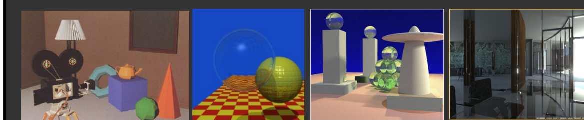
Computer Graphics II: Rendering

CSE 168 [Spr 25], Lecture 1: Overview and Ray Tracing

Ravi Ramamoorthi

http://viscomp.ucsd.edu/classes/cse168/sp25/



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Goals

- **Systems:** Write a modern 3D image synthesis program (path tracer with importance sampling)
- **Theory:** Mathematical aspects and algorithms underlying modern physically-based rendering
- **Topics:** Other modern topics like image-based, real-time, precomputed, volumetric rendering
- This course is ***not*** about the specifics of 3D rendering software like PBRT, Mitsuba etc. New, we optionally encourage OptiX, a real-time raytracing API for NVIDIA GPUs

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Instructor

Ravi Ramamoorthi http://www.cs.ucsd.edu/~ravir

- PhD Stanford, 2002 [with Pat Hanrahan, 2020 Turing Award] "*Spherical Harmonic Lighting*" widely used in games (e.g. Halo series), movies (e.g. Avatar), etc. (Adobe, …)
- At Columbia 2002-2008, UC Berkeley 2009-2014
- *"Monte Carlo denoising"* inspired raytracing offline, real-time
- At UCSD since Jul 2014: Director, Center for Visual Computing
- Awards for research: White House PECASE (2008), SIGGRAPH Significant New Researcher (2007), ACM Fellow
- https://www.youtube.com/watch?v=qpyCXqXGe7I
- Computer Graphics online MOOC (CSE 167x) finalist for two edX Prizes. Will use CSE 168 MOOC on edX edge as a feedback system

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Course Staff

- Ravi Ramamoorthi, ravir@cs.ucsd.edu
- Teaching Assistants:
  - Nithin Raghavan [n2raghavan@ucsd.edu]
  - Please see website (and piazza) for office hours etc.

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Rendering: 1960s (visibility)

- Roberts (1963), Appel (1967) - hidden-line algorithms
- Warnock (1969), Watkins (1970) - hidden-surface
- Sutherland (1974) - visibility = sorting

Images from FvDFH, Pixar's Shutterbug
Slide ideas for history of Rendering courtesy Marc Levoy

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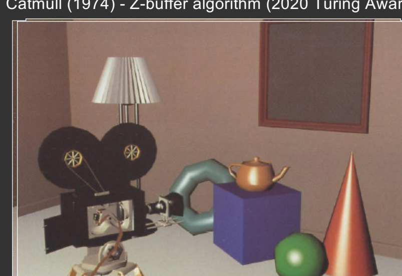
Rendering: 1970s (lighting)

1970s - raster graphics

- Gouraud (1971) - diffuse lighting, Phong (1974) - specular lighting
- Blinn (1974) - curved surfaces, texture
- Catmull (1974) - Z-buffer algorithm (2020 Turing Award)



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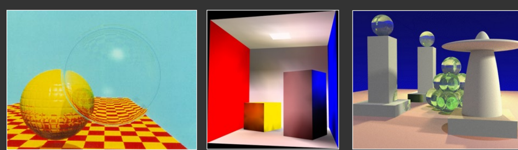
Rendering (1980s, 90s: Global Illumination)

early 1980s - global illumination
- Whitted (1980) - ray tracing
- Goral, Torrance et al. (1984) radiosity
- Kajiya (1986) - the rendering equation, path tracing (this is what this course is about, modern rendering)



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Why Study Computer Graphics Rendering?

- Applications (Movies, Games, Digital Advertising, Lighting Simulation, Digital Humans, Virtual Reality)
- Fundamental Intellectual Challenges
  - Create *photorealistic* virtual world
  - Understand physics *and* computation of light transport
  - Physically-based rendering has replaced ad-hoc approaches in industry (offline ~ 2011, real-time ~2018)
- Beautiful Imagery: Realistic Computer Graphics
  - 2020 Turing Award given for CGI in Filmmaking
- Assume taken CSE 167 or equivalent (+done well)
  - This is a challenging course, work starts immediately
  - (First 2 weeks on raytracing may be review for some)

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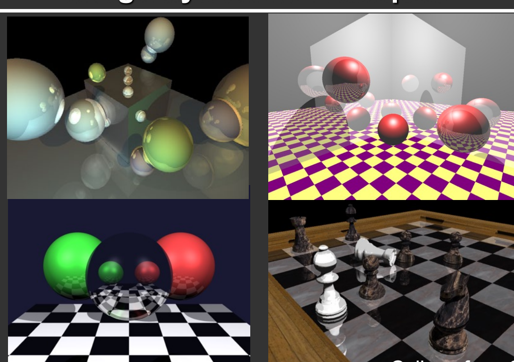
Image Synthesis Examples



Collage from 2007

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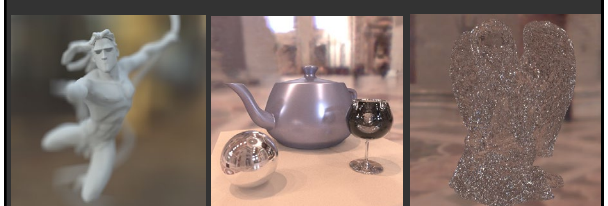
From UCB CS 294 16 years ago



Daniel Ritchie and Lita Cho

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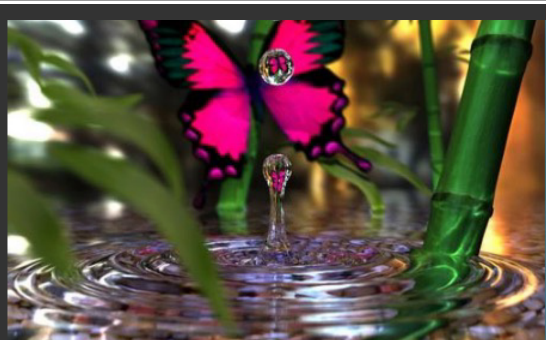
CSE 168 Contest 2007: Butterfly



