Ray Tracing

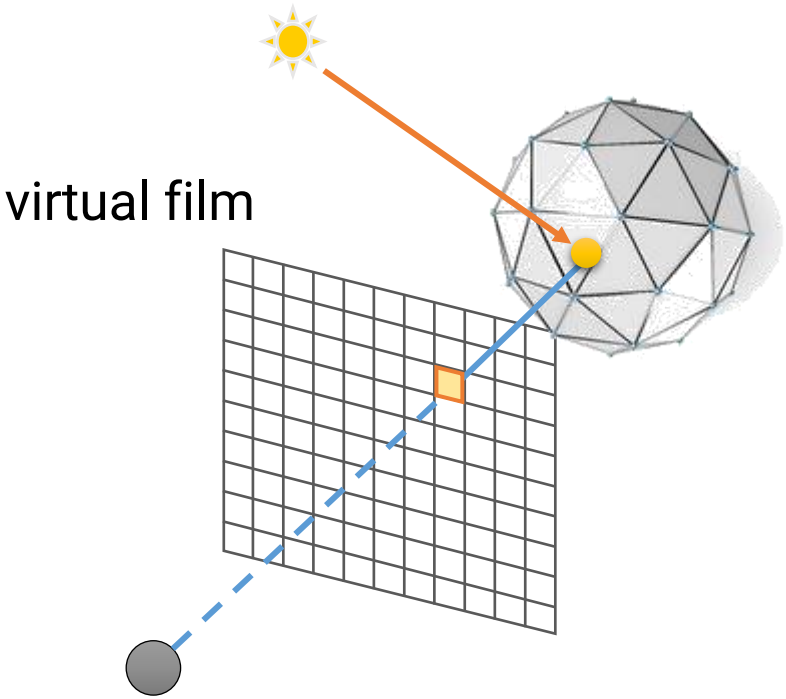
Introduction to Computer Graphics

Yu-Ting Wu

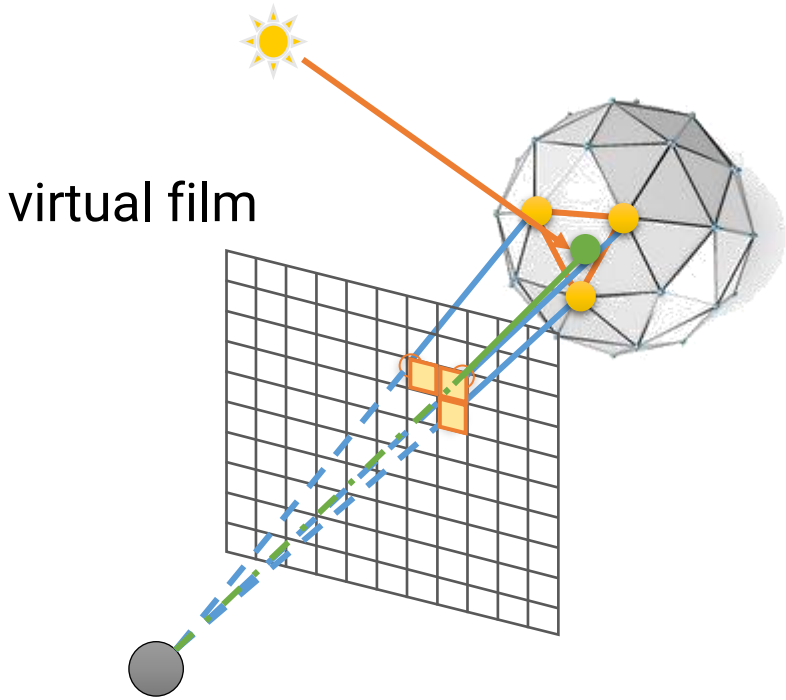
(Some of this slides are borrowed from Prof. Yung-Yu Chuang)

Recap: Digital Image Synthesis

Ray tracing

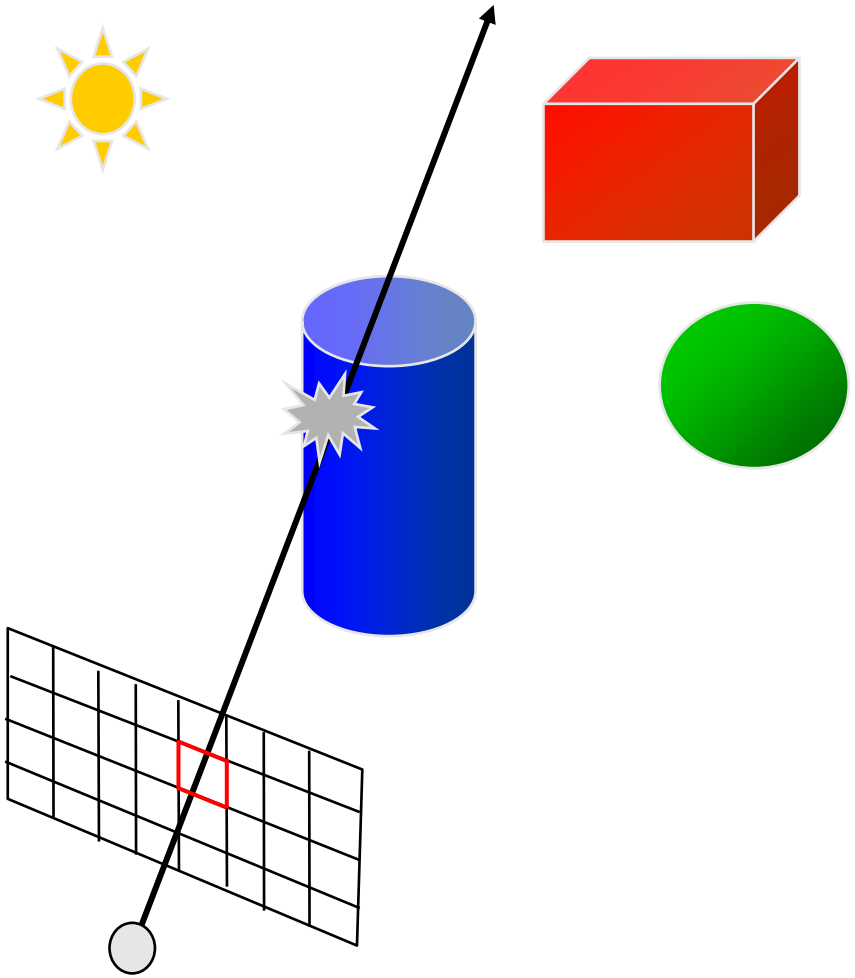


Rasterization



Ray Casting

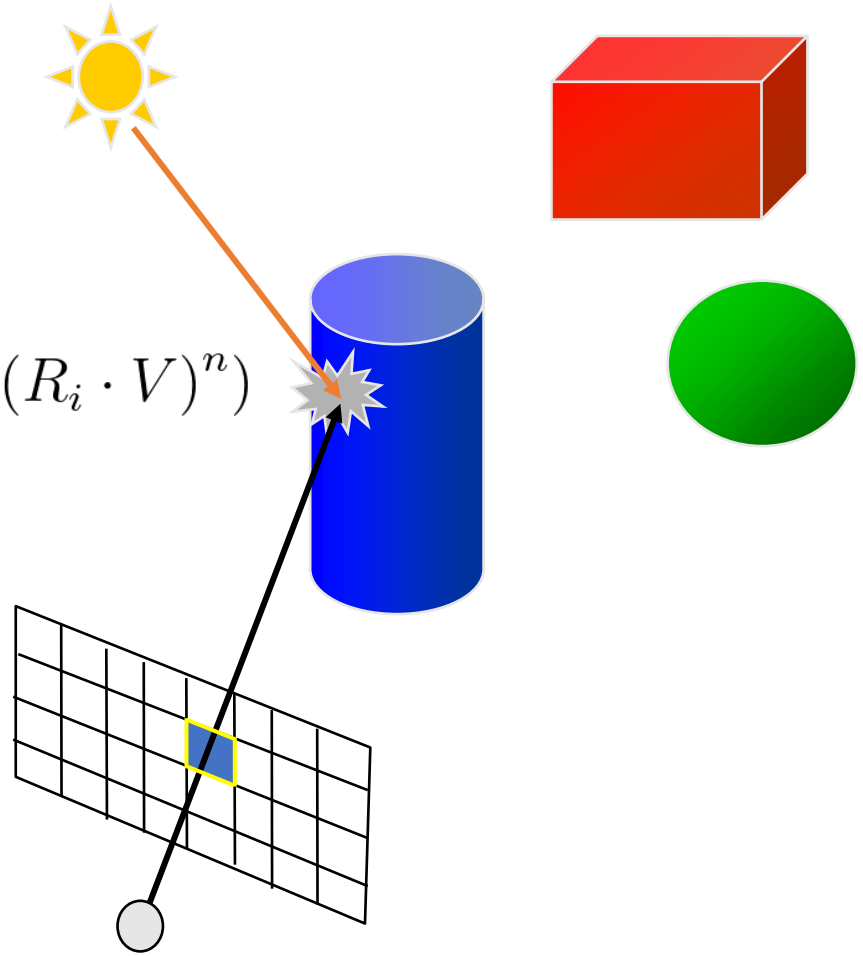
- Proposed by Appel [1968]



Ray Casting (cont.)

- Proposed by Appel [1968]

$$K_a I_a + \sum_{i=1}^{nls} I_i \left(K_d \left(L_i \cdot N \right) + K_s \left(R_i \cdot V \right)^n \right)$$



Ray Casting (cont.)

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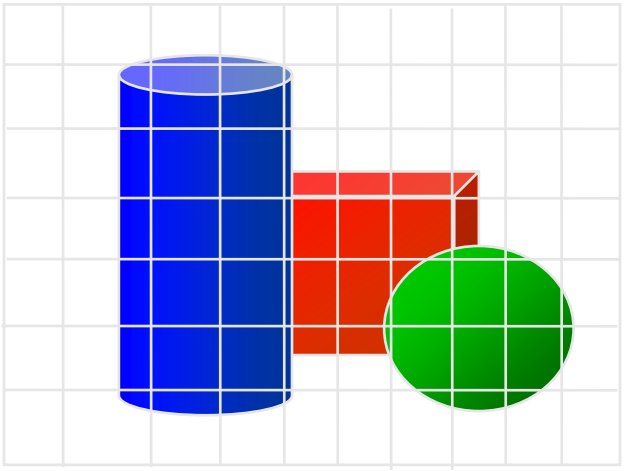
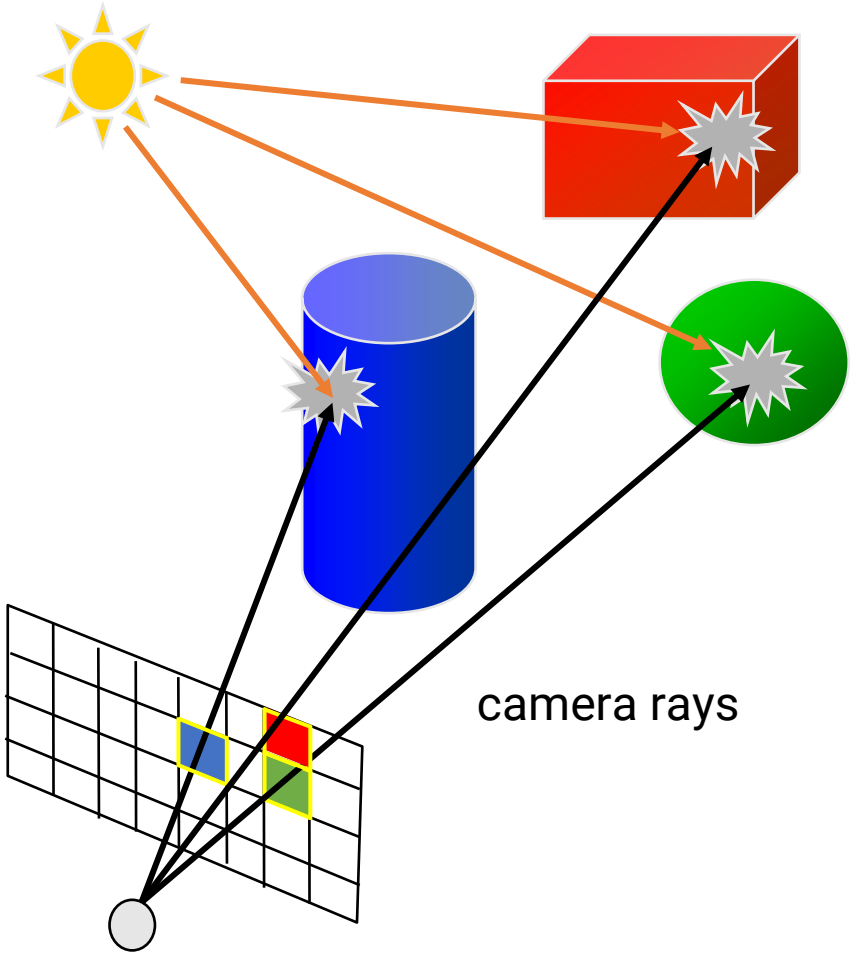
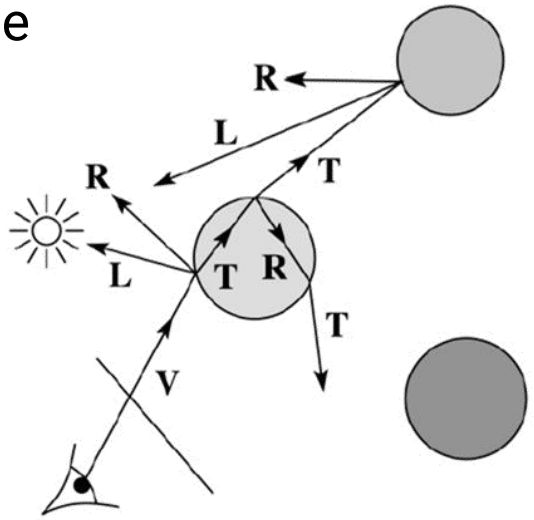


local illumination



Whitted Ray Tracing

- Proposed by Whitted, 1980
- **Recursive** trace rays for **shadows**, perfect **specular** (e.g., mirror), and perfect **transparent** (e.g., glass) objects
  - For each pixel, trace a primary ray in the direction ***V*** to the first visible surface
  - For each intersection, trace secondary rays including
    - Shadow rays (***L***) to each light source
    - Reflected ray (***R***)
    - Refracted ray (***T***)



Whitted Ray Tracing (cont.)

