Study the nature of things to imaging
-An overview of physics-based rendering

Wu Minjie

Art Technical Director, Ubisoft Montreal Studio

GDC 15 'Cn

游戏开发者大会•中国
GAME DEVELOPERS CONFERENCE CHINA
SHANGHAI INTERNATIONAL CONVENTION CENTER
SHANGHAI, CHINA · OCTOBER 25-27, 2015

The origin of PBR In the game industry

大神

Physically-Based Reflectance for Games

Siggraph 2006 Course

Naty Hoffman Dan Baker Jan Kautz

Course Description

This course discusses the practical implementation of physically-principled reflectance models in interactive graphics and video games, in current practice as well as upcoming technologies. The course begins with the visual phenomena important to the perception of reflectance in real-world materials, which it uses as background for the underlying theory and derivation of common reflectance models. After introducing the current game development pipeline, from content creation to rendering, the course then discusses rendering techniques for implementing reflectance models in games — with emphasis on real-world trade offs such as shader performance, content creation efficiency, resource size considerations, and overall rendering quality. The course will help a researcher understand constraints in the game development pipeline and it will help a game developer understand the physical phenomena underlying reflectance models.

Syllabus

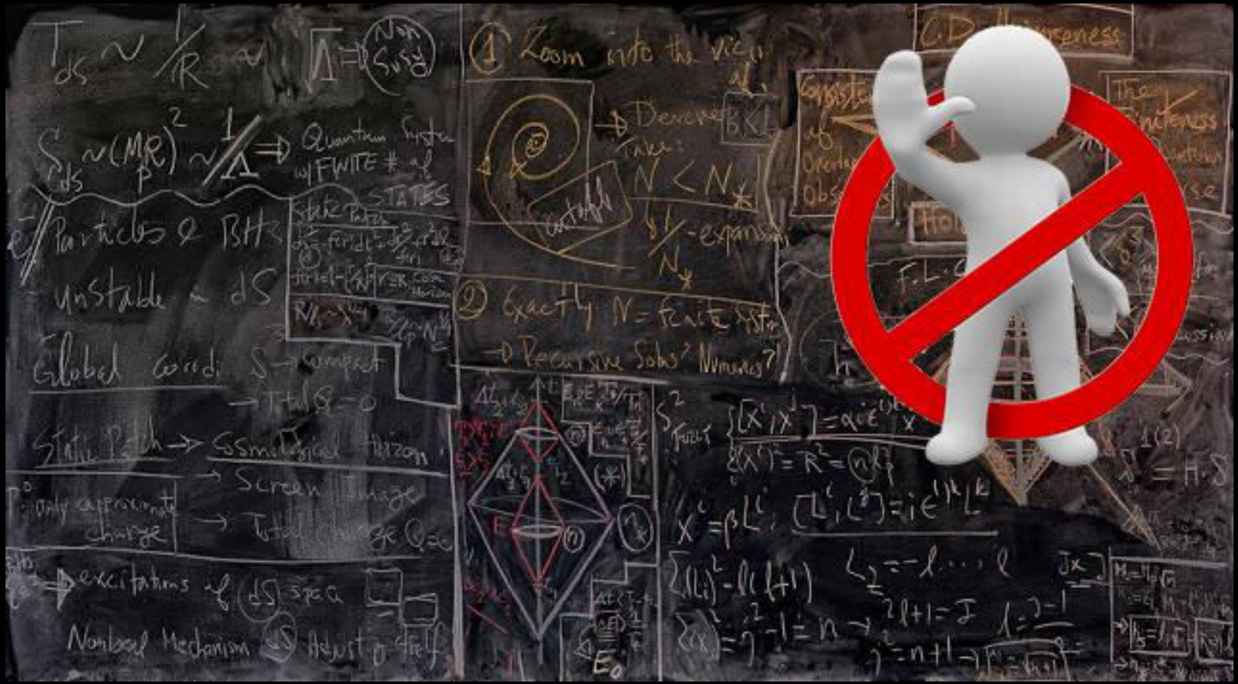
- 8:30 - 8:40 Introduction (Naty) [PDF]
  - Motivation
  - Problem Statement
- 8:40 - 9:15 Reflectance (Naty) [PDF]
  - Types of Reflectance
  - Reflectance Theory
  - Reflectance Model Foundations
- 9:15 - 10:15 Game Development (Naty and Dan) [PDF]
  - Game Platform
  - Computation and Storage Constraints
  - Production Considerations
  - The Game Rendering Environment
- 10:15 - 10:30 Break
- 10:30 - 11:15 Reflectance Rendering with Point Lights (Naty and Dan) [PDF]
  - Analytical BRDFs
  - Other Types of BRDFs
  - Anti-Aliasing and Level-Of-Detail
- 11:15 - 12:00 Reflectance Rendering with Environment Map Lighting (Jan) [PDF]
  - Environment Maps
  - Theory of Filtered Environment Maps
  - Diffuse Filtered Environment Maps
  - Glossy Filtered Environment Maps
  - Anti-Aliasing for Environment Map Rendering
  - Precomputed Radiance Transfer
- 12:00 - 12:15 Conclusions/Summary (All) [PDF]
  - Summary
  - Q&A
  - References [PDF]
  - Glossary [PDF]

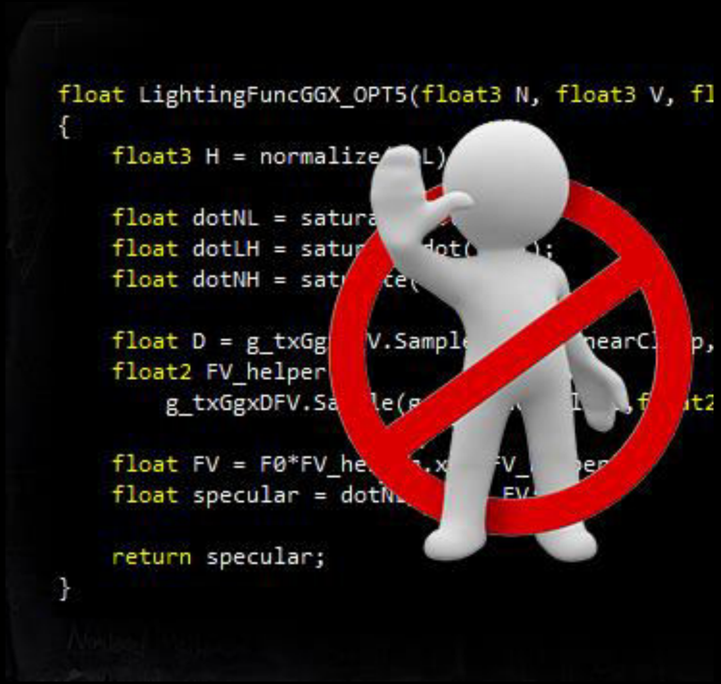
Status of PBR

Content

1. What is PBR

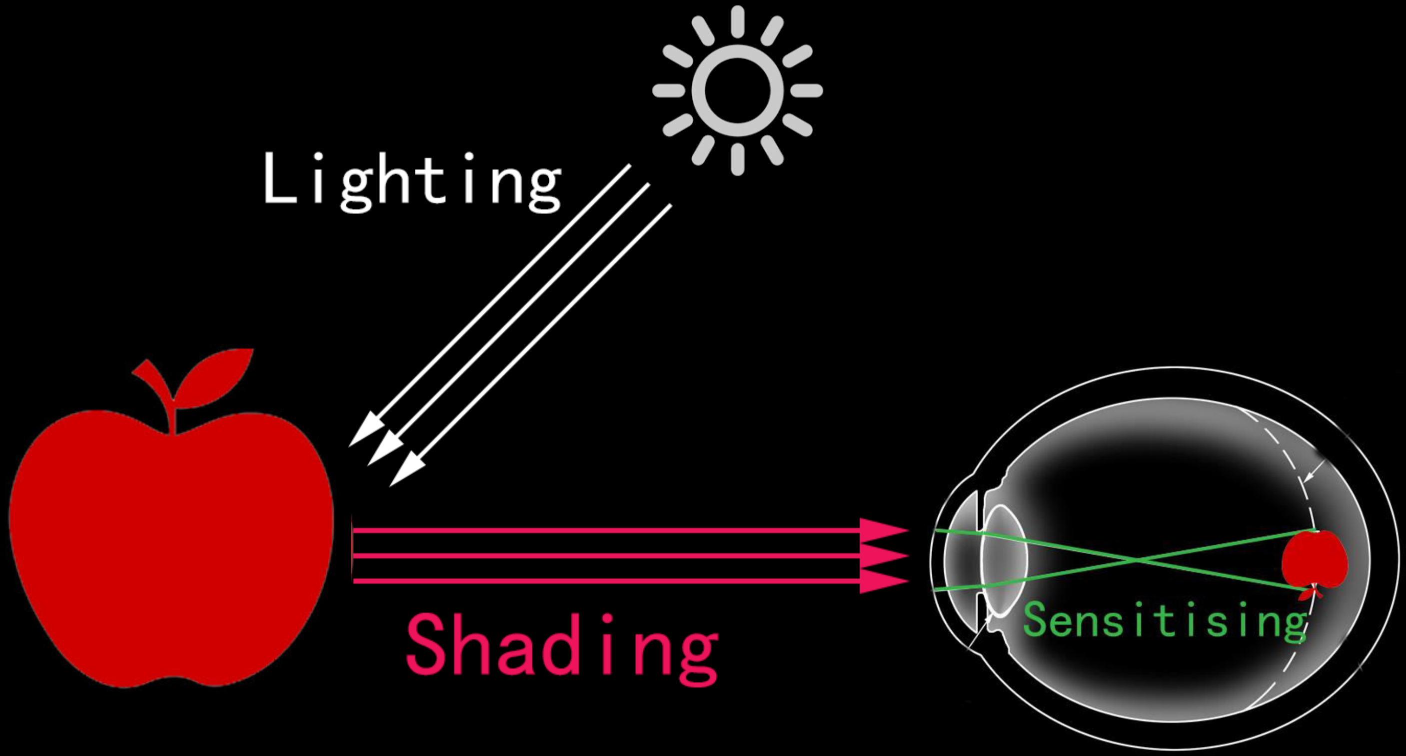
2. The influence of PBR





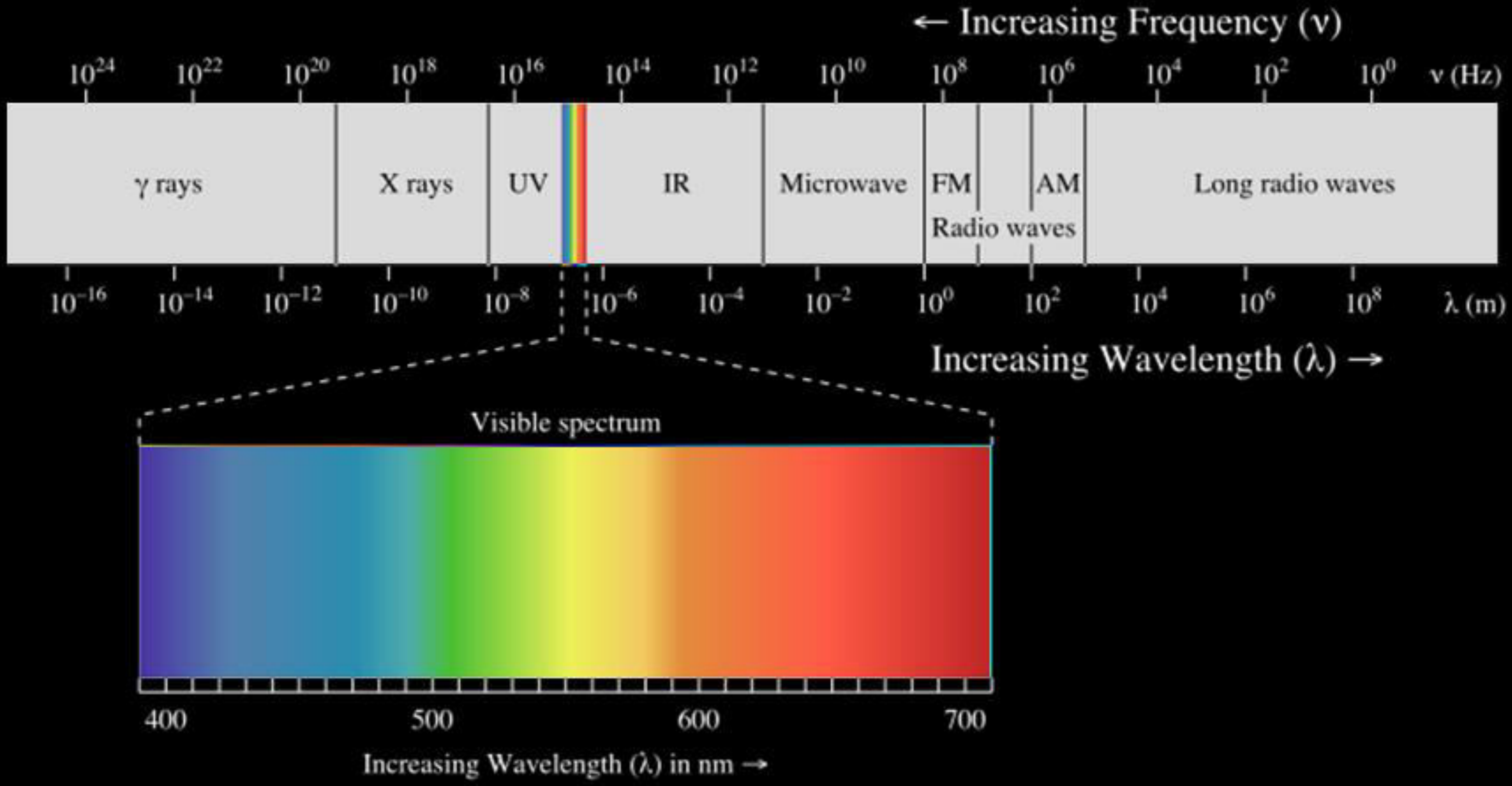
Background knowledge

Seeing is believing?



Seeing is believing?

Visible light range: 400 nm – 700 nm



What is PBR

Differences between PBR and traditional rendering

Essence: subjective and objective

PBR: Based on the physical properties of the things in the objective world

Traditional rendering: Based on the viewer's subjective image

PBR		传统的渲染
Albedo : 0.04 IOR : 1.635		Diffuse:黑色 闪亮高光 ......

Style: "process-oriented" vs "result-oriented"

PBR: Decompose a complex phenomenon into a series of formulas and parameters associated

Traditional rendering: focus on final result

PBR
(Domino effect)

Traditional rendering
(Iceberg Theory)

Function: “all-weather” vs ”single angle”

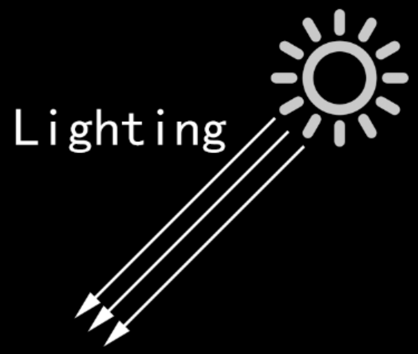
PBR: it can always adapt to the environment.
Traditional rendering: from a certain perspective, unable to take the overall situation into account

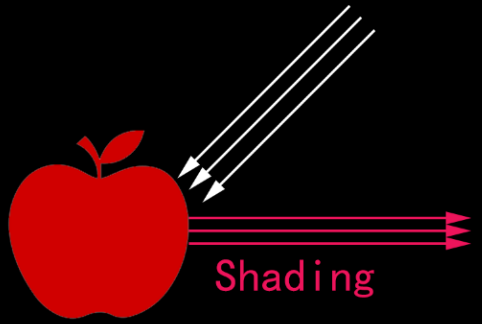
PBR

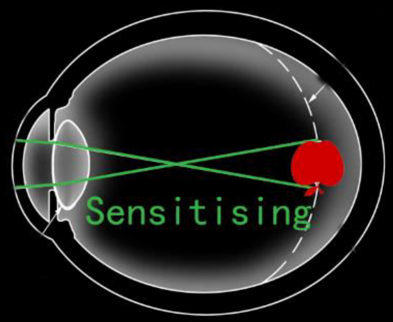
Traditional rendering

Details of PBR

1. Physically Based Lighting
2. Physically Based Shading
3. Physically Based Sensitising







Physically Based Lighting

Three elements of lighting (to discuss PBL from the perspective of artist):

1. Intensity
2. Color
3. Type

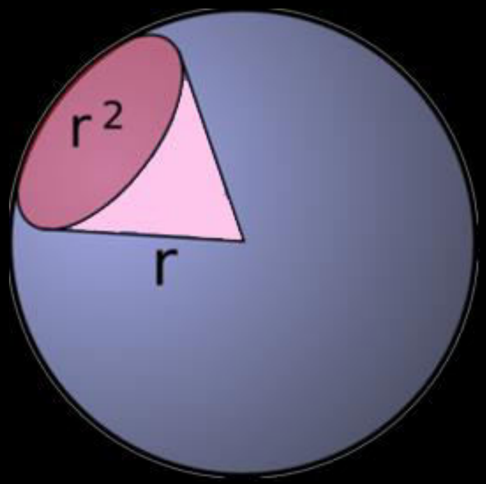
Lighting intensity

Three common physical units

1. Candela
2. Lumen
3. Lux

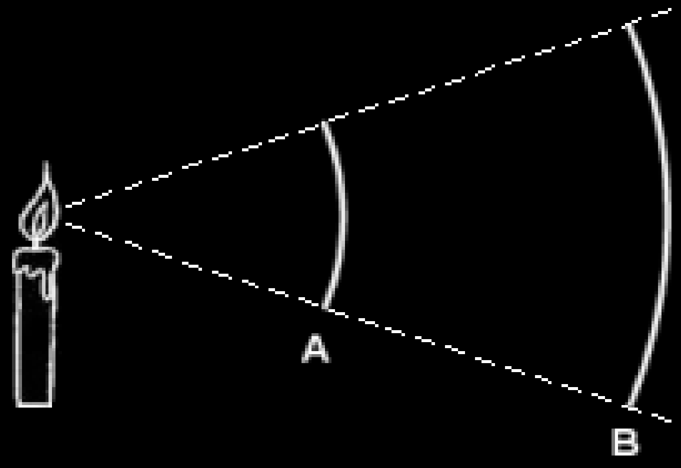
Steradian, symbol: sr

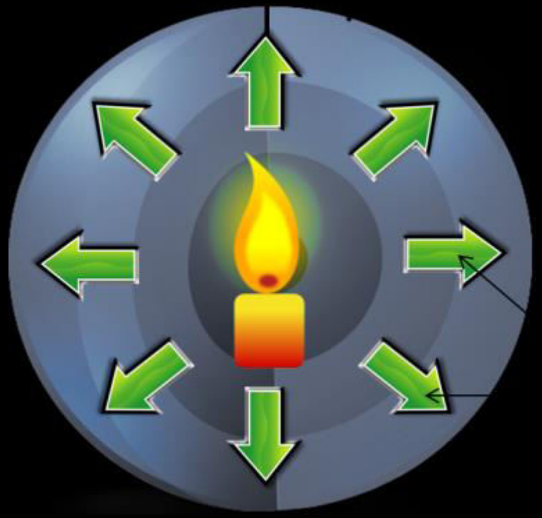
1. Unit of solid angle
2. Any closed sphere’s solid angle is 4π



Candela, symbol: cd

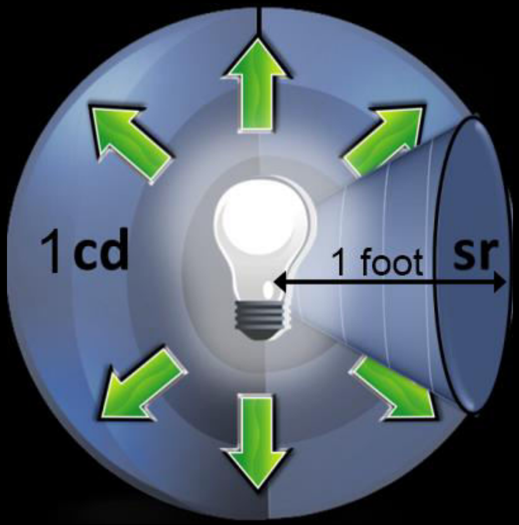
1. Unit of visible light intensity (1/683W/sr)
2. A common candle emits light with a luminous intensity of roughly one candela.