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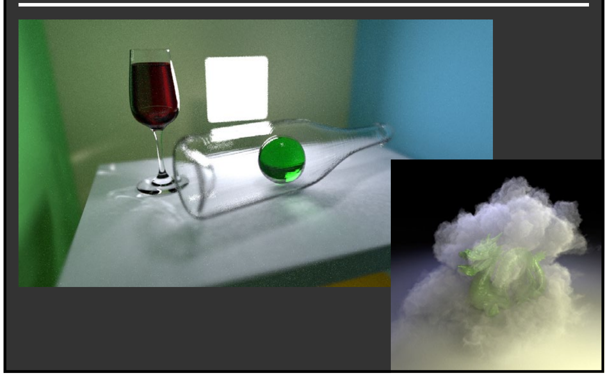
CSE 168 Spring 2020



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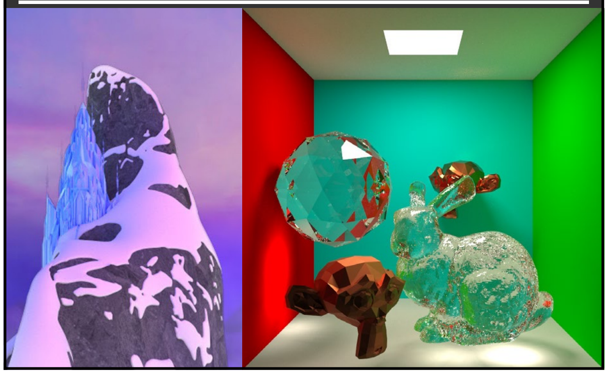
CSE 168 Spring 2021



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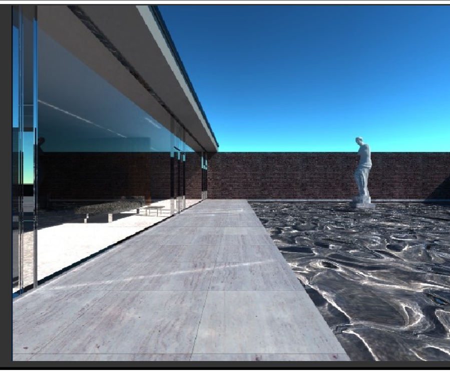
Mies House: Swimming Pool



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Logistics

- Website https://viscomp.ucsd.edu/classes/cse168/sp25/168.html has most of the information (look at it carefully)
- *We will be leveraging full MOOC infrastructure (use private SPOC)*
  - Please join course course on edX edge: **DEMO**
  - Compulsory for most assignments, feedback systems
  - *Must still submit "official" CSE 168 assignment (see website)*
  - Please do ask us if you are confused; we are here to help
  - No required texts; optional PBRT book, Digital Image Synthesis
  - Office hours: after class (Tu/Thu 11-12) in CSE 4118
- Course newsgroup on Piazza, or can use edX edge directly
- Website for late, collaboration policy (groups of 2), etc
- Do try to attend class sessions (and discussions, keep assigned section)
- Questions?

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This is a Modernized Course

- Teach Modern Physically-Based Rendering and Path Tracing, as used in industry (Prof. consulted with Pixar on change to physically-based shading, importance sampling in 2011, written many key papers; consults NVIDIA)
- Emphasis on step-by-step development, get it right (lots of subtle math, compare to reference solutions)
- Focus on offline but discuss real-time, image-based, PRT
- Homework starts right away, due in 2 weeks
- New developments: NVIDIA OptiX ray-tracing API like OpenGL, since 2018 RTX cards 10G rays/second Video
- Encourage (but optional) use of OptiX. If you use this, setup yourself but basic skeleton provided. Or really slow.

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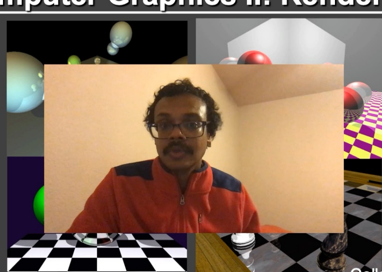
Computer Graphics II: Rendering



Collage from 2007

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Innovation: Feedback Servers

- Feedback/Grading servers for homeworks 1-4
- Submit images, compare to original
  - Program generates difference images, report url
  - Can get feedback multiple times; submit final url
  - All run on edX edge (also have alternative standalone)
- "Feedback" not necessarily grading
  - Can run extra test cases, look at code, grade fairly
  - But use of feedback servers/edX edge is mandatory
  - Note for this course; unlike 167 results not deterministic, will give information re noise/variance
  - Can use any laptop/desktop, do it offline or in OptiX
- Will test out with HW 1 images

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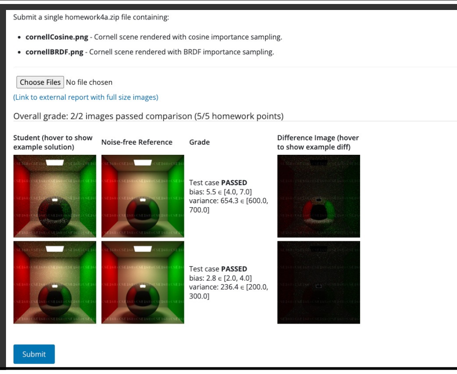
Demo of edX edge, Feedbacks



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Workload

- Lots of fun, rewarding but may involve significant work
  - Previous reviews: "Undergraduate in name only" "Most time consuming course at UCSD"
- 5 programming projects; almost all are time-consuming. Can be done in groups of two. START EARLY !!
- Graded entirely on programming, weights on 168 website
  - Writeups on 168 website for assignments really good, look at them
- Prerequisites: CSE 167, did well, enjoyed it
- First homework last assignment in my CSE 167
  - Little bit of sink or swim to continue in course (but we will also provide OptiX, embree references after assignment is due)
  - But not everyone has done a raytracer before, some additional requirements for those who have already done one
- Should be a difficult, but fun and rewarding course

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Quick Inclusion Note

Since I do occasionally get asked this question:

- You are welcome to take this course if color-blind
  - Let me know if I create too many red-green metamers
  - Some of the best-known computer graphics researchers have been color-blind (ask re some stories)
- And for most other vision issues
  - We've even had computer graphics award winners who have been extremely nearsighted (legally blind)

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CSE 168 is only a first step

