SIGGRAPH 2012

The **39th** International **Conference** and **Exhibition**
on **Computer Graphics** and **Interactive Techniques**

Beyond a Simple Physically Based Blinn-Phong Model in Real-time

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Real-time Physically Based Rendering

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- Make the entire rendering pipeline physically based (for current-gen consoles)
  - Physically based
    - shading models
      - Physically based BRDF models
    - lighting
      - Quantities based on physics
      - Film simulation (spectrum based tone-mapping)
    - camera simulation
      - Lens simulation based on real camera system

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Modified Blinn-Phong Model

- A modified Blinn-Phong model
  - Basic function
    - Blinn-Phong for NDF (D)
    - Schlick Approximation (F)
      - Spherical Gaussian Approximation
    - Neumann-Neumann GAF (G)
  - Normalized specular component
    - Fitted to a linear function
  - Energy conservation
    - Approximated for performance
  - Details on “Physically Based Shading Models at tri-Ace” [SIGGRAPH 2010]

Our Physically Based Blinn-Phong

$$L_r = \frac{R_d}{\pi}\left(1 - F_{diff}(F_0)\right) + \frac{(n+2)}{4\pi\left(2 - 2^{-\frac{n}{2}}\right)} \cdot \frac{F_{spec}(F_0)(N \cdot H)^n}{\max(N \cdot L, N \cdot E)}$$

Our modified physically based Blinn-Phong model

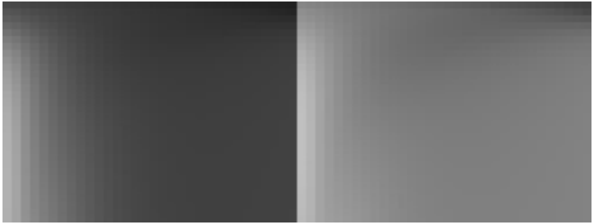
Approximation

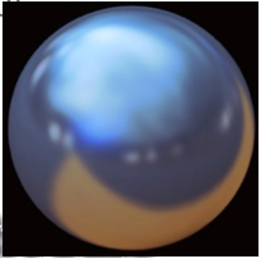
$$L_r = \frac{R_d}{\pi}\left(1 - F_0\right) + (0.0397436\,shininess + 0.0856832)\frac{F_{spec}(F_0)(N \cdot H)^{shininess}}{\max(N \cdot L, N \cdot E)}$$

Our implemented BRDF model (approximated)

Physically Based Image Based Lighting

- PBIBL is implemented for area lighting
  - AmbientBRDF
  - Pre-filtered Mipmapped Radiance Environment Map
  - Irradiance Environment Map or Spherical Harmonics
    - Details are on our past talks in [GDC 2009, 2012], [CEDEC 2007-2011] and [SIGGRAPH 2010]





More Than Physically Based Blinn-Phong

- Is this model enough?
  - In reality, there are a lot of other complicated models
  - The simple physically based Blinn-Phong models, even with anisotropic and spectral models, are not enough
  - More complicated shading
    - Translucency
    - Rough materials
    - Layered materials
    - Retro-reflectivity

Problems with the Modified Blinn-Phong

- Many real-world materials have multiple layers
  - Makes surface appearances more complicated
  - Difficult to represent with a single Blinn-Phong model

Layered Materials

- The ideal implementation allows flexibility and supports multiple layers
  - Flexibility vs. computational time
    - Any BRDF model combination
    - Number of layers

Layered Materials

- Dual-layer material implementation
  - Reasonable solution
  - Based on
    - [Weidlich et al. 2009]
      "Exploring the Potential of Layered BRDF Models"
    - [Weidlich et al. 2011]
      "Thinking in layers: modeling with layered materials"

Approximation

- Our implementation is coarsely approximated for performance in real-time
  - Approximated components
    - Color absorption computation by the top layer
    - Using our modified Blinn-Phong instead of Cook-Torrance
    - No parallax effects

Color Absorption Approximation

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- Color absorption originally takes into account refraction
  - But our implementation deals with the non-refracted distance instead of refracted distance
  - Changing the color from the bottom layer by the top layer is regarded as more important than the correct simulation

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Color Absorption Approximation

- The original absorption is based on the Bouguer-Lambert-Beer law

Absorption coefficient

$$I = I_0 e^{-\alpha l}$$

$$l = d \cdot \left(\frac{1}{\cos\theta_{i'}} + \frac{1}{\cos\theta_{r'}} \right)$$

Thickness of layer

Dot product between refracted incident angle and normal

Dot product between refracted outgoing angle and normal

Original Form

Modified coefficient combines thickness with absorption coefficient

$$I = I_0 \cdot \max\left(0, 1 - \alpha' \left(\frac{1}{N \cdot L} + \frac{1}{N \cdot E} \right) \right)$$

Dot product between incident angle and normal

Dot product between outgoing angle and normal

Approximated Form

Fresnel Component in the Bottom Layer

- The bottom-layer BRDF is evaluated with light passing through the top layer
  - Fresnel component in the bottom layer becomes

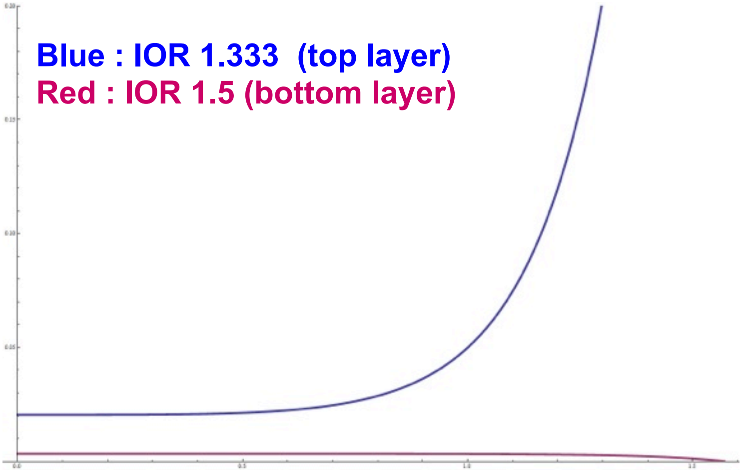
$$F_{bottom}(n_1, n_2) = \left(1 - F(n_1)\right)\left(F\left(\frac{n_2}{n_1}\right)\right)\left(1 - F\left(\frac{1}{n_1}\right)\right)$$