Lumen, symbol: lm

1. Unit of luminous flux
2. 1 lumen (lm)= 1 cd • sr
3. The luminous flux of a common candle is about lumens (220v)

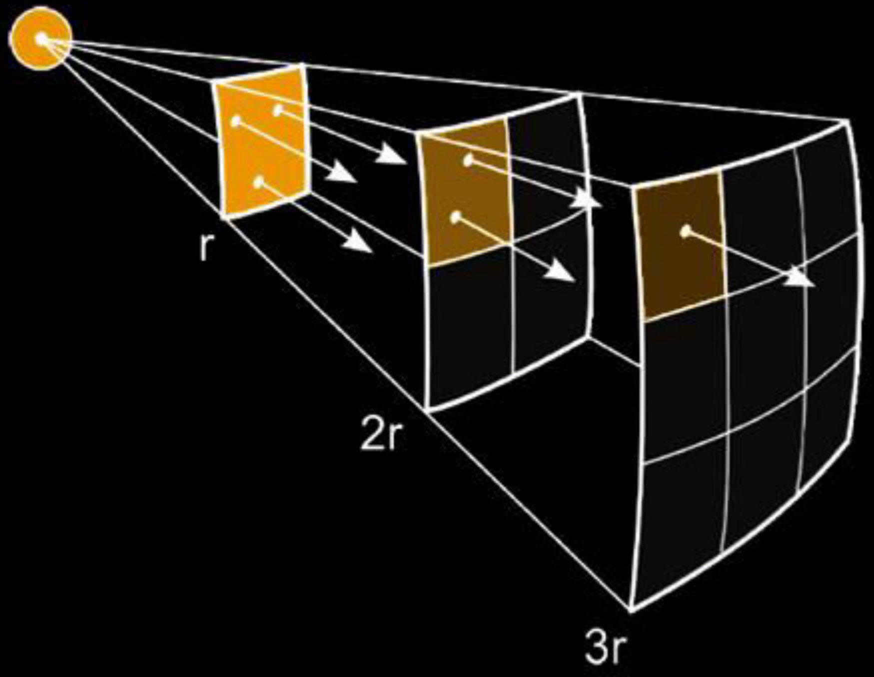


Lux, symbol: lx

1. Unit of luminous flux (Illuminance)
2. 1 lux= 1 lumen/square meter

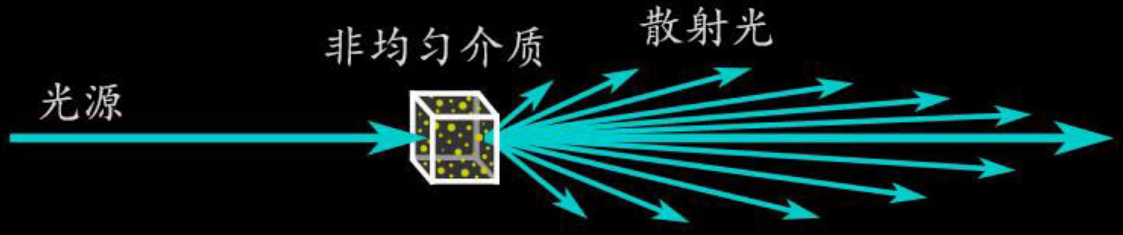
Attenuation

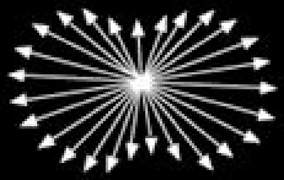
Inverse-square law: Light intensity is inversely proportional to the square of distance and attenuates (energy conservation)

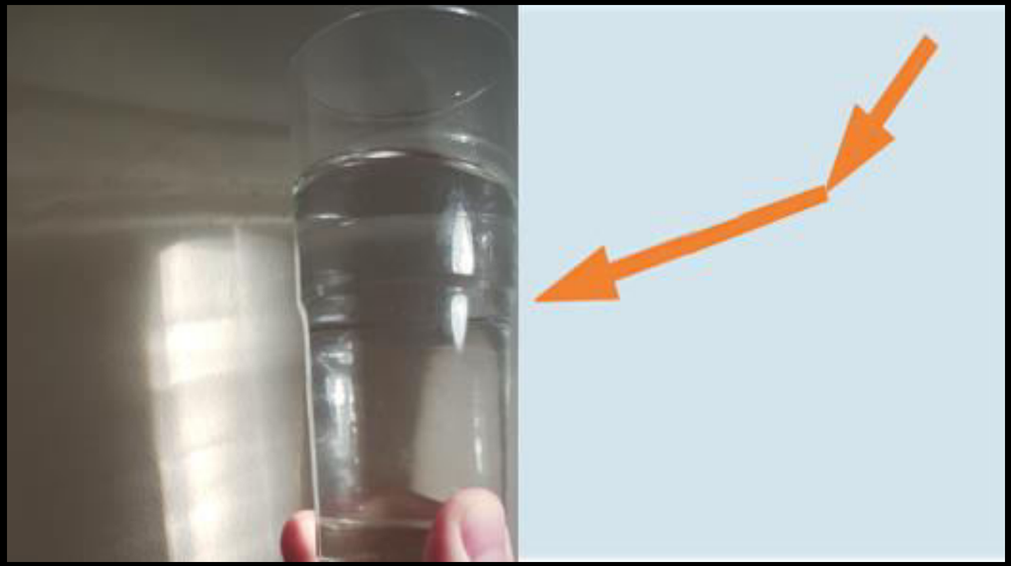


Scattering

Light is forced to deviate from a straight trajectory by one or more paths due to localized non-uniformities in the medium through which it passes.

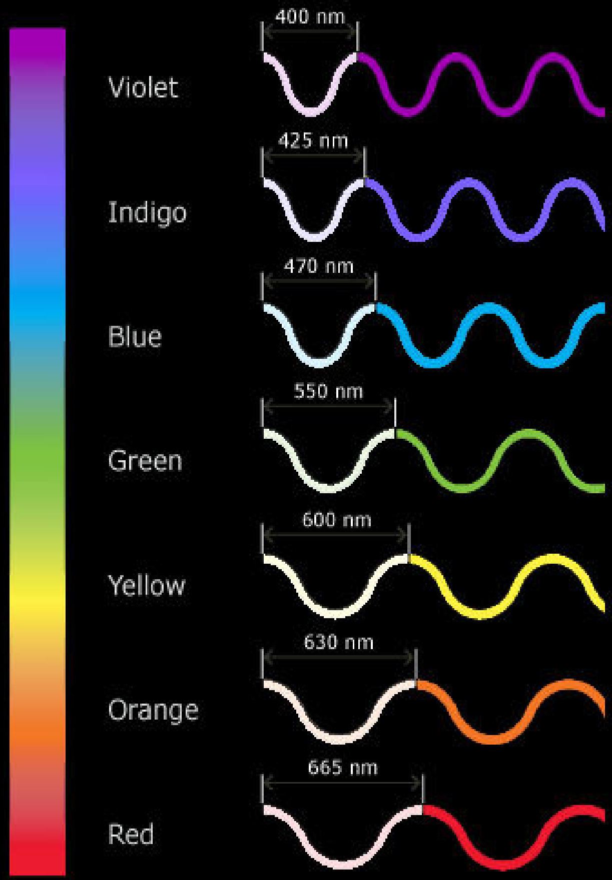


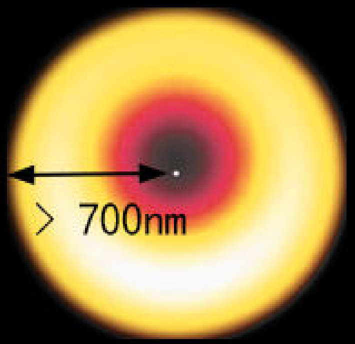




Mie scattering

Condition o: particle radius >= wavelength of the incident light

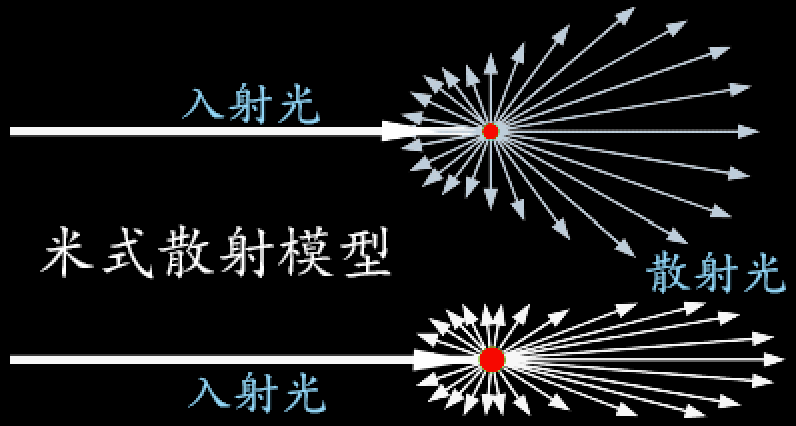




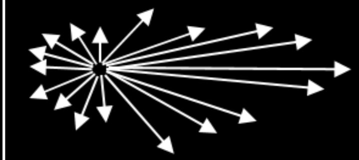
空气中的微粒

Mie scattering is as follows:

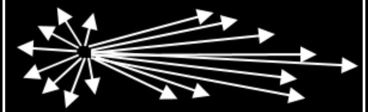
1. Most of the incident lights will scatter along the forward direction
2. particle radius will change the model of Mie scattering



Particle radius is close to the wavelength of the incident light

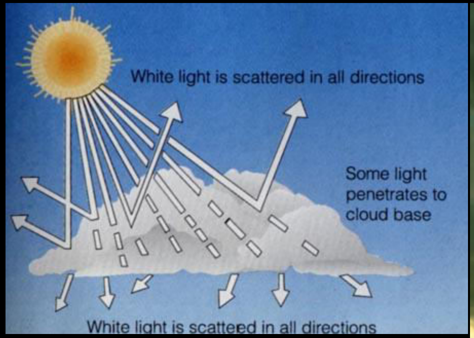


Particle radius increases



Impact on outdoor natural light intensity

weather	Transmissivity	Sky light
Sunny	About 0.85	10000 lux
Cloudy	About 0.55	1000 lux



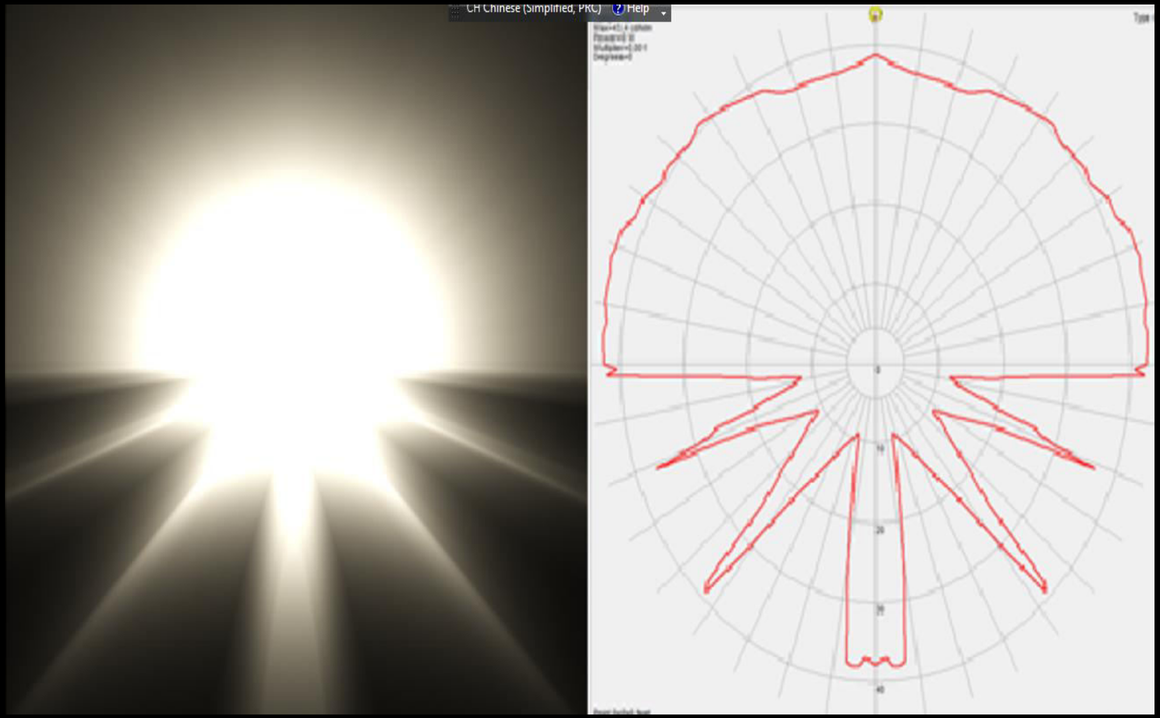


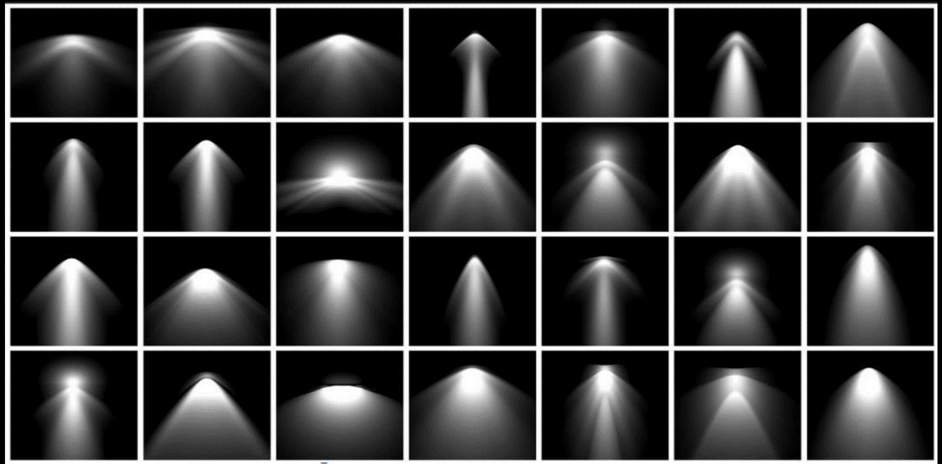
IES LIGHT

Photometric profile

IES : illuminating engineering society

IES Light = Maximum intensity (candela) X IES Photometric profile

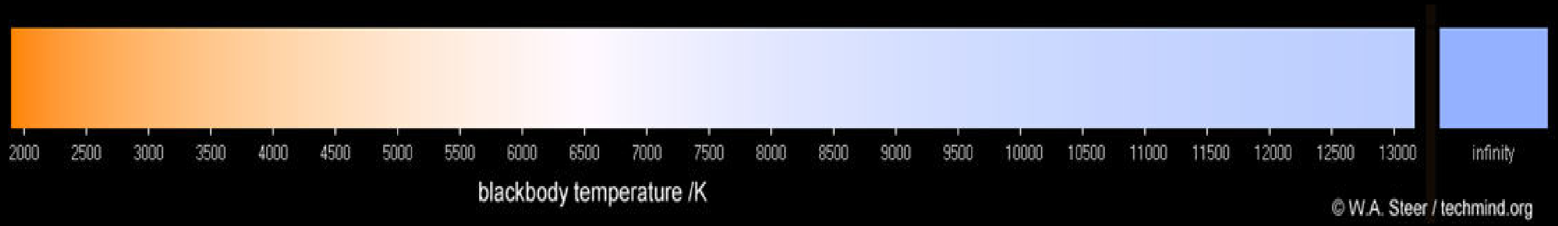




Mastercolor	
CDM-I / 25W / 40deg	CDM-i_25W_40deg.ies
CDM-I / 25W / 10deg	CDM-i_25W_10deg.ies
CDM-I / 25W / 25deg	CDM-i_25W_25deg.ies
CDM35 / 830 / PAR20 / SP	CDM35 830 PAR20 SP.ies
CDM20 / 830 / PAR20 / FL	CDM20 830 PAR20 FL.IES
CDM20 / 830 / PAR20 / SP	CDM20 830 PAR20 SP.IES

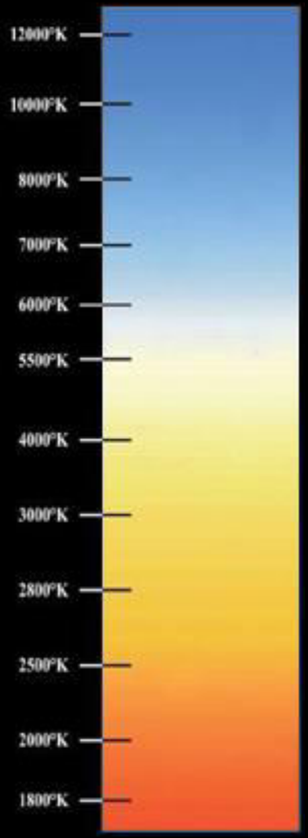
Lighting color

color temperature symbol:K



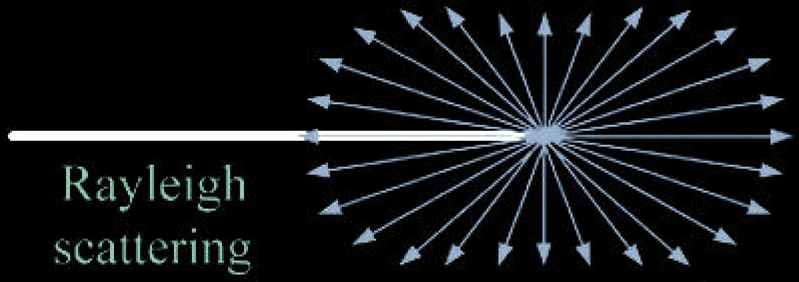
晴朗藍天	10000 ~ 12000 ˚K
多雲有雨	8000 ~ 10000 ˚K
薄雲	6500 ~ 8000 ˚K
日光型螢光燈	6500 ˚K
正午日光	5500 ˚K
電子閃光燈	5500 ˚K
早晨或下午陽光	4000 ~ 5000 ˚K
攝影棚燈光	3000 ~ 4000 ˚K
石英燈	3500 ˚K
鎢絲燈泡	2700 ~ 3200 ˚K
黎明、黃昏	2000 ~ 3000 ˚K
燭光	1800 ~ 2000 ˚K

常見的環境色溫



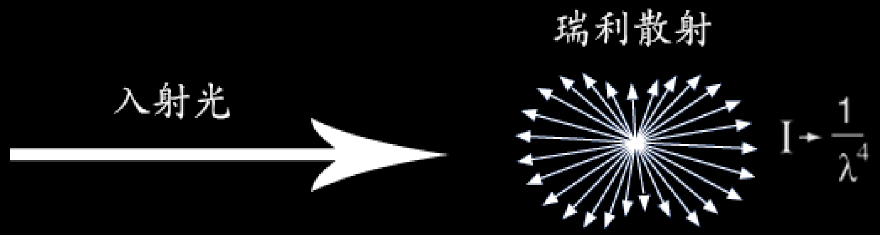
Rayleigh scattering

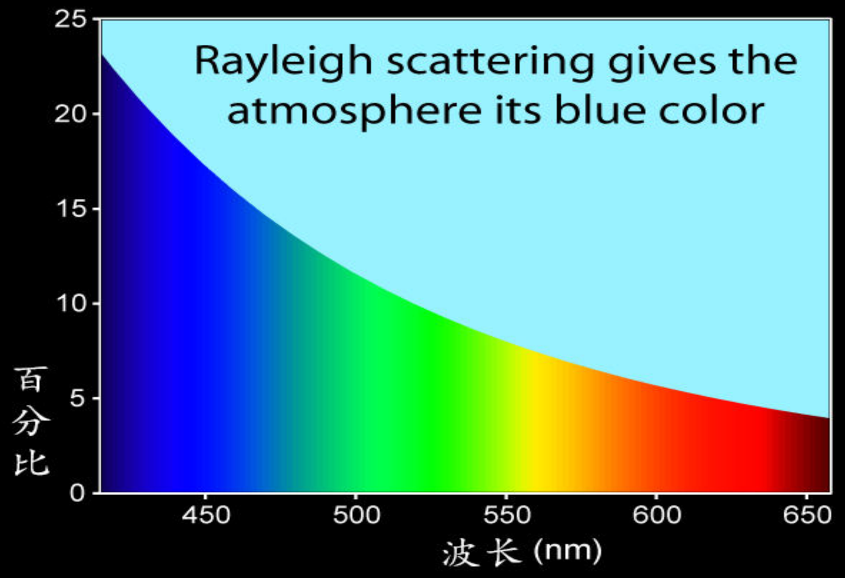
Condition: Particle radius <= One tenth of the wavelength of incident light



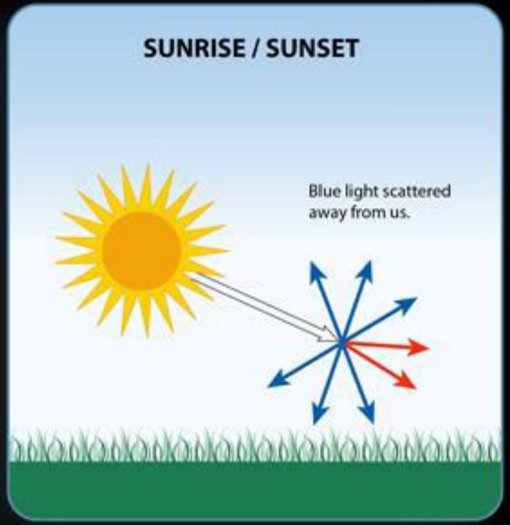
Rayleigh scattering

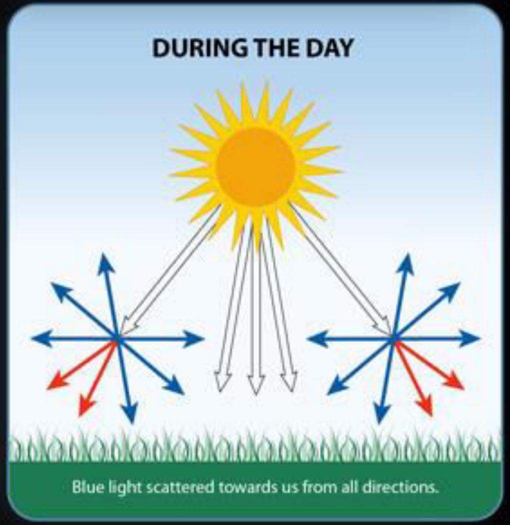
Scattering intensity: inversely proportional to the fourth power of the wavelength





