RENDERING TUTORIAL III - MATERIALS AND SHADING

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Outline — Materials and Shading

- What is material in Graphics?
- How to render materials (shading)?
- Common materials
- Material acquisition / measurement
- Advanced materials
What is material?

- Material is the **reason of appearance**
What is material?

- Material is **how the light interacts objects**
What is material?

- Material is how the light interacts objects

Diffuse
What is this material?

- Material is **how the light interacts objects**
What is material?

- Material is **how the light interacts objects**

Glass
What is this material?

Material is **how the light interacts objects**
What is material?

- Material is **how the light interacts objects**
Let’s make a material

Specular highlights

Diffuse reflection

Ambient lighting
Let’s make a material — Configuration

- Viewing direction: v
- Light direction: l
- Surface normal: n
- Surface Parameters: (color, shininess)
Let’s make a material — Diffuse Term

Light is scattered uniformly in all directions
• Surface color is the same for all viewing directions

Lambert’s cosine law

Top face of cube receives a certain amount of light
Top face of 60° rotated cube intercepts half the light
In general, light per unit area is proportional to
\[ \cos \theta = \mathbf{l} \cdot \mathbf{n} \]
Let’s make a material — Diffuse Term

intensity here: $I/r^2$

intensity here: $I$
Let’s make a material — Diffuse Term

independent of view direction

\[ L_d = k_d \left( \frac{I}{r^2} \right) \max(0, n \cdot l) \]

illumination from source

diffuse coefficient

diffusely reflected light
Let’s make a material — Diffuse Term

Produces matte appearance

$k_d$
Let’s make a material — Highlight Term

Intensity depends on view direction

• Bright near mirror reflection direction
Let’s make a material — Highlight Term

Close to mirror ⇔ half vector near normal

- Measure “near” by dot product of unit vectors

\[ h = \text{bisector}(v, l) \]
\[ = \frac{v + l}{\|v + l\|} \]

\[ L_s = k_s \left( \frac{I}{r^2} \right) \max(0, \cos \alpha)^p \]
\[ = k_s \left( \frac{I}{r^2} \right) \max(0, n \cdot h)^p \]
Let’s make a material — Highlight Term

Increasing $p$ narrows the reflection lobe
Let’s make a material — Highlight Term

\[ L_s = k_s \left( \frac{I}{r^2} \right) \max(0, n \cdot h)^p \]
Let’s make a material — Ambient Term

Does not depend on anything

• Add constant color to account for disregarded illumination and fill in black shadows

\[ L_a = k_a I_a \]
Let’s make a material — Blinn-Phong

$$L = L_a + L_d + L_s$$

$$= k_a I_a + k_d (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{l}) + k_s (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{h})^p$$
Add some color — texture mapping

- A texture is an image that specifies spatially-varying colors (Kd).
Applying the material

Shading

- In Merriam-Webster Dictionary

  shad·ing, [ˈʃeɪdɪŋ], noun

  The darkening or coloring of an illustration or diagram with parallel lines or a block of color.

- By Lingqi

  (1) The process of applying a material to an object.
  (2) The process of local rendering.
Shading == local rendering

No shadows, no indirect illumination
Shading methods

What caused the shading difference?
Shade each triangle (flat shading)

**flat shading**
- Triangle face is flat — one normal vector
- Not good for smooth surfaces
Shade each vertex (Gouraud shading)

**Gouraud** shading

- Interpolate colors from vertices across triangle
- Each vertex has a normal vector
Shade each pixel (Phong shading)

**Phong** shading

- Interpolate normal vectors across each triangle
- Compute full shading model at each pixel
- Not Phong material model
In fact...

As long as there are enough faces / vertices, any shading method works fine.
Textures can affect shading!