$F(n)$: Fresnel equation

n_1 : Refractive index of the top layer

n_2 : Refractive index of the bottom layer

Fresnel Component in the Bottom Layer



Approximation

- Fresnel component in the bottom layer can be approximated with a constant

$$F_{transmittance}(n_1) = \left(1 - F(n_1)\right)$$

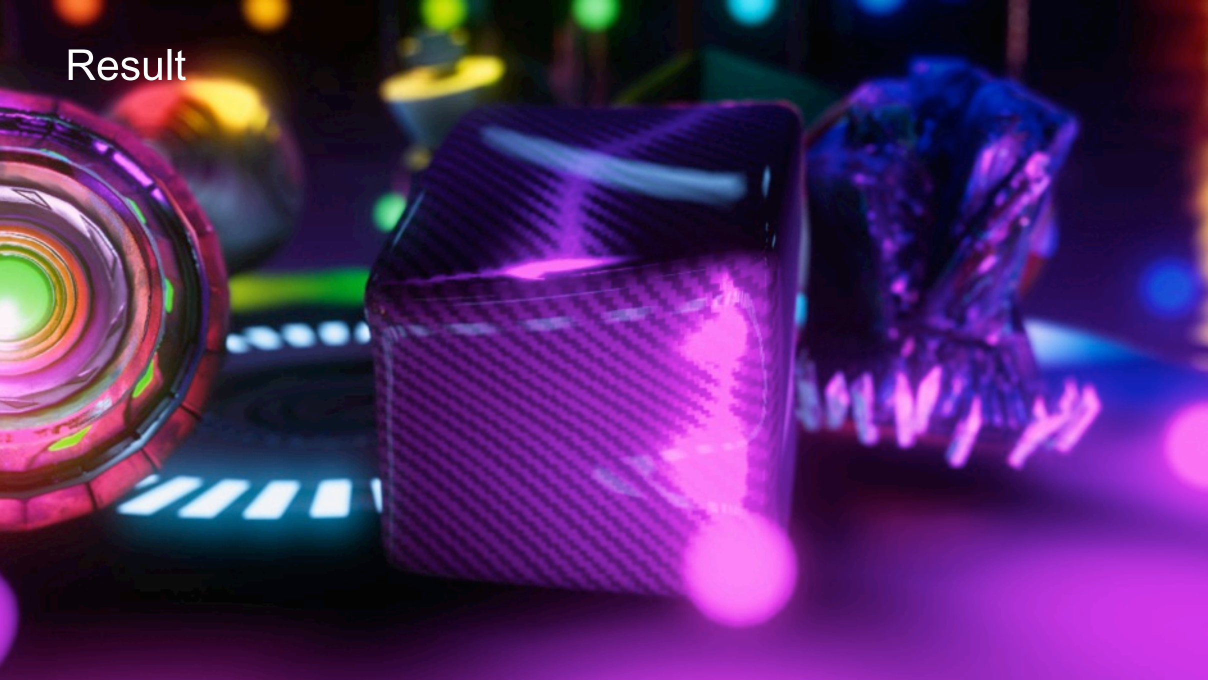
$$F_{bottom}(n_1, n_2) = \left(F_0\left(\frac{n_2}{n_1}\right)\right)\left(1 - F_0\left(\frac{1}{n_1}\right)\right)$$

$F_0(n)$: Fresnel equation for normal direction

$F_{transmittance}(n)$: Transmittance from the top layer by Fresnel term

$F_{bottom}(n_1, n_2)$: Reflectance by the bottom layer and Fresnel term

Result



Comparison

Scenes are rendered with one directional light on PS3 @ 1280x720 compared to 0.33ms using the single-layered Blinn

IBL for Layered Materials

- IBL is also important for layered materials
  - Evaluate IBL twice, once for the top layer and once for the bottom layer
  - Mathematically the absorption component must be integrated with the rendering equation
    - Also approximated with the same approach as AmbientBRDF

Pre-integration of Absorption Components

- For the specular component
  - Mathematically, it depends on the shininess value
    - Also coarsely approximated
      - Only takes into account the case where it is perfect mirror reflection $\rightarrow N \cdot L = N \cdot E$

$$\boxed{\left(\frac{1}{N \cdot L} + \frac{1}{N \cdot E}\right) = \left(\frac{1}{N \cdot E} + \frac{1}{N \cdot E}\right)}$$

Pre-integration of Absorption Components

- Multiply the derived component by the computed color from IBL to compute the specular component

$$I_s = IBL_{specular} \cdot F_{bottom}(n_1, n_2)\max\left(0, 1 - \alpha'\left(\frac{2}{N \cdot E}\right)\right)$$

Pre-integration of Absorption Components

- For the diffuse component
  - Integrate the approximated absorption function over the hemisphere with Lambert

$$\int_{\Omega}\left(\frac{1}{\cos\theta_r}+\frac{1}{\cos\theta_i}\right)\frac{1}{\pi}\cos\theta_i d\omega=\frac{1}{\pi}\int_{-\pi}^{\pi}\int_{0}^{\frac{\pi}{2}}\left(\frac{1}{\cos\theta_r}+\frac{1}{\cos\theta_i}\right)\cos\theta_i \sin d\theta_i d\theta_i d\varphi_i$$

$$=\frac{1}{\pi}\int_{-\pi}^{\pi}\frac{1}{2}(2+\frac{1}{\cos\theta_r})d\varphi_i$$

$$=2+\frac{1}{\cos\theta_r}$$

Approximated absorption

Lambertian

Integrate over hemisphere w.r.t. incident angle

Pre-integration of Absorption Components

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- Multiply the derived component by the computed color from IBL to compute the diffuse component

$$I_d = IBL_{diffuse} \cdot \left(1 - F_{bottom}(n_1, n_2)\right) \max\left(0, 1 - \alpha'(2 + \frac{1}{N \cdot E})\right)$$

