CS770/870 Spring 2017
Ray Tracing

Related material

Angel 5e: 12.1-12.3

Angel 6e: Ch 11.1-3

Hill and Kelley: Ch. 12

Preview

- Basic ray tracing model
- Coordinate systems
- Ray-object intersections
- Lighting models for ray tracing
- Aliasing and anti-aliasing in ray tracing
- Texture mapping in a ray tracer
- Ray tracing optimization

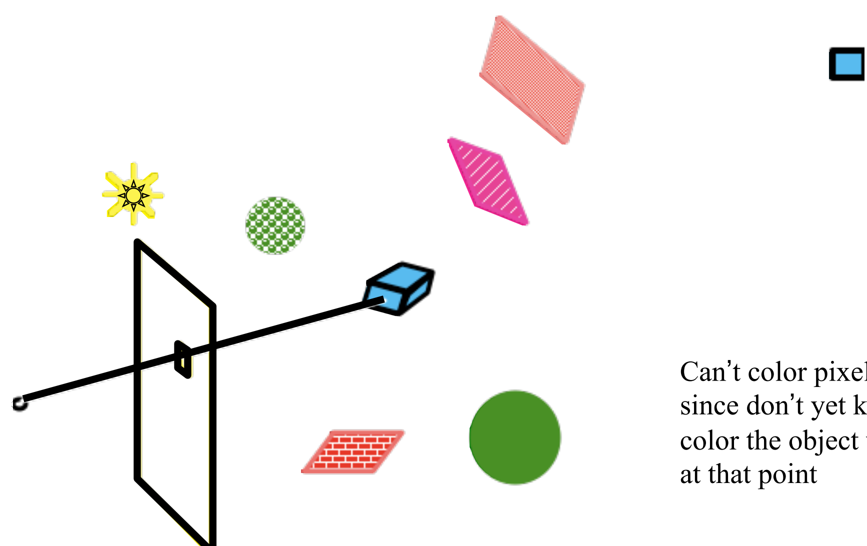
Ray Tracing Overview

- Ray tracing algorithm simulates light rays *in reverse*.
  - Rays go from eye through pixel into the scene
- Rays that hit *shiny* objects, propagate as a *reflection*.
- Rays that hit *semi-transparent* objects, propagate as *refraction*.
- *Shadows* can be computed by sending rays to each light source from each object hit.
- Pixel color is combination of all objects hit by rays spawned by initial sight ray.
- A *ray tree* is (conceptually) built while recursively generating rays
  - once all ray branches end, pixel value is built from the leaves up to the root

Ray Tracing Example - 1

Primary ray hits box

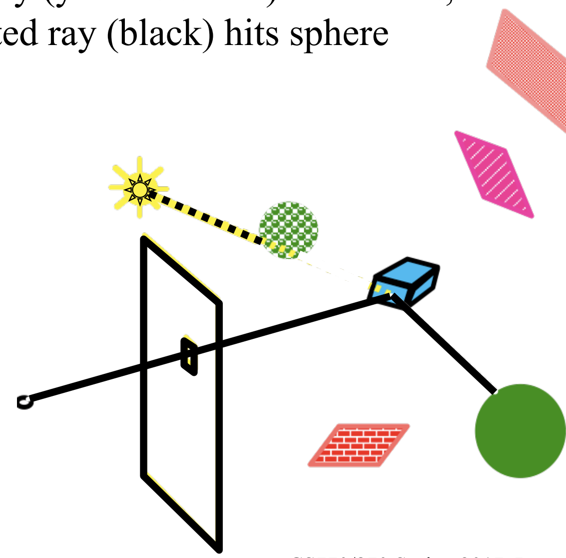
Ray Tree



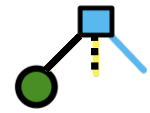
Can't color pixel yet, since don't yet know what color the object will have at that point

Ray Tracing Example - 2

Box not transparent, no refractive ray (blue/gray)
Light ray (yellow/dotted) is blocked, box in shadow
Reflected ray (black) hits sphere

