

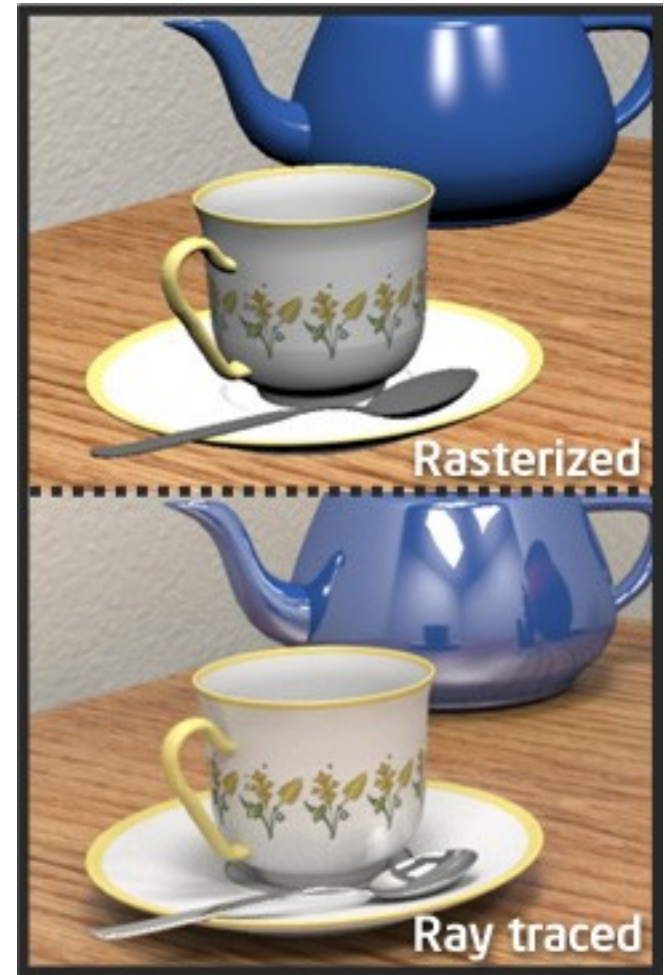
# **Ray Tracing**

**CSCI 4239/5239**

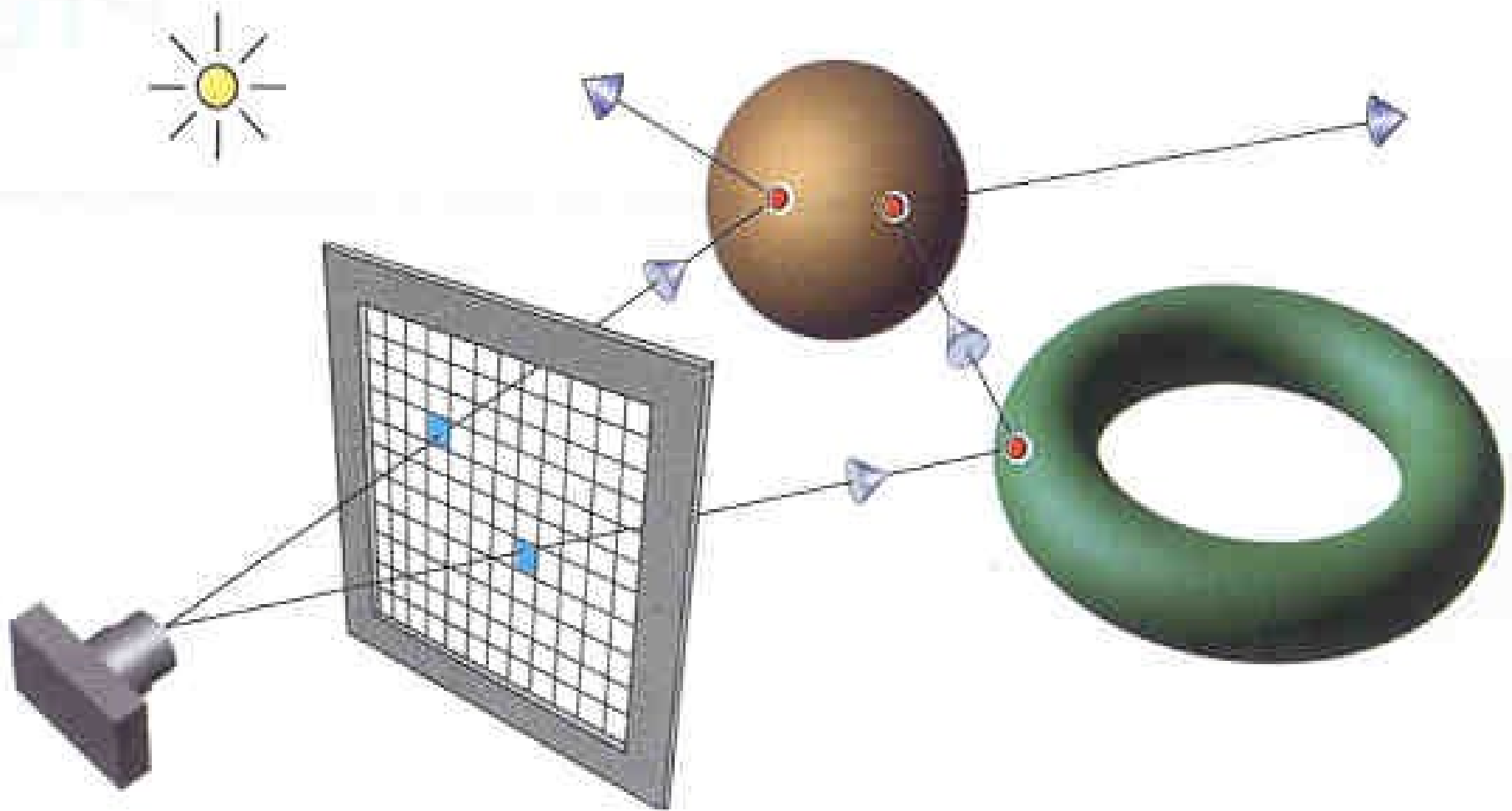
**Advanced Computer Graphics  
Spring 2019**

