Ray Tracing

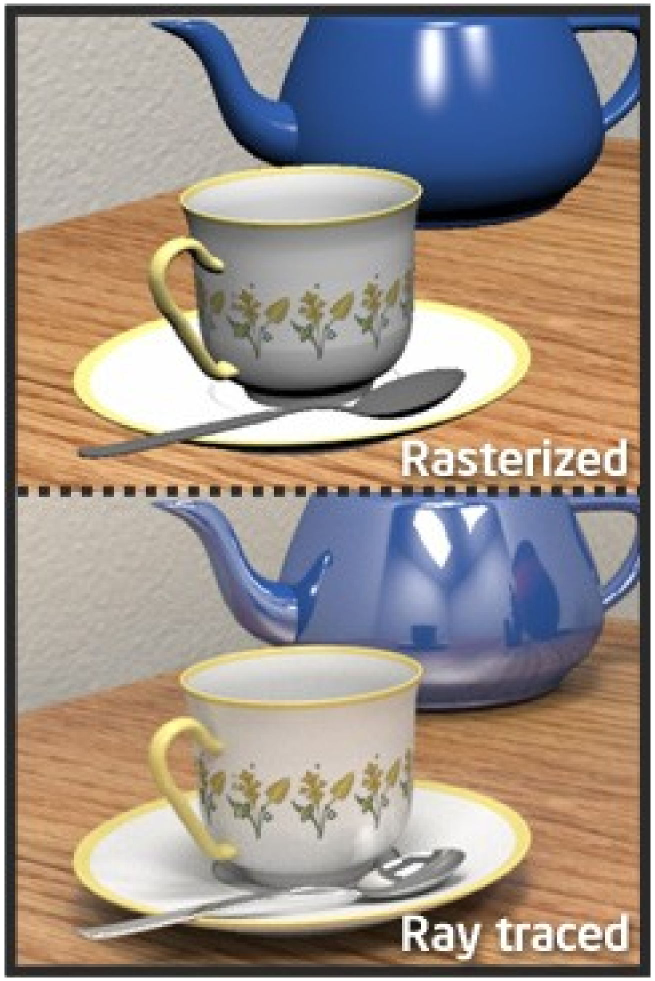
CSCI 4239/5239

Advanced Computer Graphics

Spring 2024

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?

