CS 6620
Advanced Interactive Rendering

Spring 2009

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Information

- Kavita Bala (kb@cs.cornell.edu)
  - Upson 5142
- AA: Melissa Totman (mtotman@cs.cornell.edu)
- Lectures: Mon and Wed, 1:25-2:40
  - UP 111

What is this course about?

- Practical state-of-the-art rendering algorithms
  - Industry: simulation, games, movies
- Assumptions
  - Exposure to ray tracing
  - 465/466
  - If not, talk to me

Pre-req: Ray Tracing

- Introduced in 1980 by Turner Whitted
- Trace rays from eye into scene
  - Backward ray tracing

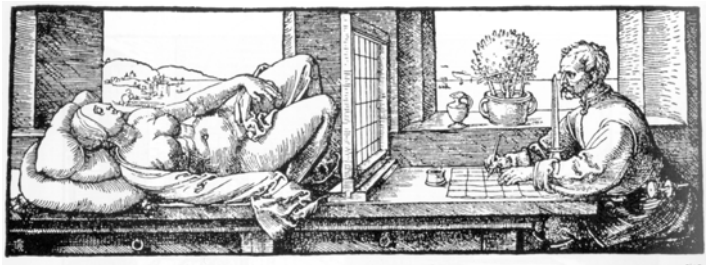
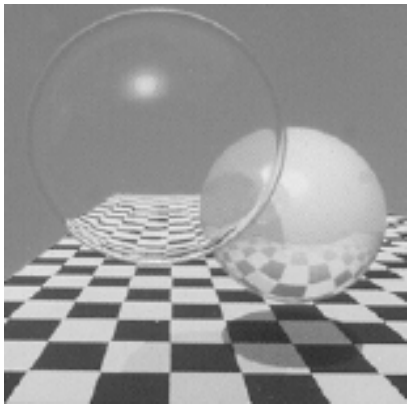


Fig. 6.9 Albrecht Dürer, illustration showing a 'veil' being used to draw a perspective image of a naked woman. From his *Underweysung der Messung mit dem Zirkel und Richtscheyt* (Nuremberg, 1525), Book 3, Figure 67.

Insights

- Find visible objects
- Shade visible points
  - Shadows
  - Reflections
  - Refractions

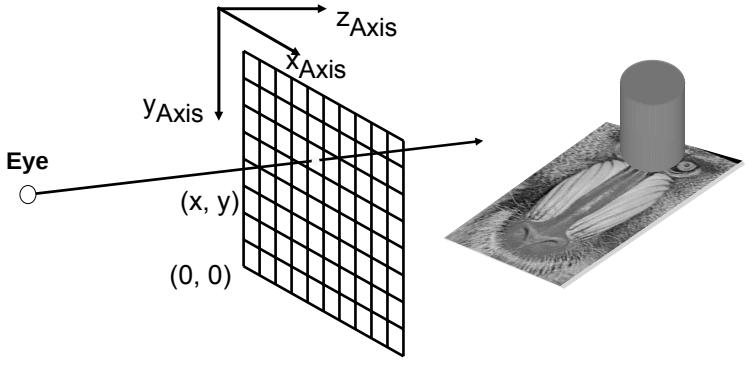


Whitted 1980: First ray traced image

- First global illumination algorithm!

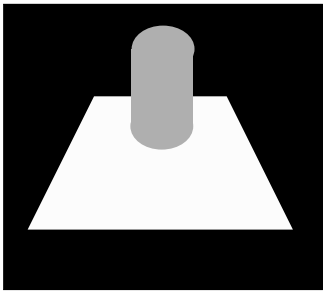
Basic Algorithm - View Rays

- Rays are cast from the eye point through each pixel in the image



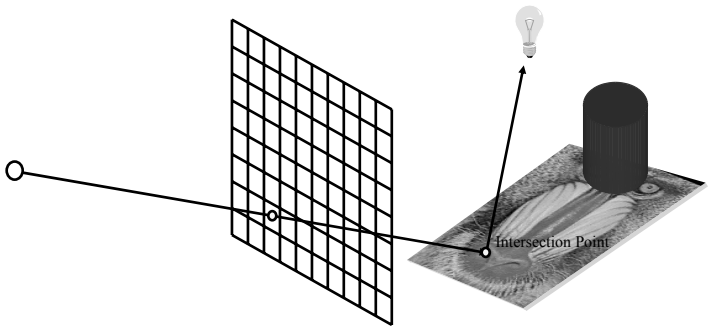
Visibility Determination

- Intersect eye ray with all objects in scene
  - Find closest object
  - Z-buffer was existing algorithm
- No intersection? Show background color



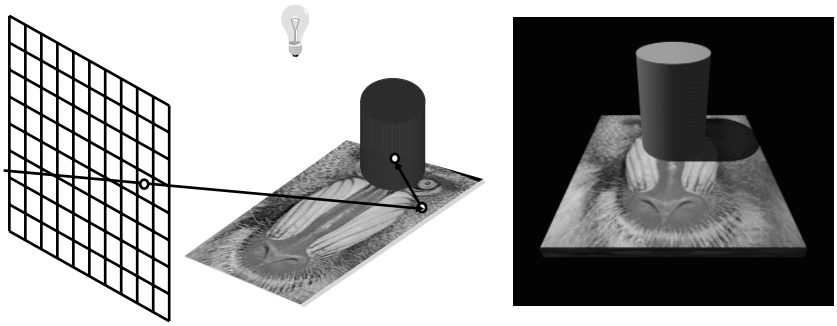
Basic Algorithm - Shadows

- Cast ray from the surface point to each light source: shadow rays



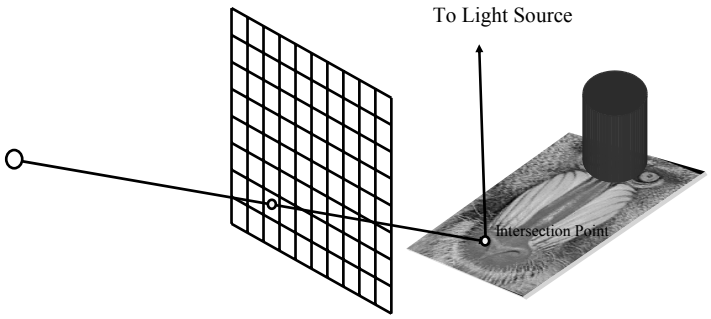
Basic Algorithm - Shadows, cont.

