Overview

- Modeling the interaction of light with surfaces to determine the final color & brightness of the surface
- Global illumination models
- Local illumination models
Why Do We Need Shading

• Suppose we build a model of a sphere using many polygons and color it with `glColor`. We get something like

• But we want

Shading

• Why does the image of a real sphere look like this?

• Light-material interactions cause each point to have a different color or shade

• Need to consider
  • Light sources
  • Material properties
  • Location of viewer
  • Surface orientation
Scattering

- Light strikes A
  - Some scattered
  - Some absorbed
- Some of scattered light strikes B
  - Some scattered
  - Some absorbed
  - Some of this scattered light strikes A and so on

Light-Material Interaction

- Light that strikes an object is partially absorbed and partially scattered (reflected)
- Amount reflected determines the color and brightness of the object
  - A surface appears red under white light because the red component of the light is reflected and the rest is absorbed
- Reflected light is scattered in a manner that depends on the smoothness and orientation of the surface
Light Sources

General light sources are difficult to work with because we must integrate light coming from all points on the source.

Simple Light Sources

- Point source
  - Model with position and color
  - Distant source = infinite distance away (parallel)
- Spotlight
  - Restrict light from ideal point source
- Ambient light
  - Same amount of light everywhere in scene
  - Can model contribution of many sources and reflecting surfaces
Surface Types

- The smoother a surface, the more reflected light is concentrated in the direction a perfect mirror would reflected the light
- A very rough surface scatters light in all directions

Global Illumination Models

- Interaction of light from all the surfaces in the scene
- Examples
  - Kajiya’s rendering equation
  - Recursive ray-tracing
  - Radiosity
Local Illumination Models

- The lights, the observer position, and the object characteristics determine its final brightness and color

Local Illumination Models

- Light Source Characteristics
  - Color, intensity, direction, angle of illumination, geometry
- Material Characteristics
  - Reflection properties, color, transparency, refraction, micro-surface geometry
- Types of Light
  - Ambient, Diffuse, Specular
Simple Local Illumination Model

- A simple model that can be computed rapidly
- Has three components
  - Diffuse
  - Specular
  - Ambient
- Uses four vectors
  - To source
  - To viewer
  - Normal
  - Perfect reflector

Representing Materials

- **Ambient**: scattered light from all directions scattered in all directions (fudge factor)
- **Diffuse**: light from a particular direction that is scattered in all directions
- **Specular**: reflected light from a particular direction
- **Emissive**: additive light from material
Ambient Light

- **Definition**
  - The light that is the result from the light reflecting off other surfaces in the environment that strikes all the surfaces in the scene from all directions
  - This is independent of direction
  - The equation for the amount of light received by a surface is
    \[ I = I_a k_a \]
  - \( I_a \) is the intensity of the ambient light in the scene
  - \( k_a \) is the ambient-reflection coefficient which determines the amount of ambient light reflected from a given surface. 0 <= \( k_a \) <= 1

Diffuse Light

- **Definition**
  - The direct illumination that an object receives from a light source that it reflects equally in all directions
  - Dull surfaces exhibit diffuse reflection
    - Also called Lambertian Reflection from Lambert's Law
  - Brightness of object is independent of observer position
    - Reflect equally in all directions
Diffuse Light

- Lambert's Law
  - \( I_d = I_p \cos(\theta) \)
  - where \( I_p \) is the point light source's intensity
  - \( I_d = I_p k_d (N \cdot L) \)
  - if \( N \) & \( L \) are normalized, \( 0 \leq k \leq 1 \)
- Combined with ambient light,
  - \( I = I_a k_a + I_p k_d (N \cdot L) \)

Effect of Ambient and Diffuse

![Diagram showing the effect of ambient and diffuse light]
Specular Reflection

- Bright spots on objects (hot spots)
- If you look around, these move as you move around
- Specular reflection is dependent on the observer position

Specular Reflection

- The half-angle vector \( H = L + V \), normalized:
  - Blinn-Phong formulation
  - The direction of maximum highlights
- If the normal is aligned with \( H \), you will have maximum highlights. As you move away from this, it will decrease.
Specular Reflection

- Phong's model (or Blinn-Phong model)
  - $I_s = k_s(N \cdot H)^n$
  - $0 \leq k_s \leq 1$, property of the material
  - $n \geq 1$, Good choice is 50

Effect of Specular Exponent

![Phong Specular Reflection Functions](image)
Effect of Diffuse and Specular

Effect of Specular Exponent
Final Illumination Model

\[ I = I_a k_a + I_p k_d (N \cdot L) + k_s (N \cdot H)^n \]
More Specular Examples

Implementing Phong Specular Illumination

- Formula for intensity
  - \( d_a = l_p k_s + l_p k_d \ (N \cdot L) \)
  - \( I = d_a + (1 - d_a) \ l_p k_s \ (N \cdot H)^n \)
  - Add specular if \( N \cdot L > 0 \) and \( N \cdot H > 0 \)
Implementing Phong Specular Illumination

