



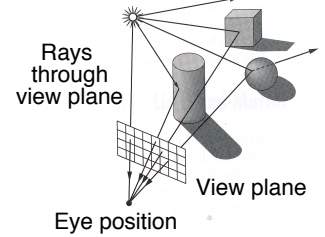
Ray Casting

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Princeton University
COS 426, Spring 2005



3D Rendering

- The color of each pixel on the view plane depends on the radiance emanating from visible surfaces

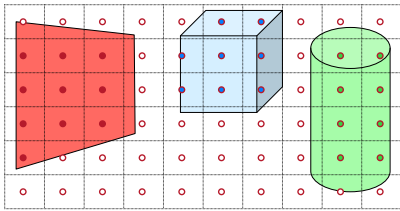


Simplest method is ray casting



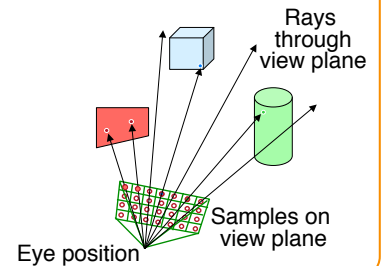
Ray Casting

- For each sample ...
 - Construct ray from eye position through view plane
 - Find first surface intersected by ray through pixel
 - Compute color sample based on surface radiance



Ray Casting

- For each sample ...
 - Construct ray from eye position through view plane
 - Find first surface intersected by ray through pixel
 - Compute color sample based on surface radiance



Ray Casting

- Simple implementation:

```
Image RayCast(Camera camera, Scene scene, int width, int height)
{
  Image image = new Image(width, height);
  for (int i = 0; i < width; i++) {
    for (int j = 0; j < height; j++) {
      Ray ray = ConstructRayThroughPixel(camera, i, j);
      Intersection hit = FindIntersection(ray, scene);
      image[i][j] = GetColor(hit);
    }
  }
  return image;
}
```

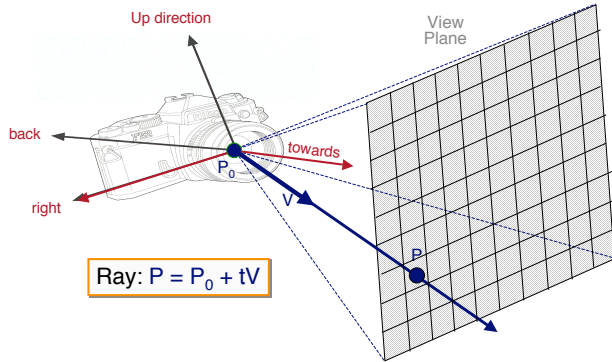


Ray Casting

- Simple implementation:

```
Image RayCast(Camera camera, Scene scene, int width, int height)
{
  Image image = new Image(width, height);
  for (int i = 0; i < width; i++) {
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  }
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```

Constructing Ray Through a Pixel



Constructing Ray Through a Pixel



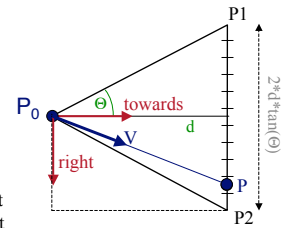
- 2D Example

Θ = frustum half-angle
 d = distance to view plane

right = towards x up

$P1 = P_0 + d * \text{towards} - d * \tan(\Theta) * \text{right}$
 $P2 = P_0 + d * \text{towards} + d * \tan(\Theta) * \text{right}$

$P = P1 + ((i + 0.5) / \text{width}) * (P2 - P1)$
 $V = (P - P_0) / \|P - P_0\|$



Ray Casting



- Simple implementation:

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    }
    return image;
}
```

Ray-Scene Intersection

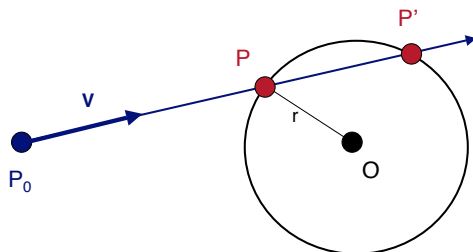


- Intersections with geometric primitives
 - o Sphere
 - o Triangle
 - o Groups of primitives (scene)
- Acceleration techniques
 - o Bounding volume hierarchies
 - o Spatial partitions
 - » Uniform grids
 - » Octrees
 - » BSP trees