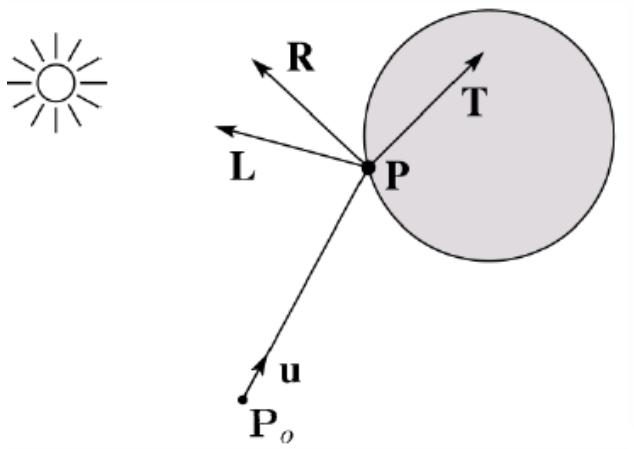
- Recursive shading
  - If $I(P_0, u)$ is the intensity seen from the point P along direction u

$$I(P_0, u) = I_{\text{direct}} + I_{\text{reflected}} + I_{\text{refracted}}$$

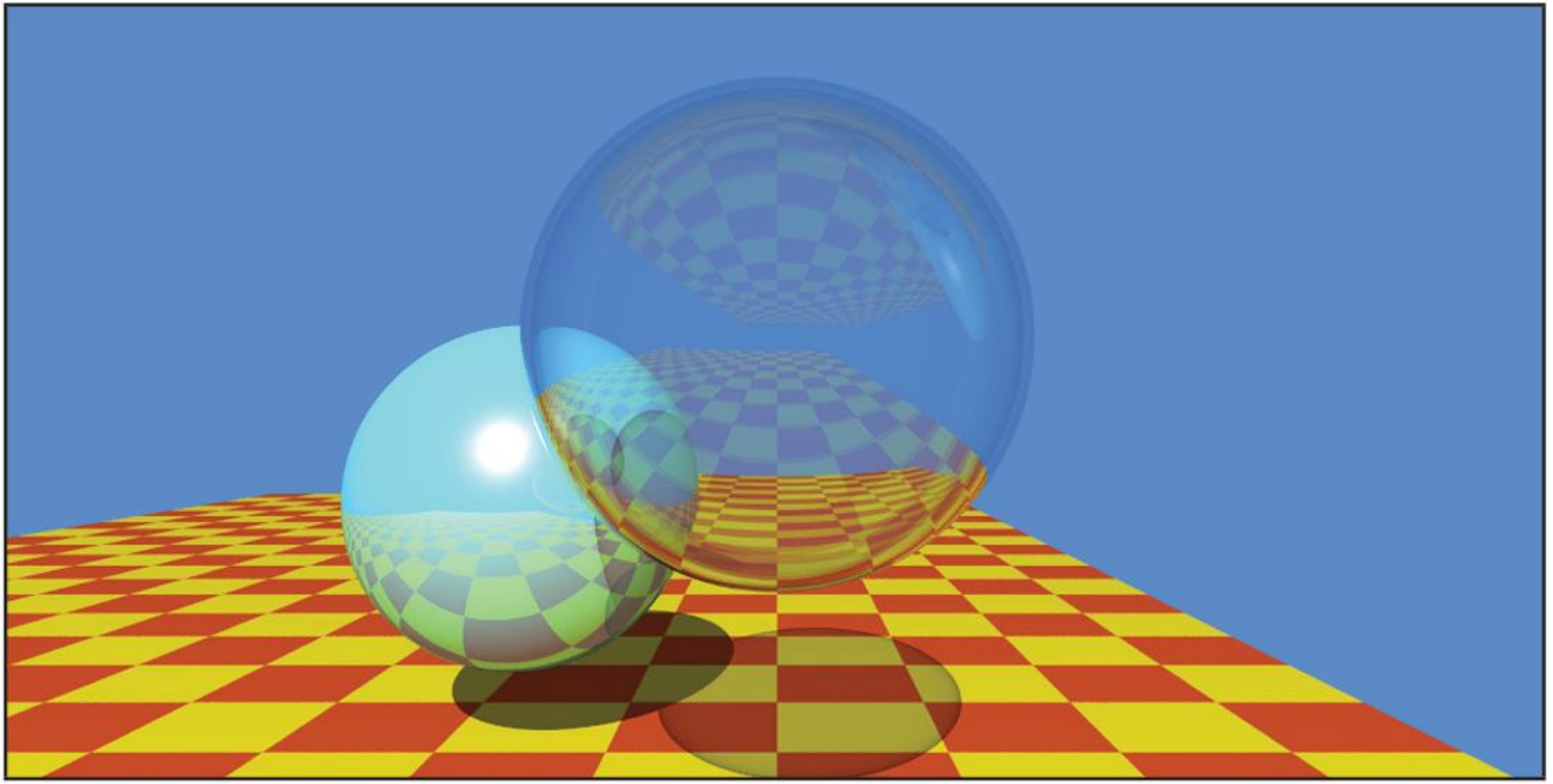
$$I_{\text{direct}} = \text{Shade}\,(N, L, u, R)$$

$$I_{\text{reflected}} = I(P, R)$$

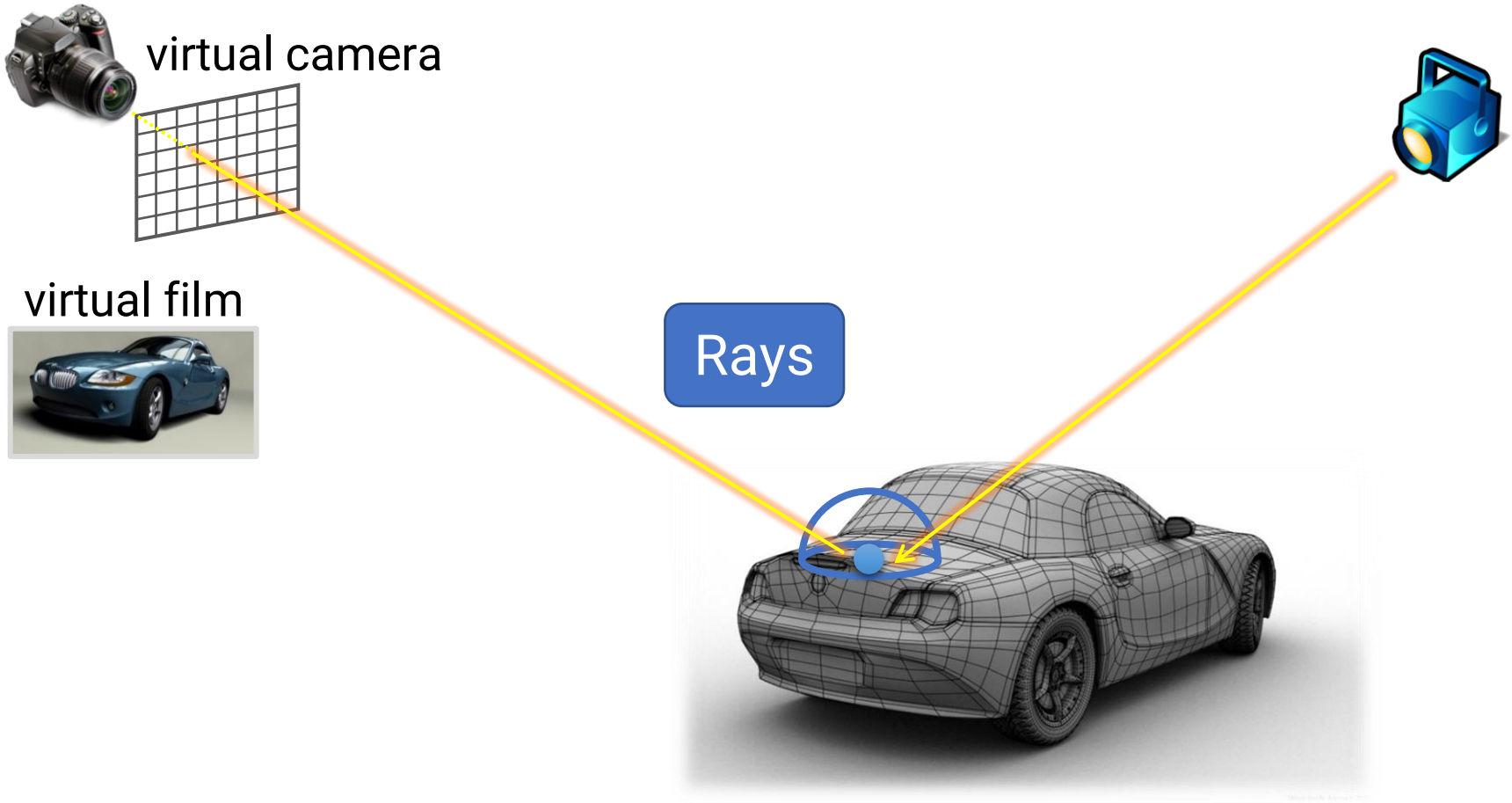
$$I_{\text{refracted}} = I(P, T)$$



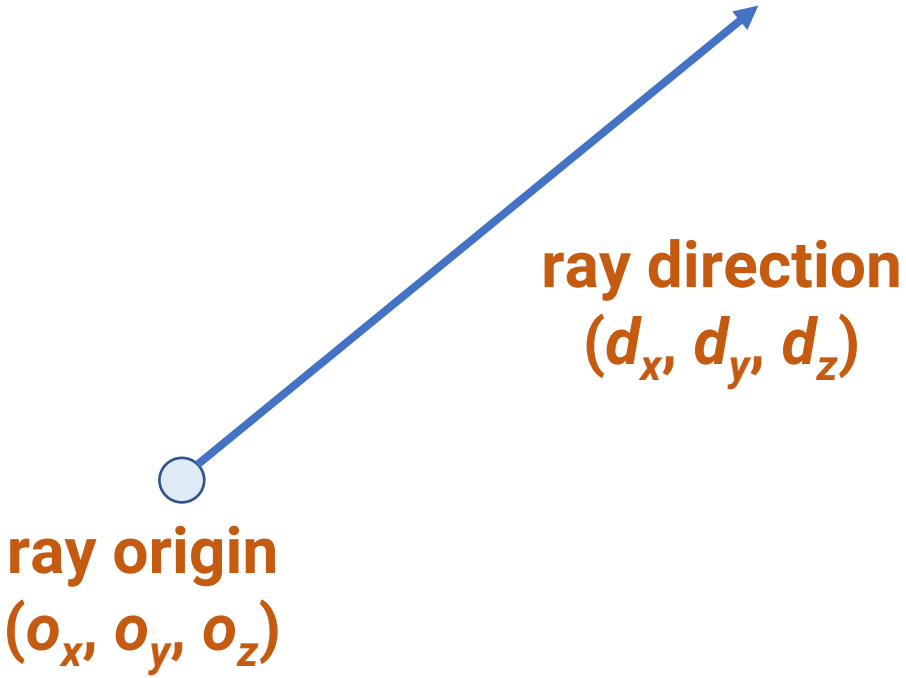
Whitted Ray Tracing (cont.)



Components of Ray Tracing

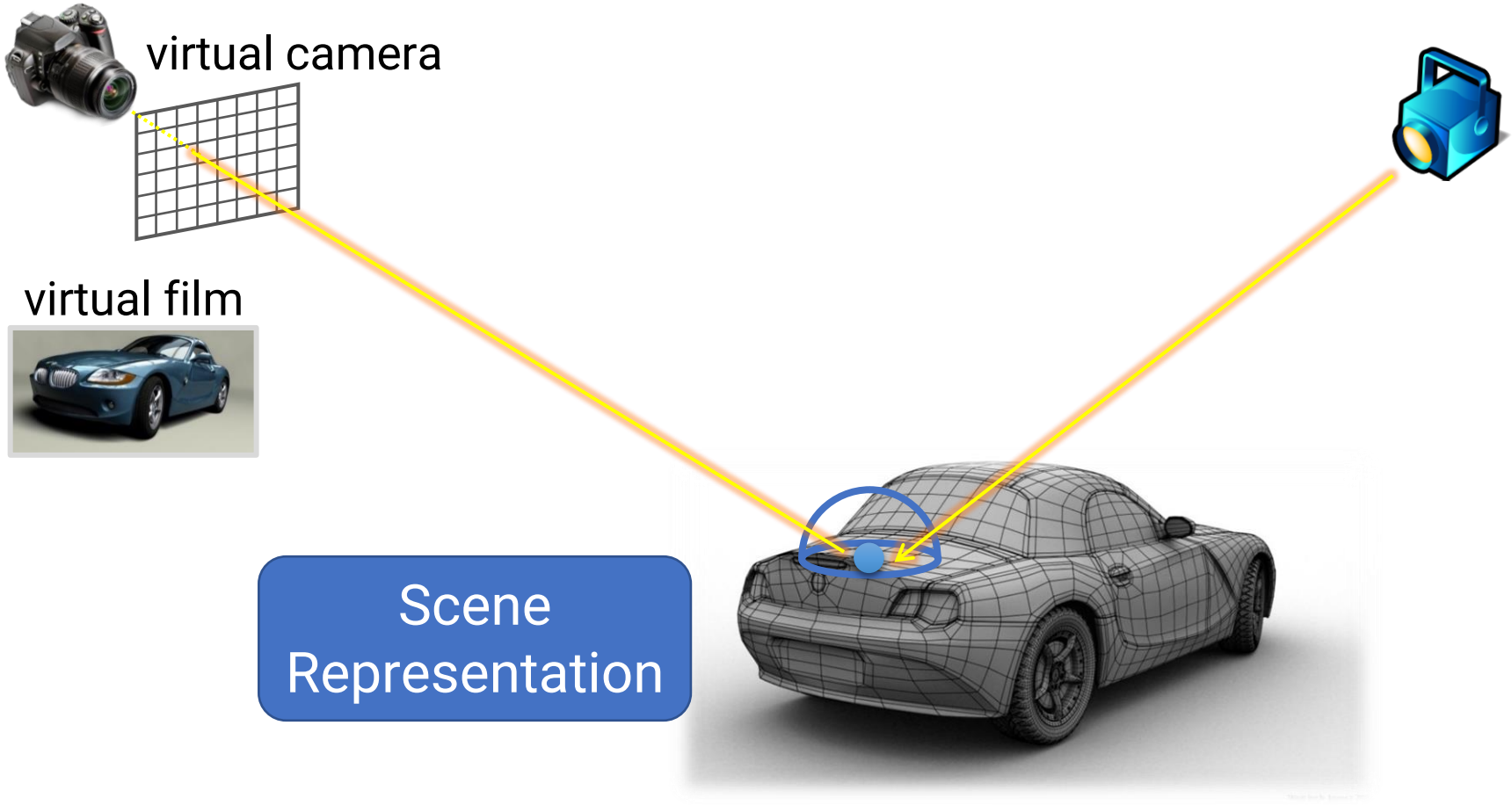


Rays



Components of Ray Tracing

- A united approach for different light transport paths



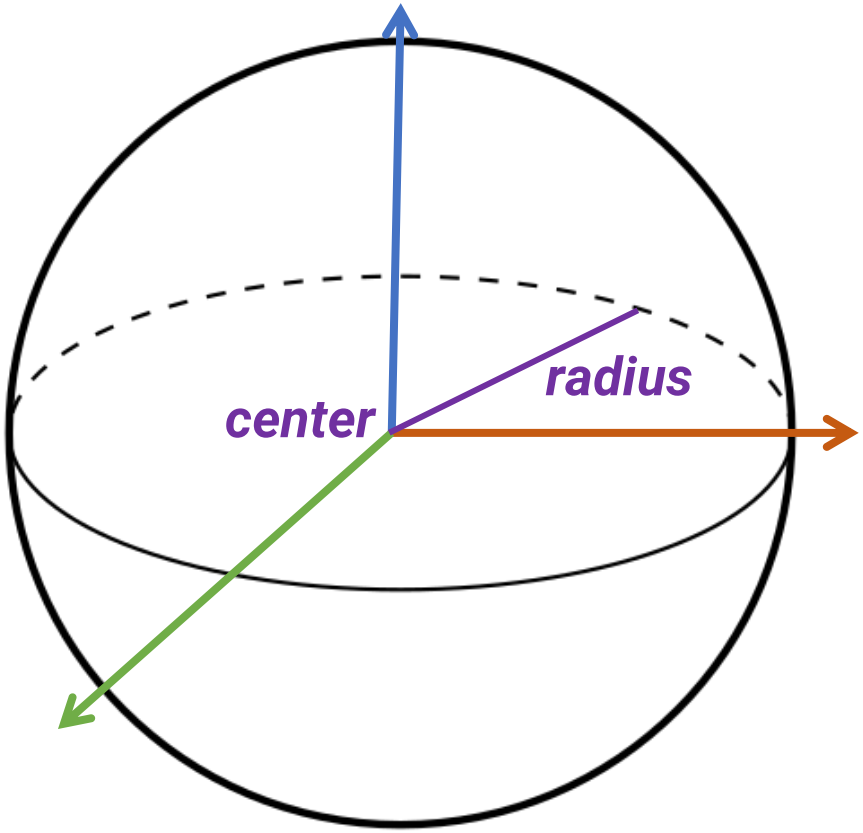
Scene Representation in Ray Tracing

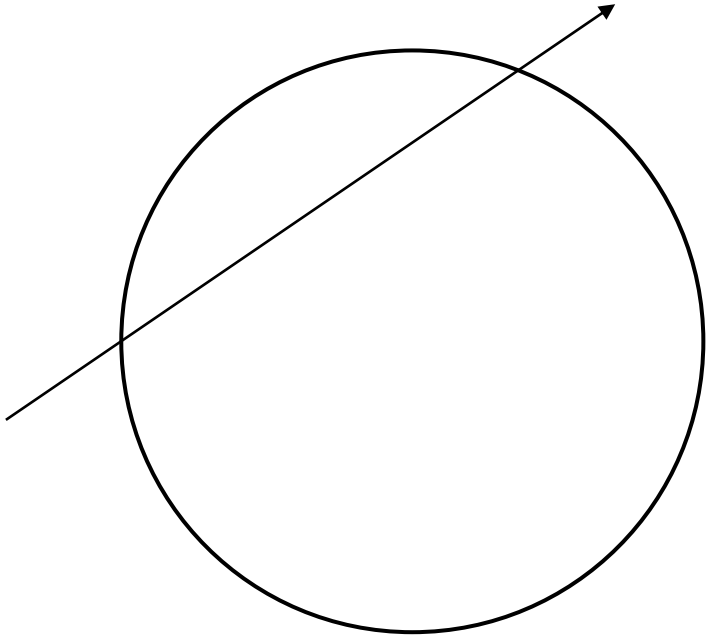
- Basically, just like what you learned in rasterization
  - Also use the idea of object instancing (world transform)
  - Also use camera space (easier to generate rays)

- But **NOT** limited to triangles
- You can use **any** representation if and only if you can **find the intersection of a ray and the surface**

Scene Representation in Ray Tracing (cont.)