- Shadow ray is blocked = shadow



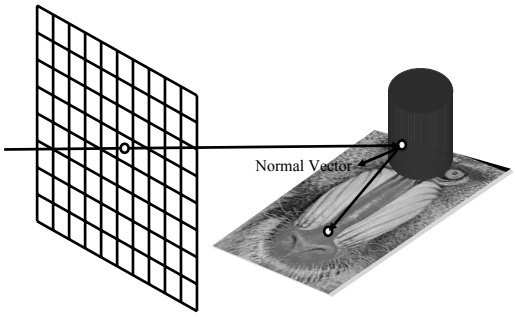
Basic Algorithm – Shadow Rays

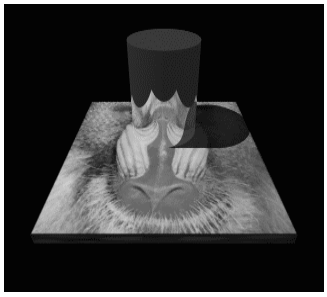
- If shadow ray not blocked, calculate color based on shading model



Basic Algorithm - Reflections

- If object specular, shoot secondary reflected rays





Ray Tracing

Advanced State-of-the-Art Rendering

- Practical algorithms used in industry
- High-quality rendering

Advanced State-of-the-Art Rendering

- High-quality rendering
  - Monte Carlo rendering
  - Photon mapping
  - Lightcuts
- Interactive rendering
  - Radiosity and variants
  - Shadow algorithms
  - GPU rendering and global illumination
  - Precomputed radiance transfer (PRT)

Advanced State-of-the-Art Rendering

- Handling Complexity
  - Acceleration Structures
  - Scalable Rendering
  - Interactive Ray Tracing
- Rendering in movies
  - Final render
  - Cinematic relighting

Advanced State-of-the-Art Rendering

- Trends in rendering research
  - Accuracy
  - Scalable rendering
  - Perceptually-Based rendering

Administration

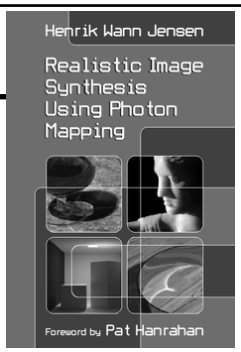
- 1 exam
- 1-2 assignments
- 1 paper presentations
  - Paper report
- Final project (in groups)
  - Project proposal
  - Final demonstration

Groups or Alone

- Groups or work alone

Book

- Photon Mapping book
  - Jensen

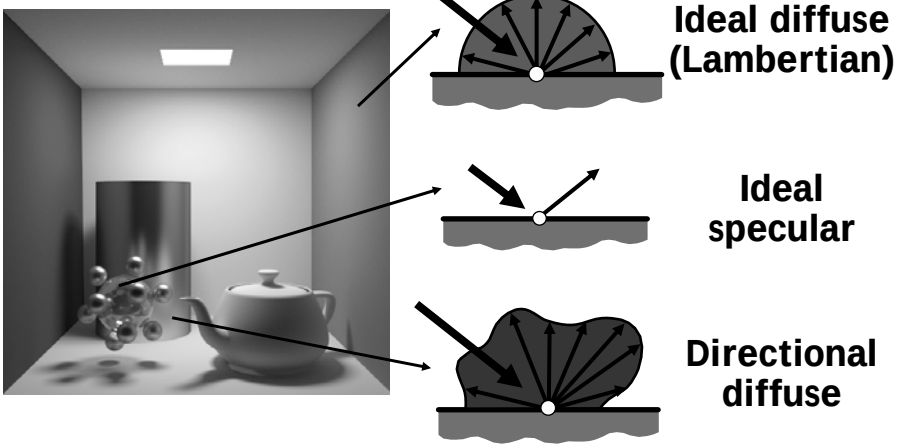


- Advanced Global Illumination
  - Dutre, Bala, Bekaert
    2nd Edition

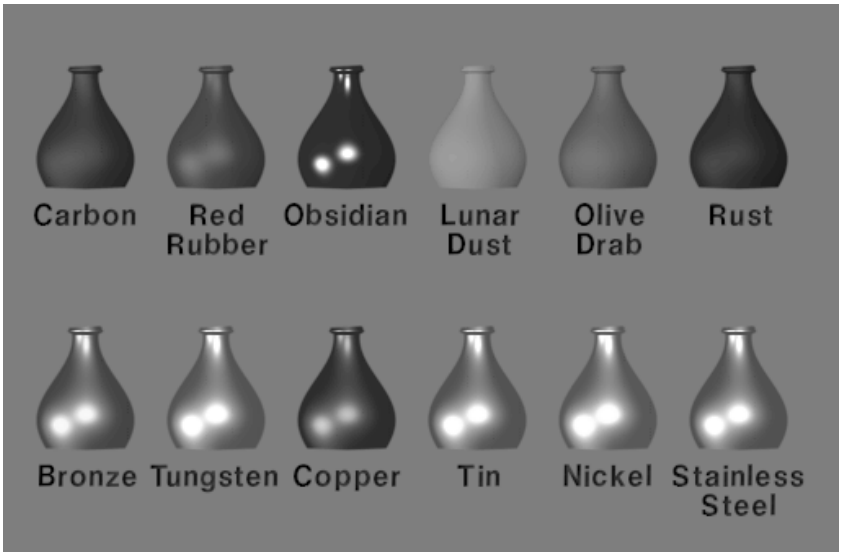
Information

- www.cs.cornell.edu/courses/cs6620/2009sp/
  - Schedule
  - Information will be posted on CMS as well
  - Check for updates and announcements