- Examples of illumination types

Ambient Illumination

Diffuse plus Ambient Illumination
1 color per polygon

Specular plus Diffuse plus Ambient Illumination
1 color per polygon

Lights and Illumination

- Colored Lights
  - The previous formulas assumed that we had white light
  - The color of the light source will, of course, affect the color of light reflected from a surface
  - Remember, the color of an object is a function of the incident wavelengths of light that it reflects
Lights and Illumination

• Examples of Lighting Effects

- Single White Light
- Single Red Light Source
- Red Light Source plus a Blue Light Source
- Red Light Source, Green Light Source, Blue Light Source

Lights and Illumination with Phong Smooth Shading

- Normal Illumination
- Angular Fall-Off with exponent = 800
- Angular Cut-off (spotlight)

4 light sources of different colors and fall-offs
Advanced Illumination

• Illumination review
  • Ambient -- approximate global illumination effects
  • Diffuse -- Lambert's Law -- absorbed and reradiated equally in all directions (depend on wavelength, independent of observer)
  • Specular -- reflects off surface => color of light in many cases is color of object
    • Need advanced model of light reflecting off surface to look right
    • Based on bidirectional reflectance

Advanced Illumination

• Cook-Torrance uses
  \[ \rho_s = \frac{F_r}{\pi} \frac{DG}{(N \cdot V)(N \cdot L)} \]
  • \( D \) is distribution function of microfacet orientations
  • \( G \) is geometrical attenuation factor -- masking and shadowing effects of the microfacets on each other
  • \( F_r \) is the Fresnel term

• Blinn's model
  \[ \rho_s = \frac{DGF}{(N \cdot V)} \]
Advanced Specular Illumination Models

- 3 Main components:
  - Microfacet model
  - Roughness term
  - Fresnel term – wavelength dependent reflection

Advanced Specular Illumination Models: Fresnel Term

- Amount of reflected and refracted light at an interface is a function of
  - Wavelength of incident light
  - Geometry of the surface
  - Angle of incidence
- Effects summarized in Fresnel’s formulas
Cook-Torrance Result

- Gold

- Copper
Improved Diffuse Reflection

- Oren and Nayar developed a surface roughness model for diffuse reflection similar to the Cook-Torrance model
- Used for textured surfaces
- What area was this research for?
  - Computer Vision

Oren-Nayar Results
Review of Local Illumination

- Previously, we handled only local / direct illumination
- In reality, the light hitting a given point on an object is a combination of direct and indirect illumination – 4 types

Global Illumination & Radiosity
Global Illumination Effects

shadow

multiple reflection

translucent surface

Global Illumination

- Global illumination must consider 4 types of light transport between pairs of surfaces
  1. Diffuse to diffuse
  2. Specular to diffuse
  3. Diffuse to specular
  4. Specular to specular
- All must be considered at once for each light propagation path
Radiosity - Overview

- Goral et. al., 1984
  - Illumination model based on principles from radiative heat transfer
  - View independent
  - Diffuse illumination only
  - Simulates color bleeding

Radiosity – Overview (cont.)

- Subdivide environment into patches
  - May correspond to the polygons in the model
  - Area over which illumination is constant
  - Compute diffuse-diffuse illumination solution at this resolution
  - Need to solve \textit{steady state} $n \times n$ radiative energy transport equations
Patches

Rendered Image

Overview

• Radiosity, $B$, of a patch
  • Total rate of energy leaving a patch
  • $B = \text{flux} = \text{energy} / \text{unit area} / \text{unit time}$

• Form factor, $F_{ij}$
  • Geometrical relationship between two patches $P_i$ and $P_j$
  • Percent of energy leaving $P_i$ that arrives at $P_j$
  • Depends on angle and distance

\[
B_i = E_i + \rho_i \sum_{j=1}^{n} B_j F_{ij} A_j
\]

\[
B_i = E_i + \rho_i \sum_{j=1}^{n} B_j F_{ij}
\]
Form Factor Issues

- High cost to compute: nontrivial
- $F_{ij}$ also must look at all other patches (shadowing/blocking)
  - Hemicube solves the above problems together
- Gathering algorithm requires storage and calculation of form factor matrix $\Rightarrow$ large storage for matrix

Form Factors – Hemicube Approximation

- The contribution of each cell on the surface of the hemicube to the form factor value is computed. This is the delta form factor for each cell.
- The polygon is projected onto the hemicube.
- The delta form factors for the covered cells are summed to get the approximation to the true form factor.
Radiosity Equations- Some Important Points to Note

- Matrix solution can be viewed at each iteration as gathering light in from all patches
- B_i's can then be used in renderer for illumination (color) at each patch \( n \) interpolated to average vertex intensities
Classical Radiosity Stages

