Materials

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Materials

• In the subject of rendering, the term material usually refers to the properties of how light reflects off of a surface.

• There are a lot of similar terms in computer graphics to refer to this concept such as shader, reflection model, BRDF, local illumination model, etc.

• We will usually just use the term material, but later in the course, we will define a more precise concept called a BRDF.

• For the purposes of this course, the concept of a material will contain all of the properties to define how an incoming beam of light is scattered (reflected) by the surface, including color, shininess, transparency, and more.

• Example materials include glass, metal, plastic, car paint, cloth, skin, etc.
Materials

• In the last lecture, we looked at how light reflects and refracts when it hits smooth metal and dielectric surfaces

• We saw that the incident beam of light was either reflected as a single beam or split into a single reflection and a single refraction (transmission) beam

• Today we will look at some more complex examples, where light is scattered off of the material into many directions
Diffuse Materials
Diffuse Materials

• Diffuse materials are often described as having a dull or matte appearance
• An *ideal diffuse reflector* scatters incoming light equally in all directions
• One important result of this is that the surface color appears the same from any viewing direction
• Paper and smooth plaster are reasonable examples of real-world materials that behave similarly to ideal diffuse reflectors
In the computer graphics community, ideal diffuse materials are often called *Lambert* materials, or *Lambertian* materials. Johann Heinrich Lambert was a Swiss mathematician and physicist (1728-1777). Lambert made a lot of contributions to science and optics, many of which are useful in computer graphics. He is perhaps best known for being the first to prove that $\pi$ is an irrational number.
Albedo

• Lambert introduced a term called *albedo* which refers to the ratio of total amount of light reflected off of a surface relative to the light incident on the surface

• The albedo of a material ranges from 0 (no reflectance) to 1 (100% reflectance)

• Albedo is usually used to describe diffuse materials, but can also be useful for other types

• Examples of albedos for some materials:
  – Snow 0.8 - 0.9
  – Concrete 0.55
  – Desert sand 0.45
  – Green grass 0.25
  – Moon 0.12
  – Charcoal 0.04
Diffuse Scattering

• Diffuse scattering is actually caused by light entering the material and then bouncing around off many particles just below the surface.

• After several bounces, the light may make it back out of the surface, but will be in an essentially random direction.
Lambert’s Cosine Law

- Lambert’s law of diffuse reflection says that the intensity of light reflected off of a surface is proportional to the cosine of the angle between the incident light direction and the normal.

\[ L_r = \frac{\rho}{\pi} \cdot L_i \cdot \cos\theta_i \]

- \( L_r \) is the intensity of the reflected light.
- \( L_i \) is the intensity of the incident light.
- \( \rho \) is the albedo (essentially the ‘color’ of the material).
- \( \theta_i \) is the angle between the incident light and the normal.
Microgeometry

• Many of the macroscopic optical properties of materials are due to the microscopic geometry of the surface.

• Many materials are not smooth at a small scale - they have lots of little bumps.

• We can think of a surface as being made up of microfacets, whose normals are described by some sort of distribution function relative to the average surface normal.
Microgeometry

• When we consider *surface roughness*, we can expect that some microfacets will shadow others from the light (*shadowing*), some will block others from view (*masking*), and some will reflect onto others (*interreflection*)

• When seen from a macroscopic point of view, we get the aggregate effect of all of these combined

• The result is a complex distribution of reflected rays coming from a single incident ray

• Many advanced material models are derived from assumptions about the distribution of microfacets, and how light interacts between these facets
Opposition Effect

• The *opposition effect* is the visible increase in brightness when one views a rough surface from the same direction as the light source.
Opposition Effect
Opposition Effect

- The opposition effect is mainly due to a phenomenon called *shadow hiding*
- When light hits a rough, bumpy surface, the lower crevices of the surface can be shadowed by the higher bumps
- These shadows are visible from most angles except when the light is coming from the viewing direction
- In this case, the shadows disappear, resulting in a visibly brighter appearance
- A second phenomenon called *coherent backscatter* is also partly responsible in certain situations when the bumps are roughly the same size as the wavelength of light, however this effect is limited to a much smaller angle
Oren-Nayar Reflectance Model

• Michael Oren and Shree Nayar developed a computer graphics reflectance model in 1993 that attempts to capture the more complex behavior of real diffuse surfaces.

