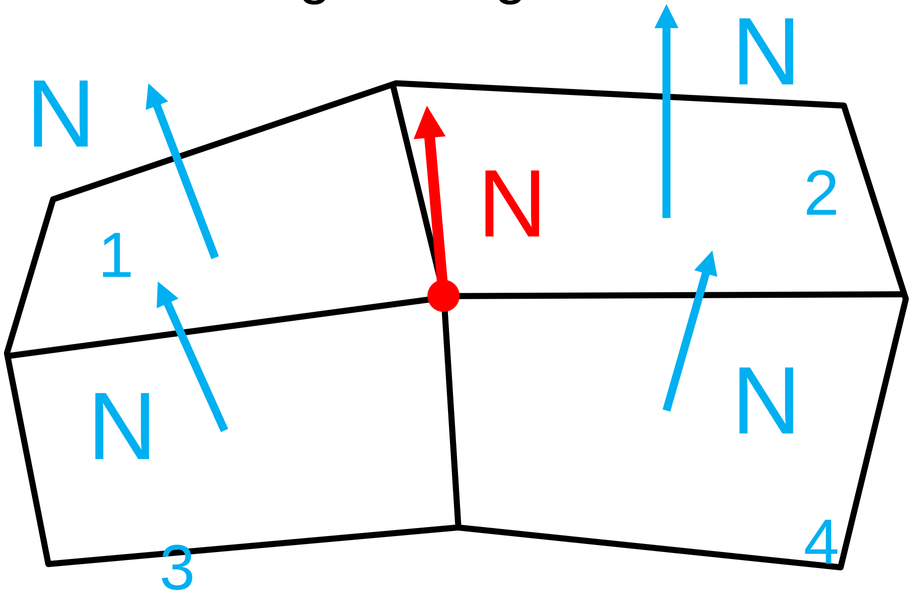
Principle of Bilinear Interpolation



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

Computing Vertex Normals

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

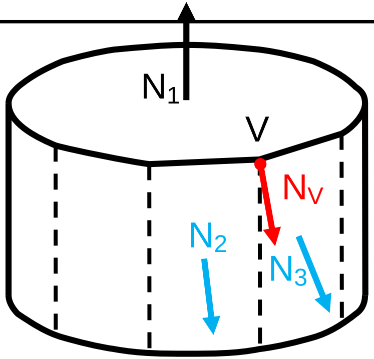


$$N = (N_1+N_2+N_3+N_4)/4$$

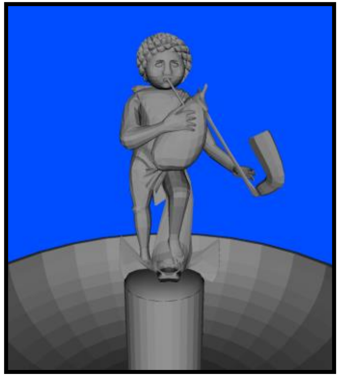
Real and Auxiliary Edges

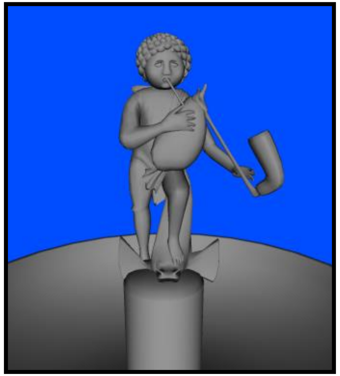
a) Stored in model:

