Local Illumination
- Object illuminations are independent
- No light scattering between objects
- No real shadows, reflection, transmission
- OpenGL pipeline uses this

Global Illumination
- Ray tracing (highlights, reflection, transmission)
- Radiosity (surface interreflections)
- Photon mapping
- Precomputed Radiance Transfer (PRT)

Object Space:
- Graphics pipeline: for each object, render
  - Efficient pipeline architecture, real-time
  - Difficulty: object interactions (shadows, reflections, etc.)

Image Space:
- Ray tracing: for each pixel, determine color
  - Pixel-level parallelism
  - Difficulty: very intensive computation, usually off-line

First idea: Forward Ray Tracing
- Shoot (many) light rays from each light source
- Rays bounce off the objects
- Simulates paths of photons
- Problem: many rays will miss camera and not contribute to image!
- This algorithm is not practical

Backward Ray Tracing
- Shoot one ray from camera through each pixel in image plane
Generating Rays

- Camera is at (0,0,0) and points in the negative z-direction
- Must determine coordinates of image corners in 3D

Determining Pixel Color

1. Phong model (local as before)
2. Shadow rays
3. specular reflection
4. Specular transmission

Steps (3) and (4) require recursion.

Shadow Rays

- Determine if light "really" hits surface point
- Cast shadow ray from surface point to each light
- If shadow ray hits opaque object, no contribution from that light
- This is essentially improved diffuse reflection
Phong Model

- If shadow ray can reach to the light, apply a standard Phong model

\[ I = L \left( k_d (l \cdot n) + k_i (r \cdot v)^q \right) \]

Where is Phong model applied in this example?

Which shadow rays are blocked?

Reflection Rays

- For specular component of illumination
- Compute reflection ray (recall: backward!)
- Call ray tracer recursively to determine color

Angle of Reflection

- Recall: incoming angle = outgoing angle
- \( r = 2(l \cdot n) n - l \)
- Compute only for surfaces that are reflective

Reflections Example

Transmission Rays

- Calculate light transmitted through surfaces
- Example: water, glass
- Compute transmission ray
- Call ray tracer recursively to determine color
**Transmitted Light**

- Index of refraction is speed of light, relative to speed of light in vacuum
  - Vacuum: 1.0 (per definition)
  - Air: 1.000277 (approximate to 1.0)
  - Water: 1.33
  - Glass: 1.49
- Compute $t$ using Snell's law
  - $\eta_i = \text{index for upper material}$
  - $\eta_t = \text{index for lower material}$

$$\frac{\sin(i)}{\sin(t)} = \eta_i = \eta_t$$

**Translucency**

- Most real objects are not transparent, but blur the background image
- Scatter light on other side of surface
- Use stochastic sampling (called distributed ray tracing)

**The Ray Casting Algorithm**

- Simplest case of ray tracing
  1. For each pixel $(x,y)$, fire a ray from COP through $(x,y)$
  2. For each ray & object, calculate closest intersection
  3. For closest intersection point $p$
    - Calculate surface normal
    - For each light source, fire shadow ray
    - For each unblocked shadow ray, evaluate local Phong model for that light, and add the result to pixel color
- Critical operations
  - Ray-surface intersections
  - Illumination calculation

**Transmission + Translucency Example**

- www.povray.org

**Recursive Ray Tracing**

- Also calculate specular component
  - Reflect ray from eye on specular surface
  - Transmit ray from eye through transparent surface
- Determine color of incoming ray by recursion
- Trace to fixed depth
- Cut off if contribution below threshold

**Ray Tracing Assessment**

- Global illumination method
- Image-based
- Pluses
  - Relatively accurate shadows, reflections, refractions
- Minuses
  - Slow (per pixel parallelism, not pipeline parallelism)
  - Aliasing
  - Inter-object diffuse reflections require many bounces
Raytracing Example I
www.yafaray.org

Raytracing Example II
www.povray.org

Raytracing Example III
www.yafaray.org

Raytracing Example IV
www.povray.org

Summary
• Ray Casting
• Shadow Rays and Local Phong Model
• Reflection
• Transmission

• Next lecture: Geometric queries