# What is it?

- Method for rendering a scene using the concept of optical rays bouncing off objects
  - More realistic
  - Reflections
  - Shadows



# How does it work?



**Figure 1.** The ray-tracing process.

# Sources

- Ray Tracing from the Ground Up
  - Kevin Suffern
  - Excellent tutorial
  - Some working examples
  - <http://www.raytracegroundup.com/>
- nVidia
- Intel
- Van Der Ploeg thesis

# Interactive Ray Tracing

- True ray tracing is VERY compute intensive
- Global problem – scene complexity adds effort
- Generally there is no upper limit to computation
- Solutions are generally software based
  - Dedicated hardware provides 3-5x speedup
  - <http://www.caustic.com/>
  - OpenRL
  - Maya Plugins
- Compare nVidia RTX



nVidia Quadra Plex  
1920x1024@30fps



nVidia Quadra Plex  
1920x1024@30fps



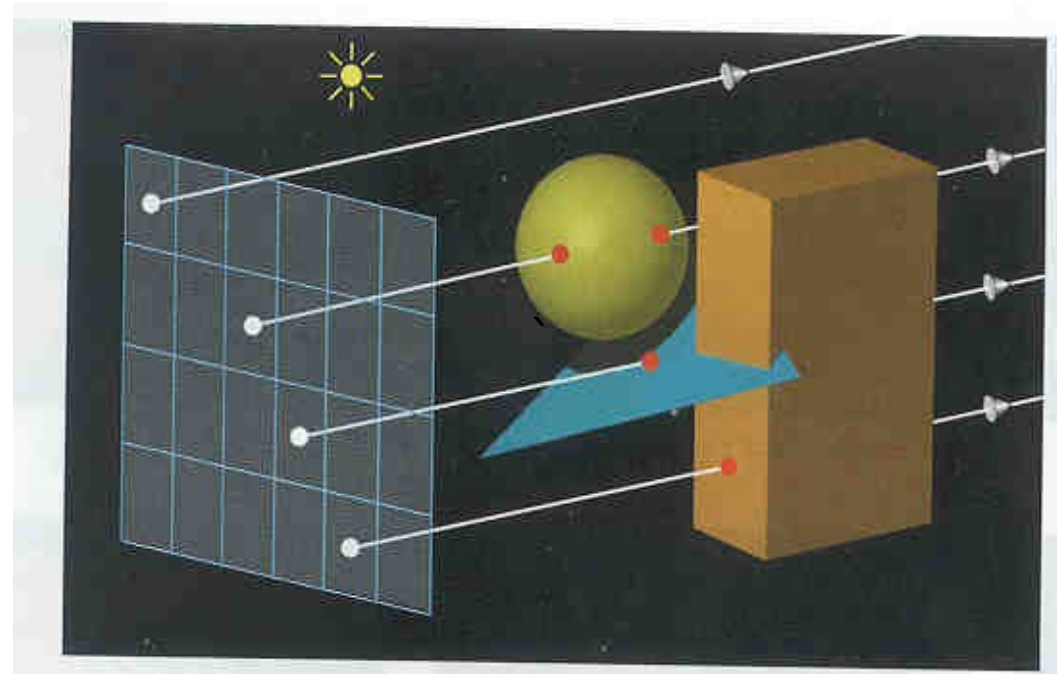
# How is it Done?

- Scene Description Language
  - Defines objects in scene
    - Geometry and properties
  - Lights
  - Eye position
- Determine color of individual pixels using ray tracing algorithms
  - Very hard to do real time



# How ray tracing works

- Define scene and view
  - objects
  - lights
  - eye
- For each pixel
  - Shoot ray from pixel
  - Find nearest hit
  - Use object properties and lights to calculate color, or set to black if no hits



# True Global Ray Tracing

- Light can bounce many times
  - Color changes at each bounce
  - Each bounce attenuates light
  - Light scatters in complex ways
  - Objects block light
- This simple scene took 2 CPU years to render
  - Cornell Box
  - Area light and three boxes