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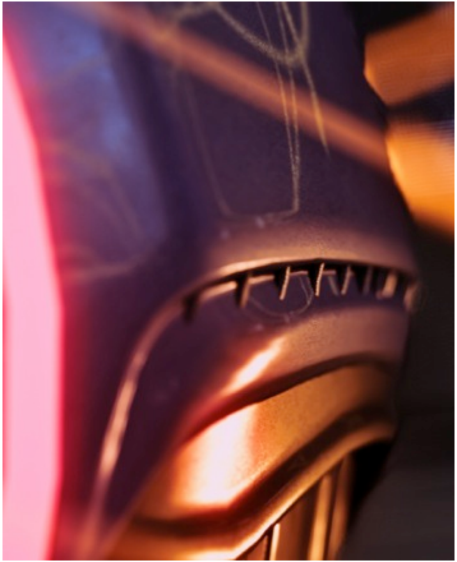
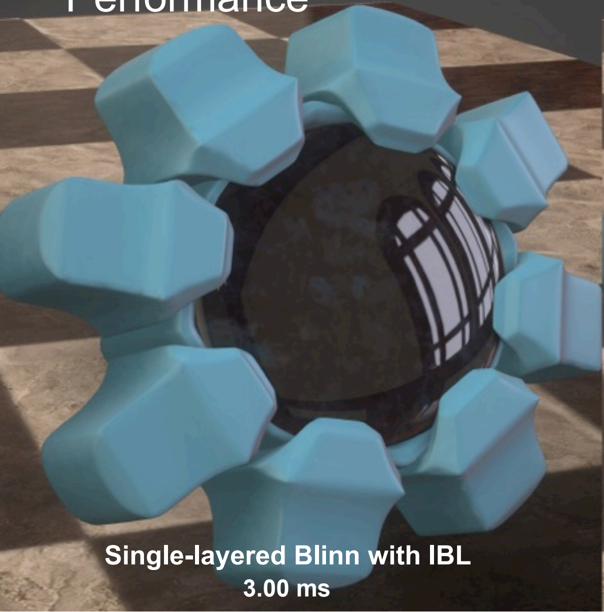
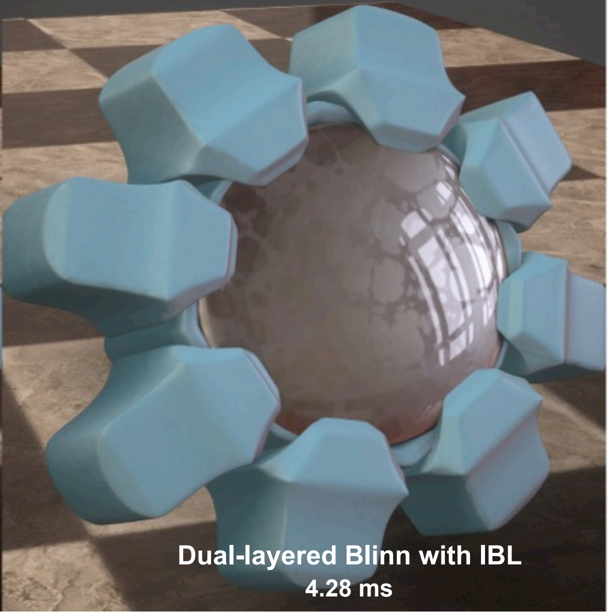
Results



Performance

PS3 @ 1280x720





Problems with the Modified Blinn-Phong

- Diffuse component is assumed to be Lambertian
  - Many materials in the real world are not Lambertian
  - Rough materials (shininess < 30) should have a matte diffuse component rather than Lambert

Oren-Nayar

- Lambert with the Torrance-Sparrow V-cavity model
  - Diffuse component with Torrance-Sparrow
    - Much more complicated than Cook-Torrance
  - Looks more “matte” than Lambert
  - View-dependent component
    - Off-peak characteristic (retro-reflectivity)
    - Shadowing / masking factor
    - Inter-reflection effect due to microfacets

Oren-Nayar

Shading Model

$$L_r(\theta_r,\theta_i,\phi_r-\phi_i;\sigma) = L_r^1(\theta_r,\theta_i,\phi_r-\phi_i;\sigma) + L_r^2(\theta_r,\theta_i,\phi_r-\phi_i;\sigma)$$

Direct Illumination Component

$$L_r^1(\theta_r,\theta_i,\phi_r-\phi_i;\sigma) = \frac{\rho}{\pi}E_0\cos\theta_i\left[C_1(\sigma)+\cos(\phi_r-\phi_i)C_2(\alpha;\beta;\phi_r-\phi;\sigma)\tan\beta+(1-\left|\cos(\phi_r-\phi_i)\right|C_3(\alpha;\beta;\sigma)\tan(\frac{\alpha+\beta}{2})\right]$$

Inter-reflection Component

$$L_r^2(\theta_r,\theta_i,\phi_r-\phi_i;\sigma) = 0.17\frac{\rho^2}{\pi}E_0\cos\theta_i\frac{\sigma^2}{\sigma^2+0.13}\left[1-\cos(\phi_r-\phi_i)(\frac{2\beta}{\pi})^2\right]$$

Coefficients

$$C_1 = 1-0.5\frac{\sigma^2}{\sigma^2+0.33}$$

$$C_2 = \begin{cases} 0.45\dfrac{\sigma^2}{\sigma^2+0.09}\sin\alpha & \text{if } \cos(\phi_r-\phi_i)\geq 0 \\ 0.45\dfrac{\sigma^2}{\sigma^2+0.09}\left(\sin\alpha-(\dfrac{2\beta}{\pi})^3\right) & \text{otherwise} \end{cases}$$

$$C_3 = 0.125\left(\frac{\sigma^2}{\sigma^2+0.09}\right)\left(\frac{4\alpha\beta}{\pi^2}\right)^2$$

$$\alpha = \mathrm{Max}(\theta_r,\theta_i) \qquad \beta = \mathrm{Min}(\theta_r,\theta_i)$$

Oren-Nayar Qualitative Model

The original paper offers an approximated model

Shading Model

$$L_r(\theta_r,\theta_i,\phi_r-\phi_i;\sigma)=\frac{\rho}{\pi}E_0\cos\theta_i\left(A+B\,\mathrm{Max}\left(0,\cos(\phi_r-\phi_i)\right)\sin\alpha\tan\beta\right)$$

Coefficients

$$A=1-0.5\frac{\sigma^2}{\sigma^2+0.33}\quad B=0.45\frac{\sigma^2}{\sigma^2+0.09}\quad \alpha=\mathrm{Max}(\theta_r,\theta_i)\quad \beta=\mathrm{Min}(\theta_r,\theta_i)$$

Is Oren-Nayar Too Complex?

$$L_r(\theta_r,\theta_i,\phi_r-\phi_i;\sigma)=\frac{\rho}{\pi}E_0\cos\theta_i\left(A+B\,\mathrm{Max}\left(0,\cos(\phi_r-\phi_i)\right)\sin\alpha\tan\beta\right)$$

