Computer Graphics

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BRDF(双向反射分布函数)

- **BRDF**
  - ***Bidirectional Reflectance Distribution Function***
  - **Describe how light is reflected from a surface**
- **Preliminary for BRDF**
- **BRDF：definition and Properties**
- **BRDF Models**
- **BRDF Measurement**

Illumination(光照、照明)

- Illumination can be classified as local or global.
  - Local illumination is concerned with how objects are directly illuminated by light sources.
  - Global illumination includes how objects are illuminated by light from locations other than light sources, Including by reflection of other objects and refraction through objects.

Illumination(光照、照明)

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  - Local illumination is concerned with how objects are directly illuminated by light sources.

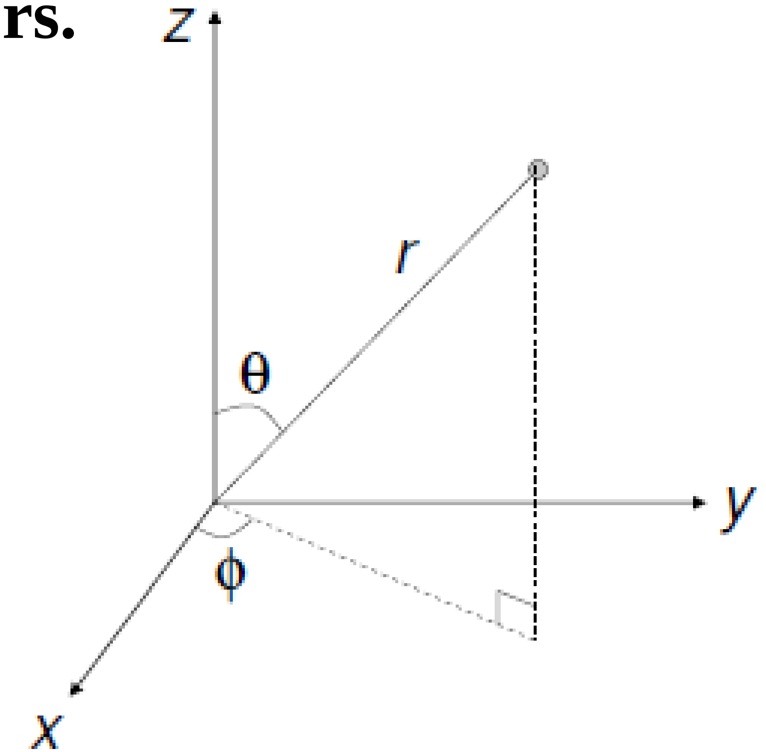
Today's Topic: a physical description of how light is reflected from a surface, which is known as BRDF.

Preliminary

- **Before introducing BRDF, we review some preliminary concepts.**
  - **Spherical Coordinate (球面坐标)**
  - **Solid Angle (立体角)**
  - **Foreshortened Area (投影面积)**
  - **Radiant Energy (光能)**
  - **Radiant Flux (光通量)**
  - **Irradiance （辉度）**
  - **Intensity （发光强度）**
  - **Radiance （光亮度）**

Spherical Coordinate (球面坐标)

- **Since light are mostly expressed in terms of directions, it is generally more convenient to describe them by spherical coordinates rather than by cartesian coordinate vectors.**



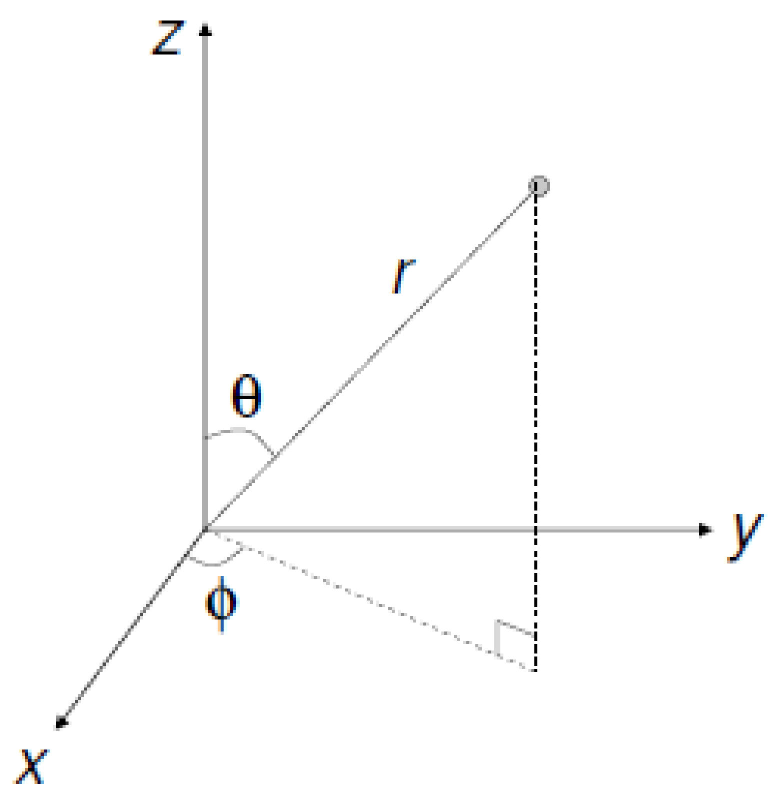
Spherical Coordinate (球面坐标)

- **Since light are mostly expressed in terms of directions, it is generally more convenient to describe them by spherical coordinates rather than by cartesian coordinate vectors.**
- **As illustrated in the figure, a vector in spherical coordinates is specified by three elements.**
  - **magnitude *r* denotes the length of the vector.**
  - ***Θ* measures the angle between the vector and the z-axis,**
  - ***ψ* represents the counterclockwise angle on the x-y plane from the x-axis to the projection of the vector onto the x-y plane.**

Spherical Coordinate (球面坐标)

- **Relationship between Cartesian(笛卡尔) and spherical coordinates**
  - **(x,y,z) ←→ (r, Θ, ψ)**
- **Conversion**
  - **r = sqrt(x^2+y^2+z^2)**
  - **Θ = acos(z/r);**
  - **ψ = atan2(y,x);**

  - **z = r cos(Θ);**
  - **y = r sin(Θ)sin(ψ);**
  - **x = r sin(Θ)cos(ψ);**

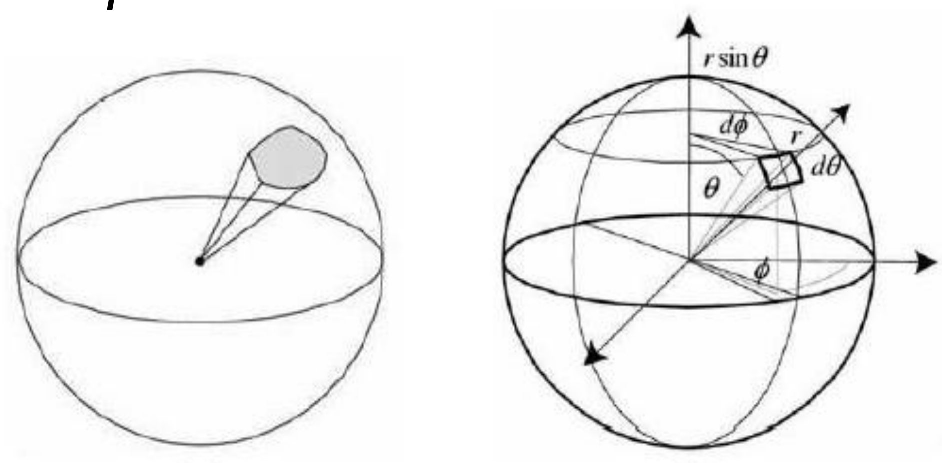


Solid Angle(立体角)

- **Light generally arrives at or leaves a surface point from a range of directions that is denoted by solid angles. solid angles represents a 3D generalization of angle formed by a region on a sphere.**

$$d\omega = \frac{ds}{r^2}$$

- **Max value of a solid angle is 4π , which is given by a sphere.**



(a) (b)

Solid Angle(立体角)

- **For a differential solid angle described by differential angles** $d\theta, d\varphi$ **in the** θ, φ **directions, its differential area *dA* on the sphere is**

$$dA = (rd\theta)(r\sin\theta d\varphi) = r^2 \sin\theta d\theta d\varphi$$

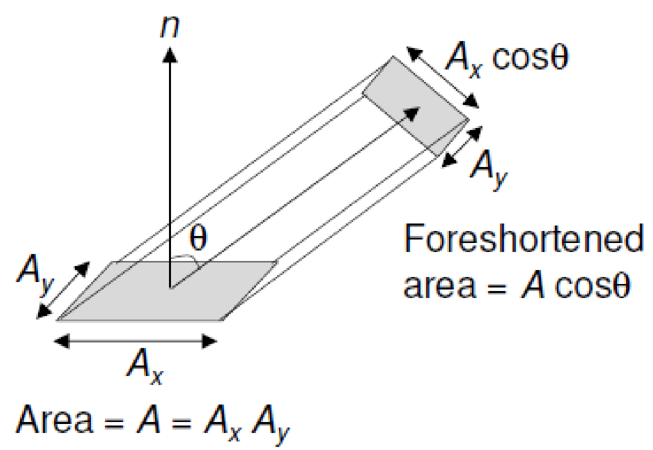
- **From the solid angle definition, the differential solid angle is given by:**

$$d\omega = \frac{dA}{r^2} = \sin\theta d\theta d\varphi$$

Foreshortened Area（投影面积）

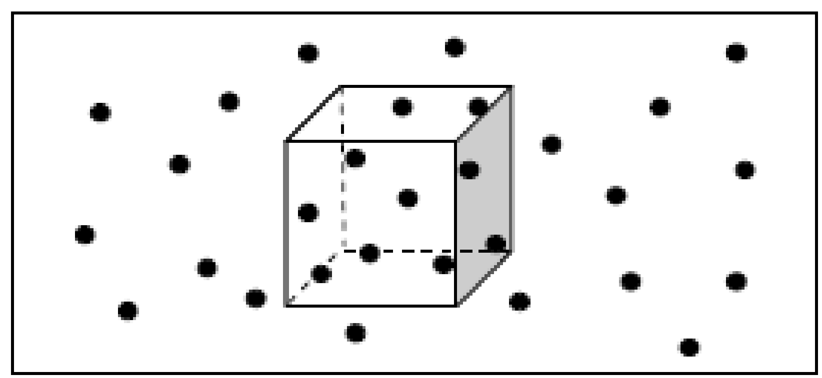
- **The apparent area of a surface patch according to the angle at which it is viewed**
- **For a surface patch of area *A*, its foreshortened area from direction θis given as *A* cos(θ), since its apparent length in the *x* direction is scaled by cos(θ).**

$$Area = A\cos\theta$$



Radiant Energy (光能)

- An amount of light energy can be thought of as the total energy of a collections of photons (光子), the quantity is referred to as radiant energy.
- Radiant energy is denoted by Q and measured in Joule (J)



