CS380: Computer Graphics
Ray Tracing

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(윤성의)

Course URL:
http://sglab.kaist.ac.kr/~sungeui/CG/

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Class Objectives

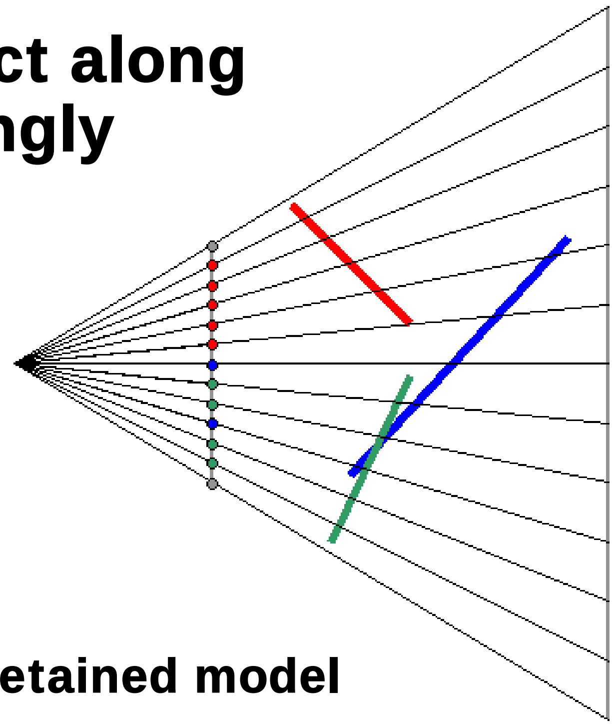
- Understand overall algorithm of recursive ray tracing
  - Ray generations
  - Intersection tests and acceleration methods
  - Basic sampling methods

Various Visibility Algorithm

- **Scan-line algorithm; briefly touched before**
- **Z-buffer**
- **Ray casting, etc.**

Ray Casting

- For each pixel, find closest object along the ray and shade pixel accordingly

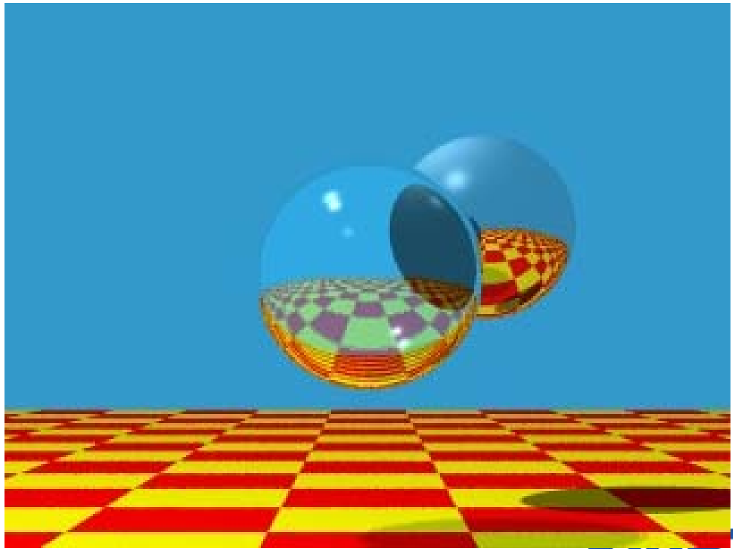


- Advantages
  - Conceptually simple
  - Can be extended to handle global illumination effects
- Disadvantages
  - Renderer must have access to entire retained model
  - Hard to map to special-purpose hardware
  - Less efficient than rasterization in terms of utilizing spatial coherence

Recursive Ray Casting

- **Ray casting generally dismissed early on because of aforementioned problems**

- **Gained popularity in when Turner Whitted (1980) showed this image**
  - ***Show recursive*** **ray casting could be used for global illumination effects**



Ray Casting and Ray Tracing

- Trace rays from eye into scene
  - Backward ray tracing
- Ray casting used to compute visibility at the eye
- Perform ray tracing for arbitrary rays needed for shading
  - Reflections
  - Refraction and transparency
  - Shadows

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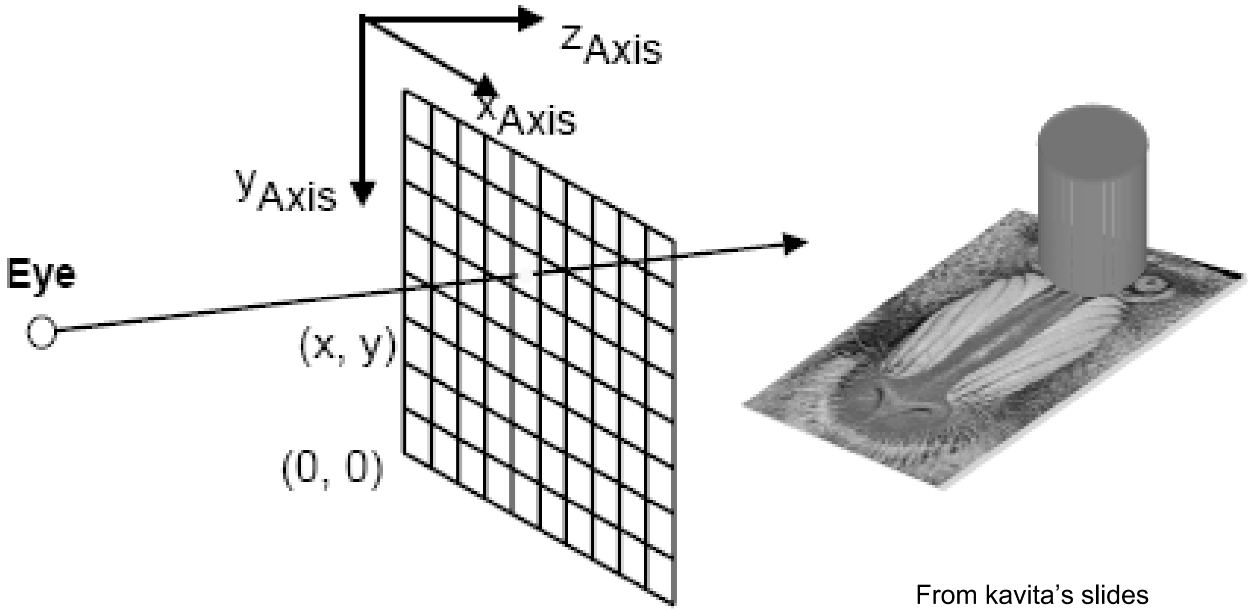
Basic Algorithms of Ray Tracing

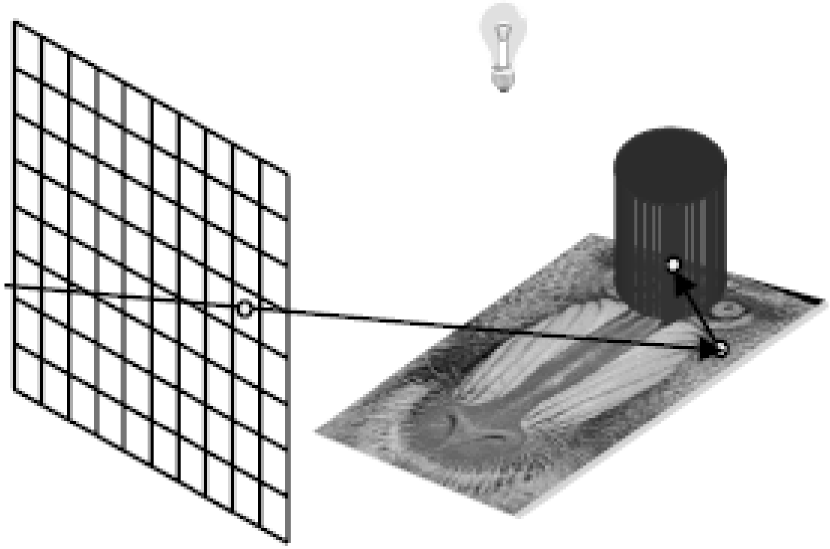
- **Rays are cast from the eye point through each pixel in the image**

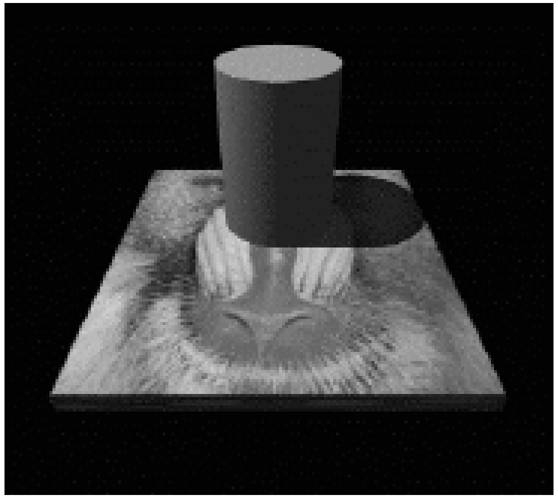


From kavita's slides

Shadows

- **Cast ray from the intersection point to each light source**
  - **Shadow rays**





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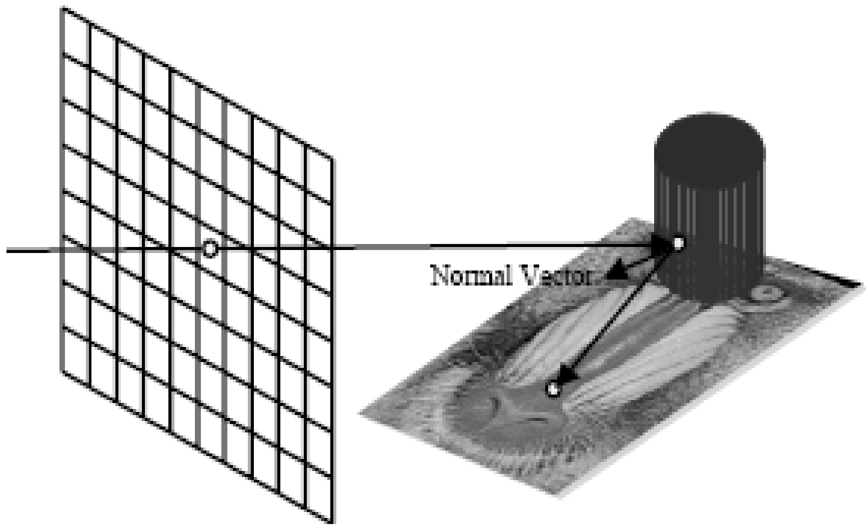
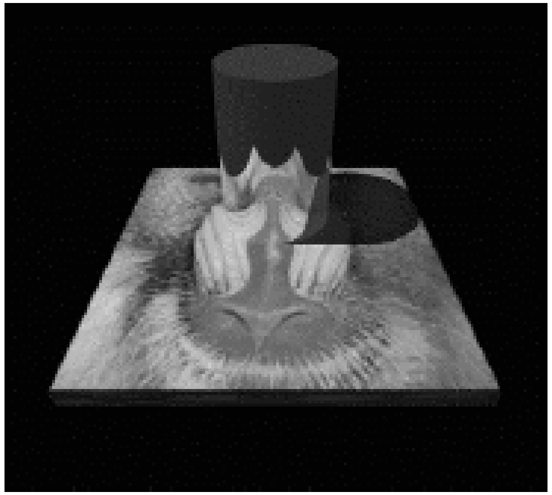
Reflections