Rewrite this model with familiar expressions

$$L_r=\frac{\rho}{\pi}E_0(N\cdot L)\left((1.0-0.5\frac{\sigma^2}{\sigma^2+0.33})+(0.45\frac{\sigma^2}{\sigma^2+0.09})\mathrm{Max}(0,\frac{E-N(N\cdot E)}{\|E-N(N\cdot E)\|}\cdot\frac{L-N(N\cdot L)}{\|L-N(N\cdot L)\|})\frac{\sqrt{(1-\mathrm{Max}(N\cdot L,N\cdot E)^2)(1-\mathrm{Min}(N\cdot L,N\cdot E)^2)}}{\mathrm{Max}(N\cdot L,N\cdot E)}\right)$$

Oren-Nayar Simplification (1)

$$L_r = \frac{\rho}{\pi} E_0 \boxed{(N\cdot L)} \left((1.0 - 0.5\frac{\sigma^2}{\sigma^2+0.33}) + (0.45\frac{\sigma^2}{\sigma^2+0.09}) \mathrm{Max}(0, \frac{(E-N(N\cdot E))\cdot(L-N(N\cdot L))}{\|E-N(N\cdot E)\|\cdot\|L-N(N\cdot L)\|}) \frac{\boxed{\sqrt{(1-\mathrm{Max}(N\cdot L, N\cdot E)^2)(1-\mathrm{Min}(N\cdot L, N\cdot E)^2)}}}{\mathrm{Max}(N\cdot L, N\cdot E)} \right)$$

Expand

If N·L is Max, then N·E is Min and vice-versa

$$L_r = \frac{\rho}{\pi} E_0 \left[\boxed{(N\cdot L)}(1.0 - 0.5\frac{\sigma^2}{\sigma^2+0.33}) + \left((0.45\frac{\sigma^2}{\sigma^2+0.09}) \mathrm{Max}(0, \frac{(E-N(N\cdot E))\cdot(L-N(N\cdot L))}{\|E-N(N\cdot E)\|\cdot\|L-N(N\cdot L)\|}) \frac{\boxed{(N\cdot L)}\boxed{\sqrt{(1-(N\cdot L)^2)(1-(N\cdot E)^2)}}}{\mathrm{Max}(N\cdot L, N\cdot E)} \right) \right]$$

Substitute $\frac{N\cdot L}{\mathrm{Max}(N\cdot L, N\cdot E)} = \mathrm{Min}(\frac{N\cdot L}{N\cdot L}, \frac{N\cdot L}{N\cdot E}) = \mathrm{Min}(1, \frac{N\cdot L}{N\cdot E})$

$$L_r = \frac{\rho}{\pi} E_0 \left[(N\cdot L)(1.0 - 0.5\frac{\sigma^2}{\sigma^2+0.33}) + \left((0.45\frac{\sigma^2}{\sigma^2+0.09}) \mathrm{Max}(0, \frac{(E-N(N\cdot E))\cdot(L-N(N\cdot L))}{\|E-N(N\cdot E)\|\cdot\|L-N(N\cdot L)\|}) \sqrt{(1-(N\cdot L)^2)(1-(N\cdot E)^2)} \boxed{\mathrm{Min}(1, \frac{N\cdot L}{N\cdot E})} \right) \right]$$

Oren-Nayar Simplification (2)

$$L_r = \frac{\rho}{\pi} E_0 \left[(N\cdot L)(1.0 - 0.5\frac{\sigma^2}{\sigma^2 + 0.33}) + \left((0.45\frac{\sigma^2}{\sigma^2 + 0.09}) \mathrm{Max}(0, \frac{(E - N(N\cdot E))\cdot(L - N(N\cdot L))}{\|E - N(N\cdot E)\|\cdot\|L - N(N\cdot L)\|}) \sqrt{(1-(N\cdot L)^2)(1-(N\cdot E)^2)}\, \mathrm{Min}(1, \frac{N\cdot L}{N\cdot E}) \right) \right]$$

Recall the original definition

$$\frac{(E - N(N\cdot E))\cdot(L - N(N\cdot L))}{\|E - N(N\cdot E)\|\cdot\|L - N(N\cdot L)\|} = \cos(\phi_r - \phi_i)$$

Derive the relational expression from Eq.(37) and (38) in the original paper

$$\cos\theta_r \cos\theta_i + \sin\theta_r \sin\theta_i \cos(\phi_r - \phi_i) = \cos(\theta_r - \theta_i)$$

Rewrite

$$(N\cdot E)(N\cdot L) + \sqrt{1-(N\cdot E)^2}\sqrt{1-(N\cdot L)^2}\cos(\phi_r - \phi_i) = E\cdot L$$

Transpose terms

$$\cos(\phi_r - \phi_i) = \frac{E\cdot L + (N\cdot E)(N\cdot L)}{\sqrt{(1-(N\cdot E)^2)(1-(N\cdot L)^2)}}$$

Substitute

Oren-Nayar Simplification (3)

$$L_r = \frac{\rho}{\pi} E_0 \left[(N \cdot L)(1.0 - 0.5 \frac{\sigma^2}{\sigma^2 + 0.33}) + \left((0.45 \frac{\sigma^2}{\sigma^2 + 0.09}) \mathrm{Max}(0, \frac{E \cdot L - (N \cdot E)(N \cdot L)}{\boxed{\sqrt{(1-(N \cdot L)^2)(1-(N \cdot E)^2)}}}) \boxed{\sqrt{(1-(N \cdot L)^2)(1-(N \cdot E)^2)}} \mathrm{Min}(1, \frac{N \cdot L}{N \cdot E}) \right) \right]$$

Simplify since $\sqrt{(1-(N \cdot L)^2)(1-(N \cdot E)^2)} \geq 0$

$$L_r = \frac{\rho}{\pi} E_0 \left[(N \cdot L)(1.0 - 0.5 \frac{\sigma^2}{\sigma^2 + 0.33}) + \left((0.45 \frac{\sigma^2}{\sigma^2 + 0.09}) \mathrm{Max}(0, E \cdot L - (N \cdot E)(N \cdot L)) \mathrm{Min}(1, \frac{N \cdot L}{N \cdot E}) \right) \right]$$

Simplified Oren-Nayar

Key component for Oren-Nayar

$$L_r = \frac{\rho}{\pi} E_0 \left[\boxed{(N \cdot L)(1.0 - 0.5 \frac{\sigma^2}{\sigma^2 + 0.33})} + \left(\boxed{(0.45 \frac{\sigma^2}{\sigma^2 + 0.09}) \mathrm{Max}(0, E \cdot L - (N \cdot E)(N \cdot L))} \boxed{\mathrm{Min}(1, \frac{N \cdot L}{N \cdot E})} \right) \right]$$

