

**DCGI**

**KATEDRA POČÍTAČOVÉ GRAFIKY A INTERAKCE**

# Light & Shading

Jiří Bittner

# Outline

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

# Surface Appearance

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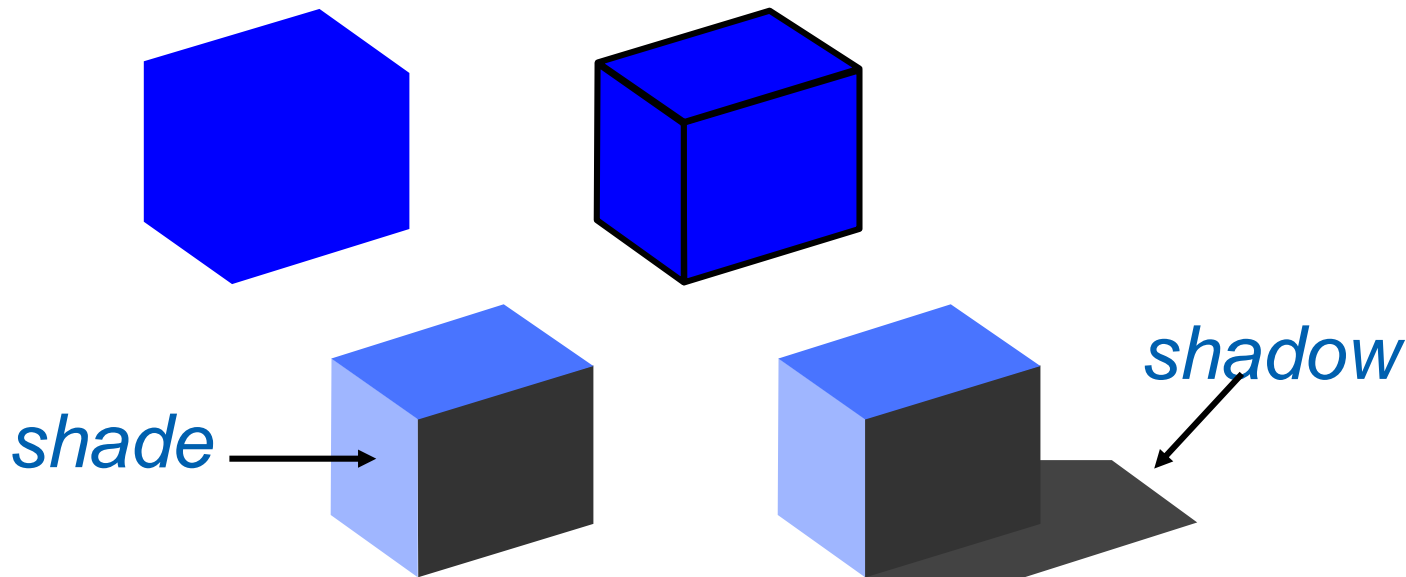
- Surface geometry
- Light sources
- Surface reflectance



# Illumination Enhances Spatial Cues

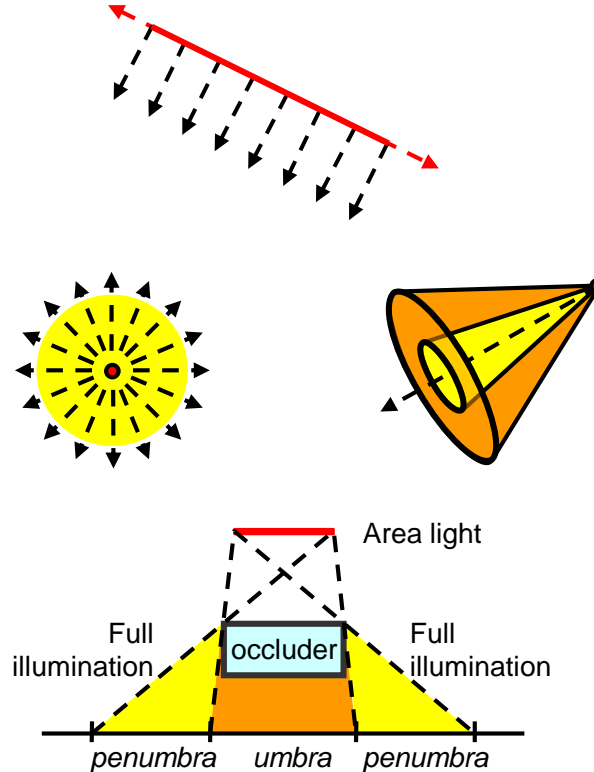
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- Perception of surfaces
  - Surface shape, structure
- Perception of object positions
  - Shadows, indirect illumination

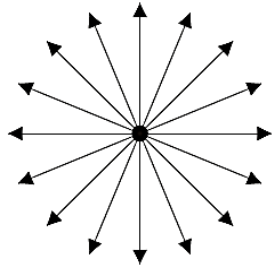


# Light Sources

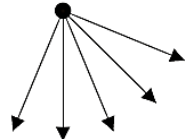
- Directinal
  - No origin
  - Constant intensity
- Point
  - Intensity decreases
- Area
  - Penumbra



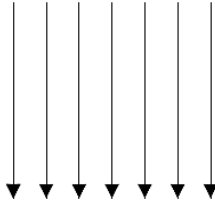
# Light Sources - examples



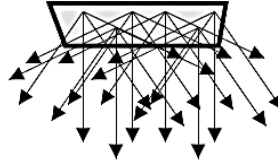
A) Omnidirectional point light



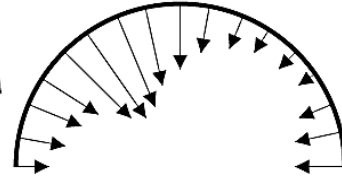
B) Spot light



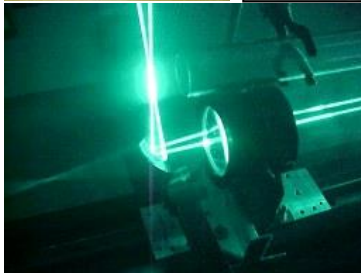
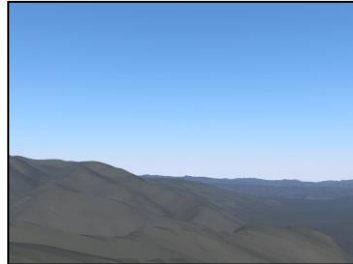
C) Directional light



