VGP352 – Week 4

- Agenda:
  - Anisotropic reflection
    - Ward BRDF
    - Ashikhmin BRDF
  - Metals
    - The skin effect
    - Lafortune BRDF
  - Complex lighting model implementation walk-through

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Anisotropy Refresher

> Anisotropy...is the property of being directionally dependent, as opposed to isotropy, which means homogeneity in all directions. It can be defined as a difference in a physical property (absorbance, refractive index, density, etc.) for some material when measured along different axes. An example is the light coming through a polarizing lens.

- We saw this last term with filter areas for texture sampling

Anisotropic Reflection

- What does anisotropy mean for lighting and reflections?
  - Some materials reflect light differently depending on the orientation of the material w.r.t. the light and viewer

Anisotropic Reflection

- What causes anisotropic reflection?
  - Think about the micro-facet theory of surfaces

Anisotropic Reflection

- What causes anisotropic reflection?
  - Think about the micro-facet theory of surfaces
  - The distribution of normals is random, but the distribution depends on the orientation

Anisotropic Reflection

- What additional information is needed to implement an anisotropic normal distribution function?
  - Our current lighting models use H, derived from N, L, and V
  - This gives no information for the relative orientation of the surface vs. the light and viewer

Anisotropic Reflection

- What additional information is needed to implement an anisotropic normal distribution function?
  - Our current lighting models use H, derived from N, L, and V
  - This gives no information for the relative orientation of the surface vs. the light and viewer
- The surface tangent!
  - If V' is the projection of V onto the plane containing T and B, $arccos(V' \cdot T)$ is the relative orientation angle

Ward's Anisotropic Model

- Map N, T, and B to the Z, X, and Y axes
  - θ_V is the angle between the vector and the Z-axis
    - We can get this from the usual dot-products
  - ϕ_V is the angle between the vector and the X-axis
    - Project V into the X/Y plane by setting Z=0 and re-normalizing
    - Take the dot-product with the tangent

Ward's Anisotropic Model

$$f(\omega_i,\omega_o)=\frac{K_d}{\pi}+\frac{K_s}{4\pi\alpha_x\alpha_y\sqrt{\cos\theta_i\cos\theta_o}}e^{-\tan^2\theta_H\left(\frac{\cos^2\phi_H}{\alpha_x^2}\frac{\sin^2\phi_H}{\alpha_y^2}\right)}$$

- α_x and α_y control the width of the highlight in the two principal directions
  - $\alpha_x = \alpha_y$ the reflection is isotropic
  - $\tan^2\theta = (1 - \cos^2\theta) / \cos^2\theta$
  - $\sin^2\theta = 1 - \cos^2\theta$

Ward's Anisotropic Model

$$f(\omega_i,\omega_o)=\frac{K_d}{\pi}+\frac{K_s}{4\pi\alpha_x\alpha_y\sqrt{\cos\theta_i\cos\theta_o}}e^{-\tan^2\theta_H\left(\frac{\cos^2\phi_H}{\alpha_x^2}\frac{\sin^2\phi_H}{\alpha_y^2}\right)}$$

- Essentially an elliptical version of the Gaussian distribution
- 1 / ($4\pi\alpha_x\alpha_y$) is a semi-magic normalization factor that “is accurate as long as α is not much greater than 0.2, when the surface becomes mostly diffuse.”

Ward's Anisotropic Model

$$f(\omega_i,\omega_o)=\frac{K_d}{\pi}+\frac{K_s}{4\pi\alpha_x\alpha_y\sqrt{\cos\theta_i\cos\theta_o}}e^{-\tan^2\theta_H\left(\frac{\cos^2\phi_H}{\alpha_x^2}\frac{\sin^2\phi_H}{\alpha_y^2}\right)}$$

- Ward presents an approximation that is cheaper to computer, but Schlick found the direct vector implementation to be both exact and faster still:

$$f(\omega_i,\omega_o)=\frac{K_d}{\pi}+\frac{K_s}{4\pi\alpha_x\alpha_y\sqrt{(N\cdot\omega_i)(N\cdot\omega_o)}}e^{-\frac{\left(\frac{H\cdot T}{a_x}\right)^2+\left(\frac{H\cdot B}{a_y}\right)^2}{(H\cdot N)^2}}$$

- Note: Because a squared dot-product of *H* appears in the numerator and denominator, we don't need to normalize *H*

Ashikhmin Model

$$f_s(\omega_i,\omega_o)=\frac{\sqrt{(n_x+1)(n_y+1)}}{8\pi}\frac{(N\cdot H)^{n_x\cos^2\phi_H+n_y\sin^2\phi_H}}{(H\cdot\omega)\,max((N\cdot\omega_i),(N\cdot\omega_o))}F(\omega\cdot H)$$

- Most of the notation is the same as on the previous slides
  - This differs from the notation in Ashikhmin's paper
- n_x and n_y are Phong-like exponents that control the shape of the specular lobe
  - Roughly analogous to α_x and α_y in Ward's model
- $F(\theta)$ is the Fresnel term

Ashikhmin Model

$$f_d(\omega_i,\omega_o)=\frac{28K_d}{23\pi}(1-F(0))\left(1-\left(1-\frac{N\cdot\omega_i}{2}\right)^5\right)\left(1-\left(1-\frac{N\cdot\omega_o}{2}\right)^5\right)$$

- $F(0)$ is the Fresnel term at an angle of 0°
- The strange constant factor is “designed to ensure energy conservation.”