Weighted Lambert term

Same Geometry Attenuation Factor as Neumann-Neumann

$$L_r = \frac{\rho}{\pi} E_0 (N \cdot L) \left((1.0 - 0.5 \frac{\sigma^2}{\sigma^2 + 0.33}) + (0.45 \frac{\sigma^2}{\sigma^2 + 0.09}) \mathrm{Max}(0, \frac{(E - N(N \cdot E)) \cdot (L - N(N \cdot L))}{\| E - N(N \cdot E) \| \cdot \| L - N(N \cdot L) \|}) \frac{\sqrt{(1 - \mathrm{Max}(N \cdot L, N \cdot E)^2)(1 - \mathrm{Min}(N \cdot L, N \cdot E)^2)}}{\mathrm{Max}(N \cdot L, N \cdot E)} \right)$$

Before simplification

Roughness Map for Oren-Nayar

- Use a shininess map for both specular and diffuse
  - It works for most cases
  - If shininess is used for specular
    - $\sigma = \sqrt{\dfrac{2}{shininess}}$
  - When the sizes of the microfacets are close to wavelengths of the visible light
    - Specular and diffuse behave differently
    - Two different shininess (roughness) maps for diffuse and specular

More Simplification

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$$L_r = \frac{\rho}{\pi} E_0 \left[(N \cdot L)(1.0 - 0.5 \frac{\sigma^2}{\sigma^2 + 0.33}) + \left((0.45 \frac{\sigma^2}{\sigma^2 + 0.09}) \mathrm{Max}(0, E \cdot L - (N \cdot E)(N \cdot L)) \mathrm{Min}(1, \frac{N \cdot L}{N \cdot E}) \right) \right]$$

Substitute $\sigma^2 = \frac{2}{shininess}$

$$L_r = \frac{\rho}{\pi} E_0 \left[(N \cdot L)(1 - 0.5 \frac{\frac{2}{shi}}{\frac{2}{shi} + 0.33}) + \left((0.45 \frac{\frac{2}{shi}}{\frac{2}{shi} + 0.09}) \mathrm{Max}(0, E \cdot L - (N \cdot E)(N \cdot L)) \mathrm{Min}(1, \frac{N \cdot L}{N \cdot E}) \right) \right]$$

Simplify

$$L_r = \frac{\rho}{\pi} E_0 \left[(N \cdot L)(1 - \frac{1}{2 + 0.33 shi}) + \left(\frac{1}{2.22222 + 0.1 shi} \mathrm{Max}(0, E \cdot L - (N \cdot E)(N \cdot L)) \mathrm{Min}(1, \frac{N \cdot L}{N \cdot E}) \right) \right]$$

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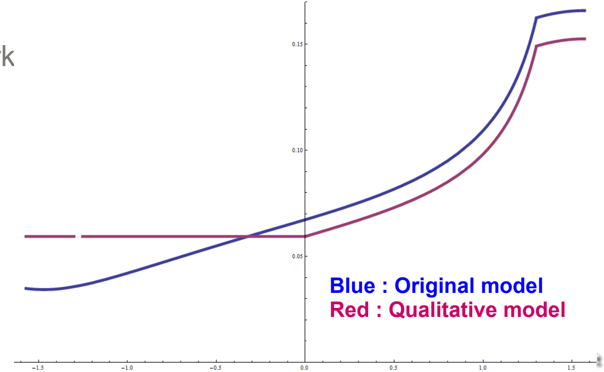
Problems with Qualitative Model

- When L·E < 0 (backward light), the qualitative model becomes Lambert, but the original doesn't
  - This problem makes the results look slightly flat
- The qualitative model doesn't contain an inter-reflection component
  - It makes the results slightly dark



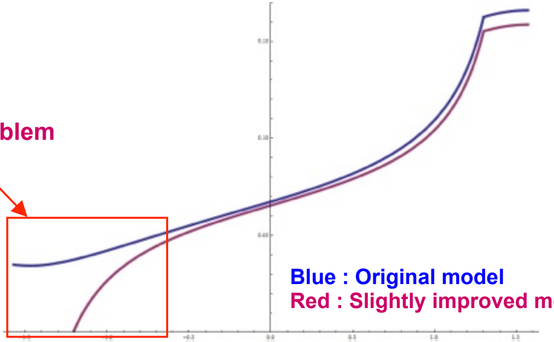
Improved Qualitative Model (1)

$$L_r = \frac{\rho}{\pi} E_0 \left[(N \cdot L)(1 - \frac{1}{2 + 0.33shi}) + \left(\frac{1}{2.22222 + 0.1shi} \mathrm{Max}(0, E \cdot L - (N \cdot E)(N \cdot L)) \mathrm{Min}(1, \frac{N \cdot L}{N \cdot E}) \right) \right]$$

Remove the first Max and tweak the coefficient

$$L_r = \frac{\rho}{\pi} E_0 \left[(N \cdot L)(1 - \frac{1}{2 + 0.65shi}) + \left(\frac{1}{2.22222 + 0.1shi} (E \cdot L - (N \cdot E)(N \cdot L)) \mathrm{Min}(1, \frac{N \cdot L}{N \cdot E}) \right) \right]$$

Still a problem



Blue : Original model
Red : Slightly improved model

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Improved Qualitative Model (2)

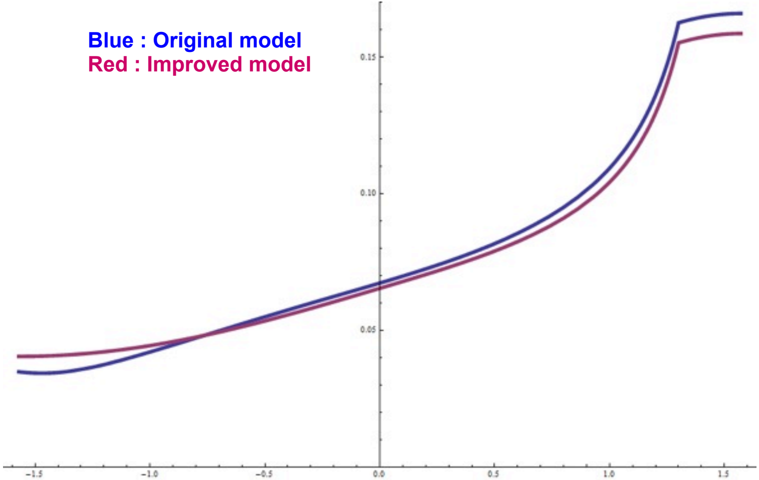
- Change the formula with respect to forward and backward lighting like C_2 in the original Oren-Nayar