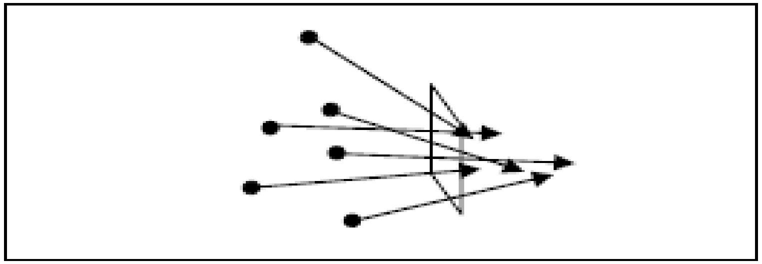
Radiant energy Q

Radiant Flux (光通量)

- **Radiant energy does not stay fixed in one position, but moves**
- **Radiant Flux describes:**
  - **The flow of energy through an area per unit time**
  - **To represent radiant energy in motion, we have**

$$\Phi = \frac{dQ}{dt}$$

  - **Measure in watt (W)(瓦特)**
  - **1 watt (W) is equivalent to one Joule(焦耳) per second**



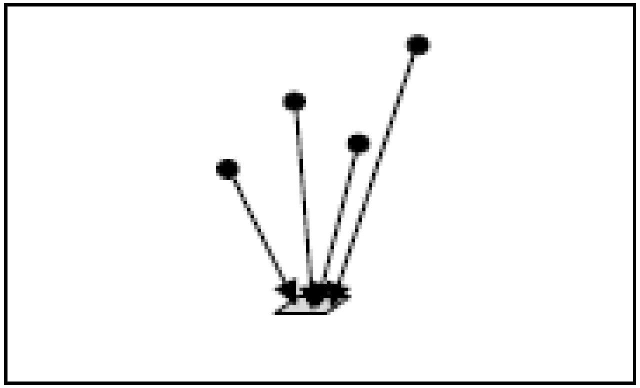
Radiant flux Φ

Irradiance （辉度）

- **To describe interactions of radiant energy and a surface**
  - **We represent the incoming radiant flux per unit surface area(单位面积的光通量) as**

$$E = \frac{d\Phi}{dA}$$

  - **measured in W/m^2**

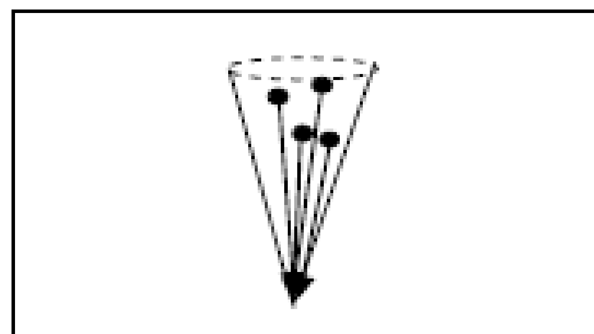


Irradiance E

Intensity （发光强度）

- **Radiant Flux （光通量） through a point can't be described by irradiance, since a point consists of Zero area.**
- **So we use Intensity, described as:**
  - **Radiant flux with respected to solid angle**

$$I = \frac{d\Phi}{d\omega}$$



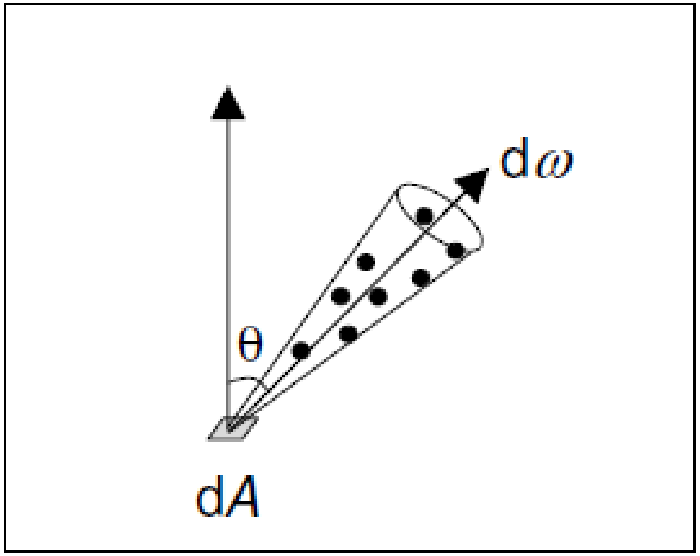
Intensity I

Radiance （光亮度）

- Radiant flux is always described in terms of both surface area and solid angle
- The measure of flux entering or leaving a surface per solid angle per unit foreshortened surface area is called

Radiance which can be measured by

$$W/(sr \cdot m^2)$$

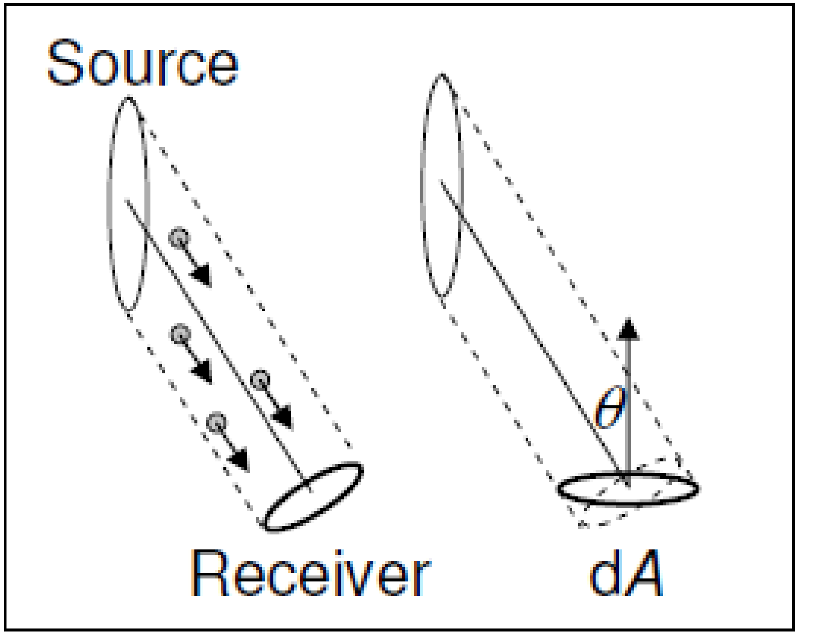


Radiance L

Radiance (光亮度）

- **Note that it is the foreshortening of surface area in radiance, which is in contrast to the other area-based quantity irradiance（辉度）that are non-directional.**

Radiance (光亮度）



Foreshortening

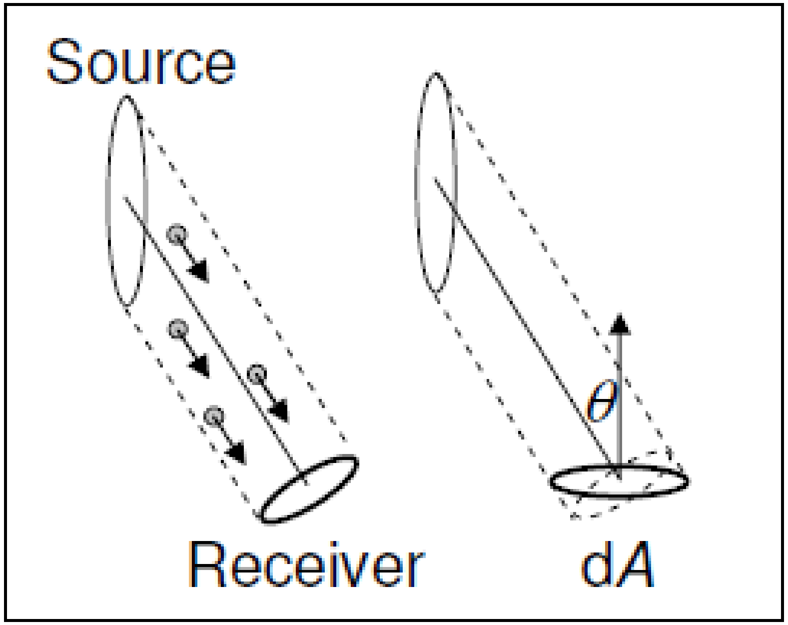
- **An intuitive way to explain this foreshortening factor in radiance is to consider radiance as a flow of energy from a source to a receiver as exhibited in the figure for a receiver perpendicular to the flow direction.**

Radiance （光亮度）

- **Defined respect to the apparent surface as:**

$$L = \frac{d\phi}{dA\cos\theta\, d\omega}$$

- **Foreshortening of Area**
  - **the area perpendicular to the flow direction**



Foreshortening

Irradiance (辉度) from radiance （光亮度）

- **Irradiance is the integral of radiance over hemisphere**

$$\frac{d\Phi}{dA} = E = \int_{\Omega} L(\omega)\cos\theta\, d\omega$$

  - Ω **is the hemisphere of incoming directions**
  - L **is the incoming radiance**

BRDF Definition and Properties

- **BRDF Definition**
- **BRDF Properties**
  - **reciprocity (可逆性)**
  - **energy conservation （能量守恒）**
  - **rendering equation （绘制方程）**

BRDF Definition

- **Appearance of a surface results from its reflection of light from the surrounding environment towards the viewer.**
- **In most computer graphics algorithms, reflections are modeled by Bidirectional Reflectance Distribution Function (BRDF)**

- **BRDF is:**
  - **A 4D function that expresses the ratio of reflected radiance （光亮度）towards a viewing direction to the irradiance （辉度）from an incoming direction:**

$$f(\omega_i \to \omega_r) = \frac{dL_r(\omega_r)}{dE_i}$$

  - **Expressed in terms of incoming radiance:**

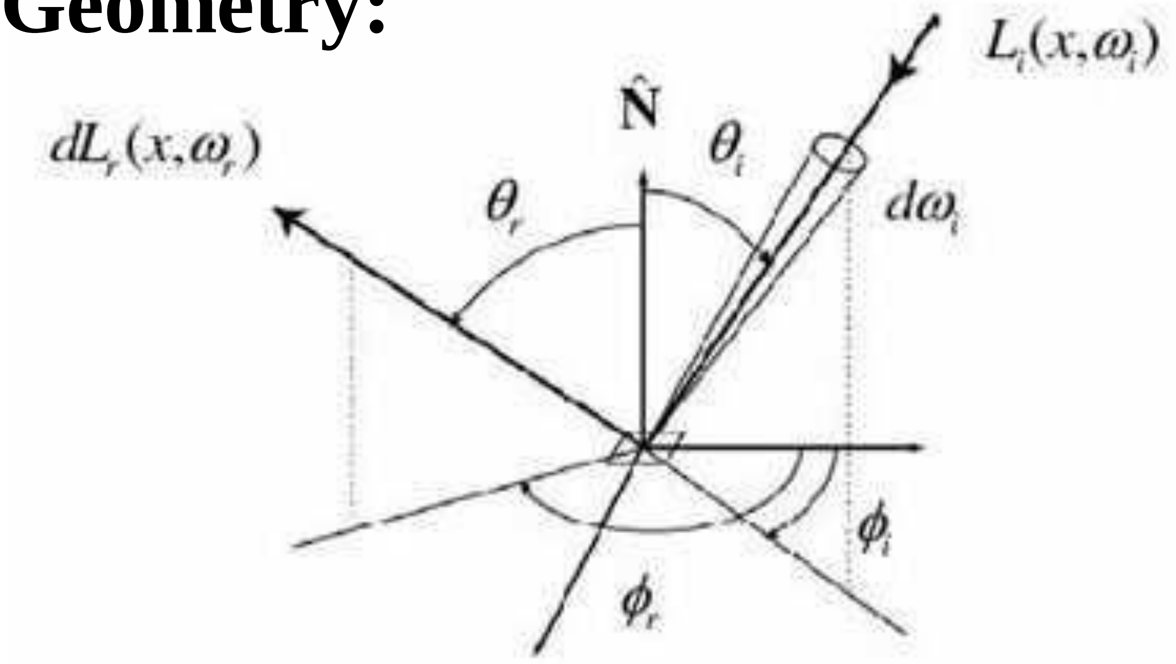
$$\boxed{f(\omega_i \to \omega_r) = \frac{dL_r(\omega_r)}{L_i(\omega_i)\cos\omega_i d\omega_i}}$$

