CSE 168: Rendering Algorithms

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UCSD
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CSE168

- Rendering Algorithms
- Instructor: Steve Rotenberg (srotenberg@ucsd.edu)
- TA: Matteo Mannino (mtmannin@eng.ucsd.edu)
- Lecture: WLH 2204 (MWF 12:00 – 12:50pm)
- Office: EBU3 4150 (MWF 10:50 – 11:50pm)
- Lab: EBU3 basement
- Discussion: WLH 2204 (W 3:00 – 3:50pm)
- Web page:
  - http://graphics.ucsd.edu/courses/cse168_s14/index.html

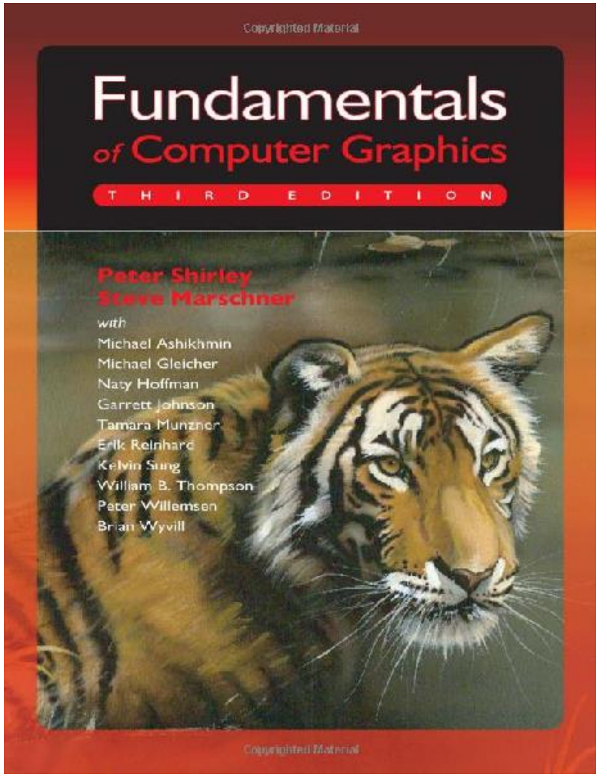
Prerequisites

- CSE167 or equivalent introduction to 3D graphics
- Familiarity with:
  – Vectors (dot products, cross products, etc.)
  – Matrices (4x4 homogeneous transforms, etc.)
  – Polygon rendering
  – Basic lighting (normals, Gouraud, Phong, etc.)
  – OpenGL, Direct3D, Java3D, or equivalent
  – Object oriented programming

Reading

- Fundamentals of Computer Graphics, Peter Shirley, Steve Marschner
- 2nd or 3rd edition

- The book is optional for this class. It covers many of the topics we will go over in class, but we won't follow the book exactly.



Programming Projects

- Project 1: Due 4/11 (Friday, week 2)
  - Basic ray tracer: render a box with basic lighting
- Project 2: Due 4/25 (Friday, week 4)
  - Add spatial data structure to efficiently render complex geometry with shadows
- Project 3: Due 5/9 (Friday, week 6)
  - Add materials, and textures
- Project 4: Due 5/23 (Friday, week 8)
  - Add path tracing
- Project 5: Due 6/6 (Friday, week 10)
  - Add your own choice of features and render a final image

Programming Projects

- You can use any programming language & operating system that you choose
- However, I would recommend using C++ for the following reasons:
  - Rendering is slow and you want a compiled language that will give you the chance of the best performance
  - Graphics tends to fit very naturally into an object oriented framework
  - There are several situations where you will need to make use of virtual functions and derived classes

Programming Assignment Turn-In

- The project must be shown to the instructor or TA before 12:00 noon on the due date (when class starts)
- They will both be in the lab from 10:00-11:50 on due days, but you can turn them in early as well
- If necessary, projects can be turned in immediately after class on due days if you speak to the instructor before hand (for example if there are too many projects to grade in time)
- If you finish on time but for some strange reason can't turn it in personally, you can email the code and images to the instructor *and* TA and demo it personally some time in the following week for full credit
- If you don't finish on time, you can turn what you have in for partial credit. Either way, you can turn it in late during the following week for -5 points. So for example on a 15 point assignment, you can turn it in for partial credit and get 6, but then finish it and turn it in late for up to 10 points
- Anything after 1 week can still be turned in but for -10 points
- Note that all projects build upon each other so you have to do them eventually…

Grading

- Project 1: 12%
- Project 2: 12%
- Project 3: 12%
- Project 4: 12%
- Project 5: 17%
- Midterm: 15%
- Final: 20%