D) Area light



E) Environment map



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# Light Measurements - Radiometry

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- Power, Radiant flux (zářivý tok)  $P$ ,  $\Phi$

$$\Phi = \frac{dQ}{dt} \text{ [W]}$$

- How fast photons stream through a given place
- Photon energy

$$E_f = h * f \text{ [J]} \quad \text{Planck-Einstein relation}$$

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

- Example

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



# Radiometry – cont.

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- Radiosity (Intenzita vyzařování, Radiozita)

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

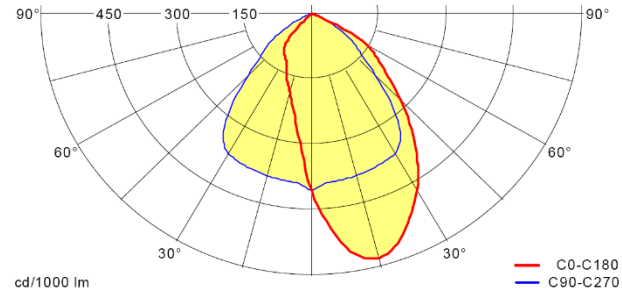
- How many photons per unit area is emitted from a given place in unit of time (power density)
- Irradiance (Intenzita ozáření)  $E$ , [W/m<sup>2</sup>]
  - How many photons per unit area and unit time reach given place

# Radiometry – cont.

- Radiant intensity (Zářivost)

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

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

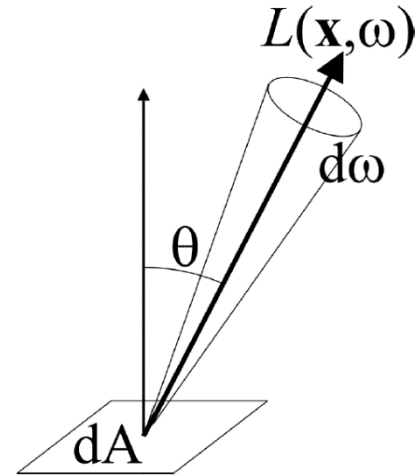


Source: G. Wallner, Geometry of arbitrary light distributions

# Radiometry – cont.

- Radiance (Zář)

$$\begin{aligned} L(\mathbf{x}, \omega) &= \frac{dE}{d\omega} \\ &= \frac{d^2\Phi(\mathbf{x})}{\cos \theta \, dA \, d\omega} \quad [\text{Wm}^{-2}\text{sr}^{-1}] \end{aligned}$$



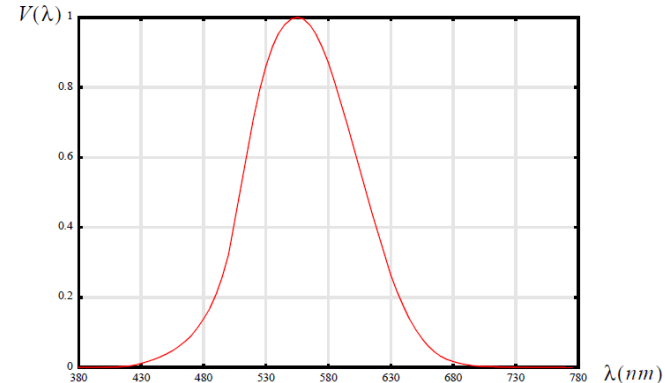
- Camera/eye sensor response is directly **proportional to radiance**
- Other quantities can be obtained by radiance integration

# Radiometry vs Photometry

- Radiometry
  - EM waves 0.01  $\mu\text{m}$  -1mm (ultraviolet to infrared)
  - Radiometric quantities functions of wavelength
- Photometry
  - Describes light – EM waves visible by human eye (380-780nm)
  - Radiometric quantities weighted by eye spectral response (CIE luminance function)

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

Zdroj: P. Dutre – Global Illumination Compendium



# Radiometric & Photometric Quantities

Radiometry			Photometry		
quantity	symbol	unit	quantity	symbol	unit
radiant flux <i>zářivý tok</i>	$\phi$	W	luminous flux <i>světelný tok</i>	$\phi_v$	Lumen
irradiance <i>intenzita ozáření</i>	E	W/m <sup>2</sup>	illuminance <i>osvětlení</i>	$E_v$	Lux
radiant intensity <i>zářivost</i>	I	W/sr	luminous intensity <i>svítivost</i>	$I_v$	cd
radiance <i>zář</i>	L	Wm <sup>-2</sup> sr <sup>-1</sup>	luminance <i>jas</i>	$L_v$	cd/m <sup>2</sup>

# Exercise

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- Radiant flux of the Sun  $3.86 \cdot 10^{26} \text{ W}$
- Distance of Earth from Sun  $1.5 \cdot 10^{11} \text{ m}$
- Irradiance at upper atmosphere layer?
  
- **$1365 \text{ W/m}^2$**
- 50% infrared light, 40% visible light, and 10% ultraviolet light
- **$546 \text{ W/m}^2$  visible light**

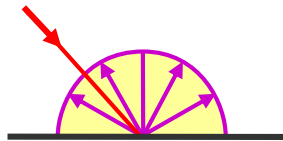
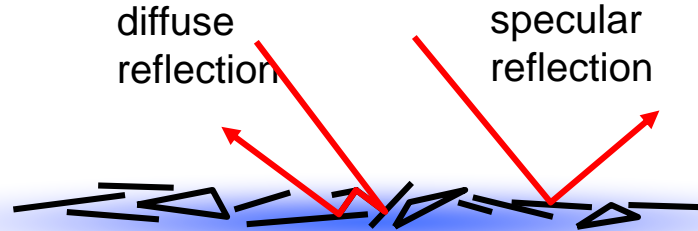
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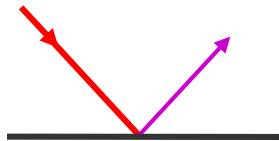
# Light Reflection at Surface