瑞利散射发生时，阳光中各波长的光所占比例



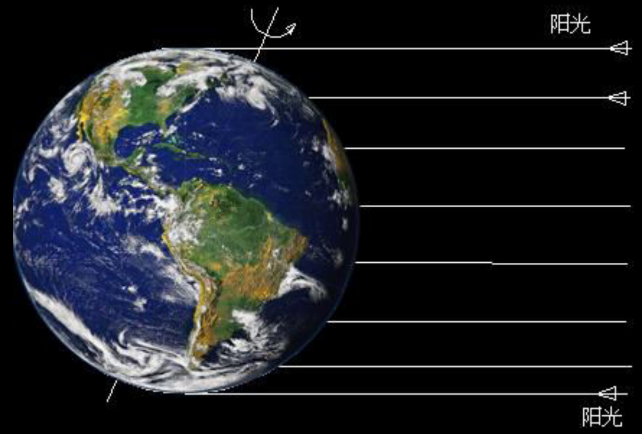


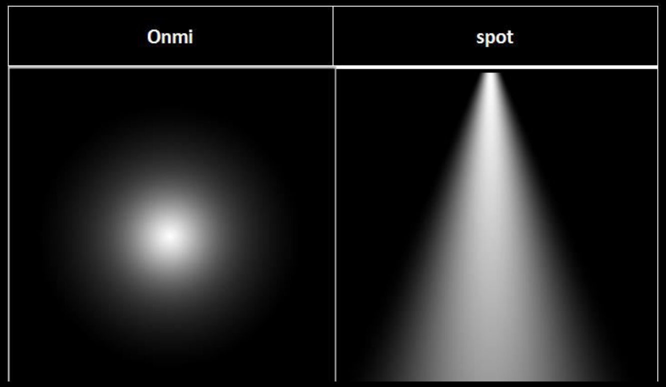
Lighting type

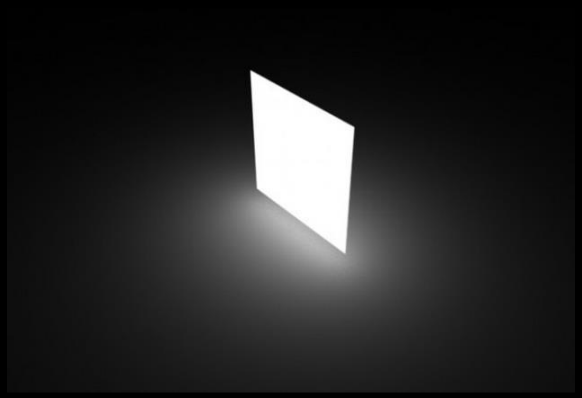
1. directional light

2. Punctual light

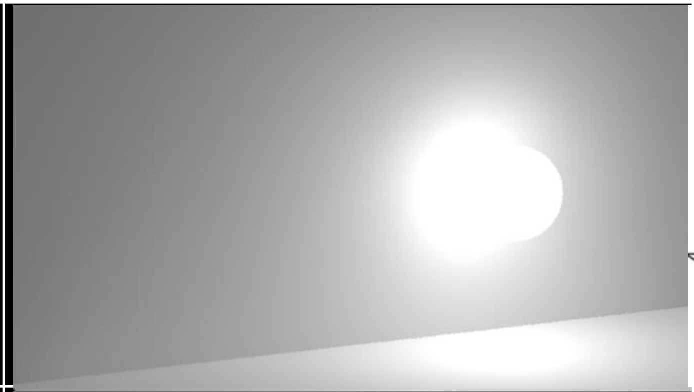
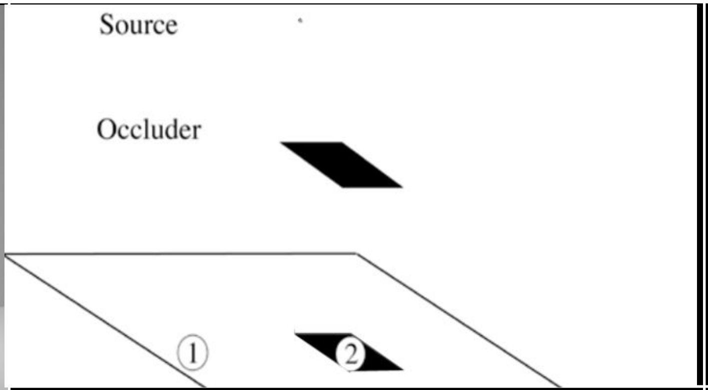
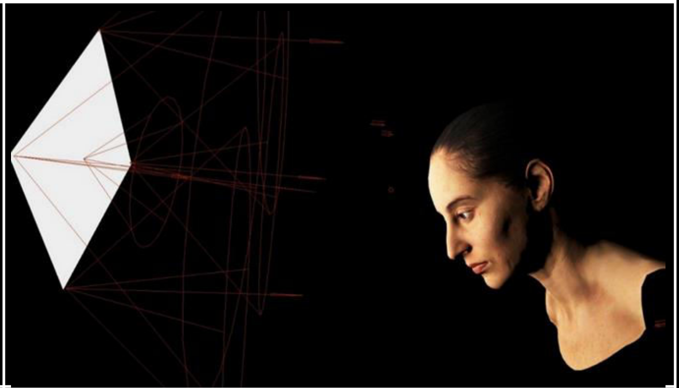
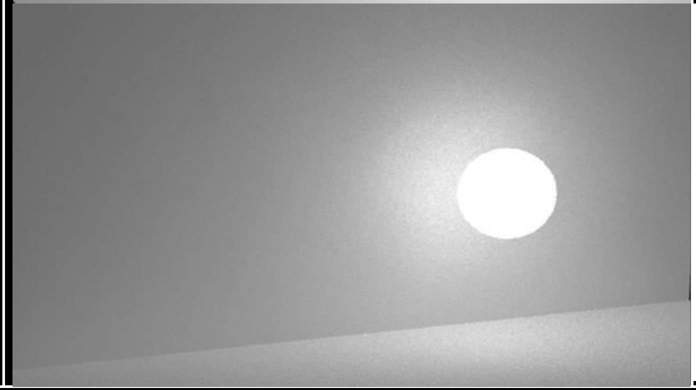
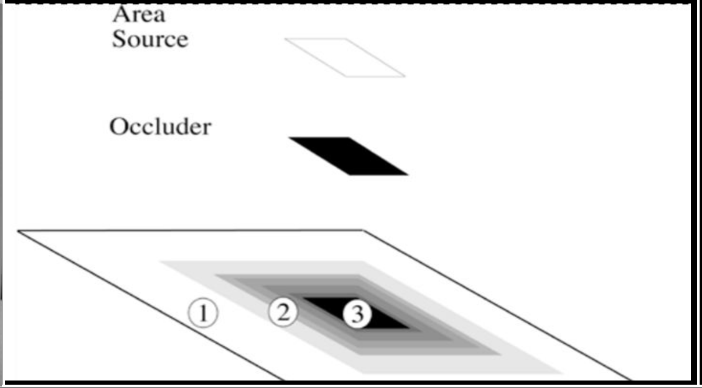
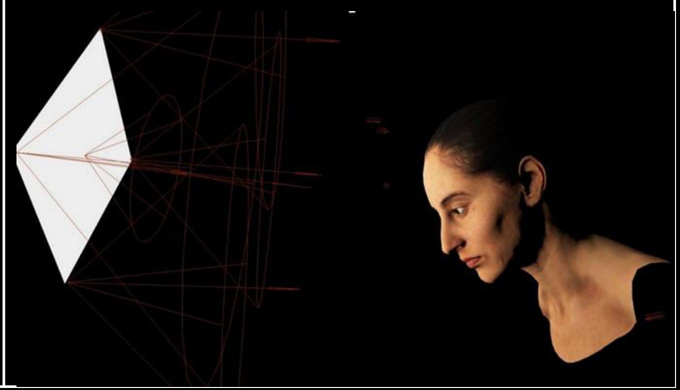
3. area light



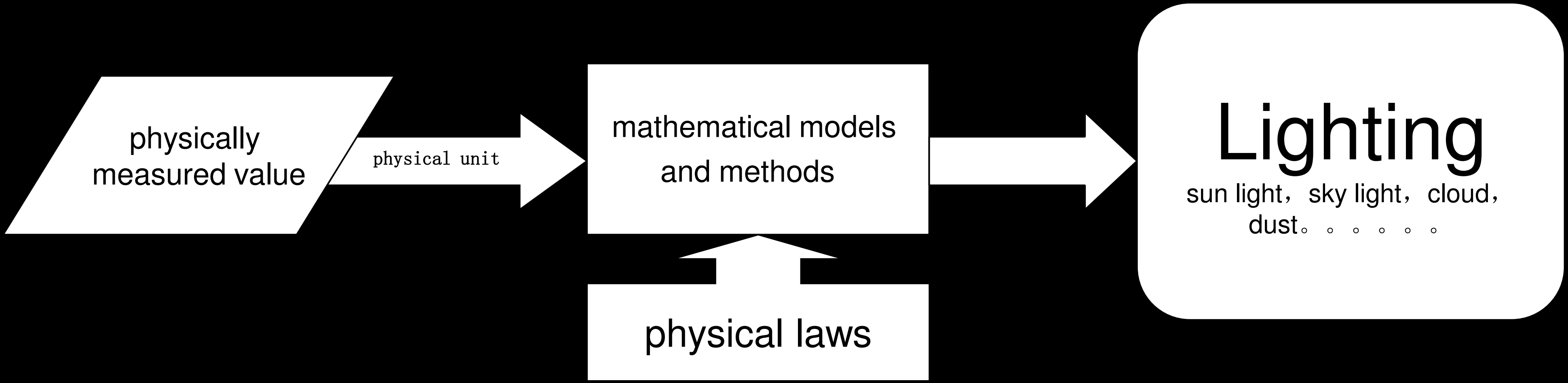




Punctual light VS Area light

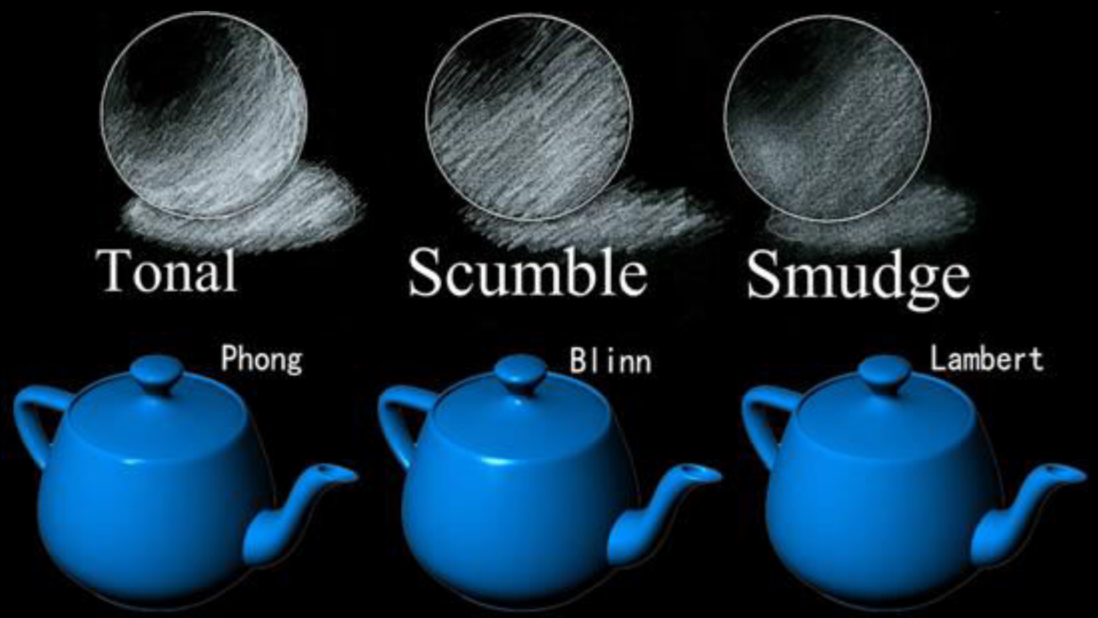
	Specular	shadow	instance
Punctual light			
Area light			

brief summary of PBL



Physically Based Shading

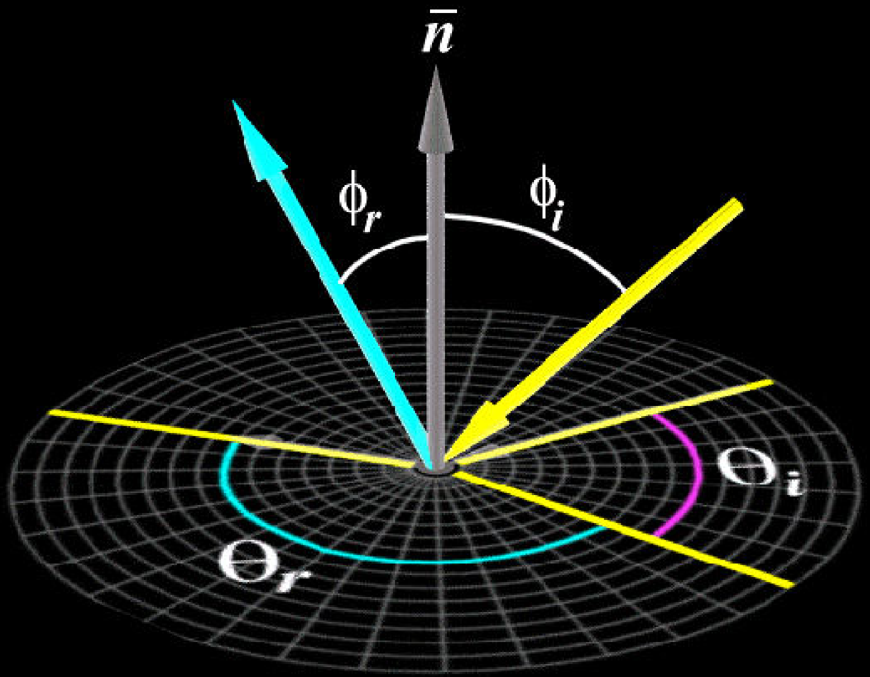
Shading：material response to lighting
Function：BRDF



BRDF 是什么

Bidirectional Reflectance Distribution Function

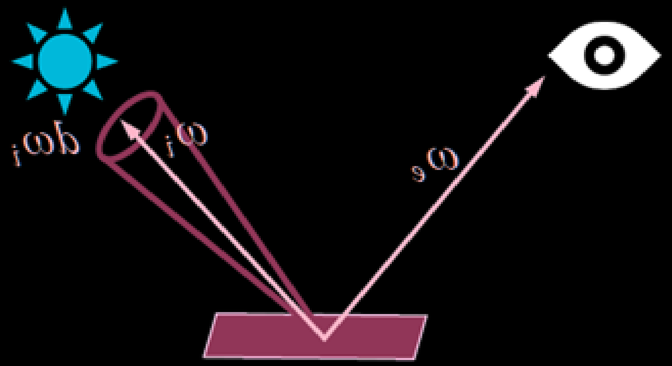
1. **Bidirectional**
2. **Reflectance**
3. **Distribution Function**



Bidirectional （双向）

1. The direction from sampling point to camera (eyes)

2. The direction from sampling point to point light source

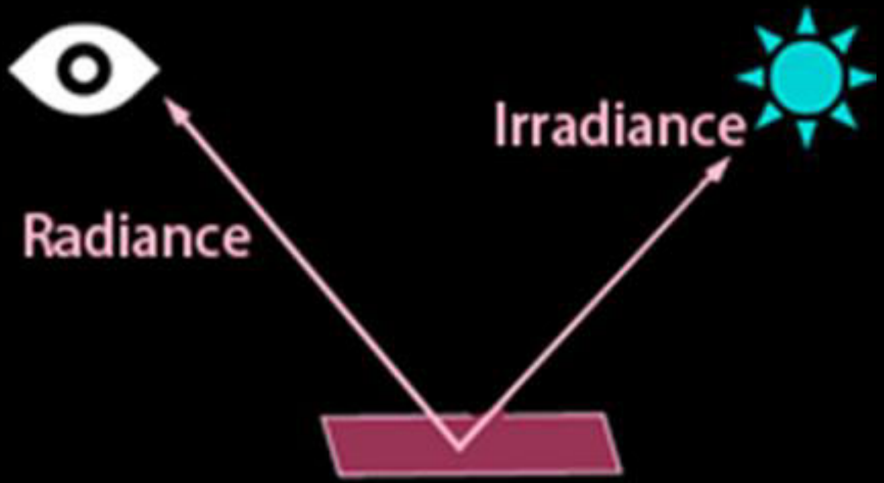


Reflectance （反射率）

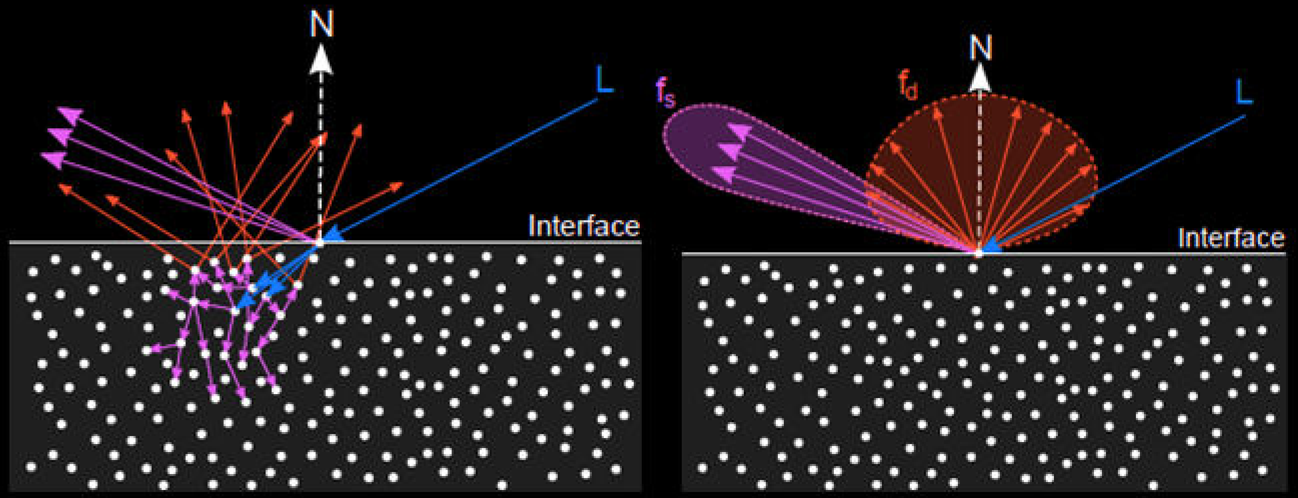
Reflectance = Radiance / irradiance

Irradiance (power/area) : the power of the light received by current point

Radiance (power/(area x solid angle)) : the power of the light emitted by current point



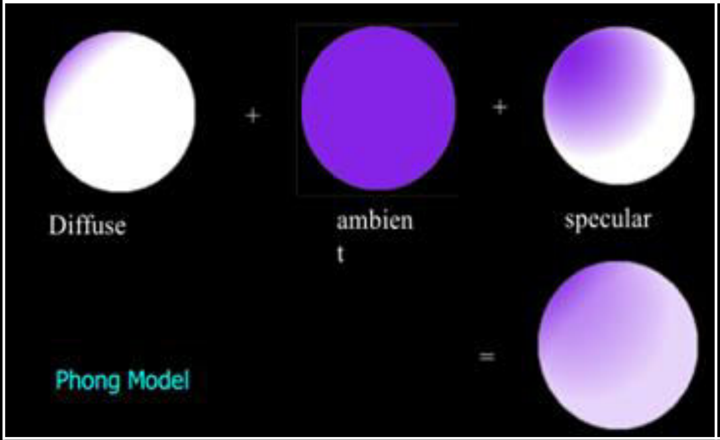
Distribution Function



(a) 光线交互示意图 (b) 分布函数建模图

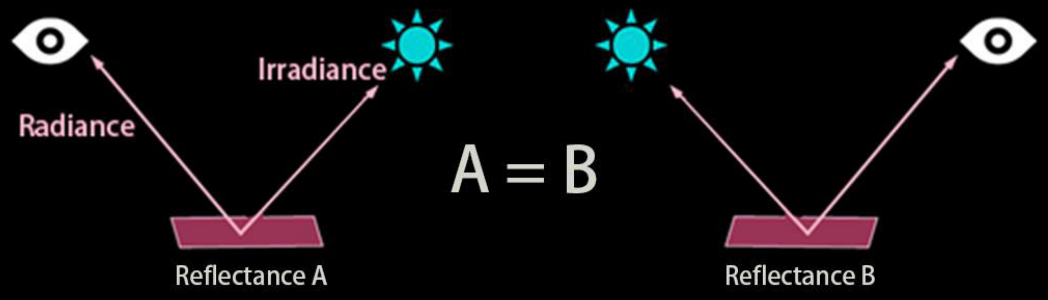
Picture from : Naty Hoffman, Background: Physics and Math of Shading

Three different types of BRDF

<table>
<tr><th>Empirical model</th><th>Physically based model</th><th>Data-driven mode</th></tr>
<tr><td>
</td><td></td><td></td></tr>
</table>

Basic principles of physics-based model

1. Reciprocal



2. Conservation of energy

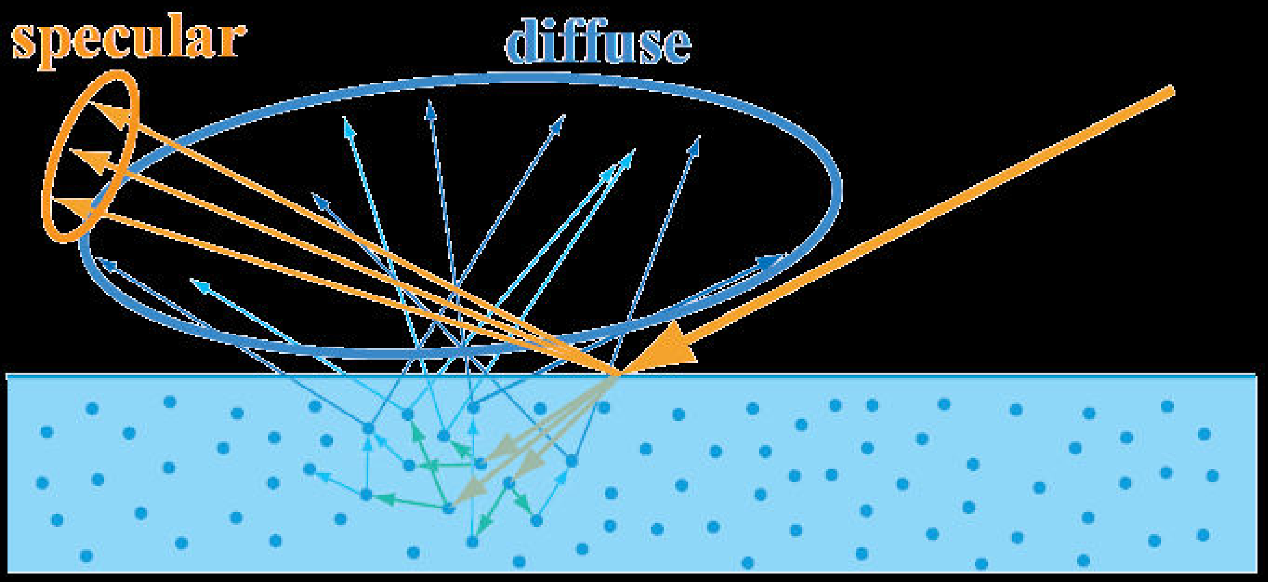
3. Constant positive (Positivity)

Generic Shader

Ci = Ka*ambient() + Kd*diffusion() + Ks*specular()