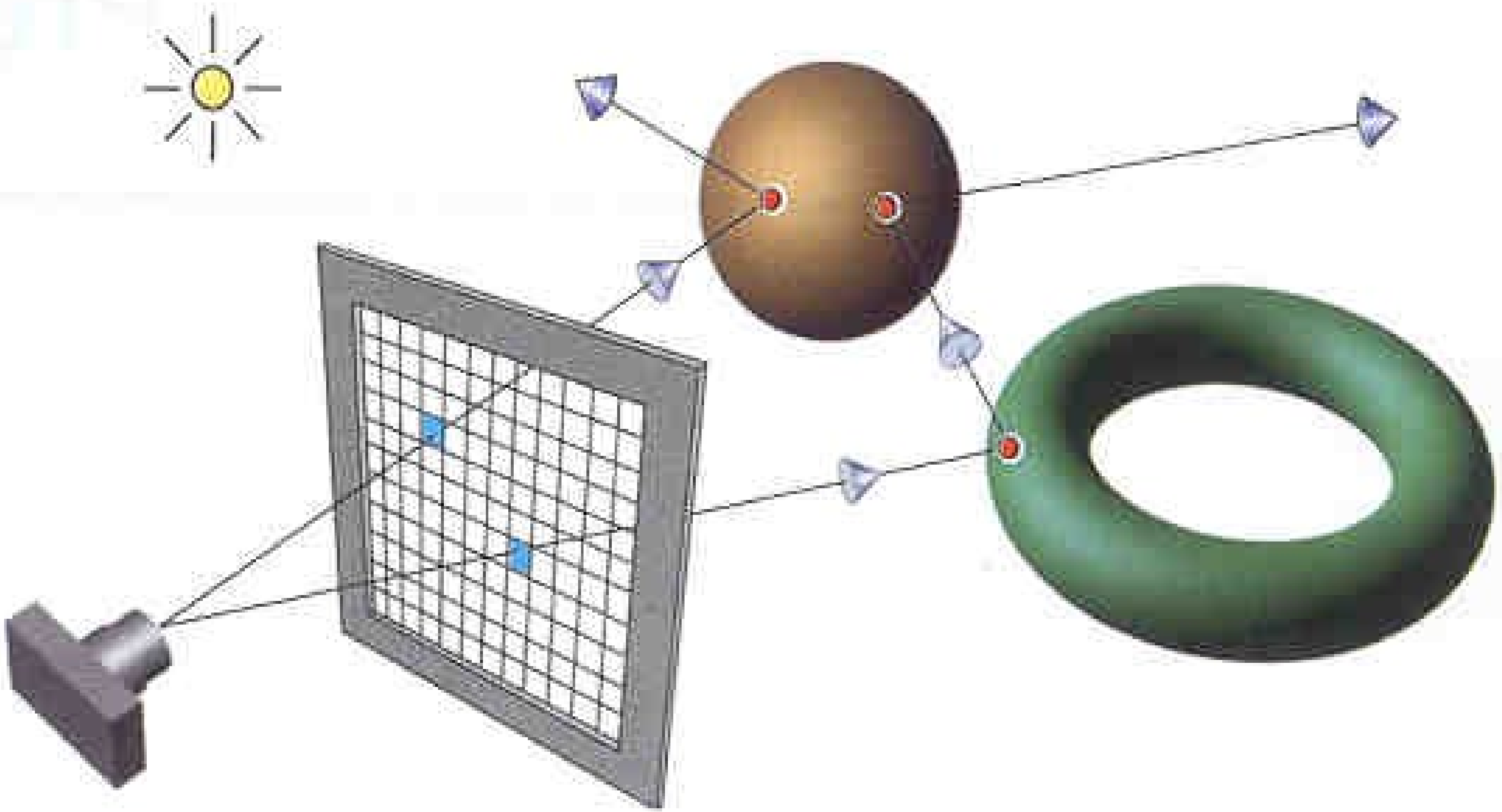


Figure 1. The ray-tracing process.

Sources

- Ray Tracing from the Ground Up
  - Kevin Suffern
  - Excellent tutorial
  - Some working examples
  - http://www.raytracegroundup.com/
- nVidia
- Intel
- PBRT (Physically Based Ray Tracing)

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

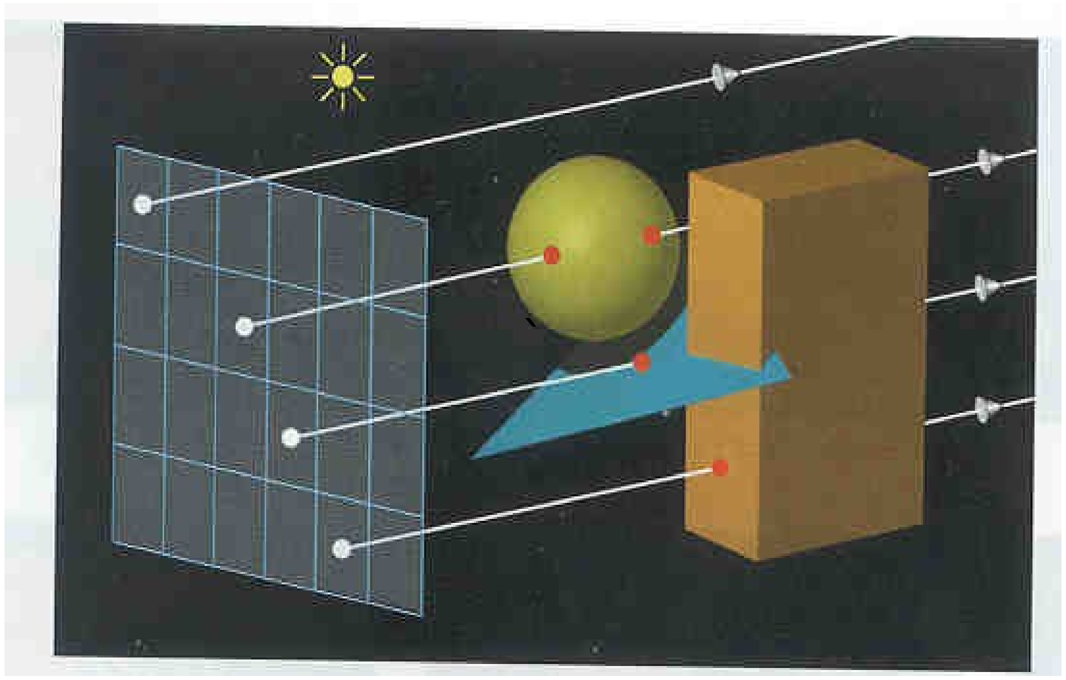
nVidia Quadra Plex 1920x1024@30fps

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 algoritms
  - 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