$$C_2 = \begin{cases} 0.45\dfrac{\sigma^2}{\sigma^2+0.09}\sin\alpha & \text{if } \cos(\phi_r-\phi_i)\geq 0 \\ 0.45\dfrac{\sigma^2}{\sigma^2+0.09}\left(\sin\alpha-(\dfrac{2\beta}{\pi})^3\right) & \text{otherwise} \end{cases}$$

$$L_r = \begin{cases} \dfrac{\rho}{\pi}E_0\left[(N\cdot L)(1-\dfrac{1}{2+0.65shi})+\left(\dfrac{1}{2.22222+0.1shi}(E\cdot L-(N\cdot E)(N\cdot L))\mathrm{Min}(1,\dfrac{N\cdot L}{N\cdot E})\right)\right] & \text{if } (E\cdot L-(N\cdot E)(N\cdot L))\geq 0 \\ \dfrac{\rho}{\pi}E_0\left[(N\cdot L)(1-\dfrac{1}{2+0.65shi})+\left(\dfrac{1}{2.22222+0.1shi}(E\cdot L-(N\cdot E)(N\cdot L))(N\cdot L)\right)\right] & \text{otherwise} \end{cases}$$

Improved model

Result


Blue : Original model
Red : Improved model
0.15
0.10
0.05
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5

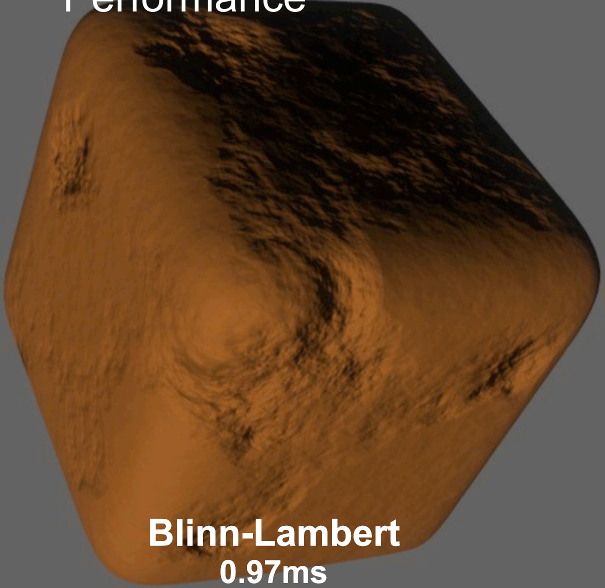
Comparison

Qualitative model

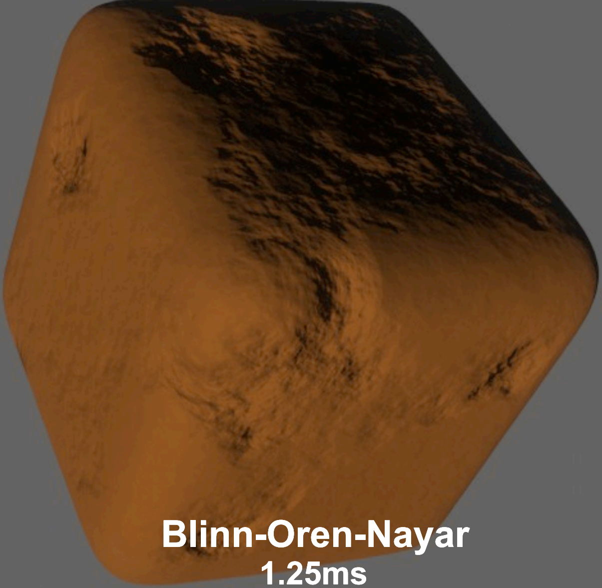

Improved model

Performance

one directional light on PS3 @ 1280x720



Blinn-Lambert
0.97ms



Blinn-Oren-Nayar
1.25ms

IBL for Oren-Nayar

- Difficult to take into account the view-dependent component with image-based lighting
  - Requires a multi-dimensional cube map like Blinn-Phong specular
  - If using SH lighting for the diffuse component
    - Can SH coefficients be tweaked to reproduce Oren-Nayar characteristics?

Oren-Nayar Characteristics

- Matte appearance
  - Using low-order SH coefficients is “matte” enough
  - Should we reduce high-order SH coefficients by roughness?
- View-dependent component
  - It gives the appearance of a very “matte-like” specular component
  - Should we control SH coefficients using the eye vector?
- Shadow / masking factor
  - Total energy changes by incident and outgoing directions
  - Should we control SH coefficients using the light and eye vectors?
- Off-peak diffuse (retro-reflective component)
  - Should we bend the normal vector?

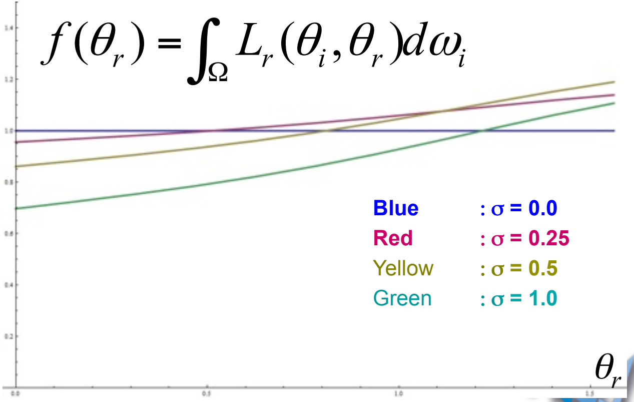
SH Oren-Nayar Approximation

- The following characteristics are reproduced in our implementation
  - View-dependent component
    - Distinctive difference between Oren-Nayar and Lambert
  - Shadow / masking factor
    - This affects brightness of shading result
- 1st-order SH is "matte" enough
  - Retro-reflective component is difficult to distinguish
    - It is not computationally reasonable

SH Oren-Nayar Approximation (1)