- **If object specular, cast secondary reflected rays**





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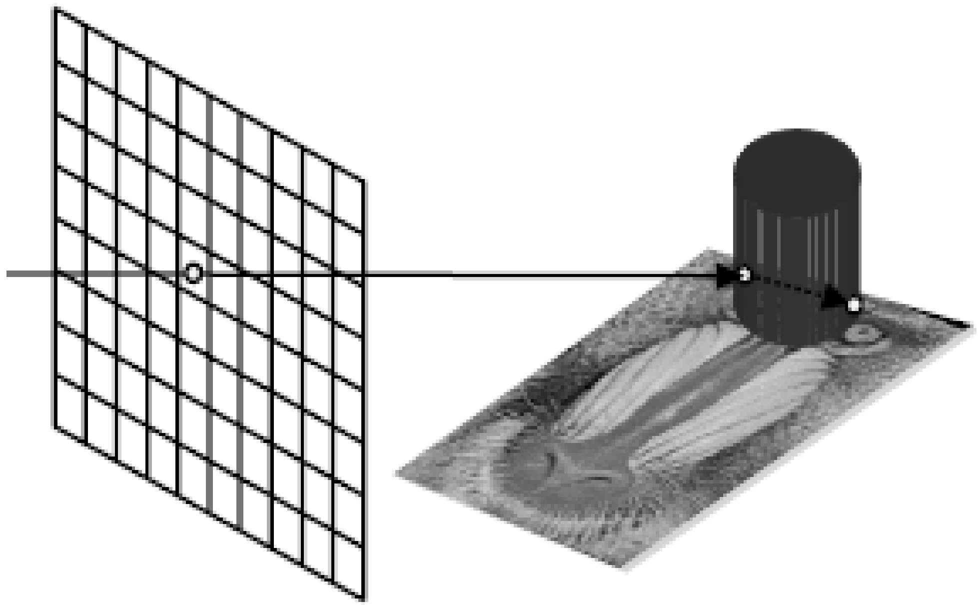
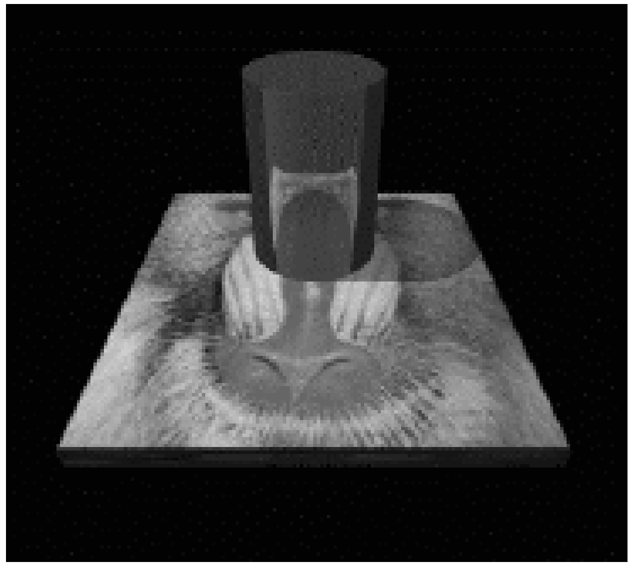
Refractions

- **If object tranparent, cast secondary refracted rays**





From kavita's slides

An Improved Illumination Model [Whitted 80]

- **Phong model**

$$I_r = \sum_{j=1}^{numLights} (k_a^j I_a^j + k_d^j I_d^j (\hat{N} \bullet \hat{L}_j) + k_s^j I_s^j (\hat{V} \bullet \hat{R})^{n_s})$$

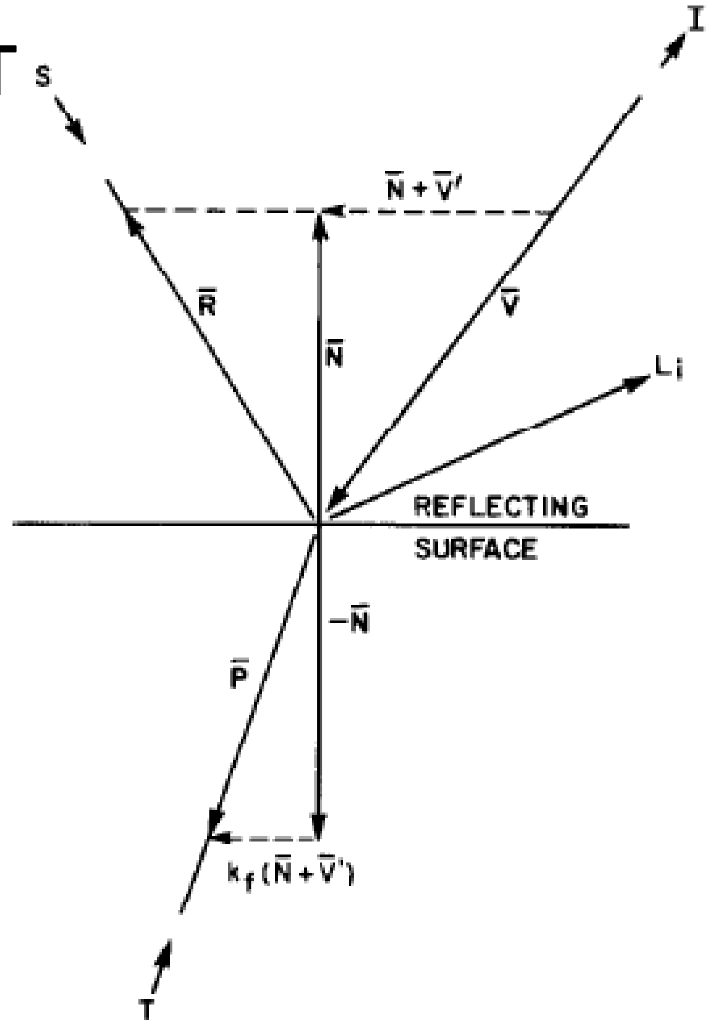
- **Whitted model**

$$I_r = \sum_{j=1}^{num\_Visible\_Lights} (k_a^j I_a^j + k_d^j I_d^j (\hat{N} \bullet \hat{L}_j)) + k_s S + k_t T$$

  - **S and T are intensity of light from reflection and transmission rays**
  - **Ks and Kt are specular and transmission coefficient**

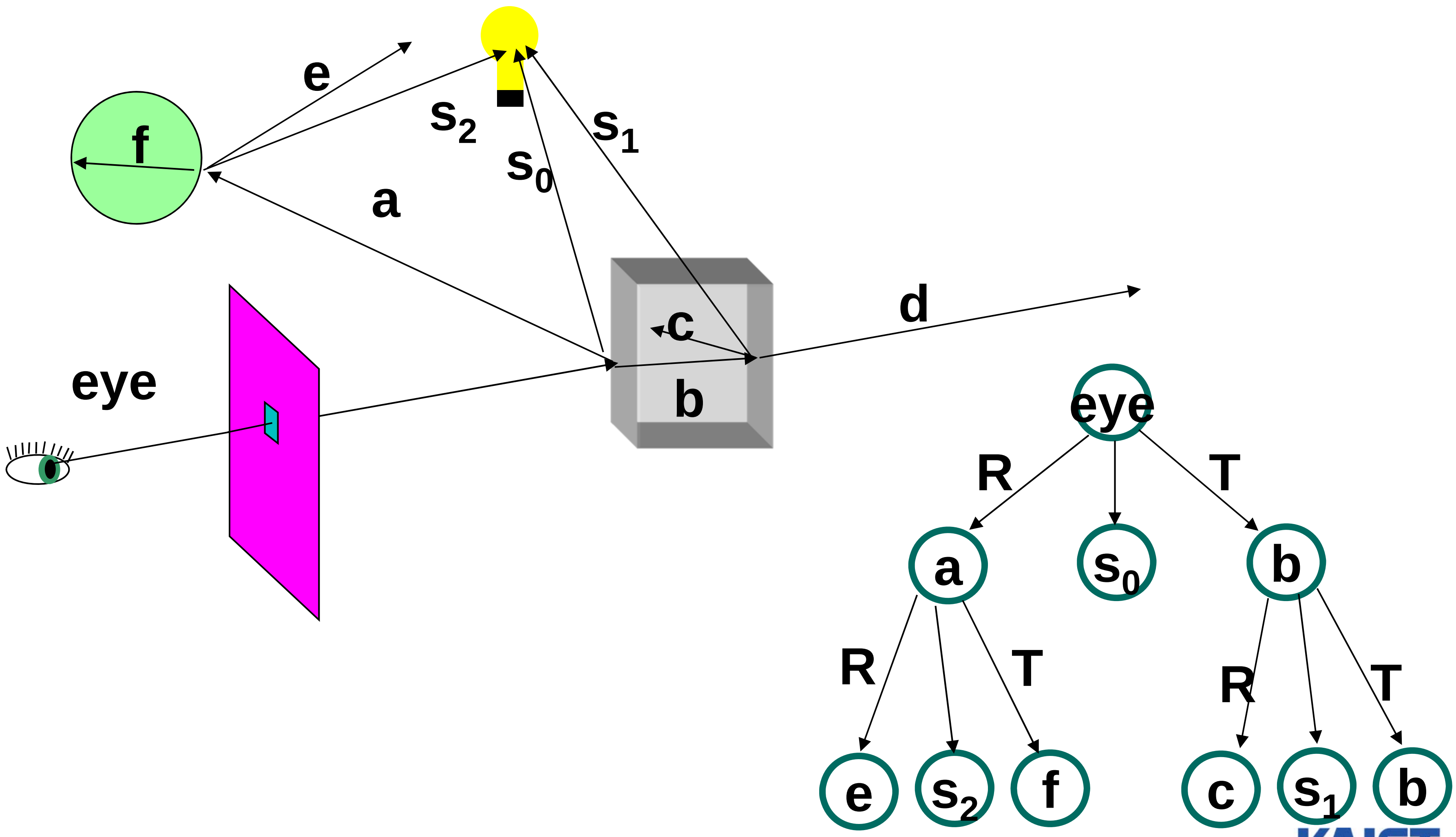
An Improved Illumination Model [Whitted 80]

$$I_r = \sum_{j=1}^{numLights} (k_a^j I_a^j + k_d^j I_d^j (\hat{N} \bullet \hat{L}_j)) + k_s S + k_t T$$