Course Outline

1. Introduction
2. Cameras & Scenes
3. Ray Intersections
4. Fresnel Surfaces
5. Materials
6. Shadows & Area Lights
7. Spatial Data Structures 1
8. Spatial Data Structures 2
9. Antialiasing
10. Texture Mapping
11. Light Physics
12. BRDFs
13. Rendering Equation
14. Path Tracing
15. (Midterm)
16. Sampling
17. Cameras
18. Volumetric Scattering
19. Sky Rendering
20. HDR
21. Photon Mapping
22. Translucency
23. Parallel & GPU Ray Tracing
24. NPR
25. (Holiday)
26. Tessellation & Displacement
27. Procedural Texture
28. Irradiance Caching
29. Environment Mapping
30. (Review)

Rendering Overview

Computer Graphics

- The subject of computer graphics has grown over its 50 year history to include a wide range of topics
- Still, however, it is often convenient to divide it into three traditional sub-topics: *modeling*, *rendering*, and *animation*

Modeling

- Modeling deals with geometry representation, creation, and analysis
- The subject of modeling includes:
  - Techniques used to specify geometry (triangles, curved surfaces, implicit surfaces, point clouds…)
  - Operations used to generate geometry (extrusions, tessellations, Boolean, L-systems…)
  - Higher level procedural modeling (procedural plants, terrain generation…)
  - Techniques for acquiring models from the real world (laser scanning, photographic techniques…)

Animation

- Animation is the subject of movement and change over time.
- Some topics include:
  - Matrix & quaternion manipulation
  - Character animation (skeletons, skinning, blending, state machines…)
  - Physics simulation (particles, rigid bodies, fluid dynamics, deformable bodies, fracture…)
  - Dynamic visual effects, etc.

Rendering

- Rendering is the process of generating a 2D image from 3D geometry, lights, materials, and camera information
- Rendering could be further split into sub-topics: *photoreal rendering*, and *non-photoreal rendering (NPR)*
- Or another way to divide it up would be into *realtime rendering*, and *non-realtime rendering*
- For this discussion, I’ll break it into three topics: *photoreal*, *NPR*, and *realtime*

Rendering

- Realtime:
  - The goal of realtime rendering is to generate a high quality image as quickly as possible (typically around 1/60th of a second)
  - This is generally based on special-purpose hardware (GPUs) and makes use of shader programming and other graphics-specific languages (OpenGL, Direct3D, GLSL, Cg…)
  - Inspired by physics and photorealism, but compromises are required to run fast
  - Typically used for video games and other interactive applications
- Photoreal:
  - Photoreal rendering refers to the goal of making an image that is indistinguishable from a photograph
  - Photoreal rendering is based on a simulation of the actual physics of light
  - *General-purpose* photoreal rendering was a major goal of the graphics research community and *practical* solutions didn't really exist until around the year 2000
- Non-photoreal:
  - NPR refers to all other types of rendering where the goal is not to achieve photorealism
  - This mainly includes various artistic types of rendering such as methods that imitate the appearance artistic media like pencils, watercolors, and oil paints, or artistic styles such as impressionism, or even methods that imitate the styles of specific artists
  - NPR also includes methods for graphical display for non-artistic purposes, such as clear illustration of complex mechanical designs, etc.

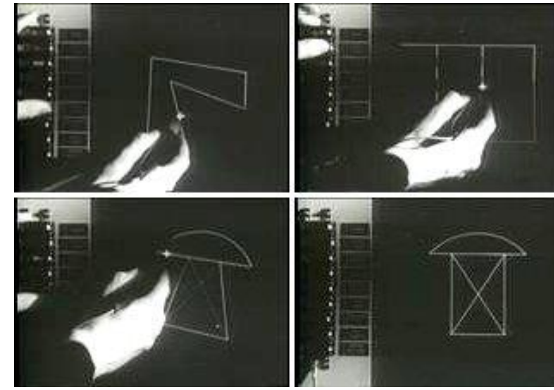
CSE168: Rendering Algorithms

- In this class, we will focus mainly on photoreal rendering algorithms
- We may have time to spend a couple lectures on NPR, but we will not be spending any time on realtime rendering
- There have been many approaches to photoreal rendering developed in the past, however, one particular class of algorithms has proven to be the most successful and general-purpose
- These are the *ray-based* approaches that evolved from the original *ray tracing* algorithm, such as *path tracing* and *photon mapping* and these will be the main focus of the class

History

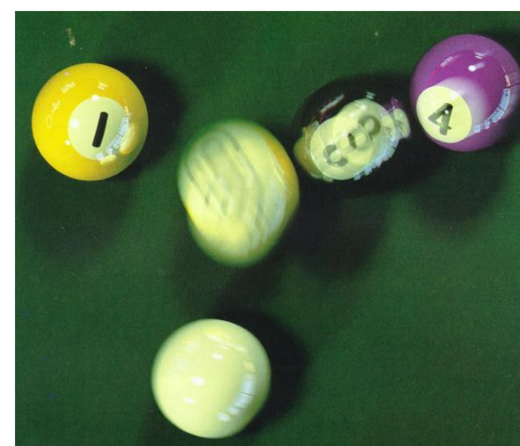
- This is a timeline of some key developments in ray-based photoreal rendering:

- 1963: ‘Sketchpad’, a project at MIT led by Ivan Sutherland, that is often considered the birth of computer graphics