- Check the total energy by integrating Oren-Nayar over the hemisphere

$$f(\theta_r) = \int_{\Omega} L_r(\theta_i, \theta_r)\, d\omega_i$$

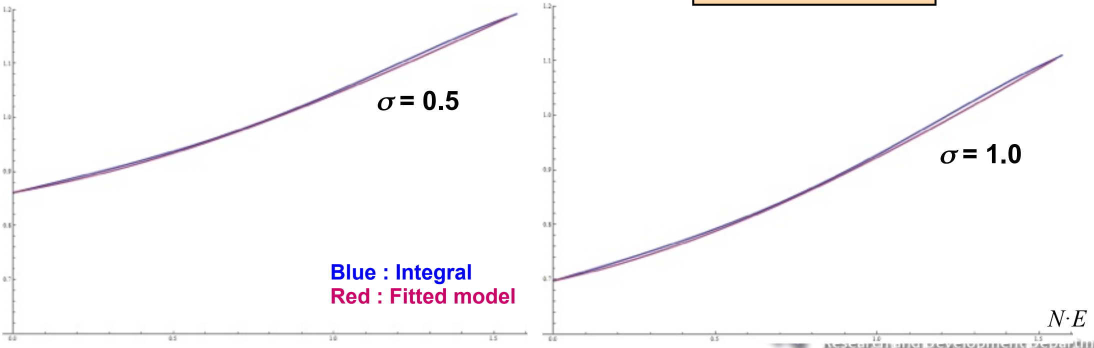


SH Oren-Nayar Approximation (2)

- Total energy affects the DC component in SH coefficients
  - The DC component can be computed as:

$$SH'_{DC} = \left(f(shi) + \frac{1}{2} g(shi) \left(1 + \frac{2\arccos(N \cdot E)}{\pi} - N \cdot E \right) \right) SH_{DC}$$

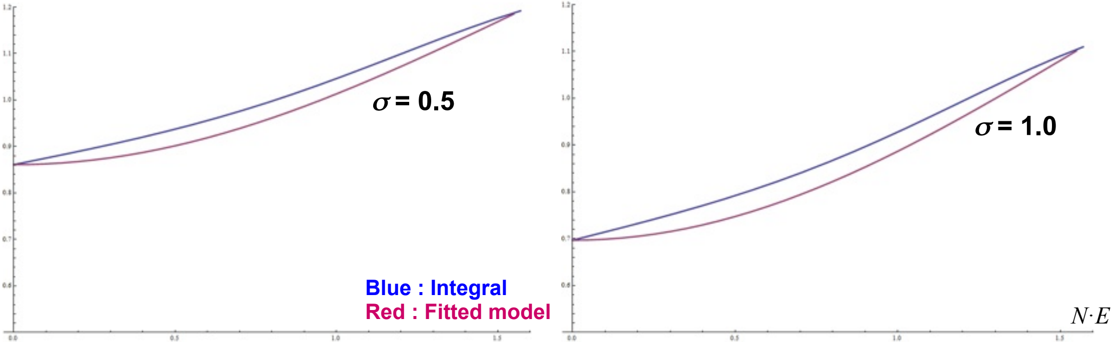
$$f(shi) = \left(1 - \frac{1}{2 + 0.65 shi}\right)$$
$$g(shi) = \left(\frac{1}{2.22222 + 0.1 shi}\right)$$



SH Oren-Nayar Approximation (3)

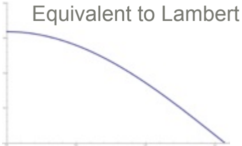
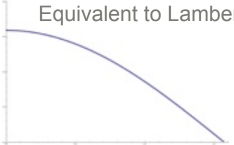
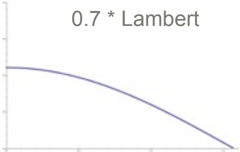
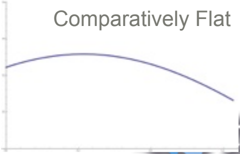
- The fitted model is still computationally expensive
  - The following coarse approximation may be useful for real-time

$$\boxed{SH'_{DC} = \big(f(shi) + g(shi)(1 - N \cdot E)\big) SH_{DC}}$$



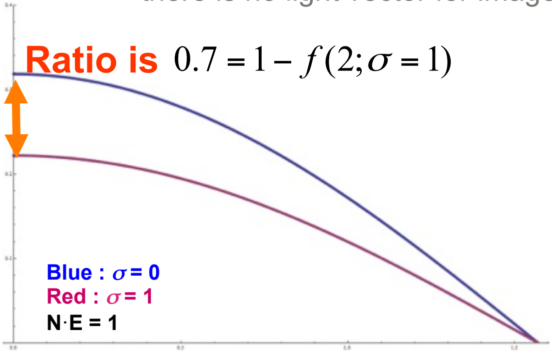
SH Oren-Nayar Approximation (4)

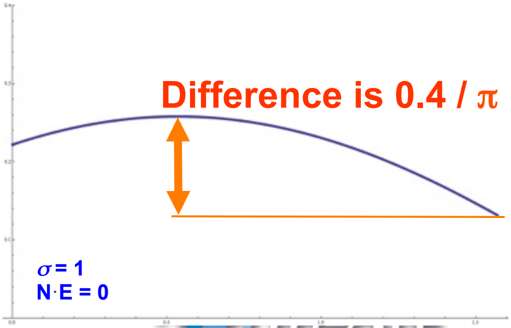
- Oren-Nayar values become a flat line (matte) as
  - σ and N·E get bigger
  - $\phi_r - \phi_i$ becomes small enough (inside the plane of incidence)

	N·E = 1	N·E = 0
σ = 0	Equivalent to Lambert 	Equivalent to Lambert 
σ = 1	0.7 * Lambert 	Comparatively Flat 

SH Oren-Nayar Approximation (5)

- Design a function to interpolate a scale factor for the linear component with a different σ and N·E
  - Try to reproduce the most noticeable characteristic ($\phi_r - \phi_i = 0$) because there is no light vector for image-based lighting





SH Oren-Nayar Approximation (5)

- Linear component can represent how “matte” it is
  - Linear component can be computed as:

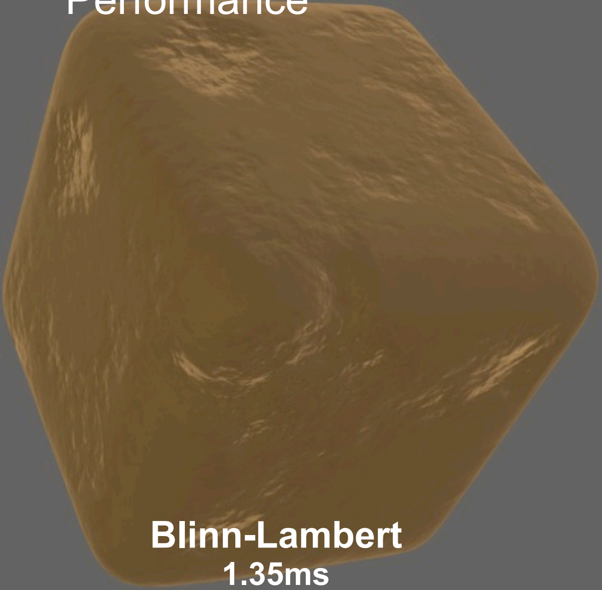
$$SH'_{linear} = S(shi, N \cdot E) SH_{linear}$$