- *If you enjoy CSE 168 and do well*:
- CSE 165 (VR course; Schulze)
- Next winter: 169 (Animation)
- Graduate: CSE 272, 274 (Topics), 273, many 291s

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To Do

- Look at website
- Various policies for course. E-mail if confused.
- Sign up for edX edge, Piazza, etc.
- Skim assignments if you want. All are ready
- Assignment 1, Due Apr 14 (see website).
- Any questions?
- Start now with raytracing lecture

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Effects needed for Realism

- (Soft) Shadows
- Reflections (Mirrors and Glossy)
- Transparency (Water, Glass)
- Interreflections (Color Bleeding)
- Complex Illumination (Natural, Area Light)
- Realistic Materials (Velvet, Paints, Glass)
- And many more

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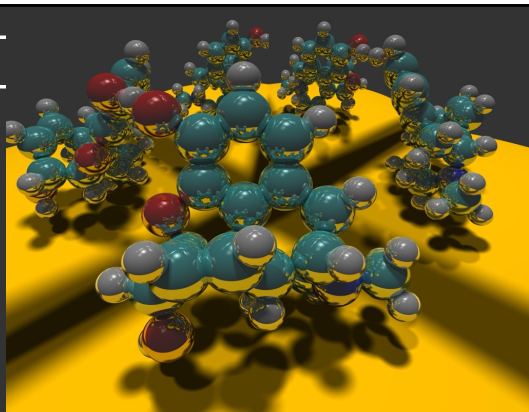

Image courtesy Paul Heckbert 1983

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Ray Tracing

- Different Approach to Image Synthesis as compared to Hardware pipeline (OpenGL)
- Pixel by Pixel instead of Object by Object
- Easy to compute shadows/transparency/etc

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Outline

- *History*
- Basic Ray Casting (instead of rasterization)
  - Comparison to hardware scan conversion
- Shadows / Reflections (core algorithm)
- Optimizations
- Current Research

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Ray Tracing: History

- Appel 68
- Whitted 80 [recursive ray tracing]
  - Landmark in computer graphics
- Lots of work on various geometric primitives
- Lots of work on accelerations
- Current Research
  - Real-Time raytracing (historically, slow technique)
  - Ray tracing architecture

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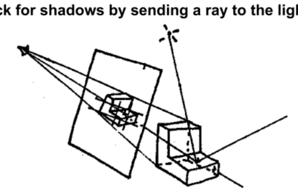
Ray Tracing History

Ray Tracing in Computer Graphics

Appel 1968 - Ray casting

1. Generate an image by sending one ray per pixel
2. Check for shadows by sending a ray to the light



CS348B Lecture 2 Pat Hanrahan, Spring 2009

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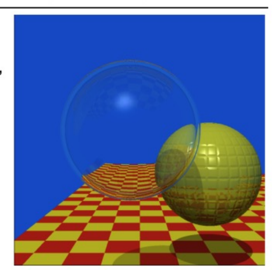
Ray Tracing History

Ray Tracing in Computer Graphics

"An improved Illumination model for shaded display," T. Whitted, CACM 1980

Resolution:
512 x 512

Time:
VAX 11/780 (1979)
74 min.
PC (2006)
6 sec.



Spheres and Checkerboard, T. Whitted, 1979

CS348B Lecture 2 Pat Hanrahan, Spring 2009

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From SIGGRAPH 18

Real Photo: Instructor and Turner Whitted at SIGGRAPH 18

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Outline

- History
- *Basic Ray Casting (instead of rasterization)*
  - Comparison to hardware scan conversion
- Shadows / Reflections (core algorithm)
- Optimizations
- Current Research

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Ray Casting

Produce same images as with OpenGL
- Visibility per pixel instead of Z-buffer
- Find nearest object by shooting rays into scene
- Shade it as in standard OpenGL

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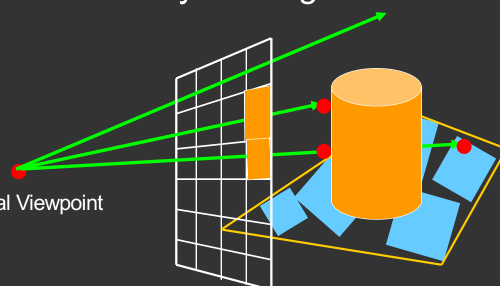
Ray Casting



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Comparison to hardware scan-line

- Per-pixel evaluation, per-pixel rays (not scan-convert each object). On face of it, costly
- But good for walkthroughs of extremely large models (amortize preprocessing, low complexity)
- More complex shading, lighting effects possible

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Outline in Code

```
Image Raytrace (Camera cam, Scene scene, int width, int height)
{
   Image image = new Image (width, height) ;
   for (int i = 0 ; i < height ; i++)
        for (int j = 0 ; j < width ; j++) {
                Ray ray = RayThruPixel (cam, i, j) ;
                Intersection hit = Intersect (ray, scene) ;
                image[i][j] = FindColor (hit) ;
                }
   return image ;
}
```

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Finding Ray Direction

- Goal is to find ray direction for given pixel i and j
- Many ways to approach problem
  - Objects in world coord, find dirn of each ray (we do this)
  - Camera in canonical frame, transform objects (OpenGL)
- Basic idea
  - Ray has origin (camera center) and direction
  - Find direction given camera params and i and j
- Camera params as in gluLookAt
  - Lookfrom[3], LookAt[3], up[3], fov

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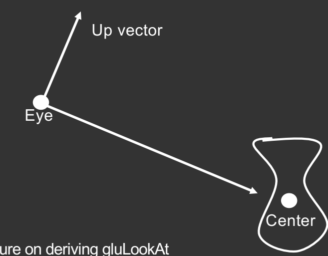
Similar to gluLookAt derivation

- gluLookAt(eyex, eyey, eyez, centerx, centery, centerz, upx, upy, upz)
- Camera at eye, looking at center, with up direction being up



From 167 lecture on deriving gluLookAt

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Constructing a coordinate frame?