Ray-Sphere Intersection



Ray: $P = P_0 + tV$
 Sphere: $\|P - O\|^2 - r^2 = 0$



Ray-Sphere Intersection I



Ray: $P = P_0 + tV$
 Sphere: $\|P - O\|^2 - r^2 = 0$

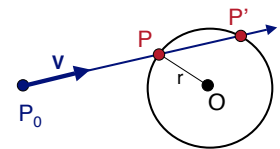
Algebraic Method

Substituting for P, we get:
 $\|P_0 + tV - O\|^2 - r^2 = 0$

Solve quadratic equation:
 $at^2 + bt + c = 0$

where:
 $a = 1$
 $b = 2V \cdot (P_0 - O)$
 $c = \|P_0 - O\|^2 - r^2 = 0$

$P = P_0 + tV$



Ray-Sphere Intersection II



Ray: $P = P_0 + tV$
 Sphere: $|P - O|^2 - r^2 = 0$

Geometric Method

$L = O - P_0$

$t_{ca} = L \cdot V$

if ($t_{ca} < 0$) return 0

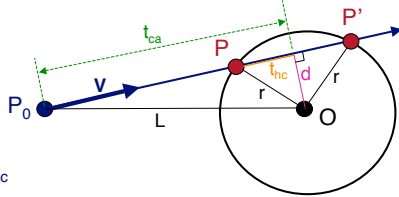
$d^2 = L \cdot L - t_{ca}^2$

if ($d^2 > r^2$) return 0

$t_{hc} = \sqrt{r^2 - d^2}$

$t = t_{ca} - t_{hc}$ and $t_{ca} + t_{hc}$

$P = P_0 + tV$

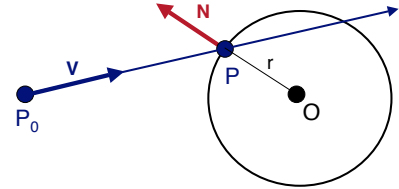


Ray-Sphere Intersection



- Need normal vector at intersection for lighting calculations

$$N = (P - O) / |P - O|$$



Ray-Scene Intersection

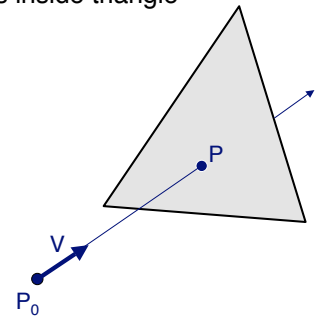


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Ray-Triangle Intersection



- First, intersect ray with plane
- Then, check if point is inside triangle



Ray-Plane Intersection



Ray: $P = P_0 + tV$
 Plane: $P \cdot N + d = 0$

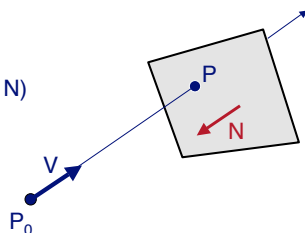
Algebraic Method

Substituting for P, we get:
 $(P_0 + tV) \cdot N + d = 0$

Solution:

$$t = -(P_0 \cdot N + d) / (V \cdot N)$$

$$P = P_0 + tV$$



Ray-Triangle Intersection I



- Check if point is inside triangle algebraically

For each side of triangle

$$V_1 = T_1 - P$$

$$V_2 = T_2 - P$$

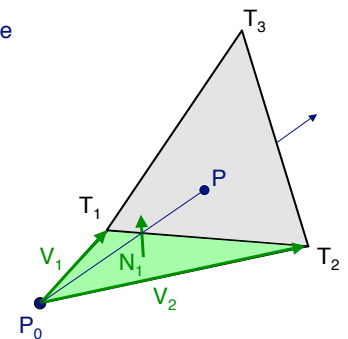
$$N_1 = V_2 \times V_1$$

Normalize N_1

if $((P - P_0) \cdot N_1 < 0)$

return FALSE;

end



Ray-Triangle Intersection II



- Check if point is inside triangle parametrically

Compute "barycentric coordinates" α, β :

$$\alpha = \text{Area}(T_1T_2P) / \text{Area}(T_1T_2T_3)$$

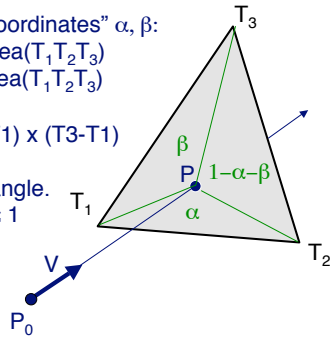
$$\beta = \text{Area}(T_1PT_3) / \text{Area}(T_1T_2T_3)$$

$$\text{Area}(T_1T_2T_3) = 1/2 (T_2-T_1) \times (T_3-T_1)$$

Check if point inside triangle.