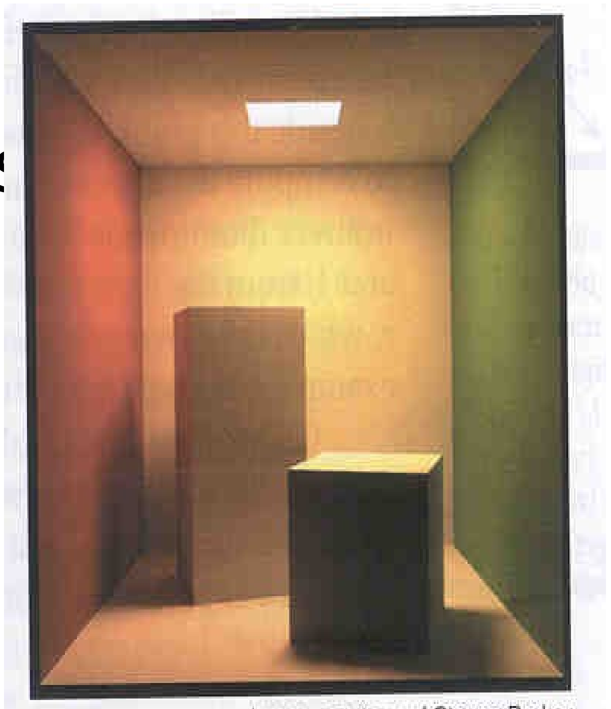


Image courtesy of Steven Parker

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

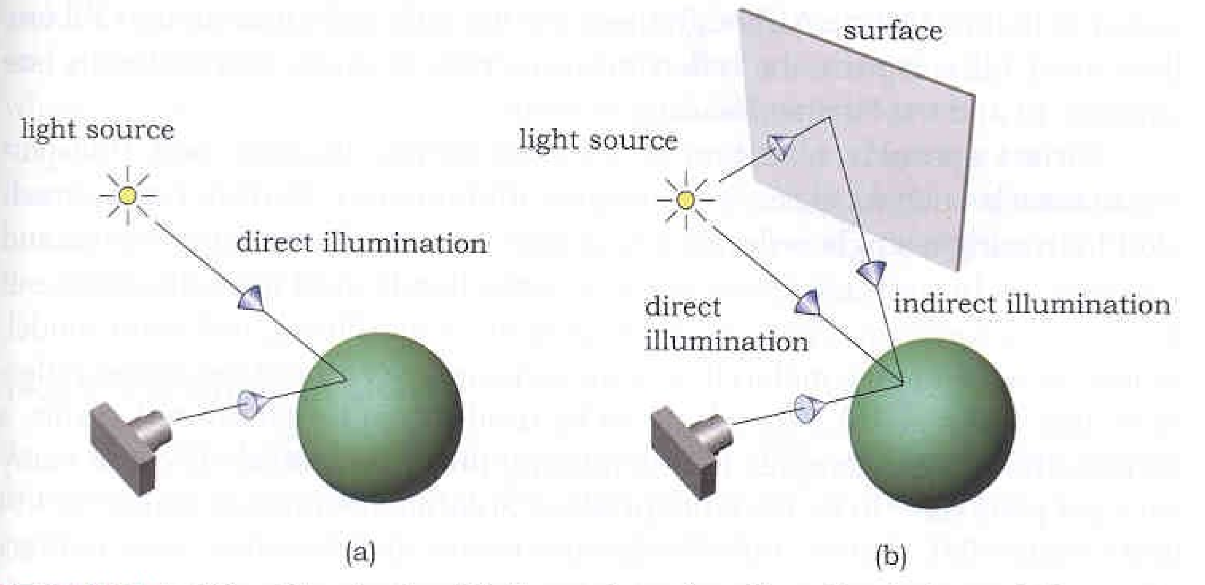


Figure 14.2. (a) Direct illumination hits the surface of an object directly from a light source; (b) indirect illumination hits a surface after being reflected from at least one other surface.