BRDF Definition

- **Measured in units of BRDF can be**

  $(sr)^{-1}$

- **Reflectance Geometry:**



BRDF Properties: reciprocity(可逆性)

- **Reciprocity**
  - **Reciprocity is arise from the Helmholtz reciprocity rule(光路可逆性)**
  - **Exchanging the directions of incoming and outgoing does not result in a change in BRDF** $f(\omega_i \to \omega_r) = f(\omega_r \to \omega_i)$

BRDF Properties: energy conservation(能量守恒)

- **Another physical law that governs BRDFs is conservation of energy, which requires the energy of scattered light to be equal to the energy of incoming light.**
- **Conservation of energy:**

$$Q_{incoming} = Q_{reflected} + Q_{absorb} + Q_{transmitted}$$

- **We have:**

$$Q_{reflected} \le Q_{incoming}$$

BRDF Properties: energy conservation(能量守恒)

- **So the BRDF must satisfy the following condition according to energy conservation:**

$$\int_{\Omega} f(\omega_i \rightarrow \omega_r) \cos \omega_r d\omega_r \leq 1$$

BRDF Properties: rendering equation

- **BRDF is formulated in a manner that accounts for the fact that the total radiance observed in direction ω_r arises from incoming radiance from multiple directions.**
- **The viewed radiance is computed as an integration of light reflected from different incoming angles:**

$$\boxed{L_r = \int_\Omega f(\omega_i \to \omega_r) L(\omega_i) \cos\omega_i \, d\omega_i}$$

- **The above is referred to as the rendering equation**

BRDF Models (BRDF 模型)

- For convenient and efficient use of 4D BRDFs, they are customarily represented by parametric BRDF models.
- The numerous models of BRDF that have been proposed can be classified into three general categories
  - **Empirical Models (经验模型)**
  - **Physical-based Models (基于物理的模型)**
  - **Data-driven Models (数据表达的模型)**

BRDF Models (BRDF 模型)

- **Empirical Models (经验模型)**
  - designed experimentally to yield a reasonable appearance at a low computation cost.
- **Physical-based Models (基于物理的模型)**
  - describe reflectance according to the geometric and optical properties of a material
- **Data-driven Models (数据表达的模型)**
  - describe reflectance directly based on tabulated data

Empirical Models (经验模型)

- **Empirical Models**
  - **Given in Simple forms that allow for rapid computation of reflectance**
  - **Ignore material properties, only provide a rough approximation of actual reflectance,**
  - **do not satisfy physical principles such as Helmholtz reciprocity and energy conservation**
  - **nevertheless, they are the most commonly used ones because of practical advantages.**

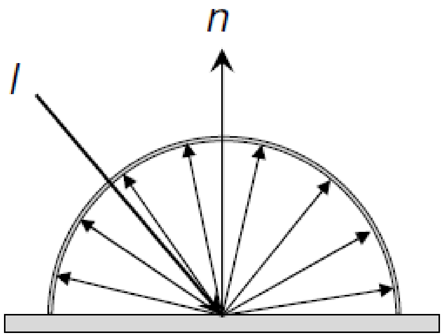
Empirical models(1): Lambertain

- **Lambertain's Model: the most basic model**
  - **incoming light is reflected equally in all directions**
  - **BRDF function f is a constant among all directions**
- **Albedo(反射率)** ρ
  - **The ratio of exit irradiance to incoming irradiance**

$$L_r(\omega_r) = \int_\Omega f L_i(\omega_i) \cos\omega_i d\omega_i$$

$$= f \int_\Omega L_i(\omega_i) \cos\omega_i d\omega_i = fE$$

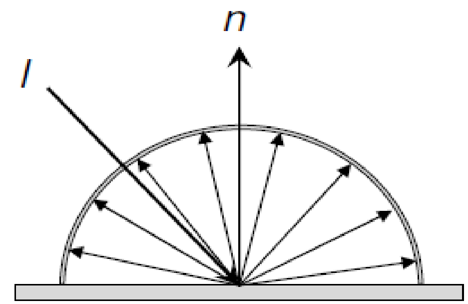
$$\rho = \frac{M}{E} = \frac{\int_\Omega L_r(\omega_r) \cos\omega_r d\omega_r}{E} = \frac{fE\pi}{E} = \pi f$$



Lambertian

Empirical models: Lambertain

- **Lambertain's Model**
  - **Well representing the reflectance of objects that exhibit purely diffuse reflection (漫反射)**
  - **However, for those materials, such as metal(金属), with a significant specular component, lambertain's model could not represent it well**
  - **Because of its simplicity and reasonable modeling, it has been incorporated into several more sophisticated models, such as Phong Model**



Lambertian

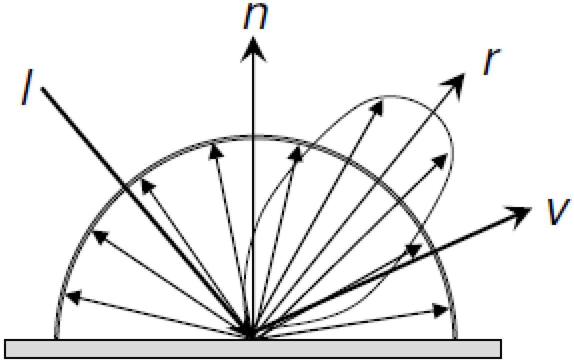
Empirical models(2): Phong

- **Phong Model**
  - **is to empirically adds a specular lobe in the mirror direction of the incoming direction**
  - **Expressed as:**

$$f(l \to v) = \rho_d + \rho_s \frac{(r \cdot v)^s}{(n \cdot l)}$$

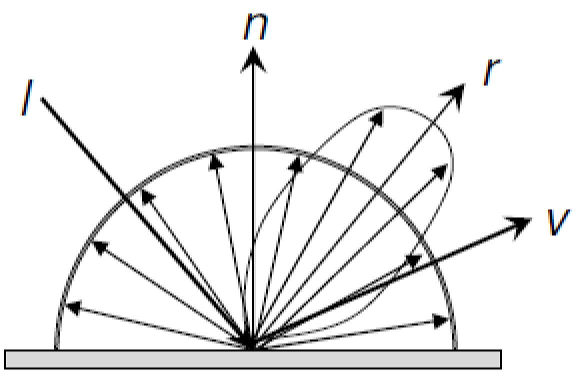
  - **Reciprocity property does not hold**

$$f(l \to v) \neq f(v \to l)$$



Phong

Empirical models(2): Phong



Phong

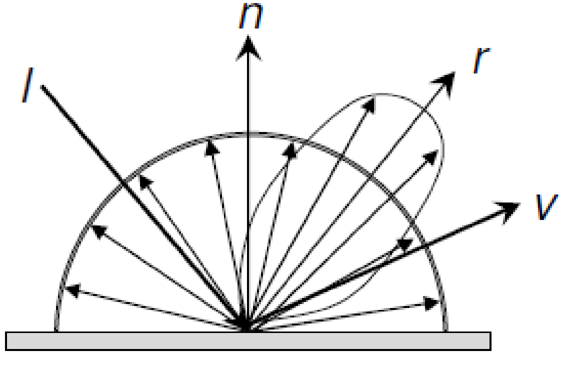
- **Phong Model**
  - **is to empirically adds a specular lobe in the mirror direction of the incoming direction**
  - **Expressed as:**

$$f(l \rightarrow v) = \rho_d + \rho_s \frac{(r \cdot v)^s}{(n \cdot l)}$$

where ρ_d; ρ_s denote albedos of diffuse and specular reflections, respectively, and *s* signifies a shininess factor that modulates the sharpness of specular reflections.

Empirical models: Phong

- **Phong Model**
  - **Although the Phong Model lacks a physical explanation and has been shown to be inaccurate for a broad range of materials, it has long been the most popular BRDF model in computer graphics**
  - **Largely due to its efficiency in computation and acceptable appearance**



Phong

Extensions of Phong Model

- **Most extensions are proposed towards faster computation**
- **Blinn-Phong Model**
  - **utilize the bisector(角分线) h of light direction l and view direction v instead of the mirror direction r of l**
  - **simpler computation**

$$f(l \to v) = \rho_d + \rho_s \frac{(n \cdot h)^s}{(n \cdot l)} \quad \text{where } h = (v + l)/2$$

Extensions of Phong Model

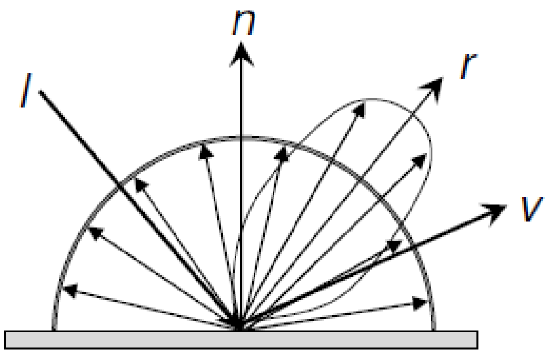
- **Modified Phong Model**
  - **Phong model doesn't hold reciprocity property**

$$f(l \to v) = f(v \to l)$$

  - **We may cancel out the equation's cosine term**

$$f(l \to v) = \rho_d + \rho_s (r \cdot v)^s$$

to have reciprocity property



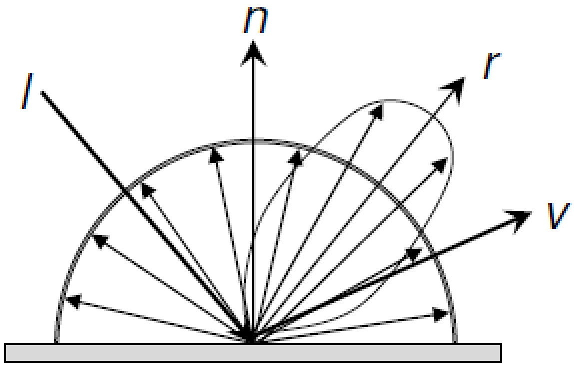
Phong

Extensions of Phong Model

- ***Fast Phong Shading*** **： Tabulate and Interpolate the specular exponent function (Bishop and Weimer, SIGGRAPH 86)**