• It is a generalization of Lambert diffuse reflectance for surfaces with bumpy microgeometry.

• It assumes that each microfacet is a pure Lambertian reflector, and it considers both shadow hiding as well as diffuse interreflection between microfacets.

• As a result, it can produce the opposition effect, resulting in more realistic diffuse materials.
Oren-Nayar Reflectance Model

\[
L_r = \frac{\rho}{\pi} \cdot L_i \cdot \cos \theta_i \cdot \left( A + (B \cdot \max(0, \cos(\varphi_i - \varphi_r)) \sin \alpha \cdot \tan \beta) \right)
\]

where

\[
A = 1 - 0.5 \frac{\sigma^2}{\sigma^2 + 0.33}
\]

\[
B = 0.45 \frac{\sigma^2}{\sigma^2 + 0.09}
\]

\[
\alpha = \max(\theta_i, \theta_r)
\]

\[
\beta = \min(\theta_i, \theta_r)
\]

\[
\sigma = \text{roughness (ranges from 0 to around 0.5)}
\]

\[
\varphi_i - \varphi_r = \text{angle between incident and reflected rays projected onto the plane}
\]
Oren-Nayar Reflectance Model

Real Image | Lambertian Model | Oren-Nayar Model

\( \sigma = 0 \) | \( \sigma = 0.1 \) | \( \sigma = 0.3 \)
Oren-Nayar Reflectance Model

• When the surface roughness is equal to 0 (perfectly smooth), the model reduces to the ideal Lambertian diffuse reflection model.

• By the way, the model shown on the previous slide is their ‘qualitative model’, which makes a few simplifying assumptions and reduces the computational cost.

• The original paper also proposed some more elaborate models.

• The original paper is called ‘Generalization of Lambert’s Reflection Model’.
Specular Materials
Specular Materials

• The term *specular* refers to mirror-like reflection
• It isn’t limited to perfectly smooth mirror surfaces however
• Rough metallic surfaces appear shiny, although they don’t act like perfect mirrors
Cook-Torrance Reflectance Model

• The Cook-Torrance reflection model is based on the assumption that the surface is made up of microfacets—each of which is an ideal Fresnel metal reflector

• It was proposed by Michael Cook and Kenneth Torrance in 1981

• The Oren-Nayar model was inspired by this model

• The Cook-Torrance model was based on an earlier model by Torrance and Sparrow from 1967 that evolved from research in radar reflections
Cook-Torrance Reflection Model

• They use a vector called $\mathbf{v}$, which is the view vector, a vector pointing towards the viewer (this is generally going to be $-\mathbf{d}$ vector if $\mathbf{d}$ is the ray direction coming from the camera)
• They also use a vector $\mathbf{L}$, which points towards the light (I’m using a capital L because the lower case l looks like an I)
• They introduce a vector $\mathbf{h}$, called the halfway vector which lies halfway between $\mathbf{v}$ and $\mathbf{L}$
• $\mathbf{h}$ refers to the normal of a hypothetical microfacet that would reflect the light directly towards the viewer

\[
\mathbf{h} = \frac{\mathbf{v} + \mathbf{L}}{|\mathbf{v} + \mathbf{L}|}
\]
Cook-Torrance Model

\[ L_r = L_i \cdot \frac{F \cdot G \cdot D}{\pi (n \cdot L)(n \cdot v)} \]

- \( F \) = Fresnel term
- \( G \) = Geometric attenuation term
- \( D \) = Microfacet distribution function
Fresnel Term

• The Fresnel term $F$ can be the Fresnel equation for metals that we looked at in the previous lecture
• There are also various simplifications that have been proposed
Geometric Attenuation

- *Geometric attenuation* refers to the decrease in light reflection due to both shadowing and masking

\[ G = \min \left( 1, \frac{2(n \cdot h)(n \cdot v)}{(v \cdot h)}, \frac{2(n \cdot h)(n \cdot L)}{(v \cdot h)} \right) \]
Microfacet Distribution Function

- There have been various functions proposed that describe the distribution of microfacets around the average surface normal