Materials - Three Forms



Rob Cook's vases

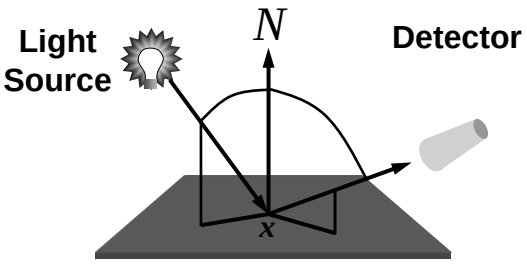


Source: Cook, Torrance 1981

Teapot

BRDF

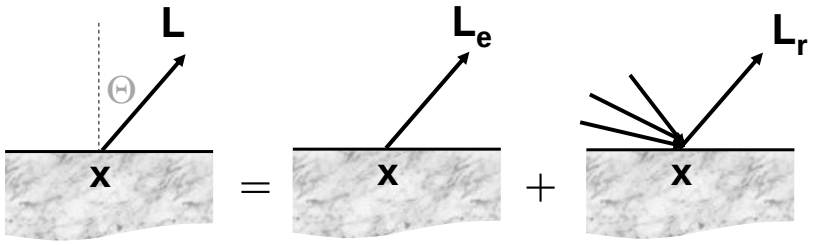
- Bidirectional Reflectance Distribution Function



$$f_r(x, \Psi \rightarrow \Theta) = \frac{dL(x \rightarrow \Theta)}{dE(x \leftarrow \Psi)}$$

$\frac{W}{m^2 sr}$ $\frac{W}{m^2}$

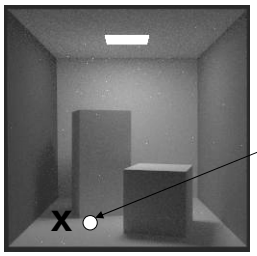
Rendering Equation



$$L(x \rightarrow \Theta) = L_e(x \rightarrow \Theta) + \int_{hemisphere} L(x \leftarrow \Psi)\, f_r(x, \Psi \leftrightarrow \Theta) \cos(\mathbf{N}_x, \Psi)\, d\omega_\Psi$$

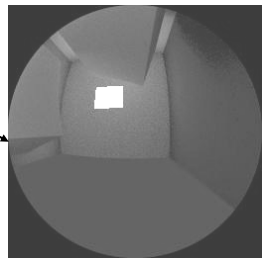
- **Applicable for each wavelength**

Rendering Equation



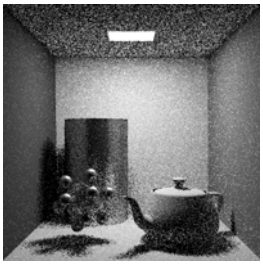
$$L(x \rightarrow \Theta) = L_e(x \rightarrow \Theta) + \int_{hemisphere} L(x \leftarrow \Psi)\, f_r(x, \Psi \leftrightarrow \Theta) \cos(\mathbf{N}_x, \Psi)\, d\omega_\Psi$$