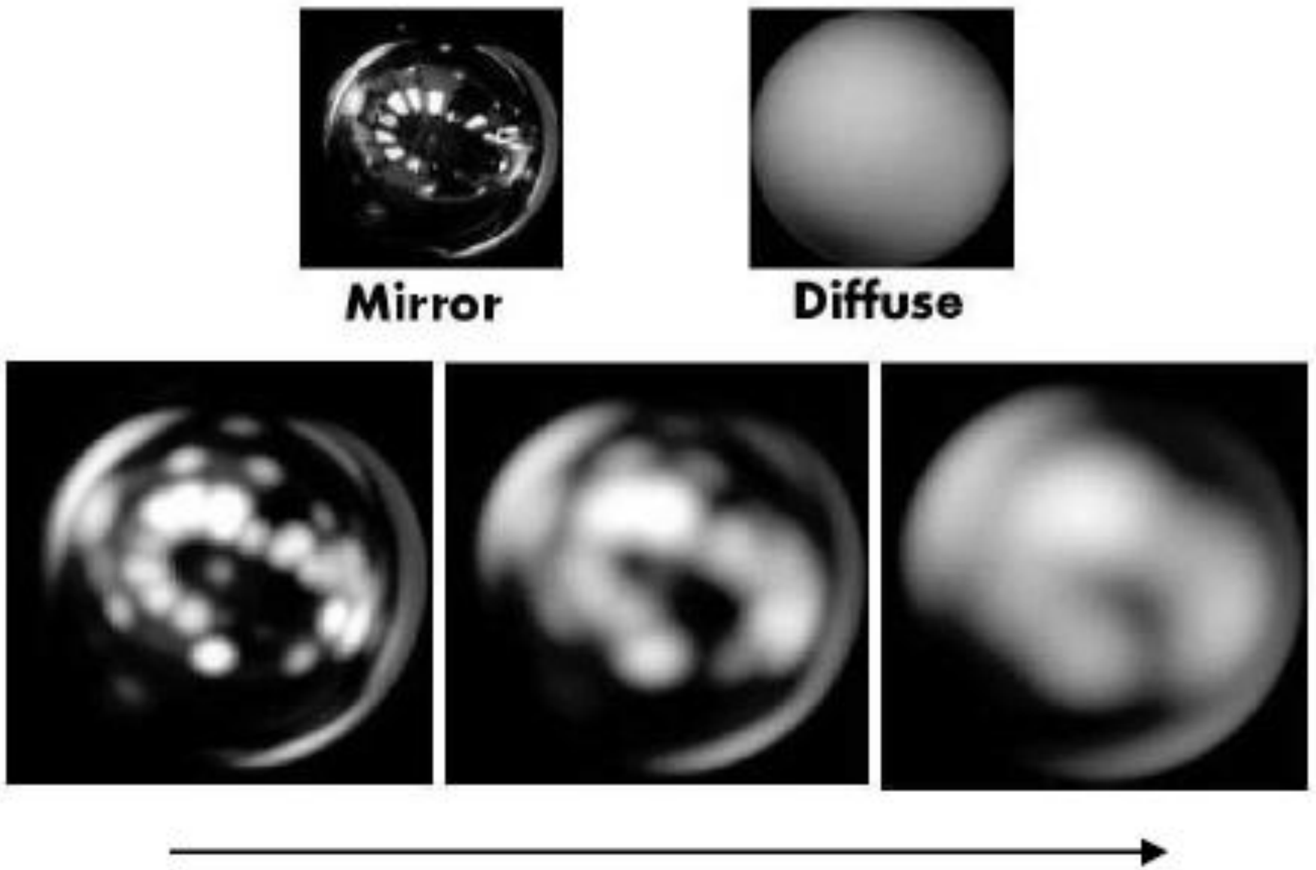
$$(r \cdot v)^s$$

  - **It is known that exponential computation is costly**
  - **to reduce the computation of the specular component**
  - **We can tabulate the exponential function and interpolate it**

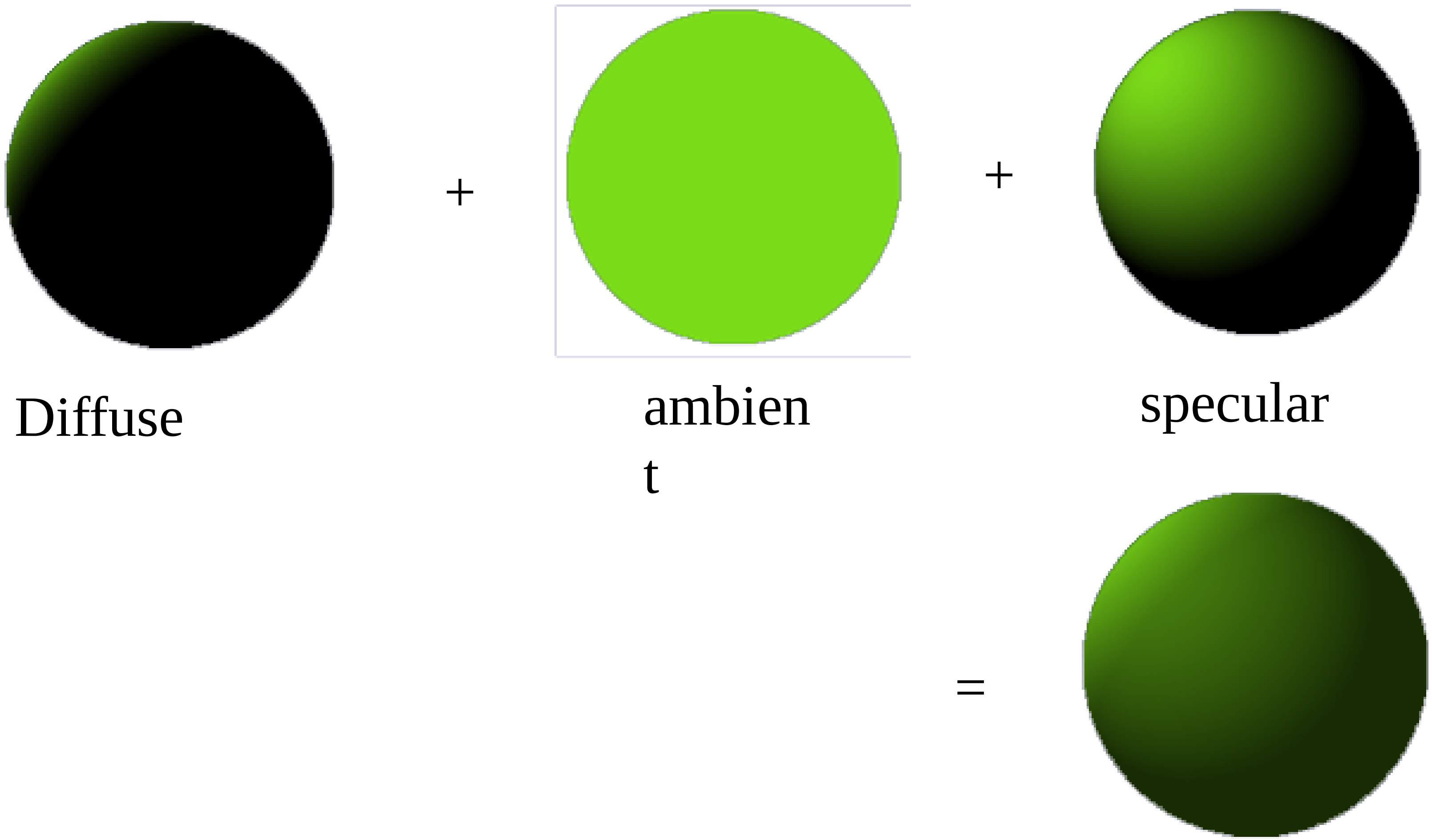


Phong

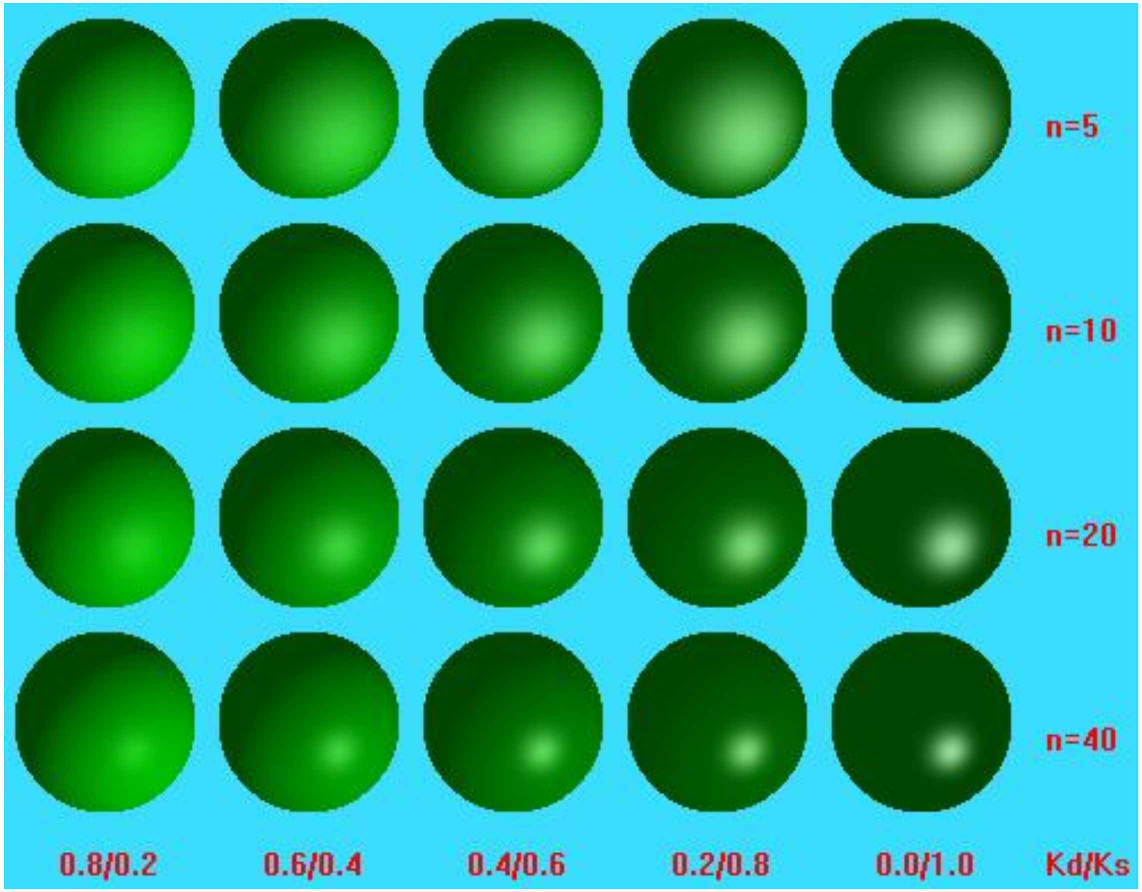
Results of Phong Model



Phong model examples_1



Phong model examples _2

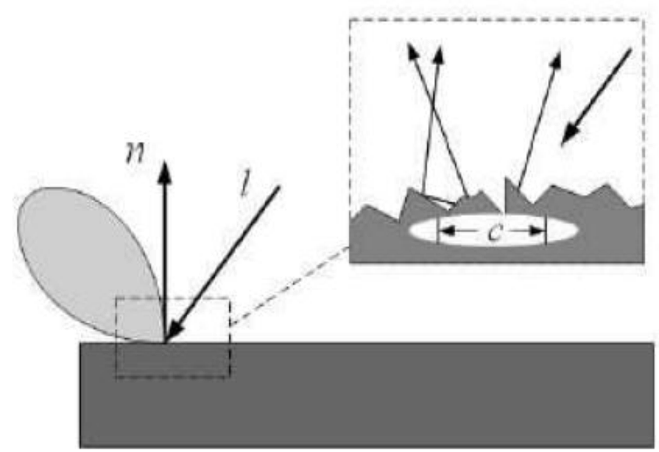


Physical-Based Models (物理模型)