- For example, you can represent a sphere using its center and radius

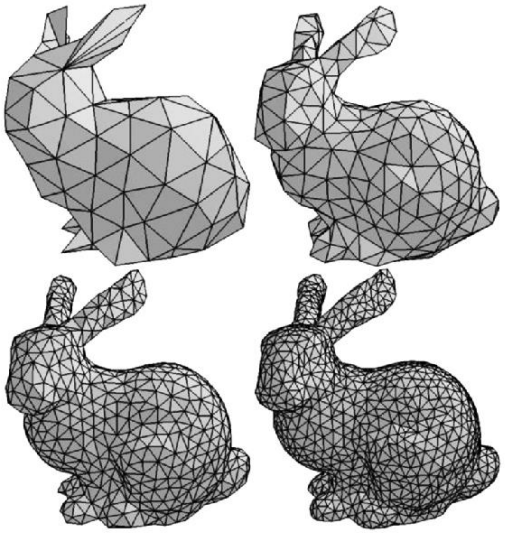


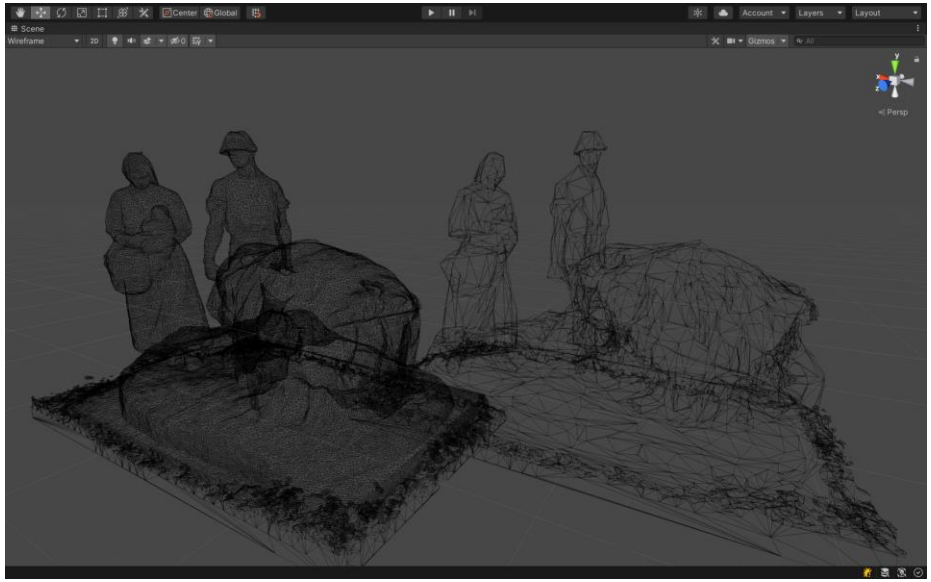


Solve math for the intersection

Scene Representation in Ray Tracing (cont.)

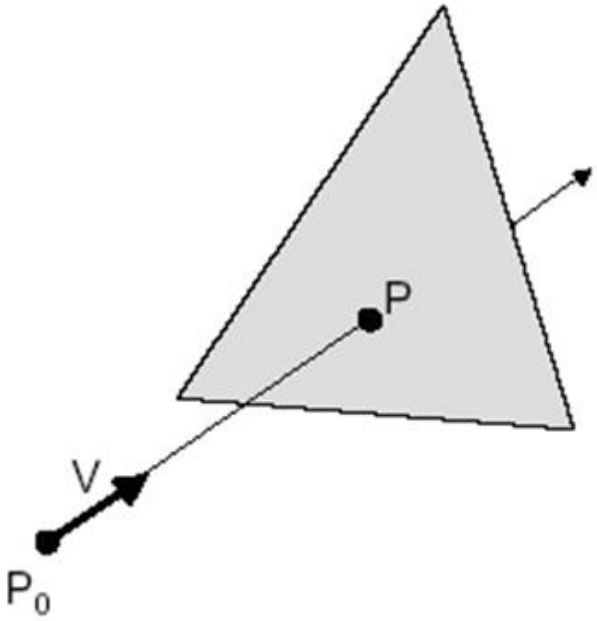
- Triangles are still the most commonly used representation because they can represent arbitrary shapes
- In offline rendering, we usually break up the triangles of objects and treat them "**triangle soup**"
  - A triangle mesh is not considered a **primitive**

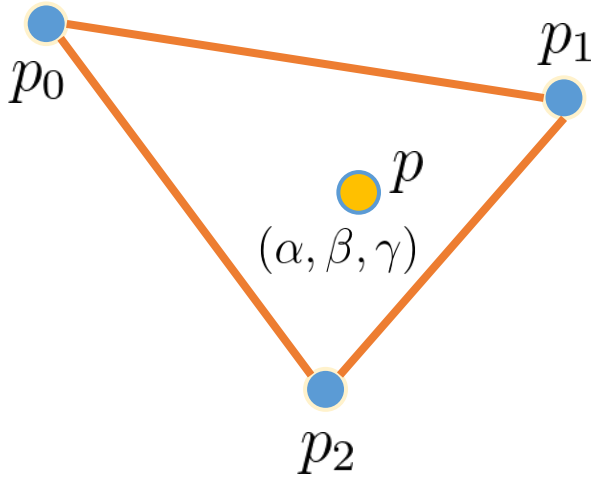




Scene Representation in Ray Tracing (cont.)

- **Ray-triangle intersection**
  - Intersect ray with the plane the triangle locates
  - Check if the intersection point is inside the triangle
    - Can use barycentric coordinate



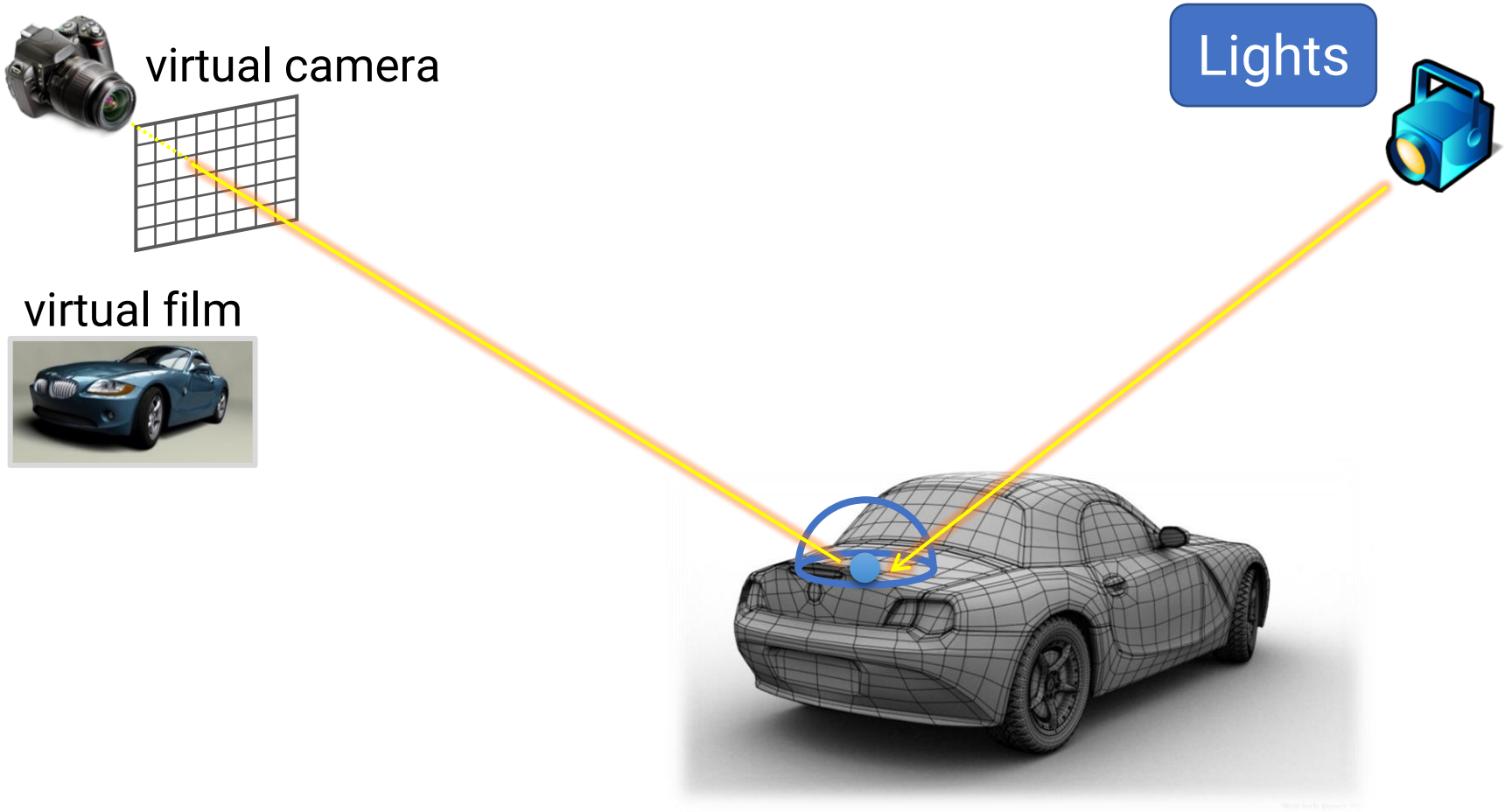


$$p = \alpha p_0 + \beta p_1 + \gamma p_2$$

The values $\alpha, \beta, \gamma \in [0, 1]$ **if and only if *p* is inside the triangle**

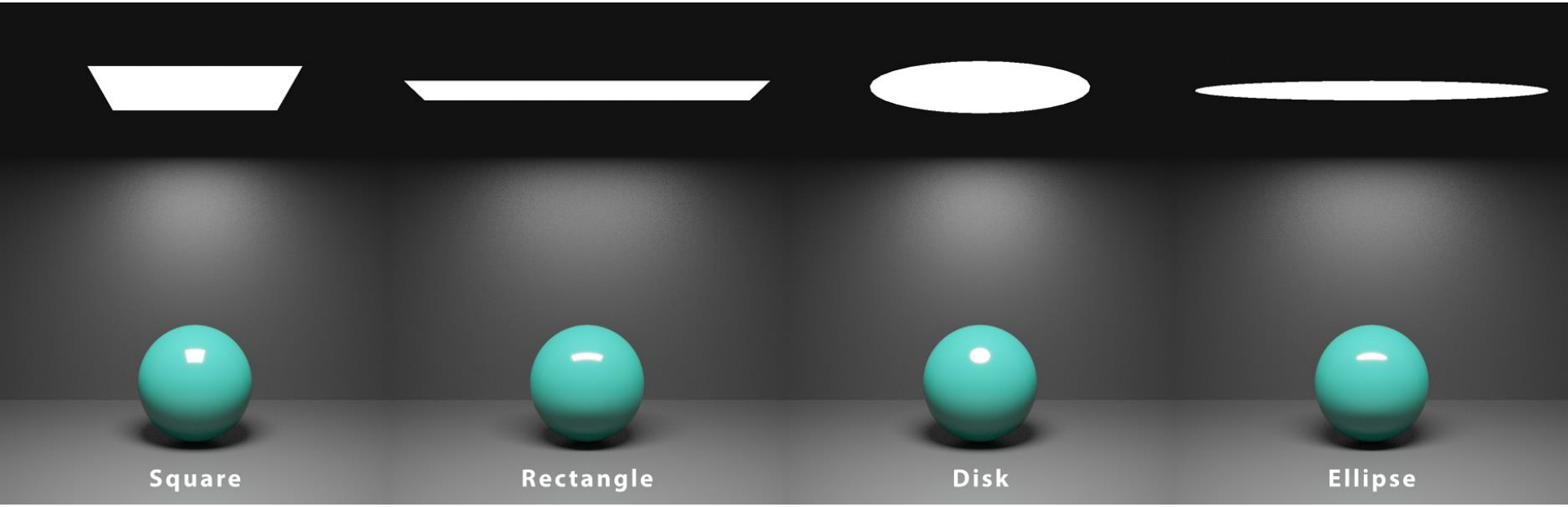
Components of Ray Tracing

- A united approach for different light transport paths



Lights in Ray Tracing

- Basically, just like what you learned in rasterization
- But more complex lights such as area lights and environment lighting are also used for photorealism
  - Estimate the lighting contribution by **sampling**