Intersections

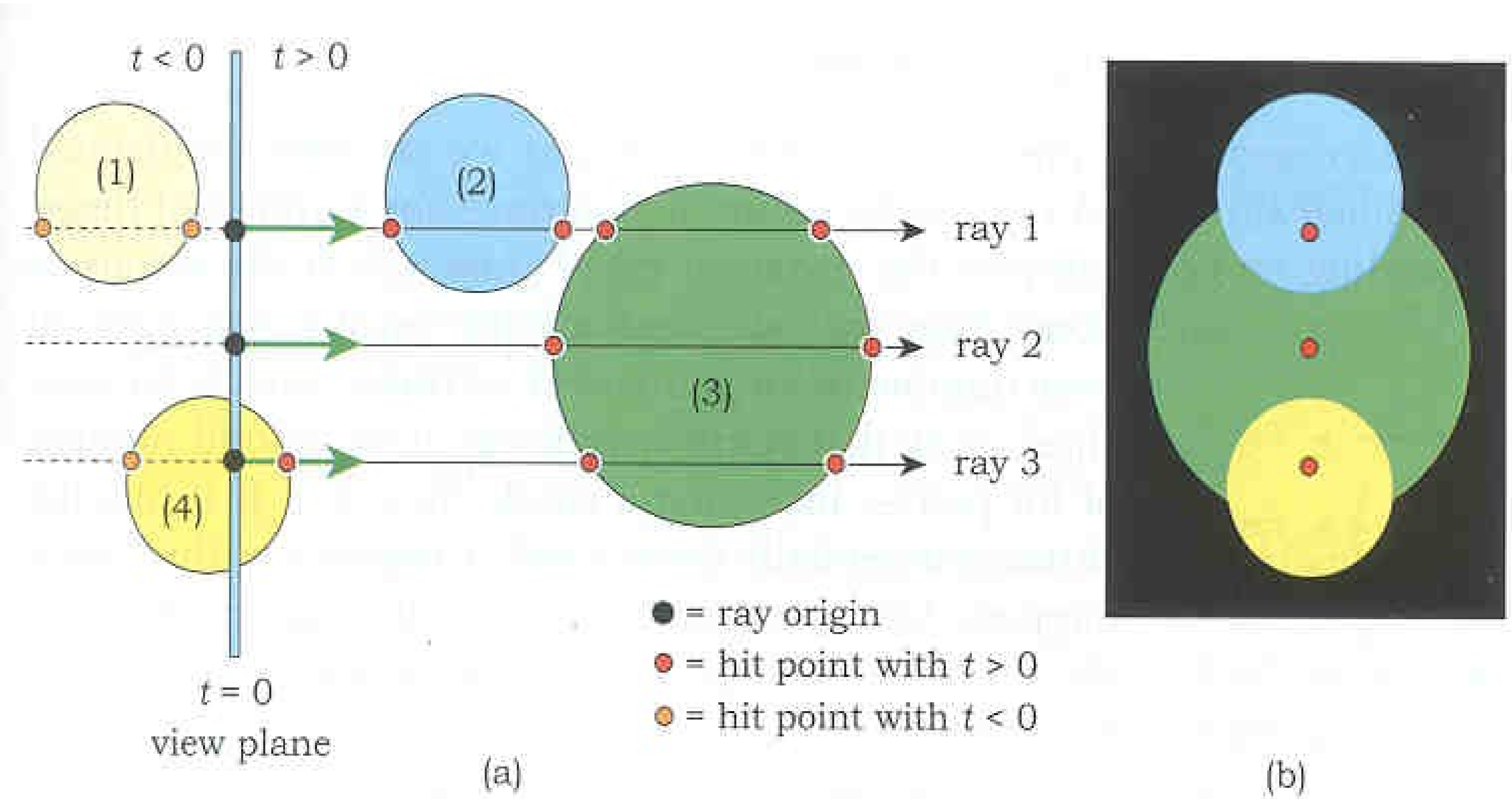


Figure 3.4. (a) Rays and their intersections with spheres; (b) ray-traced image of the spheres.

Intersecting a Sphere

- Simplest 3D object
  - Center
  - Radius
- Smooth normal
- Intersections
  - none
  - once
    - tangent
    - internal
  - twice

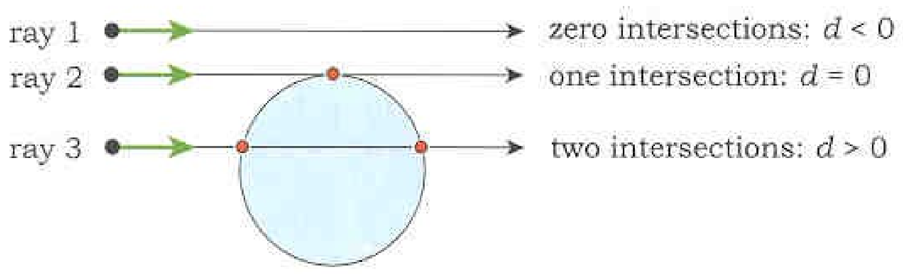

ray 1
ray 2
ray 3
zero intersections: $d < 0$
one intersection: $d = 0$
two intersections: $d > 0$

Figure 3.7. Ray-sphere intersections.

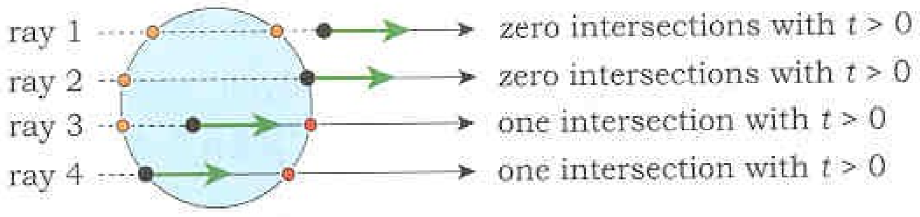

ray 1
ray 2
ray 3
ray 4
zero intersections with $t > 0$
zero intersections with $t > 0$
one intersection with $t > 0$
one intersection with $t > 0$