- Physical-Based Models
  - While empirical models originate from the intuition and practical experience of the designers, physical-based models are built on scientific knowledge of light interaction.
  - These models Incorporate various geometric and optical properties of materials with the goal of representing real-world materials as accurate as possible

Physical-Based Models (物理模型)

- **Physical-Based Models**
  - **Generally established from fine-level geometric structure called surface roughness (表面光泽度)**
  - **Roughness:**
    - **from the microscopic view, almost no surface is perfectly smooth**
    - **Micro-scale surface geometry is modeled by a collection of planar microfacets**
    - **Roughness is represented as a statistical distribution of microfacet orientations**



Physical-Based Models (物理模型)

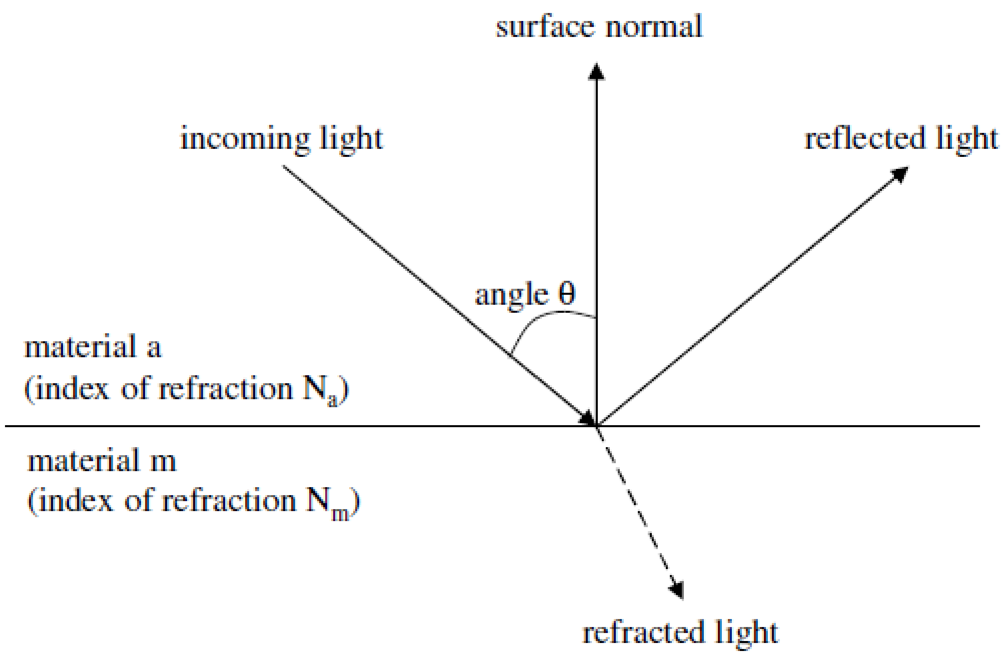
- **Fresnel Term**
  - In reality, we found that specularity increased near grazing angles

  - The amount of incident light that reflects is determined by the Fresnel reflection formulas from Maxwell’s equations for electromagnetic waves.

Physical-Based Models (物理模型)

- **Fresnel Term**

Fresnel Reflectance Geometry



Physical-Based Models (物理模型)

- **Fresnel Term**
  - **defined as below:**

$$F_s = \frac{a^2+b^2-2a\cos\theta+\cos^2\theta}{a^2+b^2+2a\cos\theta+\cos^2\theta}$$
$$F_p = F_s\frac{a^2+b^2-2a\sin\theta\tan\theta+\sin^2\theta\tan^2\theta}{a^2+b^2+2a\sin\theta\tan\theta+\sin^2\theta\tan^2\theta}$$

$$2a^2 = \sqrt{(\eta^2-\kappa^2-\sin^2\theta)^2+4\eta^2\kappa^2}+(\eta^2-\kappa^2-\sin^2\theta)$$
$$2b^2 = \sqrt{(\eta^2-\kappa^2-\sin^2\theta)^2+4\eta^2\kappa^2}-(\eta^2-\kappa^2-\sin^2\theta)$$

$$\eta = \frac{\eta_m\eta_a+\kappa_m\kappa_a}{\eta_a^2+\kappa_a^2}$$
$$\kappa = \frac{\eta_a\kappa_m-\eta_m\kappa_a}{\eta_a^2+\kappa_a^2}$$

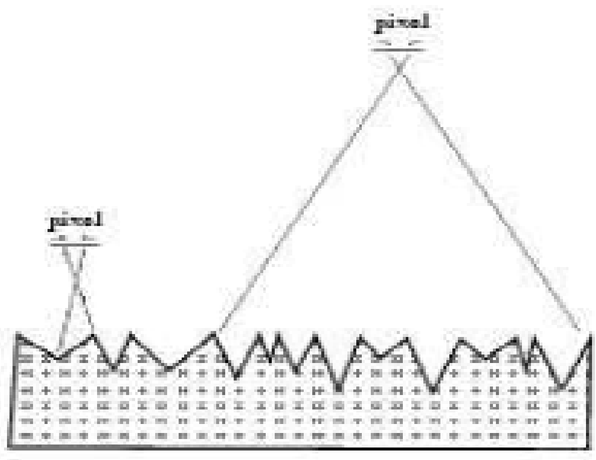
  - **Fresnel Reflectance:** $F = (F_p + F_s)/2$

Cook-Torrance Model

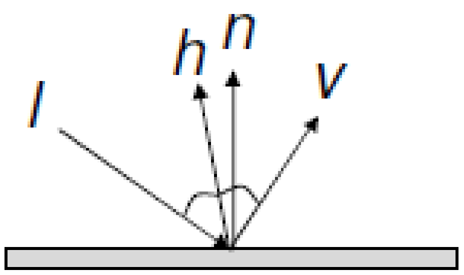
- **Cook-Torrance Model**
  - **Proposed by Cook and Torrance in [*A Reflectance Model for Computer Graphics*, ACM SIGGRAPH, 1981]**
  - **The earliest physical-based BRDF model used in computer graphics**
  - **An adaptation of the Torrance-Sparrow model developed by applied physicists [*Theory for O®-Specular Reflection from Roughened Surfaces*, J. Optical Society of America, 1975]**

Cook-Torrance Model

- **Cook-Torrance Model**
  - **microfacets are assumed to be mirror reflectors**
  - **microfacets are assumed to be arranged as V-shaped grooves as exhibited in the figures**



V-grooves



Directions

Physical-Based Models : Cook-Torrance Model

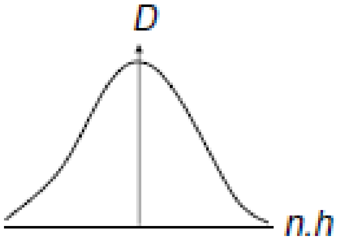
- **Cook-Torrance Model**
  - **combining a Lambertian diffuse term with a specular term based on microfacet reflections:**

$$\boxed{f_\lambda = d\,\frac{\rho_d}{\pi} + sF_\lambda\,\frac{DG}{4\pi(n\cdot l)(n\cdot v)}}$$

  - **where F_λ is the Fresnel factor, D is the distribution function of the microfacet normal, G is the geometrical attenuation factor, and s,d are specular and diffuse coefficients**

Cook-Torrance Model

- **Distribution Function of the microfacet normal D**
  - **since microfacets are mirror reflectors, only those with a normal along the bisector direction h contributes to specular reflection**



depends on roughness of surface

  - **the Bechmann distribution is used:**

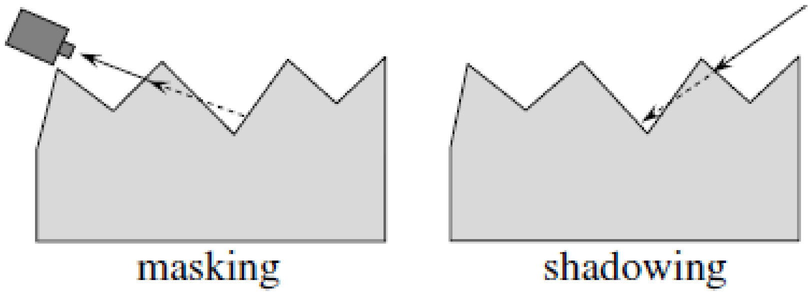
$$D(h) = \frac{1}{m^2 \cos^4 \beta} e^{-\frac{\tan^2 \beta}{m^2}}$$

where m is the roughness value of the surface, β **is the angle between n and h**

Cook-Torrance Model

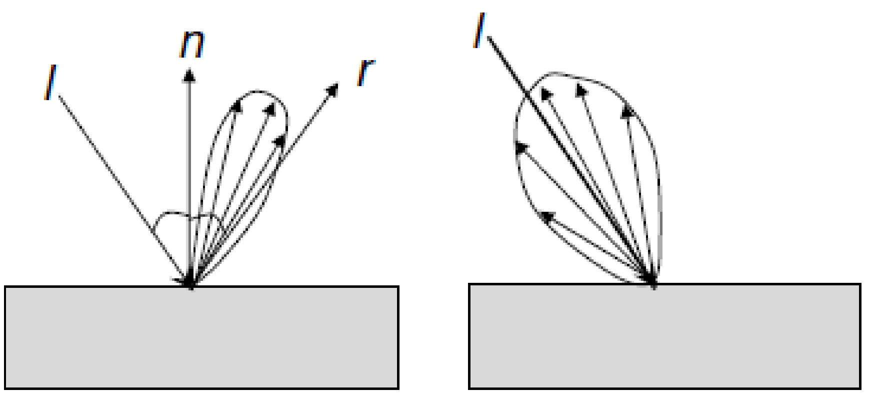
- **Geometric Attenuation Factor G**
  - **Accounts for masking of microfacets from viewing direction and for shadowing from the light direction**
  - **To exclude masked and shadowed microfacets, G is defined as:**

$$\boxed{G(n,l,v) = \min\left\{1, \frac{2(n\cdot h)(n\cdot v)}{(v\cdot h)}, \frac{2(n\cdot h)(n\cdot l)}{(v\cdot h)}\right\}}$$