$$0 \leq \alpha \leq 1 \text{ and } 0 \leq \beta \leq 1$$

$$\alpha + \beta \leq 1$$



Other Ray-Primitive Intersections



- Cone, cylinder, ellipsoid:
 - Similar to sphere
- Box
 - Intersect 3 front-facing planes, return closest
- Convex polygon
 - Same as triangle (check point-in-polygon algebraically)
- Concave polygon
 - Same plane intersection
 - More complex point-in-polygon test

Ray-Scene Intersection

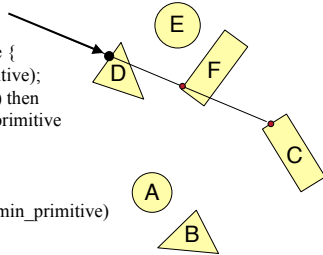


- Find intersection with front-most primitive in group

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 Intersect(min_t, min_primitive)
}
    
```



Ray-Scene Intersection

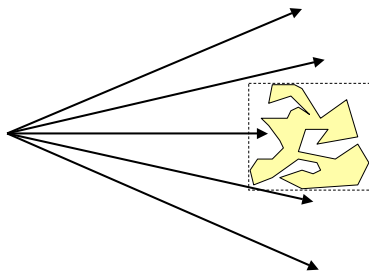


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Bounding Volumes



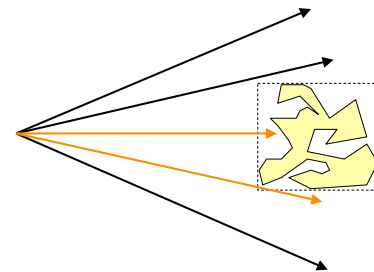
- Check for intersection with simple shape first



Bounding Volumes



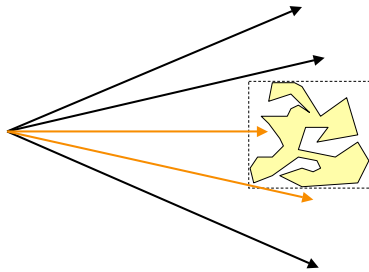
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Bounding Volumes



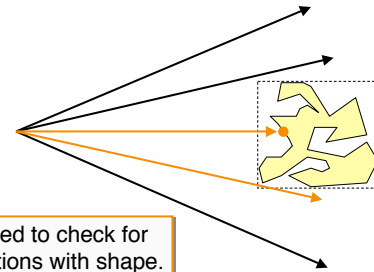
- Check for intersection with simple shape first
 - If ray doesn't intersect bounding volume, then it doesn't intersect its contents



Bounding Volumes



- Check for intersection with simple shape first
 - If ray doesn't intersect bounding volume, then it doesn't intersect its contents

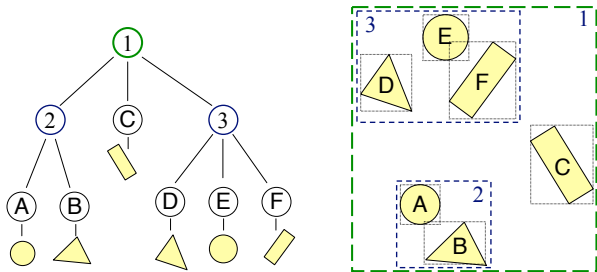


Still need to check for intersections with shape.

Bounding Volume Hierarchies I



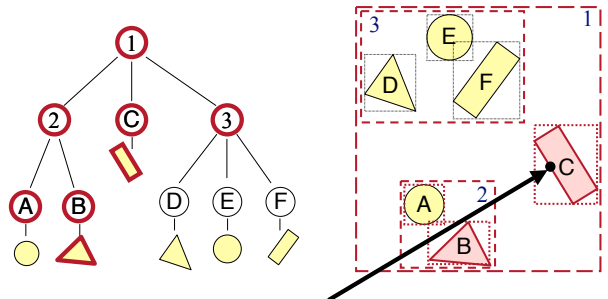
- Build hierarchy of bounding volumes
 - Bounding volume of interior node contains all children



Bounding Volume Hierarchies



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



Bounding Volume Hierarchies III



- 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;
}
    
```

Ray-Scene Intersection

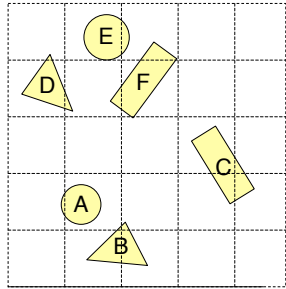


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Uniform Grid



- Construct uniform grid over scene
 - Index primitives according to overlaps with grid cells