Computing reflection and transmitted/refracted rays is based on Snell's law (refer to Chapter 13.1)

Ray Tree



Overall Algorithm of Ray Tracing

- Per each pixel, compute a ray, R

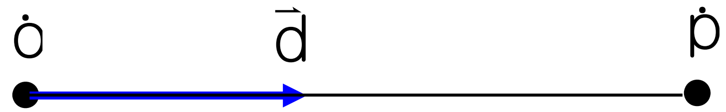
Def function RayTracing (R)

- Compute an intersection against objects
- If no hit,
  - Return the background color
- Otherwise,
  - Compute shading, c
  - General secondary ray, R'
  - Perform c' = RayTracing (R')
  - Return c+c'

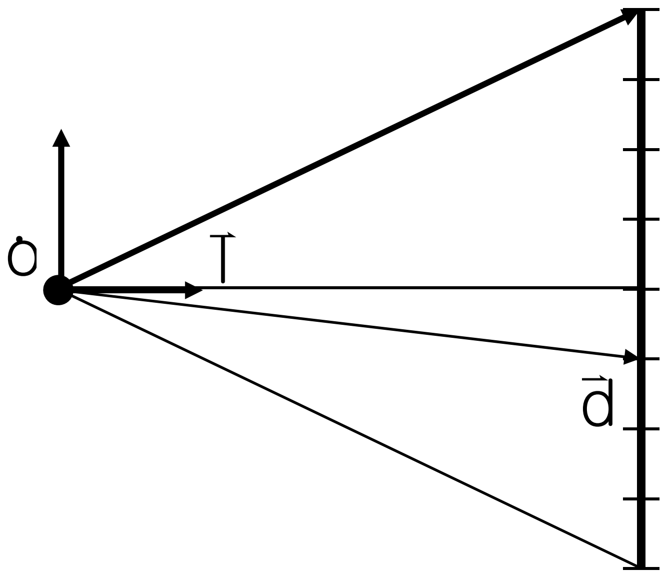
Ray Representation

- **We need to compute the first surface hit along a ray**
  - **Represent ray with origin and direction**
  - **Compute intersections of objects with ray**
  - **Return the closest object**

$$\dot{p}(t) = \dot{o} + t\vec{d}$$



Generating Primary Rays



Generating Secondary Rays

- **The origin is the intersection point p_0**
- **Direction depends on the type of ray**
  - **Shadow rays – use direction to the light source**
  - **Reflection rays – use incoming direction and normal to compute reflection direction**
  - **Transparency/refraction – use snell's law**

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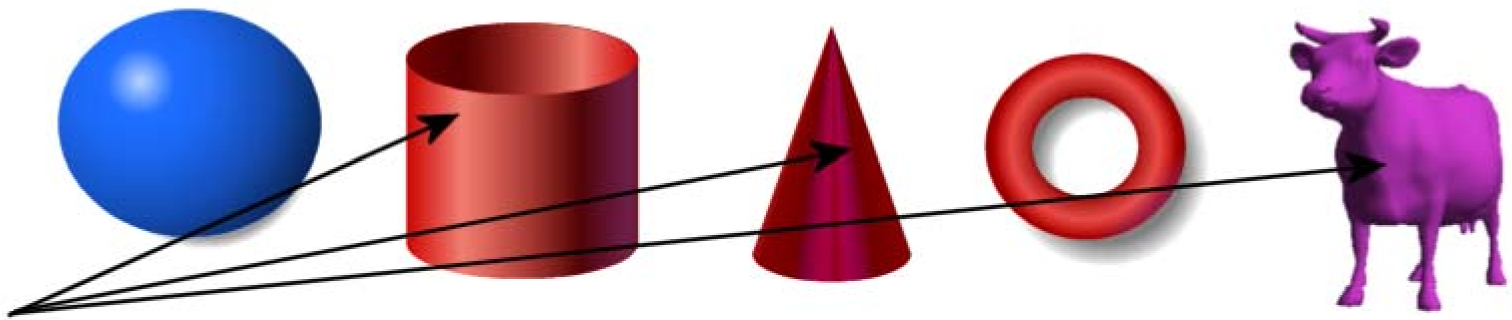
Intersection Tests

Go through all of the objects in the scene to determine the one closest to the origin of



Strategy: Solve of the intersection of the Ray with a mathematical description of the object

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Simple Strategy

- **Parametric ray equation**
  - **Gives all points along the ray as a function of the parameter**

$$\dot{p}(t) = \dot{o} + t\vec{d}$$

- **Implicit surface equation**
  - **Describes all points on the surface as the zero set of a function**

$$f(\dot{p}) = 0$$

- **Substitute ray equation into surface function and solve for t**

$$f(\dot{o} + t\vec{d}) = 0$$

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Ray-Plane Intersection

- **Implicit equation of a plane:**

$$\vec{n} \cdot \dot{p} - d = 0$$

- **Substitute ray equation:**

$$\vec{n} \cdot (\dot{o} + t\vec{d}) - d = 0$$

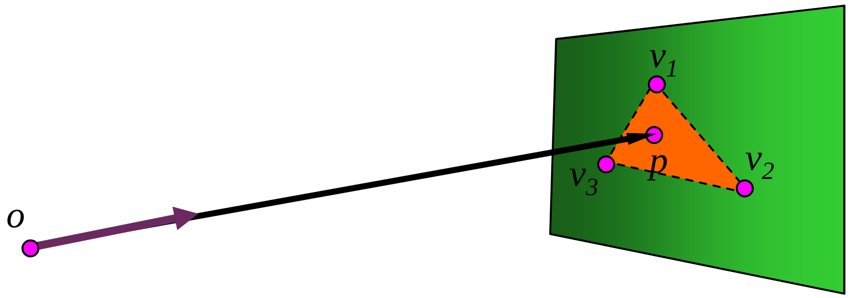
- **Solve for t:**

$$t(\vec{n} \cdot \vec{d}) = d - \vec{n} \cdot \dot{o}$$

$$t = \frac{d - \vec{n} \cdot \dot{o}}{\vec{n} \cdot \vec{d}}$$

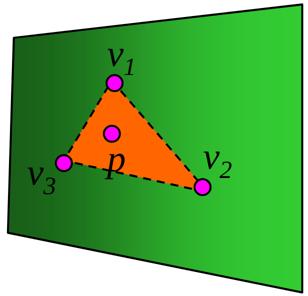
Generalizing to Triangles

- **Find of the point of intersection on the plane containing the triangle**
- **Determine if the point is inside the triangle**
  - **Barycentric coordinate method**
  - **Many other methods**

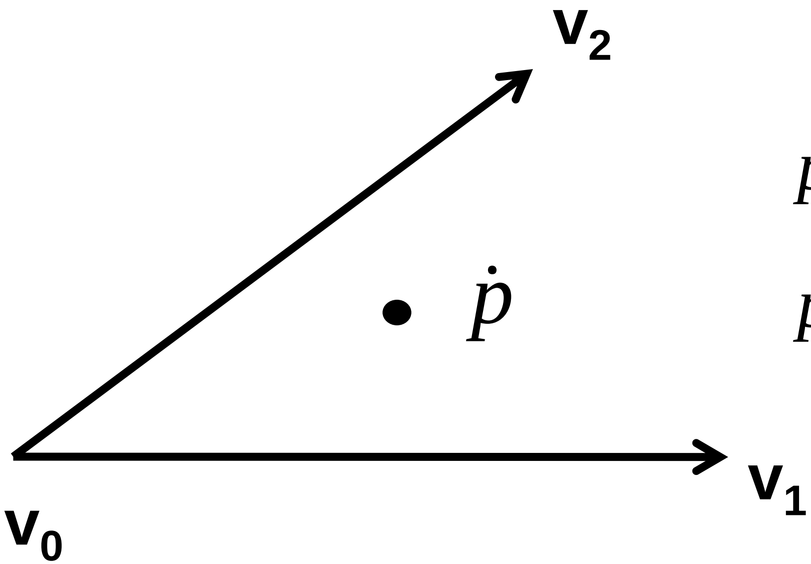


Barycentric Coordinates

- **Points in a triangle have positive barycentric coordinates:**



$$\dot{p} = \alpha\dot{v}_0 + \beta\dot{v}_1 + \gamma\dot{v}_2 \quad \text{,where } \alpha + \beta + \gamma = 1$$

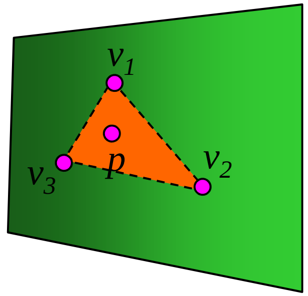


$$\dot{p} = \dot{v}_0 + \beta(\dot{v}_1 - \dot{v}_0) + \gamma(\dot{v}_2 - \dot{v}_0)$$

$$\dot{p} = (1 - \beta - \gamma)\dot{v}_0 + \beta\dot{v}_1 + \gamma\dot{v}_2$$

Barycentric Coordinates

- **Points in a triangle have positive barycentric coordinates:**



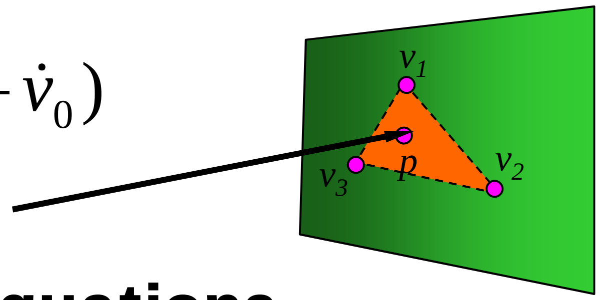
$$\dot{p} = \alpha\dot{v}_0 + \beta\dot{v}_1 + \gamma\dot{v}_2 \quad \text{,where } \alpha + \beta + \gamma = 1$$

- **Benefits:**
  - **Barycentric coordinates can be used for interpolating vertex parameters (e.g., normals, colors, texture coordinates, etc)**