Cook-Torrance Model

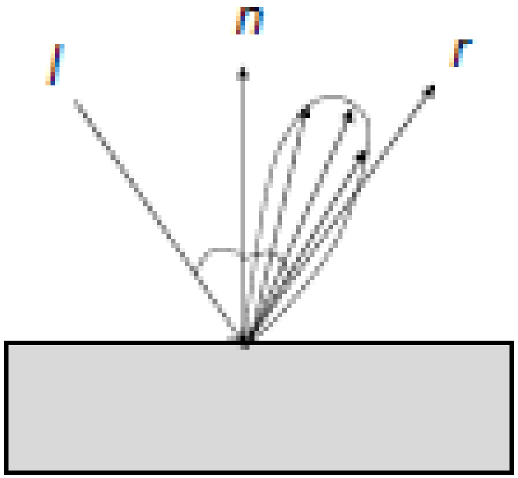
- **Geometric Attenuation Factor G**
  - **This consideration of microfacet masking and shadowing allows certain reflectance features to be generated**
  - **One is off-specular reflection**
  - **Another is retroreflection**



off-specular reflection retroreflection

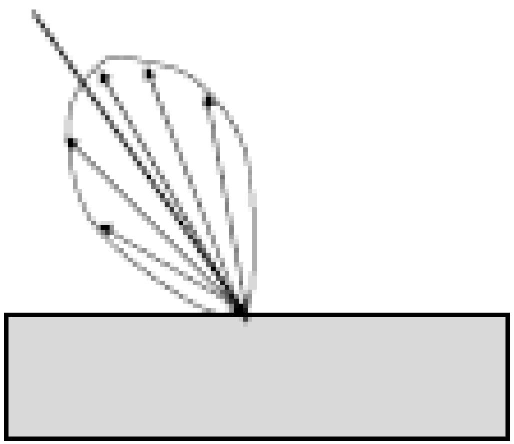
Cook-Torrance Model

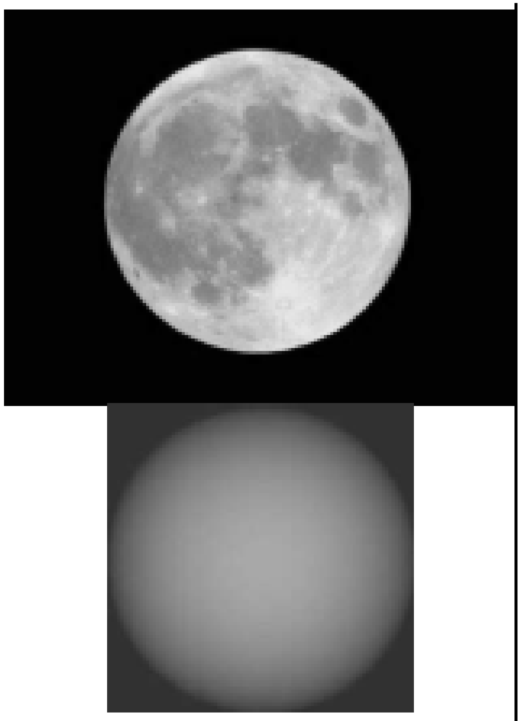
- **Off-specular reflection**
  - **Specular lobe is not centered on the mirror direction**
  - **This characteristic is typical of rough surfaces**



Cook-Torrance Model

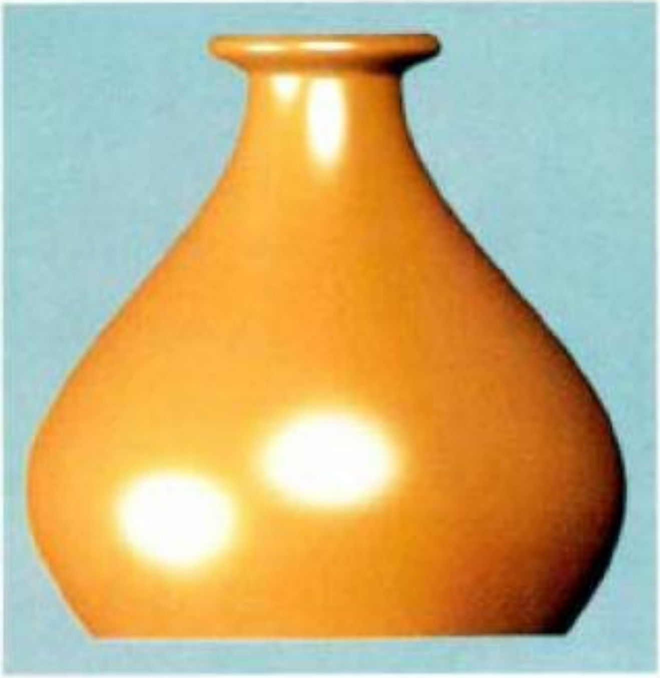
- **Retroreflection**
  - **A significant amount of light is directed back towards the light direction.**
  - **See the full moon, the edges appear as bright as the center**



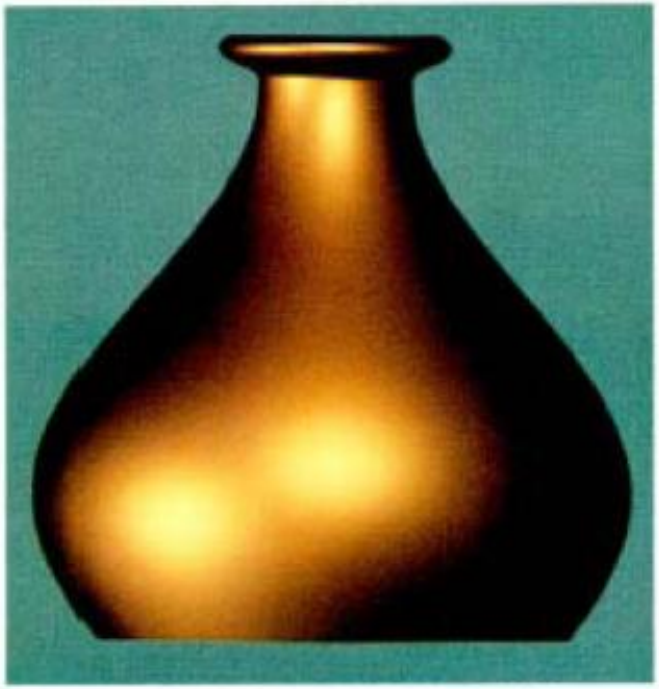


Results of Cook-Torrance Model
(Compared to Phong)

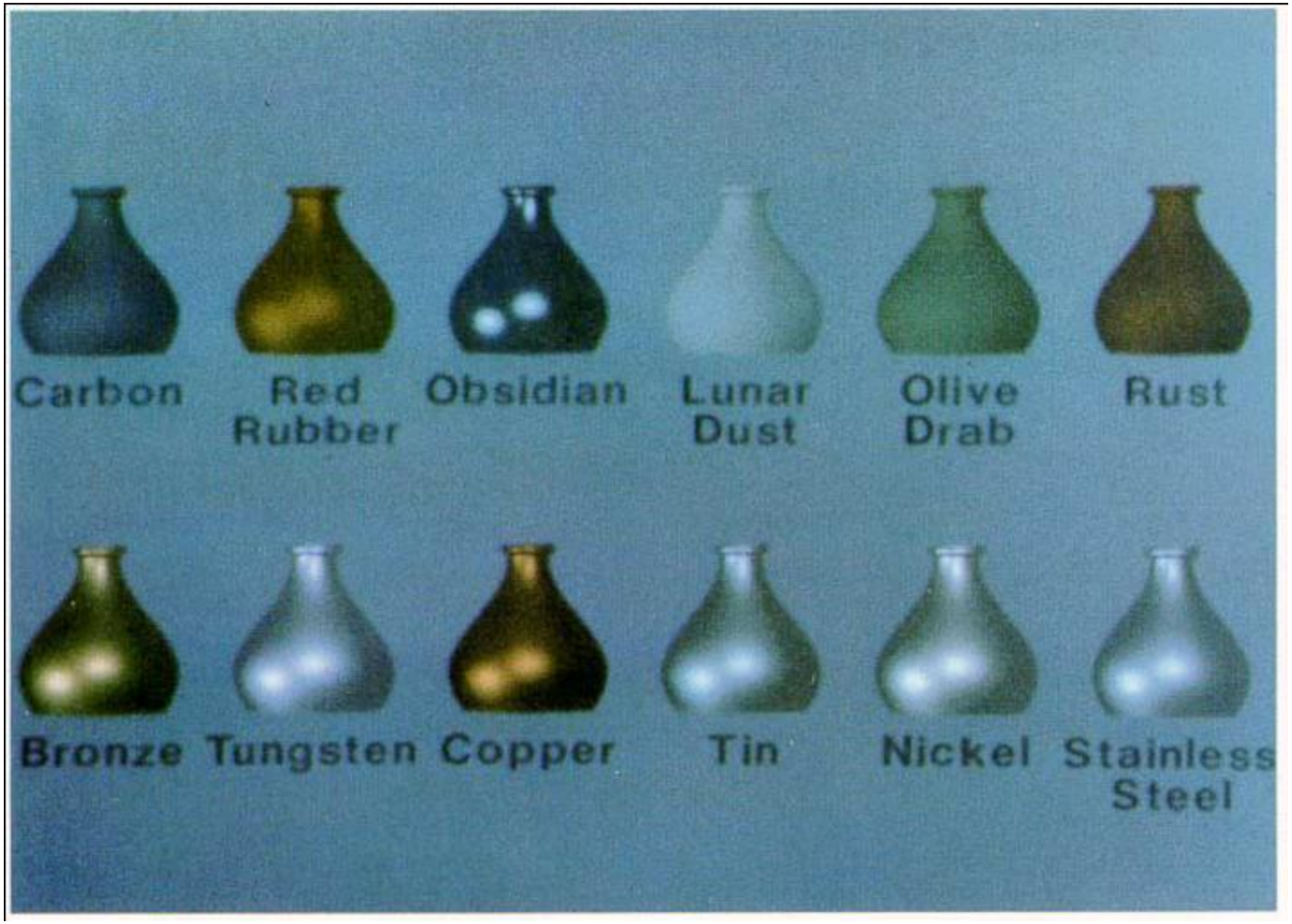
Plastic-looking copper rendered using Phong model



A Copper Vase with a more metallic appearance



More Cook-Torrance Results



Other Physical-Based Models (物理模型)

