Lesson 10 – Physically-based rendering

PV227 – GPU Rendering

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Physically-based rendering (PBR)

- Think about the physics behind everything:
  - Light
  - Lights
  - **Materials**
  - Sensors / Eyes
- In practice, still approximations
- More and more popular in real-time rendering, in rendering engines

Light propagation – Homogeneous media

- Light interacts with the material it travels through
- In homogeneous materials, the light is absorbed
  - Loses some of its energy
  - Clean water, glass, air, oil, ...

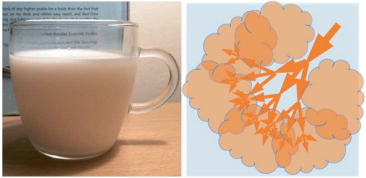
Low Absorbtion

High Absorbtion

Light propagation – Heterogeneous media

- Light interacts with the material it travels through
- In heterogeneous materials, the light is scattered
  - Scatters the energy without losses
  - Milk, skin, wood, (dirty water, air with fog), . . .

Low Scattering



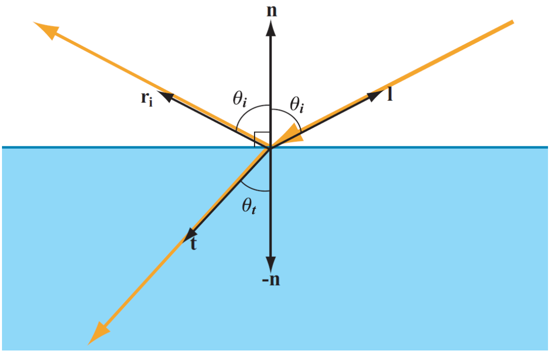
High Scattering

Light propagation – Absorbtion vs. Scattering

Absorbtion vs. Scattering

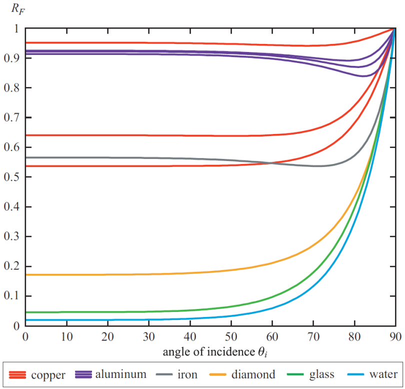
Light interaction – Materials

- Light changes its direction at the boundary between two materials
  - Reflection
  - Refraction
  - Without losses of energy



Reflection

- Perfect reflection: $\theta_i = \theta_o$
- Amount of reflected light depends on θ_i and on the wavelength
- Described by Fresnel equations



Fresnel reflection

- Depends on the wavelength, reflection has a color (!)
- Metals have usually higher values
- Dielectrics have usually lower values
- Mostly without any change until 50°, then goes straight to one
- In practice: Schlick's approximation:

$$F_{Schlick}(F_0, L, N) = F_0 + (1 - F_0)(1 - L \cdot N)^5$$

where F_0 is Fresnel reflection at 0°, L is direction to light, N is surface normal

Fresnel reflection at 0°

Material	$F(0°)$ **(Linear)**	$F(0°)$ **(sRGB)**	**Color**
Water	0.02,0.02,0.02	0.15,0.15,0.15	
Plastic / Glass (Low)	0.03,0.03,0.03	0.21,0.21,0.21	
Plastic High	0.05,0.05,0.05	0.24,0.24,0.24	
Glass (High) / Ruby	0.08,0.08,0.08	0.31,0.31,0.31	
Diamond	0.17,0.17,0.17	0.45,0.45,0.45	
Iron	0.56,0.57,0.58	0.77,0.78,0.78	
Copper	0.95,0.64,0.54	0.98,0.82,0.76	
Gold	1.00,0.71,0.29	1.00,0.86,0.57	
Aluminum	0.91,0.92,0.92	0.96,0.96,0.97	
Silver	0.95,0.93,0.88	0.98,0.97,0.95	