Ray-Triangle Intersection

- A point in a ray intersects with a triangle

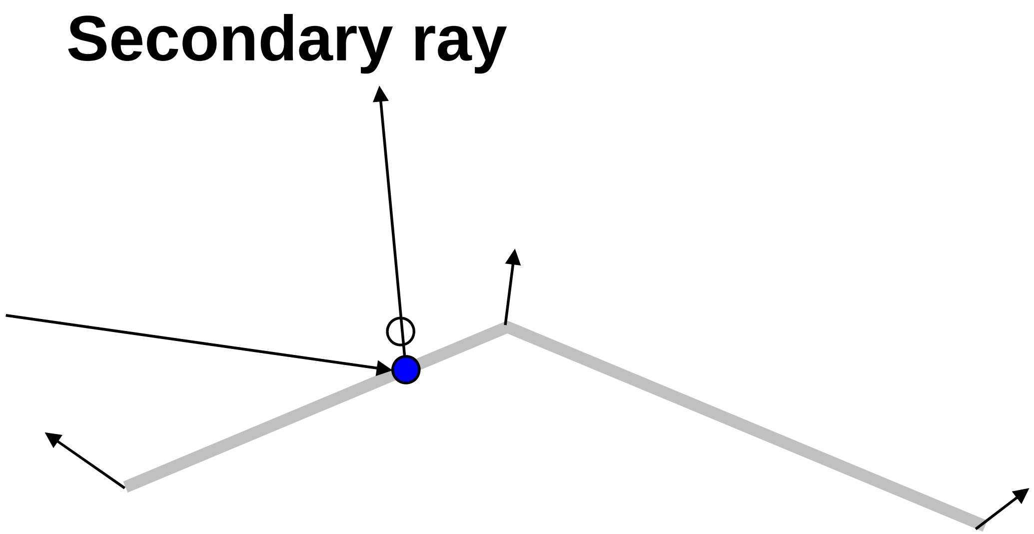
$$\dot{p}(t) = \dot{v}_0 + \beta(\dot{v}_1 - \dot{v}_0) + \gamma(\dot{v}_2 - \dot{v}_0)$$



  - Three unknowns, but three equations
  - Compute the point based on t
  - Then, check whether the point is on the triangle
  - Refer to Sec. 4.4.2 in the textbook for the detail equations

Robustness Issues

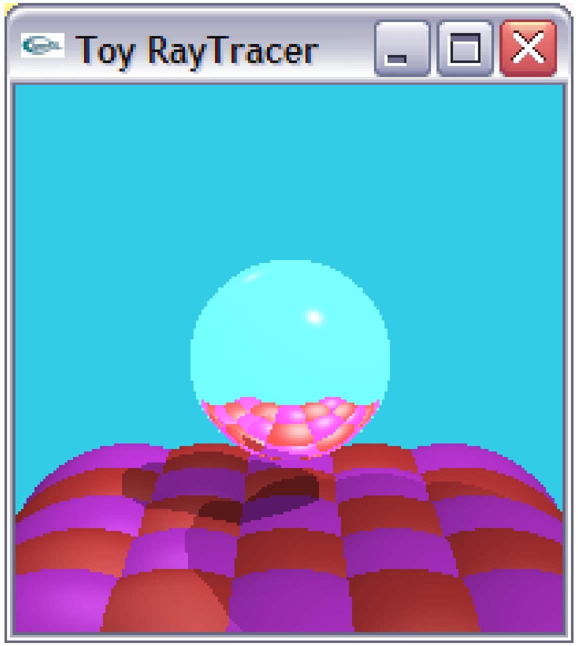
- False self-intersections
  - One solution is to offset the origin of the ray from the surface when tracing secondary rays



Pros and Cons of Ray Tracing

Advantages of Ray Tracing:

- **Very simple design**
- **Improved realism over the graphics pipeline**

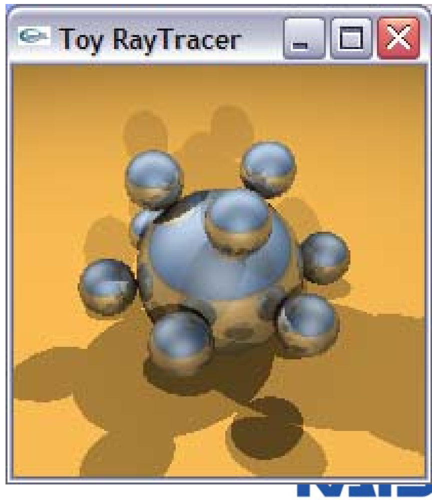


Disadvantages:

- **Very slow per pixel calculations**
- **Only approximates full global illumination**
- **Hard to accelerate with special-purpose H/W**

Acceleration Methods

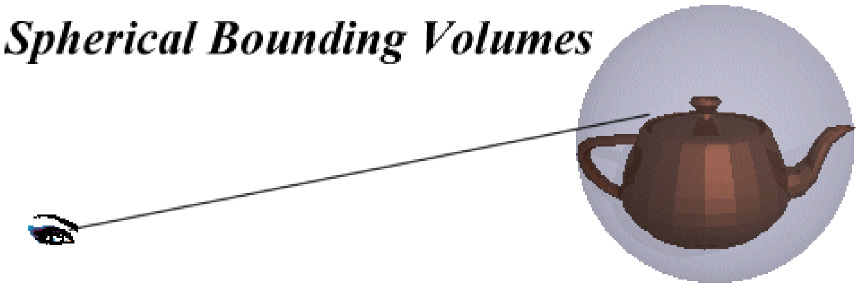
- Rendering time for a ray tracer depends on the number of ray intersection tests per pixel
  - The number of pixels X the number of primitives in the scene
- Early efforts focused on accelerating the ray-object intersection tests
- More advanced methods required to make ray tracing practical
  - Bounding volume hierarchies
  - Spatial subdivision



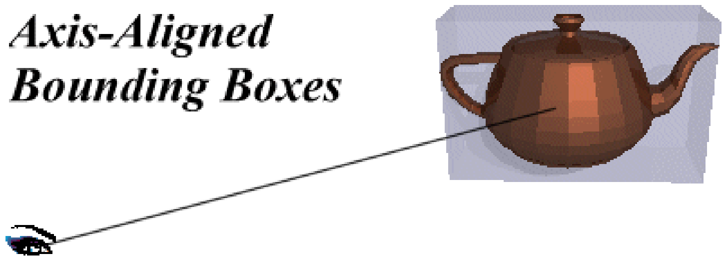
Bounding Volumes

- Enclose complex objects within a simple-to-intersect objects
  - If the ray does not intersect the simple object then its contents can be ignored
  - The likelihood that it will strike the object depends on how tightly the volume surrounds the object.

Spherical Bounding Volumes



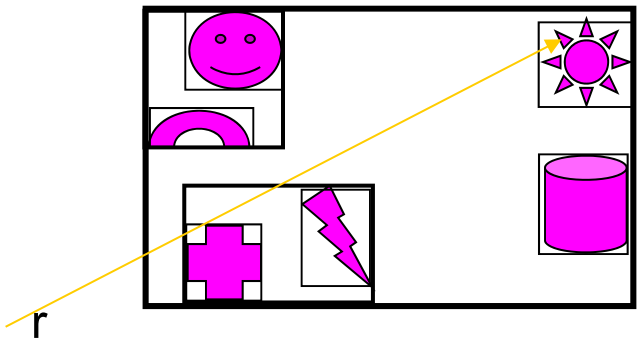
Axis-Aligned Bounding Boxes

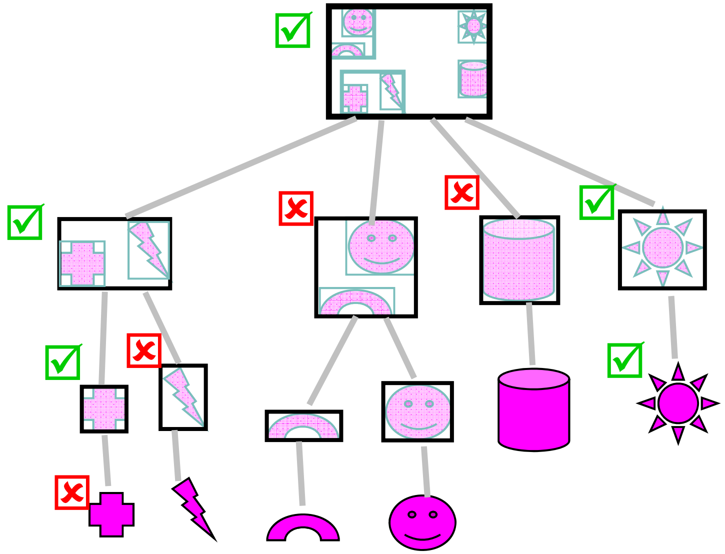


Potentially tighter fit, but with higher computation

Hierarchical Bounding Volumes

- Organize bounding volumes as a tree
- Each ray starts with the root BV of the tree and traverses down through the tree