- Textures doesn’t have to only represent colors
  - What if it stores the height / normal?
  - Bump / normal mapping
- **Fake** the detailed geometry

Relative height to the underlying surface

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**DEPENDANCE ON SCALE**

One feature of the perturbation calculation is that the perturbation amount is not invariant with the scale at which the object is drawn. If the X, Y, and Z surface definition functions are scaled up by 2, then the normal vector length, $N$, scaled up by a factor of 4, while the perturbation amount, $D$, is only scaled by 2. This effect is due to the fact that the object is being scaled but the displacement function $F$ is not. (Scale changes due to the object moving nearer or farther from the viewer in perspective space do not affect the size of the wrinkles, only scale changes applied directly to the object.) The net effect of this is that if an object is scaled up, the wrinkles flatten out. This is illustrated in figure 9.

![Figure 9 - stretched Bump Texture](image)

This effect might be desirable for some applications but undesirable for others. A scale invariant perturbation, $D'$, must scale at the same rate as $N$. An obvious choice for this is $D' = a \frac{D_{INI}}{D_{ID}}$ where $a$ is independent of scales in $P$. The value of $a$ is then the tangent of the effective rotation angle.

$\tan^+ = \frac{D'_{1}}{lN_{1}} = a$

This can be defined in various ways. One simple choice is a generalization from the simple, flat unit square patch $X(u,v) = u$, $Y(u,v) = v$, $Z(u,v) = 0$. For this patch the original normal vector perturbation gives $N = (0,0,1)$, $D = (-F_u,-F_v,0)$, $\tan^+ = \sqrt{F_u' + F_v'}$. Here the value of $a$ is purely a function of $F$. Use of the same function for arbitrary patches corresponds to a perturbation of $D' = a \sqrt{F_u' + F_v'}$, $D' = a \frac{D}{lN_{1}/lD_{1}}$, $N'' = N + D'$.

The texture defining function $F$ is now no longer being used as an actual displacement added to the position of the surface. It just serves to provide (in the form if its derivatives) a means of defining the rotation axis and angle as functions of $u$ and $v$.

**5. ALIASING**

In an earlier paper, the author described the effect of aliasing on images made with color texture mapping. The same problems can arise with this new form. That is, undesirable artifacts can enter the image in regions where the texture pattern maps into a small screen region. The solution applied to color textures was to average the texture pattern over the region corresponding to each picture element in the final image. The bump texture definition function, however, does not have a linear relationship to the intensity of the final image. If the bump texture is averaged, the effect will be to smooth out the bumps rather than average the intensities. The correct solution to this problem would be to compute the intensities at some high sub-pixel resolution and average them. Simply filtering the bump function can, however, reduce the more offensive artifacts of aliasing. Figure 10 shows the result of such an operation.

![Figure 10 - Filtering Bump Texture](image)
Textures can affect shading!

- Displacement mapping — a more advanced approach
- Actually subdivides the mesh and **modify** the geometry
Physically-based materials
What is material?

Recap: the Rendering Equation

\[ L_o(x, \omega_o) = L_e(x, \omega_o) + \int_{H^2} L_i(x, \omega_i) f_r(x, \omega_i \rightarrow \omega_o) \cos \theta_i \, d\omega_i \]

outgoing radiance  emission  incident radiance  BRDF (Bidirectional Reflection Distribution Function)
BRDF (Bidirectional Reflection Distribution Function)

At any position, it represents how much light is reflected into each outgoing direction from each incoming direction.

- 4D function
  - 2D for incoming direction
  - 2D for outgoing direction
Material == BRDF
Material == BRDF

Because BRDF defines **how the light interacts objects**

- **Diffuse**
- **Glossy**
- **Specular**
Microfacet BRDF
Microfacet model in the real world
Microfacet Theory

- Rough surface
  - Macroscale: flat & rough
  - Microscale: bumpy & specular

- Individual elements of surface act like mirrors
- Known as Microfacets
- Each microfacet has its own normal
Microfacet BRDF