incoming radiance

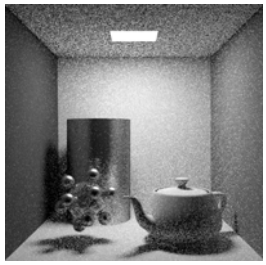


Monte Carlo Sampling

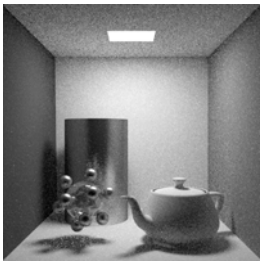
1 sample/ pixel



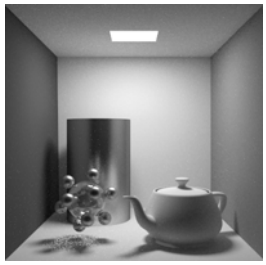
4 samples/ pixel



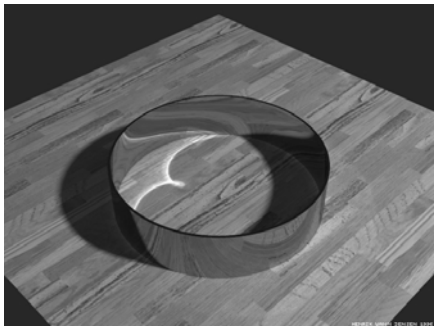
16 samples/ pixel



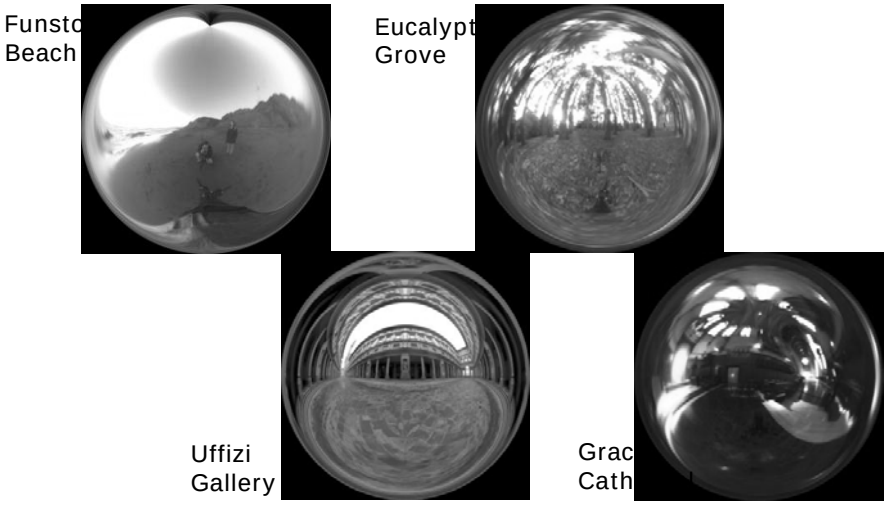
256 samples/ pixel



Photon Mapping

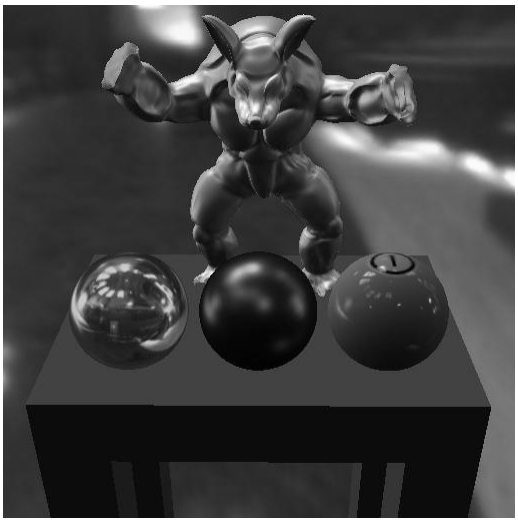


Real-World HDR Lighting Environments

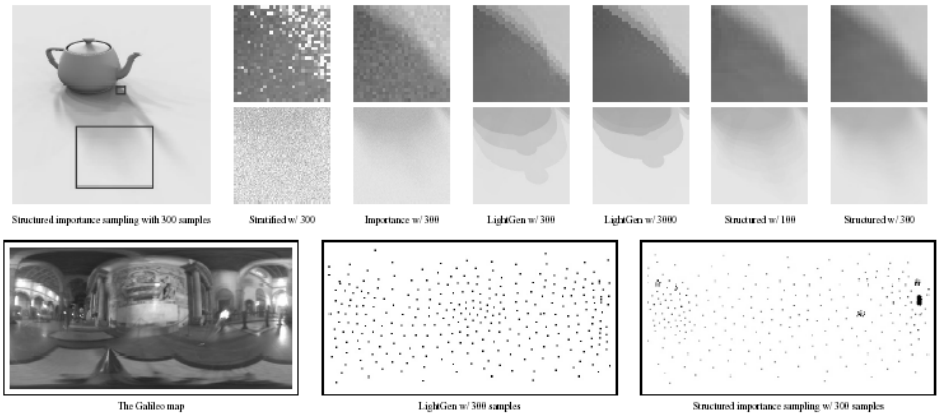


Lighting Environments from the Light Probe Image Gallery:
http://www.debevec.org/Probes/

Environment Map Rendering



Environment Maps



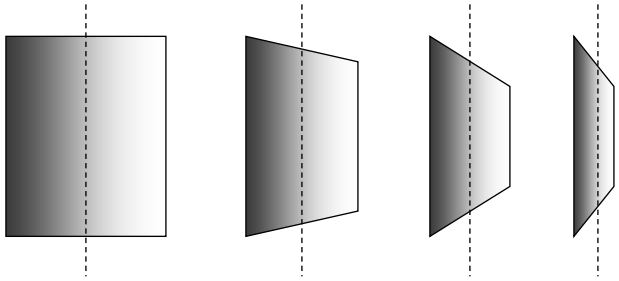
Advanced State-of-the-Art Rendering

- Interactive rendering
  - Radiosity and variants
  - Shadow algorithms
    - Shadow maps, shadow volumes, percentage closer filtering, soft shadows
  - GPU rendering and global illumination
    - Instant radiosity
    - Antiradiance
  - Precomputed radiance transfer (PRT)

Radiosity

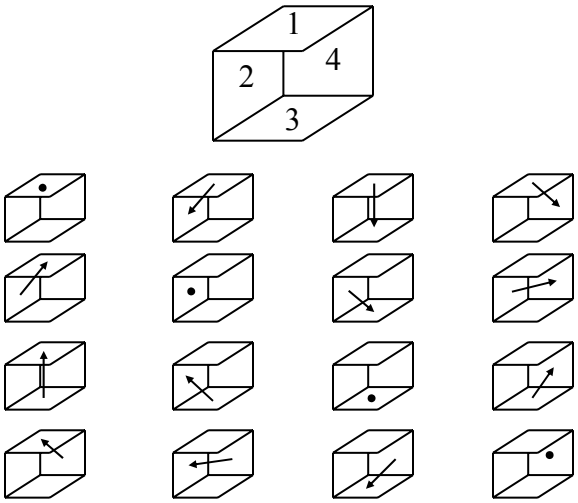
- Introduced in 1984
- Diffuse inter-reflections

Key Idea #1: diffuse only

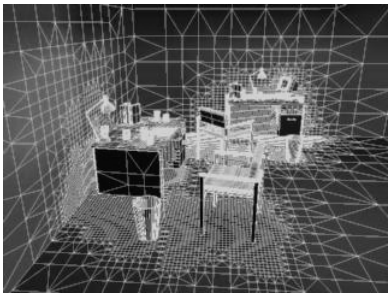


- Radiance independent of direction
- Surface looks the same from any viewpoint
- No specular reflections