Lights in Ray Tracing

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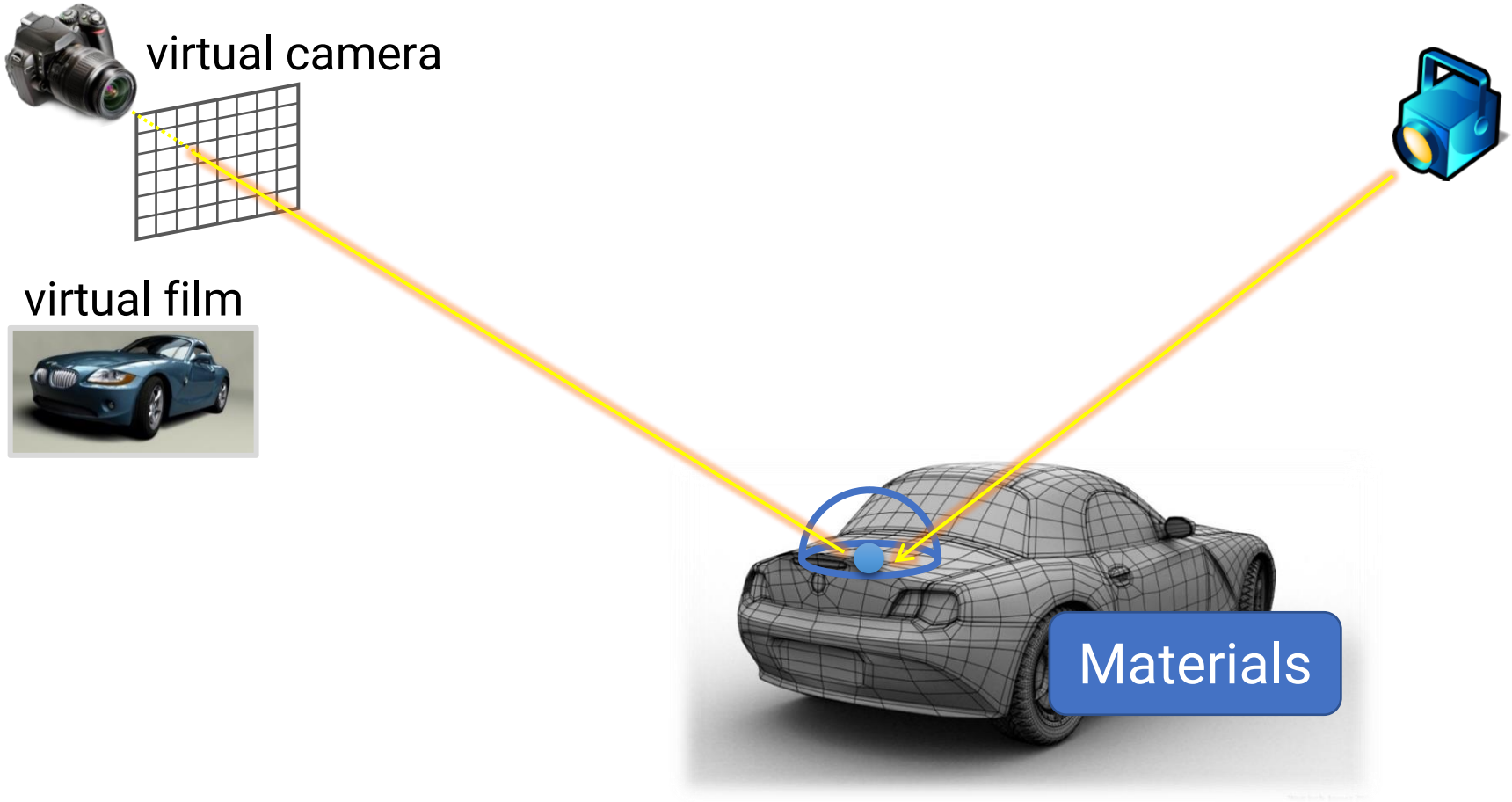
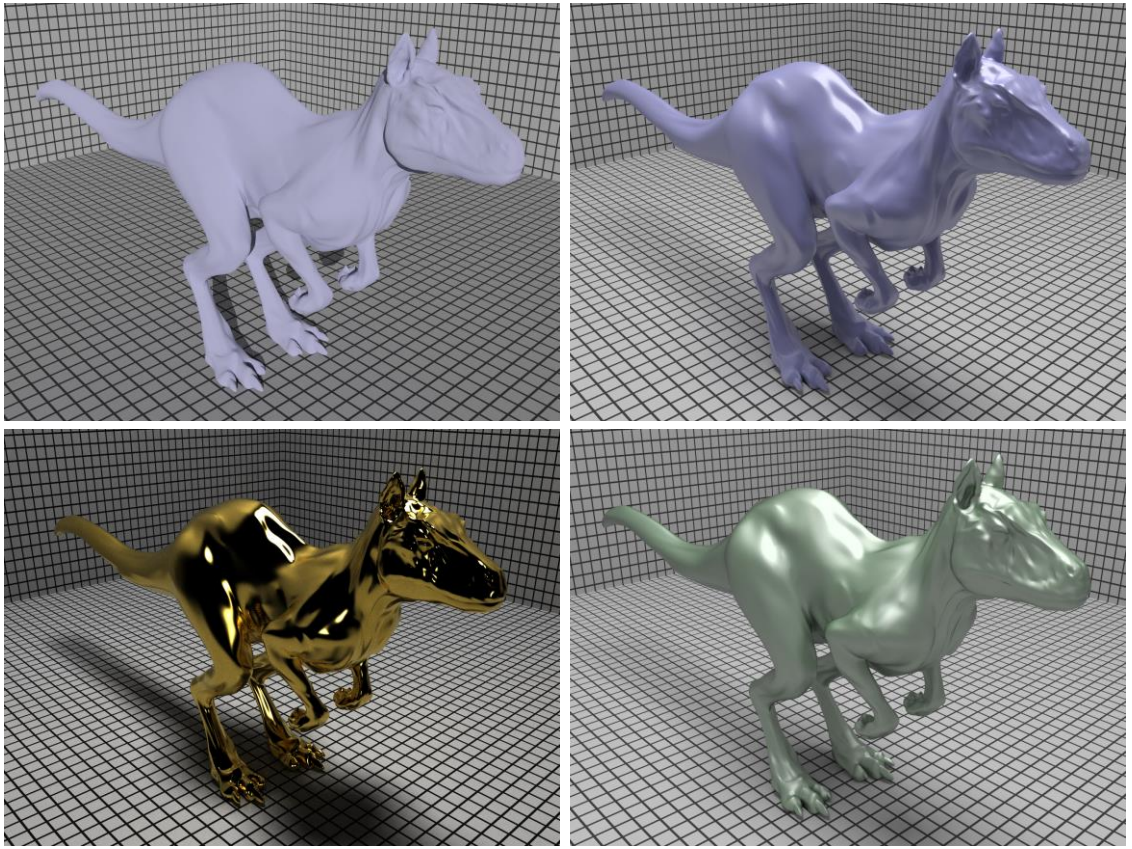
Components of Ray Tracing

- A united approach for different light transport paths



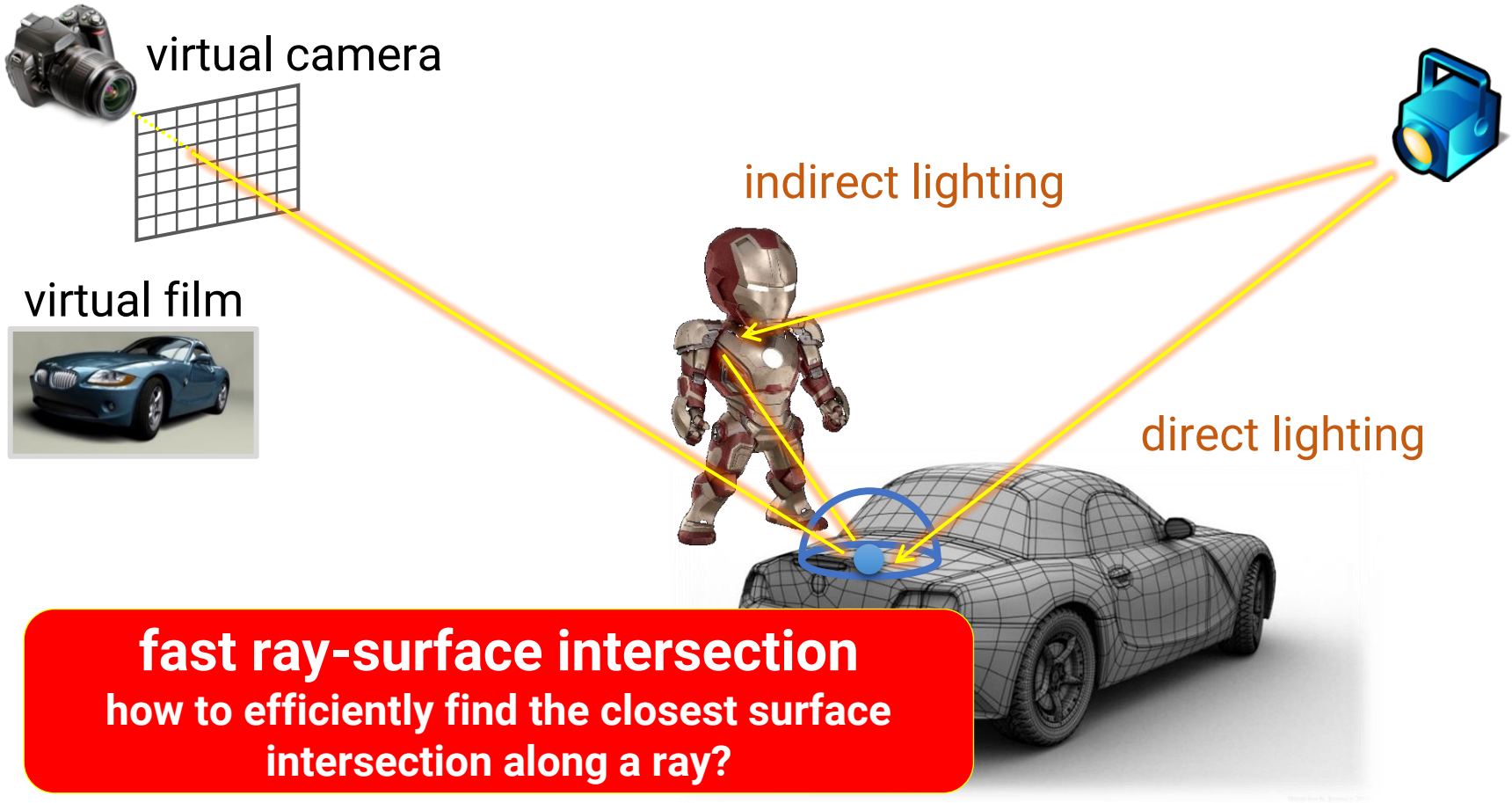
Materials in Ray Tracing

- Basically, just like what you learned in rasterization
- But more complex materials such as the microfacet models



Key: Fast Ray-Surface Intersection

- A united approach for different light transport paths

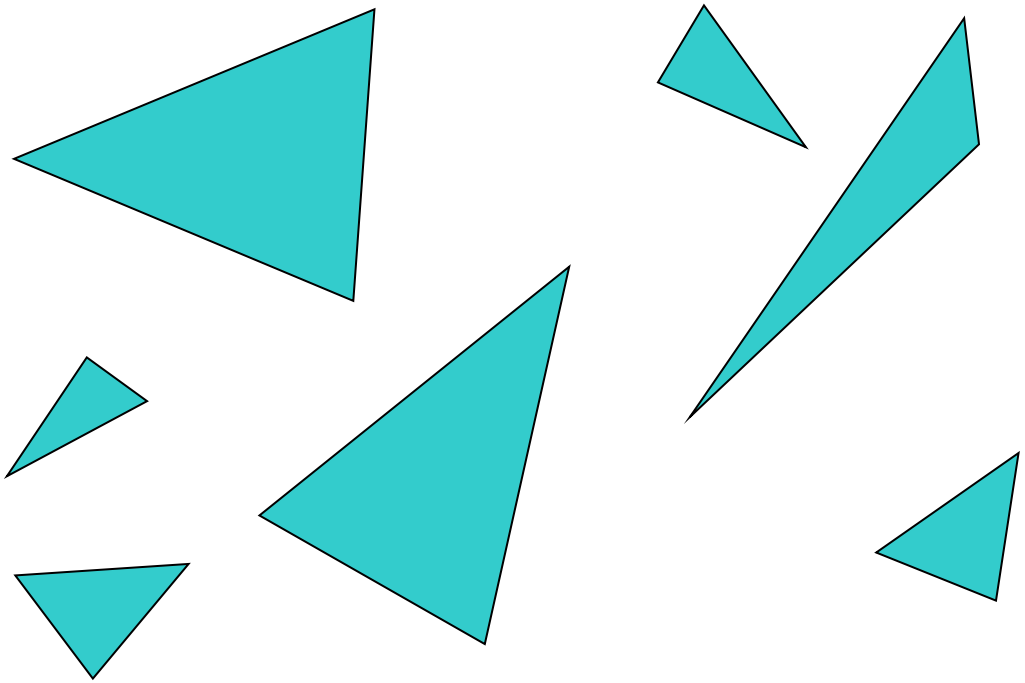


fast ray-surface intersection
how to efficiently find the closest surface intersection along a ray?

Acceleration Structure

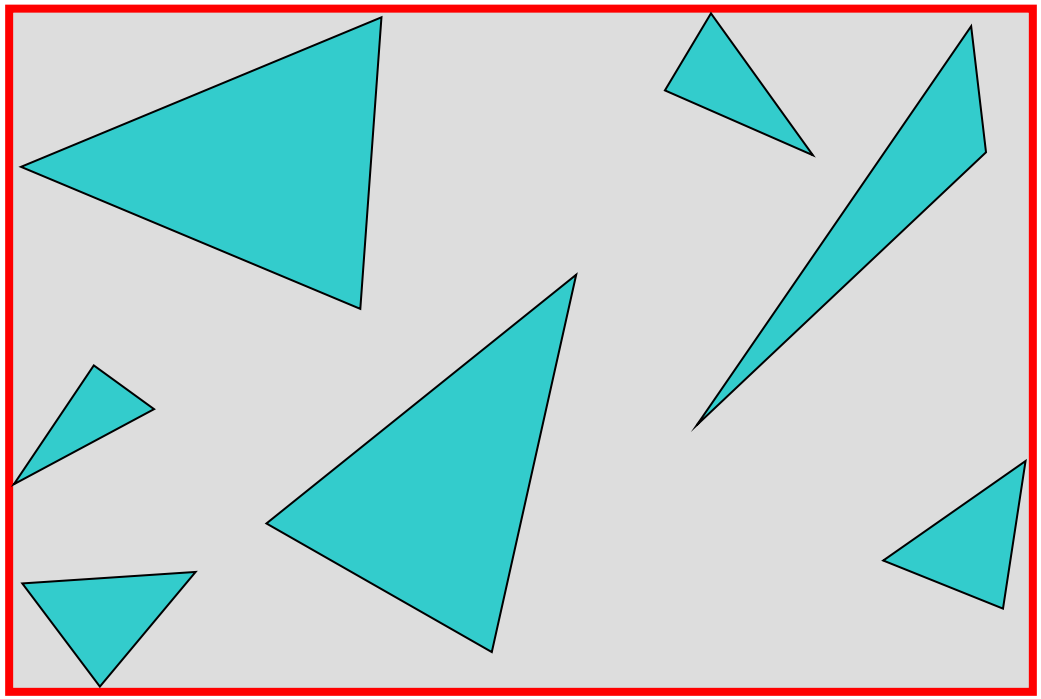
- **Reduce the required number of ray-surface intersection**
- Common acceleration structures
  - Bounding volume hierarchy (BVH)
  - Space subdivision

Bounding Volume Hierarchy



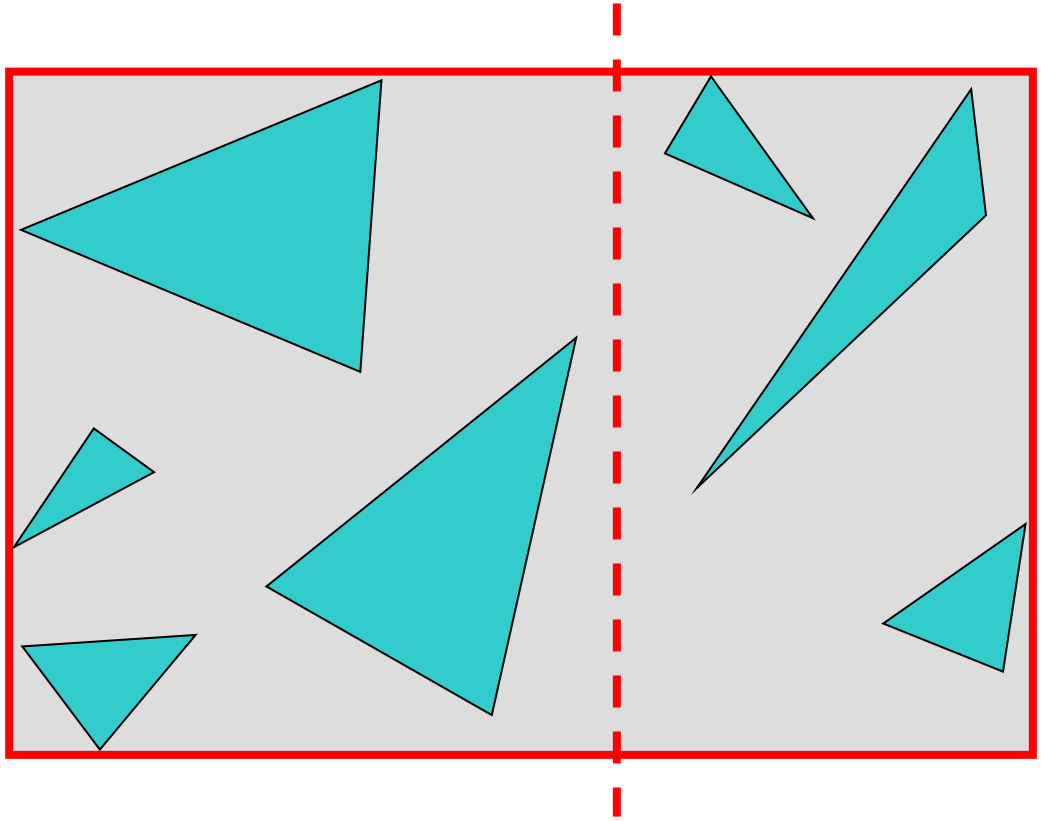
Bounding Volume Hierarchy (cont.)