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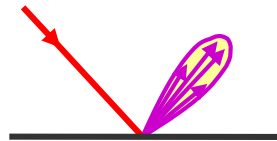
ideal diffuse

*(surface color dominates)*



ideal specular

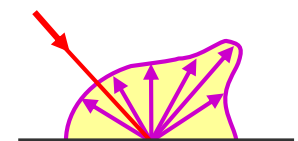
*(light color dominates)*



glossy



retro-reflection



real reflection



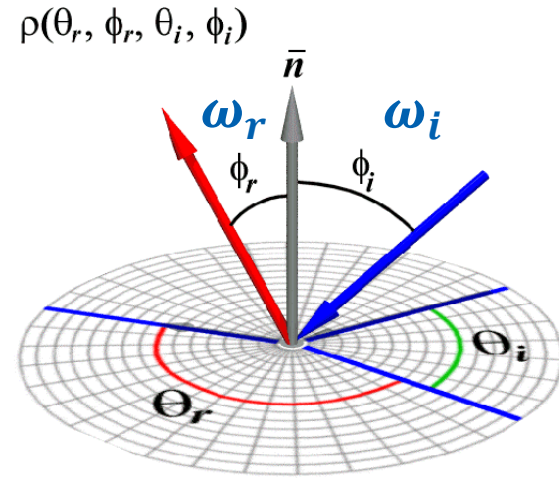
# Light reflection at Surface

- BRDF (bidirectional reflection distribution function)

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

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

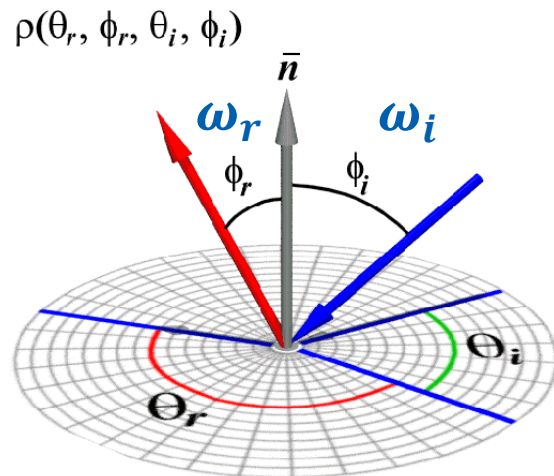
$$L_r(\omega_r) = \int_{\Omega} f_r(\omega_i, \omega_r) L_i(\omega_i) \cos \Phi_i d\omega_i$$



Reflection equation / Rendering equation

# BRDF properties

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

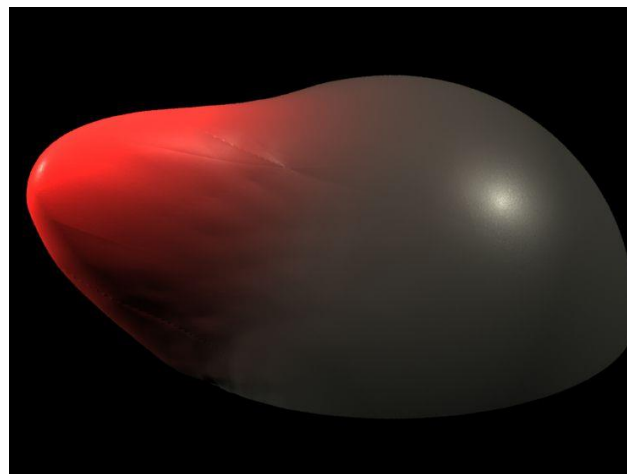
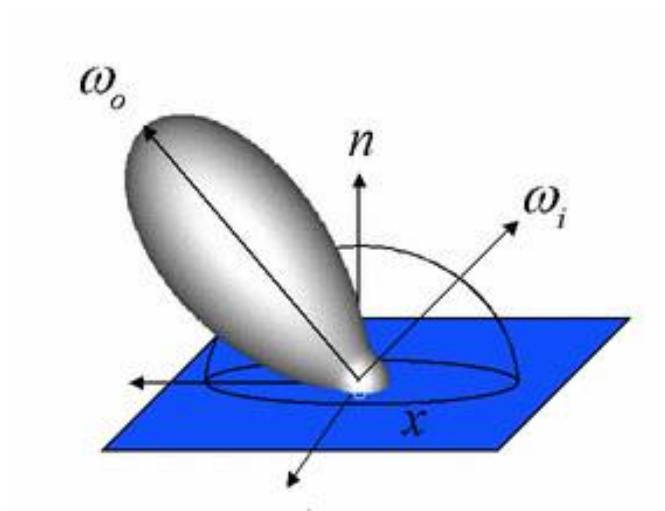
Energy conservation

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

Helmholtz reciprocity

# BRDF Visualization

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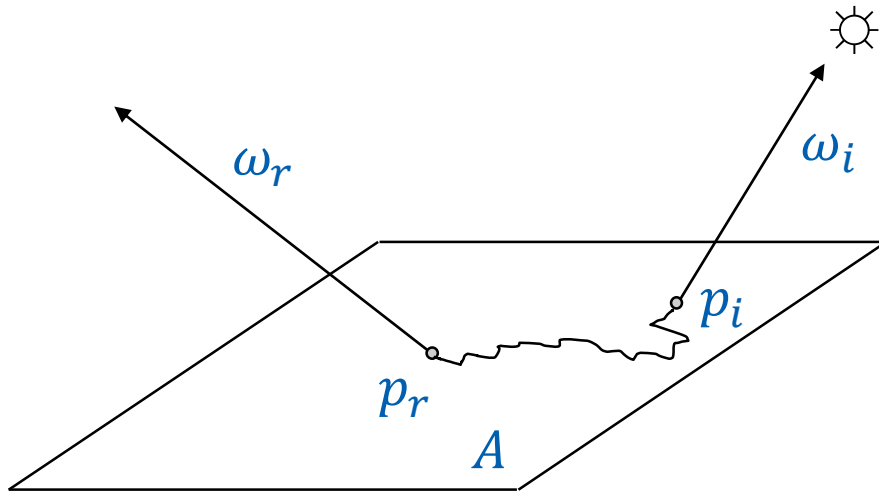
# More General Descriptions

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- 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