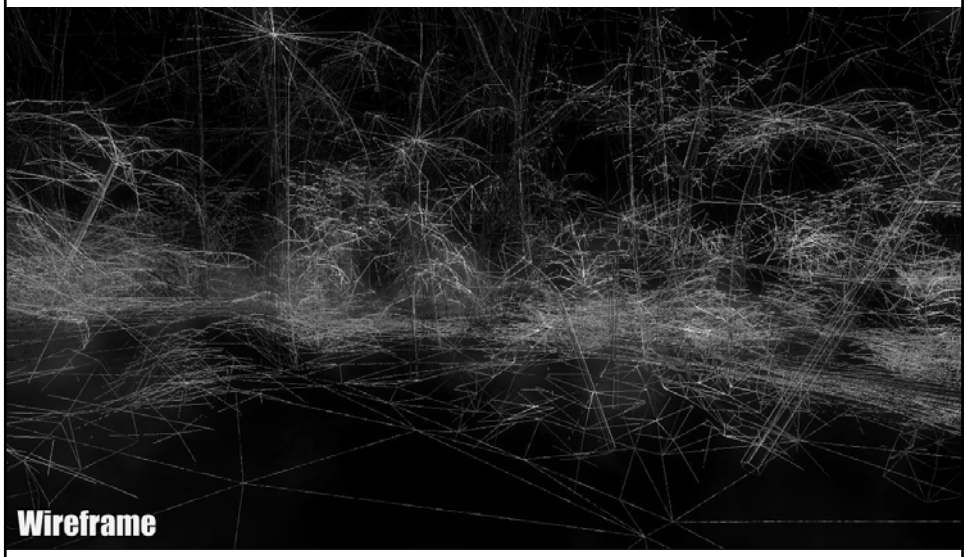
Linear System



Algorithm



Radiosity in Games



Radiosity in Games

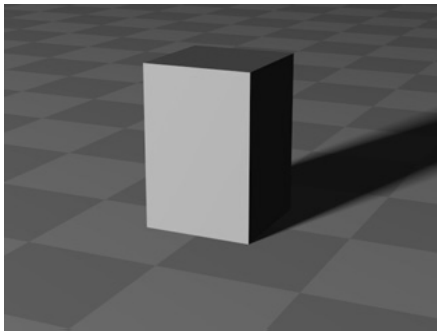
Radiosity in Games

Radiosity in Games

Radiosity in Games

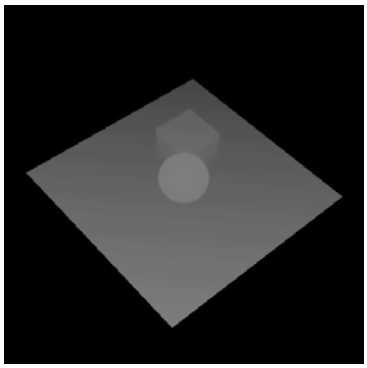
Why Shadows?

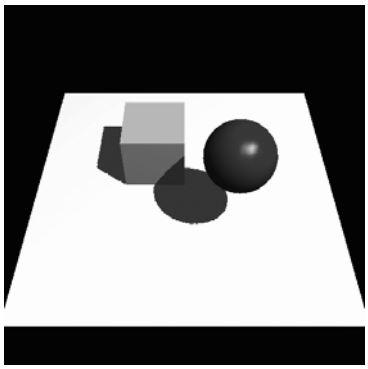
- Crucial for spatial and depth perception



Shadow Maps

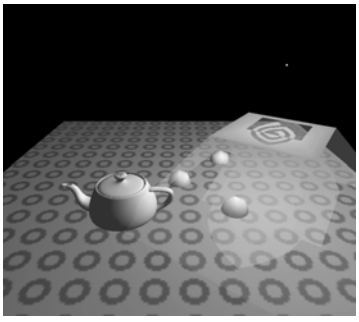
- Introduced by Lance Williams (SIGGRAPH 1978)
- Render scene from light's view
  - black is close, white is far

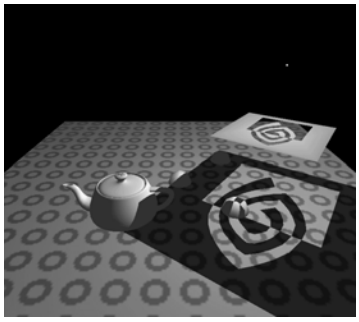




Shadow Volumes

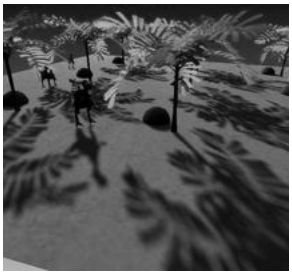
- Clever counting method using stencil buffer
- Can cast shadows onto curved surfaces



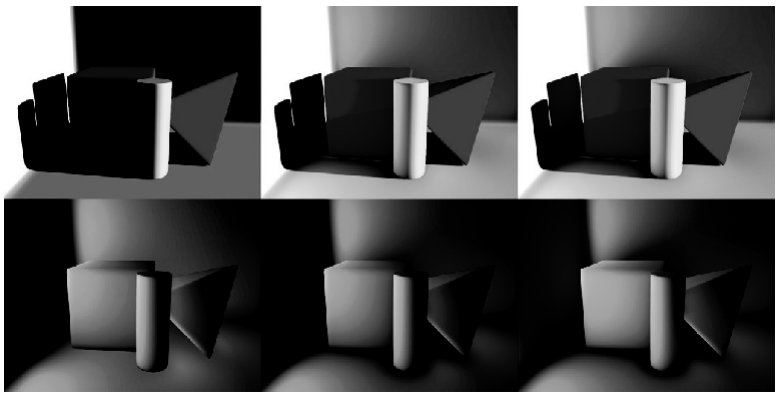


 Mark Kilgard, NVIDIA Inc.

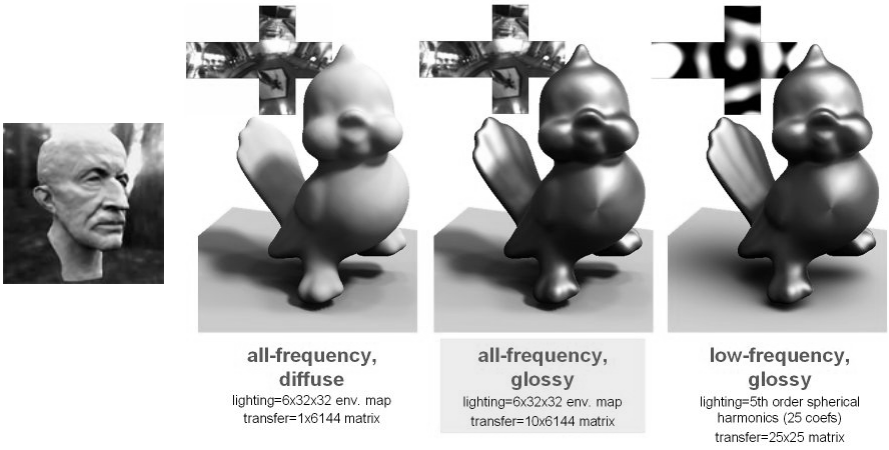
Percentage Closer Filtering



Instant Radiosity/Dynamic Ambient Occlusion



Precomputed Radiance Transfer

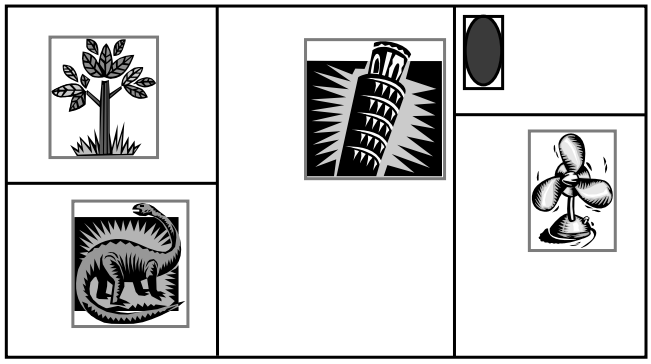


Advanced State-of-the-Art Rendering

- Handling Complexity
  - Acceleration Structures
  - Scalable Rendering
  - Interactive Ray Tracing