We want to associate **w** with **a**, and **v** with **b**

- But **a** and **b** are neither orthogonal nor unit norm
- And we also need to find **u**

$$w = \frac{a}{\|a\|}$$

$$u = \frac{b \times w}{\|b \times w\|}$$

$$v = w \times u$$

From 167 basic math lecture - Vectors: Orthonormal Basis Frames

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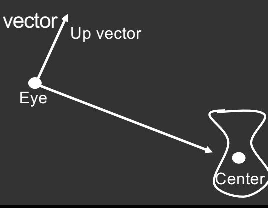
Camera coordinate frame

$$w = \frac{a}{\|a\|} \qquad u = \frac{b \times w}{\|b \times w\|} \qquad v = w \times u$$

- We want to position camera at origin, looking down –Z dirn
- Hence, vector **a** is given by **eye** – **center**
- The vector **b** is simply the **up** vector



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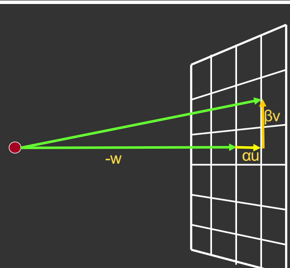
Canonical viewing geometry



$$ray = eye + t\frac{\alpha u + \beta v - w}{|\alpha u + \beta v - w|}$$

$$\alpha = \tan\left(\frac{fovx}{2}\right) \times \left(\frac{j - (width/2)}{width/2}\right) \qquad \beta = \tan\left(\frac{fovy}{2}\right) \times \left(\frac{(height/2) - i}{height/2}\right)$$

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   for (int i = 0 ; i < height ; i++)
      for (int j = 0 ; j < width ; j++) {
            Ray ray = RayThruPixel (cam, i, j) ;
            Intersection hit = Intersect (ray, scene) ;
            image[i][j] = FindColor (hit) ;
            }
   return image ;
}
```

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Ray/Object Intersections

- Heart of Ray Tracer
  - One of the main initial research areas
  - Optimized routines for wide variety of primitives
- Various types of info
  - Shadow rays: Intersection/No Intersection
  - Primary rays: Point of intersection, material, normals
  - Texture coordinates
- Work out examples
  - Triangle, sphere, polygon, general implicit surface

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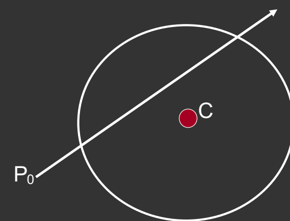
Ray-Sphere Intersection

$$ray \equiv \vec{P} = \vec{P}_0 + \vec{P}_1 t$$

$$sphere \equiv (\vec{P} - \vec{C}) \bullet (\vec{P} - \vec{C}) - r^2 = 0$$



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Ray-Sphere Intersection

$$ray \equiv \vec{P} = \vec{P}_0 + \vec{P}_1 t$$

$$sphere \equiv (\vec{P} - \vec{C}) \bullet (\vec{P} - \vec{C}) - r^2 = 0$$

Substitute

$$ray \equiv \vec{P} = \vec{P}_0 + \vec{P}_1 t$$

$$sphere \equiv (\vec{P}_0 + \vec{P}_1 t - \vec{C}) \bullet (\vec{P}_0 + \vec{P}_1 t - \vec{C}) - r^2 = 0$$

Simplify

$$t^2(\vec{P}_1 \bullet \vec{P}_1) + 2t\,\vec{P}_1 \bullet (\vec{P}_0 - \vec{C}) + (\vec{P}_0 - \vec{C}) \bullet (\vec{P}_0 - \vec{C}) - r^2 = 0$$

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Ray-Sphere Intersection

$$t^2(\vec{P}_1 \bullet \vec{P}_1) + 2t\,\vec{P}_1 \bullet (\vec{P}_0 - \vec{C}) + (\vec{P}_0 - \vec{C}) \bullet (\vec{P}_0 - \vec{C}) - r^2 = 0$$

Solve quadratic equations for t

- 2 real positive roots: pick smaller root
- Both roots same: tangent to sphere
- One positive, one negative root: ray origin inside sphere (pick + root)
- Complex roots: no intersection (check discriminant of equation first)

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Ray-Sphere Intersection

- Intersection point: $ray \equiv \vec{P} = \vec{P}_0 + \vec{P}_1 t$
- Normal (for sphere, this is same as coordinates in sphere frame of reference, useful other tasks)

$$normal = \frac{\vec{P} - \vec{C}}{|\vec{P} - \vec{C}|}$$

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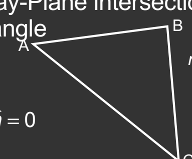
Ray-Triangle Intersection

- One approach: Ray-Plane intersection, then check if inside triangle
- Plane equation:

$$plane \equiv \vec{P} \bullet \vec{n} - \vec{A} \bullet \vec{n} = 0$$



$$n = \frac{(C-A)\times(B-A)}{|(C-A)\times(B-A)|}$$

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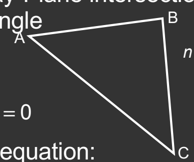
Ray-Triangle Intersection

- One approach: Ray-Plane intersection, then check if inside triangle
- Plane equation:



$$n = \frac{(C-A)\times(B-A)}{\left|(C-A)\times(B-A)\right|}$$

$$plane \equiv \vec{P}\cdot\vec{n} - \vec{A}\cdot\vec{n} = 0$$

- Combine with ray equation:

$$ray \equiv \vec{P} = \vec{P}_0 + \vec{P}_1 t$$

$$(\vec{P}_0 + \vec{P}_1 t)\cdot\vec{n} = \vec{A}\cdot\vec{n} \qquad t = \frac{\vec{A}\cdot\vec{n} - \vec{P}_0\cdot\vec{n}}{\vec{P}_1\cdot\vec{n}}$$

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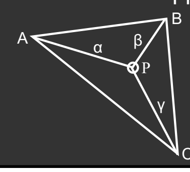
Ray inside Triangle

- Once intersect with plane, still need to find if in triangle
- Many possibilities for triangles, general polygons (point in polygon tests)
- We find parametrically [barycentric coordinates]. Also useful for other applications (texture mapping)



$$P = \alpha A + \beta B + \gamma C$$
$$\alpha \geq 0, \beta \geq 0, \gamma \geq 0$$
$$\alpha + \beta + \gamma = 1$$

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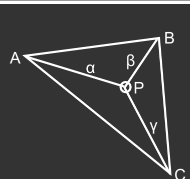
Ray inside Triangle



$$P = \alpha A + \beta B + \gamma C$$
$$\alpha \geq 0, \beta \geq 0, \gamma \geq 0$$
$$\alpha + \beta + \gamma = 1$$

$$P - A = \beta(B-A) + \gamma(C-A)$$
$$0 \leq \beta \leq 1\ ,\ 0 \leq \gamma \leq 1$$
$$\beta + \gamma \leq 1$$

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Other primitives

- Much early work in ray tracing focused on ray-primitive intersection tests
- Cones, cylinders, ellipsoids
- Boxes (especially useful for bounding boxes)
- General planar polygons
- Many more
- Consult chapter in Glassner (handed out) for more details and possible extra credit

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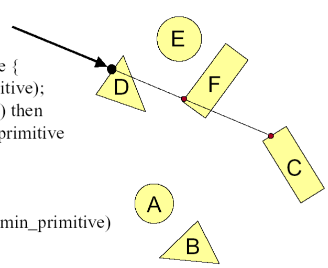
Ray Scene Intersection