- Find the bounding box of all objects



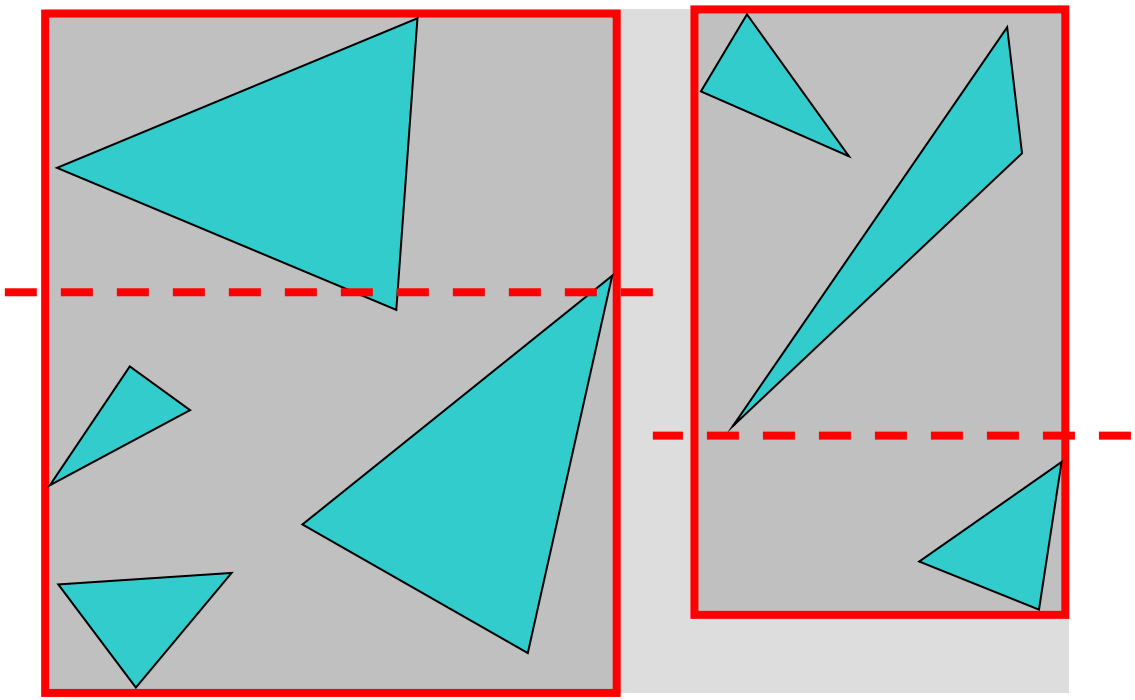
Bounding Volume Hierarchy (cont.)

- Find the bounding box of all objects
- Split shapes into two groups



Bounding Volume Hierarchy (cont.)

- Find the bounding box of all objects
- Split shapes into two groups
- Recursive



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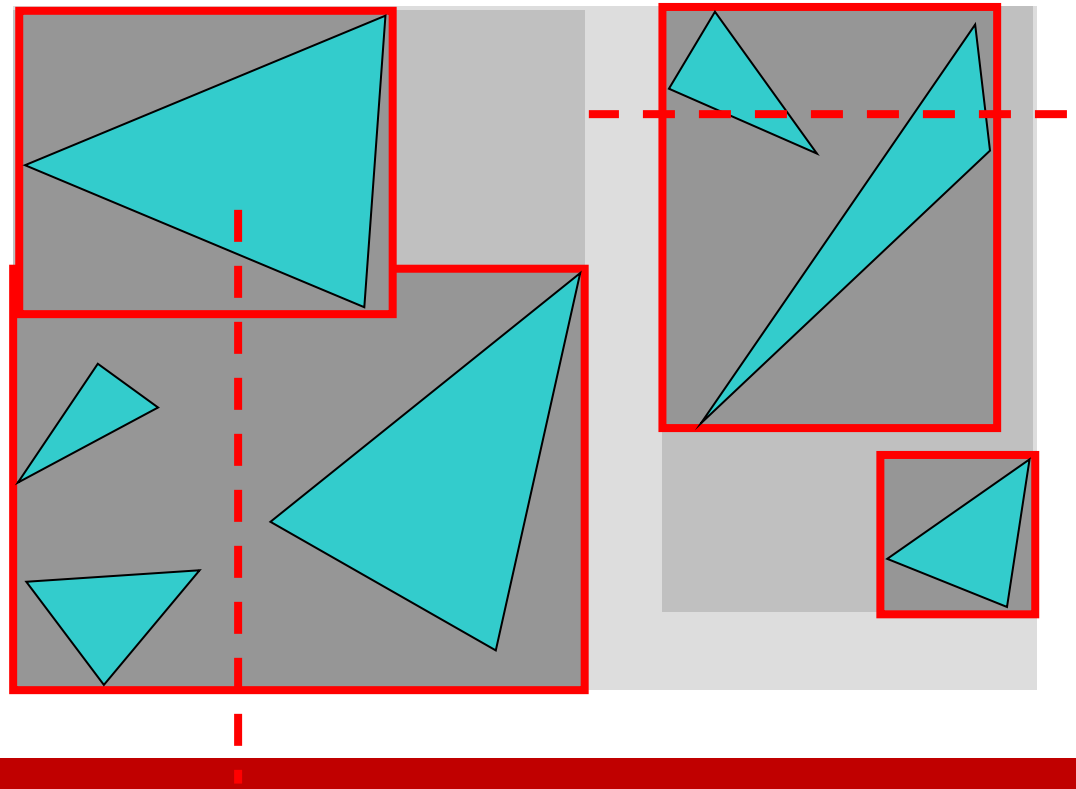

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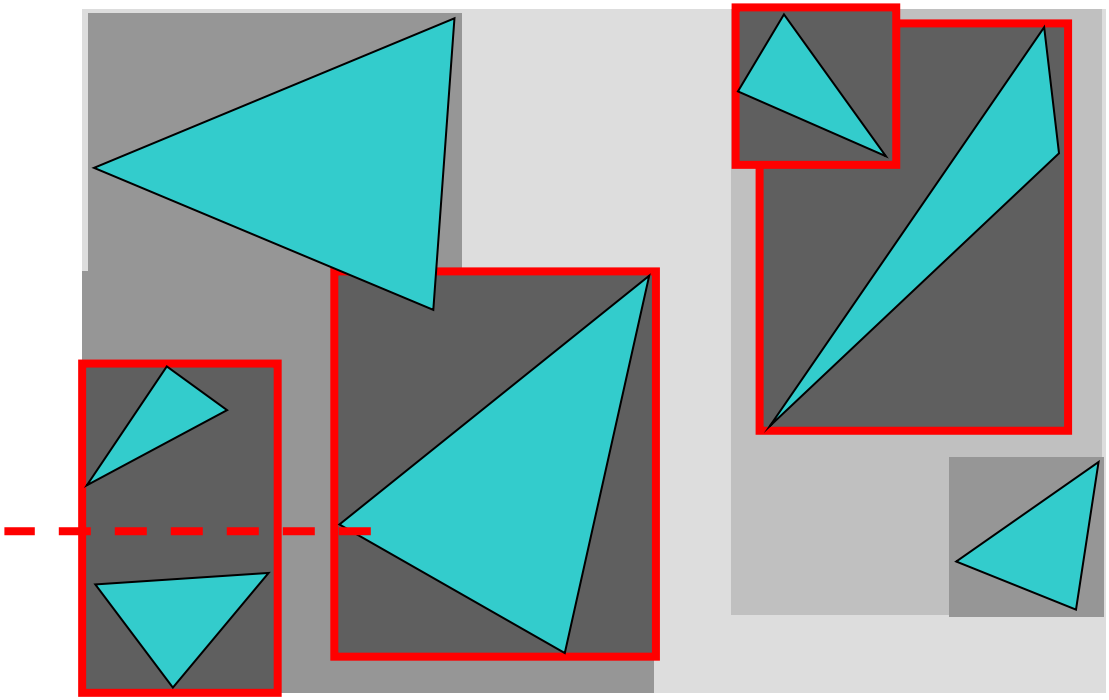
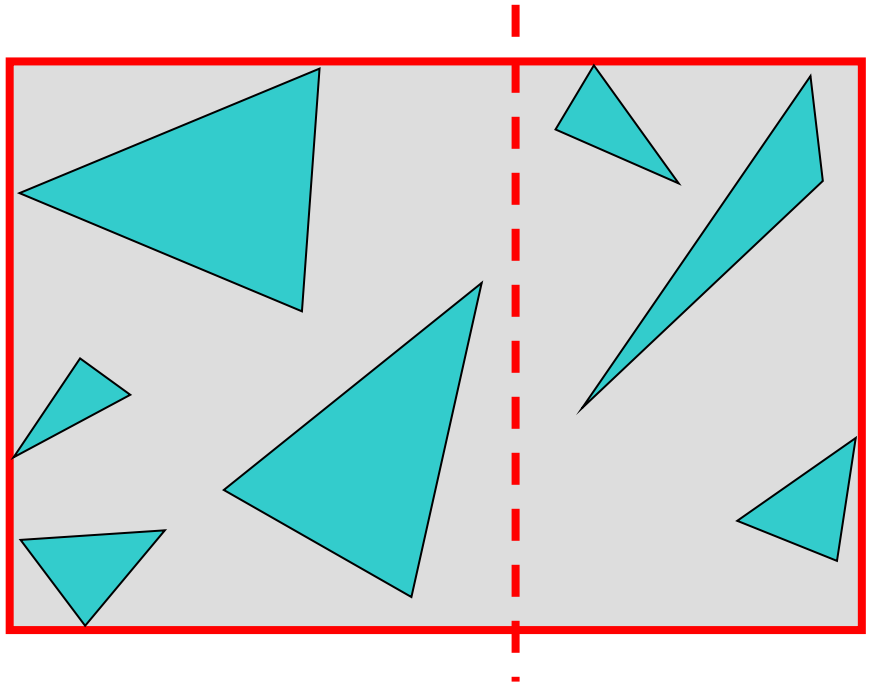


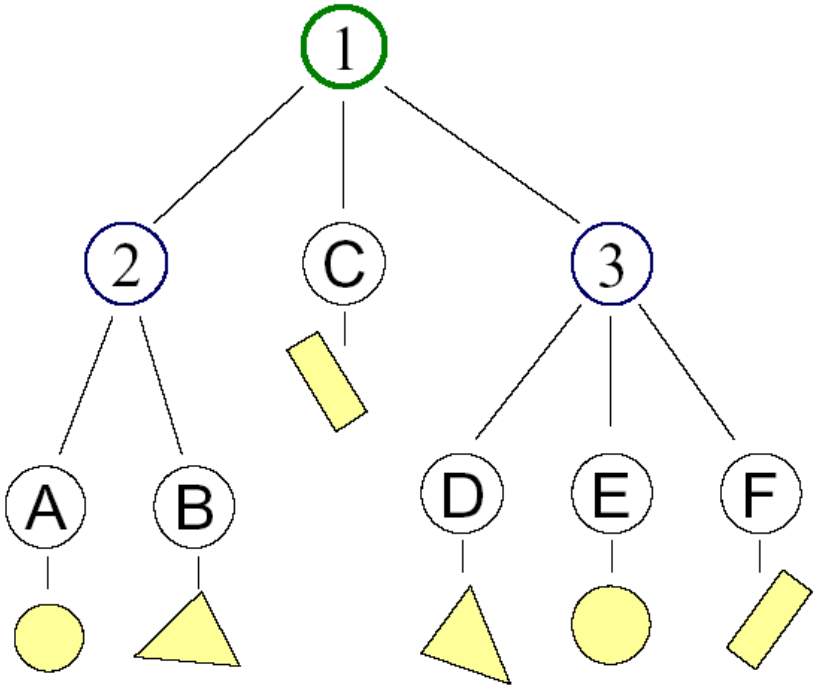
Bounding Volume Hierarchy (cont.)

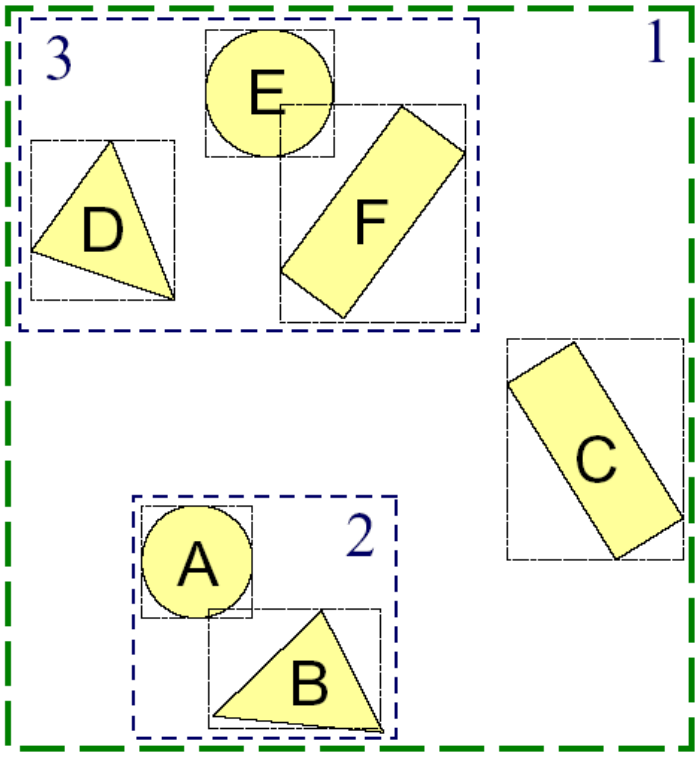
- Where to split?
  - At midpoint
  - Put half of the shapes on each side
  - Use some objective functions (such as SAH)



Bounding Volume Hierarchy (cont.)