K-dimensional (kd) Tree

- Spatial subdivision

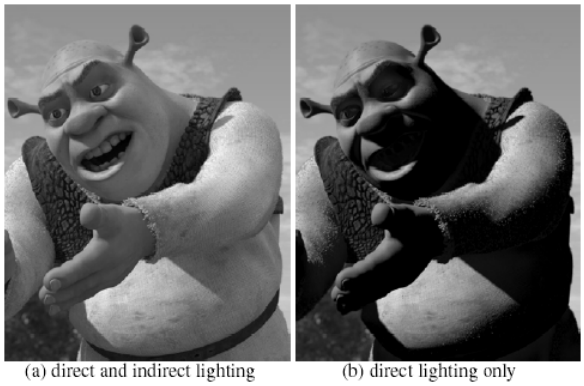


Interactive Ray Tracing

Advanced State-of-the-Art Rendering

- Rendering in movies
  - Final render
    - PDI (Shrek)
  - Cinematic relighting
    - Pixar, Cornell
    - ILM (Lightspeed)
- Trends in rendering research
  - Scalable rendering
  - Perceptually-Based Rendering
  - Depiction

GI for Movies

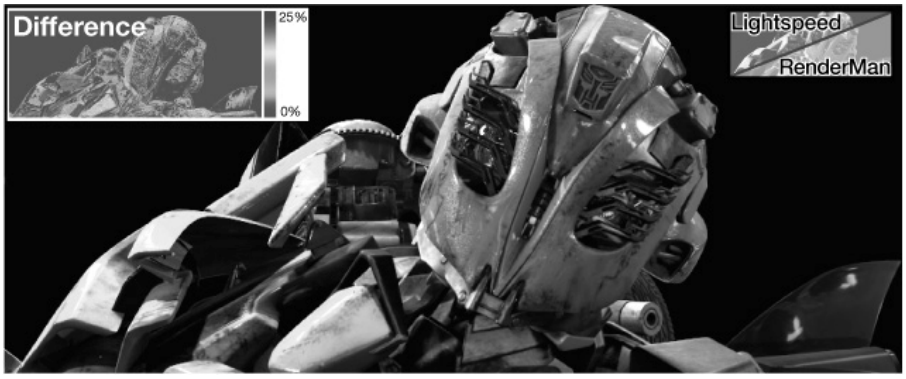


(a) direct and indirect lighting (b) direct lighting only

Figure 1: Example of a character in outside lighting conditions. (a) and (b) were rendered respectively with and without indirect lighting.

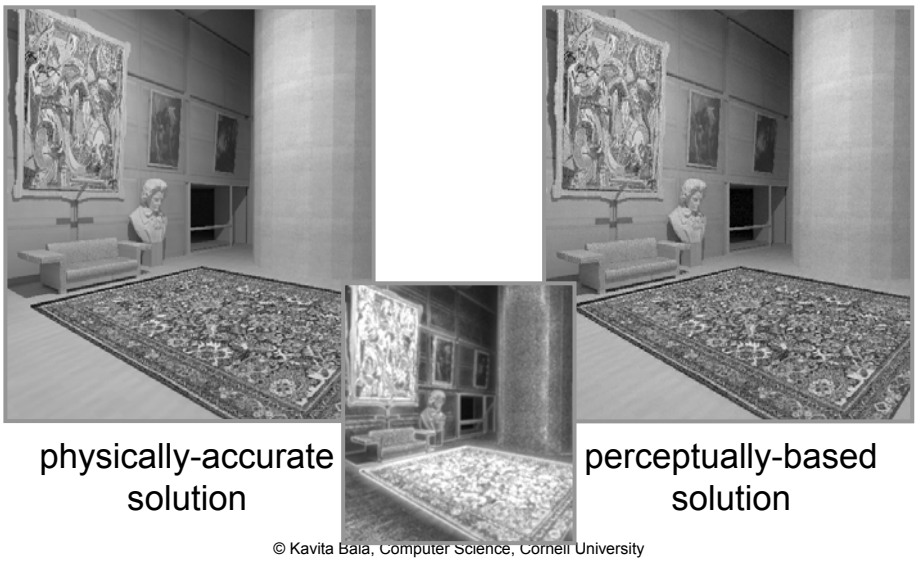
Rendering in Movies

Lightspeed



Perceptually-Based Rendering

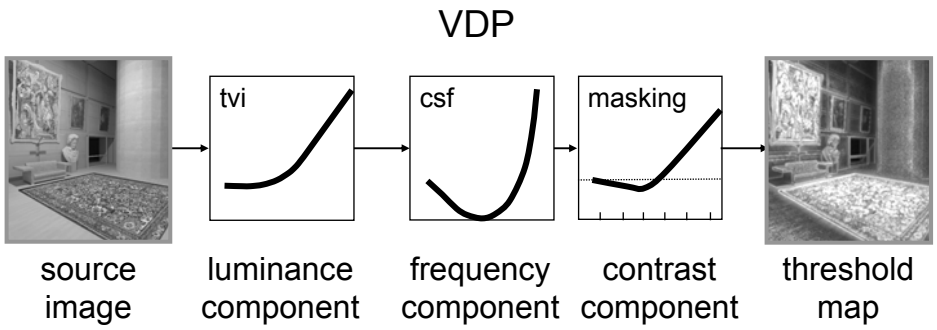
5% effort



physically-accurate solution

perceptually-based solution

Perceptually-driven rendering



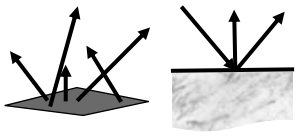
By the end of the course…

Fundamental understanding of:

- State-of-the-art practical rendering algorithms
  - For games, movies, simulation
  - Complex scene management
    - Lighting
    - Materials
    - Illumination
    - Geometry

What is the behavior of light?