Key: the **distribution** of microfacets’ normals

- Concentrated $\iff$ glossy
- Spread $\iff$ diffuse
Microfacet BRDF

What kind of microfacets reflect \( \mathbf{w}_i \) to \( \mathbf{w}_o \)?
(hint: microfacets are mirrors)

\[ f(\mathbf{i}, \mathbf{o}) = F(\mathbf{i}, \mathbf{h})G(\mathbf{i}, \mathbf{o}, \mathbf{h})D(\mathbf{h}) \]

- Fresnel term
- Shadowing-masking term
- Distribution of normals

\[ 4(\mathbf{n}, \mathbf{i})(\mathbf{n}, \mathbf{o}) \]
Fresnel Reflection / Term

Reflectance depends on incident angle (and polarization of light)

This example: reflectance increases with grazing angle
Fresnel Term (Dielectric, $\eta = 1.5$)
Fresnel Term (Conductor)
Microfacet BRDF: Examples

[Autodesk Fusion 360]
Isotropic / Anisotropic Materials (BRDFs)

- So far, Point light + Metal = Round / Elliptical highlight
- What can we see inside an elevator?

Inside an elevator
Isotropic / Anisotropic Materials (BRDFs)

- Key: **directionality** of underlying surface

![Isotropic Surface (normals)](image1)

![BRDF (fix wi, vary wo)](image2)

![Anisotropic Surface (normals)](image3)

![BRDF (fix wi, vary wo)](image4)
Anisotropic BRDF: Brushed Metal

- How is the pan brushed?
Anisotropic BRDF: Nylon

[Westin et al. 1992]
Anisotropic BRDF: Velvet

[Westin et al. 1992]
Anisotropic BRDF: Velvet
Material Capture
(BRDF measurement)
Image-Based BRDF Measurement
Measuring BRDFs: gonioreflectometer

Spherical gantry at UC San Diego
Tabular Representation

\[(\theta_i, \theta_o, |\phi_i - \phi_o|)\]

- Store regularly-spaced samples in
- Better: reparameterize angles to better match specularities
- Generally need to resample measured values to table
- Very high storage requirements

MERL BRDF Database
[Matusik et al. 2004]
90*90*180 measurements
Before we proceed

- A brief summary
  - Material == BRDF
    - [Non-physically-based] Blinn-Phong material
    - [Physically-based] Microfacet material
  - Material acquisition / measurement
  - Shading methods
    - Flat (triangle) / Gouraud (vertex) / Phong (pixel)
  - Texture mapping, bump/normal/displacement mapping
Advanced materials
(including state of the art research)

- Detailed / glinty material (non-statistical BRDF)
- Hair / fur (BCSDF)
- Participating media
- Translucent material (BSSRDF)
- Cloth
- Granular material
- Procedural appearance
- ...

Detailed / Glinty material
Motivation

[Car rendered in NVIDIA Iray]

[Mouse rendered in Autodesk 3DS Max]
Real world is more complicated

[Real photograph of a car] [Real video of a mouse]
Why details?

Microfacet model
Why details?

[Yan et al. 2014, 2016]
Why details?

[Yan et al. 2014, 2016]
Recap: Microfacet BRDF

Surface = Specular microfacets + statistical normals

$$f(i, o) = \frac{F(i, h)G(i, o, h)D(h)}{4(n, i)(n, o)}$$

NDF: Normal Distribution Function

$h$: half vector
Statistical NDF vs. Actual NDF

Distribution of Normals (NDF)

What we have
(microfacet — statistical)

What we want
Define details

Normal map resolution:
\( \approx 200K \times 200K \)
Define details
Different details

Metallic flakes
Ocean waves
Detailed / Glinty Material: Application

[Rise of the Tomb Raider. 2016 Square Enix]
Hair and fur
Hair Appearance
Kajiya-Kay Model