- Gaussian: \( D = c e^{-\left(\frac{\alpha}{m}\right)^2} \)

- Beckmann: \( D = \frac{1}{m^2 \cos^4 \alpha} e^{-\left(\frac{\tan^2 \alpha}{m^2}\right)} \)

where

\( \alpha = \cos(n \cdot h) \)

\( m = \text{root mean square slope of microfacets} \)

\( c = \text{an arbitrary constant (?)} \)
Cook-Torrance Reflection Model
Anisotropic Materials
Isotropic vs. Anisotropic

• Lets say that we place a sample of a material flat on a table in front of us, and we have a light source in the room shining at the table.

• Then, without moving the light or changing our viewing angle, we rotate the material on the table.

• If the reflected color we see remains constant as the material rotates, we call the material isotropic (isos=equal/same, tropos=turning/circle).

• If the reflected color changes as the material rotates, we call it anisotropic (an=not).
Isotropic Materials

• Many common materials are isotropic due to the overall random distribution of surface microgeometry combined with random distribution of pigment particles in the medium

• There is no inherent directionality at the microscopic scale which leads to no visible directionality at the macroscopic scale
Anisotropic Materials

- Some materials do have some sort of inherent directionality at the microscopic level
- A common example is brushed metals, where the metal surface is roughened along one particular direction
Anisotropic Materials

• Cloth is another example of an isotropic material, due to the directionality of the threads in the weave
• Satin and velvet are two good examples of complex fabrics
Anisotropic Materials

• Wood and some other natural materials sometimes have a anisotropic appearance due to the directional alignment of cells
Anisotropic Materials

- Hair and fur are also strongly anisotropic
Anisotropic Materials

• To render an anisotropic material, we need more information about a surface than just the position and normal
• We need some sort of information about the orientation of the material in the plane
• Typically, we use tangent vectors, which are in the plane and provide a reference frame for the material orientation
• We will look at this in more detail in a later lecture, as well as looking at some anisotropic reflection models
Other Material Properties
Rough Dielectrics

- We can derive models for rough dielectric surfaces, similar in concept to the Cook-Torrance model for rough metals.
Retroreflection

- *Retroreflection* refers to specular reflection back towards the light source
- It is not the same as the opposition effect, but it is another type of *backscatter* phenomenon
Iridescence

- Iridescence refers to property of some materials changing color depending on the view direction
- This can be caused by different phenomena such as constructive and destructive interference in thin films like bubbles, oil on water, or surface coatings
Diffraction

- Diffraction of light on bumps near the wavelength of light can also cause iridescent effects.
Translucency

- Translucency and subsurface scattering are other common properties that can be captured
- We’ll look at these some more in a later lecture
Material Rendering
Materials

• Because there are a wide range of materials, it is nice to allow a flexible definition of materials, instead of just having one single material model.

• This is a perfect place to take advantage of derived classes and virtual functions in C++.

• We can create a base class Material and derive various specific material types from that.
Material Class

class Material {
public:
    Material();
    virtual void ComputeReflectance(Color &col, Vector3 &in, Vector3 &out,
    Intersection &hit)=0;
};
Colors

• The subject of color is actually quite complex and we will discuss it in a lot more detail in a later lecture

• For now, I just want to mention that it is important to have a Color class that is used in all places where the renderer does operations on colors

• It is tempting to just use a Vector3, since we think of colors as having 3 components (red, green, blue), and we do a lot of similar operations as vectors (addition, scaling, etc.)

• However, as we will see later, colors really should be treated as spectral distributions across all visible wavelengths (not just 3!)

• If we use a Color class and just make it simple RGB for now, then we can later swap in a more sophisticated color class that uses the same interface (Add(), Scale()...) and upgrade to a more realistic color model with minimal effort
class Color {
    public:

        Color();

    void Add(const Color c);
    void AddScaled(const Color c, float s);
    void Scale(float s);
    void Multiply(const Color c);

    void Exponent(); // Computes e^c
    void Gamma(float exp); // Computes pow(c,exp);

    int ToInt(); // Converts to 24 bit RGB
    void FromInt(int c); // Converts from 24 bit RGB
};