Fresnel reflections at 0° for some materials

Refraction

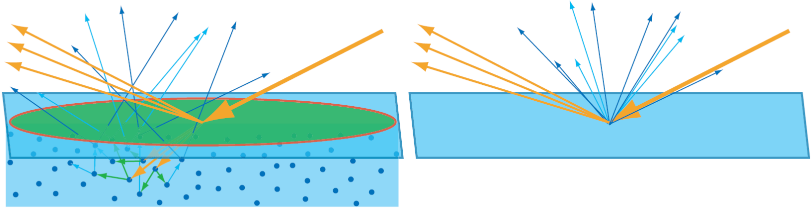
- Snell's law

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{v_1}{v_2}$$

- In metals, all energy is absorbed
- In homogeneous materials, the light continues in different direction
- In heterogeneous materials (including skin, wood, plastic, ...), the light is scattered and absorbed

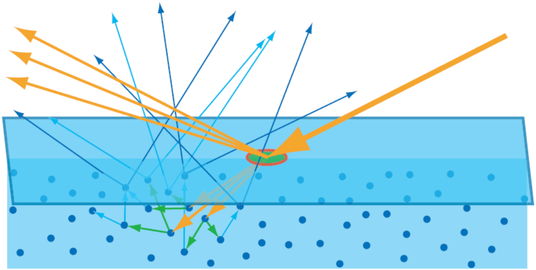
Refraction – diffuse light

- Diffuse lighting
  - When all the (non-absorbed) light exits the surface at approximately the same point as the light enters.



Refraction – sub-surface scattering

- Sub-surface scattering (SSS)
  - When all the (non-absorbed) light exits the surface at different places.



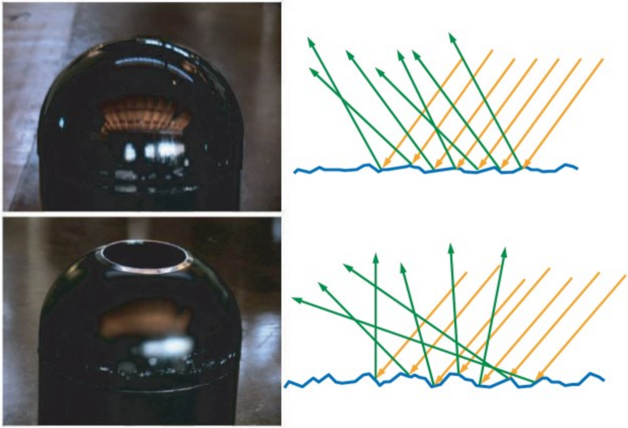
Ambient lighting?

- "Does not exist in PBR"
- Average of lighting coming from all directions.

Microfacets

- Only some objects are flat (mirrors, water surface, ...), others are not
- With microfacets, the surface is represented with very small facets
  - Smaller then 'pixel', not for displacement in geometry, not for normal mapping
  - (Larger than light's wavelength)
  - Each mifrofacet is a flat surface
- Many microfacets models, for different materials
  - Different distribution of orientation of facets
  - Different shadowing between facets
  - Different approximation of the model

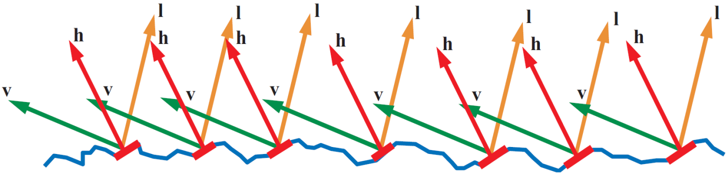
Microfacets



Top: smooth surface, Bottom: rough surface

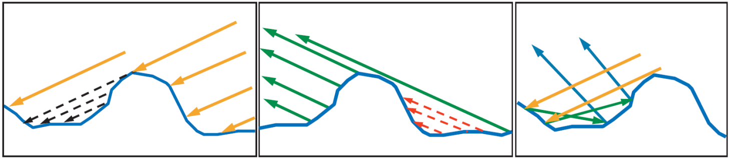
Distribution of microfacets

- We are usually interested in facets which are oriented in the proper direction to give us perfect reflection.
  - i.e. facets that are oriented in the half-vector direction
- Gaussian distribution, ...