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- Reflection/Shading/Lighting/Illumination model
  - Modeling BSDF / BRDF
- Scattering model determines surfaces appearance
  - light reflection / refraction
- 1. Empirical
  - Blinn, Phong, Minuart, ...
- 2. Physically based
  - Cook-Torrance, Torrance-Sparrow, ...
- 3. Measured BRDF data

# Empirical Scattering Models

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

# Phong Illumination Model

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- Bui-Tuong Phong, dissertation 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

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

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

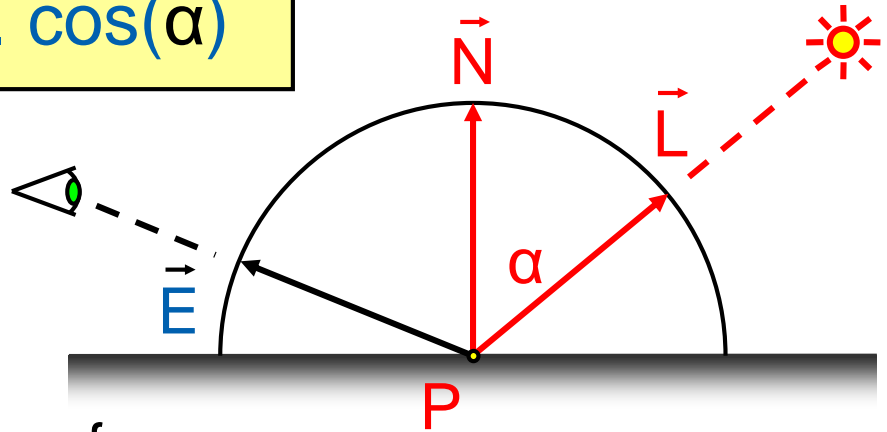
- $C_A$  – color of ambient light
- $C_D$  – surface color (as for diffuse component)
- $k_A \in \langle 0,1 \rangle$  – ambient reflection coefficient

# 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.
- $\cos(\alpha)$  = dot product of L and N

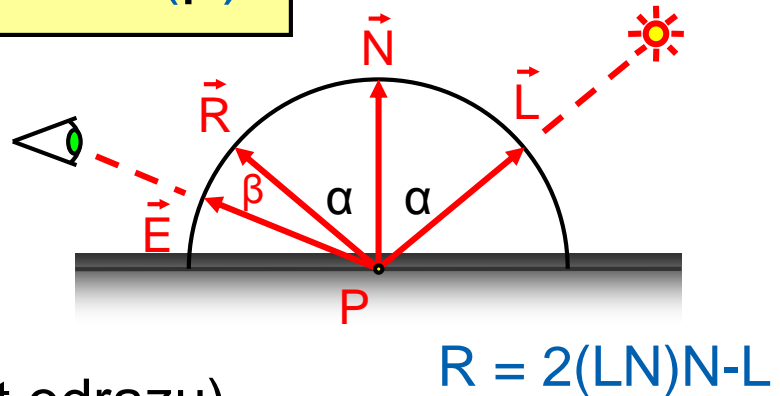


# Specular Component

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

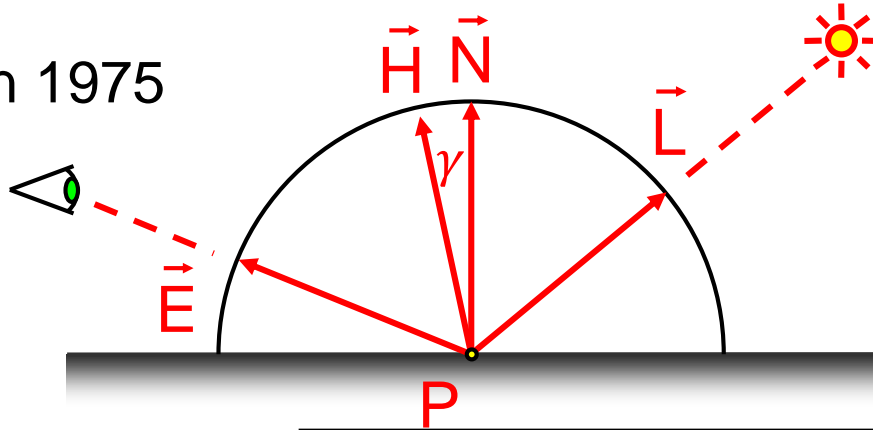
$$I_S = C_L \cdot C_S \cdot k_S \cdot \cos^h(\beta)$$

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



# Blinn-Phong Illumination Model

- Jim Blinn 1975

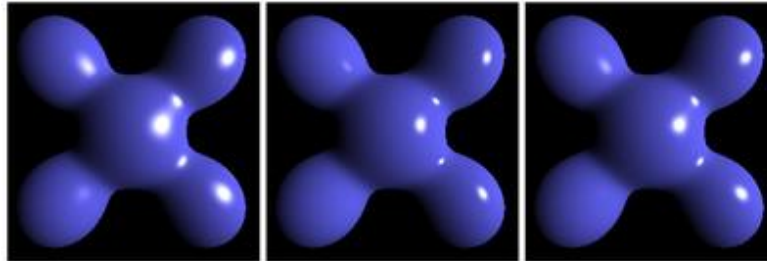


$$H = (L + E) / 2$$

$$I_s = C_L \cdot C_s \cdot k_s \cdot \cos^h(\gamma)$$

OpenGL / DirectX

Use 4x higher h than Phong!