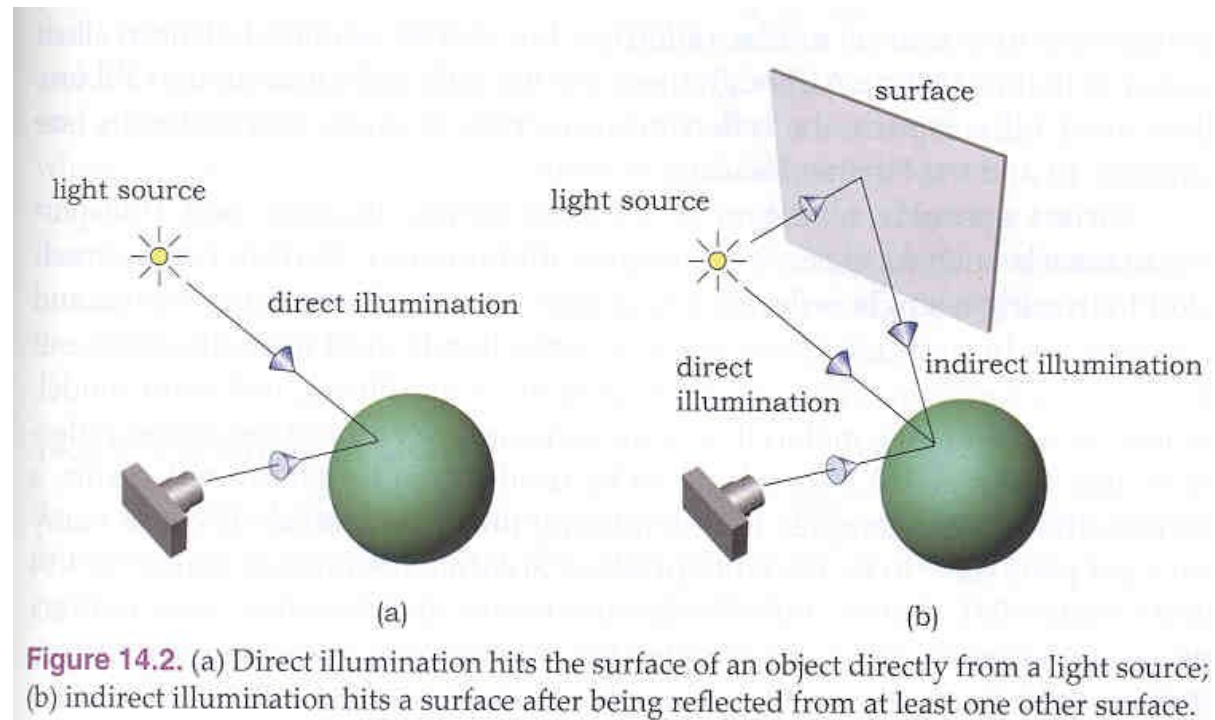


# Efficiency and Complexity

- Most ray tracers written in C++
  - Object Oriented paradigm for objects, rays, colors
  - Good efficiency/readability trade-off
- Efficiency is a HUGE deal
  - Pushing the envelope of hardware
  - Algorithm is global by definition
- Recursion and complexity
  - Need clean interface on objects

# What is a Ray?

- $\mathbf{p} = \mathbf{o} + t \mathbf{d}$
- Types of rays
  - Primary rays
  - Secondary rays
  - Shadow rays
  - Light rays
- Rays are one directional