- **BRDFs can be classified into two groups**
  - **Isotropic (各向同性)**
    - Reflectance independent of rotation about a given surface normal
    - Random surface microstructure
  - **Anisotropic(各向异性)**
    - Reflectance changes with rotation around a given surface normal
    - Patterned surface microstructure
    - Brushed metal, satin, hair

- **However, None of Phong or Cook-Torrance BRDF models could handle anisotropic effects**

- **Now we introduce Another BRDF Model: Ward Model**

Ward Model

- **Ward Model:**
  - **Proposed by Ward in 1992[**Measuring and Modeling Anisotropic Reflection, ACM SIGGRAPH, 1992**]**
  - **presents a more general surface normal representation as a collection of ellipsoids(椭圆体), that allows for anisotropic reflection**
  - **However, exclude the Fresnel factor and geometric attenuation factor, make it viewed as somewhat empirical**

Ward Model

- **Isotropic Ward Model, defined as:**

$$\rho_{bd,iso}(\theta_i,\phi_i;\theta_r,\phi_r) = \frac{\rho_d}{\pi} + \rho_s \cdot \frac{1}{\sqrt{\cos\theta_i \cos\theta_r}} \cdot \frac{\exp[-\tan^2\delta/\alpha^2]}{4\pi\alpha^2} \quad (4)$$

where:

ρ_d is the diffuse reflectance

ρ_s is the specular reflectance

δ is the angle between vectors $\hat{n}$ and $\hat{h}$ shown in Figure 5

α is the standard deviation (RMS) of the surface slope

  - **Replaced (Fresnel factor and geometric attenuation factor) with a single normalization factor that simply ensures the distribution will integrate easily over the hemisphere**

Ward Model

- **Anisotropic Ward Model, Defined as:**

$$\rho_{bd}(\theta_i,\phi_i;\theta_r,\phi_r) = \frac{\rho_d}{\pi} + \rho_s \cdot \frac{1}{\sqrt{\cos\theta_i \cos\theta_r}} \cdot \frac{\exp[-\tan^2\delta\,(\cos^2\phi/\alpha_x^2 + \sin^2\phi/\alpha_y^2)]}{4\pi\alpha_x\alpha_y} \qquad (5a)$$

where:

ρ_d is the diffuse reflectance

ρ_s is the specular reflectance

α_x is the standard deviation of the surface slope in the $\hat{x}$ direction

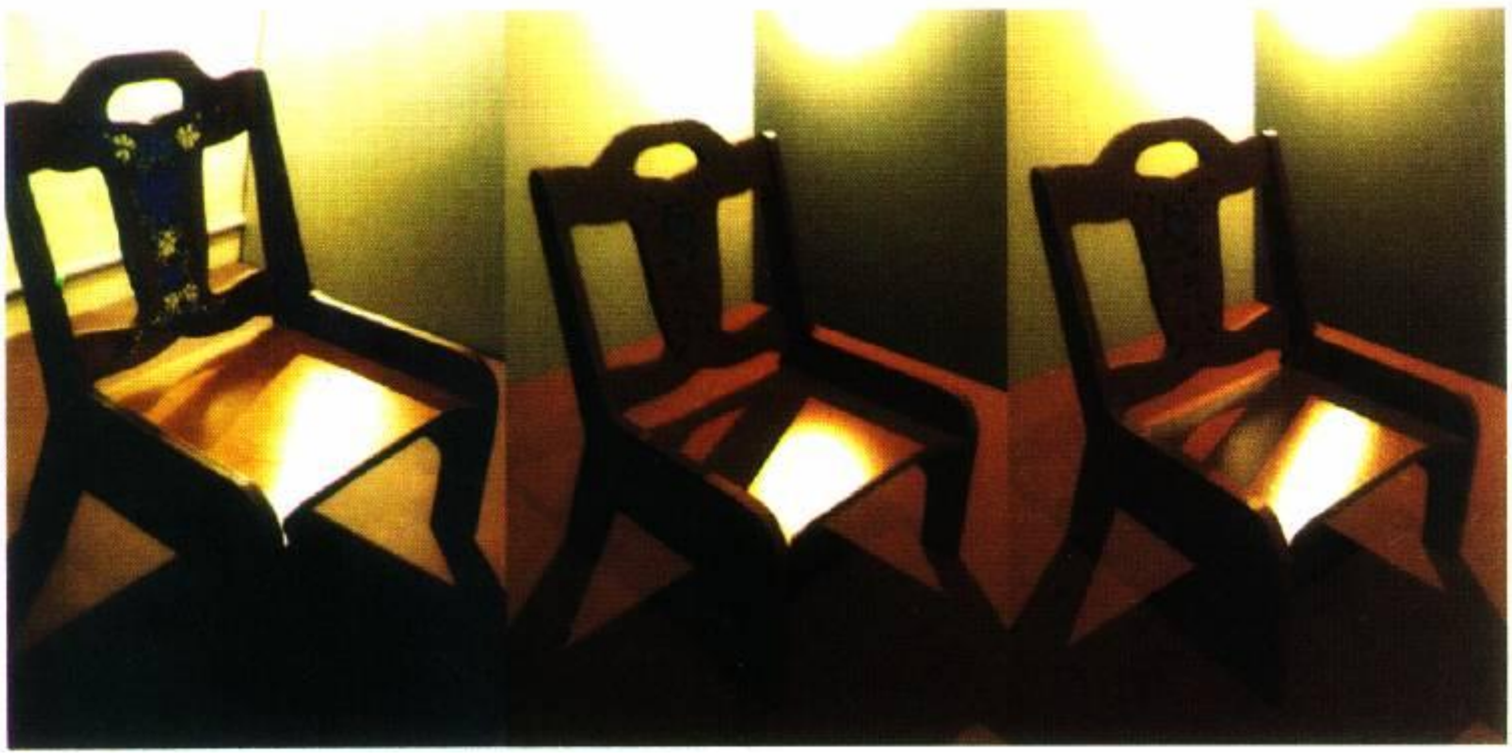
α_y is the standard deviation of the surface slope in the $\hat{y}$ direction

δ is the angle between the half vector, $\hat{h}$ and the surface normal, $\hat{n}$.

ϕ is the azimuth angle of the half vector projected into the surface plane.

Results of Ward Model

Photograph **Isotropic Ward** **Anisotropic Ward**



More BRDF Models

- **More BRDF Models**
  - **Oren-Nayar model** [*Generalization of Lambert's Reflectance Model* ACM SIGGRAPH, 1994]
    - **Treats microfacets as Lambertian reflectors rather than as mirrors**
  - **Poulin-Fournier model** [*A Model for Anisotropic Reflection*, ACM SIGGRAPH, 1990]
    - represents microfacet normals using groups of parallel cylinders, also handle anisotropic effects

More BRDF Models

- **Wave optic related Models (波动光学)**
  - **Developed from principles of wave optics**
  - **Materials with a microfacet size comparable to wavelengths of light**
  - **Based on diffraction(衍射) theory, two main work** [He, et al., *A Comprehensive Physical Model for Light Reflection*, ACM SIGGRAPH, 1991] and [Stam, *Diffraction Shaders*, ACM SIGGRAPH, 1999]
  - **Although have great power, but their high complexity limits their use**

More BRDF Models

- **Effects of the model wave optic related (波动光学)**

a picture of a CD illuminated by a directional light source. Notice that all the highlights appear automatically in the correct places

Data-Driven BRDF Models

- **Measured BRDF of a large set of materials, and record them as high-dimensional vectors**
- **From this data, a lower dimensional manifold is computed using dimensional reduction methods**
- **Representative work:** Matusik et al. [*A Data-Driven Reflectance Model*, ACM SIGGRAPH, 2003]

Comparison of BRDF Reprentations

- **Empirical Models:**
  - Computationally simple, visually acceptable
- **Physical-Based Models:**
  - Parameters physically meaningful
  - Built on scientific knowledge
- **Data-driven Models:**
  - Flexibility, no assumption about materials
  - Large data set, usually needs data reduction methods to compress data
  - Needs interpolating data, missing high light parts

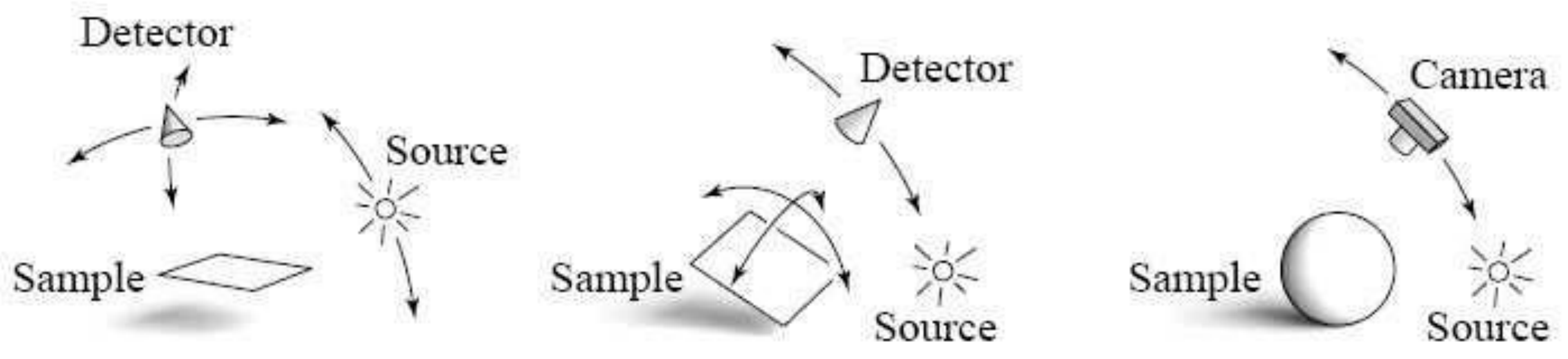
- Some demo
  - Real-time BRDF editing in complex lighting
  - Time-Varying BRDFs

BRDF Measurement

- **Motivation**
  - For modeling of materials with unknown reflectance properties and for obtaining highly realistic appearance
  - The process of recovering BRDF and other scene attributes, which is sometimes referred to as inverse rendering
  - We give an overview of BRDF measurement
    - Measurement devices
    - Practical issues