1. Ambient
2. Diffusion
3. Specular

www.renderstory.com

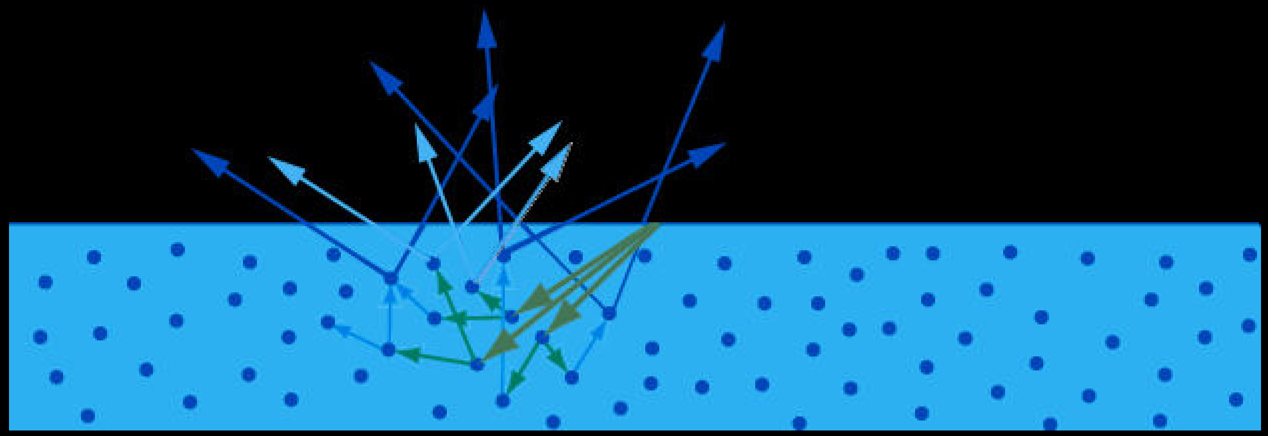


Picture from : Naty Hoffman, Background: Physics and Math of Shading

Diffusion

The process of diffusion:

1. Refracting into a material
2. Scattering in the material
3. Scattering out from the material



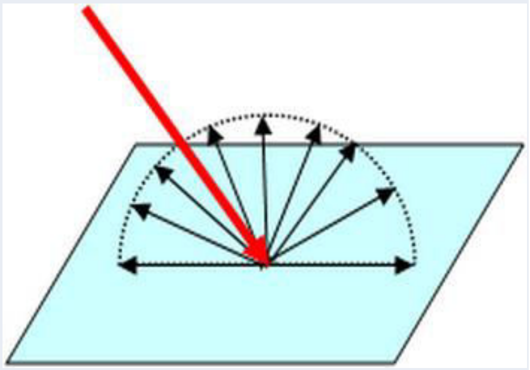
Picture from : Naty Hoffman,Background: Physics and Math of Shading

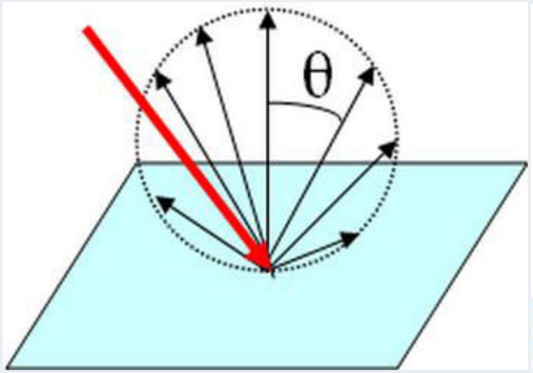
Diffusion model

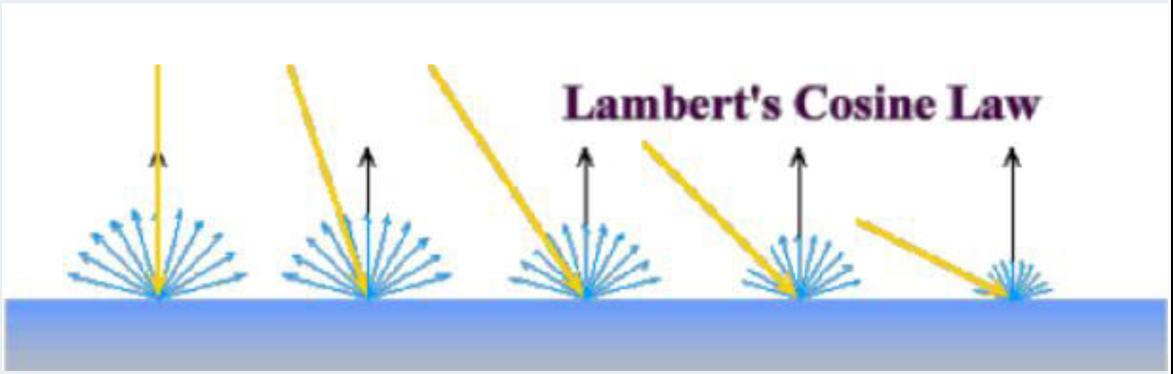
1. Lambert ： Based on smooth material surface.

Lambert model characteristics: ：

Isotropic (camera view)	Light intensity distribution is in line with the cosine law (light angle)
$F_{lambert} = \dfrac{\rho}{\pi}$	$F_{lambert} = \dfrac{\rho}{\pi} \cdot E_o \cdot \cos\theta_i$





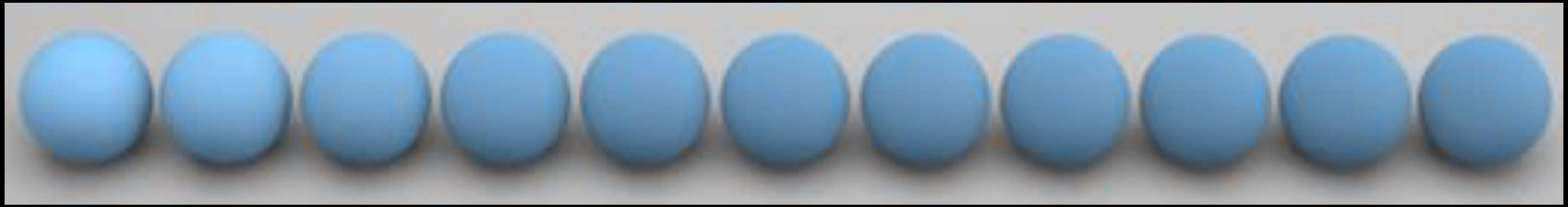


2. Oren-Nayar

derived from Lambert model

extended to the rough surface

controlled by roughness(0-1.0)



光滑表面

粗燥表面

http://www.cs.columbia.edu/CAVE/software/curet/html/sample.html (Pictures of the 61 samples)

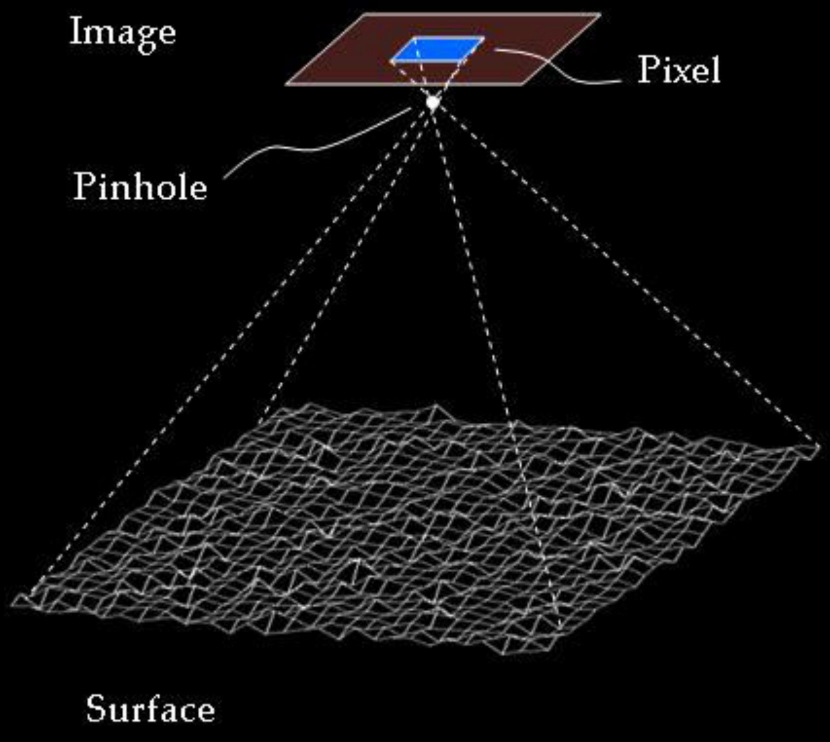
1. Felt 0.414686	2. Polyester 0.576862	3. Terrycloth 0.458514
4. Rough Plastic 0.278057	5. Leather 0.179776	6. Sandpaper 0.513084
7. Velvet 0.751002	8. Pebbles 0.443289	9. Frosted Glass 0.416384
10. Plaster_a 0.362825	11. Plastic_b 0.543788	12. Rough Paper 0.311376
13. Artificial Grass 1.378872 (Red. More than 1?)	14. Roof Shingle 0.819147	15. Aluminum Foil 0.252702
16. Cork 0.659956	17. Rough Tile 0.204088	18. Rug_a 0.566478
19. Rug_b 0.613889	20. Styrofoam 0.509725	21. Sponge 0.872413
22. Lambswool 0.978133	23. Lettuce Leaf 0.241785	24. Rabbit Fur 0.933632
25. Quarry Tile 0.360574	26. Loofa 0.300436	27. Insulation 0.136013
28. Crumpled Paper 0.274957	29. Polyester (Zoomed) 0.522950	30. Plaster_b (Zoomed) 0.520868
31. Rough Paper (Zoomed) 0.318498	32. Roof Shingle (Zoomed) 0.950521	33. Slate_a 0.356822
34. Slate_b 0.309590	35. Painted Spheres 1.211948	36. Limestone 0.413544
37. Brick_a 0.893379	38. Ribbed Paper 0.215297	39. Human Skin 0.579386
40. Straw 0.717587	41. Brick_b 0.275990	42. Corduroy 0.699112
43. Salt Crystals 0.481594	44. Linen 0.514593	45. Concrete_a 0.600672
46. Cotton 0.482679	47. Stones 1.107168 (Red. More than 1?)	48. Brown Bread 0.784827
49. Concrete_b 0.308956	50. Concrete_c 0.461930	51. Corn Husk 0.387725
52. White Bread 0.507820	53. Soleirolia Plant 0.758465	54. Wood_a 0.598438
55. Orangle Peel 0.235808	56. Wood_b 0.351271	57. Peacock Feather 0.308792
58. Tree Bark 0.293226	59. Cracker_a 0.505978	60. Cracker_b 0.722678
61. Moss 0.542447		

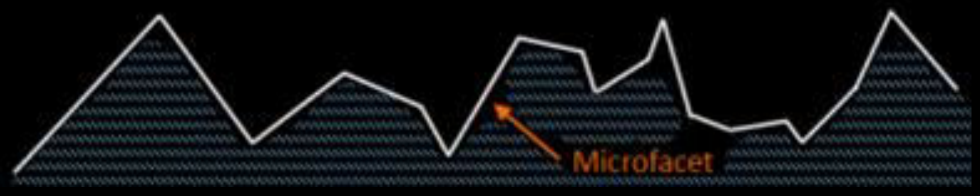
Theoretical basis of Oren-Nayar model

Based on microfacet model theory

Composed of many microfacets

Every facet can be seen as a Lambertreflection plane





Oren-Nayar formula

$$F_{Oran-Nayar} = \frac{\rho}{\pi} \cdot E_o \cdot \cos\theta_i (A + (B \cdot \max[0, \cos(\phi i - \phi r)] \cdot \sin\alpha \cdot \tan\beta))$$

$$A = \frac{1}{\pi}\left(1 - 0.5\frac{\sigma^2}{\sigma^2 + 0.33} + 0.17\rho\frac{\sigma^2}{\sigma^2 + 0.13}\right)$$

$$B = \frac{1}{\pi}\left(0.45\frac{\sigma^2}{\sigma^2 + 0.09}\right)$$

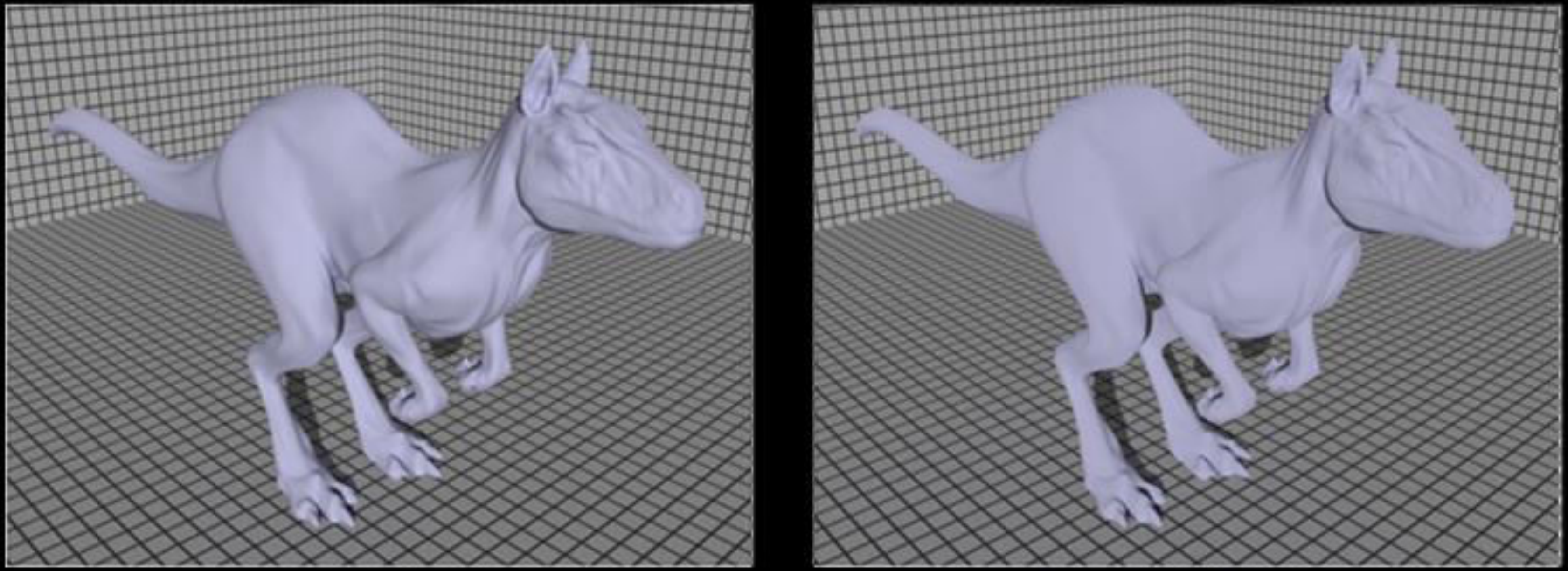
σ： roughness

$$F_{Lambert} = \frac{\rho}{\pi} \cdot E_o \cdot \cos\theta_i$$

$$F_{Oran-Nayar} = \frac{\rho}{\pi} \cdot E_o \cdot \cos\theta_i \cdot \text{粗燥因子}$$

$$F_{Oran-Nayar} = F_{Lambert} \cdot \text{粗燥因子}$$

当 σ = 0：
A =1， B=0， 粗燥因子 = 1



Lambertian Oren-Nayar

Images by Pharr and Humphreys [Physically Based Rendering, Morgan Kaufmann/Elsevier, 2004] what is ρ

ρ = Albedo

$$F_{Oran-Nayar} = \frac{\rho}{\pi} \cdot E_o \cdot \cos\theta_i (A + (B \cdot \max[0, \cos(\phi i - \phi r)] \cdot \sin\alpha \cdot \tan\beta)) \quad F_{Lambert} = \frac{\rho}{\pi} \cdot E_o \cdot \cos\theta_i$$

Physical meaning of Albedo:

A ration of solar radiation reflected by the object to solar radiation received

Sample albedos

Surface	Typical albedo
Fresh asphalt	0.04[2]
Worn asphalt	0.12[2]
Conifer forest (Summer)	0.08,[3] 0.09 to 0.15[4]
Deciduous trees	0.15 to 0.18[4]
Bare soil	0.17[5]
Green grass	0.25[5]
Desert sand	0.40[6]
New concrete	0.55[5]
Ocean ice	0.5–0.7[5]
Fresh snow	0.80–0.90[5]

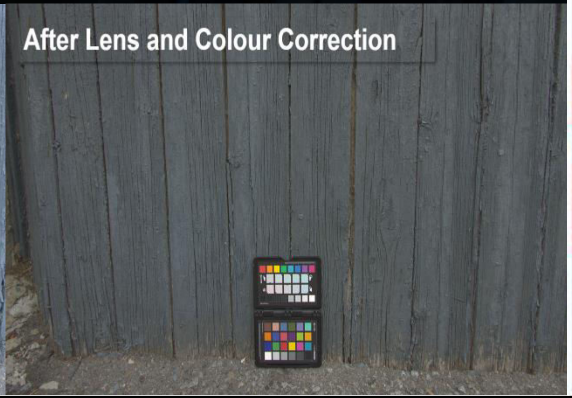
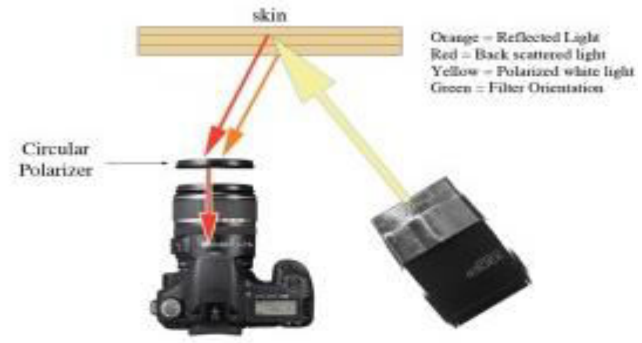
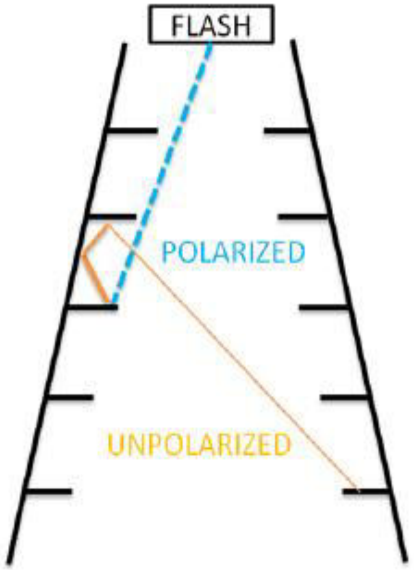
Albedo definition by rendering engine:

1. Not affected by additional information of lighting (specular, ambient light, shadow ....)

2. Not affected by exposure bias

3. Not affected by color temperature deviation

Two kinds of Albedo texture acquisition

color checker	Cross -polarized lighting with spectralon
  	   

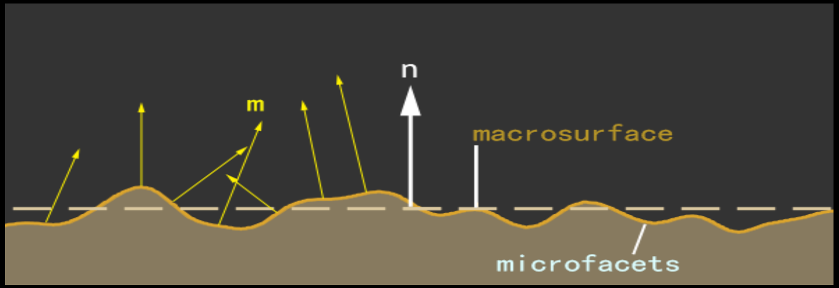
Specular:

Cook－Torrance reflection model:

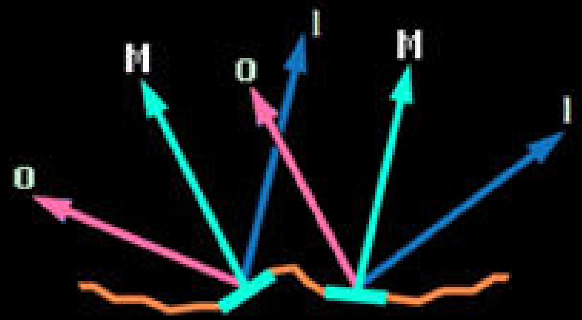
microfacet theory:

1 . The surface is composed microfacets, every facet only does specular reflection

2 .



2 . Based on microfacetnormal M, every facet only reflects the light of single direction



数学公式:

$$F_{Cook\text{–}Torrance} = \frac{D() \cdot G() \cdot F()}{4(\mathrm{l} \cdot \mathrm{n})(\mathrm{v} \cdot \mathrm{n})}$$

Molecule:
D（） ：Distribution function
G（） ：Geometry attenuation function
F（） ：Fresnel function

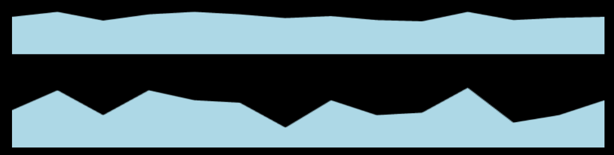
Denominator:
4（n.l） （v.n）： Correction factor for conversion between micro mirror surface and the overall surface

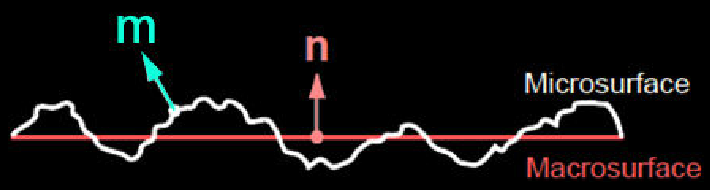
Influences from microstructure of the material surface:

Roughness:

Value range between 0-1

Square root of slope of facet

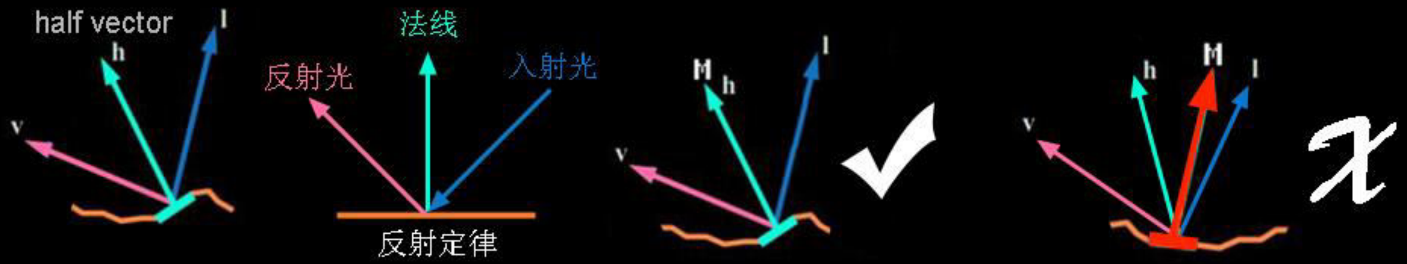




Half Vector:

The angle between the hvector bisecting the incident light I and observation direction v.