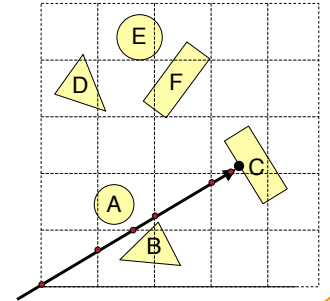


Uniform Grid



- Trace rays through grid cells
 - Fast
 - Incremental

Only check primitives in intersected grid cells



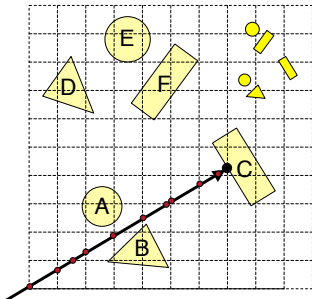
Uniform Grid



- Potential problem:
 - How choose suitable grid resolution?

Too little benefit if grid is too coarse

Too much cost if grid is too fine



Ray-Scene Intersection



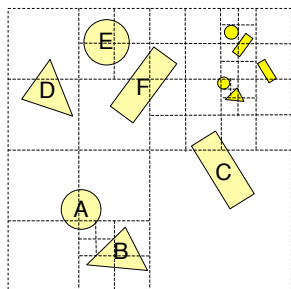
- Intersections with geometric primitives
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Octree



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

Generally fewer cells

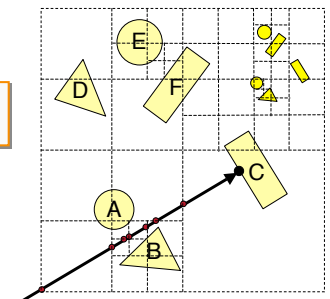


Octree



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

Trade-off fewer cells for more expensive traversal



Ray-Scene Intersection

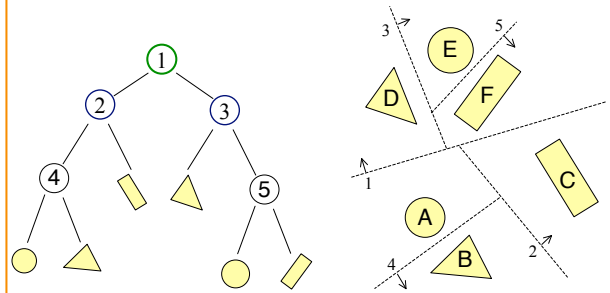


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Binary Space Partition (BSP) Tree



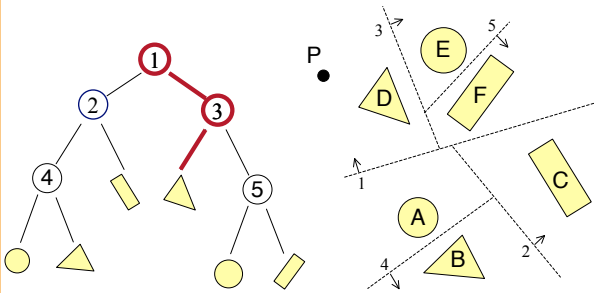
- Recursively partition space by planes
 - Every cell is a convex polyhedron



Binary Space Partition (BSP) Tree



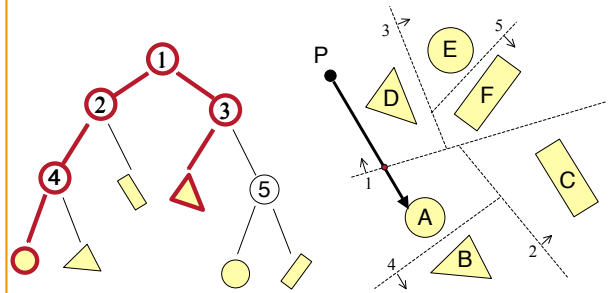
- Simple recursive algorithms
 - Example: point finding



Binary Space Partition (BSP) Tree



- Trace rays by recursion on tree
 - BSP construction enables simple front-to-back traversal



Binary Space Partition (BSP) Tree



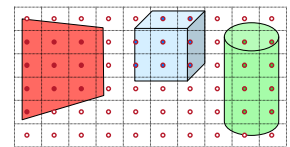
```

RayTreeIntersect(Ray ray, Node node, double min, double max)
{
    if (Node is a leaf)
        return intersection of closest primitive in cell, or NULL if none
    else
        dist = distance of the ray point to split plane of node
        near_child = child of node that contains the origin of Ray
        far_child = other child of node
        if the interval to look is on near side
            return RayTreeIntersect(ray, near_child, min, max)
        else if the interval to look is on far side
            return RayTreeIntersect(ray, far_child, min, max)
        else if the interval to look is on both side
            if (RayTreeIntersect(ray, near_child, min, dist)) return ...;
            else return RayTreeIntersect(ray, far_child, dist, max)
}
    
```