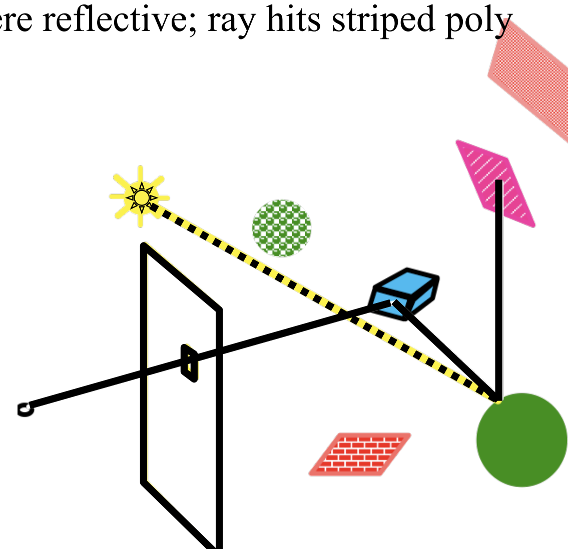


Ray Tree

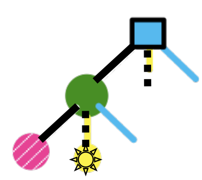


Ray Tracing Example - 3

Sphere not transparent; empty blue/gray link
Light ray not blocked
Sphere reflective; ray hits striped poly