[Image courtesy of Chiwei Tseng]
Kajiya-Kay Model

[Yuksel et al. 2008]
Marschner Model

[Image courtesy of Chiwei Tseng]
Marschner Model

- Glass-like cylinder

- 3 types of light interactions:
  R, TT, TRT
  (R: reflection, T: transmission)

[Marschner et al. 2003]
Marschner model

[Marschner et al. 2003] [d’Eon et al. 2011]
Hair Appearance Model: Application
Hair Appearance Model: Application

[Zootopia. 2016 Disney]
Even more advanced: Double Cylinder Model

[War for the Planet of the Apes. 2017 movie]
(2018 Oscar Nominee for Best Visual Effects)
Participating Media
Participating Media: Fog

[Novák et al. 2012]
Participating Media: Cloud
Participating Media

- At any point as light travels through a participating medium, it can be (partially) absorbed and scattered.
Participating Media: Application

[Big Hero 6, 2014 Disney]
Participating Media: Application

[Assassin’s Creed Syndicate. 2015 Ubisoft]
Participating Media: Demo
Translucent Material
(a specific participating medium)
Translucent Material: Jade
Translucent Material: Jellyfish
Subsurface Scattering

- Visual characteristics of many surfaces caused by light exiting at different points than it enters
  - Violates a fundamental assumption of the BRDF

- Different from transparent

[Jensen et al 2001]

[Donner et al 2008]
Scattering Functions

- BSSRDF: generalization of BRDF; exitant radiance at one point due to incident differential irradiance at another point:
  \[ S(x_i, \omega_i, x_o, \omega_o) \]

- Generalization of rendering equation: integrating over all points on the surface and all directions (!)
  \[ L(x_o, \omega_o) = \int_A \int_{H^2} S(x_i, \omega_i, x_o, \omega_o) L_i(x_i, \omega_i) \cos \theta_i \, d\omega_i \, dA \]
BRDF

[Jensen et al. 2001]
BSSRDF

[Jensen et al. 2001]
BRDF vs BSSRDF

[Jensen et al. 2001]
BSSRDF: Application

https://cgelves.com/10-most-realistic-human-3d-models-that-will-wow-you/

[Artist: Teruyuki and Yuka]
[Artist: Hyun Kyung]
[Artist: Dan Roarty]
Cloth
Cloth

- A collection of twisted fibers!
- Two levels of twist

- Woven or knitted
Cloth: Render as Surface

- Given the weaving pattern, calculate the overall behavior
- Render using a BRDF

[Sadeghi et al. 2013]
Render as Surface — Limitation

[Westin et al. 1992]
Cloth: Render as Participating Media

- Properties of individual fibers & their distribution -> scattering parameters
- Render as a participating medium

[Jakob et al. 2010] [Schroder et al. 2011]
Cloth: Render as Actual Fibers

- Render every fiber explicitly!
Cloth: Application

[The BFG. 2016 Disney]
Granular Material
Granular Material

- What is granular material?

[Meng et al. 2015]
Granular Material

- Can we avoid explicit modeling of all granules?
  - Yes with **procedural** definition.
Granular Material

[Meng et al. 2015]
Granular Material: Application
Procedural Material
Procedural Model

- Can we define details without textures?
  - Yes! Compute a noise function on the fly.

[Lagae et al. 2009]
Procedural Model

- Can we define details without textures?
  - Yes! Compute a noise function on the fly.
  - 3D noise -> internal structure if cut or broken

[Lagae et al. 2009]
Procedural Model

- Can we define details without textures?
  - Yes! Compute a noise function on the fly.
  - Thresholding
    (noise $\rightarrow$ binary noise)

Example:

```python
if noise(x, y, z) > threshold:
    reflectance = 1
else:
    reflectance = 0
```

[Lagae et al. 2009]
Procedural Model

- Complex noise functions can be very powerful.
Procedural Model

- Complex noise functions can be very powerful.
Procedural Model

- Complex noise functions can be very powerful.
Procedural Model

- Complex noise functions can be very powerful.
Thank you!