Other Accelerations



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



Acceleration



- Intersection acceleration techniques are important
 - Bounding volume hierarchies
 - Spatial partitions
- General concepts
 - Sort objects spatially
 - Make trivial rejections quick
 - Utilize coherence when possible

Expected time is sub-linear in number of primitives

Summary



- Writing a simple ray casting renderer is easy
 - Generate rays
 - Intersection tests
 - Lighting calculations

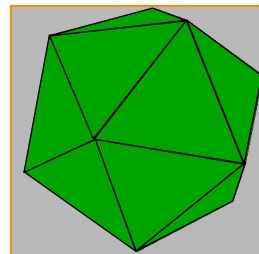
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{
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    for (int i = 0; i < width; i++) {
        for (int j = 0; j < height; j++) {
            Ray ray = ConstructRayThroughPixel(camera, i, j);
            Intersection hit = FindIntersection(ray, scene);
            image[i][j] = GetColor(hit);
        }
    }
    return image;
}
```

Heckbert's business card ray tracer

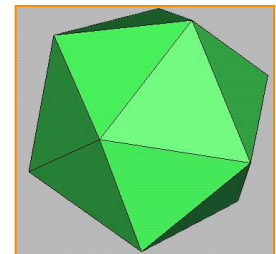


- ```
typedef struct{double x,y,z;}vec;vec U,black,amb={.02,.02,.02};struct sphere{ vec cen,color;
double rad,kd,ks,kt,ki,ir}*s,*best,sph[]={0.6,.5,1.1,1.1,.9,.05,.2,.85,0.1,7,-1.8,-.5,1.1,.5,2,1.
7,.3,0,.05,1.2,1.8,-.5,1.8,.8,1.1,.3,.7,0,0,1.2,3,-.6,.15,1.1,.8,1.7,0,0,0,.6,1.5,-3,-.3,.12,
.8,1.1,1.5,0,0,0,.5,1.5};yx:double u,b,tmin,sqrt(),tan();double vdot(A,B)vec A,B;{return A.x
*B.x+A.y*B.y+A.z*B.z;}vec vcomb(a,A,B)double a;vec A,B;{B.x+=a*A.x;B.y+=a*A.y;B.z+=a*A.z;
return B;}vec vunit(A)vec A;{return vcomb(1./sqrt(vdot(A,A)),A,black);}struct sphere*intersect
(P,D)vec P,D;{best=0;tmin=1e30;s= sph+5;while(s-->sph)b=vdot(D,U=vcomb(-1.,P,s->cen)),
u=b*b-vdot(U,U)+s->rad*s->rad,u=u>0?sqrt(u):1e31,u=b-u>1e-7?b-u:b+u,tmin=u>=1e-7&&
u<tmin?best=s,u:tmin;return best;}vec trace(level,P,D)vec P,D;{double d,eta,e;vec N,color;
struct sphere*s,*i;if(!level-->return black;if(s=intersect(P,D));else return amb;color=amb;eta=
s->ir;d= -vdot(D,N=vunit(vcomb(-1.,P=vcomb(tmin,D,P),s->cen)));if(d<0)N=vcomb(-1.,N,black),
eta=1/eta,d= -d;|=sph+5;while(!-->sph)if((e=| ->k|*vdot(N,U=vunit(vcomb(-1.,P,->cen))))>0&&
intersect(P,U)=!)color=vcomb(e,->color,color);U=s->color;color.x*=U.x;color.y*=U.y;color.z
*=U.z;e=1-eta*eta*(1-d*d);return vcomb(s->kt,e>0?trace(level,P,vcomb(eta,D,vcomb(eta*d-
sqrt(e),N,black))):black,vcomb(s->ks,trace(level,P,vcomb(2*d,N,D)),vcomb(s->kd,color,vcomb
(s->ki,U,black)));}main(){printf("%d %d\n",32,32);while(yx<32*32) U.x=yx%32-32/2,U.z=32/2-
yx+32/2,U.y=32/2/tan(25/114.5915590261),U=vcomb(255.,trace(3,black,vunit(U)),black),printf
("%0f %0f %0f\n",U);}/*minray!*/
```

## Next Time is Illumination!



Without Illumination



With Illumination