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

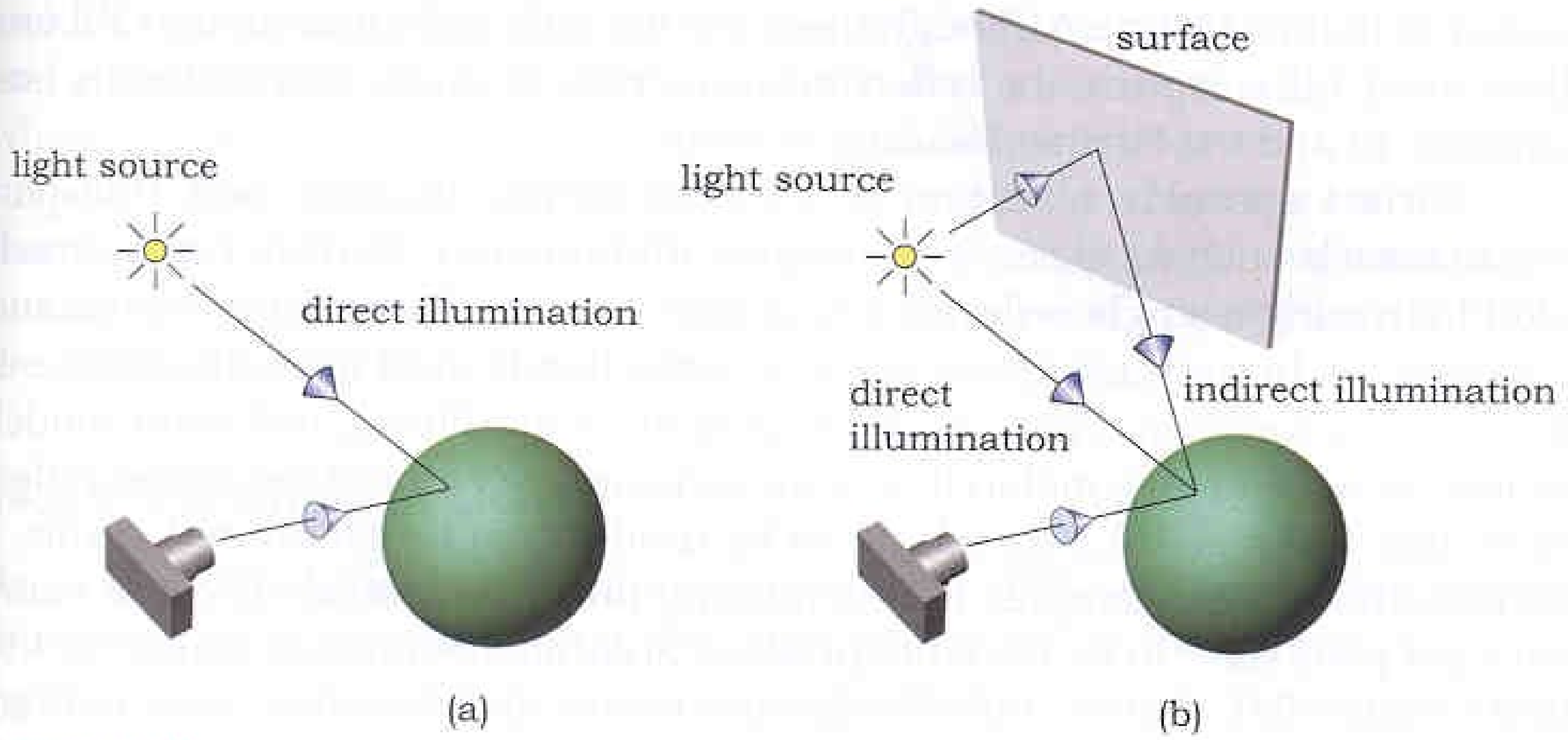


Figure 14.2. (a) Direct illumination hits the surface of an object directly from a light source; (b) indirect illumination hits a surface after being reflected from at least one other surface.