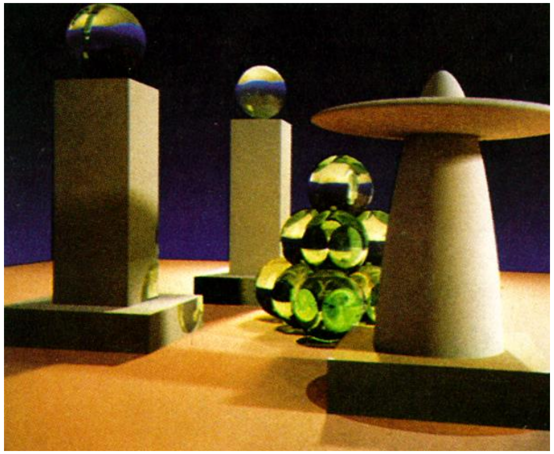


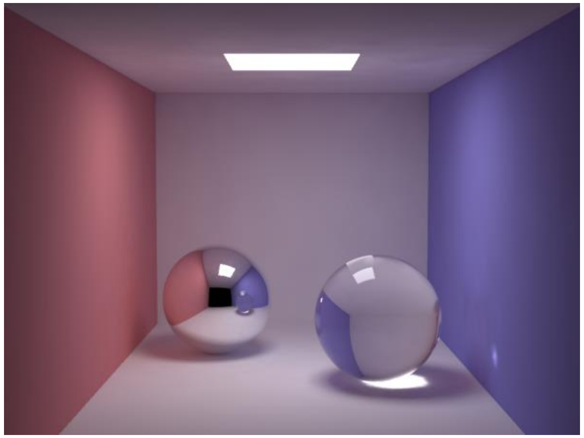
- 1980: ‘Ray-Tracing’, a rendering algorithm developed by Turner Whitted that greatly improved the quality of rendered images by adding complex shadows, reflections, and refraction

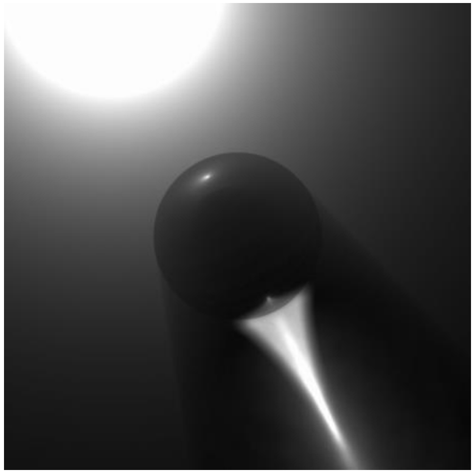
- 1984: ‘Distribution Tracing’, an extension to ray tracing that traced a distribution of multiple rays to allow for soft and blurry effects such as soft shadows, blurry reflections, motion blur, and camera focus



History





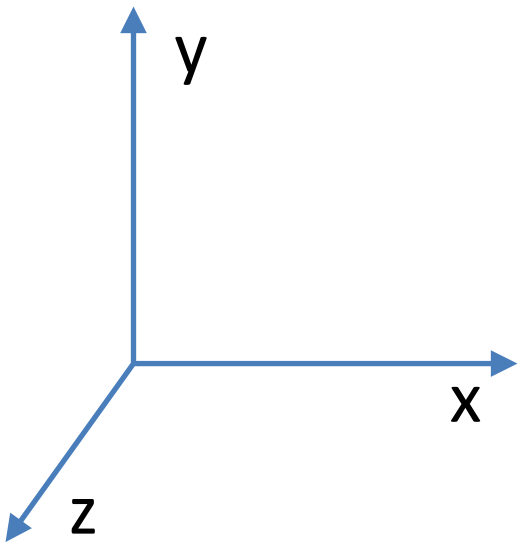


- 1986: ‘Path Tracing’, a method introduced in James Kajiya’s seminal paper called ‘The Rendering Equation’, that further extended ray tracing to become the first truly photoreal rendering algorithm, capable of all previous effects plus full global illumination and diffuse light bouncing. Path tracing was capable of great things, but was very slow on the hardware of the day
- 1995: ‘Photon Mapping’, a method introduced by UCSD’s professor Henrik Wann Jensen that works in conjunction with all previous ray based methods. Photon mapping improves the performance of many rendering situations and also makes it much more practical to handle focused light effects such as ‘caustics’ created by curved glass or mirrors, or the dancing lights at the bottom of a swimming pool
- 1998: Volumetric Photon Mapping: The photon mapping algorithm was extended to handle volumetric scattering in media like fog