Blinn-Phong

Phong

Blinn-Phong  
(higher exponent)

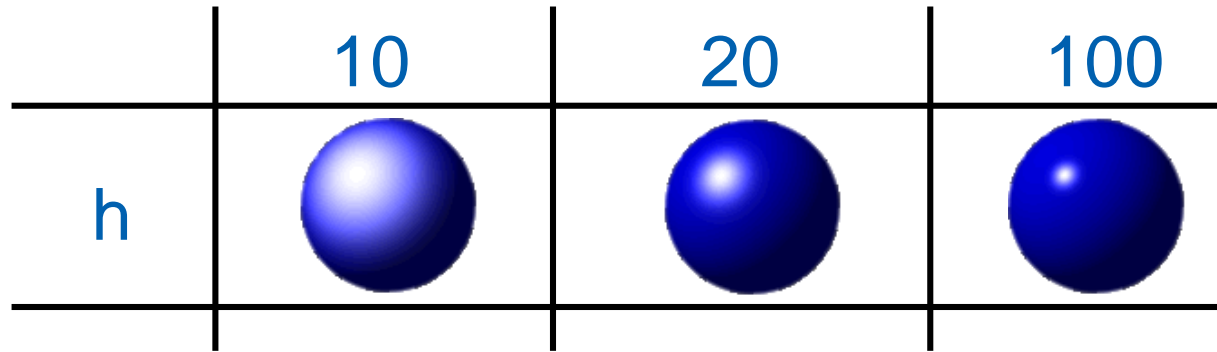
# Examples - Phong

$k_S \backslash k_D$	0.0	0.5	1.0
0.0			
0.5			
1.0			

$k_A = 0.0, h = 50$

# Shininess - Phong

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$$k_A = 0.0$$

$$k_D = 0.5$$

$$k_S = 1$$

# Blinn-Phong Model Summary

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- More light sources  $L_i$

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

- Practical setting of Phong model

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

- Attenuation of light intensity with distance (point + spot lights)
  - Quadratic:  $1/d^2$
  - Softer attenuation:  $1/(c_0 + c_1 \cdot d + c_2 \cdot d^2)$

# Physically Plausible Phong Model

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- [Lafortune & Willem's 1994]

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

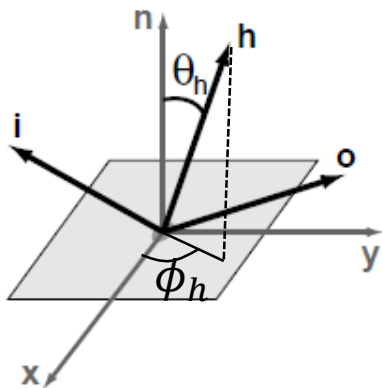
$$k_s + k_d \leq 1$$

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



# Ward BRDF

- Empirical (as Phong, Blinn)
- Good to fit measured data
- Gaussian specular reflection
- Anisotropic reflection!



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

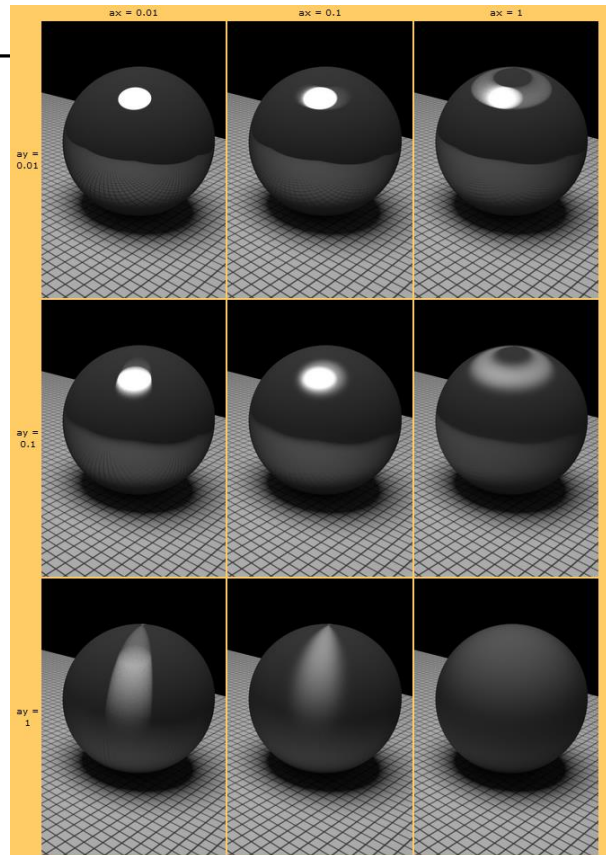
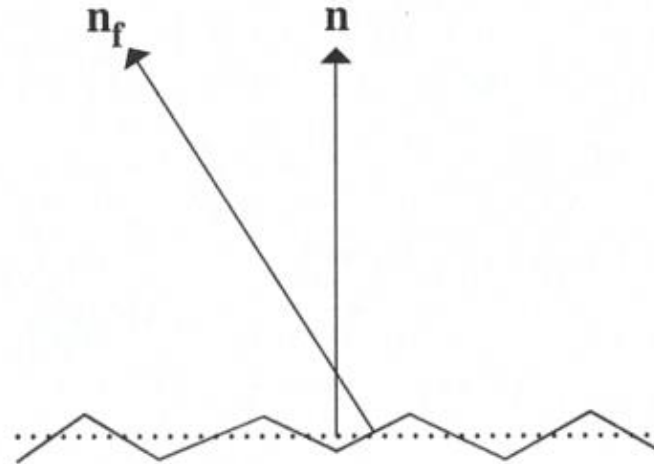
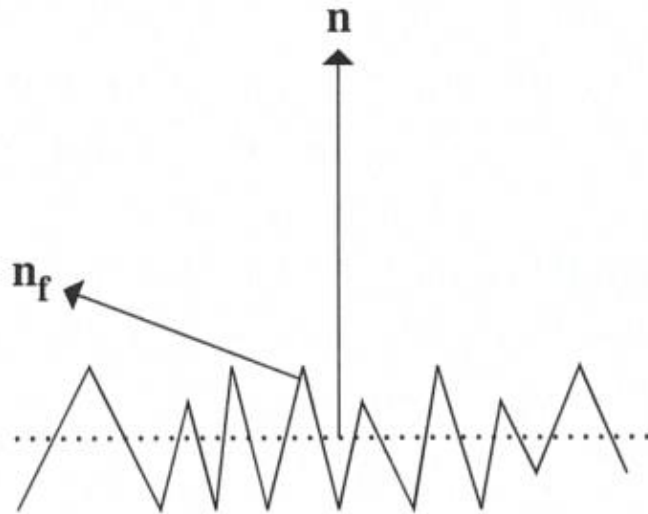