Geometrical attenuation

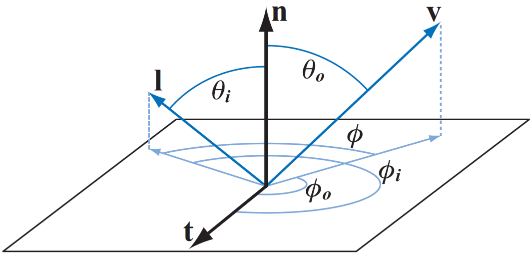
- Shadowing: Facets occlude the light for other facets
- Masking: Facets cannot be seen due to other facets
- Interreflection: Facets reflect the light to other facets, and then the light is reflected to the viewer



Task: Implement microfacets models

- Cook-Torrance (1982)
- Oren-Nayar (1994)
- Ashikhmin-Shirley (2000)
- Normalized Blinn-Phong (2008)

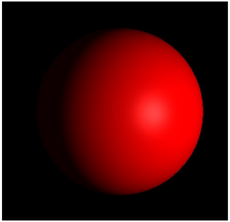
Legend to the following equations

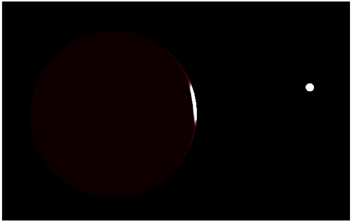


- $\vec{N}$, $\vec{T}$, $\vec{B}$ are surface normal, tangent, and bitangent
- $\vec{L}$ is direction to the light, $\vec{V}$ is direction to the viewer
- $\vec{H}$ is half-vector, vector between the light and the viewer
- All dot products are non-negative, e.g.: $\max(0, \vec{N} \cdot \vec{L})$
- All vectors are normalized
- All results must be multiplied by light's intensity and color
- $Fresnel(\vec{V} \cdot \vec{H}) = F_0 + (1 - F_0)(1 - \vec{V} \cdot \vec{H})^5$

Cook-Torrance

- Useful for most surfaces, metals,
- All microfacets are perfect mirrors
- Single parameter m (roughness), usually in range (0, 1)





Cook-Torrance cont.

- Diffuse:

$$I_{diff} = Color_{diff} \cdot (\vec{N} \cdot \vec{L})$$

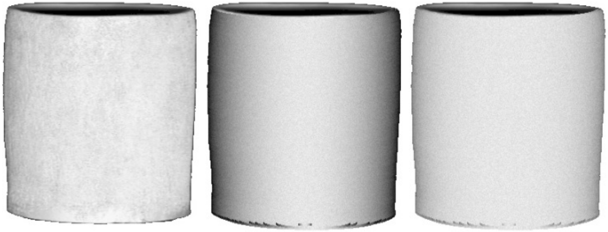
- Specular:

$$I_{spe} = \frac{F \cdot G \cdot D}{4 \cdot (\vec{N} \cdot \vec{V})}$$

  where
  - Fresnel $F = Fresnel(\vec{V} \cdot \vec{H})$
  - Geom. atten. $G = min(1, \frac{2 \cdot (\vec{N} \cdot \vec{H}) \cdot (\vec{N} \cdot \vec{V})}{(\vec{V} \cdot \vec{H})}, \frac{2 \cdot (\vec{N} \cdot \vec{H}) \cdot (\vec{N} \cdot \vec{L})}{(\vec{V} \cdot \vec{H})})$
  - Beckmann distribution $D = \frac{e^{\frac{(\vec{N} \cdot \vec{H})^2 - 1}{m^2 \cdot (\vec{N} \cdot \vec{H})^2}}}{m^2 \cdot (\vec{N} \cdot \vec{H})^4}$
  - (m is roughness of the material)
- Diffuse is energy-conserving, specular is energy-conserving, but not together

Oren-Nayar

- For non-shiny objects like concrete, flowerpots, bricks, Moon
- All microfacets are Lambertian (diffuse) surfaces
- No specular highlights
- Retroreflections at boundaries
- Single parameter *m* (roughness)



(a) Image (b) Lambertian (c) Model

Oren-Nayar cont.