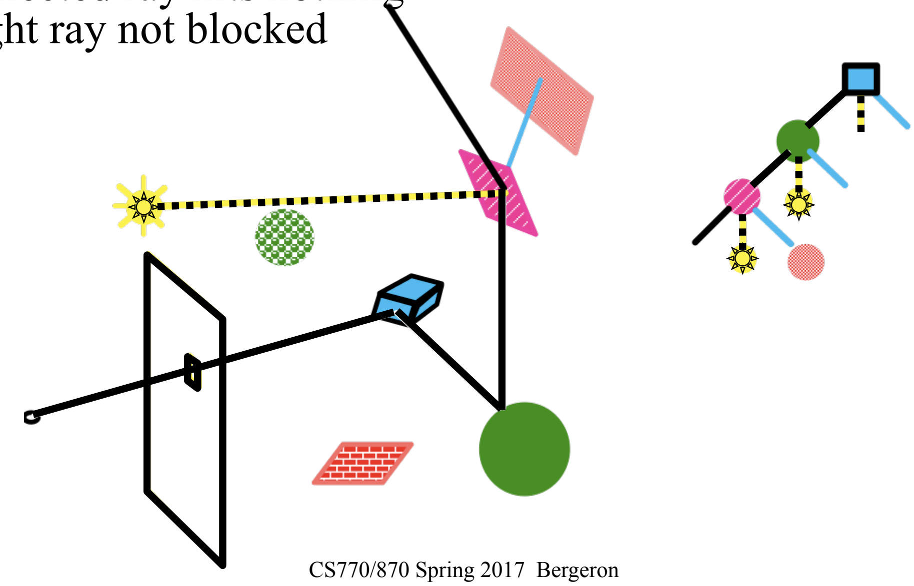
Ray Tree



Ray Tracing Example - 4

Striped object transmits light
Reflected ray hits nothing
Light ray not blocked

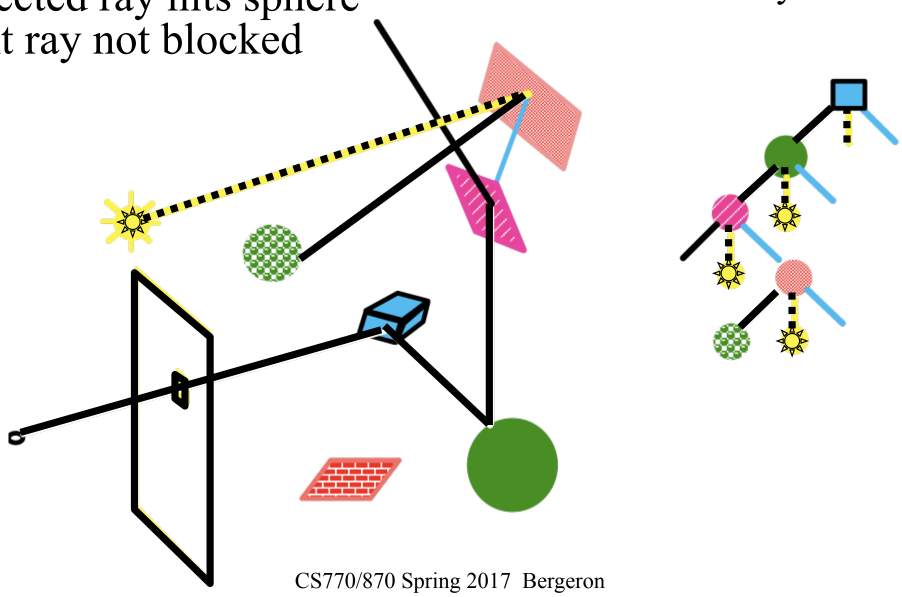
Ray Tree



Ray Tracing Example - 5

Object not transparent
Reflected ray hits sphere
Light ray not blocked

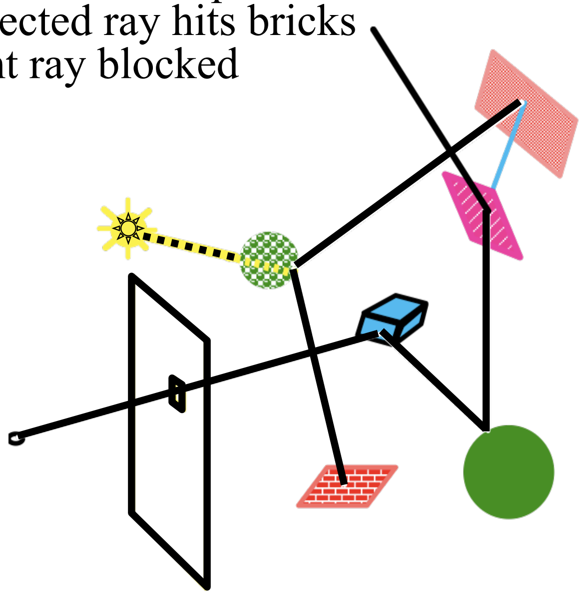
Ray Tree

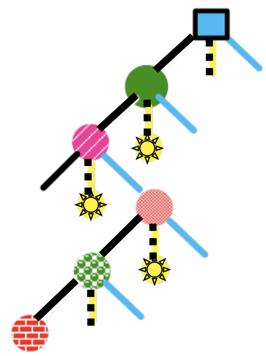


Ray Tracing Example - 6

Sphere not transparent
Reflected ray hits bricks
Light ray blocked

Ray Tree

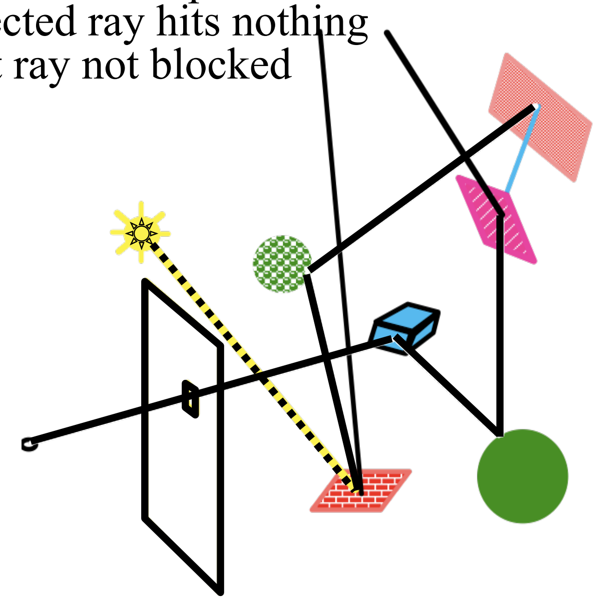


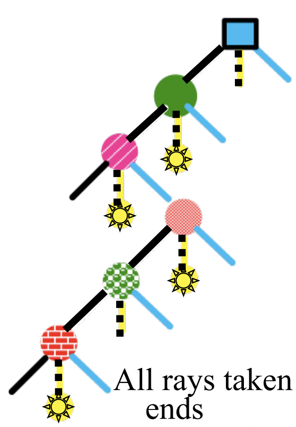


Ray Tracing Example - 7

Bricks not transparent
Reflected ray hits nothing
Light ray not blocked

Ray Tree





All rays taken to their ends
Now, build pixel value from bottom up

Ray Tracing Main Algorithm

```
Create mapping to eye coord system
Define resolution of viewport
Let RayHit class represent a ray/object
  intersection: object, ray, hit point, …
for each pixel
  P(t) = parametric ray from eye to pixel
  RayHit closestHit = findClosest( P(t) )
  if ( closest == null )
     color pixel with background
  else
     pixel.color = shade( closestHit )
```