# Intersections

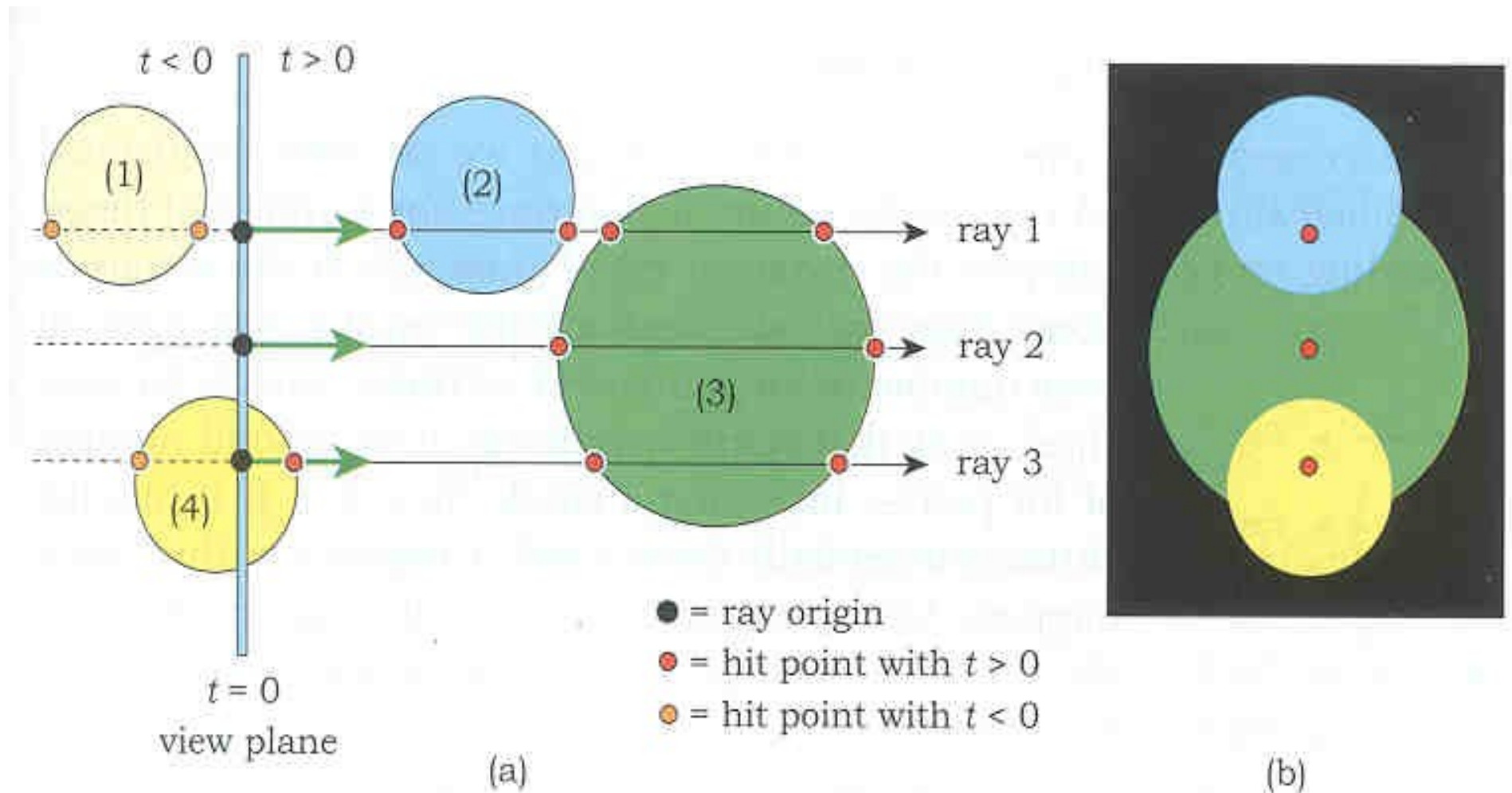


Figure 3.4. (a) Rays and their intersections with spheres; (b) ray-traced image of the spheres.

# Intersecting a Sphere

- Simplest 3D object

- Center
- Radius

- Smooth normal

- Intersections

- none

- once

- tangent

- internal

- twice

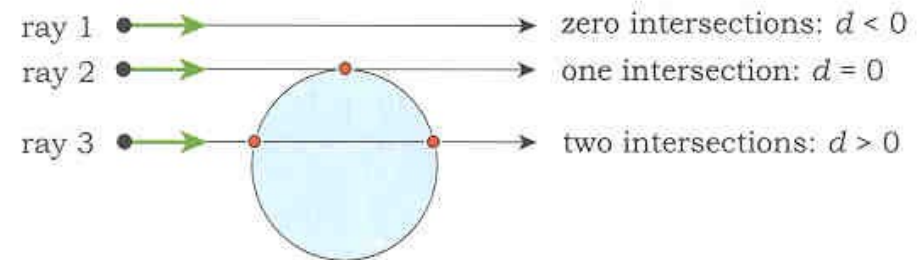


Figure 3.7. Ray-sphere intersections.