Linear Algebra Review

Coordinate Systems

- Right handed coordinate system



Vector Arithmetic

$$\mathbf{a} = \begin{bmatrix} a_x & a_y & a_z \end{bmatrix}$$

$$\mathbf{b} = \begin{bmatrix} b_x & b_y & b_z \end{bmatrix}$$

$$\mathbf{a} + \mathbf{b} = \begin{bmatrix} a_x + b_x & a_y + b_y & a_z + b_z \end{bmatrix}$$

$$\mathbf{a} - \mathbf{b} = \begin{bmatrix} a_x - b_x & a_y - b_y & a_z - b_z \end{bmatrix}$$

$$-\mathbf{a} = \begin{bmatrix} -a_x & -a_y & -a_z \end{bmatrix}$$

$$s\mathbf{a} = \begin{bmatrix} sa_x & sa_y & sa_z \end{bmatrix}$$

Vector Magnitude

- The magnitude (length) of a vector is:

$$|\mathbf{v}| = \sqrt{{v_x}^2 + {v_y}^2 + {v_z}^2}$$

- A vector with length=1.0 is called a *unit vector*
- We can also *normalize* a vector to make it a unit vector:

$$\frac{\mathbf{v}}{|\mathbf{v}|}$$

Dot Product

$$\mathbf{a} \cdot \mathbf{b} = \sum a_i b_i$$

$$\mathbf{a} \cdot \mathbf{b} = a_x b_x + a_y b_y + a_z b_z$$

$$\mathbf{a} \cdot \mathbf{b} = |\mathbf{a}||\mathbf{b}|\cos\theta$$

$$\mathbf{a} \cdot \mathbf{b} = \mathbf{a}^T \mathbf{b}$$

$$\mathbf{a} \cdot \mathbf{b} = \begin{bmatrix} a_x & a_y & a_z \end{bmatrix} \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix}$$

Properties of the Dot Product

- $\mathbf{a} \cdot \mathbf{b}$ is a scalar value that tells us about the relationship of two vectors
- If the dot product is positive, it means the angle between the vectors is less than 90 degrees and if its negative, the angle is more than 90 degrees
- If the dot product is 0, then the two vectors are either perpendicular or one or both are degenerate (0,0,0)

Cross Product

$$\mathbf{a} \times \mathbf{b} = \begin{vmatrix} i & j & k \\ a_x & a_y & a_z \\ b_x & b_y & b_z \end{vmatrix}$$

$$\mathbf{a} \times \mathbf{b} = [a_y b_z - a_z b_y \quad a_z b_x - a_x b_z \quad a_x b_y - a_y b_x]$$

Properties of the Cross Product

- $\mathbf{a} \times \mathbf{b}$ is a *vector* perpendicular to both **a** and **b**, in the direction defined by the right hand rule

- The *magnitude* of the cross product:

$$|\mathbf{a} \times \mathbf{b}| = |\mathbf{a}||\mathbf{b}|\sin\theta$$

$$|\mathbf{a} \times \mathbf{b}| = \text{area of parallelogram } \mathbf{ab}$$

$$|\mathbf{a} \times \mathbf{b}| = 0 \text{ if } \mathbf{a} \text{ and } \mathbf{b} \text{ are parallel}$$

Vector Class

```
class Vector3 {
public:
    Vector3()                                          {x=0.0f; y=0.0f; z=0.0f;}
    Vector3(float x0,float y0,float z0)                {x=x0; y=y0; z=z0;}
    void Set(float x0,float y0,float z0)               {x=x0; y=y0; z=z0;}
    void Add(Vector3 &a)                               {x+=a.x; y+=a.y; z+=a.z;}
    void Add(Vector3 &a,Vector3 &b)                    {x=a.x+b.x; y=a.y+b.y; z=a.z+b.z;}
    void Subtract(Vector3 &a)                          {x-=a.x; y-=a.y; z-=a.z;}
    void Subtract(Vector3 &a,Vector3 &b)               {x=a.x-b.x; y=a.y-b.y; z=a.z-b.z;}
    void Negate()                                      {x=-x; y=-y; z=-z;}
    void Negate(Vector3 &a)                            {x=-a.x; y=-a.y; z=-a.z;}
    void Scale(float s)                                {x*=s; y*=s; z*=s;}
    void Scale(Vector3 &a,float s)                     {x=s*a.x; y=s*a.y; z=s*a.z;}
    float Dot(Vector3 &a)                              {return x*a.x+y*a.y+z*a.z;}
    void Cross(Vector3 &a,Vector3 &b)                  {x=a.y*b.z-a.z*b.y; y=a.z*b.x-a.x*b.z; z=a.x*b.y-a.y*b.x;}
    float Magnitude()                                  {return sqrtf(x*x+y*y+z*z);}
    void Normalize()                                   {Scale(1.0f/Magnitude());}

    float x,y,z;
};
```

Translation

- Let’s say we have a 3D model that has an array of position vectors describing its shape: $\mathbf{v}_n$ where $0 \le n < NumVerts$
- Say we want to move our 3D model from its current location to somewhere else…
- We want to compute a new array of positions $\mathbf{v}'_n$ representing the new location
- If the vector **d** represents the relative offset that we want to move our object by, then we can compute $\mathbf{v}'_n = \mathbf{v}_n + \mathbf{d}$ to compute the new array of positions