- Diffuse:

$$I_{diff} = Color_{diff} \cdot (\vec{N} \cdot \vec{L}) \cdot (A + B \cdot \max(0, \cos(\phi)) \cdot C)$$

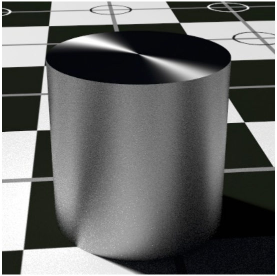
where

- $\theta_i = \arccos(\vec{N} \cdot \vec{L})$
- $\theta_o = \arccos(\vec{N} \cdot \vec{V})$
- $\alpha = max(\theta_i, \theta_o)$
- $\beta = min(\theta_i, \theta_o)$
- $\cos(\phi) = norm\left(\vec{V} - \vec{N} \cdot (\vec{V} \cdot \vec{N})\right) \cdot norm\left(\vec{L} - \vec{N} \cdot (\vec{L} \cdot \vec{N})\right)$
- $A = 1.0 - 0.5 \cdot \frac{m^2}{m^2+0.57}$
- $B = 0.45 \cdot \frac{m^2}{m^2+0.09}$
- $C = \sin(\alpha) \cdot \tan(\beta)$

- Diffuse is energy-conserving

Ashikhmin-Shirley

- For brushed objects (metal) with anisotropic reflections
- All microfacets are perfect mirrors
- Two parameters $shin_T$, $shin_B$: shininess exponents in tangent and bitangent directions, usually greater than 1



Ashikhmin-Shirley cont.

- Diffuse (not energy-conserving with specular):

$$I_{diff} = Color_{diff} \cdot (\vec{N} \cdot \vec{L})$$

- or diffuse (energy-conserving with specular):

$$I_{diff} = Color_{diff} \cdot (\vec{N} \cdot \vec{L}) \cdot \\ \cdot \frac{28}{23}(1 - F_0)\left(1 - \left(1 - \frac{(\vec{N} \cdot \vec{L})}{2}\right)^5\right)\left(1 - \left(1 - \frac{(\vec{N} \cdot \vec{V})}{2}\right)^5\right)$$

where

- F_0 is Fresnel reflection at 0°

Ashikhmin-Shirley cont.

- Specular:

$$I_{spe} = Fresnel(\vec{V} \cdot \vec{H}) \cdot (\vec{N} \cdot \vec{L}) \cdot$$

$$\cdot \frac{\sqrt{(shin_T + 1)(shin_B + 1)}}{8} \cdot \frac{(\vec{N} \cdot \vec{H})^{\frac{shin_T \cdot (\vec{T} \cdot \vec{H})^2 + shin_T \cdot (\vec{B} \cdot \vec{H})^2}{1 - (\vec{N} \cdot \vec{H})^2}}}{(\vec{V} \cdot \vec{H}) \cdot \max((\vec{N} \cdot \vec{L}), (\vec{N} \cdot \vec{V}))}$$

Normalized Blinn-Phong

- Improvement of the original Blinn-Phong (1977)
- Specular is energy conserving, without creating or losing energy
- Diffuse is the same

$$I_{diff} = Color_{diff} \cdot (\vec{N} \cdot \vec{L})$$

- Original specular

$$I_{spe} = (\vec{N} \cdot \vec{L}) \cdot Color_{spe} \cdot (\vec{N} \cdot \vec{H})^{shin}$$

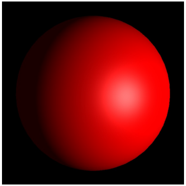
- Normalized specular

$$I_{spe} = (\vec{N} \cdot \vec{L}) \cdot Color_{spe} \cdot \frac{shin + 8}{8} (\vec{N} \cdot \vec{H})^{shin}$$

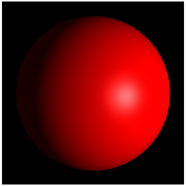
where *shin* is shininess exponent

Normalized Blinn-Phong cont.