```
Intersection FindIntersection(Ray ray, Scene scene)
{
    min_t = infinity
    min_primitive = NULL
    For each primitive in scene {
        t = Intersect(ray, primitive);
        if (t > 0 && t < min_t) then
            min_primitive = primitive
            min_t = t
        }
    }
    return Intersection(min_t, min_primitive)
}
```



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Transformed Objects

- E.g. transform sphere into ellipsoid
- Could develop routine to trace ellipsoid (compute parameters after transformation)
- May be useful for triangles, since triangle after transformation is still a triangle in any case
- But can also use original optimized routines

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Ray-Tracing Transformed Objects

We have an optimized ray-sphere test
- But we want to ray trace an ellipsoid…

Solution: Ellipsoid transforms sphere
- Apply inverse transform to ray, use ray-sphere
- Allows for instancing (traffic jam of cars)
- Same idea for other primitives

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Transformed Objects

- Consider a general 4x4 transform M
  - Will need to implement matrix stacks like in OpenGL
- Apply inverse transform M^{-1} to ray
  - Locations stored and transform in homogeneous coordinates
  - Vectors (ray directions) have homogeneous coordinate set to 0 [so there is no action because of translations]
- Do standard ray-surface intersection as modified
- Transform intersection back to actual coordinates
  - Intersection point p transforms as Mp
  - Distance to intersection if used may need recalculation
  - Normals n transform as $M^{-t}n$. Do all this before lighting

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Outline

- History
- Basic Ray Casting (instead of rasterization)
  - Comparison to hardware scan conversion
- *Shadows / Reflections (core algorithm)*
- Optimizations
- Current Research

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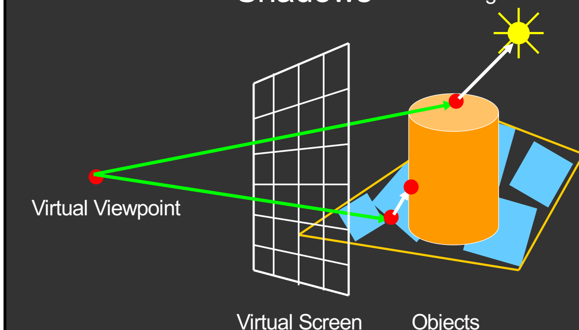
Shadows



Shadow ray to light is blocked: object in shadow

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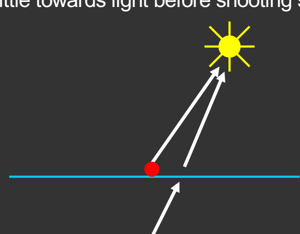
Shadows: Numerical Issues

- Numerical inaccuracy may cause intersection to be below surface (effect exaggerated in figure)
- Causing surface to incorrectly shadow itself
- Move a little towards light before shooting shadow ray



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  for (int i = 0 ; i < height ; i++)
     for (int j = 0 ; j < width ; j++) {
          Ray ray = RayThruPixel (cam, i, j) ;
          Intersection hit = Intersect (ray, scene) ;
          image[i][j] = FindColor (hit) ;
          }
  return image ;
}
```

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Lighting Model

- Similar to OpenGL
- Lighting model parameters (global)
  - Ambient r g b
  - Attenuation const linear quadratic

$$L = \frac{L_0}{const + lin * d + quad * d^2}$$

- Per light model parameters
  - Directional light (direction, RGB parameters)
  - Point light (location, RGB parameters)

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Material Model

- Diffuse reflectance (r g b)
- Specular reflectance (r g b)
- Shininess s
- Emission (r g b)
- All as in OpenGL

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Shading Model

$$I = K_a + K_e + \sum_{i=1}^{n} V_i L_i (K_d \max(l_i \cdot n, 0) + K_s (\max(h_i \cdot n, 0))^s)$$

- Global ambient term, emission from material
- For each light, diffuse specular terms
- Note visibility/shadowing for each light (not in OpenGL)
- Evaluated per pixel per light (not per vertex)

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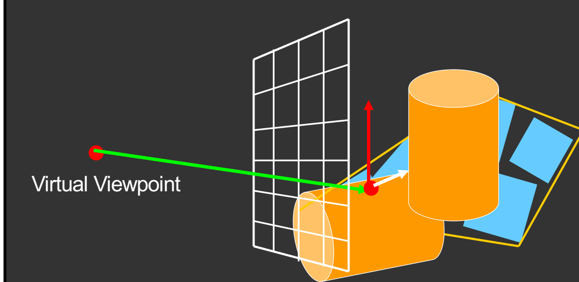
Mirror Reflections/Refractions



Generate reflected ray in mirror direction,
Get reflections and refractions of objects

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Recursive Ray Tracing

For each pixel
- Trace Primary Eye Ray, find intersection
- Trace Secondary Shadow Ray(s) to all light(s)
  - Color = Visible ? Illumination Model : 0 ;
- Trace Reflected Ray
  - Color += reflectivity * Color of reflected ray

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Recursive Shading Model

$$I = K_a + K_e + \sum_{i=1}^{n} V_i L_i (K_d \max(l_i \cdot n, 0) + K_s (\max(h_i \cdot n, 0))^s) + K_s I_R + K_T I_T$$

- Highlighted terms are recursive specularities [mirror reflections] and transmission (latter is extra credit)
- Trace secondary rays for mirror reflections and refractions, include contribution in lighting model
- GetColor calls RayTrace recursively (the I values in equation above of secondary rays are obtained by recursive calls)