Transformations

$$\mathbf{v}'_n = \mathbf{v}_n + \mathbf{d}$$

- This translation represents a very simple example of an object *transformation*
- The result is that the entire object gets moved or *translated* by $\mathbf{d}$
- From now on, we will drop the $_n$ subscript and just write

$$\mathbf{v}' = \mathbf{v} + \mathbf{d}$$

- Just keep in mind that this is actually a loop over several *different* $\mathbf{v}_n$ vectors applying the *same* vector $\mathbf{d}$ every time

Rotation

- Now, let's rotate the object in the *xy* plane by an angle θ, as if we were spinning it around the *z* axis

$$
\begin{aligned}
v'_x &= v_x \cos\theta - v_y \sin\theta \\
v'_y &= v_x \sin\theta + v_y \cos\theta \\
v'_z &= v_z
\end{aligned}
$$

- Note: a *positive* rotation will rotate the object *counterclockwise* when the rotation axis (z) is pointing *towards* the observer

Rotation

$$v'_x = v_x \cos\theta - v_y \sin\theta$$
$$v'_y = v_x \sin\theta + v_y \cos\theta$$
$$v'_z = v_z$$

- We can re-write this in matrix form as:

$$\begin{bmatrix} v'_x \\ v'_y \\ v'_z \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}$$

- Or just:

$$\mathbf{v}' = \mathbf{M} \cdot \mathbf{v}$$

Matrix Transformations

- We can rotate a vector by multiplying it by a 3x3 rotation matrix
- We can also do other *linear transformations* with a 3x3 matrix such as:
  - Uniform & non-uniform scale
  - Shear (i.e., turning a rectangle into a parallelogram)
  - Reflection
- However, we can’t use a 3x3 matrix to perform a translation

Homogeneous Transforms

- So, in computer graphics, we use 4x4 *homogeneous matrices* to combine translations with rotations (and shears, scales, and reflections)
- We can also integrate viewing transformations such as perspective projections into this system, however it turns out that we won't need to do that in this class, and all of our 4x4 transformation matrices will have the form:

$$\mathbf{M} = \begin{bmatrix} a_x & b_x & c_x & d_x \\ a_y & b_y & c_y & d_y \\ a_z & b_z & c_z & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Positions & Directions

- Both positions and directions can be represented as 3D vectors
- When we transform a 3D vector with a 4x4 matrix, we have to turn the 3D vector into a 4D vector
- For positions, we put a 1 in the 4^{th} coordinate (w-coordinate), and for directions, we put a 0 in the 4^{th} coordinate
- The result is that a position gets rotated & translated by the matrix, but a direction only gets rotated

Positions & Directions

$$\mathbf{p} = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \rightarrow \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix}$$

$$\mathbf{p}' = \begin{bmatrix} a_x & b_x & c_x & d_x \\ a_y & b_y & c_y & d_y \\ a_z & b_z & c_z & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix}$$

$$\mathbf{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} \rightarrow \begin{bmatrix} n_x \\ n_y \\ n_z \\ 0 \end{bmatrix}$$

$$\mathbf{n}' = \begin{bmatrix} a_x & b_x & c_x & d_x \\ a_y & b_y & c_y & d_y \\ a_z & b_z & c_z & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} n_x \\ n_y \\ n_z \\ 0 \end{bmatrix}$$

Object Space

- The space that an object is defined in is called *object space* or *local space*
- Usually, the object is located at or near the origin and is aligned with the xyz axes in some reasonable way
- The units in this space can be whatever we choose (i.e., meters, etc.)
- A 3D object would be stored on disk and in memory in this coordinate system
- When we go to draw the object, we will want to transform it into a different space

World Space

- We will define a new space called *world space* or *global space*
- This space represents a 3D world or scene and may contain several objects placed in various locations
- Every object in the world needs a matrix that transforms its vertices from its own object space into this world space
- We will call this the object's *world matrix*, or often, we will just call it the object's matrix
- For example, if we have 100 chairs in the room, we only need to store the object space data for the chair once, and we can use 100 different matrices to transform the chair model into 100 locations in the world