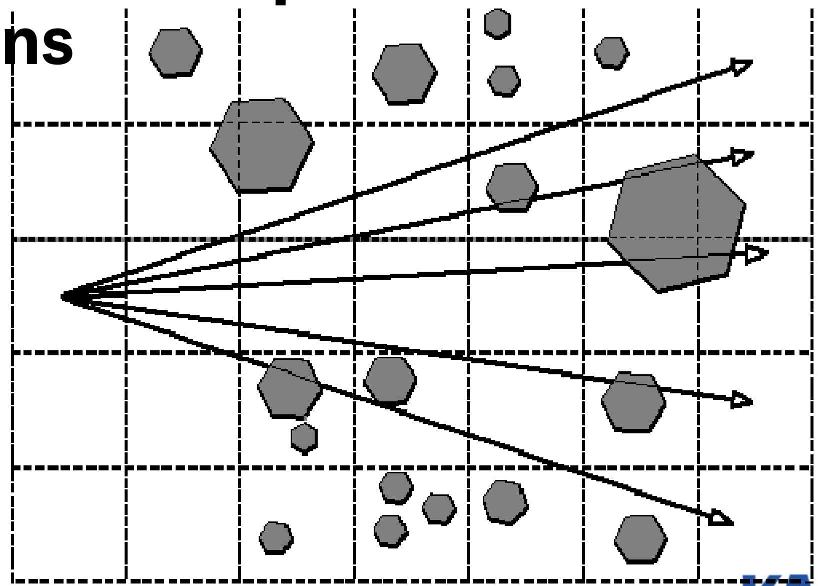




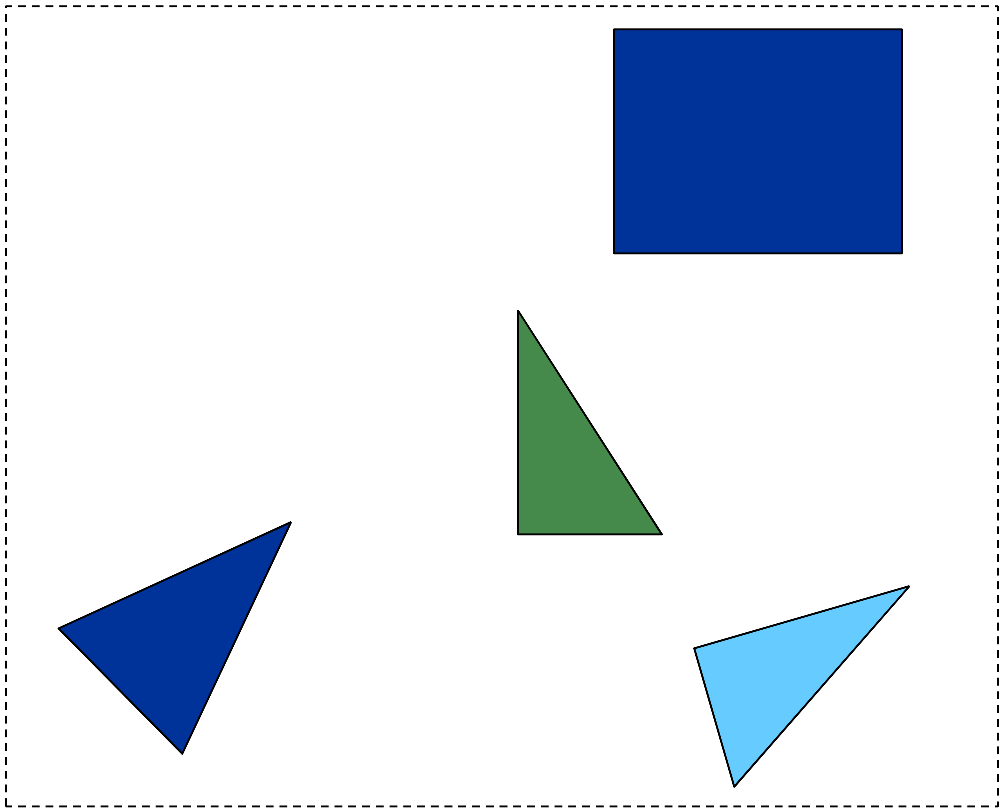
Spatial Subdivision

Idea: Divide space in to subregions

- **Place objects within a subregion into a list**
- **Only traverse the lists of subregions that the ray passes through**
- **"Mailboxing" used to avoid multiple test with objects in multiple regions**
- **Many types**
    - **Regular grid**
    - **Octree**
    - **BSP tree**
    - **kd-tree**



Kd-tree: Example



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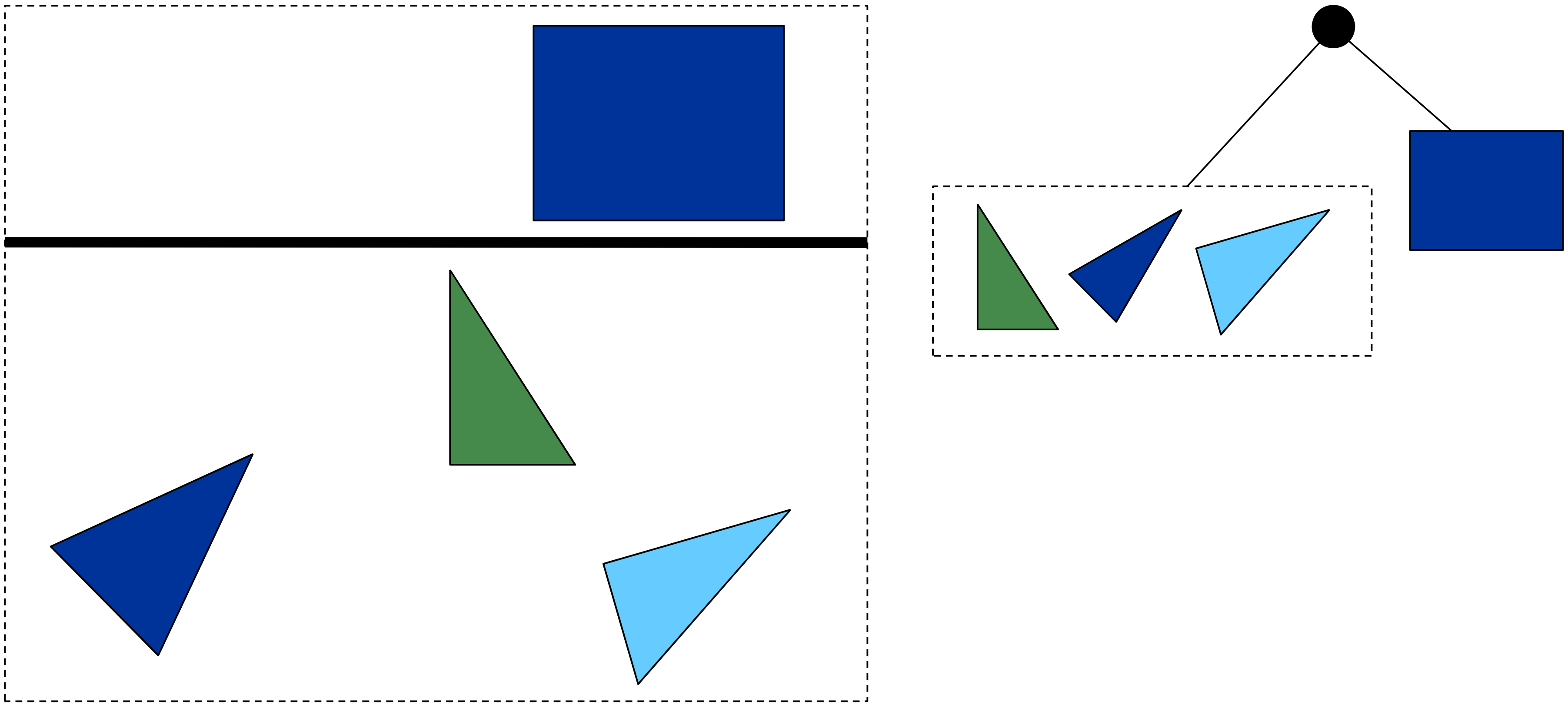
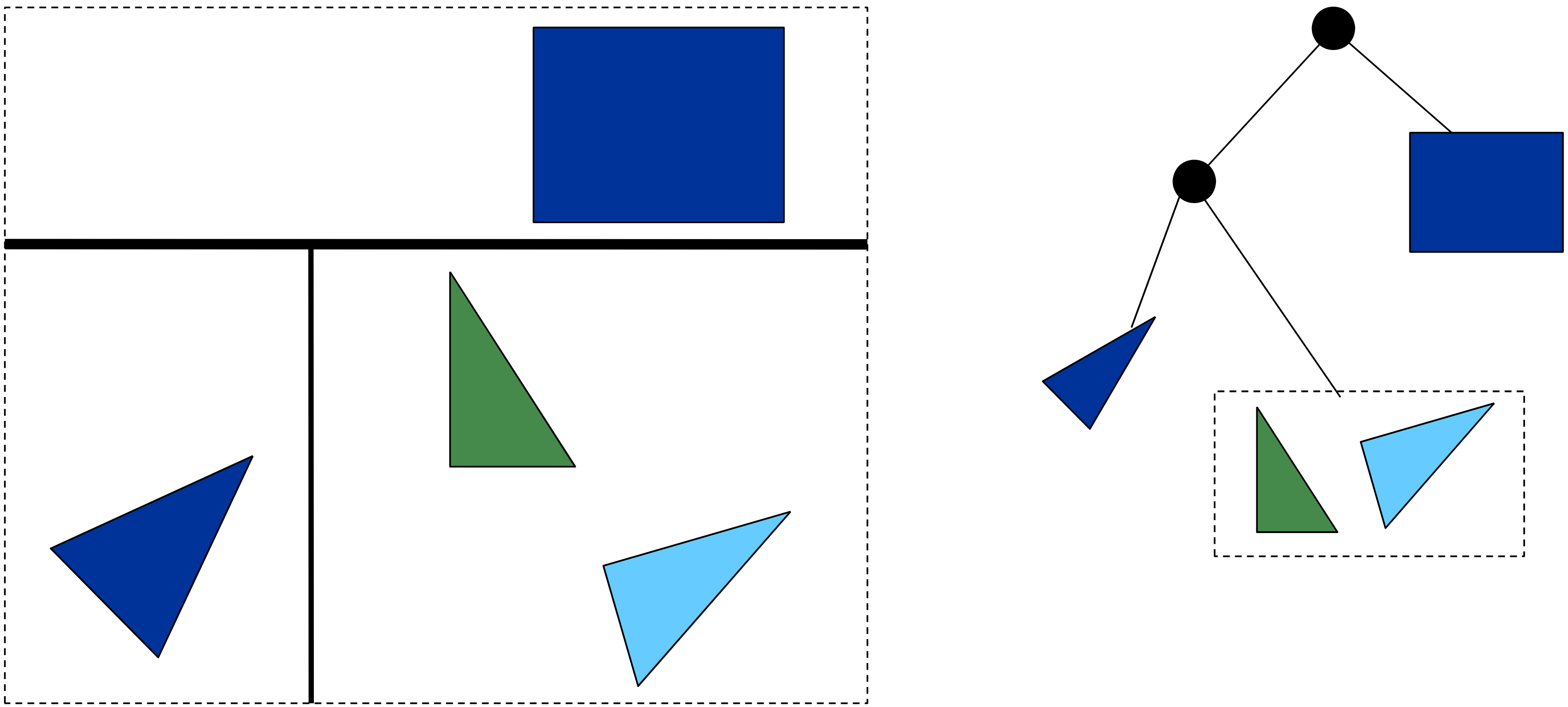
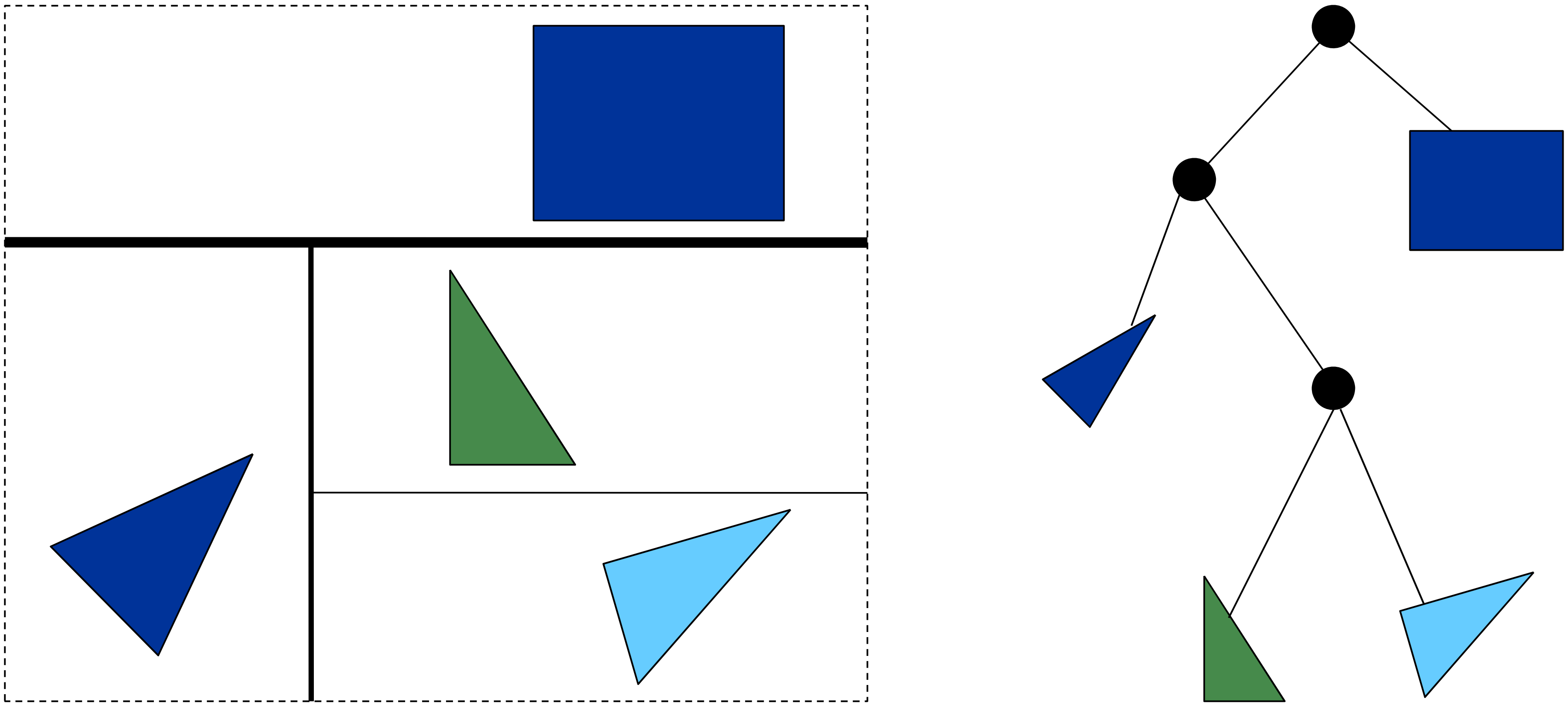
Kd-tree: Example