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Problems with Recursion

- Reflection rays may be traced forever
- Generally, set maximum recursion depth
- Same for transmitted rays (take refraction into account)

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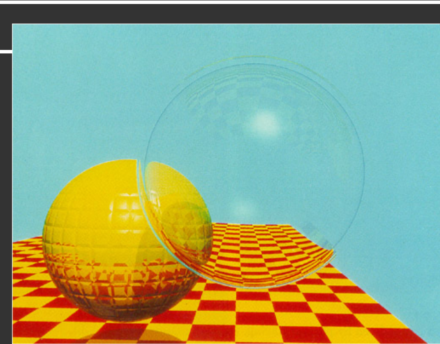

Turner Whitted 1980

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Effects needed for Realism

- (Soft) Shadows
- Reflections (Mirrors and Glossy)
- Transparency (Water, Glass)
- Interreflections (Color Bleeding)
- Complex Illumination (Natural, Area Light)
- Realistic Materials (Velvet, Paints, Glass)

Discussed in this lecture
Not discussed but possible with distribution ray tracing
Hard (but not impossible) with ray tracing; radiosity methods
All are possible with path tracing developed in this course

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Some basic add ons

- Area light sources and soft shadows: break into grid of n x n point lights
  - Use jittering: Randomize direction of shadow ray within small box for given light source direction
  - Jittering also useful for antialiasing shadows when shooting primary rays
- More complex reflectance models
  - Simply update shading model
  - But at present, we can handle only mirror global illumination calculations
- Some of these required for those who have already done a raytracer (167 with Chern or me)

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Outline

- History
- Basic Ray Casting (instead of rasterization)
  - Comparison to hardware scan conversion
- Shadows / Reflections (core algorithm)
- *Optimizations*
- Current Research

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Acceleration

Testing each object for each ray is slow
- Fewer Rays
  Adaptive sampling, depth control
- Generalized Rays
  Beam tracing, cone tracing, pencil tracing etc.
- Faster Intersections
  - Optimized Ray-Object Intersections
  - ***Fewer Intersections***

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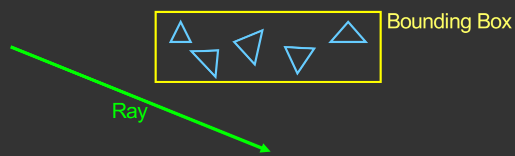
Acceleration Structures

Bounding boxes (possibly hierarchical)

If no intersection bounding box, needn't check objects



Spatial Hierarchies (Oct-trees, kd trees, BSP trees)

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Ray Tracing Acceleration Structures

- Bounding Volume Hierarchies (BVH)
- Uniform Spatial Subdivision (Grids)
- Binary Space Partitioning (BSP Trees)
  - Axis-aligned often for ray tracing: kd-trees
- Conceptually simple, implementation a bit tricky
  - Lecture relatively high level: Start early
  - Remember that acceleration a small part of grade
  - But will struggle in future if developing in software

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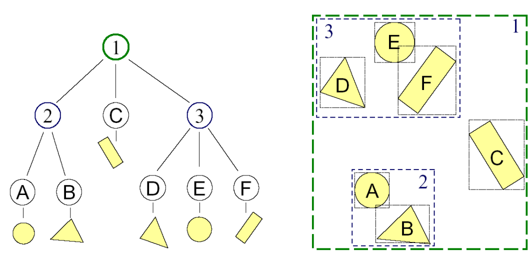
Bounding Volume Hierarchies 1

- Build hierarchy of bounding volumes
  - Bounding volume of interior node contains all children



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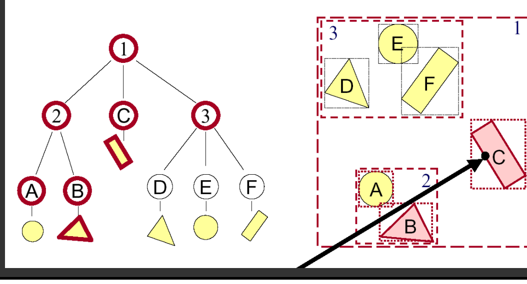
Bounding Volume Hierarchies 2

- Use hierarchy to accelerate ray intersections
  - Intersect node contents only if hit bounding volume



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Bounding Volume Hierarchies 3

- Sort hits & detect early termination

```
FindIntersection(Ray ray, Node node)
{
    // Find intersections with child node bounding volumes
    ...
    // Sort intersections front to back
    ...
    // Process intersections (checking for early termination)
    min_t = infinity;
    for each intersected child i {
        if (min_t < bv_t[i]) break;
        shape_t = FindIntersection(ray, child);
        if (shape_t < min_t) { min_t = shape_t;}
    }
    return min_t;
}
```

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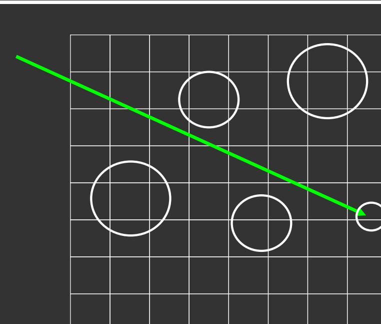
Acceleration Structures: Grids



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Acceleration and Regular Grids

- Simplest acceleration, for example 5x5x5 grid
- For each grid cell, store overlapping triangles
- March ray along grid (need to be careful with this), test against each triangle in grid cell
- More sophisticated: kd-tree, oct-tree bsp-tree
- Or use (hierarchical) bounding boxes
- Try to implement some acceleration in HW

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Note on Optix, Code Reuse

- *No Copying Code previous students, solutions, or any online resources*
- *AI agents like chatGPT may be used only as a search engine for example for explaining the way specific commands are used, but you should not copy code from them.*
- *No posting code online including to github*
- Some students felt skeleton only for OptiX unfair
  - And in spring 20 tried copying to compensate. *Bad!!*
- Optix skeleton only Optix setup, no raytracing
  - Because writing from scratch in new language is hard
  - Acceleration structures are built-in, can use
  - *Still likely harder option, because of learning curve* (but great performance for course)

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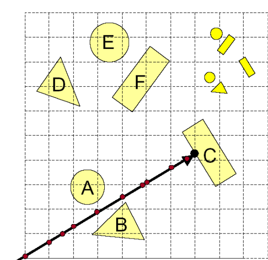
Uniform Grid: Problems

- Potential problem:
  - How choose suitable grid resolution?