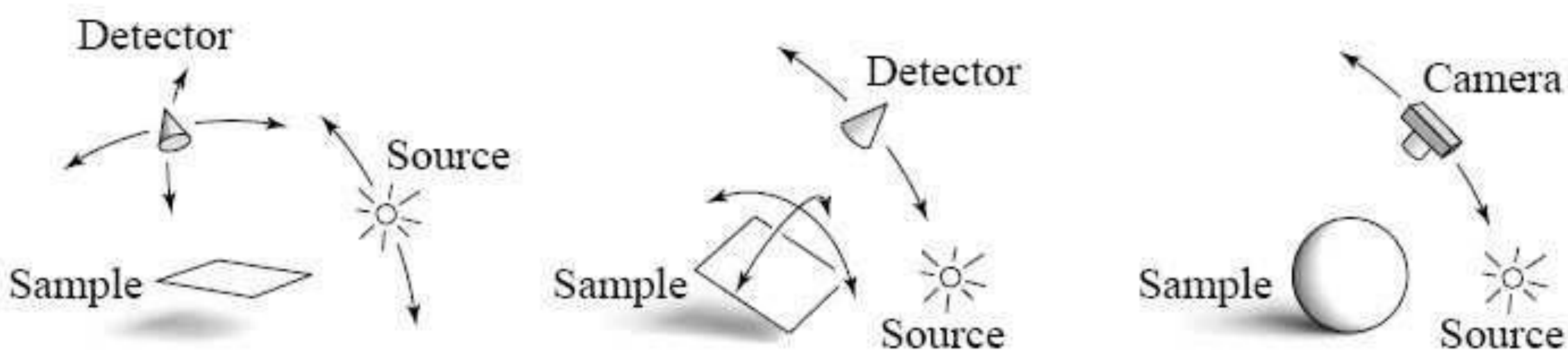
BRDF Measurement

- **Measurement Devices**
  - **Since the BRDF is a function of lighting and viewing directions, measurement involves sampling 2D space of light directions and 2D space of viewing directions**



BRDF Measurement

- **Measurement Devices**
  - **Fix material sample, move light source and camera**
  - **Fix light source, move the camera and tilt the sample**
  - **Fix light source and sample, move the camera, if the target object consists of a single material and has a known convex geometry**



Measurement Device: Light Stage

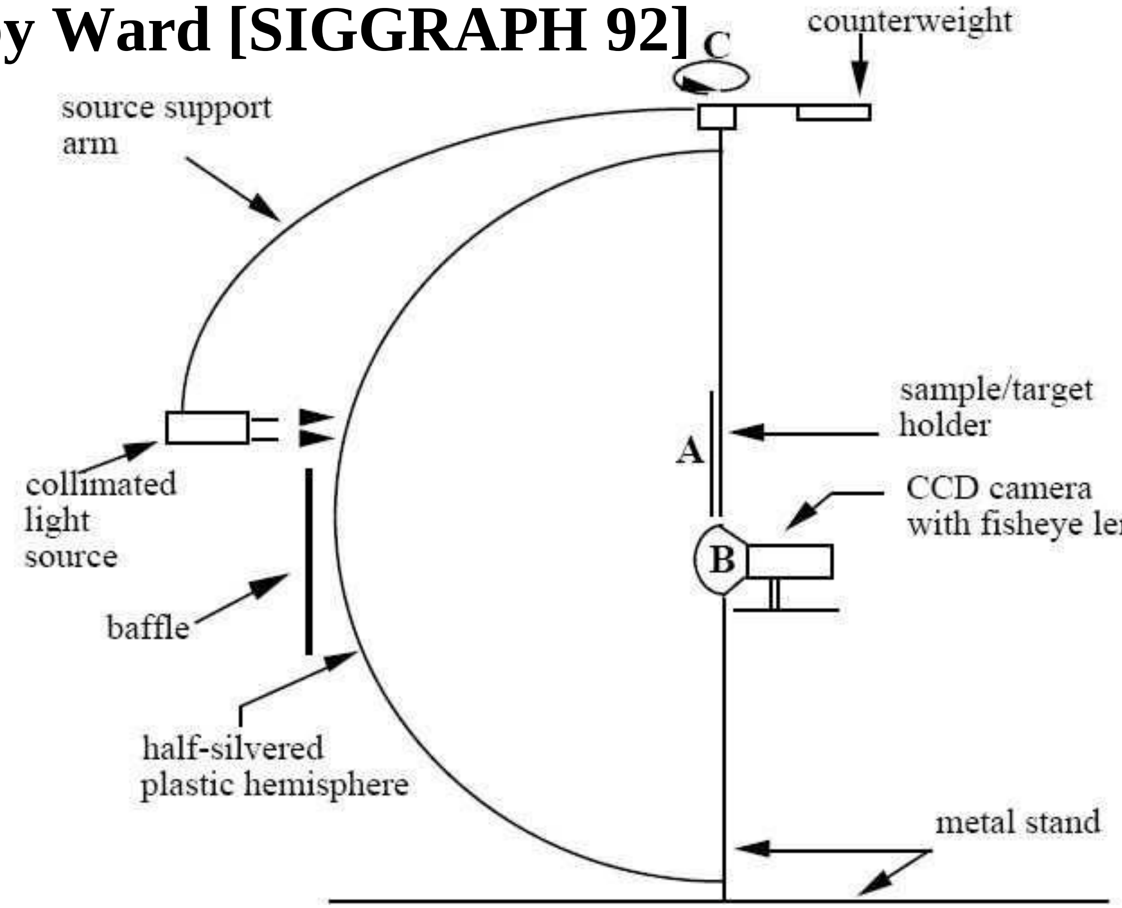
- **Light Stage**
  - **Debevec et al. [SIGGRAPH 2000]**
  - **BRDFs are measured from a fixed object or person**
  - **Images are captured from a few viewing directions with about 2000 different lighting directions**
  - **Distinct BRDFs can be measured for all the image points simultaneously.**

Measurement Device: Light Stage

- **Re-illuminate the face**

Measurement Device: **Gonioreflectometer**

- **Gonioreflectometer**
  - **Developed by Ward [SIGGRAPH 92]**



Measurement Device: **Gonioreflectometer**

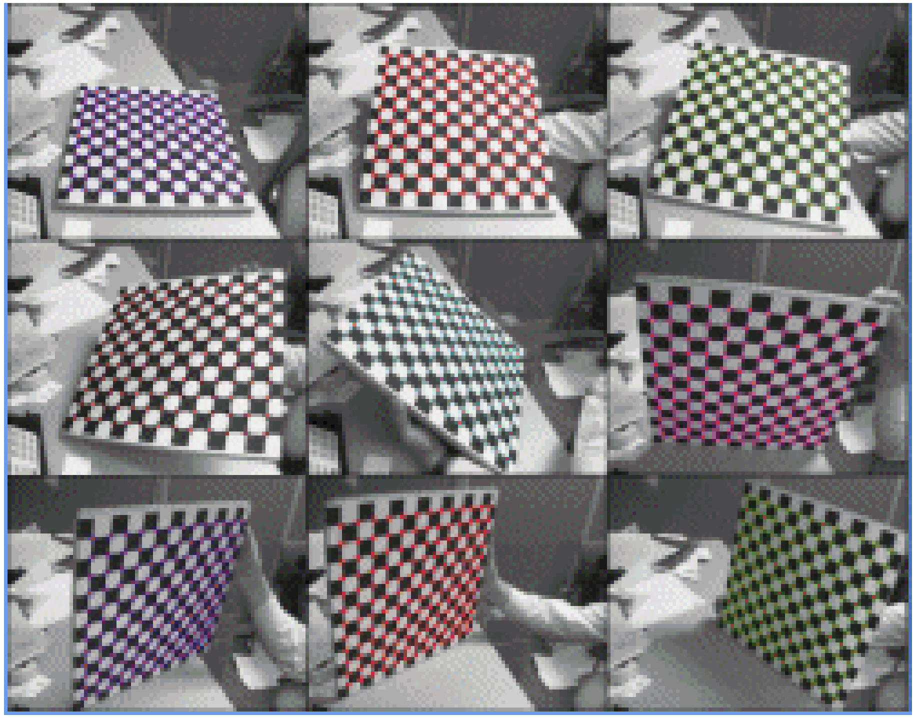
- **Gonioreflectometer**
  - **Utilize a half-silvered hemisphere to view a material sample from multiple directions at the same time**
  - **A light source from outside the hemisphere illuminate the sample**
  - **A camera with a fisheye lens captures the entire hemisphere at once**
  - **Eliminating two degrees of freedom, only light source needs to move**

Practical Issues:

- **Camera Calibration (相机参数矫正)**
  - **To measure a BRDF, the camera must be calibrated in a few respects**
  - **The external parameters, such as its location and orientation; the internal parameters, includes its focal length and camera center**
  - **Using Zhang’s method [Zhang00, a flexible new technique for camera calibration, IEEE PAMI] by capturing several pattern images**

Practical Issues:

- **Camera Calibration (相机参数矫正)**



- Next week's topic:

Ray Tracing

More on course project

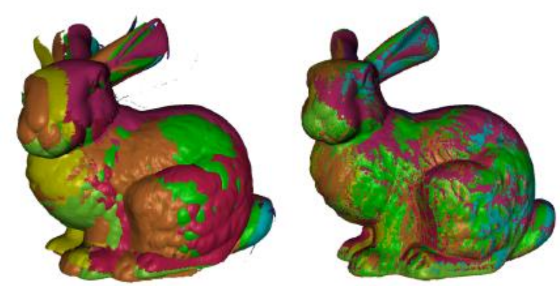
- Acquisition and modeling pipeline

Bunny Entity

Scan

Point Patches

Registration



Point Representation

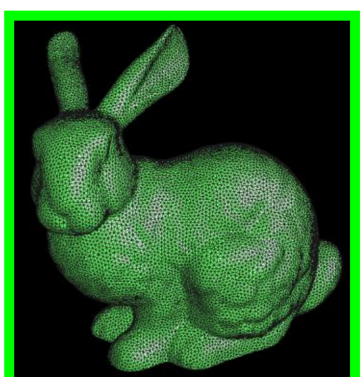
Mesh Generation

Remeshing

Mesh Repair

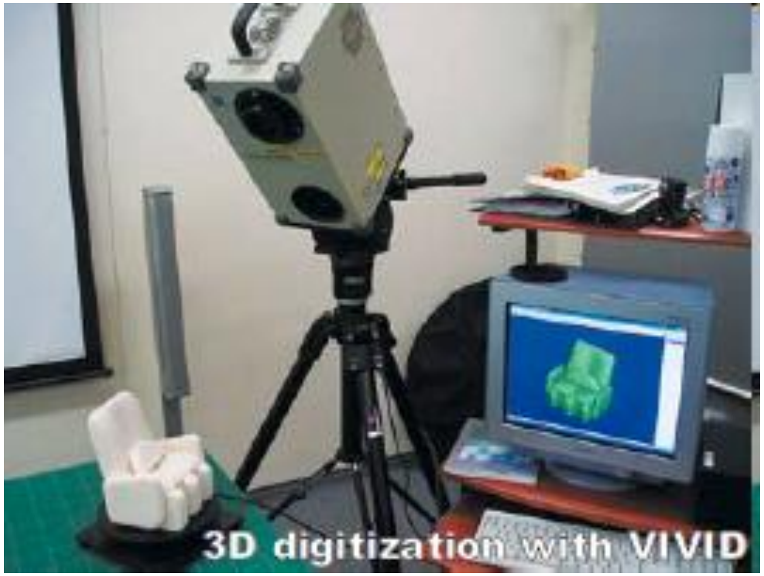
Topology Editing

…



Bunny Mesh Model

- 激光扫描设备：ViViD910



Thanks!