Image: Chia-Kai Liang

# Physically Based Models

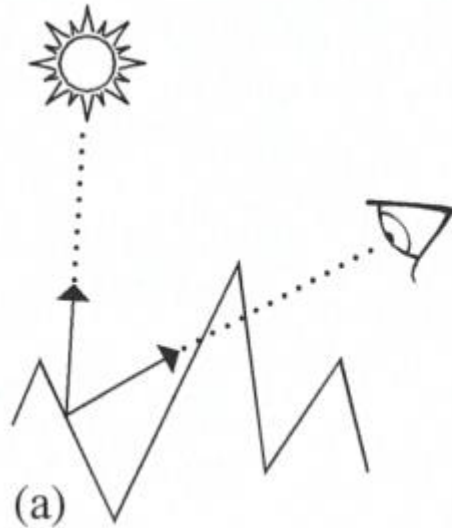
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- Microfacet distribution – “V” grooves
  - Model surface roughness

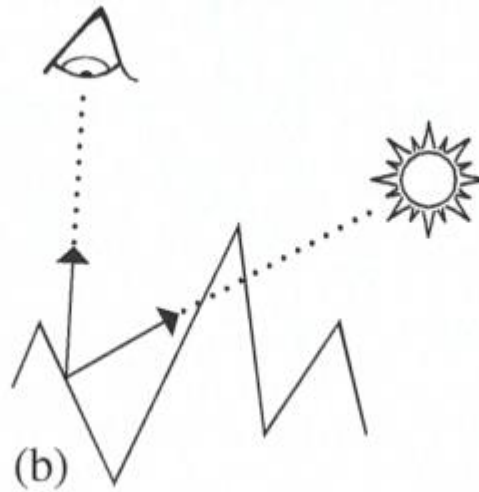


# Microfacet models

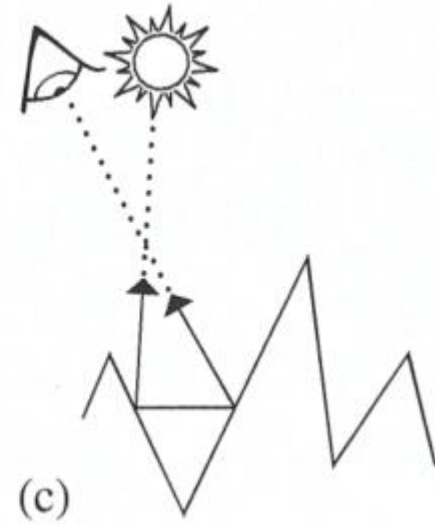
- Normal distribution (D), shadowing-masking (G), Fresnel term (F)



masking



shadowing



interreflection

# Physically Based Models

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- Diffuse microfacets
  - Oren-Nayar
- Specular microfacets
  - Torrance-Sparrow & Cook-Torrance

# Cook-Torrance BRDF

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

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

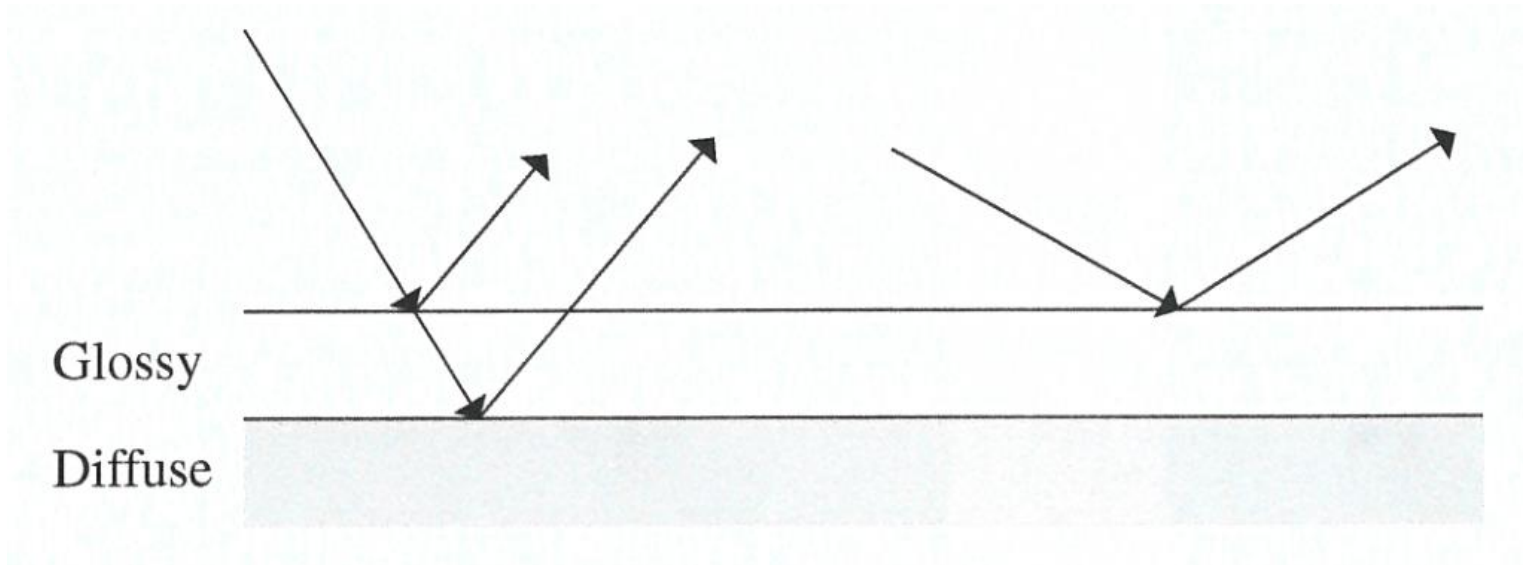
$$D = \frac{e^{(-\tan^2 \theta_h)/\alpha^2}}{\pi \alpha^2 \cos^4 \theta_h} \quad \alpha \text{ roughness}$$