findClosest method

```
findClosest( Ray R(t) ):
closestT = +infinity
RayHit closeHit = new RayHit(inf,null)
foreach object
  RayHit hit = intersect( R, object )
  if hit.t < closeHit.t
    closeHit = hit
return closeHit
```

intersect method

RayHit intersect(R(t), object):

- Ray/object intersection is object dependent; in an OO world it is cleanest to have the objects implement the intersection. We'll come back to this issue.
- Usually most efficient to do the intersection in object coordinates
  - Consider a rectangular box; probably defined in its coord system as axis aligned: makes ray intersections even easier
  - Consider a sphere; ray-sphere intersection is especially easy, but affine transform can map sphere to a sheared ellipsoid
- Need to map the Ray by the inverse modeling transform
  - But, that's easy and cheap and a ray maps to a ray

shade method

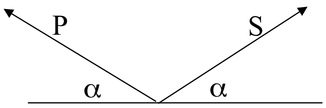
shade(RayHit hit)

```
Object objFace = hit.getHitFace
color  = hit.ka * ambientLight( objFace )
color += hit.ks * specularReflection( hit )
color += hit.kt * specularTransmission( hit )
foreach light, L,
  color += directLight( L, hit )
```

ambientLight(objFace)

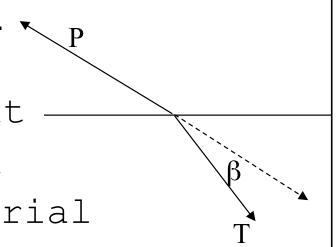
```
return objFace.color * ambientLight.color;
                // * multiplies corr elements
```

specularReflection method




```
specularReflection( RayHit hit )
// specular reflection only occurs along ray;
//   there is no cos^n term as in direct light
Object objFace = hit.getHitFace
if objFace is shiny enough
  create S(t): dir of principal specular refl
  reflectHit = findClosest( S )
  if reflectHit != null
     return shade( reflectHit )
return 0
```

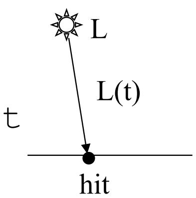

specularTransmission method




```
specularTransmission( RayHit hit )
Object objFace = hit.getHitFace
if objFace is partially transparent
  create T(t): dir of transmission
  // β is refraction angle, a material
  prop
  transmitHit = findClosest( T )
  if transmitHit != null
     return shade( transmitHit )

return 0
```

directLight method




```
directLight( Light L, RayHit hit )
Object objFace = hit.getHitFace
create L(t), vector from L to hit point
lightHit = findClosest( L(t) )
col = object color at hit point (rgb)
I_L = intensity of light L (rgb)
if ( lightHit == rayHit ) // object sees
  light
   directColor = kd *(col * I_L)* dot( L, N )
   directColor += ks *(col * I_L)*(dot(H,N))^n
   return directColor
else
   return 0
```

Note: rgb*rgb $\Longrightarrow$ $(r_1*r_2, g_1*g_2, b_1*b_2)$

Ray Tracing Algorithm Notes

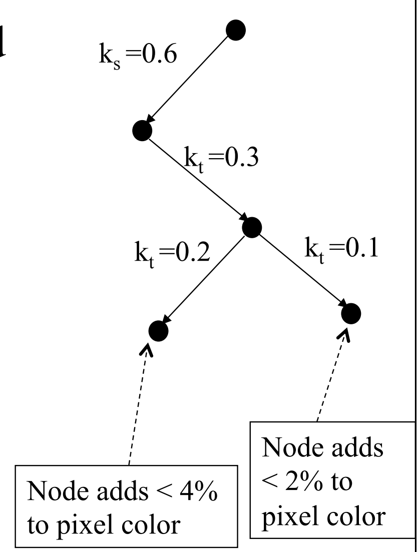
- No explicit ray tree is built in this version
  - the recursive stack tree encapsulates the ray tree
- This is a high-level pedagogic presentation
  - real algorithms would make the shiny and transparent tests prior to the recursive calls
- Care must be taken in creating the rays to insure that you don't hit yourself in the recursion
  - ray start must be just off the surface on the plus side for reflection and minus side for refraction
- Lots of room for efficiency improvements