References

Neil Blevins, “Anisotropic Reflections.” June 19th, 2002. http://www.neilblevins.com/cg_education/aniso_ref/aniso_ref.htm

Ashikhmin, M., Shirley, P. "An Anisotropic Phong BRDF Model" Journal of Graphics Tools, v.5, no. 2 (2000), pp.25-32. http://www.cs.utah.edu/~michael/brdfs/

Ward, G. J. 1992. Measuring and modeling anisotropic reflection. *SIGGRAPH Computer Graphics* 26, 2 (July 1992), 265-272. http://www.cs.virginia.edu/~gfx/Courses/2006/DataDriven/bib/appearance/ward92.pdf

Walter, B. Notes on the Ward BRDF. *Technical report PCG-05-06*, Program of Computer Graphics, Cornell University, April 2005. http://www.graphics.cornell.edu/pubs/2005/Wal05.html

E.M. Waves in Conductors

- Electromagnetic waves in conductors cause free electrons in the material to oscillate
    - The frequency of this oscillation is proportional to the frequency of the electromagnetic wave
    - These oscillations create eddy currents inside the material
    - These eddy currents force the primary current very near the surface
    - The change in current density w.r.t. change of depth is known as the *skin effect*

E.M. Waves in Conductors

- Higher frequency waves cause the current to be limited to thinner and thinner skins on the material
  - A 1GHz wave in copper is restricted to ~0.5mm
  - A 60Hz wave in copper is restricted to ~10mm
  - Note: I'm trading a lot of physics here for a lot of hand waving!

E.M. Waves in Conductors

- What does this have to do with lighting?!?

E.M. Waves in Conductors

- What does this have to do with lighting?!?
  - Light is “just” an electromagnetic wave
  - Visible light is ~400THz - ~700THz
    - THz is tera-Hz or 1,000GHz
- As a result, light cannot penetrate deeply into metals
  - Most of the cause of diffuse reflection in dielectrics is caused light penetrating into the material
  - Lacking this, metal doesn't have a traditional diffuse reflection component
    - Cook & Torrance pointed this out as well

Metals

- Two main components to metallic reflection:
  - A mostly pure specular component
    - A la Phong or Blinn
  - A *directional* diffuse component
    - Diffuse in the sense that the reflected color is the color of the material
- None of our current models have a directional diffuse component

Lafortune BRDF

- Remember Phong:

$$K = K_s (V \cdot R)^s I_s$$

  - R is the ideal reflection vector
  - Calculation using vectors:

$$R = 2(N \cdot L) N - L$$

  - Calculation using the Householder matrix:

$$R = L^T (2\mathrm{NN}^T - I) = L^T M$$

Lafortune BRDF

- What if we could replace M with some other matrix?

Lafortune BRDF

- What if we could replace M with some other matrix?
  - We could move the specular lobe!
  - The new matrix must be symmetric ($M = M^T$) or it will violate Helmoltz Reciprocity
  - It turns out that almost all cases except very unusual types of anisotropy, M is also diagonal
    - $C_x = C_y$ is also typical

$$M = \begin{bmatrix} C_x & 0 & 0 \\ 0 & C_y & 0 \\ 0 & 0 & C_z \end{bmatrix}$$

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Lafortune BRDF

- We can rearrange the math a bit:

$$K = K_s \left((M\,R) \cdot V \right)^s I_s$$

$$K = K_s \left(C_x R_x V_x + C_y R_y V_x + C_z R_z V_z \right)^s I_s$$

- What if we could fit measured data to a series of cosine lobes?

$$K = \sum_i K_s (C_{x,i} R_x V_x + C_{y,i} R_y V_y + C_{z,i} R_z V_z)^{s_i} I_s$$

Lafortune BRDF

- What does the data look like?
  - For matte steel:

	C_{xy}	C_z	s
Lobe 1, red	-1.11954	1.01272	15.8708
Lobe 1, green	-1.11845	1.01469	15.6489
Lobe 1, blue	-1.11999	1.01942	15.4571
Lobe 2, red	-1.05334	0.69541	111.267
Lobe 2, green	-1.06409	0.662178	88.9222
Lobe 2, blue	-1.08378	0.626672	65.2179
Lobe 3, red	-1.01684	1.00132	180.181
Lobe 3, green	-1.01635	1.00112	184.152
Lobe 3 blue	-1.01529	1.00108	195.773

References

Lafortune, E. P., Foo, S., Torrance, K. E., and Greenberg, D. P. 1997. Non-linear approximation of reflectance functions. In *Proceedings of the 24th Annual Conference on Computer Graphics and interactive Techniques International Conference on Computer Graphics and Interactive Techniques*. ACM Press/Addison-Wesley Publishing Co., New York, NY, 117-126. http://www.graphics.cornell.edu/pubs/1997/LFTG97.html

http://en.wikipedia.org/wiki/Skin_depth

Next week...

- Fur and hair
  - Two final BRDFs
    - Grand unifying theory of anisotropic BRDFs
    - BRDFs for hair
  - Fins and shells
- Quiz #2

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