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

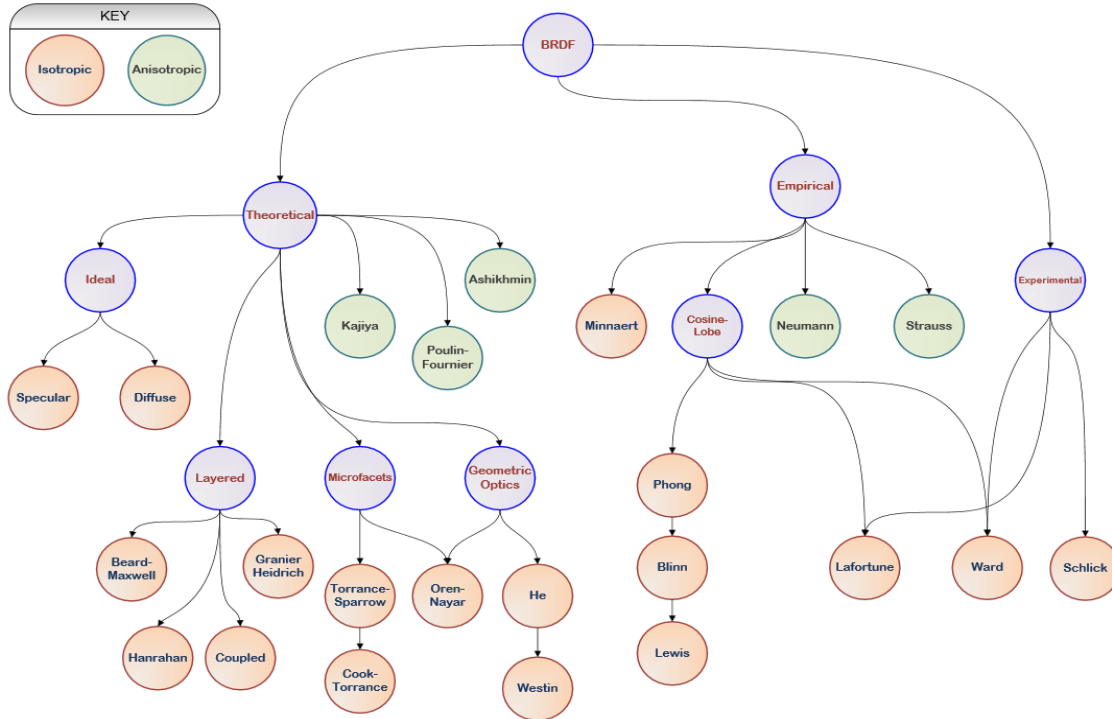
$$F = F_0 + (1 - F_0)(1 - \cos(\theta))^5, F_0 = \left(\frac{\eta_1 - \eta_2}{\eta_1 + \eta_2}\right)^2$$

# Layered models

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# BRDF Models - Overview



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

# Scattering Models - Timeline

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- 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

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- DEMO

# Outline

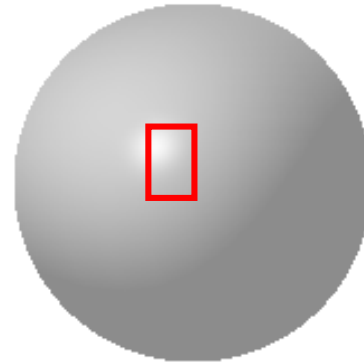
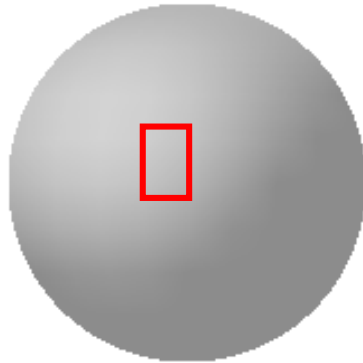
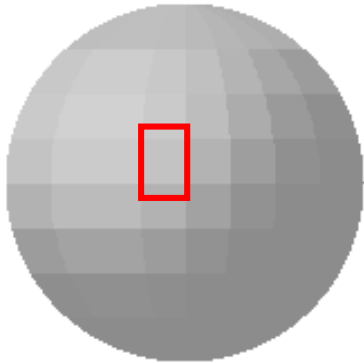
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# Shading

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



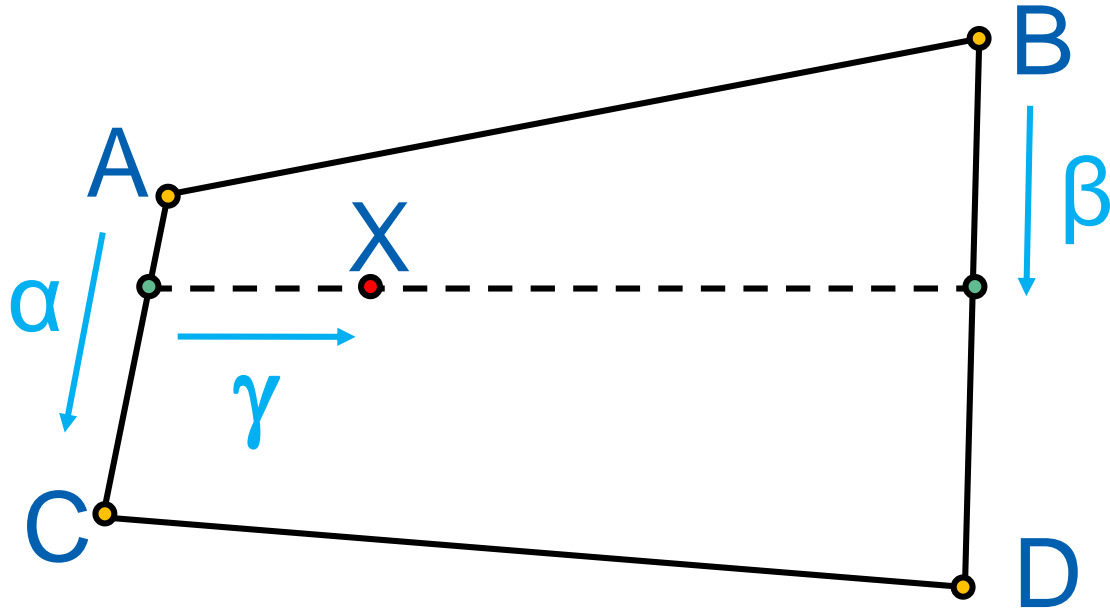
# Smooth Shading

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- 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