Efficiency Options

- Ray-Object intersection is the major cpu load
- Two basic kinds of efficiencies (not really disjoint)
  - reduce number of intersection tests
  - reduce cost of the intersection tests
- Vast majority of ray-object intersect tests fail
  - i.e., ray fails to intersect the object
  - need ways to identify failure quickly
  - some of these can be interpreted as either reducing cost or count
- Reducing number of tests
  - Limit tree depth
  - Bounding volume tests
  - Space partitioning
- Reducing cost of tests

Limiting Tree Traversal

- Terminate tree depth after some fixed depth
  - what happens if there are 2 mirrors in the scene facing each other?
- Each color computation uses a *k* coefficient that is less than one (and often much less than 1)
  - Each tree level, therefore, contributes only a fraction of its color to its parent
  - These fractions are multiplied and often get very small very fast

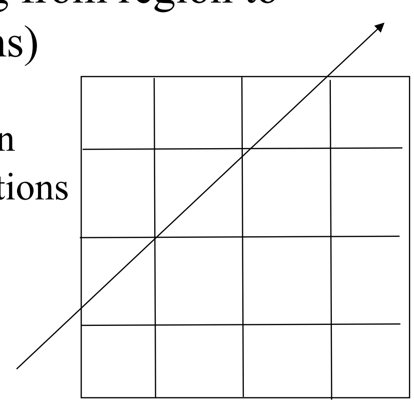


Bounding Volume Tests

- Many world objects are composed of many parts
  - objects are often fairly compact
  - or, are made of compact subparts
- Enclose the object (or its subparts) in bounding volumes, like a sphere
  - first test ray with bounding volume
  - if it misses, don't need to test any of the parts
  - fast failure test
- Typical bounding volumes:
  - spheres
  - axis aligned boxes
  - parallel planes

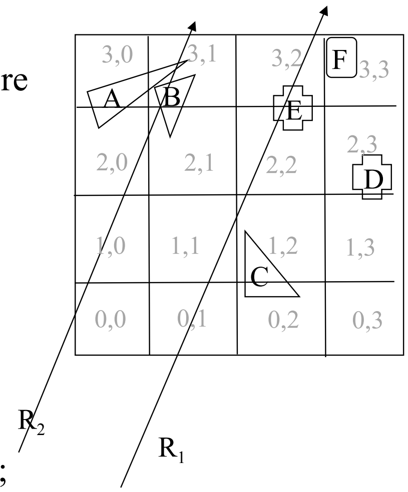
Spatial Partitioning

- Partition world space into axis aligned regions
- Each region contains list of objects that have any part in that region
- Ray intersection proceeds along from region to region (very cheap computations)
  - once enter a region, only need to intersect with objects in the region
  - can dramatically reduce computations



Spatial Partitioning Examples

- R_1 goes through
  - partitions [0,1], [1,1], [1,2],[2,2],[3.2]
  - only needs to test objects C and E before finding E
- R_2 goes through
  - [0,0], [1,0], [2,0], [2,1] and [3,1]
  - intersects A while in [2,0]
    - but it's not right, can tell since intersection is **not** in the partition
  - intersects B while in [2,1], also wrong
  - intersects B and A in [3,1], picks B
  - do not need to recompute intersections; can save them for current ray



Binary Space Partitioning

- Choose a plane that roughly partitions objects in the scene into two subtrees:
  - those on + side of plane and
  - those on – side of plane
  - this is root of a BSP tree
- for each subtree
  - choose a partitioning plane
- Ray/plane intersection is cheap
  - once ray crosses a plane, only test objects on that side
  - each tree node (ideally) cuts in ½ number of objects left to test.