Too little benefit if grid is too coarse

Too much cost if grid is too fine



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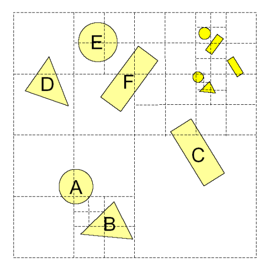
Octree

- Construct adaptive grid over scene
  - Recursively subdivide box-shaped cells into 8 octants
  - Index primitives by overlaps with cells

Generally fewer cells



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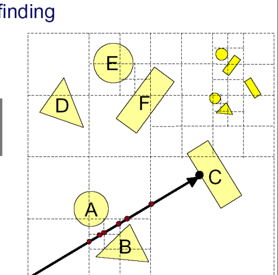
Octree traversal

- Trace rays through neighbor cells
  - Fewer cells
  - More complex neighbor finding

Trade-off fewer cells for more expensive traversal



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Math of 2D Bounding Box Test

- Can you find a t in range

$t > 0$

$t_{xmin} \leq t \leq t_{xmax}$

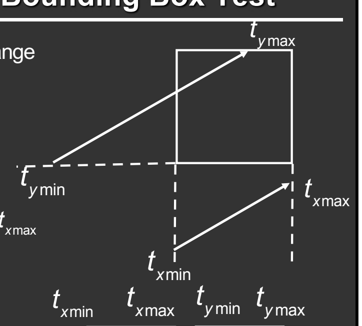
$t_{ymin} \leq t \leq t_{ymax}$

if $t_{xmin} > t_{ymax}$ *OR* $t_{ymin} > t_{xmax}$

return false;

else

return true;



No intersection if x and y ranges don't overlap

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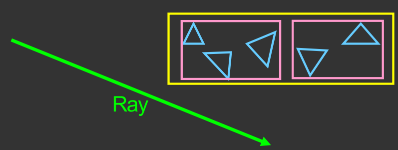
Bounding Box Test

- Ray-Intersection is simple coordinate check
- Intricacies with test, see Shirley book
- Hierarchical Bounding Boxes



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Hierarchical Bounding Box Test

- If ray hits root box
  - Intersect left subtree
  - Intersect right subtree
  - Merge intersections (find closest one)
- Standard hierarchical traversal
  - But caveat, since bounding boxes may overlap
- At leaf nodes, must intersect objects

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Creating Bounding Volume Hierarchy

```
function bvh-node::create (object array A, int AXIS)
    N = A.length() ;
    if (N == 1) {left = A[0]; right = NULL; bbox = bound(A[0]);}
    else if (N == 2) {
        left = A[0] ; right = A[1] ;
        bbox = combine(bound(A[0]),bound(A[1])) ;
    else
        Find midpoint m of bounding box of A along AXIS
        Partition A into lists of size k and N-k around m
        left = new bvh-node (A[0…k],(AXIS+1) mod 3) ;
        right = new bvh-node(A[k+1…N-1],(AXIS+1) mod 3);
        bbox = combine (left -> bbox, right -> bbox) ;
```

From page 305 of Shirley book

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Area Heuristics

- Instead of mid-point of bounding box, alternating axes, pick the axis and the location to split carefully
- The algorithm can test several splitting planes (at least 9 recommended) across x,y,z and chooses best one
- Area Heuristic: min $a_1 n_1 + a_2 n_2$ considering areas of each child box and number of primitives contained in each
- Longer for construction but better balanced
- Ideally speeds up raytracing *(in Optix BVH built in)*
- (Optional, but if interested read up on Surface Area Heuristic [SAH] and similar methods. Also see fast updates for animations, dynamic scenes)

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Uniform Spatial Subdivision

- Different idea: Divide space rather than objects
- In BVH, each object is in one of two sibling nodes
  - A point in space may be inside both nodes
- In spatial subdivision, each space point in one node
  - But object may lie in multiple spatial nodes
- Simplest is uniform grid (have seen this already)
- Challenge is keeping all objects within cell
- And in traversing the grid

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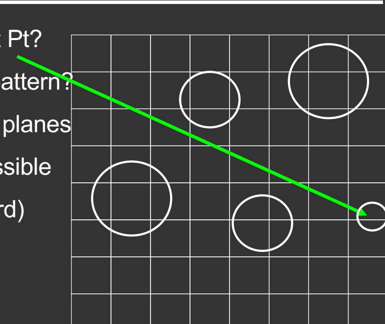
Traversal of Grid High Level

- Next Intersect Pt?
- Irreg. samp. pattern?
- But regular in planes
- Fast algo. possible
- (more on board)



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BSP Trees

- Used for visibility and ray tracing
  - Book considers only axis-aligned splits for ray tracing
  - Sometimes called kd-tree for axis aligned
- Split space (binary space partition) along planes
- Fast queries and back-to-front (painter's) traversal
- Construction is conceptually simple
  - Select a plane as root of the sub-tree
  - Split into two children along this root
  - Random polygon for splitting plane (may need to split polygons that intersect it)

BSP slides courtesy Prof. O'Brien

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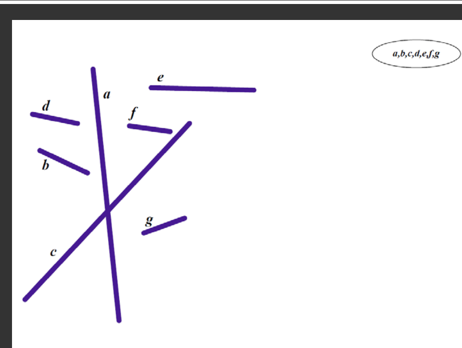
Initial State



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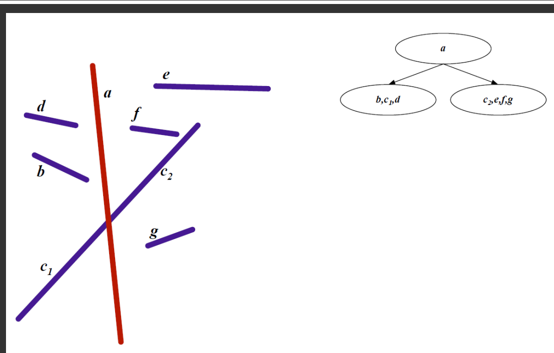
First Split