Bouncing Rays from Surfaces

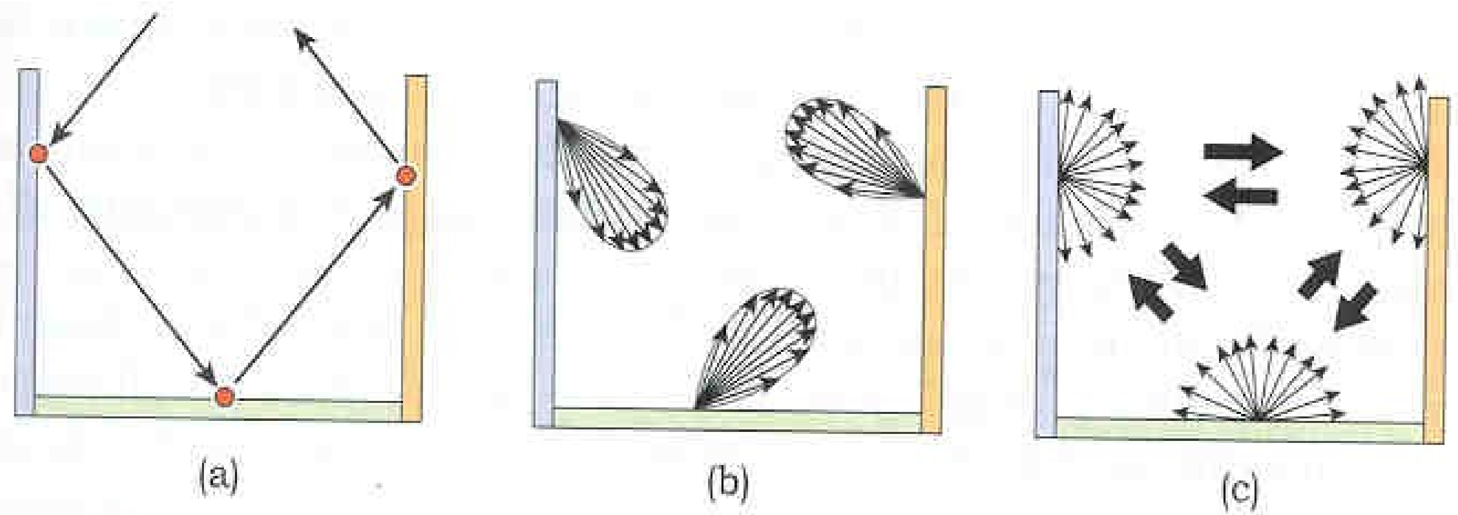


Figure 14.4. (a) Mirror reflection can be modeled by tracing a single reflected ray at each hit point; (b) modeling glossy specular light transport between surfaces requires many rays to be traced per pixel; (c) modeling perfect diffuse light transport between surfaces also requires many rays to be traced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

Light Reflection

- Diffuse (Lambertian) reflection
  - Intensity Factor N•L

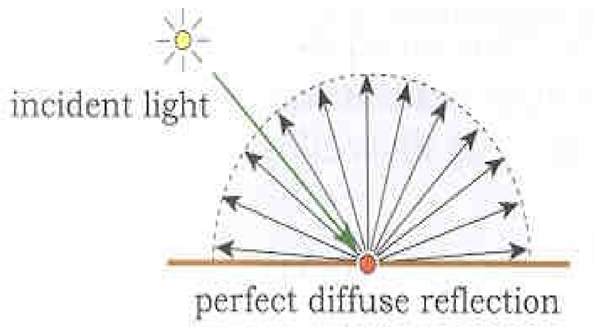


Figure 13.6. Light being scattered from a perfectly diffuse surface.

- Specular reflection
  - R = 2(N•L)N-L
  - Intensity Factor

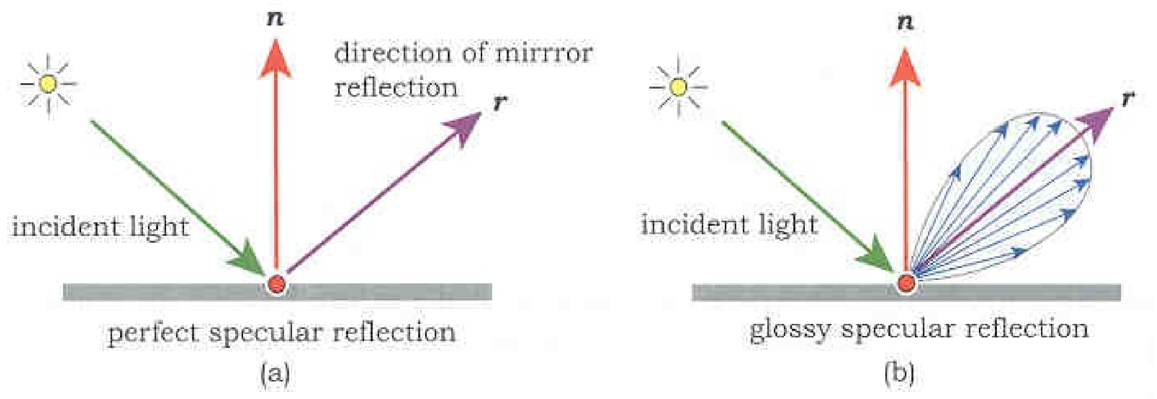

n
direction of mirrror reflection
r
incident light
perfect specular reflection
(a)
n
r
incident light
glossy specular reflection
(b)

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 $\alpha_1,\alpha_2,\alpha_3,\ldots$
- Specular Reflection Color

  $\alpha_1(C_1 + \alpha_2(C_2+\alpha_3(C_3+\ldots)))$

  $= \alpha_1 C_1 + \alpha_1\alpha_2 C_2+\alpha_1\alpha_2\alpha_3 C_3+\ldots$
- Since light is assumed to be linearly additive, just keep track of α and add light along successive bounces of the ray
- White specular means α can be a scalar