- Discretize scene
- Calculate form factors
- Solve Radiosity Matrix
- Rendering Viewing

- Change geometry
- Change to form factor characteristics
- Change wavelength dependent characteristics
- Change view

Radiosity Stages

- Computational Bottleneck
  - Form factor calculations: $O(n^2)$
- Discretization resolution determines accuracy of solution
  - Need finer resolution where radiosity gradient is high
Progressive Refinement

- Progressively increase the realism
- In traditional "gathering" method, a solution for one row produces the radiosity for a single patch

- Estimate of radiosity of patch $i$ based on current value of all other patches $\Rightarrow$ gathering illumination

$$B_i = E_i + \rho_i \sum_{j=1}^{n} B_j F_{ij}$$

Progressive Refinement

- Shooting method
- At each step, radiosity from a patch is shot onto all other patches $\Rightarrow$ entire image gets better at each step
- For all $j$,

$$B_j = B_j + B_i \left( \rho_j F_{ji} \right)$$

where $F_{ji} = F_{ij} A_i / A_j$
Progressive Refinement

- Shooting Algorithm: Improvements
  - Order patches by $B_j$, so shoot brightest patches first
  - Add an ambient approximation
    - to keep illumination of scene nearly constant
    - decrease as solution gets more accurate

$$I_a = \mu \sum_{j=1}^{N} \Delta B_j F_{j(\text{estimated})}$$

$\mu$: overall reflection factor

Progressive Radiosity Example

The above images show increasing levels of global diffuse illumination. From left to right: 0 bounces, 1 bounce, 3 bounces.
More Examples

More Examples
Global Illumination

- Radiosity does
  - diffuse to diffuse correctly
- Ray tracing does
  - specular to specular correctly
  - diffuse to specular empirically
  - specular to diffuse can be added in by a 2 pass method:
    - Pass1 -- backward trace light from source to environment
    - Pass2 -- normal tracing using illumination from Pass1

Global Illumination

- Post processing radiosity solution with ray-tracing won't work!
  - Why?
    - some specular may be result of earlier diffuse reflection
    - some diffuse may be re-reflected specular
Global Illumination

- Combining Ray Tracing and Radiosity -- Two pass method:
  - Pass 1: Enhanced Radiosity - View Independent [Rushmerier 90]
    - handles:
      - diffuse – diffuse
      - specular – diffuse
  - Pass 2: "Enhanced Ray-Tracing" -- View Dependent
    - Specular-specular -- normal ray tracing
    - Diffuse-specular
      - Integrate light arriving at reflection point by using a square pyramid in the direction of specular bump
      - Divide into grid and do a z-buffer at low resolution to see what is visible -- use radiosity calculated intensities here
      - can do recursively
    - Only handles special cases of specular transmission and specular-diffuse reflection
Overview of Photon Mapping

- Why use photon mapping?
  - Direct illumination
  - Global illumination

Another option is radiosity. Radiosity solves diffuse to diffuse well. How about specular to diffuse, specular to specular?

Overview of Photon Mapping

- What is photon mapping?
- Photon:
  - Particle of light that carries flux (i.e., power, in Watts).
  - e.g., Given $k$ Watt light bulb, emit $N$ photons. Then each photon has the power $k/N$ Watts.
Overview of Photon Mapping

• What is photon mapping? (cont.)
• Photon map:
  – A global data structure, e.g. kd-tree, which stores illumination information (power, position, incident direction) of photons.
  – Can be seen as a cache of light paths

Overview of Photon Mapping

• What is photon mapping (cont.)
• Photon mapping:
  • A two-pass method for computing global illumination.
  • The first pass builds the photon map by tracing photons from each light source.
  • The second pass renders the scene using the photon map.
**Light Transport in Space**

- Light transport in space involves the interaction of light with surfaces, such as reflections and transmissions.

**Light Transport Equation (LTE)**

- The outgoing radiance at any surface location in a model is:
  \[ L_O(x, \omega) = L_e(x, \omega) + L_r(x, \omega) \]
  - \( L_e \) is the emitted radiance.
  - \( L_r \) is the reflected radiance.

- The total reflected radiance is:
  \[ L_r(x, \omega) = \int_{\Omega} f_r(x, \omega', \omega)L_i(x, \omega')(\omega' \cdot \hat{n})d\omega' \]
  - \( f_r \) is the BRDF.
  - \( L_i \) is the incident radiance.
Caustic from a glass sphere

10000 photons / 50 photons in radiance estimate

Reflection inside a metal ring

50000 photons / 50 photons in radiance estimate
Caustic on glossy surface

340000 photons / ~100 photons in radiance estimate

Global illumination

100000 photons / 50 photons in radiance estimate
Global illumination

500,000 photons / 500 photons in radiance estimate

Box

200,000 global photons / 50,000 caustic photons
Box: Global Photons

200000 global photons

Fractal Box

200000 global photons, 50000 caustic photons