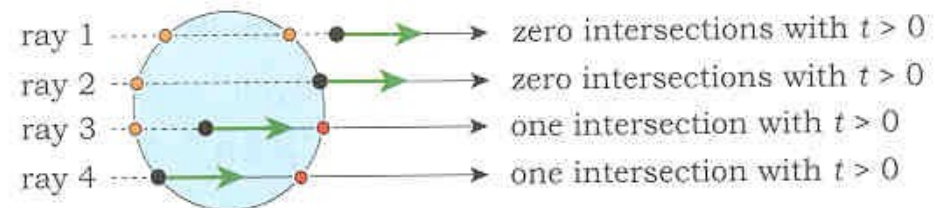
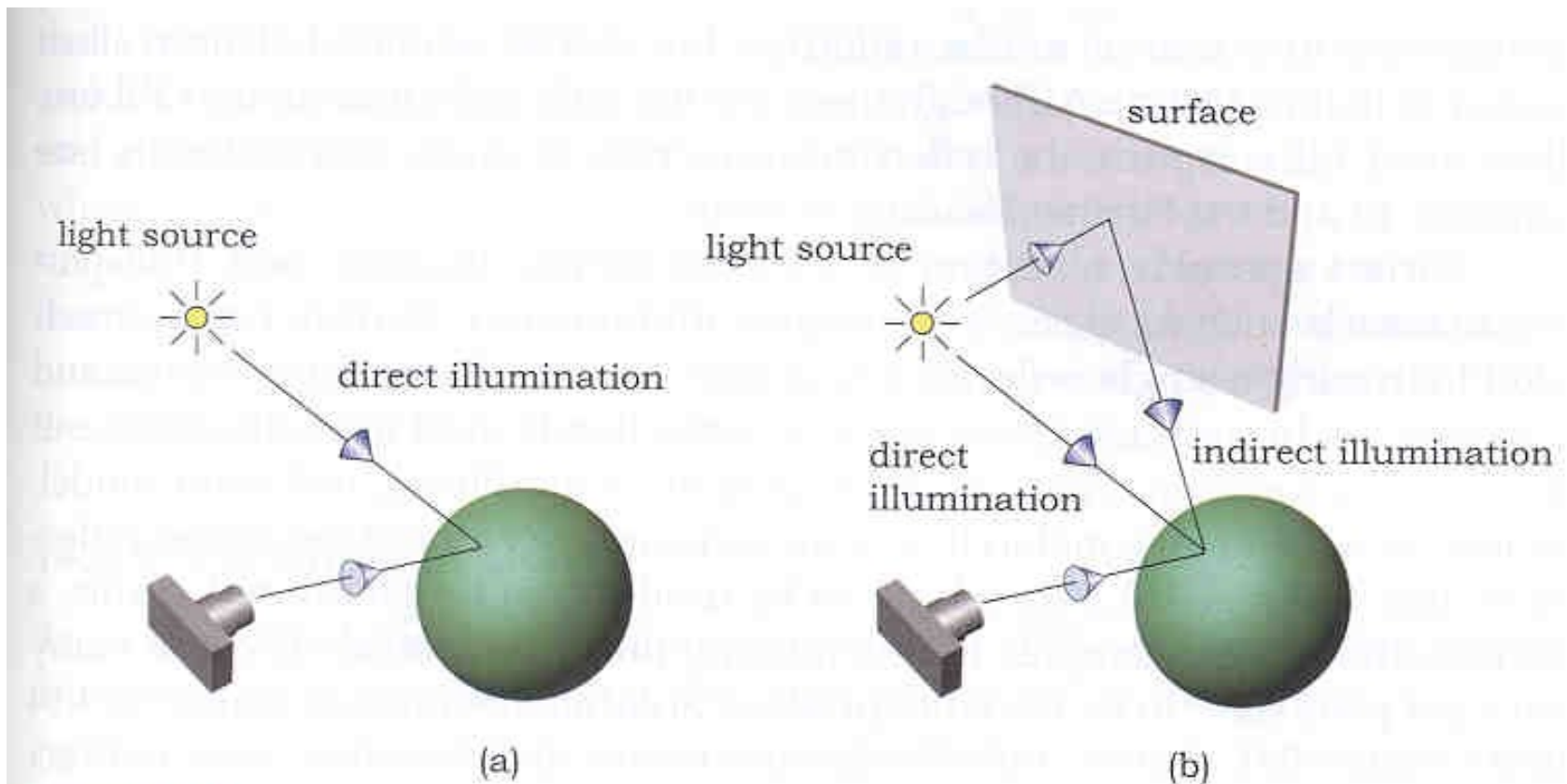


Figure 3.8. Further ray-sphere intersections.

# Implicit Surfaces

- General
  - $f(x,y,z) = 0$
- Plane: Point **a** and Normal **n**
  - $(p-a) \bullet n = 0$
- Sphere
  - $(\mathbf{p}-\mathbf{a}) \bullet (\mathbf{p}-\mathbf{a}) - r^2 = 0$
- Triangle
  - Limit plane

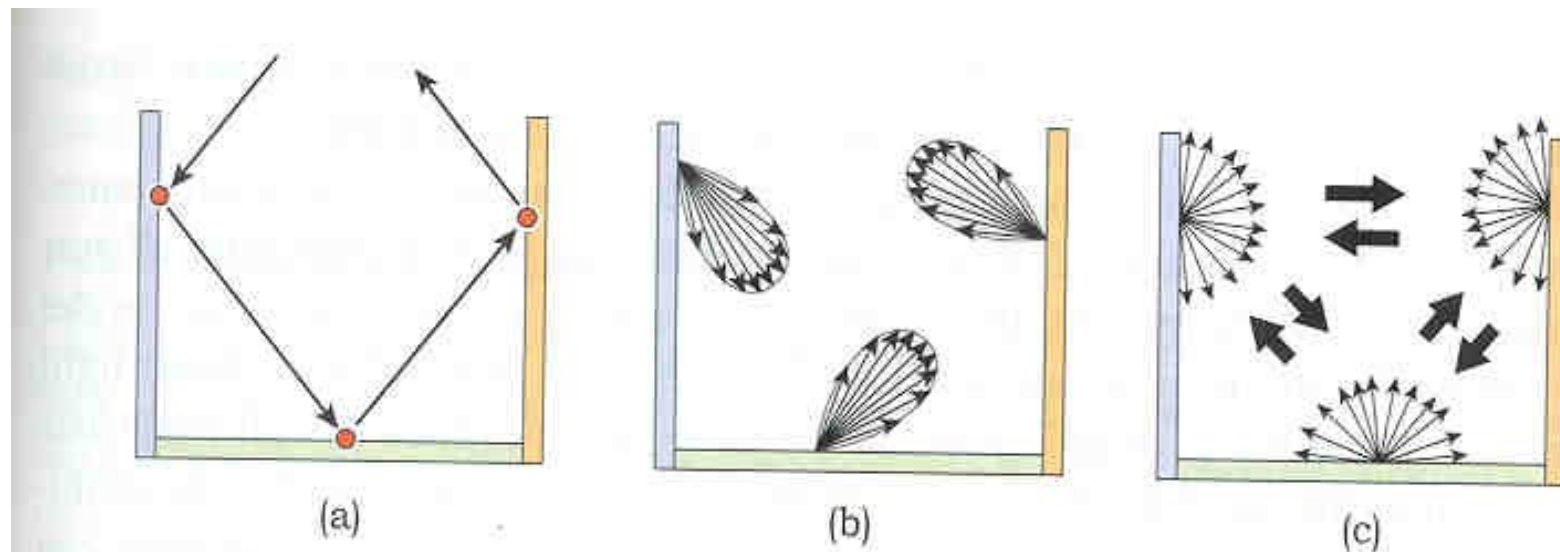
# Interaction between Lights and Objects



**Figure 14.2.** (a) Direct illumination hits the surface of an object directly from a light source; (b) indirect illumination hits a surface after being reflected from at least one other surface.