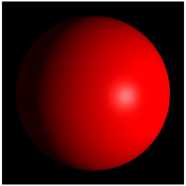
- Original Blinn-Phong, $Color_{spe} = 120/255$



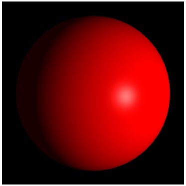
$shin = 25$



$shin = 50$

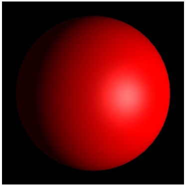


$shin = 75$

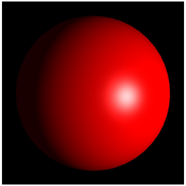


$shin = 100$

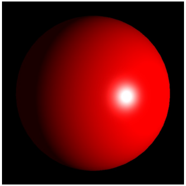
- Normalized Blinn-Phong, $Color_{spe} = 32/255$



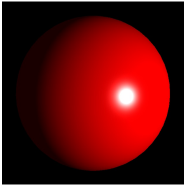
$shin = 25$



$shin = 50$



$shin = 75$



$shin = 100$

Task: Implement microfacets models

- **Task 1:** Implement Normalized Blinn-Phong
  - Fragment shader *BlinnPhongNormalized_fragment.glsl*
  - Parameters in variables:
    - $Color_{diff}$ in *material_diffuse*
    - $Color_{spe}$ in *material_specular*
    - *shin* in *material_shininess*
  - Compare with the original Blinn-Phong

Task: Implement microfacets models

- **Task 2:** Implement Cook-Torrance
  - Fragment shader *CookTorrance_fragment.glsl*
  - Parameters in variables:
    - $Color_{diff}$ in *material_diffuse*
    - F_0 in *material_fresnel*
    - m in *material_roughness*
  - Notice the highlight when looking from near surface angles
  - Comparative with Blinn-Phong. To get approx. the same result:
    - Set Specular color and Fresnel color to the same value
    - Set $roughness = \sqrt{\frac{2}{2+shininess}}$

Task: Implement microfacets models

- **Task 3:** Implement Oren-Nayar
  - Fragment shader *OrenNayar_fragment.glsl*
  - Parameters in variables:
    - $Color_{diff}$ in *material_diffuse*
    - *m* in *material_roughness*
  - Set *roughness* to 0.5 and compare with Blinn-Phong with black *specular*

Task: Implement microfacets models

- **Task 4:** Implement Ashikhmin-Shirley
  - Fragment shader *AshikhminShirley_fragment.glsl*
  - Parameters in variables:
    - $Color_{diff}$ in *material_diffuse*
    - F_0 in *material_fresnel*
    - $shin_T$ in *material_shininess_tangent*
    - $shin_B$ in *material_shininess_bitangent*
  - Test on cylinder or teapot, set different shininess in tangent and bitangent directions (e.g. 20 and 500)
  - When using simple computation for diffuse color, and setting shininess to the same values, the result should be compatible with Blinn-Phong.

Further reading

- SIGGRAPH cources on PBR:
  - http://renderwonk.com/publications/s2010-shading-course/
  - http://blog.selfshadow.com/publications/s2012-shading-course/
  - http://blog.selfshadow.com/publications/s2013-shading-course/
  - http://blog.selfshadow.com/publications/s2014-shading-course/
  - http://blog.selfshadow.com/publications/s2015-shading-course/
  - http://blog.selfshadow.com/publications/s2016-shading-course/

Further reading

- Cook, R., Torrance, K.: *A Reflectance Model for Computer Graphics*
- Oren, M., Nayar, S.: *Generalization of Lambert's Reflectance Model*
- Ashikhmin, M., Shirley, P.: *An Anisotropic Phong BRDF Model*
- Akenine-Möller, T., et al.: *Real-Time Rendering*
- Pharr, M., et al.: *Physically Based Rendering, From Theory to Practice*