ABCD Vectors

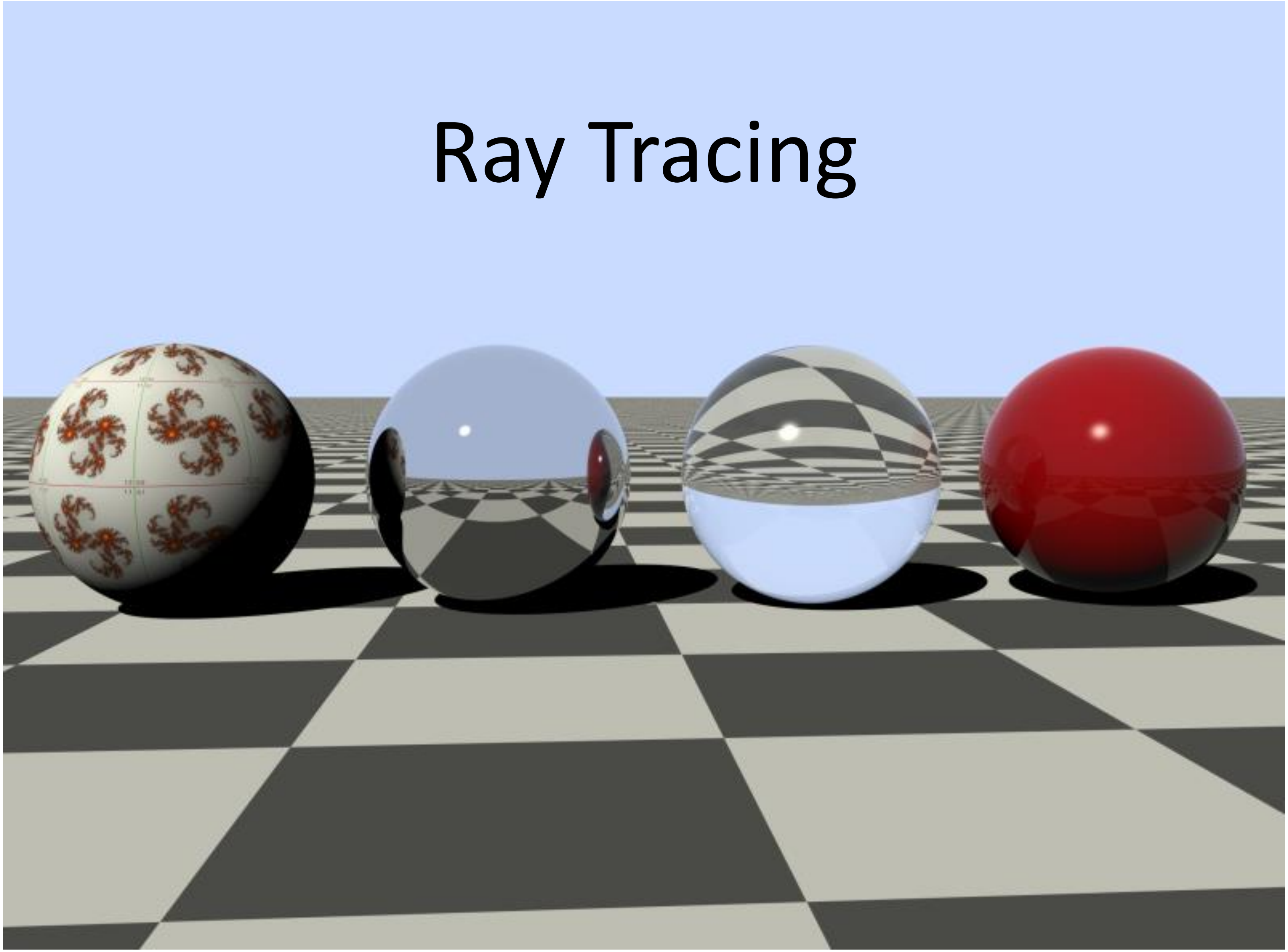
$$\mathbf{M} = \begin{bmatrix} a_x & b_x & c_x & d_x \\ a_y & b_y & c_y & d_y \\ a_z & b_z & c_z & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- As the bottom row of our 4x4 matrices will always be 0 0 0 1, we can really think of the matrix as having only 12 relevant numbers, broken into 4 vectors, **a**, **b**, **c**, and **d**
- Vector **d** represents the translation of the matrix
- If we think of the matrix as transforming from object space to world space, then the **a** vector represents the object's x-axis rotated into world space, **b** is its y-axis in world space and **c** is its z-axis

Matrix Class

```
class Matrix34 {
public:
        Matrix34();

        void Dot(const Matrix34 &m,const Matrix34 &n);

        void Transform(const Vector3 &in,Vector3 &out) const;
        void Transform3x3(const Vector3 &in,Vector3 &out) const;

        void Inverse();
        void Transpose();

        void MakeRotateX(float t);
        void MakeRotateY(float t);
        void MakeRotateZ(float t);

        etc.
public:
        Vector3 a,b,c,d;
};
```