# Bouncing Rays from Surfaces



**Figure 14.4.** (a) Mirror reflection can be modeled by tracing a single reflected ray at each hit point; (b) modeling glossy specular light transport between surfaces requires many rays to be traced per pixel; (c) modeling perfect diffuse light transport between surfaces also requires many rays to be traced per pixel.

# Light Reflection

- Diffuse (Lambertian) reflection
  - Intensity Factor  $N \cdot L$

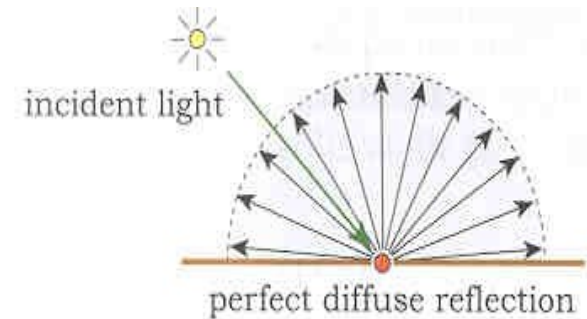


Figure 13.6. Light being scattered from a perfectly diffuse surface.

- Specular reflection
  - $R = 2(N \cdot L)N - L$
  - Intensity Factor

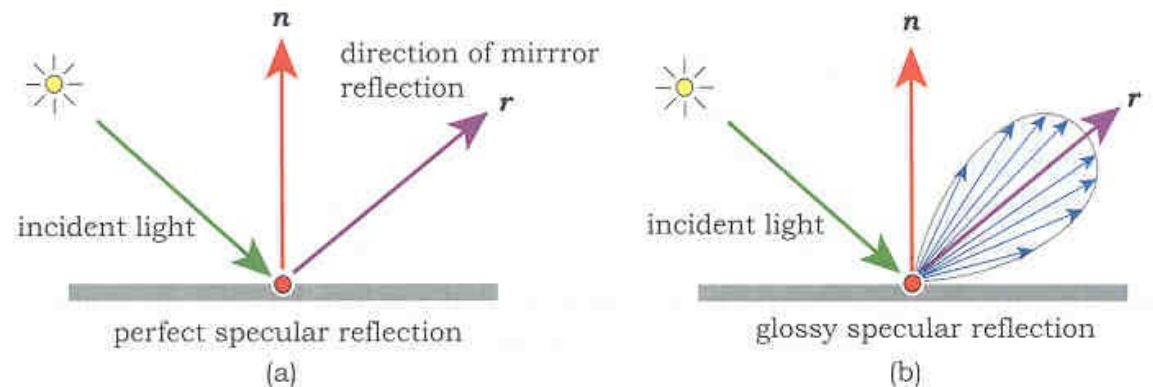


Figure 14.3. (a) Perfect specular reflection; (b) glossy specular reflection.

# Specular Reflected Light

- Assume the ray (from the eye) hits objects 1,2,3,... with reflection coefficients  $\alpha_1, \alpha_2, \alpha_3, \dots$
- Specular Reflection Color
$$\alpha_1(C_1 + \alpha_2(C_2 + \alpha_3(C_3 + \dots)))$$
$$= \alpha_1 C_1 + \alpha_1 \alpha_2 C_2 + \alpha_1 \alpha_2 \alpha_3 C_3 + \dots$$
- Since light is assumed to be linearly additive, just keep track of  $\alpha$  and add light along successive bounces of the ray
- White specular means  $\alpha$  can be a scalar

# Simple Ray Tracing Algorithm

- Initialize ray ( $\mathbf{O}, \mathbf{d}$ )
  - color = black
  - coef = 1
- Find closest intersection  $\mathbf{P}$ 
  - color += coef\*ambient\*material
  - *if not in shadow* color += coef\* $\mathbf{N} \cdot \mathbf{L}$ \*diffuse\*material
  - coef \*= reflectivity
  - redirect ray from  $\mathbf{P}$  to  $\mathbf{d} - 2(\mathbf{d} \cdot \mathbf{N})\mathbf{N}$
- Stop when no intersection, or coef  $\ll 1$ , or maximum number of bounces

# Ex 26: Three Ray Traced Spheres

- Simple scene
  - Three highly reflective spheres
  - Two white lights (one close, one far)
  - OpenMP for parallel processing
- Support classes
  - Vec3, Mat3, Color
- Base classes
  - Ray, Material, Light
- Object classes
  - Sphere

# Implementation Notes

- Written in ***very bad*** C++
  - *KISS*
  - No object abstraction
- Use STL `vector<>` class for lists
- Calculate array of pixel values *width x height*
  - View by transforming pixel location
  - OpenMP parallel calls to `RayTracePixel()`
  - Copy to screen using *glDrawPixels*
- All calculations in ***global*** coordinates
  - Preprocess scene as needed