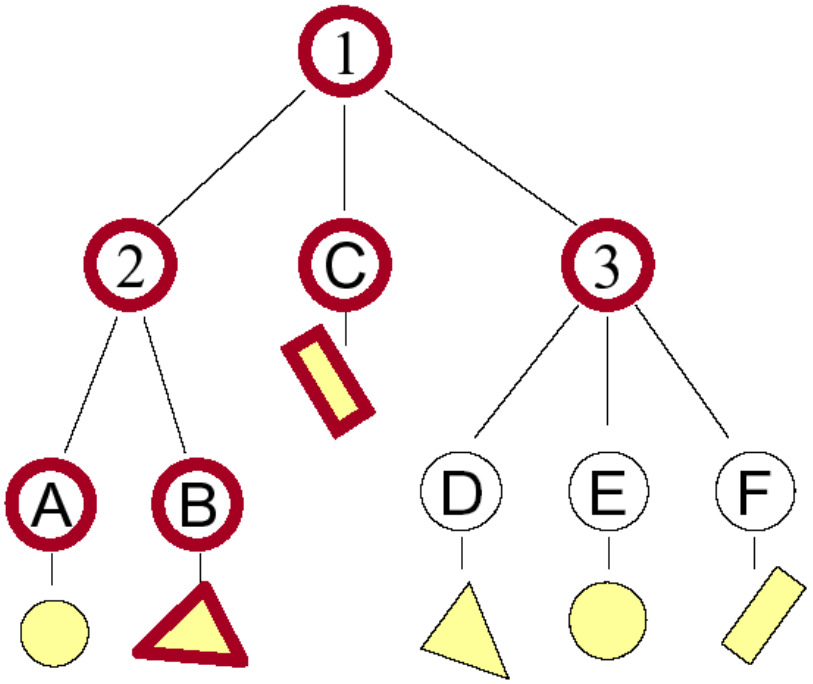
- **Preprocess:** build a hierarchy of bounding volumes
  - The bounding volume of an interior node contains all children

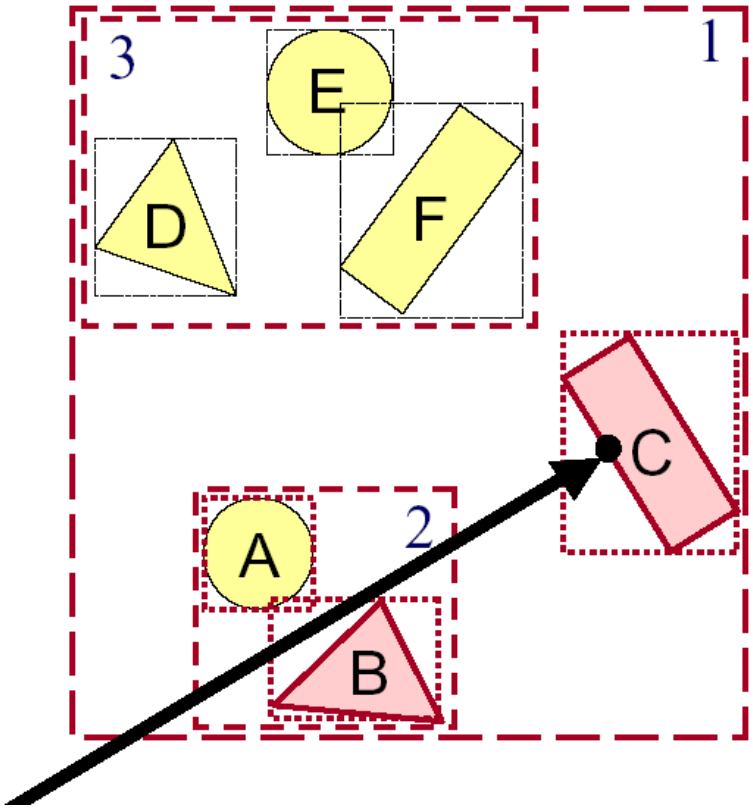




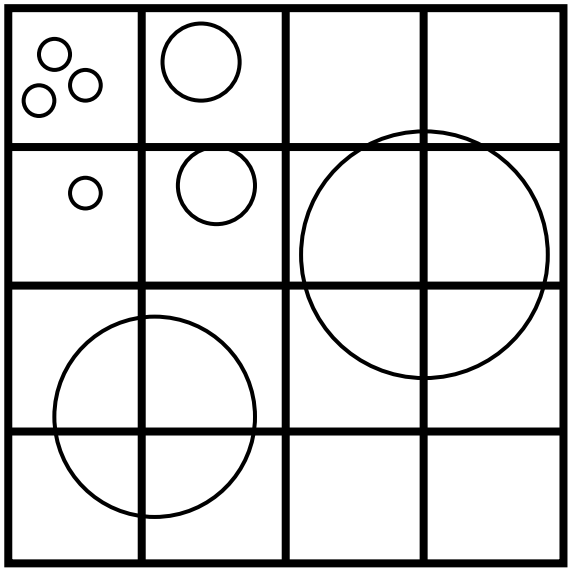
Bounding Volume Hierarchy (cont.)

- **Rendering:** use the hierarchy to accelerate ray intersections
  - Test node contents only if the ray hits the bounding volume

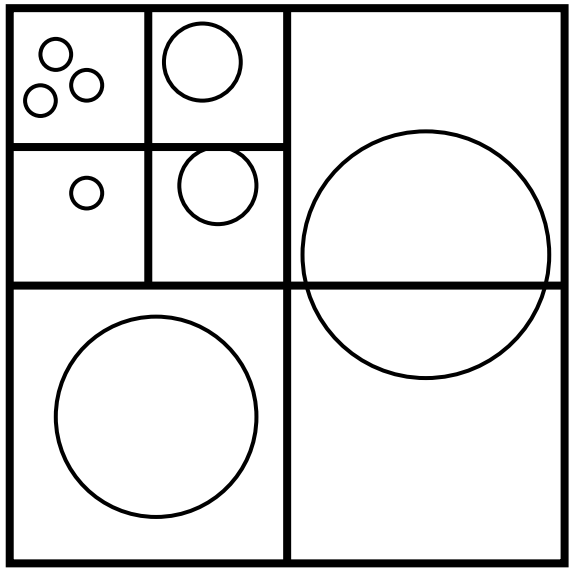




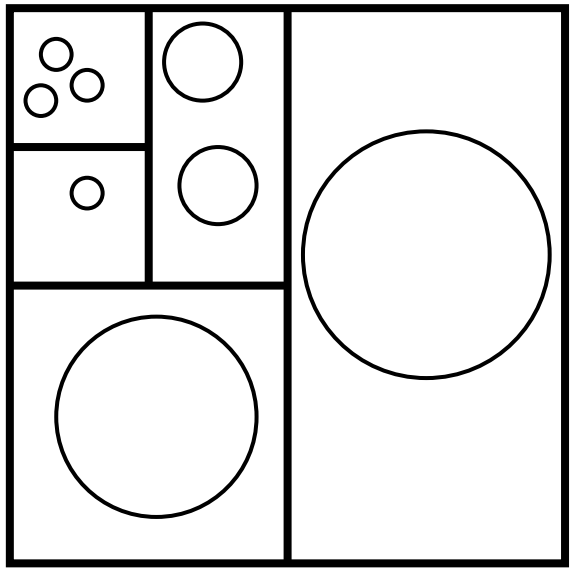
Space Subdivision Approaches



uniform grid

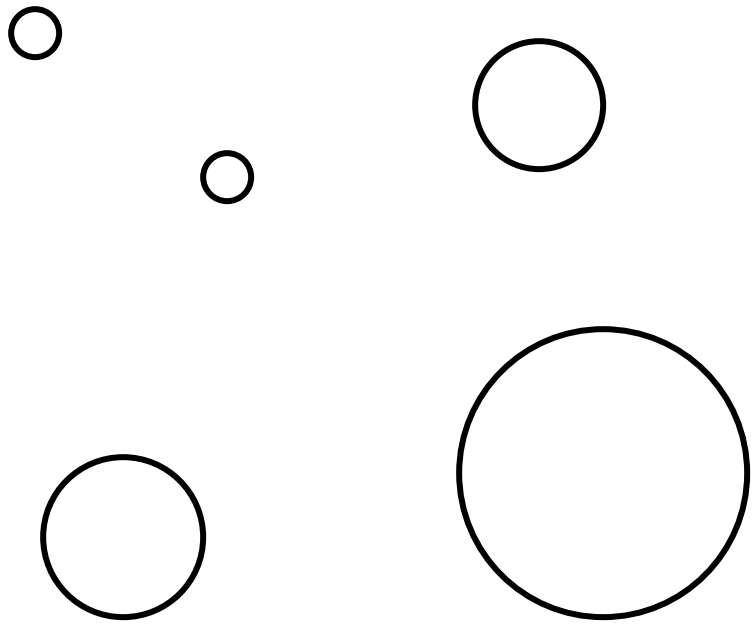


octree

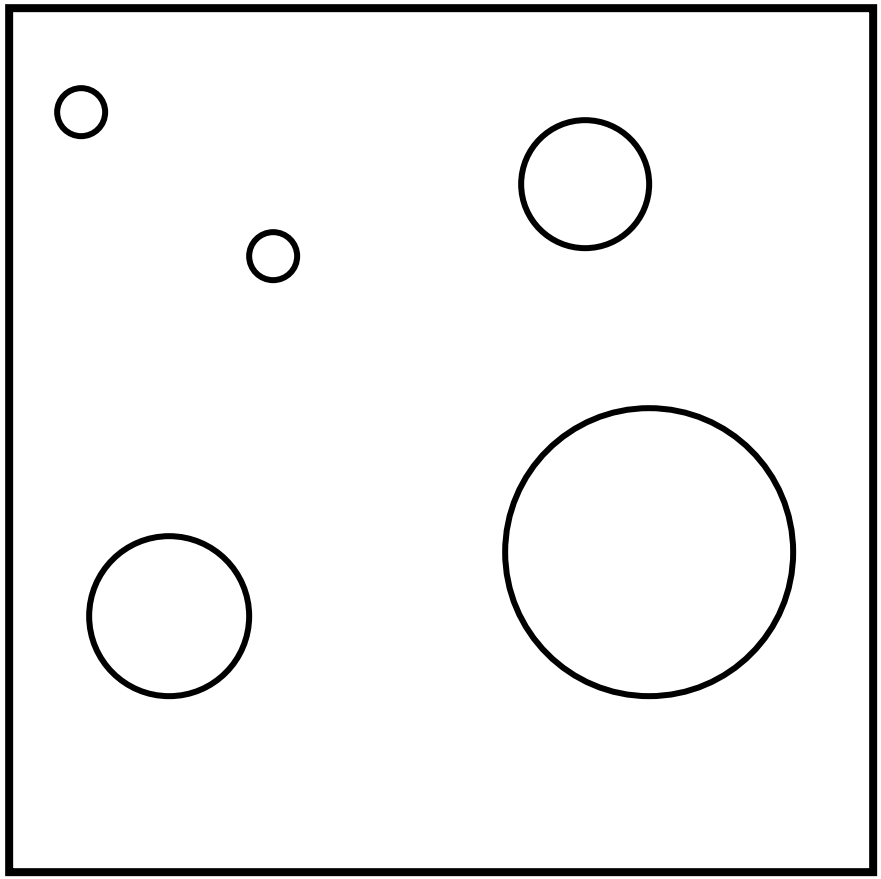


kd tree

Uniform Grid

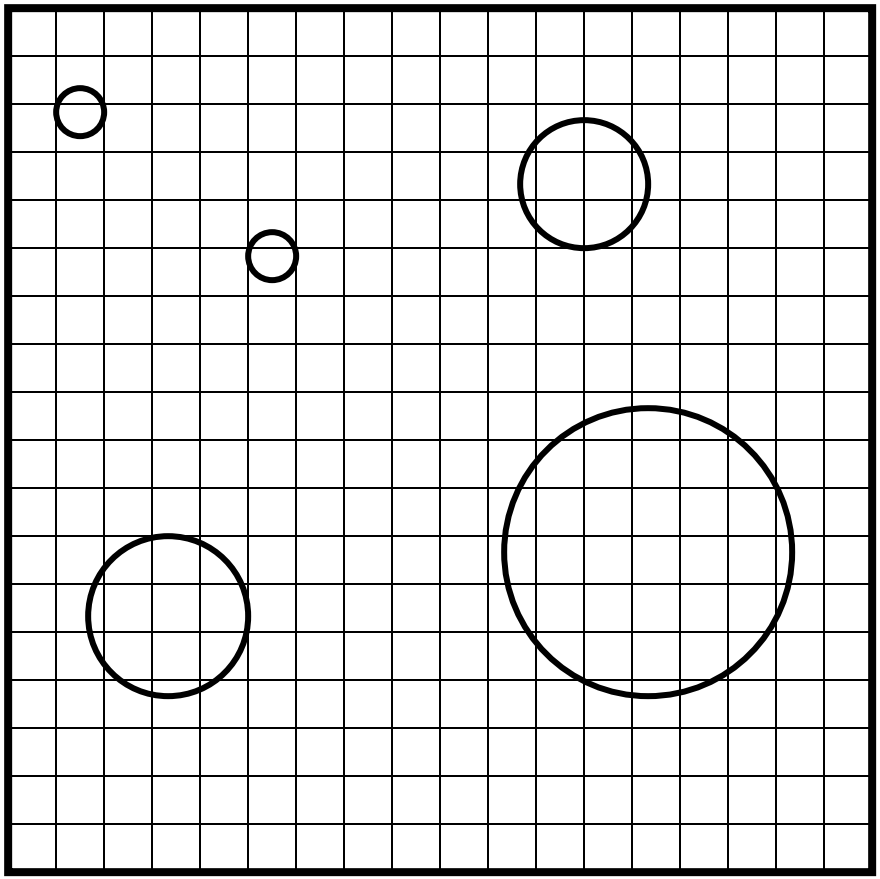


Uniform Grid (cont.)



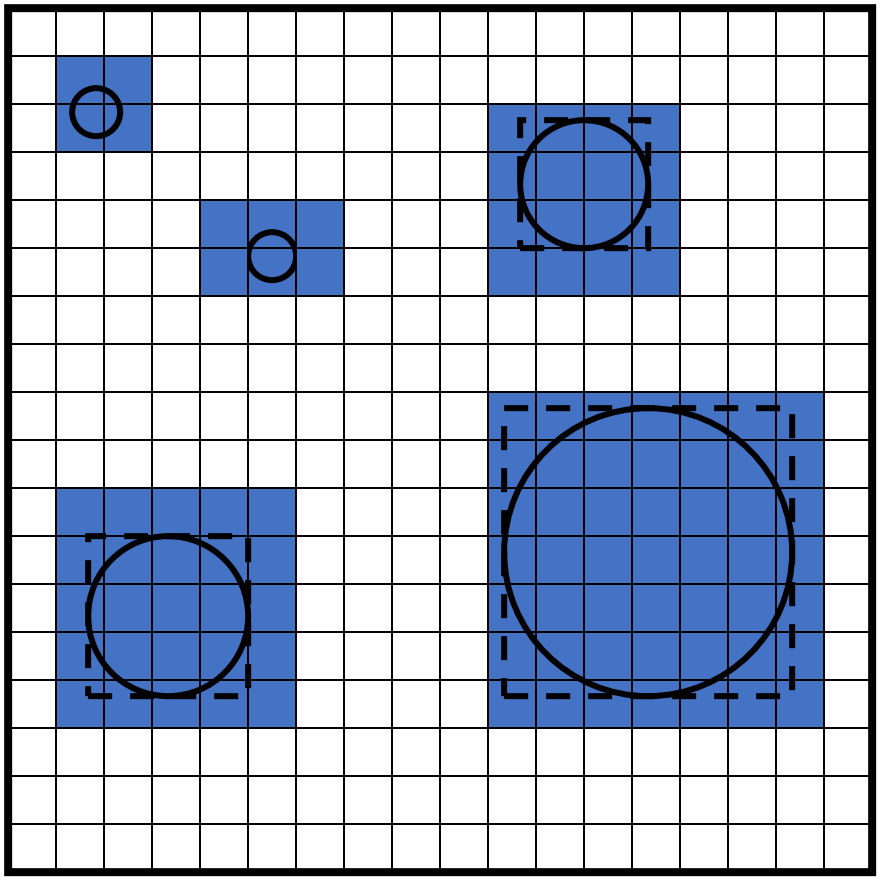
- **Preprocess**
  - Find the bounding box

Uniform Grid (cont.)