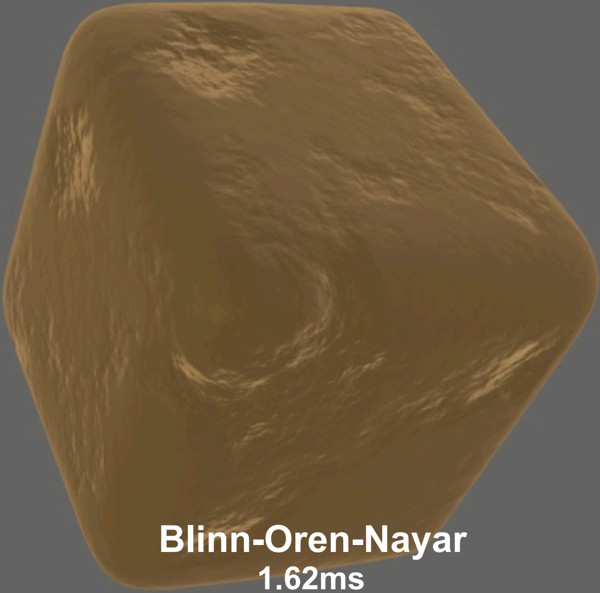
$$S(s, x) = f(s) + (f(s) - 1)(1 - x)$$

	N·E = 1	N·E = 0
$\sigma = 0$	Equivalent to Lambert $S(\infty, 1.0) = 1.0$	Equivalent to Lambert $S(\infty, 0.0) = 1.0$
$\sigma = 1$	0.7 * Lambert $S(2, 1.0) = f(2) \approx 0.7$	Comparatively Flat $S(2, 0.0) = 2f(2) - 1 \approx 0.4$

Performance

one IBL on PS3 @ 1280x720





Thoughts on Human Skin

- Human skin is composed of
  - a coat of oil and moisture
  - skin (epidermis, dermis, blood vessels)
    - Subsurface scattering
    - Roughness component
      - E.g. Roughness is 0.58 for Oren-Nayar

Simplest Implementation

- With only a single physically based Blinn-Phong
  - Control specular by using a shininess map to represent oil
  - Skin appearance is reproduced with an ad-hoc approach such as drawing highlights into the albedo textures

Subsurface Scattering Implementation

- Blinn-Phong + subsurface scattering
  - Single-layered material with a subsurface scattering algorithm
  - Try to represent not only the translucent component, but also a matte appearance without a more "matte" diffuse component
    - Too much translucency
    - Looks like a wax figure

Layered Material + Oren-Nayar

- Better appearance than the simplest implementation
  - The top layer represents oil and moisture
  - The bottom layer represents the skin itself (matte specular and diffuse)
  - No translucency

More Realistic

- Layered materials
  - Oil and moisture
  - Matte specular and diffuse for the skin surface
- Additionally
  - Multiple layered subsurface scattering for epidermis, dermis, and blood vessels

Result

Performance

one directional light + one IBL on PS3 @ 1280x720

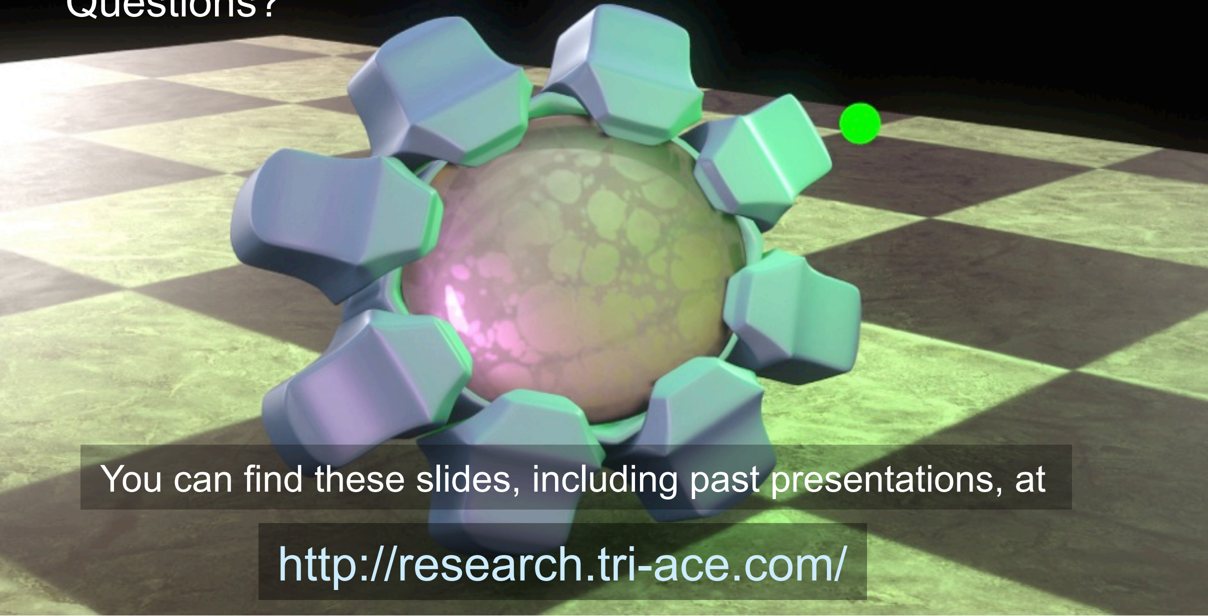
Conclusion

- Even physically based Blinn-Phong or Cook-Torrance is not enough to represent realistic materials
- Layered materials and Oren-Nayar are computationally inexpensive to implement even for current-gen consoles
  - Realistic diffuse shading is very important
  - They can be selectively used based on performance
  - These materials could become the standard for next-gen consoles

Acknowledgements

- Tatsuya Shoji
- Shawn (L. Spiro) Wilcoxen
- Elliott Davis

Questions?



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http://research.tri-ace.com/