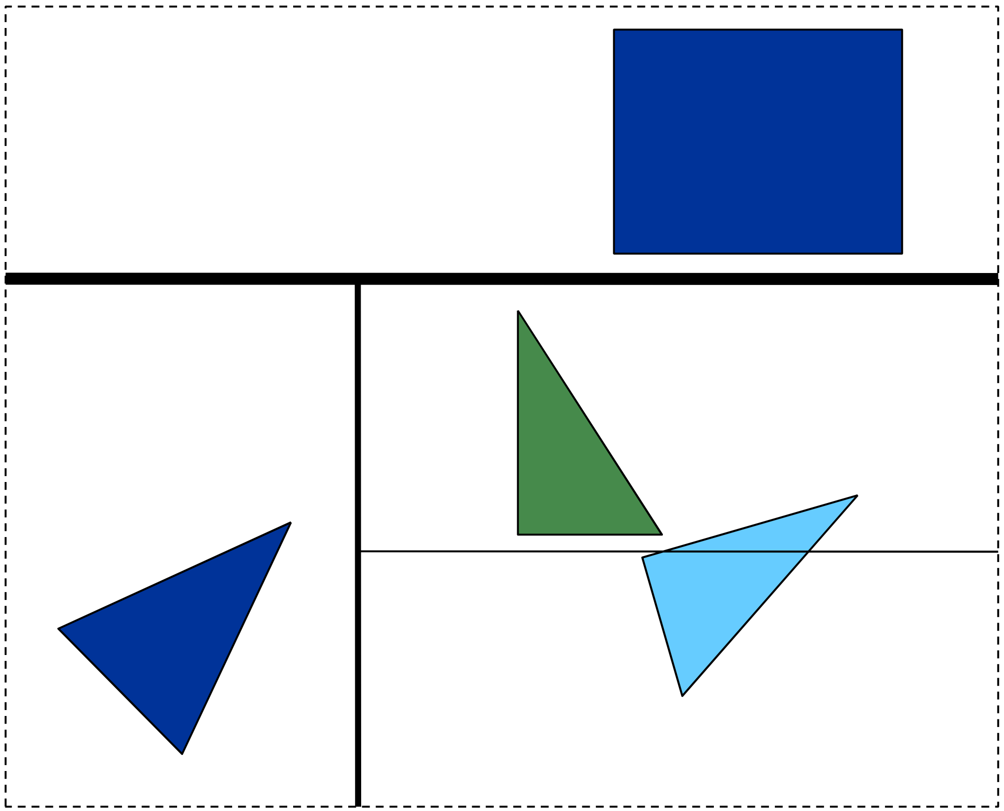
Kd-tree: Example



Example

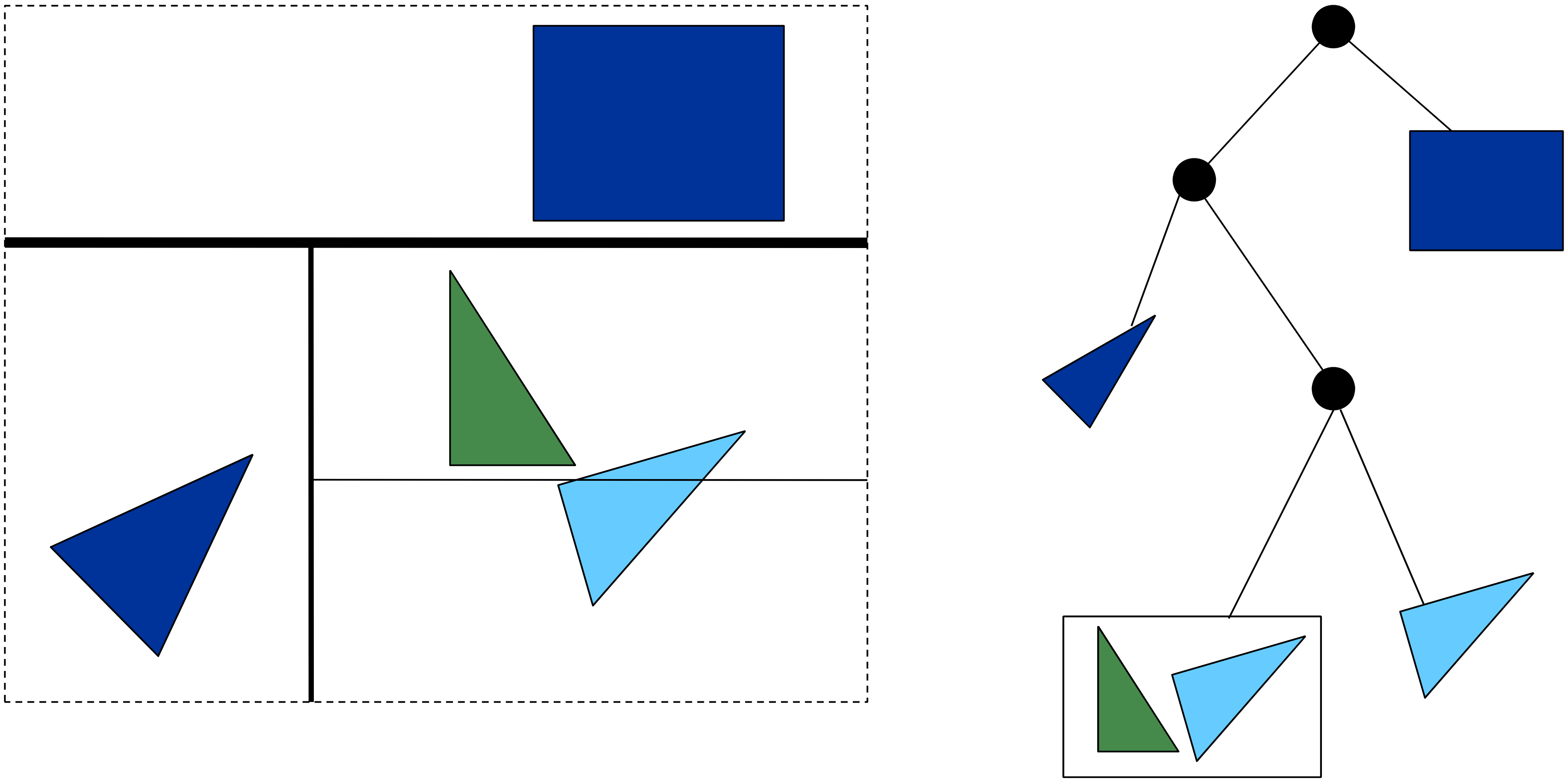


Kd-tree: Example



What about triangles overlapping the split?

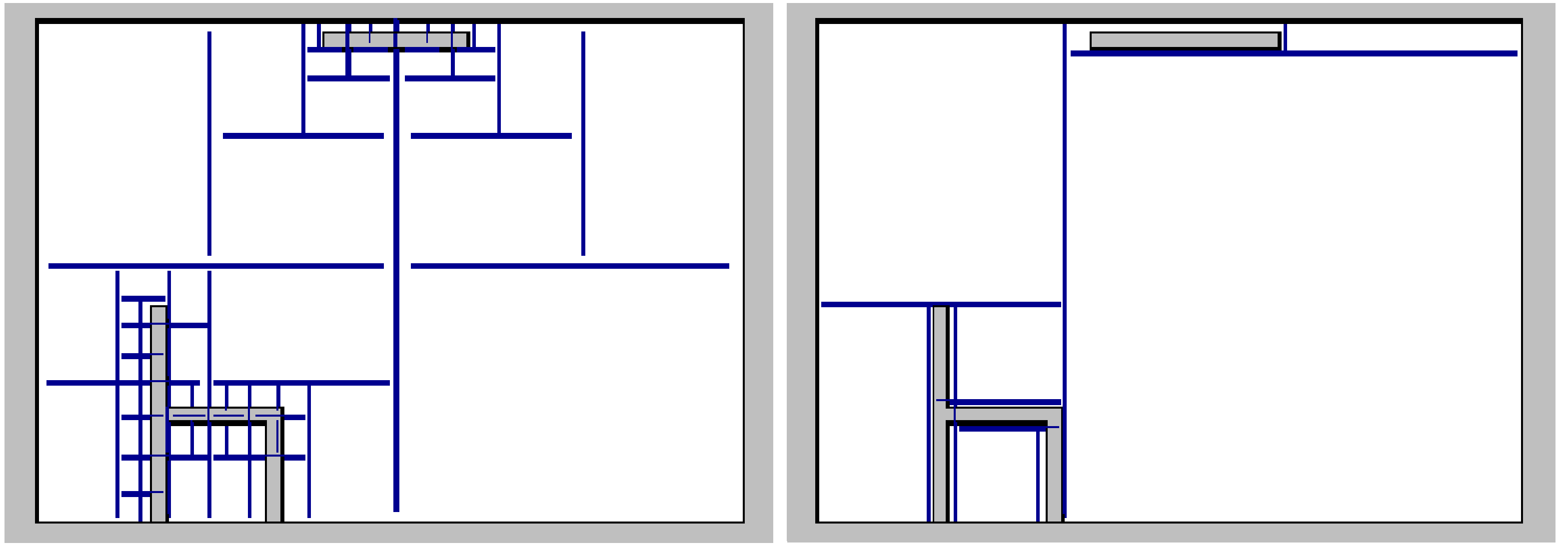
Kd-tree: Example



Split Planes

- How to select axis & split plane?
  - Largest dimension, subdivide in middle
  - More advanced:
    - Surface area heuristic
- Makes large difference
  - 50%-100% higher *overall* speed