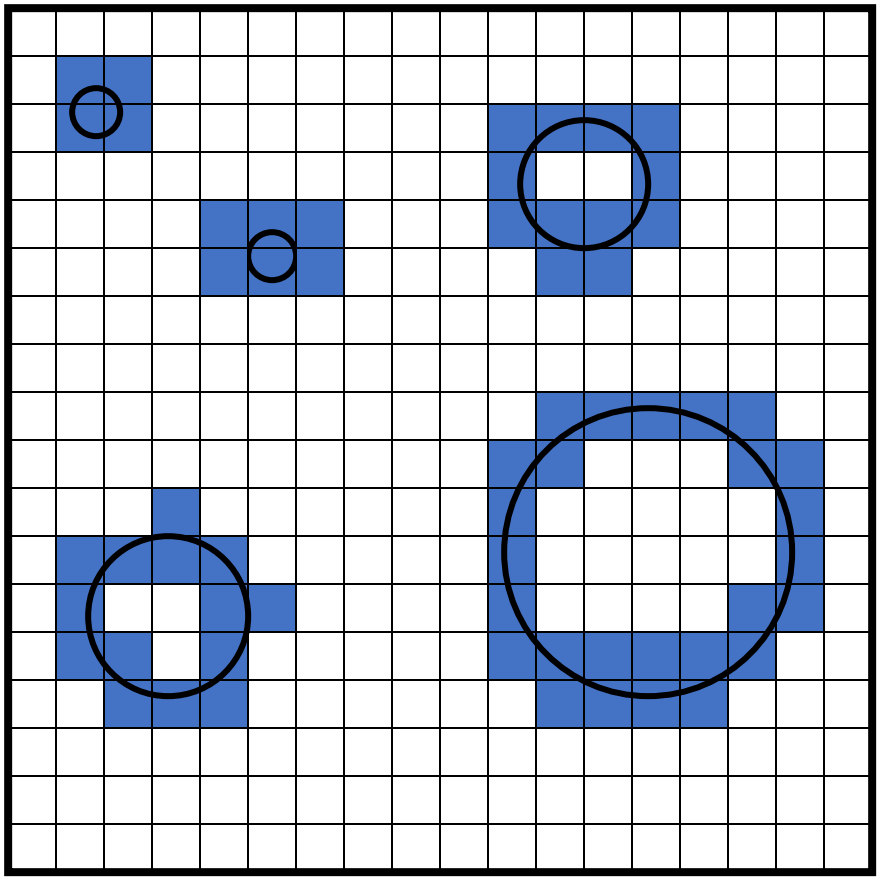
- **Preprocess**
  - Find the bounding box
  - Determine grid resolution

Uniform Grid (cont.)



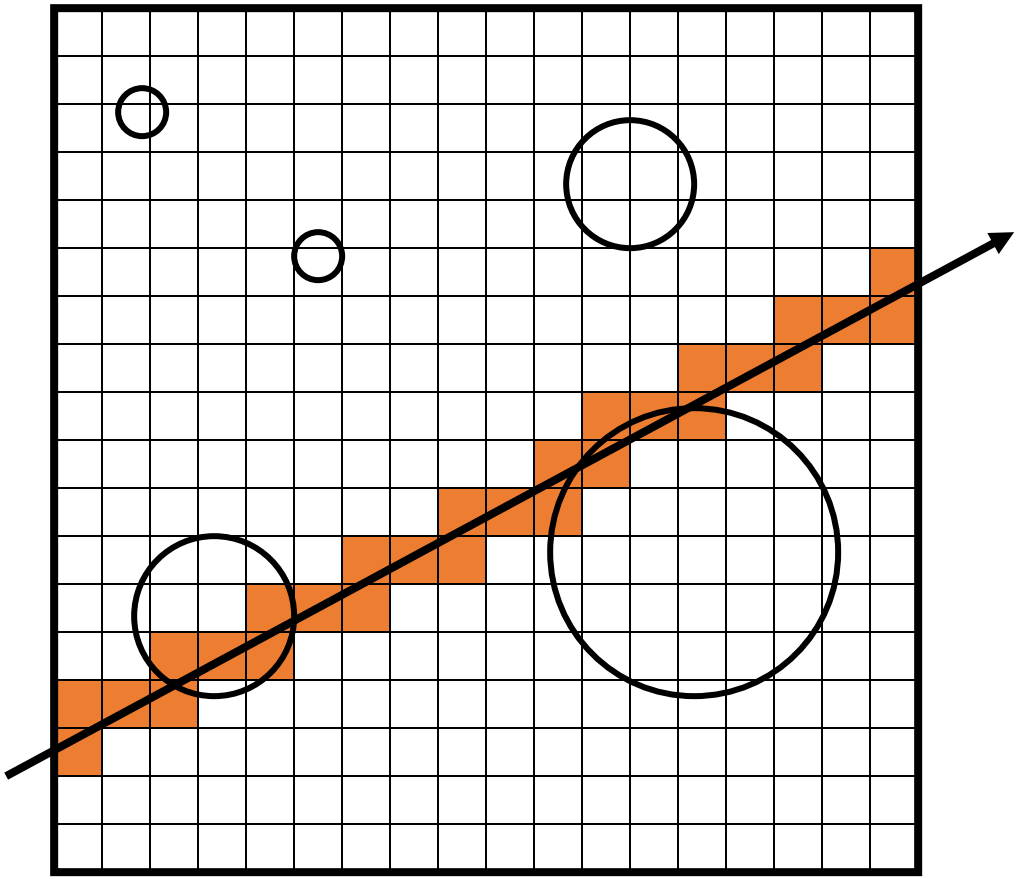
- **Preprocess**
  - Find the bounding box
  - Determine grid resolution
  - Place a shape in a cell if its bounding box overlaps the cell

Uniform Grid (cont.)



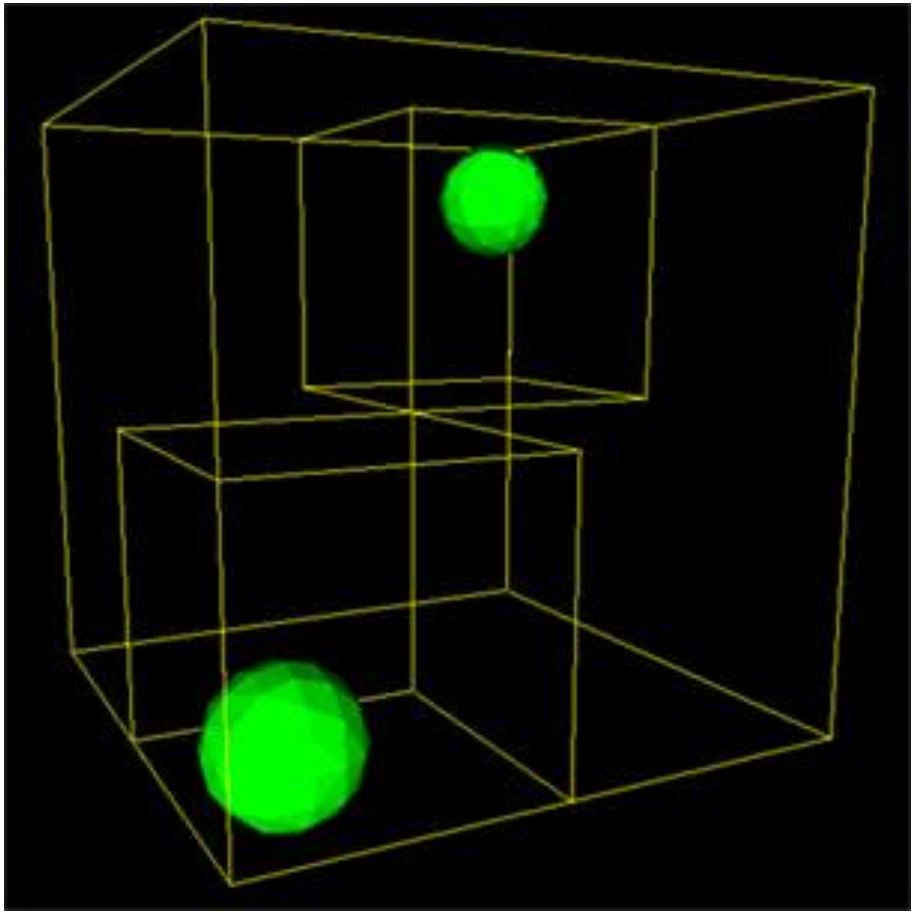
- **Preprocess**
  - Find the bounding box
  - Determine grid resolution
  - Place a shape in a cell if its bounding box overlaps the cell
  - Check that if the shape overlaps the cell

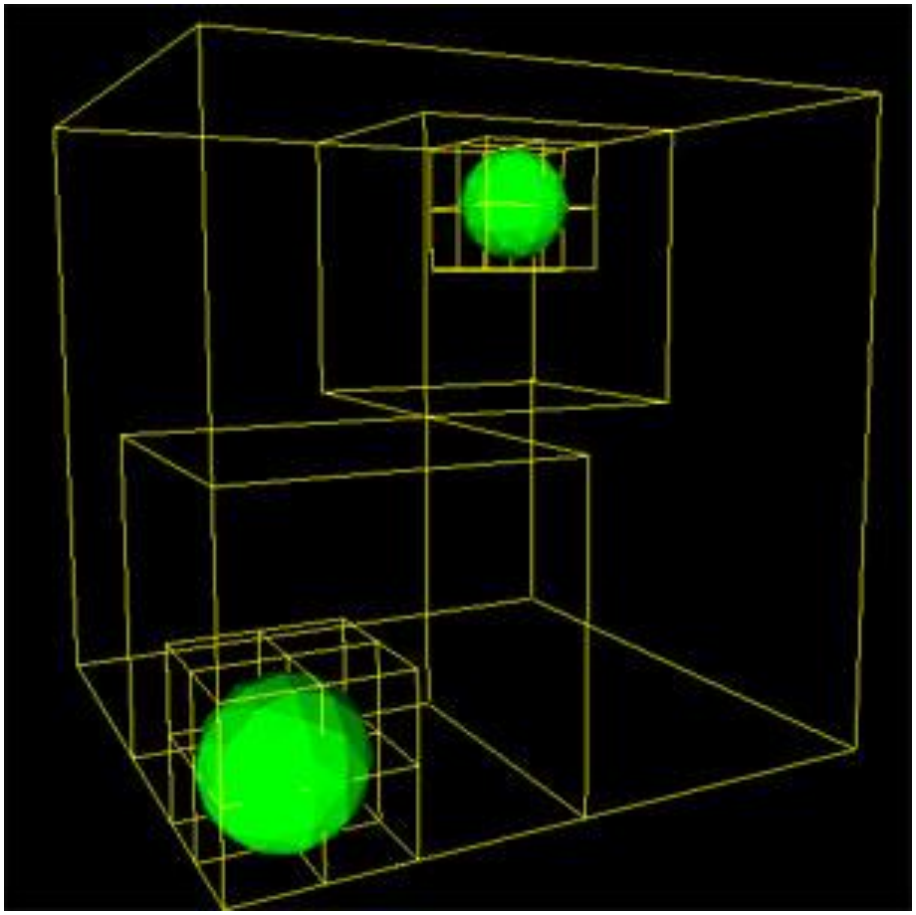
Uniform Grid (cont.)



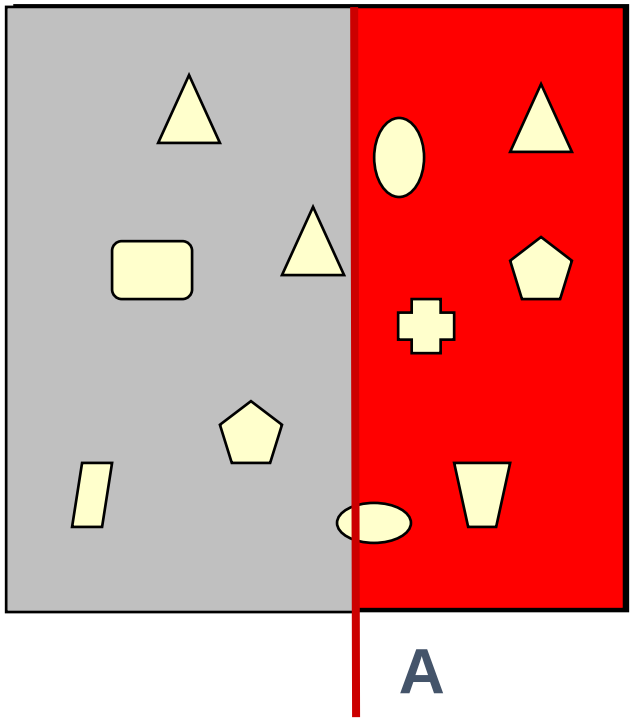
- **Preprocess**
  - Find the bounding box
  - Determine grid resolution
  - Place a shape in a cell if its bounding box overlaps the cell
  - Check that if the shape overlaps the cell
- **Rendering**
  - Use 3D-DDA to traverse the grid

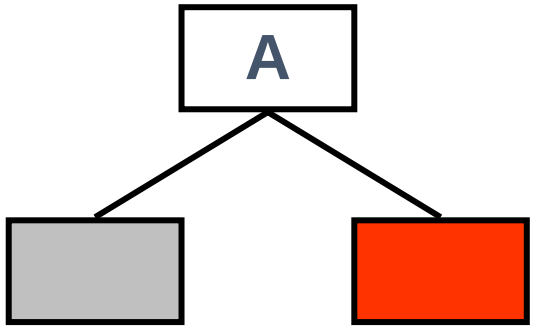
Octree





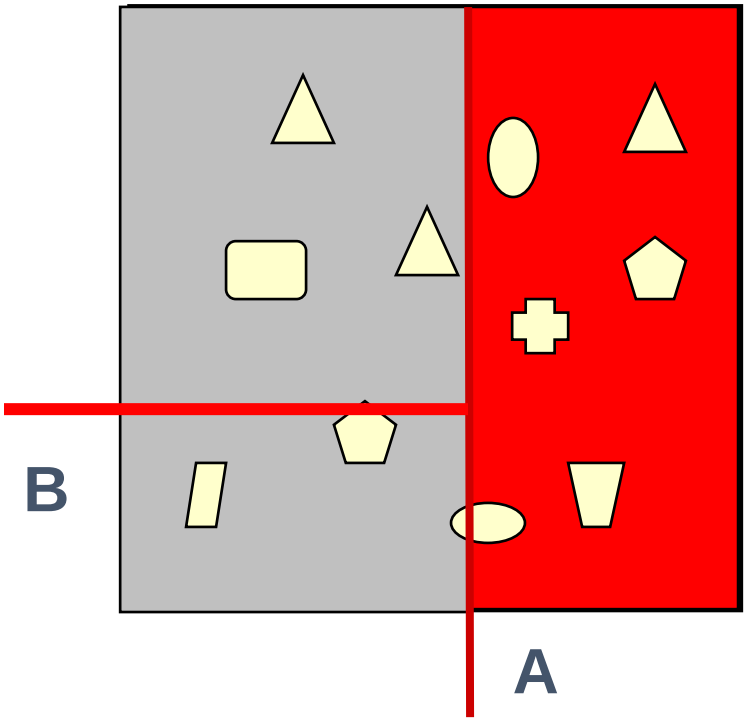
Kd Tree

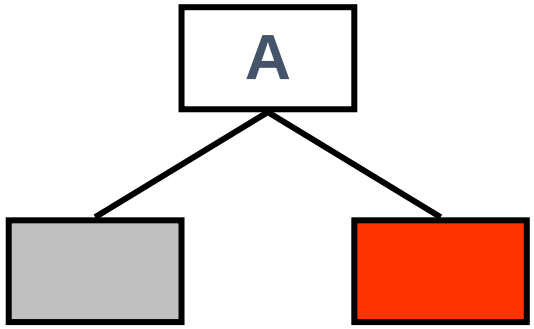




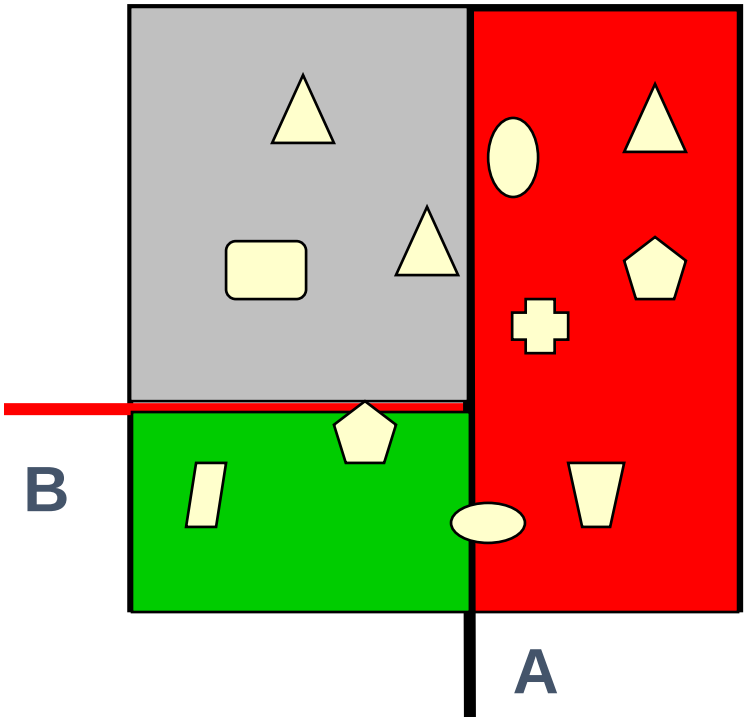
Leaf nodes correspond to unique regions in space