# Building a real Ray Tracer in C++

- Base classes
  - Ray
  - Object
  - Light
  - Material
- Derived Object Classes
  - Sphere
  - Cube
  - Triangle
  - Triangle Mesh

# Object Class

- Type of object
  - Implicit Surface
    - Sphere
    - Torus, cylinder, cube, ...
  - Compound objects
    - Triangular mesh
- Intersection with a ray
  - Point of intersection
  - Normal
  - Textures, etc



# Virtual Methods

- Base class
  - hit
  - sample
  - color
- Each object class overrides the base class

# Intersecting a Complex Object

- Defining a complex object
  - Triangle mesh on vertexes
  - Gouraud shading
- Expensive to ray trace
  - Test every ray against every triangle in the object
  - Test bounding box of entire object
- Intersections
  - Plane
  - Axis-aligned box
  - Generic triangle

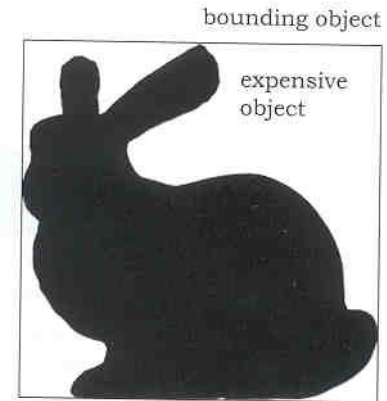
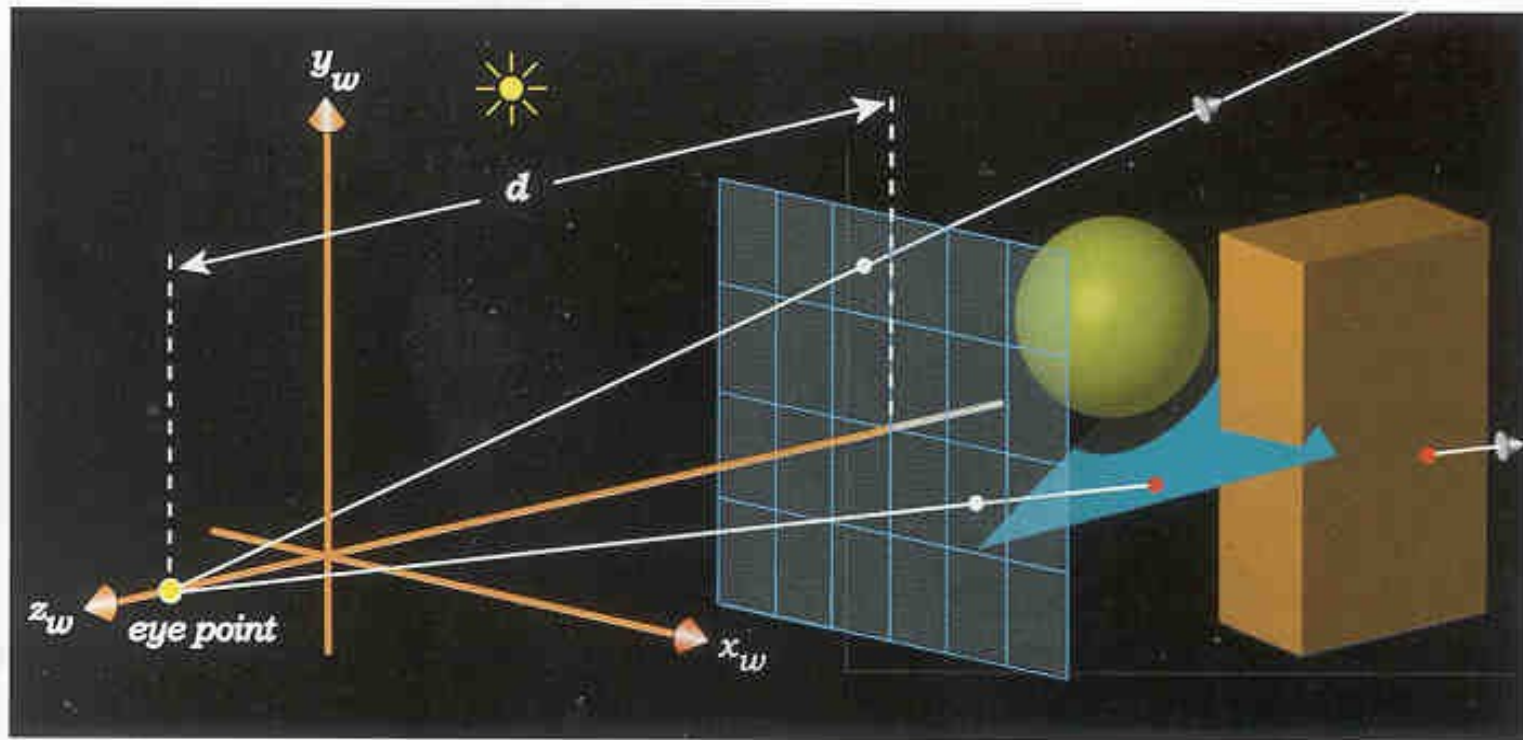