Median vs. SAH



(from [Wald04])

Ray Tracing with kd-tree

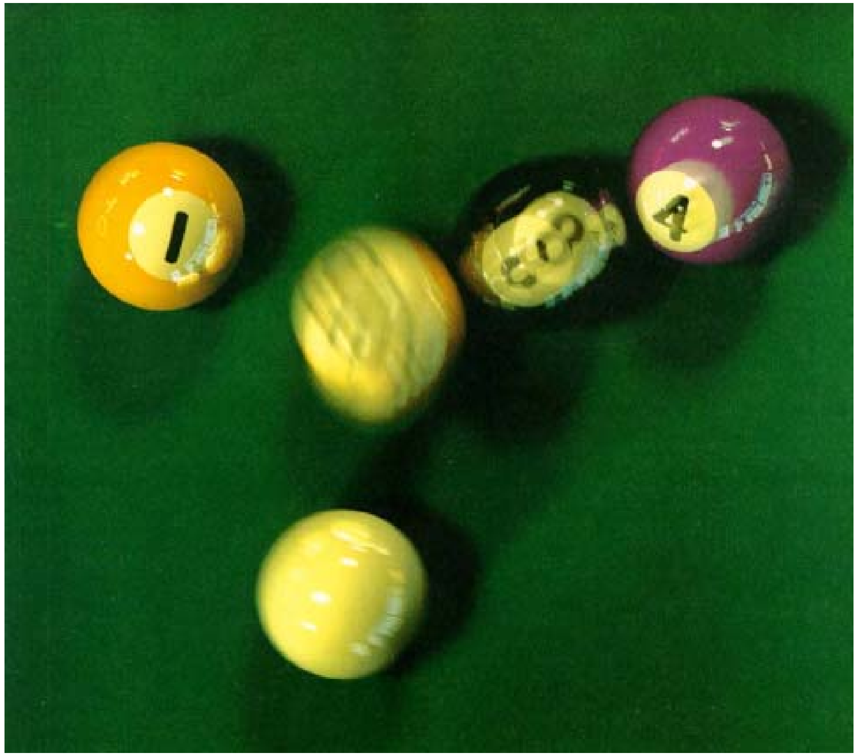
- Goal: find closest hit with scene
- Traverse tree front to back (starting from root)
- At each node:
  - If leaf: intersect with triangles
  - If inner: traverse deeper

Other Optimizations

- Shadow cache
- Adaptive depth control
- Lazy geometry loading/creation

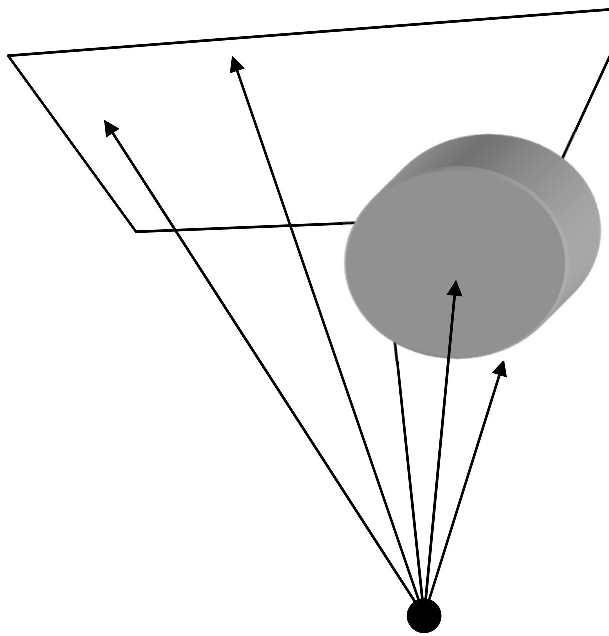
Distributed Ray Tracing [Cook et al. 84]

- Cook et al. realized that ray-tracing, when combined with randomized sampling, which they called "jittering", could be adapted to address a wide range of rendering problems:



Soft Shadows

- **Take many samples from area light source and take their average**
  - **Computes fractional visibility leading to penumbra**



Antialiasing

- **The need to sample is problematic because sampling leads to aliasing**
- **Solution 1: super-sampling**
  - **Increases sampling rate, but does not completely eliminate aliasing**
  - **Difficult to completely eliminate aliasing without prefiltering because the world is not band-limited**

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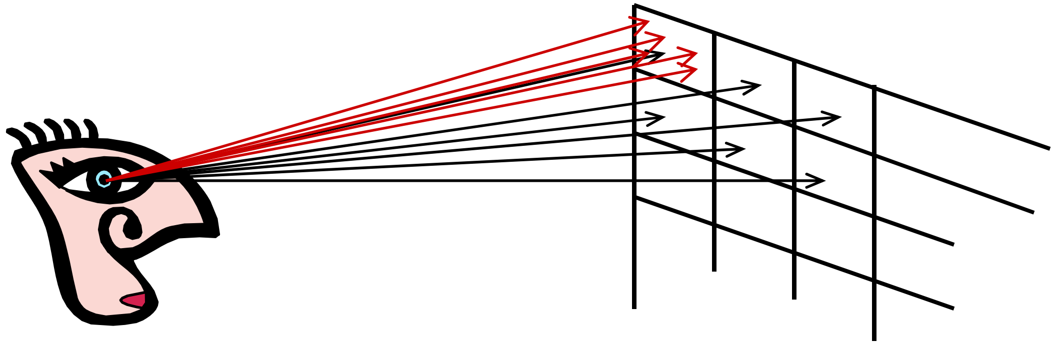
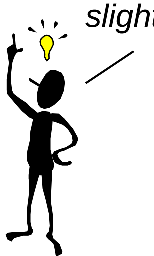
Antialiasing

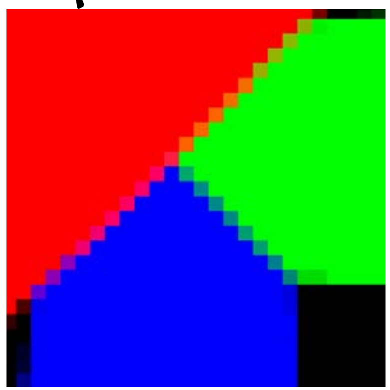
- **Solution 2: distribute the samples randomly**
  - **Converts the aliasing energy to noise which is less objectionable to the eye**



Instead of casting one ray per pixel, cast several sub- sampling.

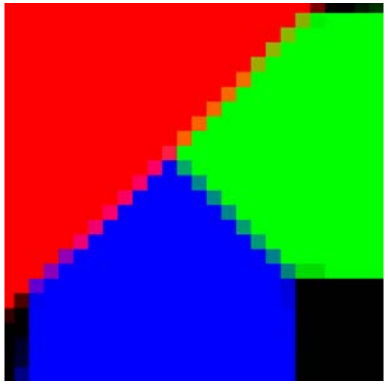
Instead of uniform sub-sampling, jitter the pixels slightly off the grid.