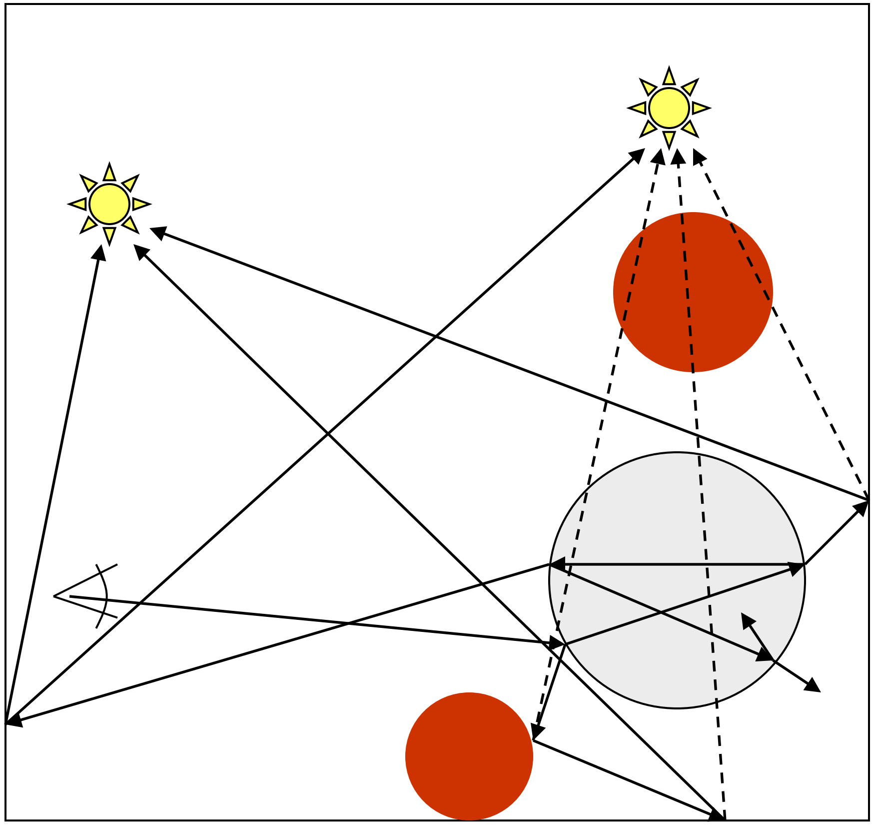
Ray Tracing

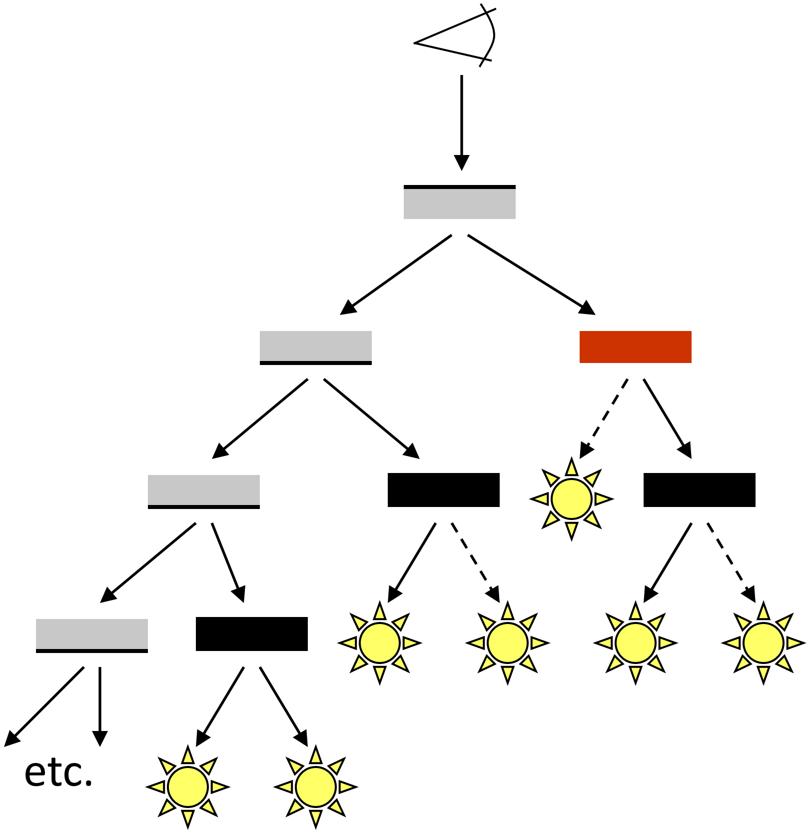


Ray Tracing

- Ray tracing involves tracing virtual rays throughout a 3D environment to determine object visibility and lighting
- Classic ray tracing shoots rays out from the camera position through each pixel to determine the first surface (triangle) hit
- From there, other rays can be spawned from the intersection point towards each light source to determine if the point is lit or in shadow
- Additional rays can be traced to simulate reflections off of mirrored surfaces or refraction through surfaces such as glass

Recursive Ray Tracing





Rays

- We think of a ray as starting at an origin **p** and then shooting off infinitely in some direction **d**

$$\mathbf{r}(t) = \mathbf{p} + t\mathbf{d}$$

- Where $\mathbf{r}(t)$ is a function representing the ray and t is the distance traveled along the ray
- Usually, when we're rendering, we're interested in finding the first surface hit along the ray's travel from the origin, or the intersection with the smallest value of t (but larger than 0)

Ray Class

```
class Ray {
public:
		Vector3 Origin;
		Vector3 Direction;
};
```

NOTE: All data is public because the ray is a low-level class storing simple data.