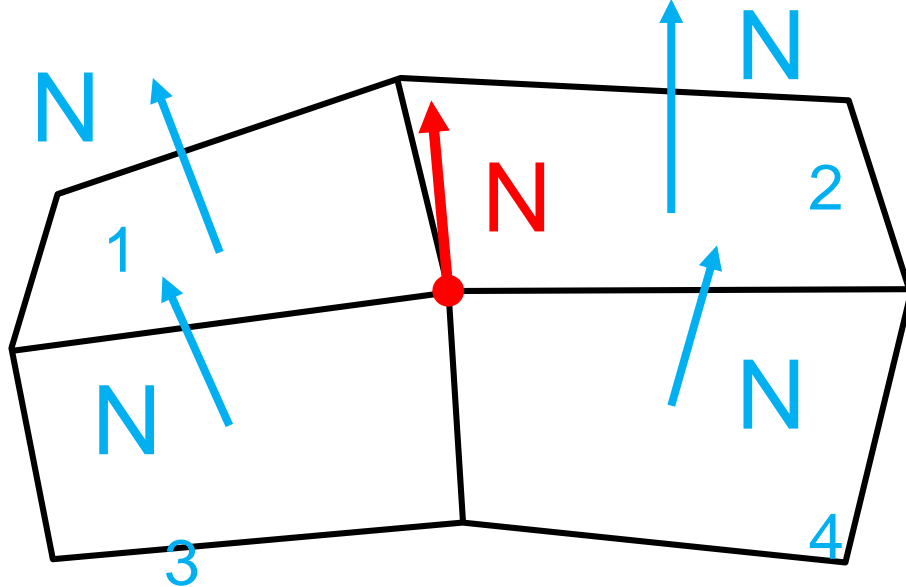
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$$f_X = (1-\gamma) \cdot [(1-\alpha) \cdot f_A + \alpha \cdot f_C] + \gamma \cdot [(1-\beta) \cdot f_B + \beta \cdot f_D]$$

# Computing Vertex Normals

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

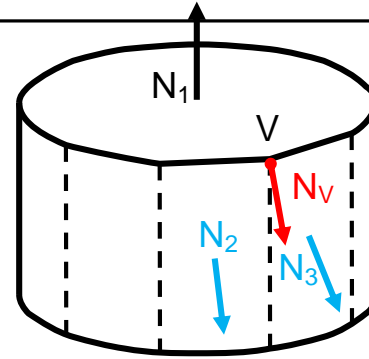


$$N = (N_1 + N_2 + N_3 + N_4) / 4$$

# Real and Auxiliary Edges

a) Stored in model:

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

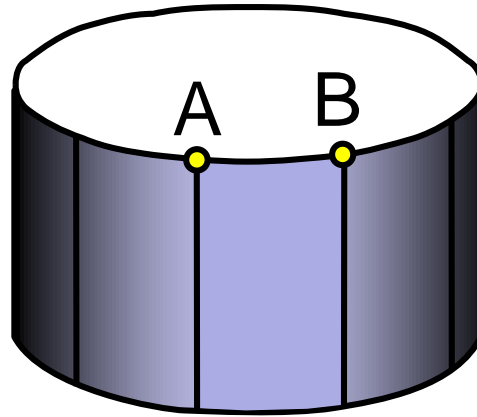
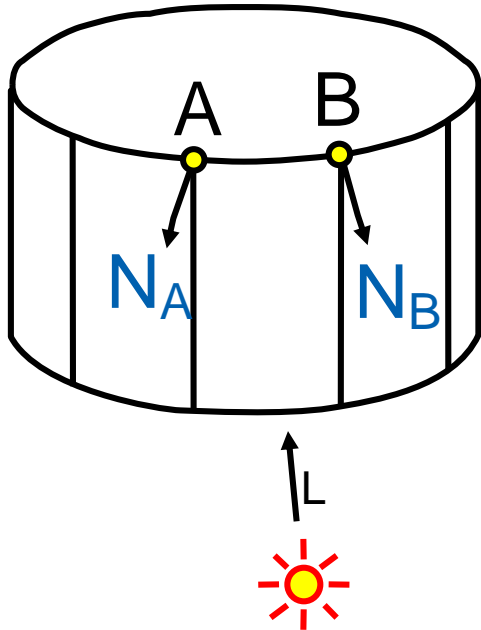


b) *Computed using crease angle*

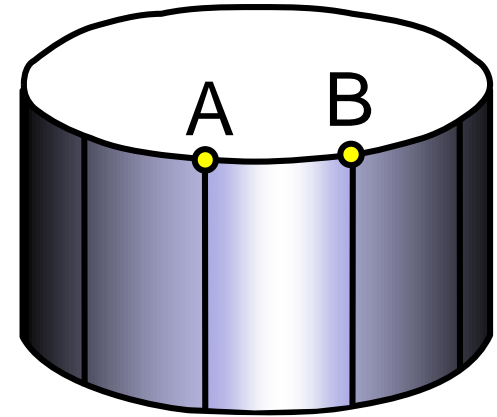


# Gouraud versus Phong Shading

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



Gouraud



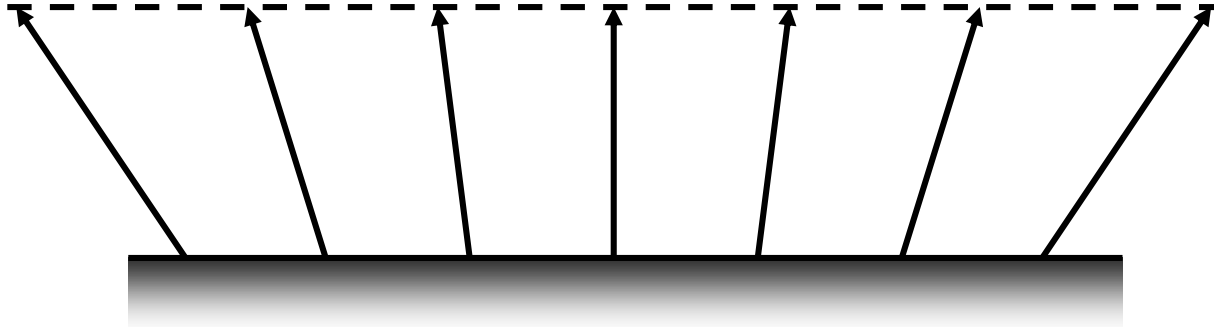
Phong



# Normal Interpolation

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



# Outline

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



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**Questions?**