- Physics of light
- Radiometry
- Material properties

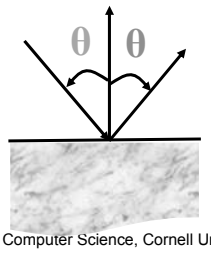


- **Rendering Equation**

Brief history of Optics: 350 B.C.

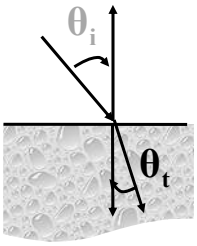
- Greek philosophers (350 B.C.)
  - Pythagoras, Plato, Aristotle
  - Light emanated from the eye
- By 300 B.C.,
  - Understood rectilinear propagation of light
  - Euclid described law of reflection

reflection



Brief history of Optics: Dark Ages

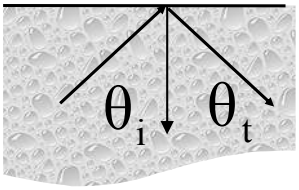
- Ptolemy (130 A.D.)
  - Refraction



- Not much in Dark Ages except for Alhazen (elaborated law of reflection)
  - Angles of incidence and reflection in the same plane as normal N

Brief history of Optics: 17th century

- 17th century: telescopes, microscopes
- Kepler (1611)
  - Total internal reflection

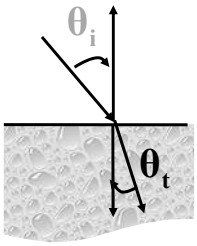


Brief history of Optics: 17th century

- Snell (1621): Law of refraction

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{\eta_t}{\eta_i}$$

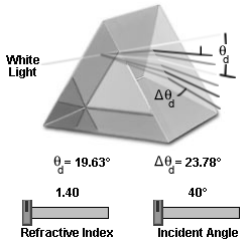
$$\eta_i \sin\theta_i = \eta_t \sin\theta_t$$



- Descartes published the sine form of law of refraction
- Fermat (1657)
  - Law of refraction from *principle of least time*

Brief history of Optics: 17th century

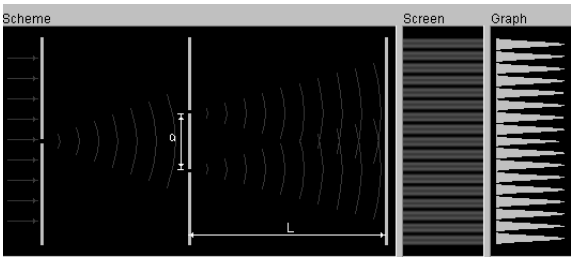
- Newton (1642-1727)
  - Dispersion
    - Light splits into component colors
  - Corpuscular/emission theory



- Huygens (1629-1695)
  - Developed wave theory of light
  - Discovered polarization
- Two conflicting theories: wave vs. emission

Brief history of Optics (contd.)

- Young (1801)
  - Principle of interference
  - Double-slit experiment



- Fresnel
  - 1816: Diffraction and interference
  - 1821: Fresnel equations for reflection and refraction

Brief history of Optics (contd.)

- Maxwell (1831-1879)
  - Electricity and magnetism
  - Maxwell's equations

  $\nabla \cdot \mathbf{E} = 0$

  $\nabla \cdot \mathbf{B} = 0$

  $\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$

  $\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \partial \mathbf{E}/\partial t$
  - Theoretical validation of measured speed of light
- Light is electromagnetic radiation

Brief history of Optics (contd.)

- Hertz (1887)
  - Discovered the photoelectric effect

    The process whereby electrons are liberated from materials under the action of radiant energy
- Einstein (1905)
  - Explained photoelectric effect
  - Light is a stream of quantized energy packets called quanta (photons)
  - $E = h \nu$

Brief history of Optics (contd.)

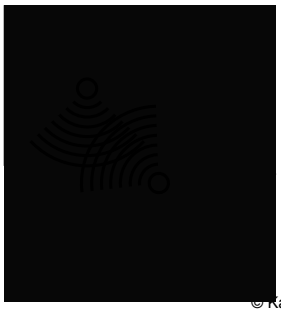
- Particle and wave theory seemingly mutually exclusive
- Quantum Mechanics
  - Bohr, Born, Heisenberg, Schrodinger, Pauli
  - Sub-microscopic phenomena
  - Unite particle and wave behavior of light
  - QED by Feynman

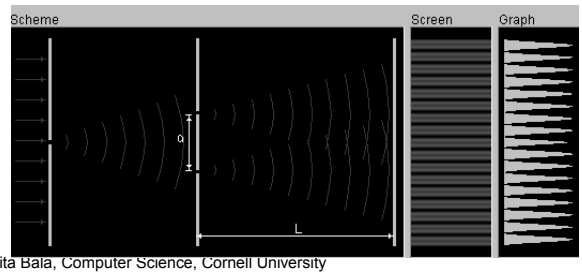
Models of Light

- Geometric Optics
  - Emission
  - Reflection / Refraction
  - Absorption
- Simplest model
- Size of objects > wavelength of light

Models of light

- Wave Model
  - Maxwell's Equations
  - Object size comparable to wavelength
  - Diffraction, Interference, Polarization



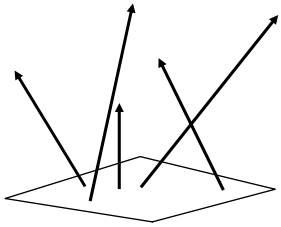


Models of light

- Quantum Model
  - Fluorescence
  - Phosphorescence
  - Relativistic effects
- Most complete model

Geometric Optics: Properties

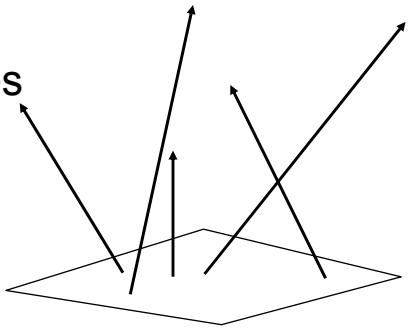
- Light travels in straight lines
- Rays do not interact with each other
- Rays have color(wavelength), intensity