Also note that the Vector3 constructors will run automatically, making it unnecessary to have a Ray constructor

Ray Intersection

- The fundamental operation in a ray tracer is the *ray intersection* routine
- The ray starts at a point known as the ray *origin* and shoots off in a 3D *direction*
- The ray shoots into a 3D environment with potentially millions of triangles or other primitives
- We are interested in knowing the *first* surface the ray hits
- The *ray intersection* routine takes a ray as input, as well as a scene containing geometry, and determines if and where the ray hits

```
bool Scene::Intersect(const Ray &ray,Intersection &hit);
```

Intersection Class

```
class Intersection {
public:
	Intersection()		{Mtl=0; Obj=0; HitDistance=1e10;}

	// Results of intersection test
	float HitDistance;
	Vector3 Position;
	Vector3 Normal;
	Material *Mtl;

	// Results of shading
	Color Shade;
};
```

NOTE: We will talk about Materials and Colors in a future lecture

Shading

- Once we have found an intersection (and the associated normal and material properties) we can do the process of *shading*
- Shading involves all of the calculations that compute the color reflected back along the initial ray towards the viewer
- This may (and often does) involve recursively tracing additional rays to determine shadows, reflections, and refractions

Ray Intersection & Shading

- Together, ray intersection and shading make up the two main routines in a ray tracer
- They are also the fundamental routines used in extensions such as path tracing and photon mapping

Ray Intersection Performance

- The fundamental issue of ray intersection is handling large scene complexity with reasonable performance
- Scenes often contain millions of triangles and one must trace millions of rays to render an image
- Consider a 800 x 600 image with two light sources and no reflective or refractive materials
- One must trace 800 x 600 = 480000 initial rays from the camera
- Assuming 2/3 of these hit objects (1/3 hit the sky), we then have to spawn two additional shadow rays, for an additional 640000 ray intersections and a total of 1.12 million rays
- High quality lighting and rendering effects often involve testing hundreds or thousands of rays *per pixel*
- Therefore, the performance of the ray intersection test is *critical*

Shading Performance

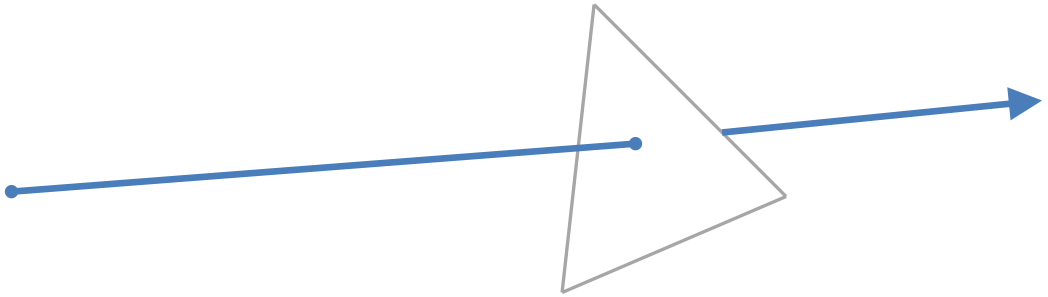
- Shading functions are called many times, but less than ray intersection (maybe 10%-50% as often)
- Shading functions often contain relatively quick computations and so aren’t usually too expensive in themselves
- However, most shading involves recursively spawning more rays, which means more intersection and more shading
- Therefore, optimizing shading functions typically involves making them spawn as few rays as possible to produce the desired image quality

Triangles

- Triangles are used throughout computer graphics as the primitive of choice for rendering
- Most ray tracers *only* support triangles at the low level, and only perform actual ray intersection testing with triangles
- However, other surface types (such as curved surfaces, NURBS, subdivision surfaces, spheres, cylinders, implicit surfaces…) can still be supported as long as they can be *tessellated* into a bunch of small triangles
- This way, any surface type can be supported as long as they provide a tessellation routine
- Optionally, one could also implement ray intersection routines for each of those surface types, but in most cases, it significantly impacts the performance of ray intersection testing, and this is generally not done in commercial renderers

Ray-Triangle Intersection

- The ray-triangle intersection test is at the heart of the ray intersection problem, and often makes up the single biggest performance bottleneck in most ray tracers
- We will look at some ray-triangle intersection algorithms in an upcoming lecture



Vertex Class

```
class Vertex {
public:
	Vector3 Position;
	Vector3 Normal;
	Vector3 TexCoord;
};
```

NOTE: We’ll use a Vector3 for the TexCoord so we don’t need to implement a Vector2 class. Also, we can use it later to support 3D textures…

Triangle Class

```
class Triangle {
public:
	Triangle();

	bool Intersect(const Ray &ray, Intersection &hit);

private:
	Vertex *Vtx[3];
	Material *Mtl;
};
```

Project 1

- Project 1 will be a basic ray tracer that can render a box
- It will be defined in detail in the next lecture
- If you want to get started early, you can start with the Ray, Intersection, Vertex, and Triangle classes defined within and implement the function Triangle::Intersect()