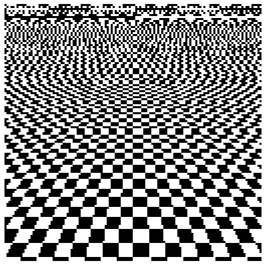


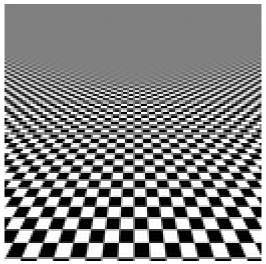


Jittering Results for Antialiasing

2x2 sub-sampling

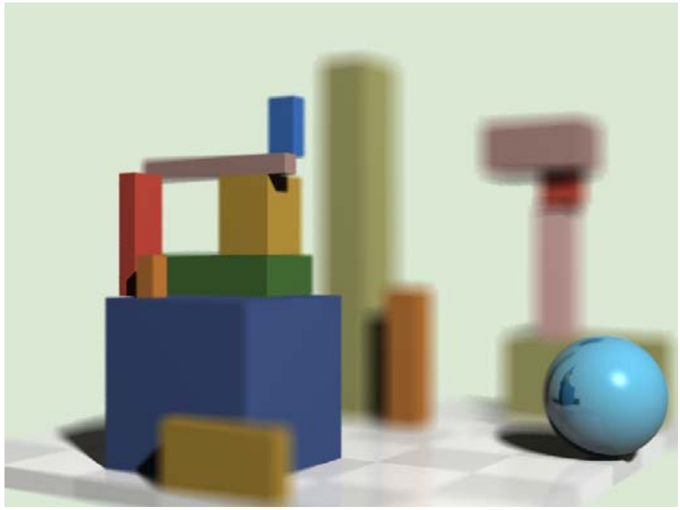




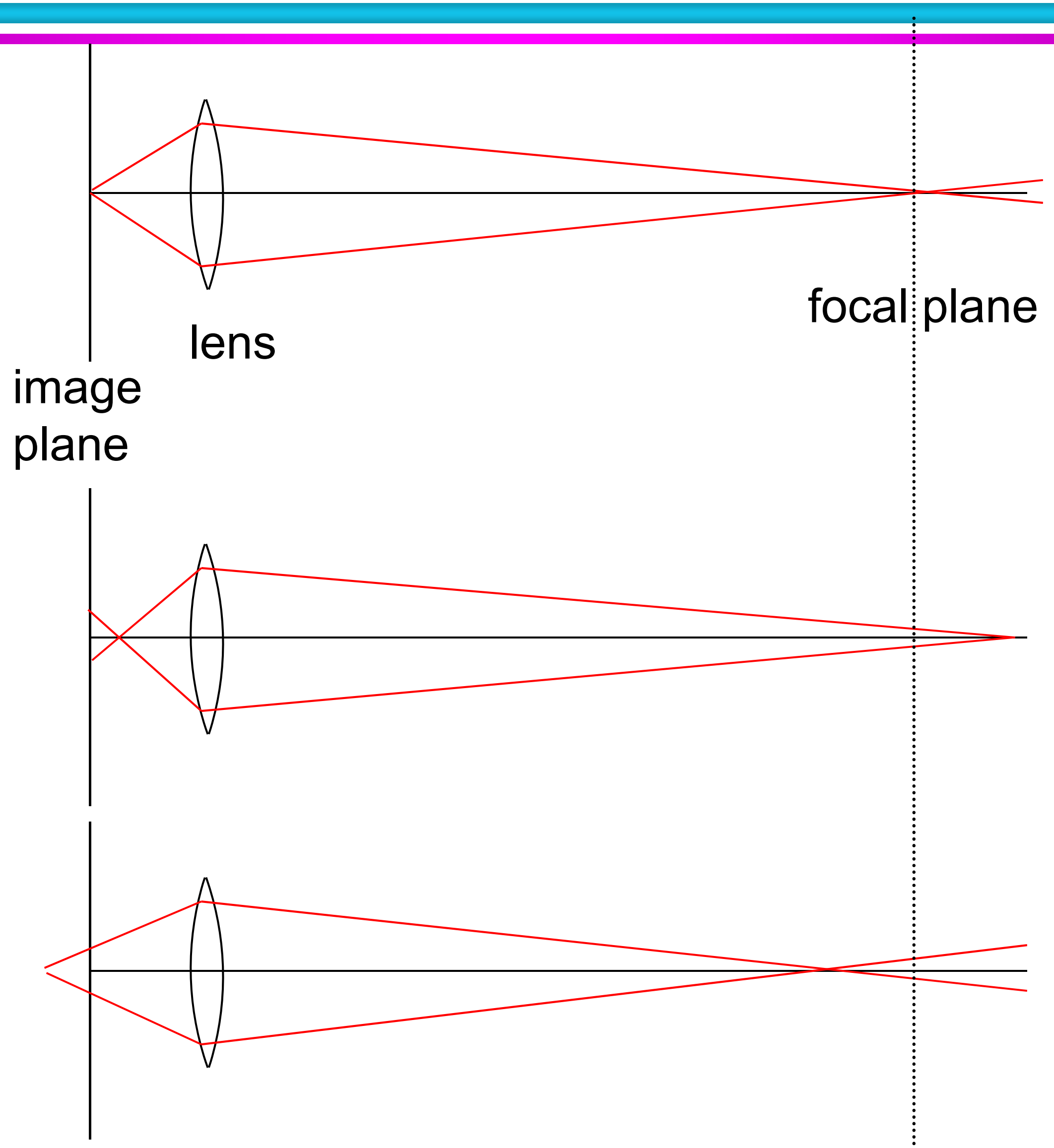


Depth-of-Field

- **Rays don't have to all originate from a single point.**
- **Real cameras collects rays over an aperture**
  - **Can be modeled as a disk**
  - **Final image is blurred away from the focal plane**
  - **Gives rise to depth-of-field effects**

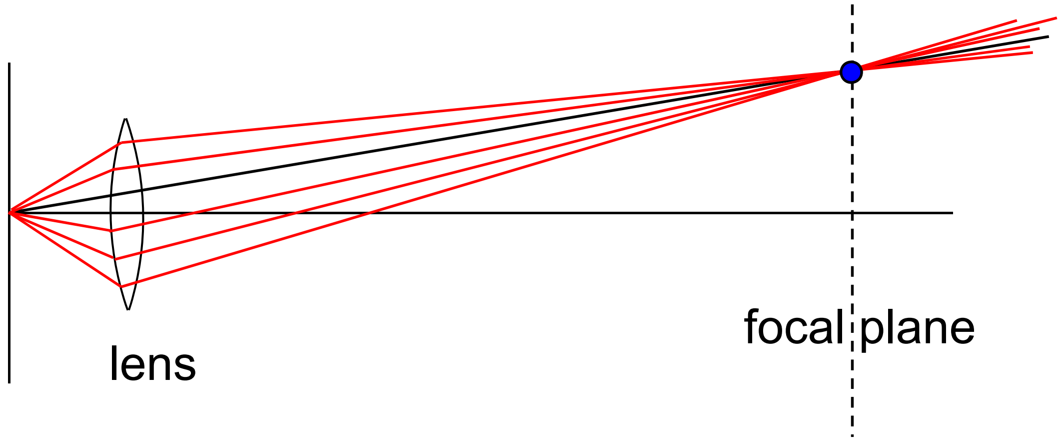


Depth of Field

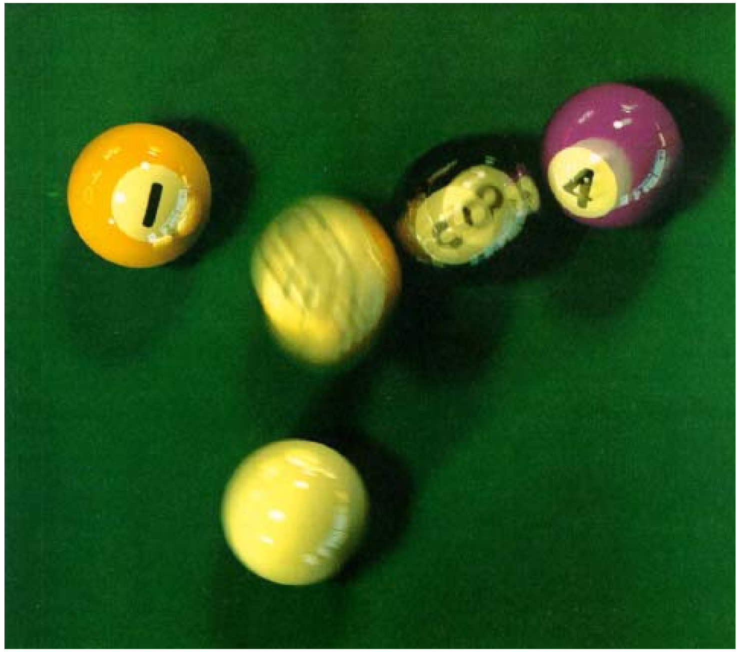


Depth of Field

- Start with normal eye ray and find intersection with focal plane
- Choose jittered point on lens and trace line from lens point to focal point

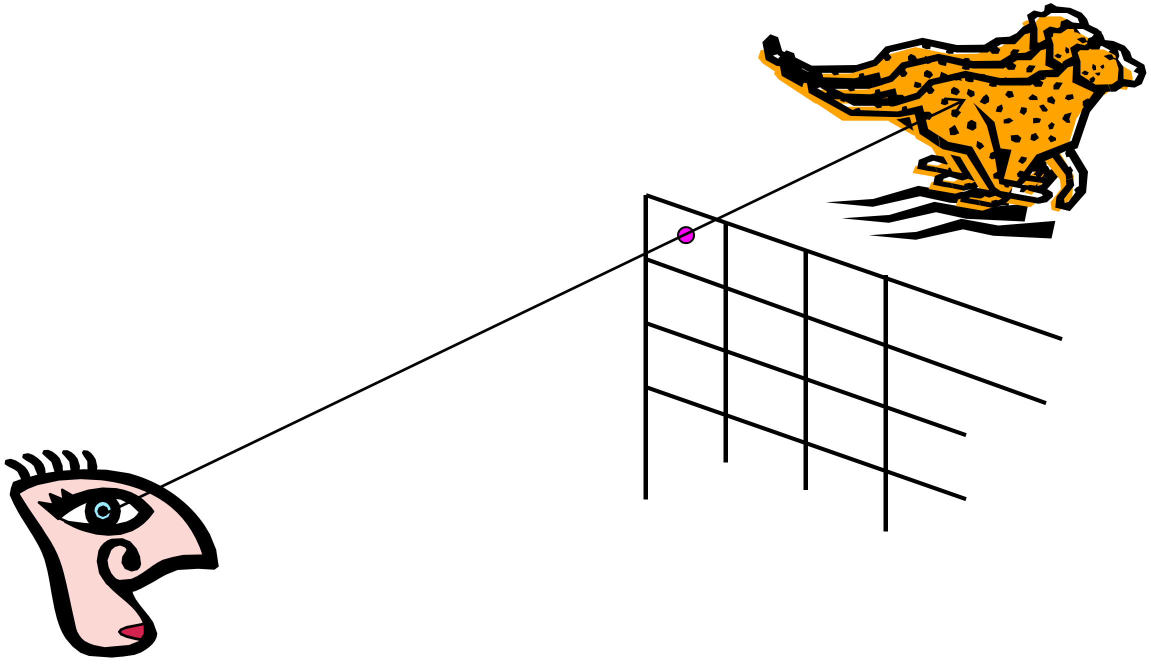


Motion Blur



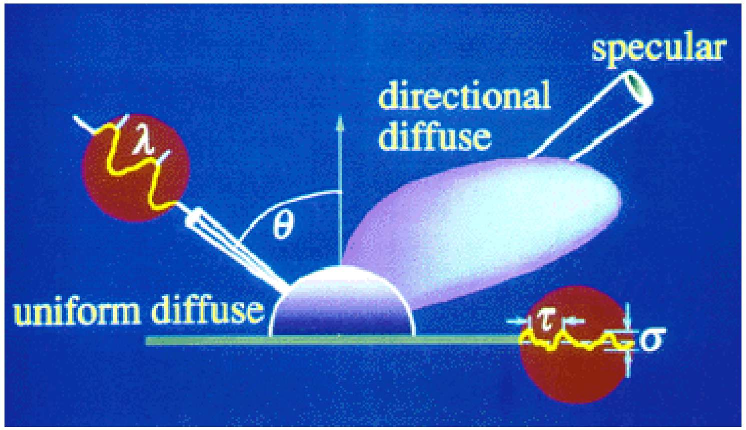
- Jitter samples through time
  - Simulate the finite interval that a shutter is open on a real camera

Motion Blur



Complex Interreflection

- Model true reflection behavior as described by a full BRDF
- Randomly sample rays over the hemisphere, weight them by their BRDF value, and average them together
  - This technique is called "Monte Carlo Integration"



Related Courses

- CS580: Advanced Computer Graphics
  - Focus on rendering techniques that generate photo-realistic images

- CS482: Interactive Computer Graphics
  - Interactive global illumination implemented by rasterization approaches
  - Techniques used in recent games
  - I'll teach it at Fall of 2015

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