Emission

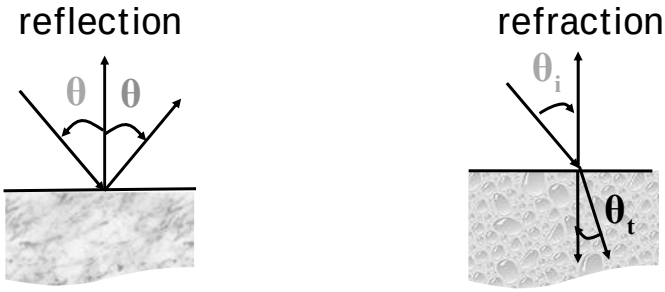
- New rays due to:
  - chemical
  - electrical
  - nuclear

  processes



Reflections/Refractions

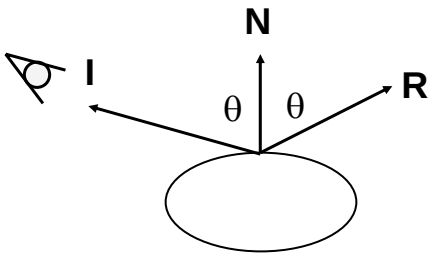
- Interface between 2 materials



- Specular reflections and refractions
  - One direction

Specular Reflections

Reflected ray R

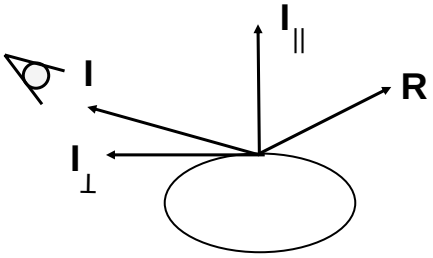


$I_{||} = (I.N)\ N$

$I_{\perp} = I - (I.N)\ N$

$R = I_{||} + (-I_{\perp})$

$= 2\ (I.N)\ N - I$



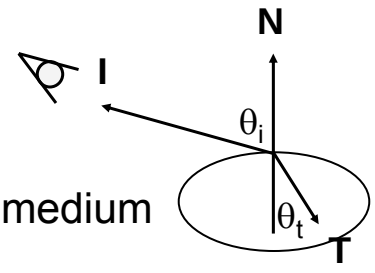
Specular Refractions

- Compute refracted ray T
- Index of refraction: $\eta = c_{vacuum} / c_{material}$
- Snell's law:

$$\frac{\sin\theta_t}{\sin\theta_i} = \frac{\eta_i}{\eta_t}$$

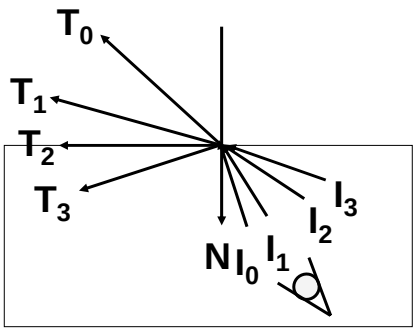
$$\eta_i \sin\theta_i = \eta_t \sin\theta_t$$

- Ray from rare to dense medium



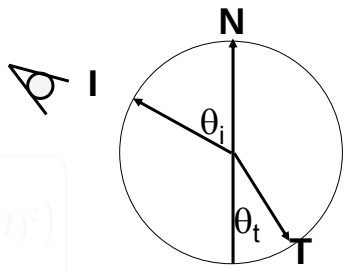
Total Internal Reflection

- Consider ray from dense to rare



$$\frac{\sin\theta_i}{1} = \frac{\eta_t}{\eta_i}$$

Transmitted Ray



$$T = -\frac{\eta_i}{\eta_t} I + N\left(\frac{\eta_i}{\eta_t}(N.I) - \sqrt{1 - \left(\frac{\eta_i}{\eta_t}\right)^2 (1 - (N.I)^2)}\right)$$

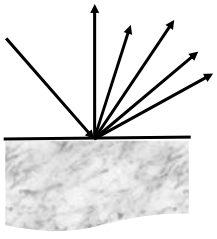
$$T = -\eta I + N\left(\eta \cos\theta_i - \sqrt{1 - \eta^2 \sin^2\theta_i}\right)$$

$$\cos\theta_i = (N.I)$$

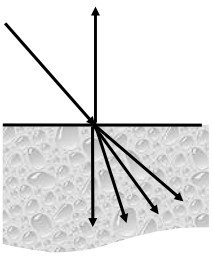
$$\eta = \frac{\eta_i}{\eta_t}$$

Realistic Reflections/Refractions

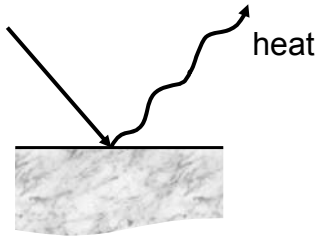
reflection



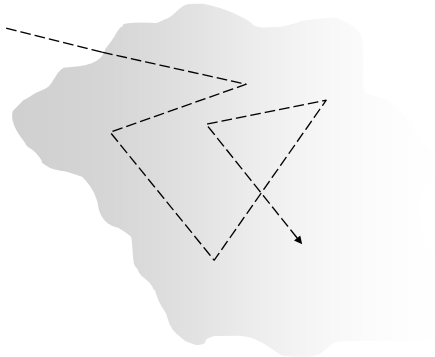
refraction



Absorption



Interaction with matter

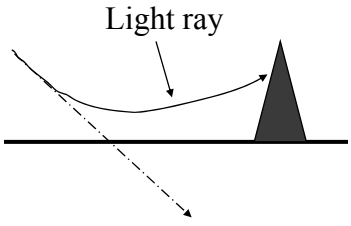


participating medium

Interaction with matter

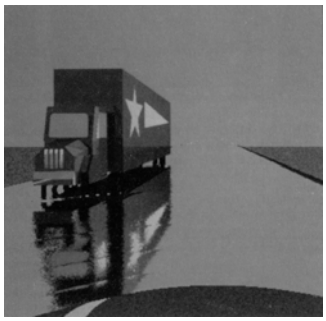
Interaction with matter

- Continuously varying refractive index



Interaction with matter

(Minnaert)



(Berger)