Simple Ray Tracing Algorithm

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

Ex 24: 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

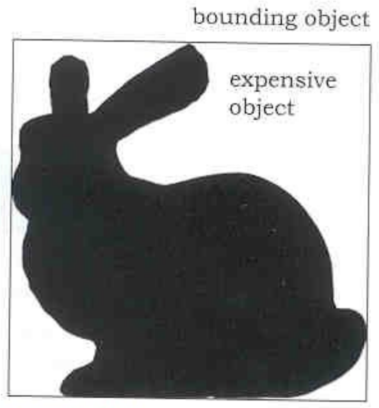


Figure 19.1. The Stanford bunny and a bounding box.

Perspective Ray Tracing

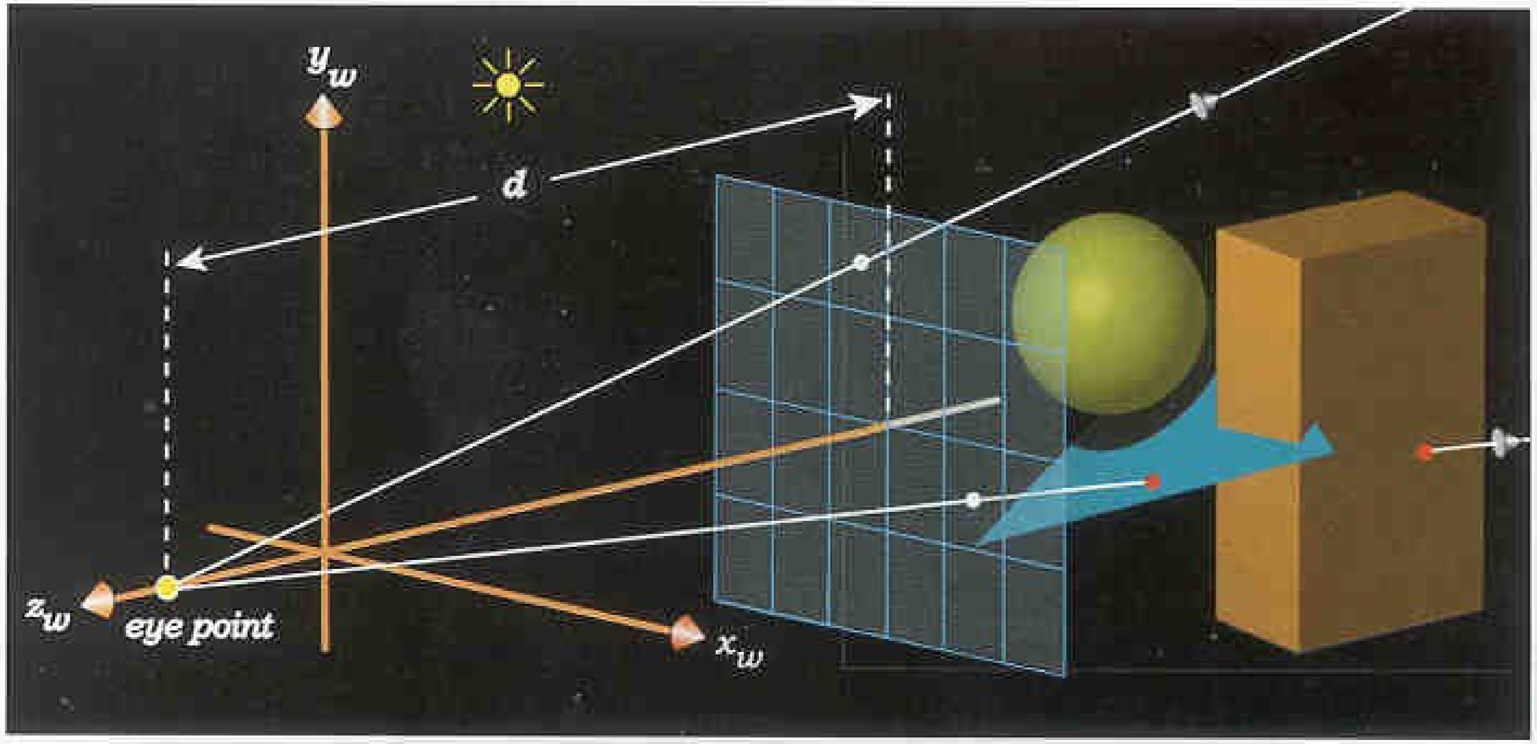
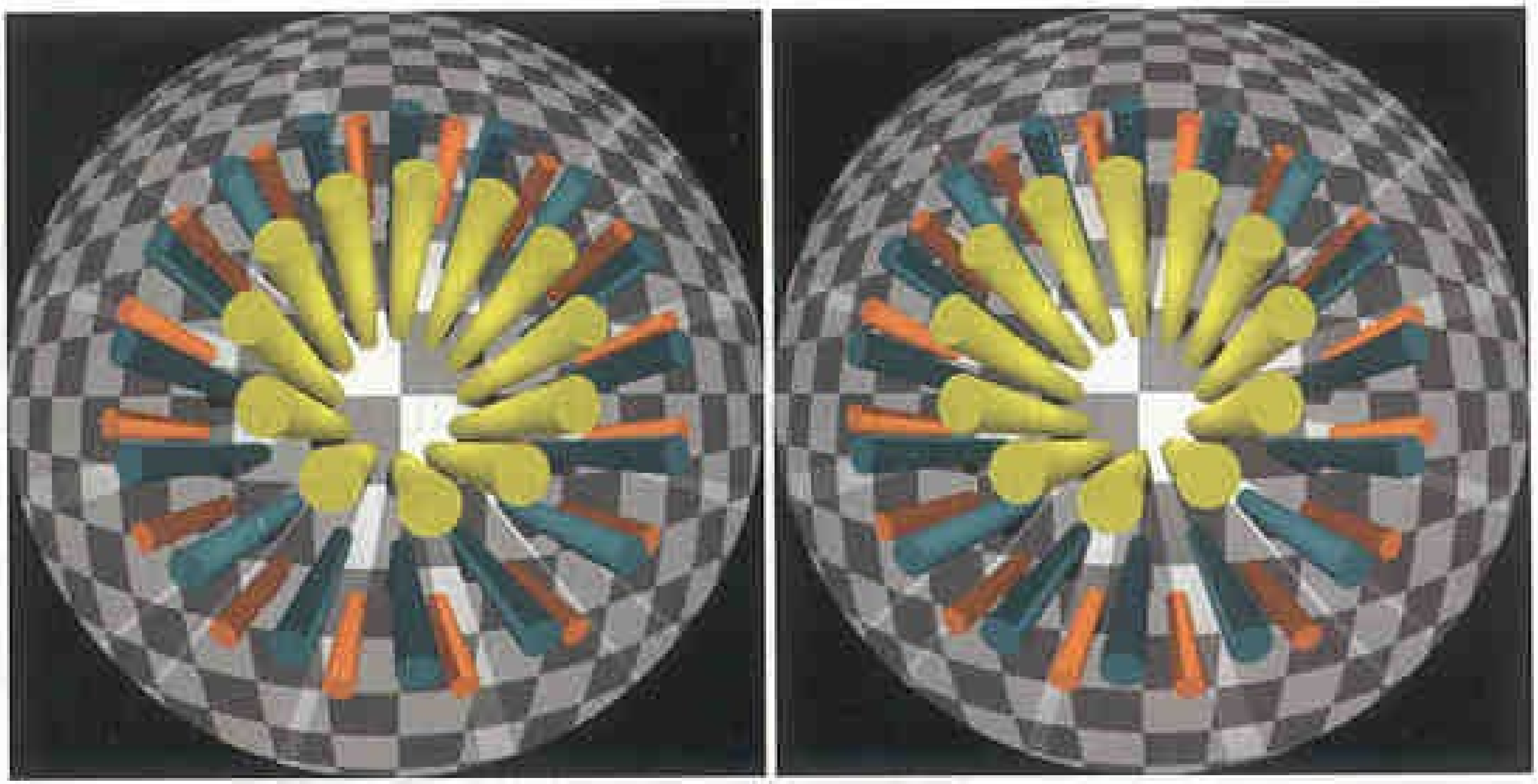


Figure 8.14. Set-up for axis-aligned perspective viewing with the eye point and two rays going through pixel centers.

Stereoscopy



Installing PBRTv3

- Build code from github
  - `git clone --recursive https://github.com/mmp/pbrt-v3.git`
  - `cd pbrt-v3`
  - `mkdir build`
  - `cd build`
  - `cmake ..`
  - `make -j8`
  - `sudo make install`
- Run using `pbrt foo.pbrt`
- Examples `ex25-3.pbrt` and `ex25-3.png`

Installing PBRTv4

- Build code from github
  - `git clone --recursive https://github.com/mmp/pbrt-v4.git`
  - `git clone git://git.pbrt.org/pbrt-v4-scenes`
  - `cd pbrt-v4`
  - `mkdir build`
  - `cd build`
  - `cmake PBRT_OPTIX7_PATH=xxxx ..`
  - `make -j8`
  - `sudo make install`
- Run using `pbrt --gpu foo.pbrt`
- Examples `ex25-4.pbrt` and `ex25-4.png`
- See differences in input with
  `diff ex25-3.pbrt ex25-4.pbrt`