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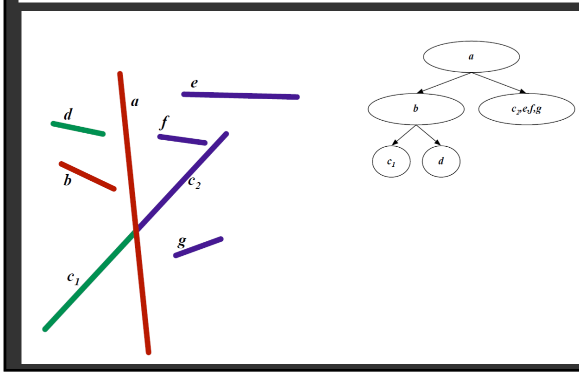
Second Split



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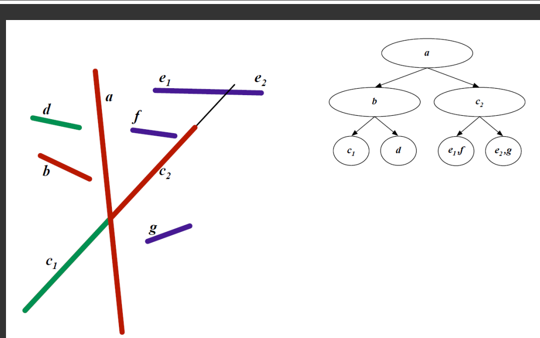
Third Split



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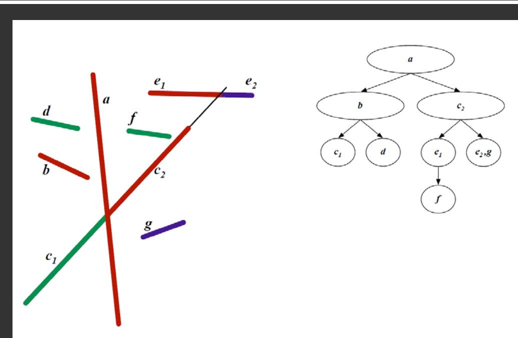
Fourth Split



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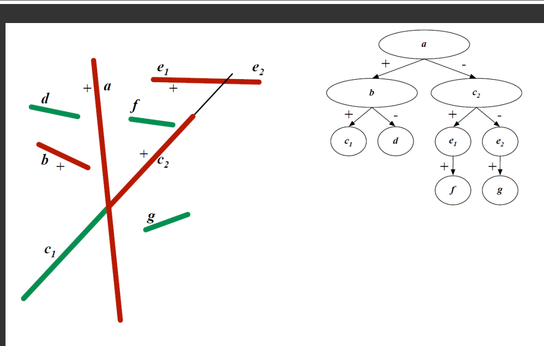
Final BSP Tree



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BSP Trees Cont’d

- Continue splitting until leaf nodes
- Visibility traversal in order
  - Child one
  - Root
  - Child two
- Child one chosen based on viewpoint
  - Same side of sub-tree as viewpoint
- BSP tree built once, used for all viewpoints

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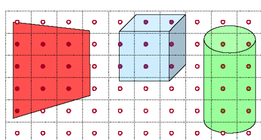
Other Accelerations

- Screen space coherence
  - Check last hit first
  - Beam tracing
  - Pencil tracing
  - Cone tracing
- Memory coherence
  - Large scenes
- Parallelism
  - Ray casting is “embarassingly parallelizable”
- etc.



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Outline

- History
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- Shadows / Reflections (core algorithm)
- Optimizations
- *Current Research*

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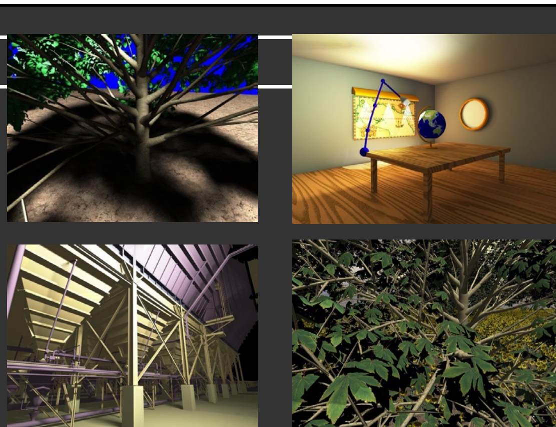

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Interactive Raytracing

- Ray tracing historically slow
- Now viable alternative for complex scenes
  - Key is sublinear complexity with acceleration; need not process all triangles in scene
- Allows many effects hard in hardware
- Today graphics hardware and software (NVIDIA Optix 6, RTX chips 10G+ rays per second). Video
- Tiger Demo (NVIDIA; see slide)

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Today: Real-Time Denoising at 1spp

NVIDIA Tiger Demo 2021

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Raytracing on Graphics Hardware

- Modern Programmable Hardware general streaming architecture
- Can map various elements of ray tracing
- Kernels like eye rays, intersect etc.
- In vertex or fragment programs
- Convergence between hardware, ray tracing

[Purcell et al. 2002, 2003]

http://graphics.stanford.edu/papers/photongfx

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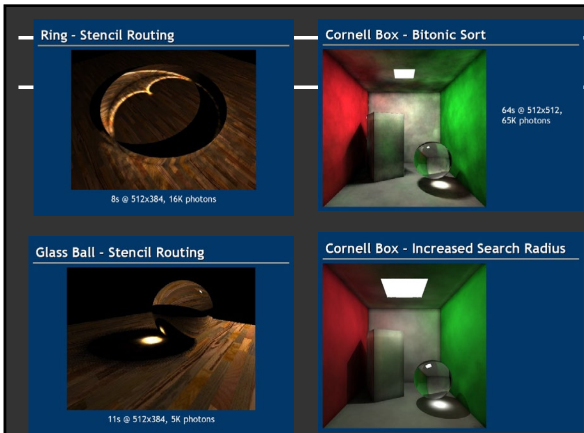

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