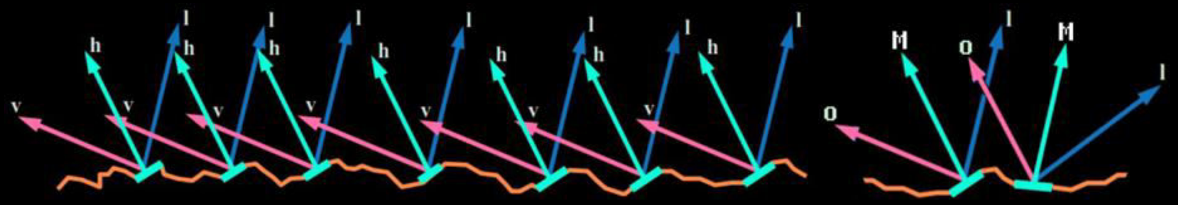
Only when h coincides with the facet’ s normal M, the microfacetwill be ″activated.″



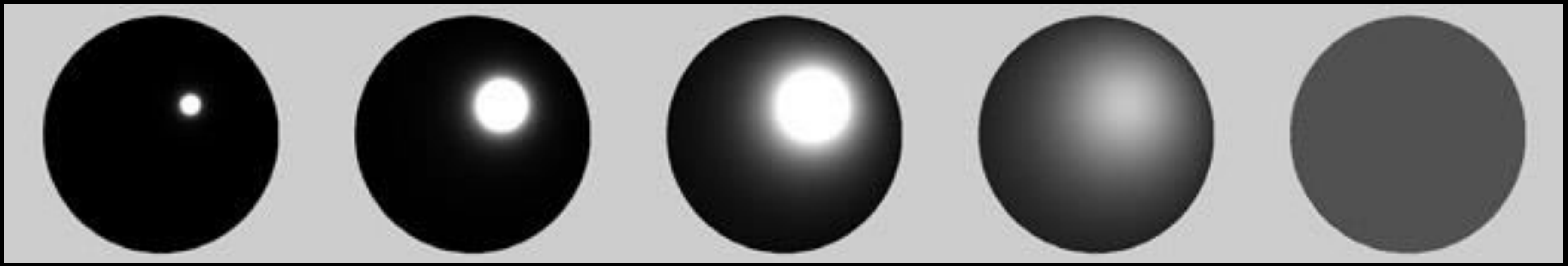
Picture from : Naty Hoffman,Background: Physics and Math of Shading

Distribution functionD ( ) :

Normal distribution probability of activated facets

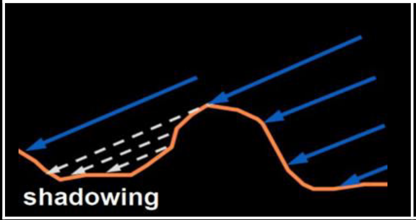
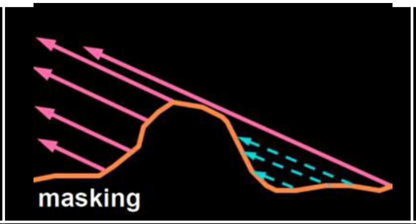
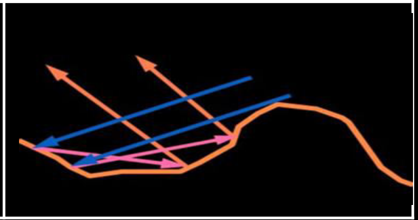


The performance of distribution function with different roughness (GGX)



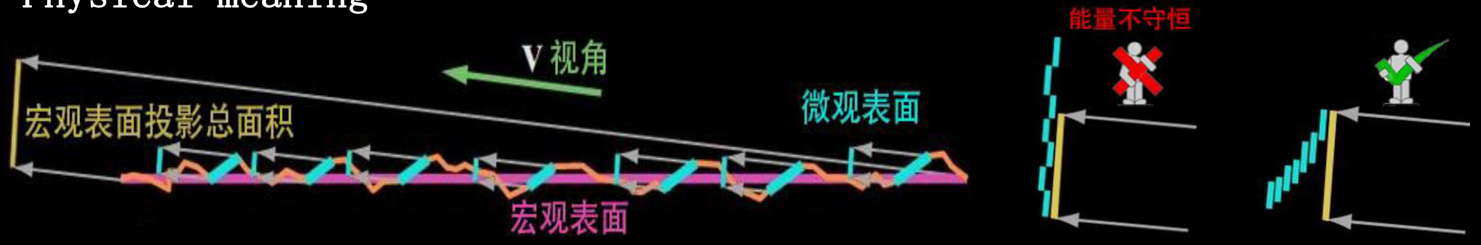
Geometry attenuation function G ( ) :

Distribution probability of facet blocking incident light and reflected light

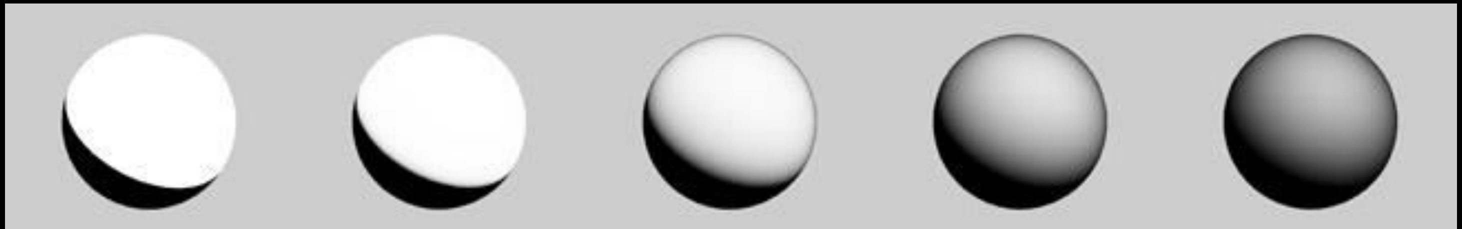
Incident light blocked	Reflected light blocked	Multiple bounce not be considered
		

Picture from : Naty Hoffman,Background: Physics and Math of Shading

Physical meaning



The performance of geometry attenuation function with different roughness (GGX)



Distribution function(D)	Geometry attenuation function(G)
Blinn-Phong	Implicit
Beckmann	Neumann
GGX	Cook-Torrance
GGX (Anisotropic)	Kelemen
	Smith
	Beckmann
	GGX
	Schlick-Beckmann
	Schlick-GGX

GGX (Trowbridge-Reitz) :

$$D_{GGX}(\mathbf{m}) = \frac{\alpha^2}{\pi((\mathbf{n}\cdot\mathbf{m})^2(\alpha^2-1)+1)^2}$$

Beckmann :

$$D_{Beckmann}(\mathbf{m}) = \frac{1}{\pi\alpha^2(\mathbf{n}\cdot\mathbf{m})^4}\exp\left(\frac{(\mathbf{n}\cdot\mathbf{m})^2-1}{\alpha^2(\mathbf{n}\cdot\mathbf{m})^2}\right)$$

Blinn-Phong :

$$D_{Blinn}(\mathbf{m}) = \frac{1}{\pi\alpha^2}(\mathbf{n}\cdot\mathbf{m})^{\left(\frac{2}{\alpha^2}-2\right)}$$

Cook-Torrance:

$$G_{Cook-Torrance}(\mathbf{l},\mathbf{v},\mathbf{h}) = \min\left(1, \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{v})}{\mathbf{v}\cdot\mathbf{h}}, \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{l})}{\mathbf{v}\cdot\mathbf{h}}\right)$$

Kelemen:

$$G_{Kelemen}(\mathbf{l},\mathbf{v},\mathbf{h}) = \frac{(\mathbf{n}\cdot\mathbf{l})(\mathbf{n}\cdot\mathbf{v})}{(\mathbf{v}\cdot\mathbf{h})^2}$$

Schlick-Beckmann:

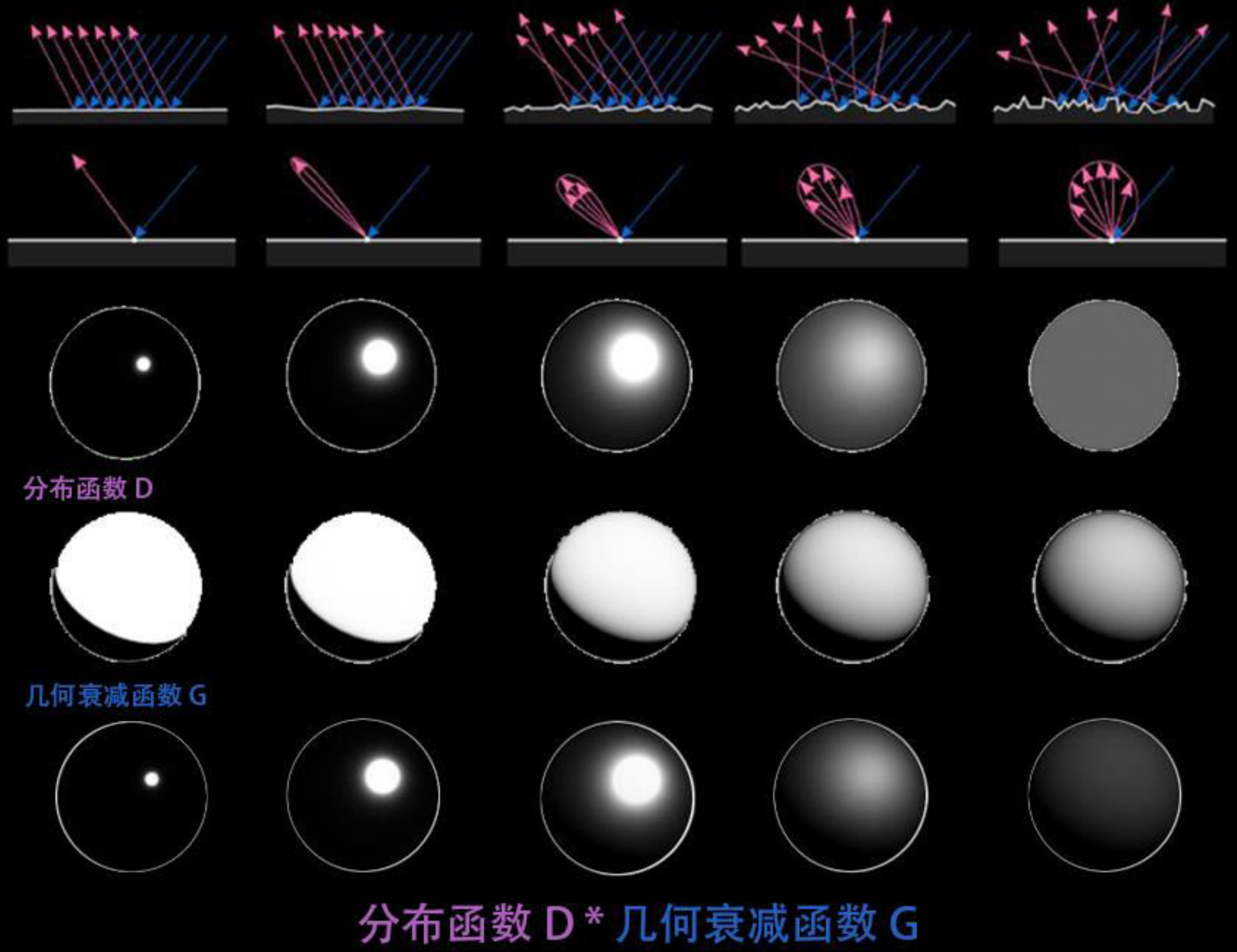
$$k = \alpha\sqrt{\frac{2}{\pi}}$$

$$G_{Schlick}(\mathbf{v}) = \frac{\mathbf{n}\cdot\mathbf{v}}{(\mathbf{n}\cdot\mathbf{v})(1-k)+k}$$

Intuitive performance of probability distribution model

Integration of distribution function and geometry attenuation function:

D() × G()

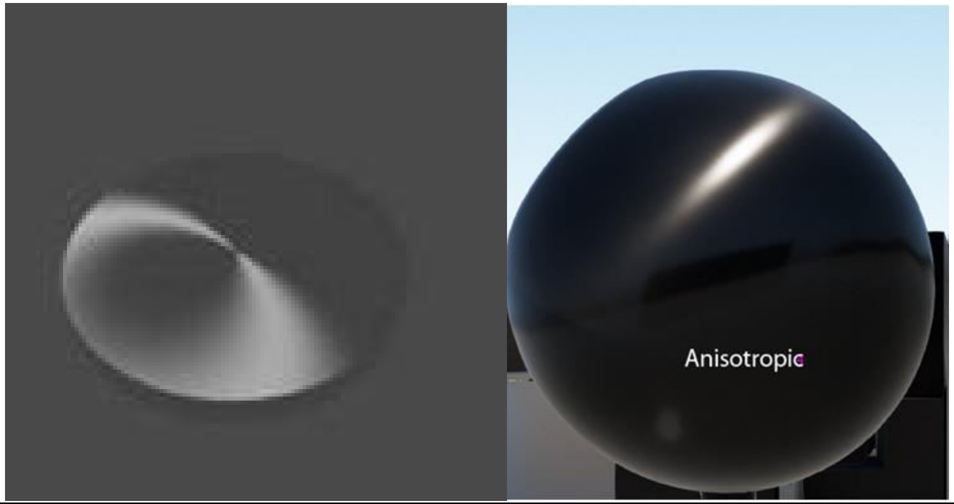


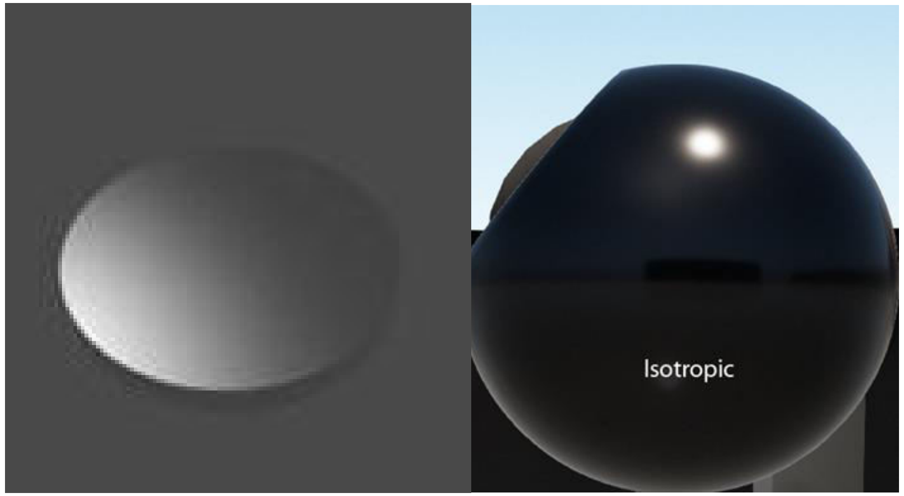
Obtain roughness measured data

Gloss meter（unit： GU）	roughness meter（unit： μm）
	

Anisotropic

Anisotropic	Isotropic
Real World: The Microstructure of material surface shows a directional arrangement, more common in artifacts **Mathematical model:** The distribution of microfacet normal is regular **Appearance:** The performance of specular is different at different directions, spot shape is stretched	**Real World:** The Microstructure of material surface is irregular, more common in natural things **Mathematical model:** The distribution of microfacet normal is random **Appearance:** The performance of specular is same at different directions, spot shape is circular

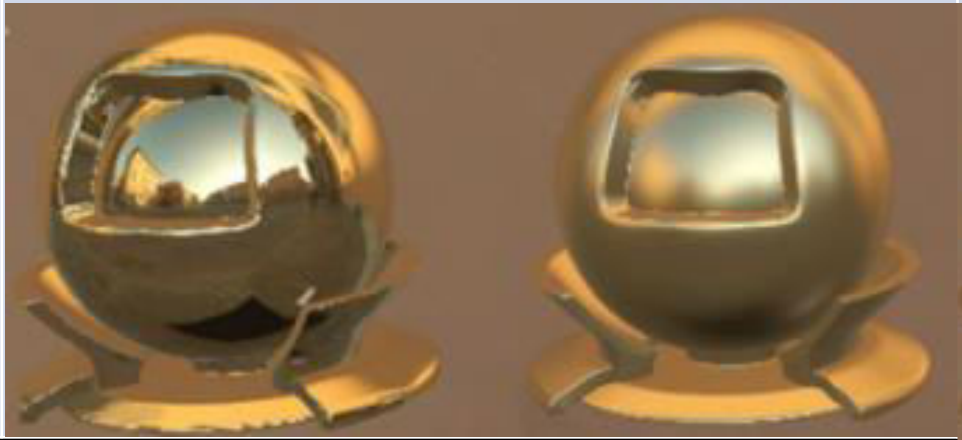
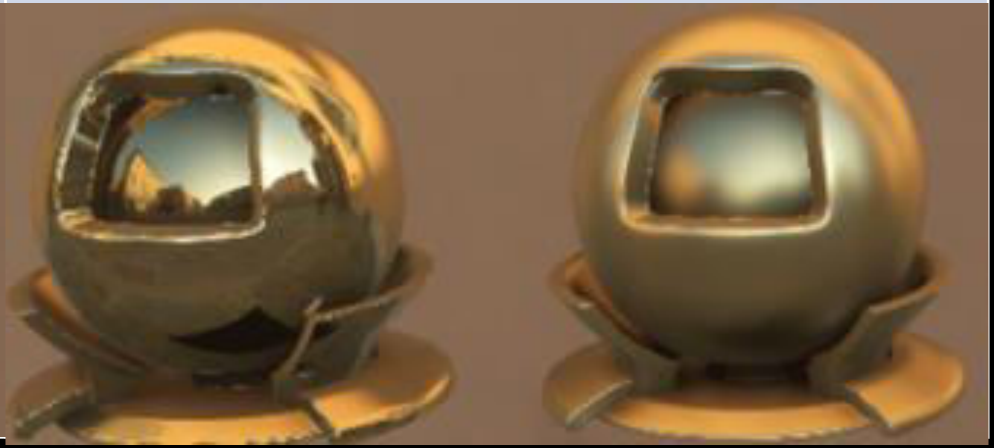




Specular Occlusion & Cavity

Specular Occlusion

1. To solve the "leakage" problem
2. Non-PBR

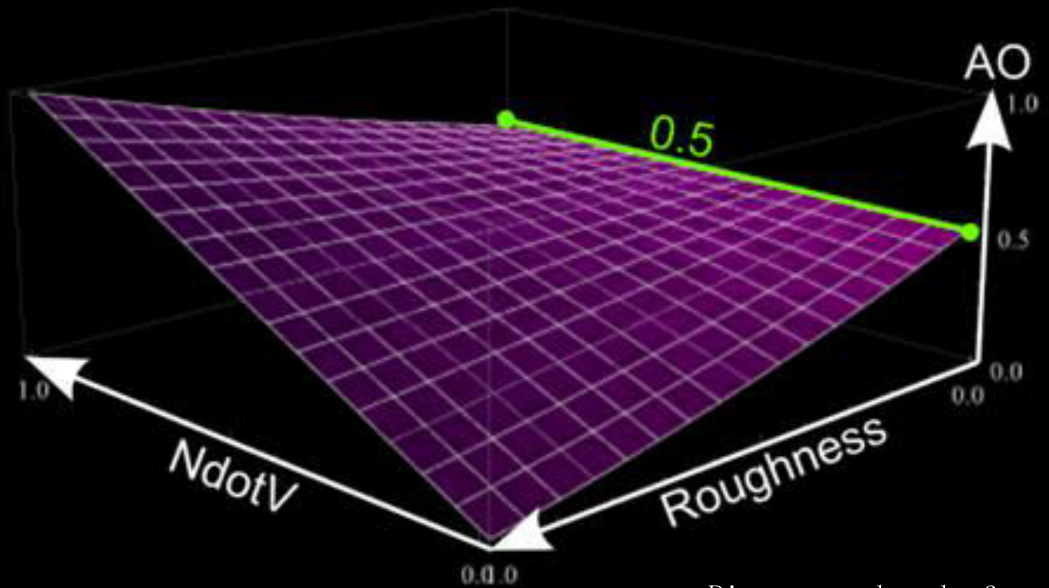
"leakage"	specular occlusion (off)	specular occlusion (on)
		

Specular Occlusion realization

1. realization with AO map
2. Camera, normal direction associated
3. Controlled by Roughness

```
float computeSpecOcclusion(float NdotV, float AO, float roughness)
{
    return saturate(pow(NdotV + AO, roughness) - 1 + AO);
}
```

Listing 26: Function for computing specular occlusion for a given roughness.