$N_V = (N_2+N_3)/2$



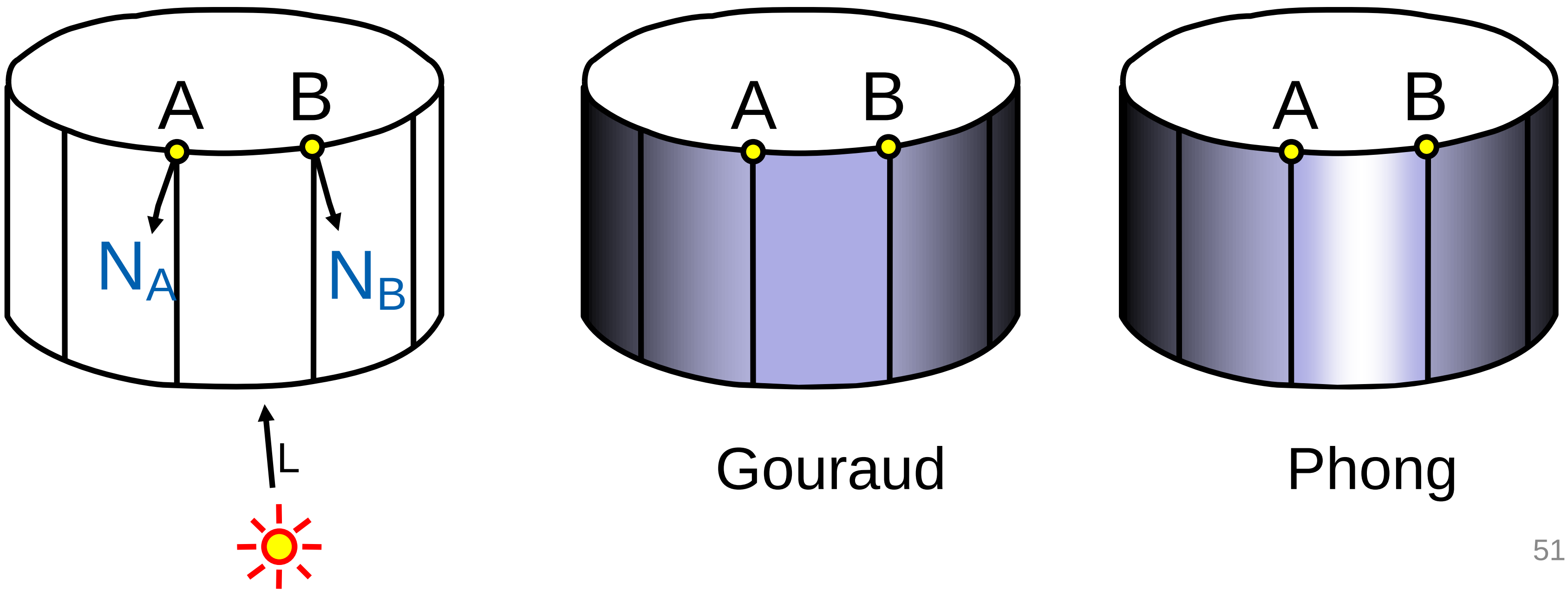
b) *Computed using crease angle*





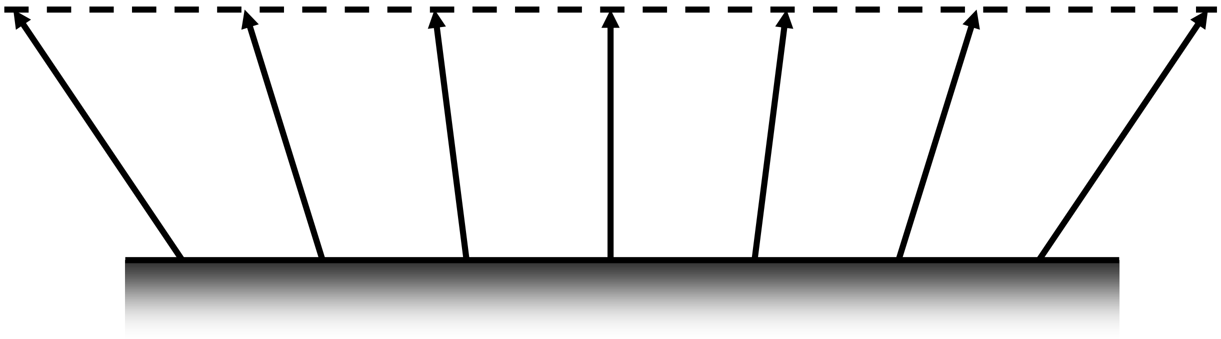
Gouraud versus Phong Shading

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



Normal Interpolation

- Simplified interpolation
  - Linear interpolation by components
  - With normalization
  - Without normalization: neglecting errror



Outline

▪ Surface appearance	MPG 10
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Questions?