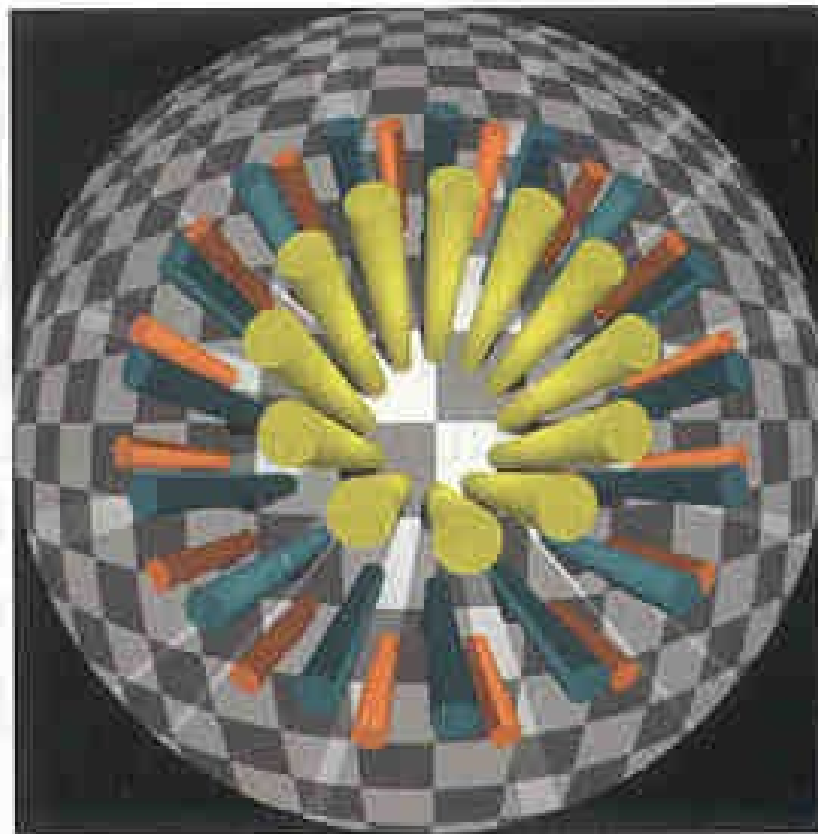
Figure 19.1. The Stanford bunny and a bounding box.

# Perspective Ray Tracing

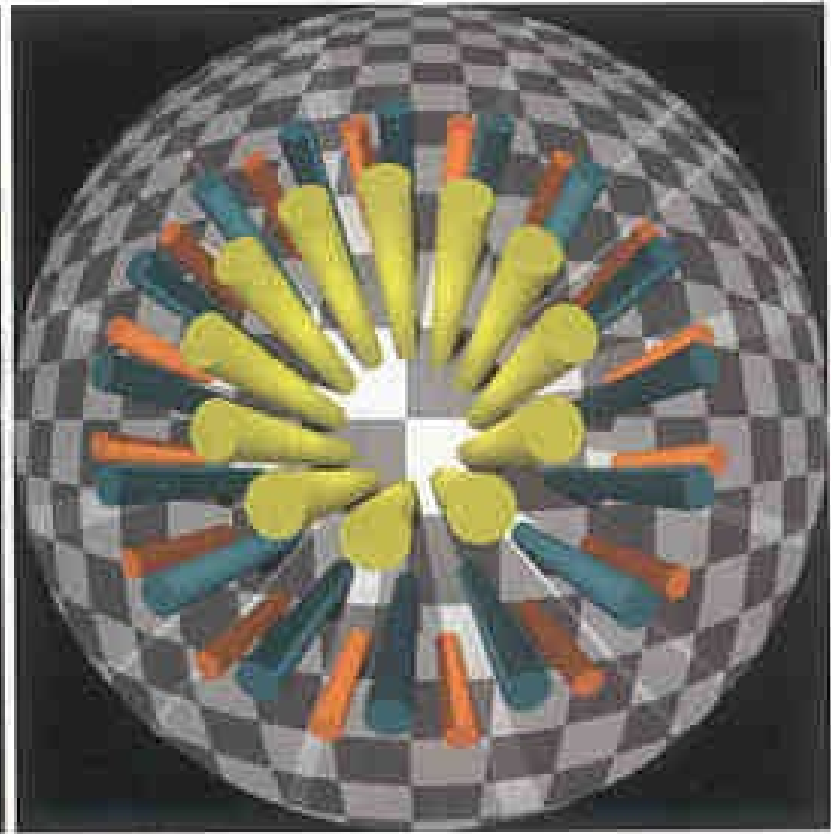


**Figure 8.14.** Set-up for axis-aligned perspective viewing with the eye point and two rays going through pixel centers.

# Stereoscopy



left-eye view



right-eye view

# Installing PBRT

- Build code from github

- `git clone --recursive https://github.com/mmp/pbrt-v3.git`
- `git clone git://git.pbrt.org/pbrt-v3-scenes`
- `apt-get install openexr-viewers`
- `cd pbrt-v3`
- `cmake .`
- `make -j8`
- `sudo make install`

- Run using `pbrt ??????.pbrt`

- `exrdisplay *.exr`