When the roughness is minimum, the intensity is 50% of AO intensity

When the roughness is maximum and the viewing angle coincides with the normal, the intensity is 100% of AO intensity

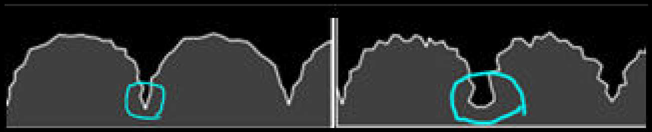
When the viewing angle is at 90 degrees to the normal, the intensity is zero

Picture and code from "Moving Frostbite to PBR"

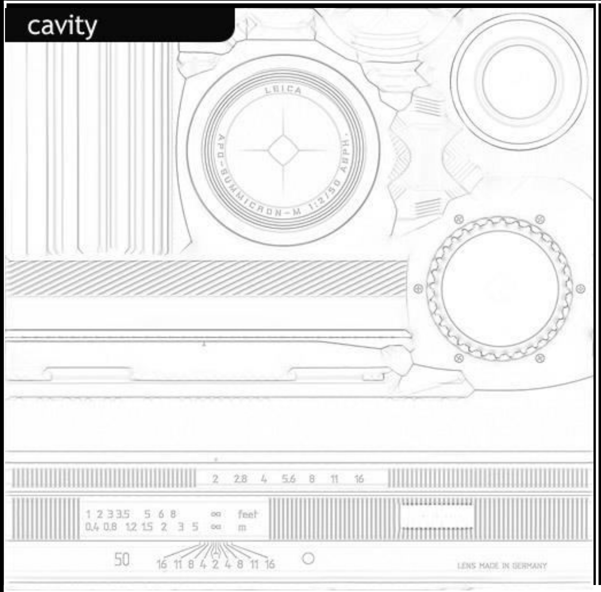
Cavity

Cavity’ s role

Simulation of recessed hole formed by microstructure
Non-PBR



Differences between CavityandSpecular Occlusion:



Small range, only affects the recessed hole formed by microfacetstructure. The intensity is between 0-0.5, irrelevant with roughness	Big range, relevant with the object shape and structure. The intensity is between 0-1, controlled by roughness
Affects both direct specular and indirect specular	**Only affect indirect specular**

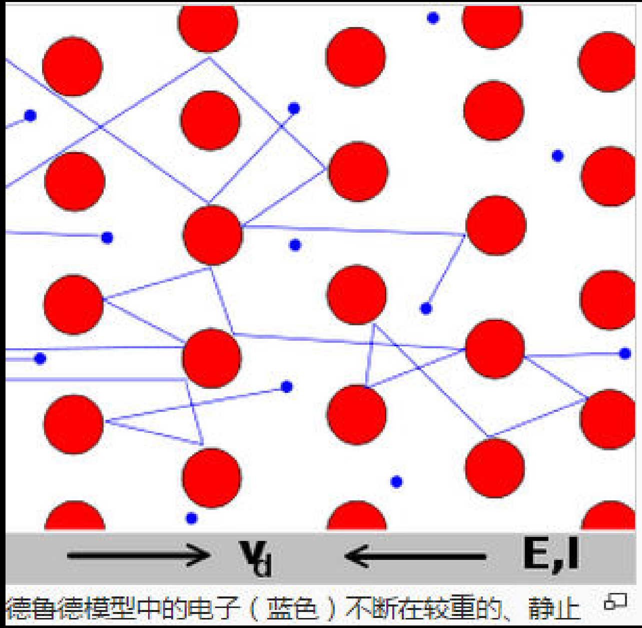
Influences from the material :

Metallicity:

nonconductor = 0 , conductor= 1:

When Metallicity = 1 :

1. No Diffusion, Only Specular
2. albedo = specular color



金属高光颜色表

金	
银	
铝	
铁	
铜	
钛	
镍	
钴	
白金	

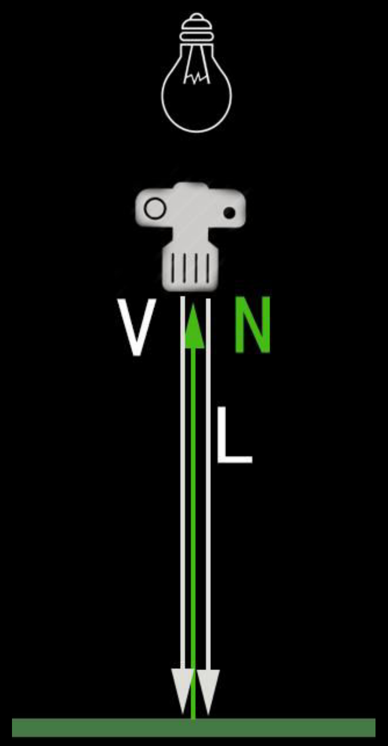
Reflectance and Fresnel:

Reflectance:

what is F_0:

the percentage of specular from the incident light

the viewing direction(V) coincides with the normal(N) and incident light(L)



How to get F0:

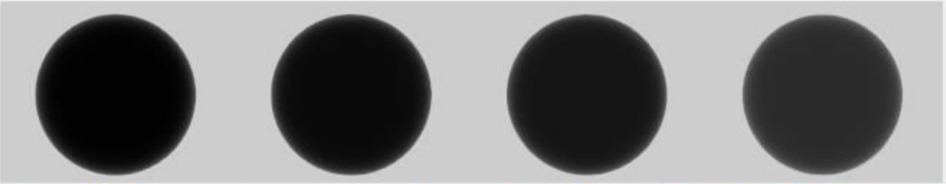
Non conduction:

based on IOR

range:0.02-0.06

$$F_0 = \frac{(1 - IOR)^2}{(1 + IOR)^2}$$

Schlick function



Dielectric Fresnel: From left to right the index of refraction is 1.2, 1.5, 1.8, 2.4

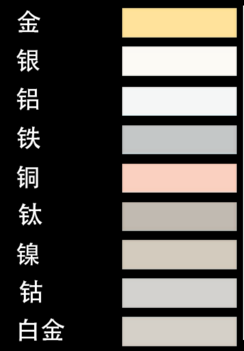
conduction:

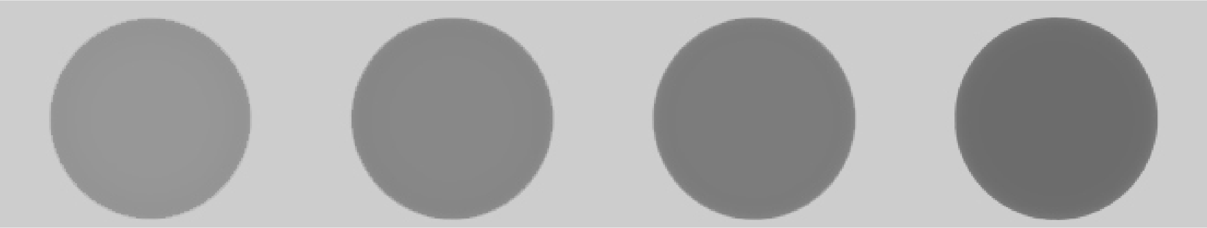
index of refraction is variation

specular color = index of refraction

range:0.65-0.95

金属高光颜色表





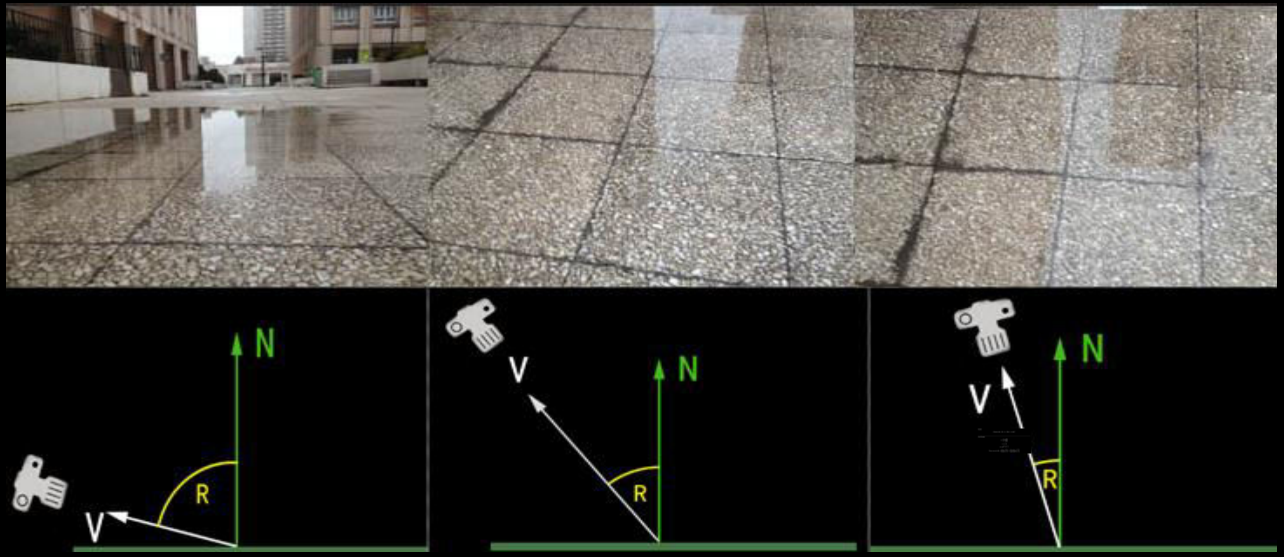
Conductor Fresnel with Absorption k = 4: From left to right the index of refraction is 1.2, 1.5, 1.8, 2.4

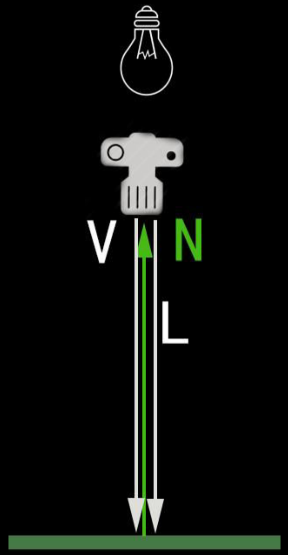
TABLE 18.1 Indices of refraction

Medium	n
Vacuum	1.00 exactly
Air (actual)	1.0003
Air (accepted)	1.00
Water	1.33
Ethyl alcohol	1.36
Oil	1.46
Glass (typical)	1.50
Polystyrene plastic	1.59
Zircon	1.96
Diamond	2.42
Silicon (infrared)	3.50

Fresnel:

the observation that things get more reflective at grazing angles.





Fresnel function F ( ) :

Variable: the angle(R)
Initial value : F0
Description reflectance

Schlick :

$$F_{Schlick}(\mathbf{v},\mathbf{h}) = F_0 + (1-F_0)(1-(\mathbf{v}\cdot\mathbf{h}))^5$$

Cook-Torrance :

$$\eta = \frac{1+\sqrt{F_0}}{1-\sqrt{F_0}}$$

$$c = \mathbf{v}\cdot\mathbf{h}$$

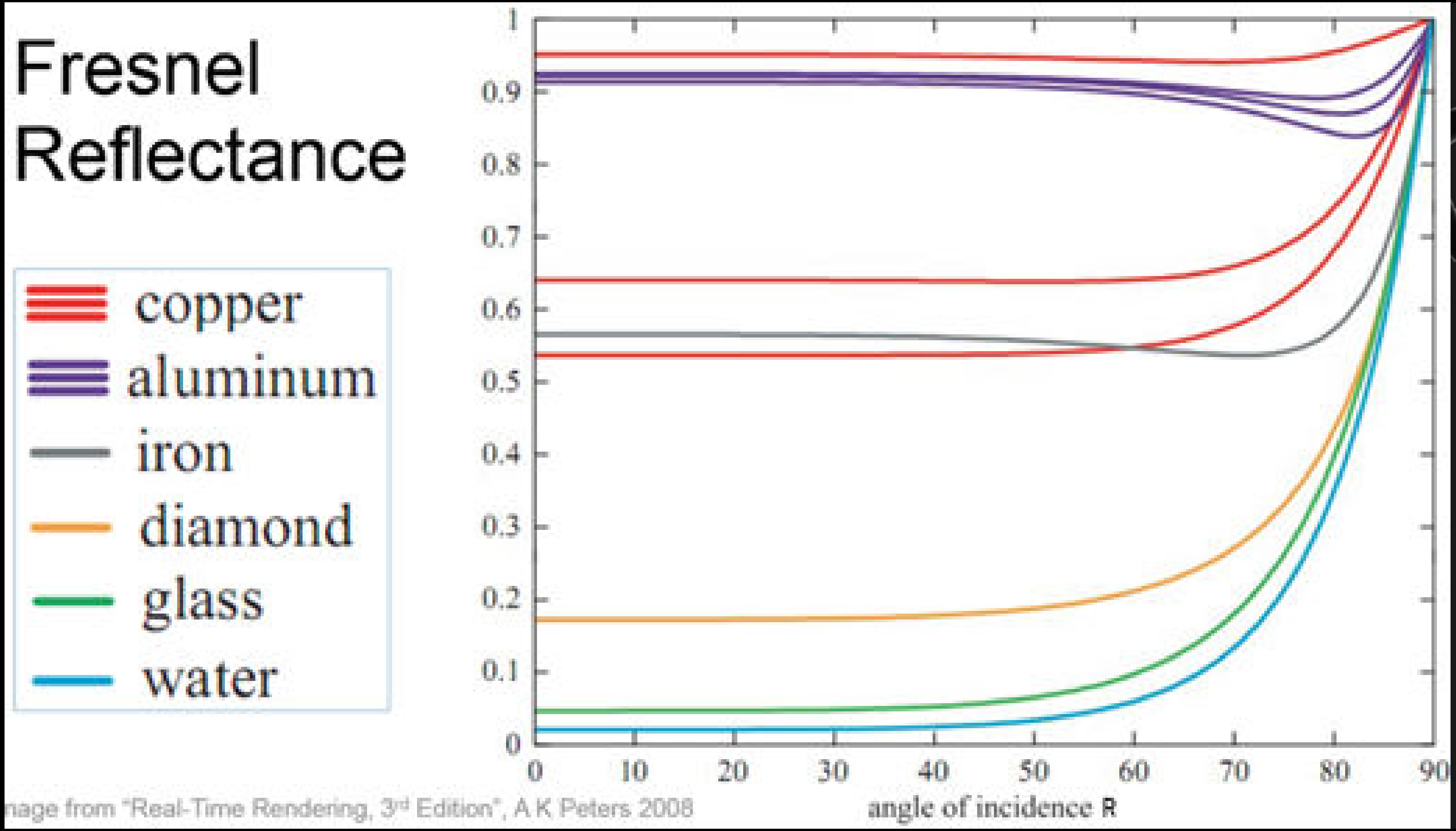
$$g = \sqrt{\eta^2 + c^2 - 1}$$

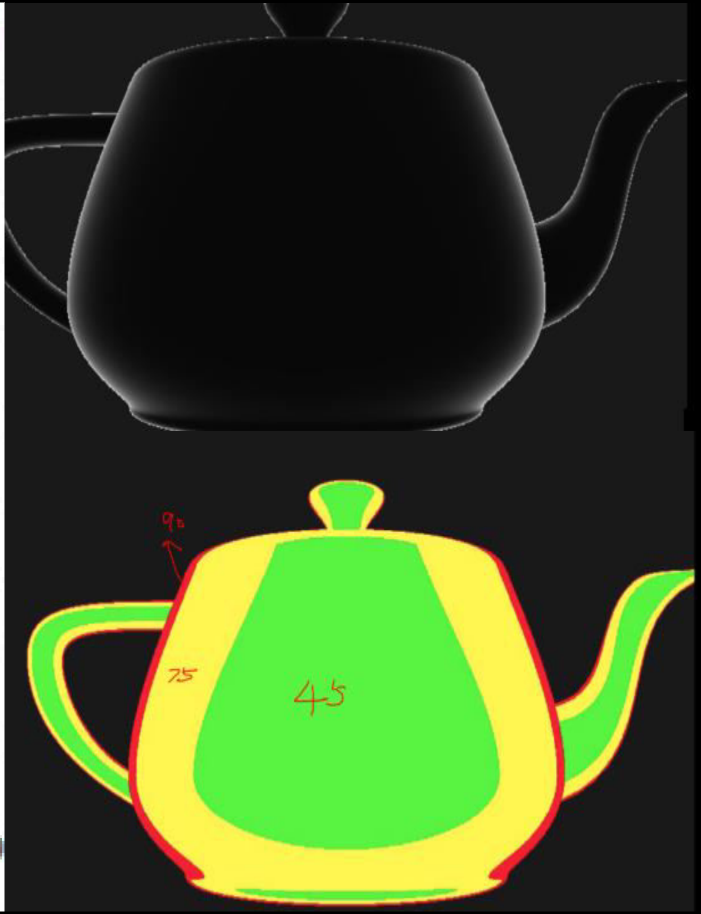
$$F_{Cook-Torrance}(\mathbf{v},\mathbf{h}) = \frac{1}{2}\left(\frac{g-c}{g+c}\right)^2\left(1+\left(\frac{(g+c)c-1}{(g-c)c+1}\right)^2\right)$$

Fresnel Reflectance Table:

X : Angle R
Y: Reflectance

F_0 : start point
Fresnel : trend

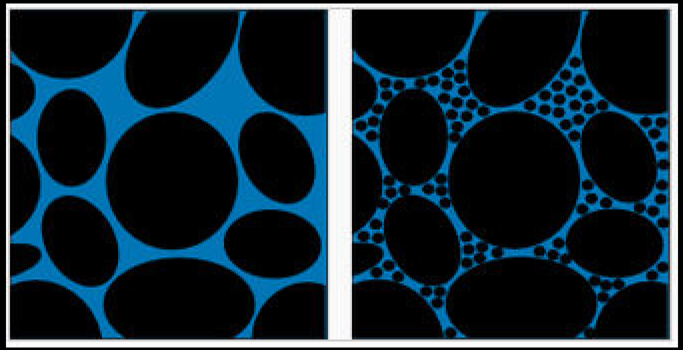




Picture from : Naty Hoffman, Background: Physics and Math of Shading

Porosity:

The ratio of the pore's volume to the total volume 范围在0到1之间，即为0到100%之间。



Porosity 's role:

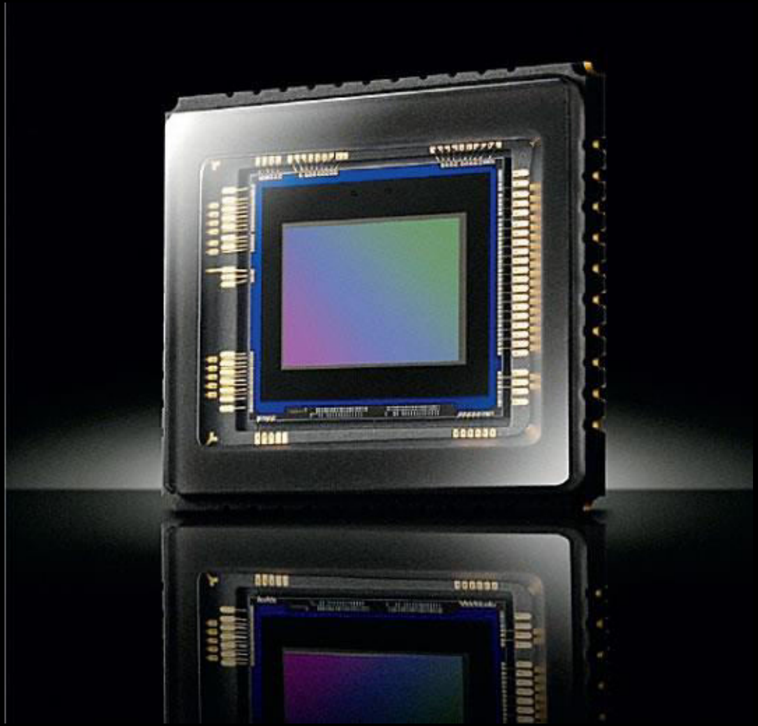
to descript the influrence from the water

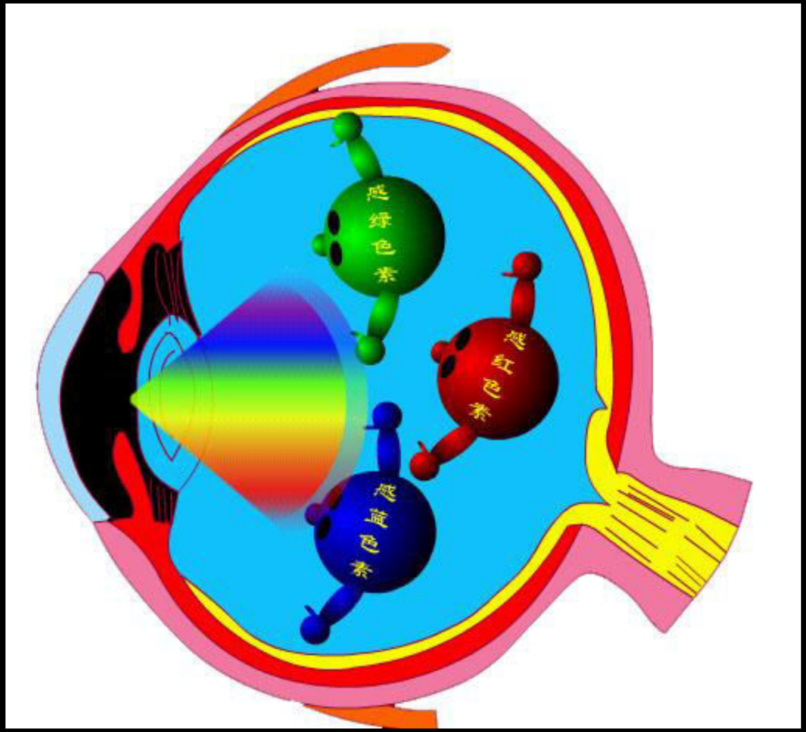
1. Darken Albedo
2. Change Glossiness
3. Boost reflectence

Physically Based Sensitising

Two types of sensor：

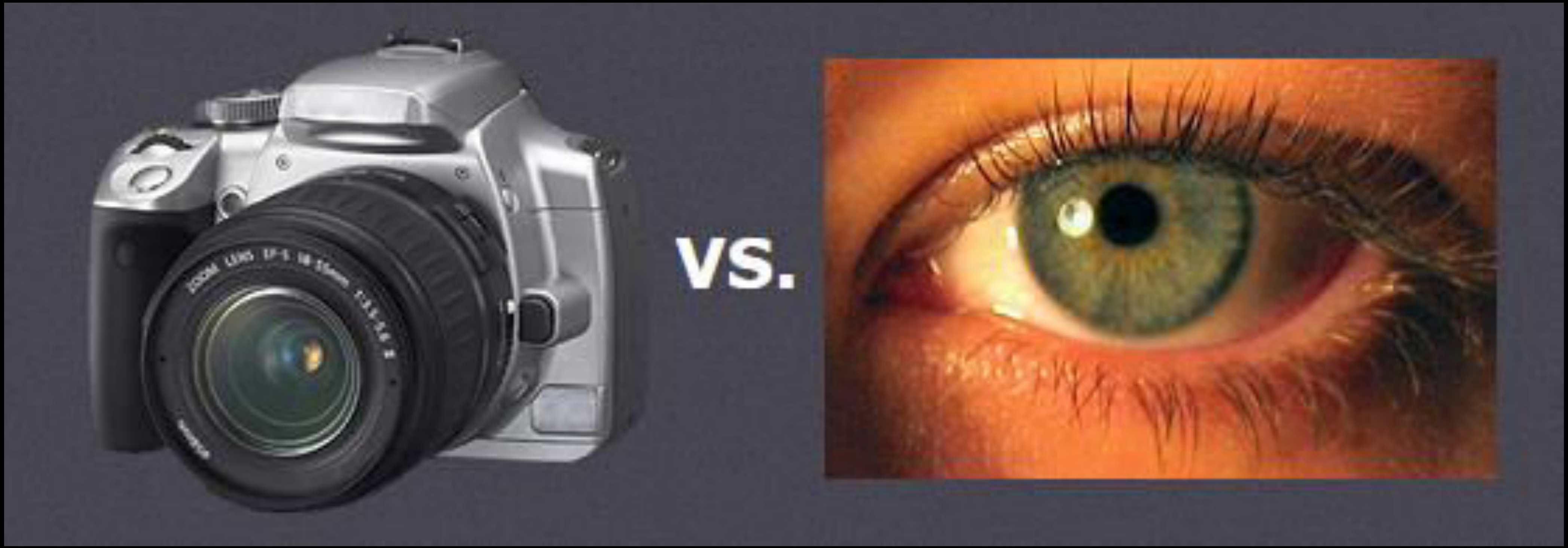
1. CMOS，CCD
2. Eye





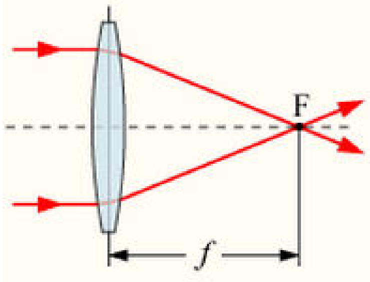
Difference:

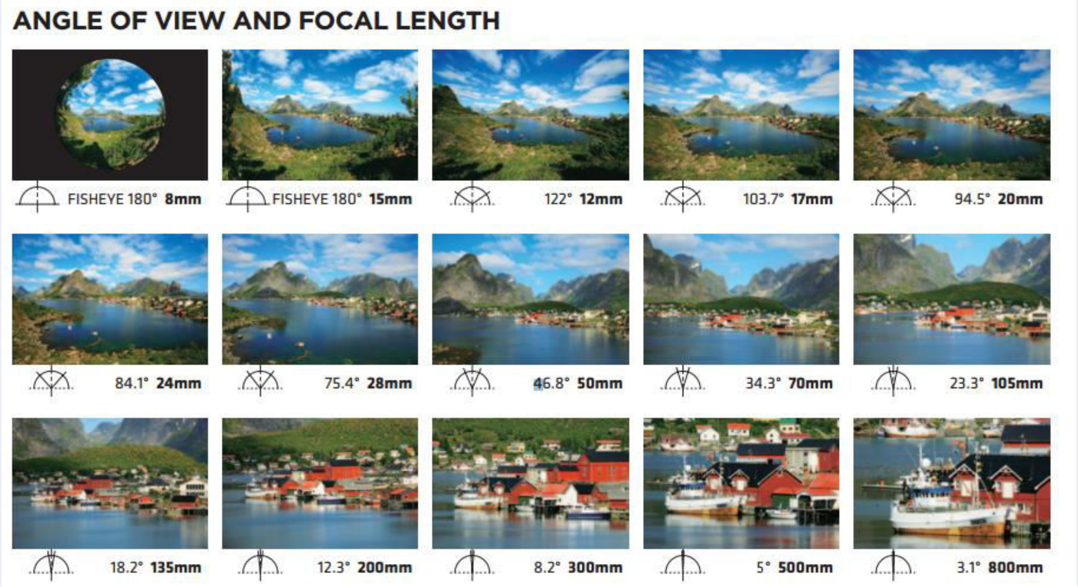
1. Angle of view
2. Dynamic range
3. Resolution

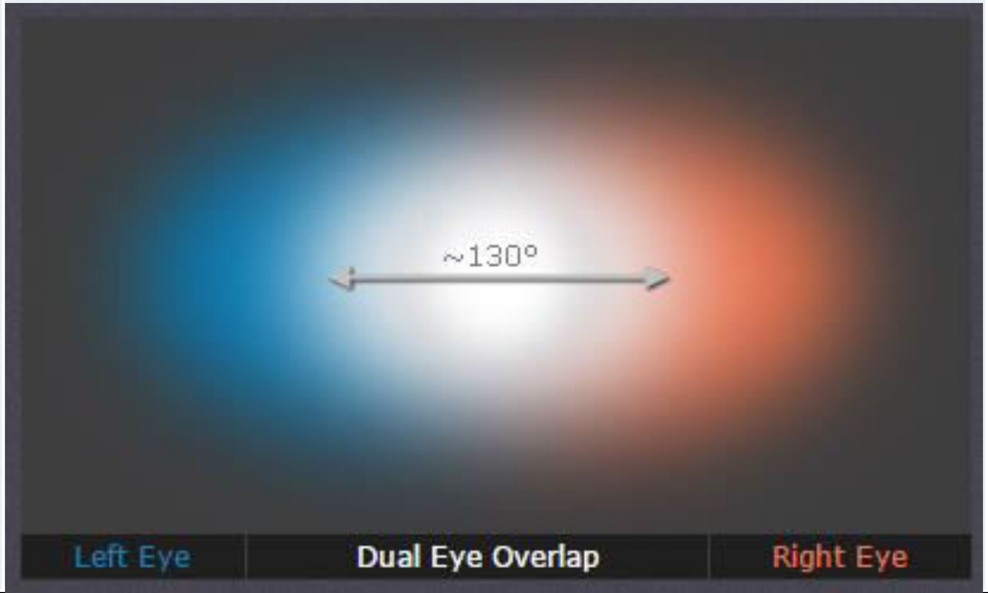


Angle of view

CMOS/CCD	EYE
the focal length of the lens	Multiple factors: 1. a focal length of approximately 22 mm 2. The overlapping region of both eyes is around 130° 3. central angle of view — around 40-60° 4. close to a 50 mm focal length lens





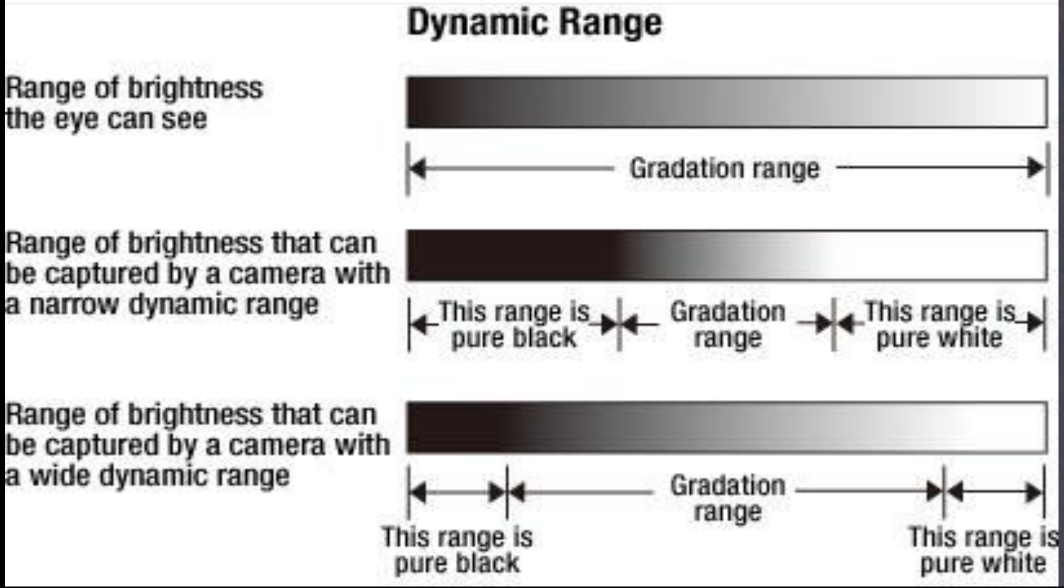


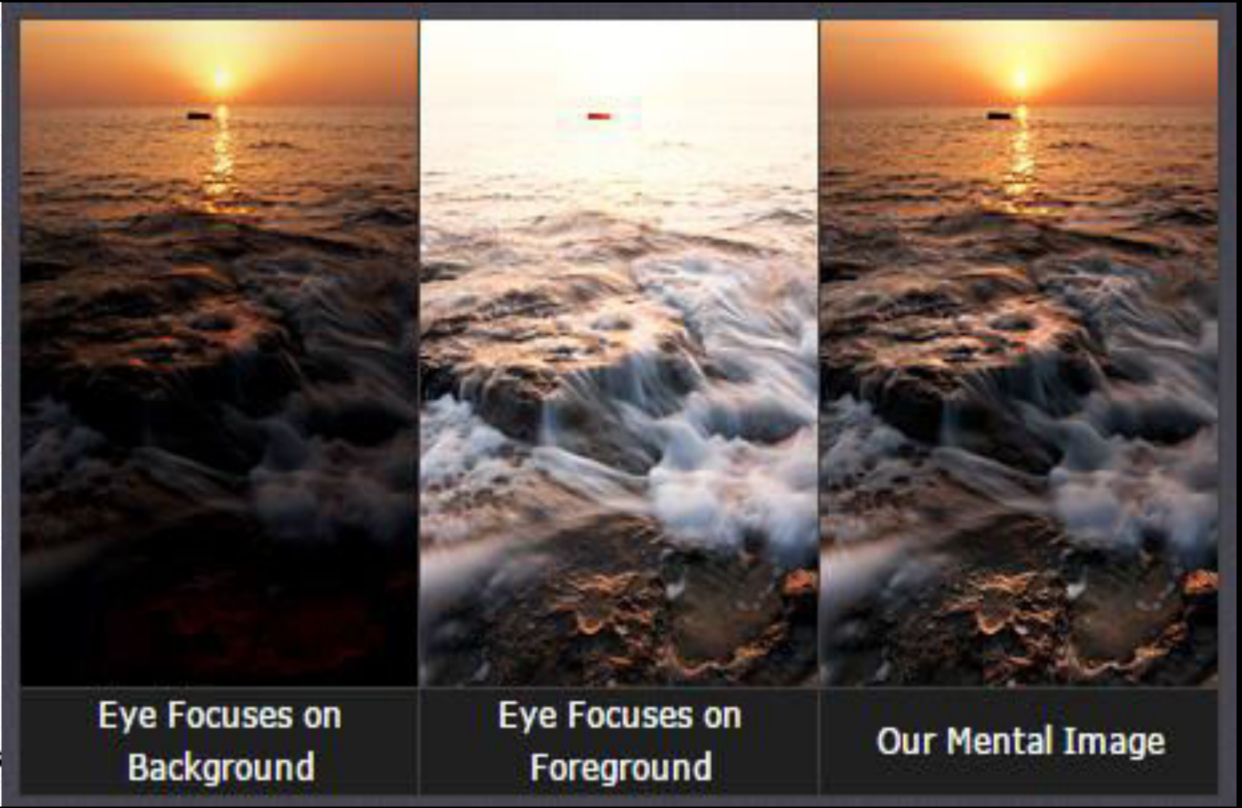
Dynamic range :

the ratio between the largest to smallest possible values of a changeable quantity.

Eye 》 CMOS/CCD

Condition	Illumination (in cd/m²)
Starlight	10^{-3}
Moonlight	10^{-1}
Indoor Lighting	10^{2}
Sunlight	10^{5}





RESOLUTION & DETAIL

CCD/CMOS：Symmetrical

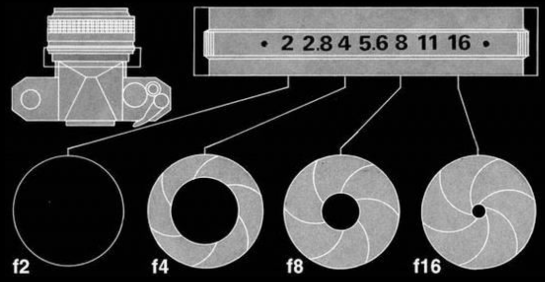
Eye：Prioritized based on interest，and asymmetrical

CCD/CMOS	**Eye -** interest	**Eye -** asymmetrical
Symmetrical	**contrast, sharpness, uniqueness, motion......(red part)**	**the central part of eyes' resolution is much higher than at the edges**
		

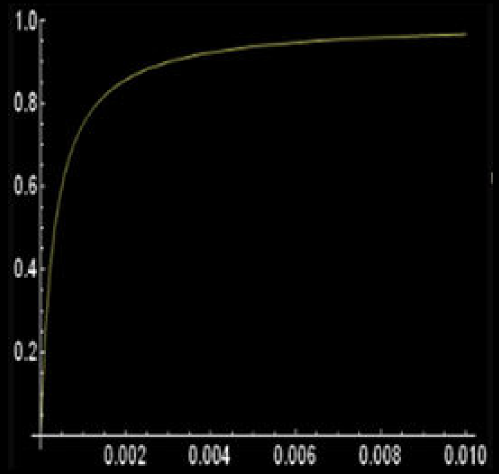
Physically Based Sensitising --》CMOS/CCD

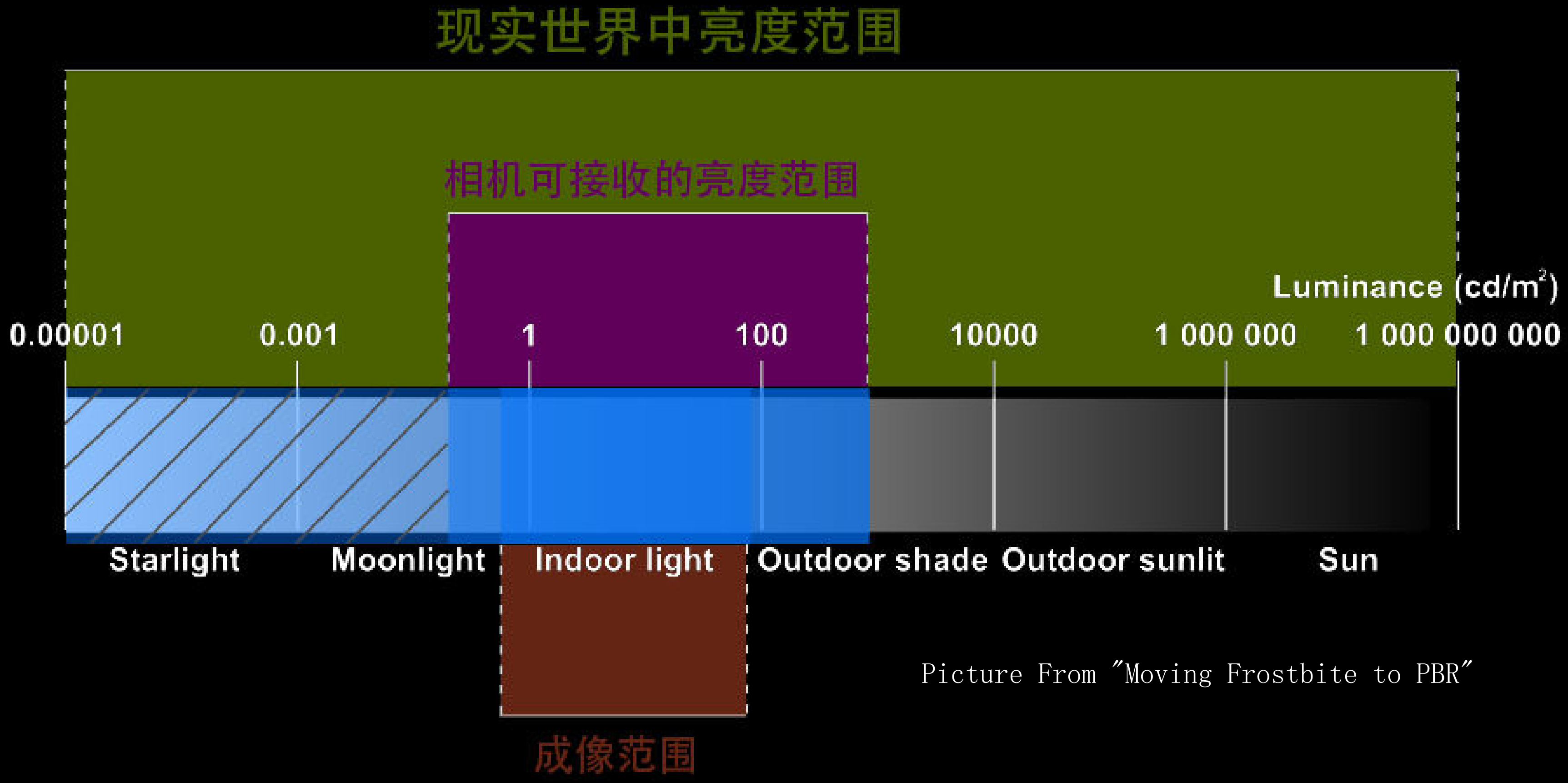
Two procedures to simulate the imaging

1. Exposure



2. HDR TONE MAPPING





Picture From "Moving Frostbite to PBR"

Exposure

Exposure value (unit : EV)

camera settings

Exposure value (unit : EV)

the photometric quantity of luminous exposure

The conversion between luminance/illuminance

EV --》 luminance

$$L = 2^{EV-3}$$

EV --》 illuminance

$$E = 2.5 * 2^{EV}$$

EV	亮度, cd/m^2	照度, lx	EV	亮度, cd/m^2	照度, lx
−4	0.008	0.156	7	16	320
−3	0.016	0.313	8	32	640
−2	0.031	0.625	9	64	1280
−1	0.063	1.25	10	128	2560
0	0.125	2.5	11	256	5120
1	0.25	5	12	512	10,240
2	0.5	10	13	1024	20,480
3	1	20	14	2048	40,960
4	2	40	15	4096	81,920
5	4	80	16	8192	163,840
6	8	160			

EV as an indicator of camera settings

户外，自然光	
彩虹	
晴朗的天空背景	15
多云的天空背景	14
日落和天际线	
日落前一刻	12–14
日落时	12
日落后一刻	9–11
月亮,[c] 高度 > 40°	
满月	15
凸月	14
四分之一月	13
新月	12
月光，月亮在高度40°以上	
满月	−3 to −2
凸月	−4
四分之一月	−6
北极光和南极光	
明亮的	−4 to −3
一般的	−6 to −5

室外，人工光源	
霓虹灯或其他明亮标志	9–10
夜间体育运动	9
火焰和起火的建筑	9
明亮的街景	8
街道夜景和橱窗	7–8
夜晚车流	5
夜市和游乐场	7
圣诞树	4–5
泛光灯照明的建筑、纪念碑和喷泉	3–5
亮灯建筑的远景	2
室内，人工光源	
画廊	8–11
体育赛事,舞台表演等等	8–9
马戏团表演	8
泛光灯照明的冰雕	9
办公室及工作场所	7–8
住房内	5–7
圣诞树	4–5

日光	
强烈阳光下的明亮沙滩和雪景（阴影锐利清晰）[a]	16
强烈阳光下的一般场景（阴影很清晰）[a,b]	15
朦胧日光下的一般场景（阴影柔和）	14
明亮阴天下的一般场景（没有阴影或勉强可见）	13
非常阴沉的一般场景（完全没有阴影）	12
强烈阳光下四周无遮挡的阴影区	12

The benefit

1. convenient， intuitive

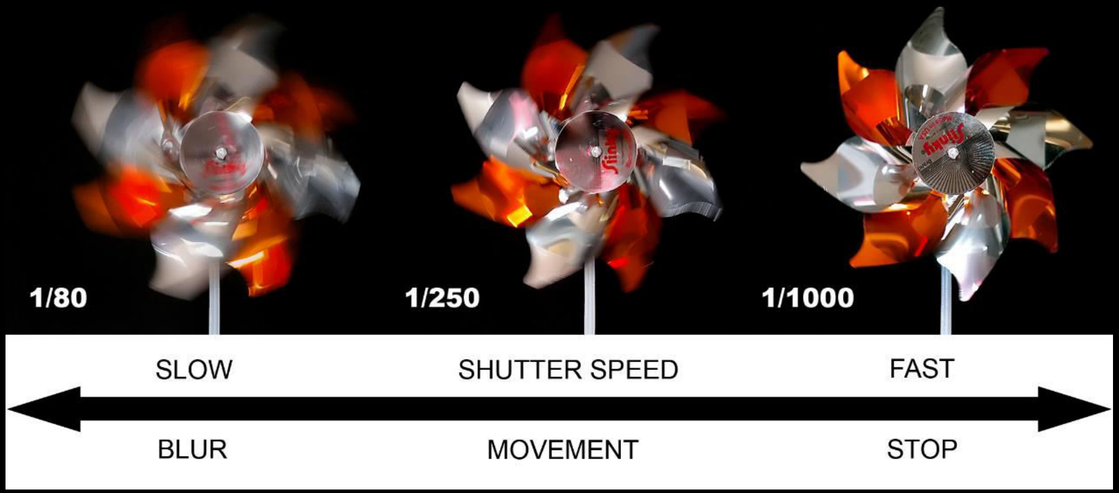
2. Ready for the post processing(i.e. DOF， motion blur。。。。。。)

表1. 曝光时间（单位秒），* 在不同的曝光值和f值下

EV	f值												
	1.0	1.4	2.0	2.8	4.0	5.6	8.0	11	16	22	32	45	64
−6	60	2 m	4 m	8 m	16 m	32 m	64 m	128 m	256 m	512 m	1024 m	2048 m	4096 m
−5	30	60	2 m	4 m	8 m	16 m	32 m	64 m	128 m	256 m	512 m	1024 m	2048 m
−4	15	30	60	2 m	4 m	8 m	16 m	32 m	64 m	128 m	256 m	512 m	1024 m
−3	8	15	30	60	2 m	4 m	8 m	16 m	32 m	64 m	128 m	256 m	512 m
−2	4	8	15	30	60	2 m	4 m	8 m	16 m	32 m	64 m	128 m	256 m
−1	2	4	8	15	30	60	2 m	4 m	8 m	16 m	32 m	64 m	128 m
0	1	2	4	8	15	30	60	2 m	4 m	8 m	16 m	32 m	64 m
1	1/2	1	2	4	8	15	30	60	2 m	4 m	8 m	16 m	32 m
2	1/4	1/2	1	2	4	8	15	30	60	2 m	4 m	8 m	16 m
3	1/8	1/4	1/2	1	2	4	8	15	30	60	2 m	4 m	8 m
4	1/15	1/8	1/4	1/2	1	2	4	8	15	30	60	2 m	4 m
5	1/30	1/15	1/8	1/4	1/2	1	2	4	8	15	30	60	2 m
6	1/60	1/30	1/15	1/8	1/4	1/2	1	2	4	8	15	30	60
7	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1	2	4	8	15	30
8	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1	2	4	8	15
9	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1	2	4	8
10	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1	2	4
11	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1	2
12	1/4000	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1
13	1/8000	1/4000	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2
14		1/8000	1/4000	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4
15			1/8000	1/4000	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8
16				1/8000	1/4000	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15

EV & post processing

Aperture --> DOF

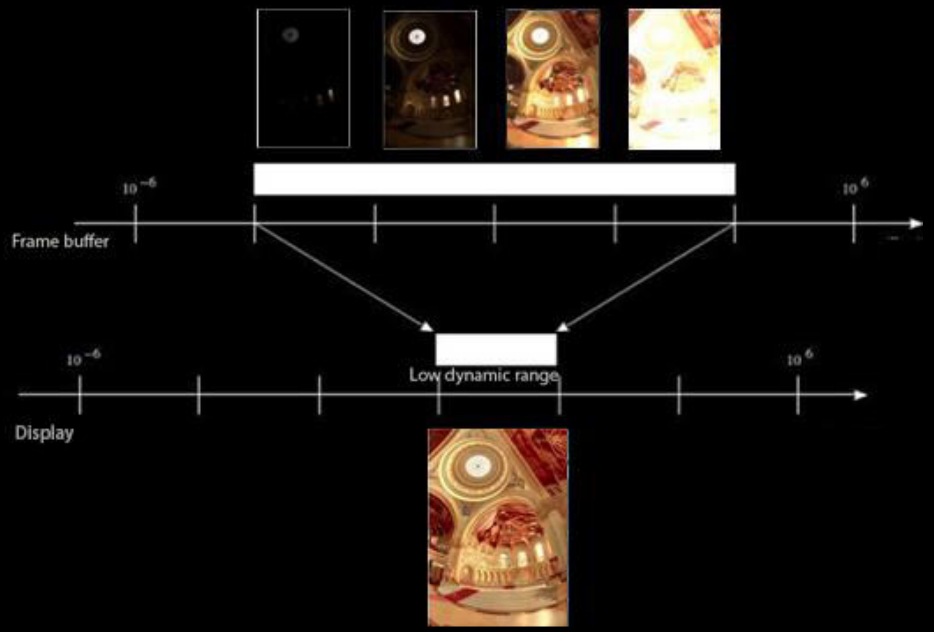


Aperture --> Vignetting

speed--> motion blur

HDR Tone Mapping

1. Display image in 8 bit low dynamic range (0-1.0)
2. Choose the discarded part in high dynamic range
3. Keep the original gradient ,contrast,detail as much as possible



Two Tone Mapping Curves

1. Reinhard
2. Filmic

$$L_{\text{Reinhard}} = \frac{x}{x+1}$$

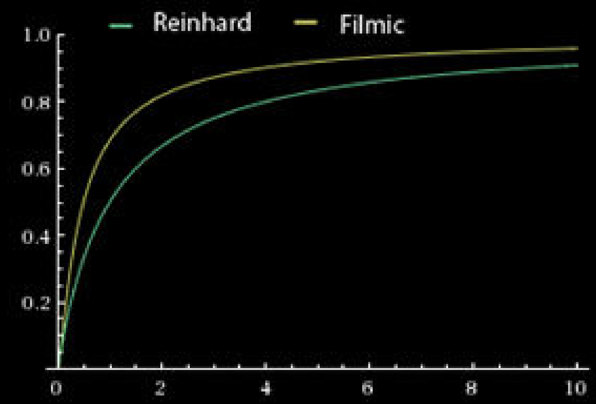
$$L_{\text{Filmic}} = \frac{((x*(A*x+C*B)+D*E)}{(x*(A*x+B)+D*F))} - E/F$$

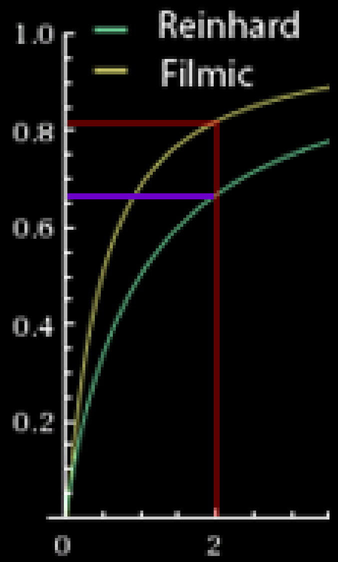
$$L_{\text{Reinha}} = \frac{x}{x+1}$$

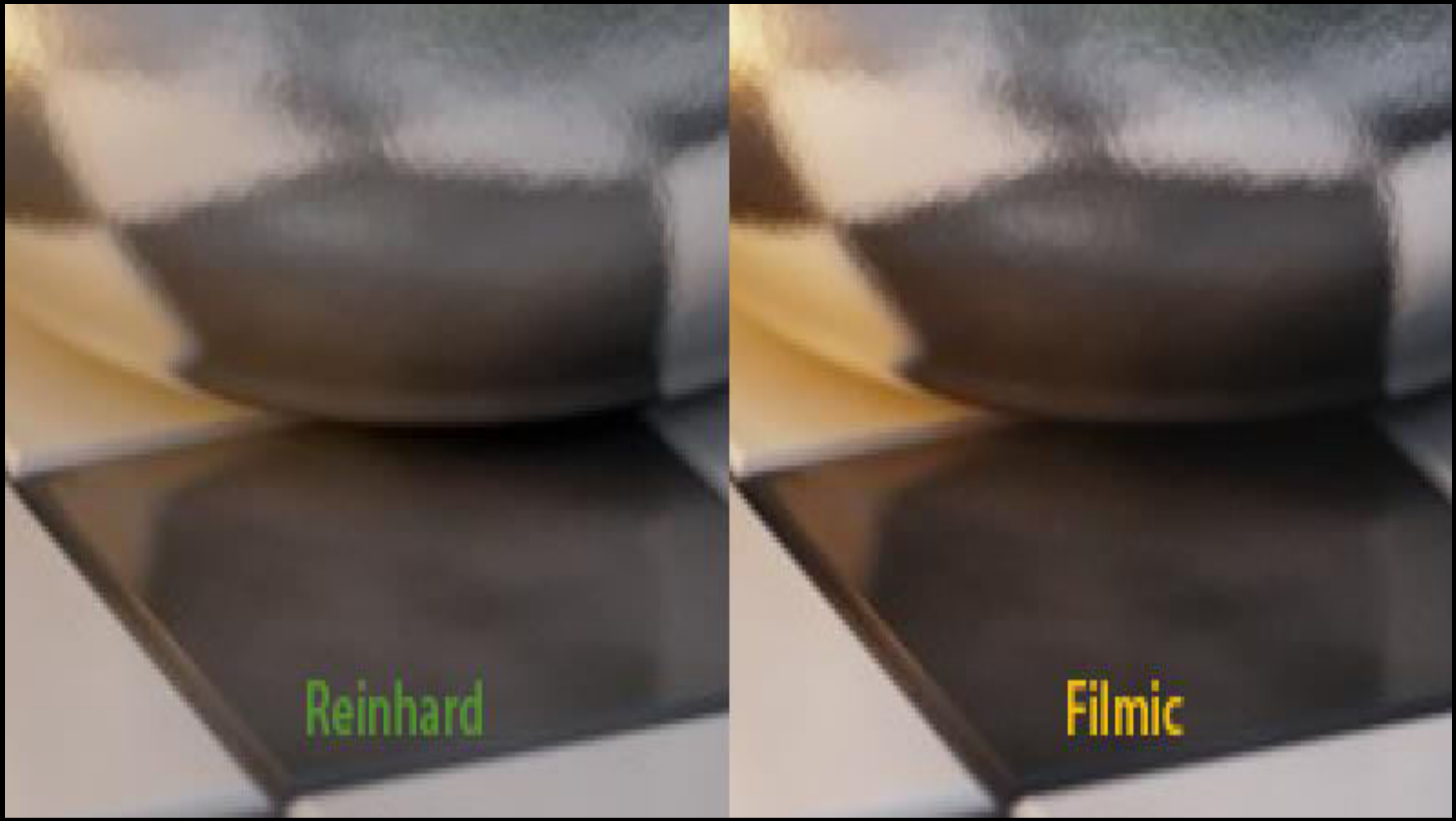
Reinhard

Filmic

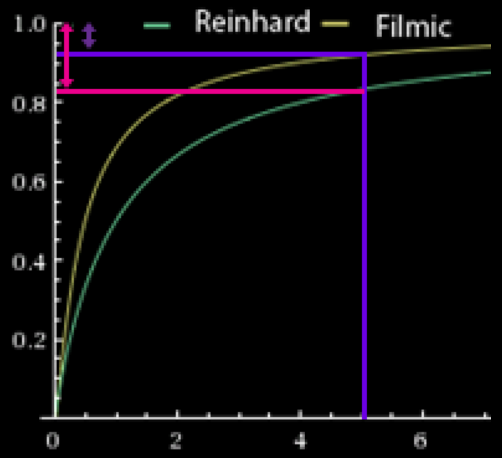
Reinhard vs Filmic

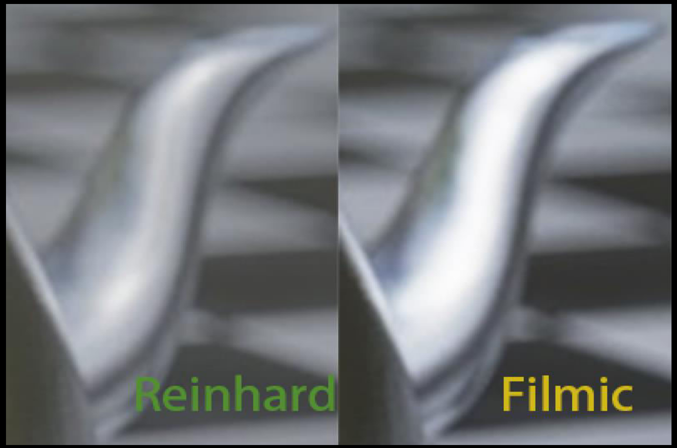


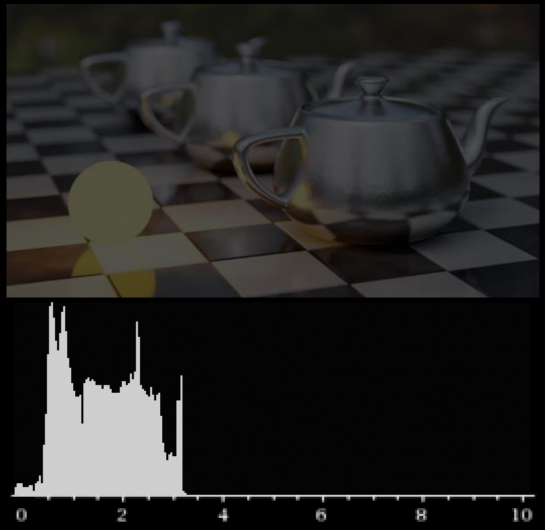


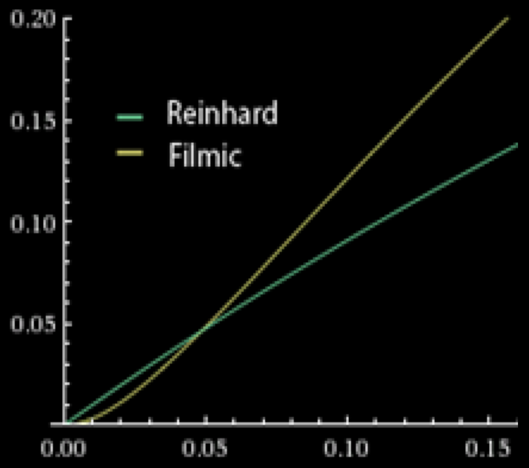


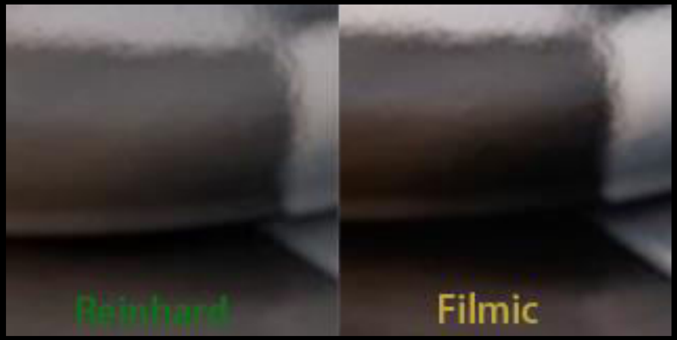
Reinhard vs Filmic

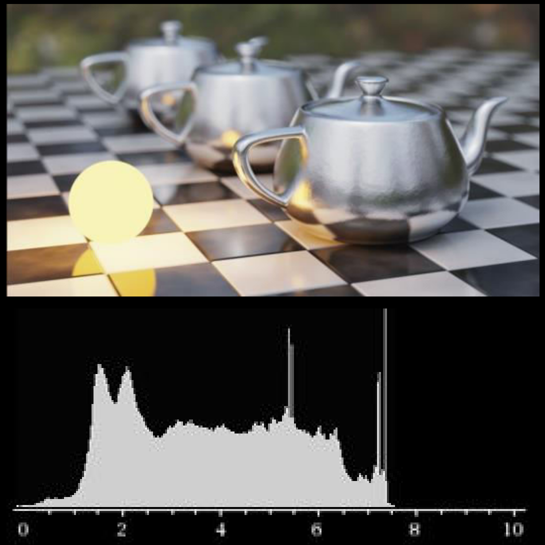






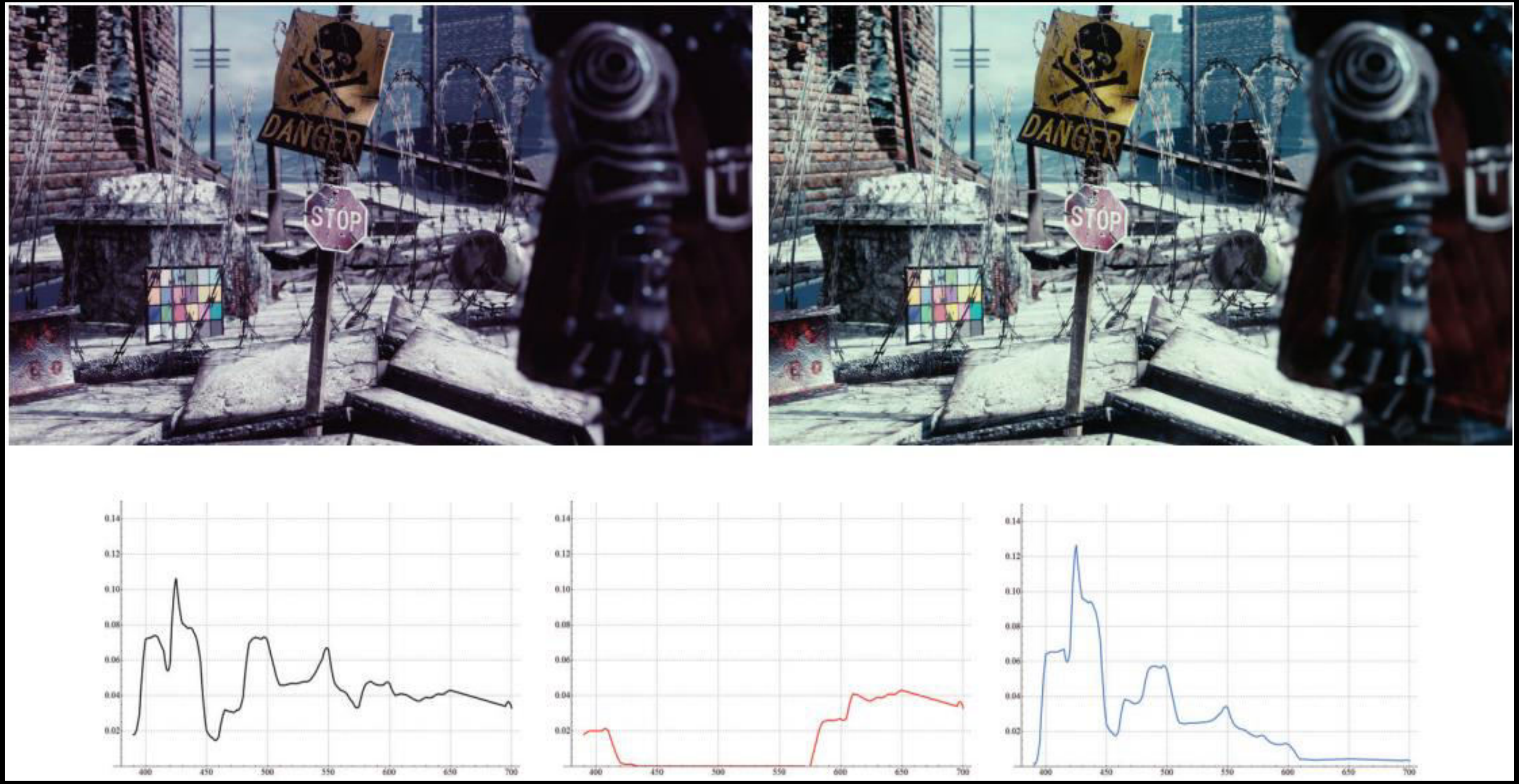






Different method:

Tri-ace's film simulation:

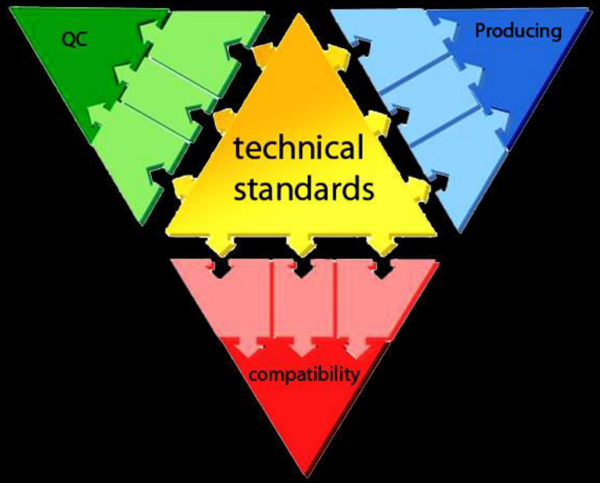


Color Enhancement and Rendering in Film and Game Production:
Film Simulation for Video Games
Yoshiharu Gotanda
tri-Ace, Inc.

The influence of PBR:

1. Essence of PBR
2. Purpose of PBR
3. Significance of PBR

Essence of PBR



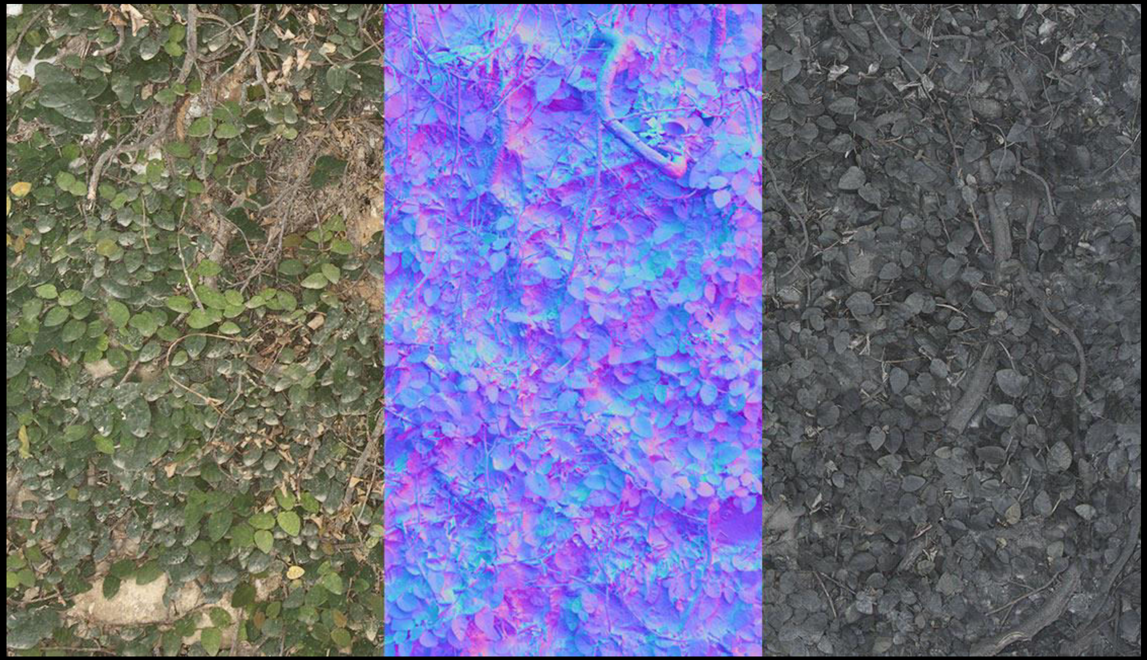
Standardization

Purpose of PBR

Automation

Purpose of PBR

Assembly line



Significance of PBR

Mass production, reduce costs, improve efficiency, quality assurance

References

Laurence MEYLAN,tone mapping for high dynamic range images,2006

Chris Wynn,An Introduction to BRDF-Based Lighting,nvidia,2006

Bruce Walter, Stephen R. Marschner, Hongsong Li,Kenneth E. Torrance, Microfacet Models for Refraction through Rough Surfaces Eurographics Symposium on Rendering (2007)

Naty Hoffman,Yoshiharu Gotanda,Adam Martinez,Ben Snow,Physically-Based Shading Models in Film and Game Production,SIGGRAPH 2010

joshua pines,color enhancement and rendering in film and game production,SIGGRAPH 2010

sebastien lagarde,Adopting a physically based shading model,2011

Dimitar Lazarov. Physically based lighting in call of duty: Black ops. SIGGRAPH 2011 Course: Advances in Real-Time Rendering in 3D Graphics and Games, 2011.

Stephen McAuley. Calibrating lighting and materials in far cry 3. SIGGRAPH 2012 Course: Practical Physically Based Shading in Film and Game Production, 2012.

Dan Baker and Stephen Hill. Rock-solid shading - image stability without sacricing detail. SIGGRAPH 2012 Course: Practical Physically Based Shading in Film and Game Production, 2012.

Brent Burley. Physically-based shading at disney. part of Practical Physically-Based Shading in Film and Game Production, SIGGRAPH, 2012.

sebastien lagarde,laurent harduin,The art and rendering of remember Me GDC2013

David Neubelt and Matt Pettineo,Crafting a Next-Gen Material Pipeline for The Order: 1886 GDC2013

Brian Karis,Specular BRDF Reference,EPIC 2013

References

Marco Alamia ,Physically Based Rendering - Cook–Torrance

Lazanyi, Szirmay-Kalos, Fresnel term approximations for Metals

Eric Heitz,Understanding the Masking-Shadowing Function in Microfacet-Based BRDFs,SIG2014

Naty Hoffman,Background: Physics and Math of Shading,SIG2014

Danny Chan,Real-World Measurements for Call of Duty: Advanced Warfare,SIG2015