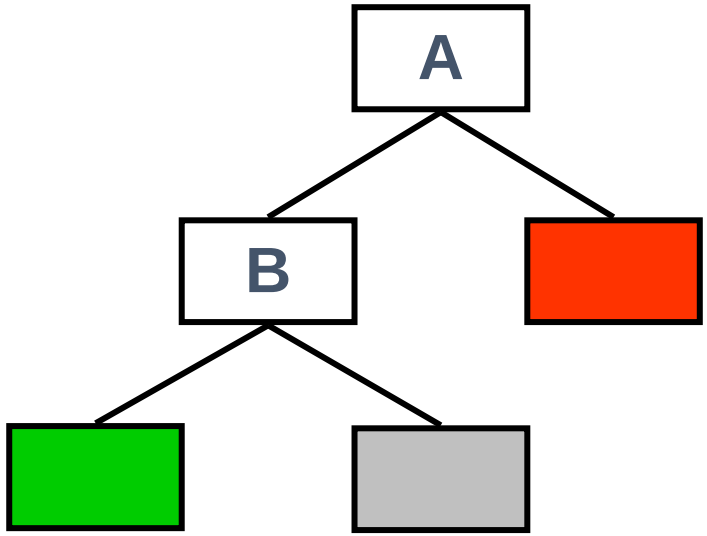
Kd Tree



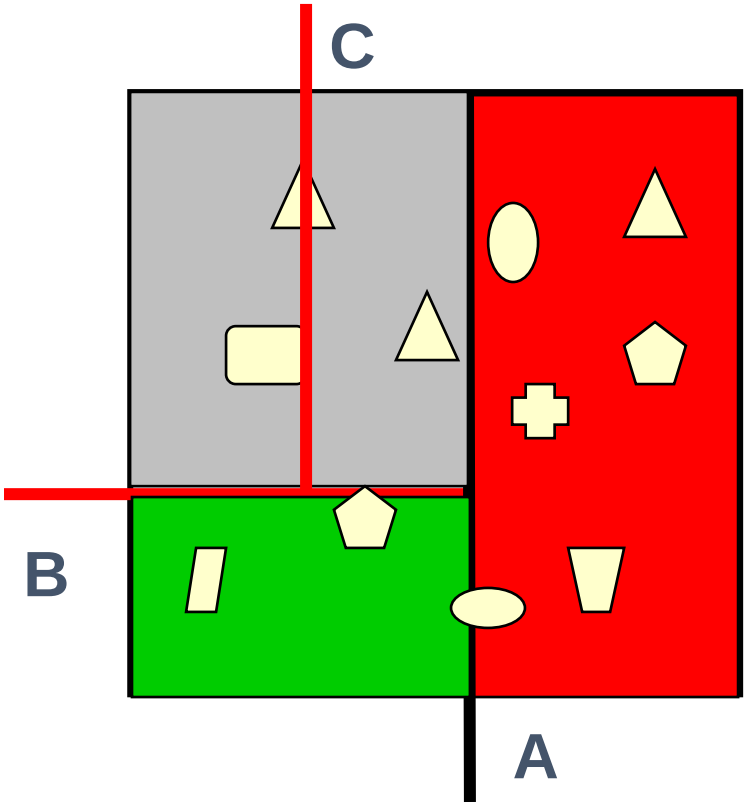


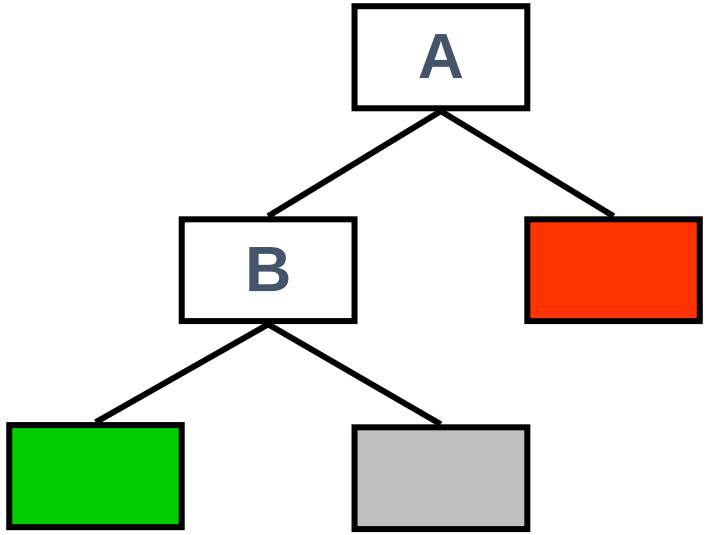
Kd Tree



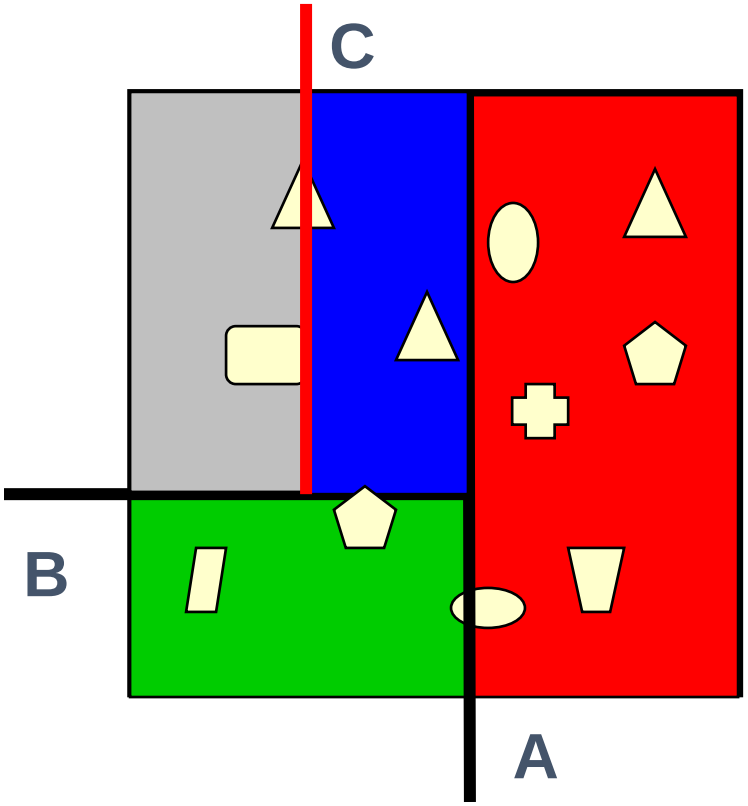


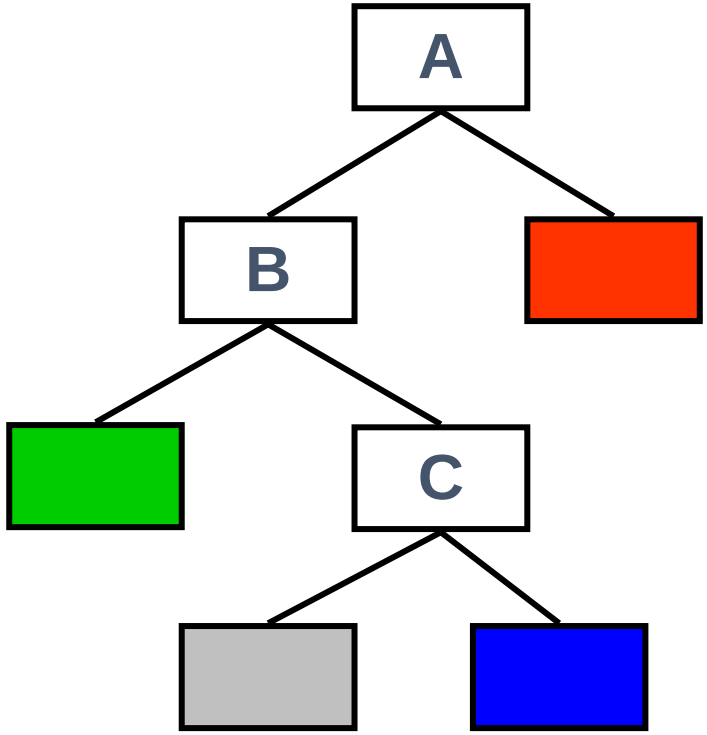
Kd Tree



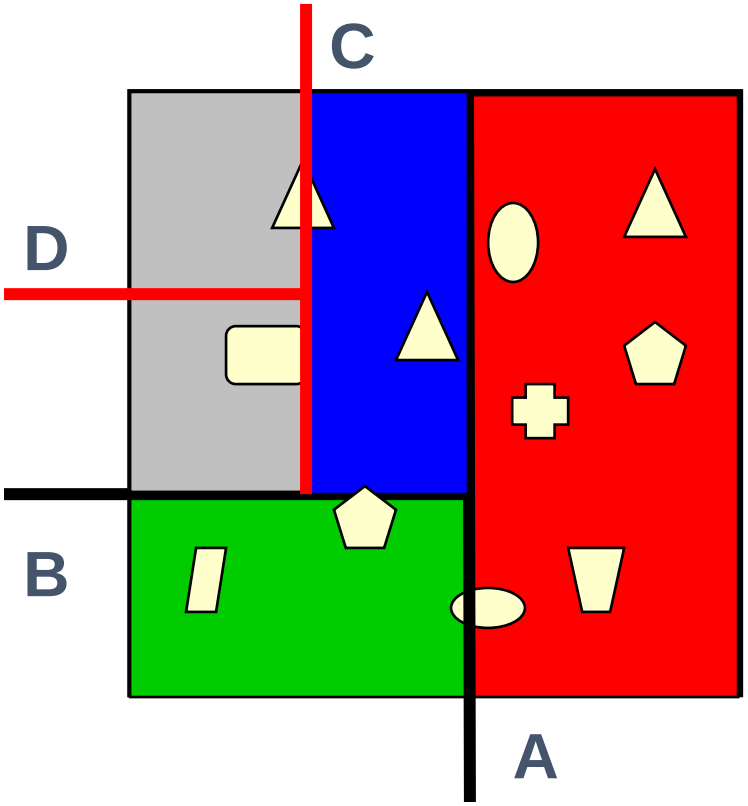


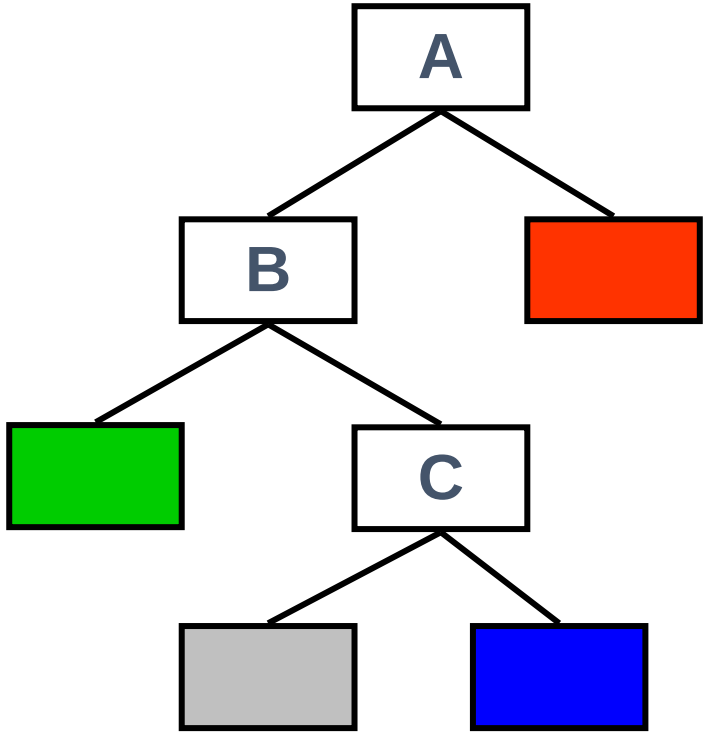
Kd Tree



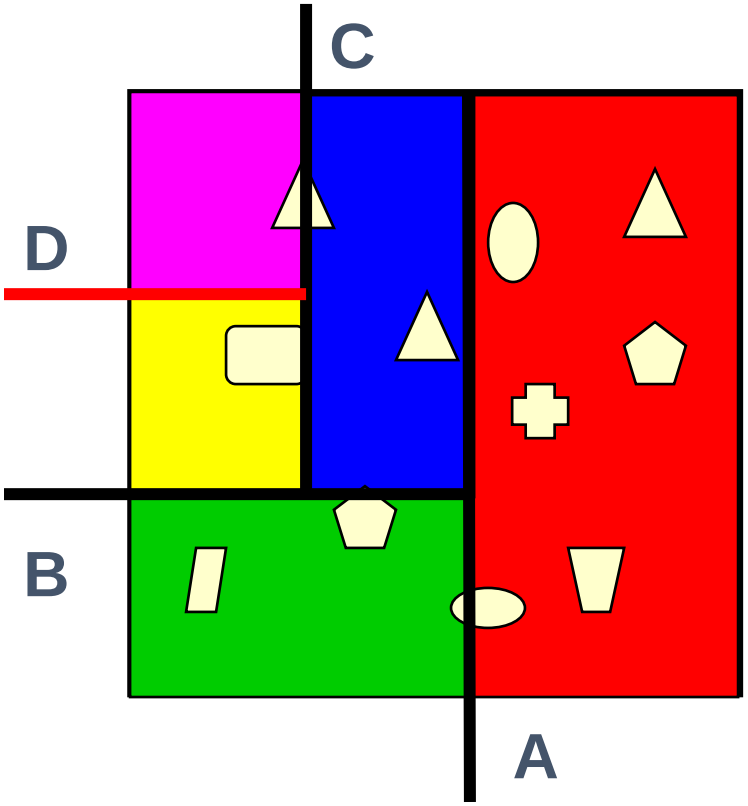


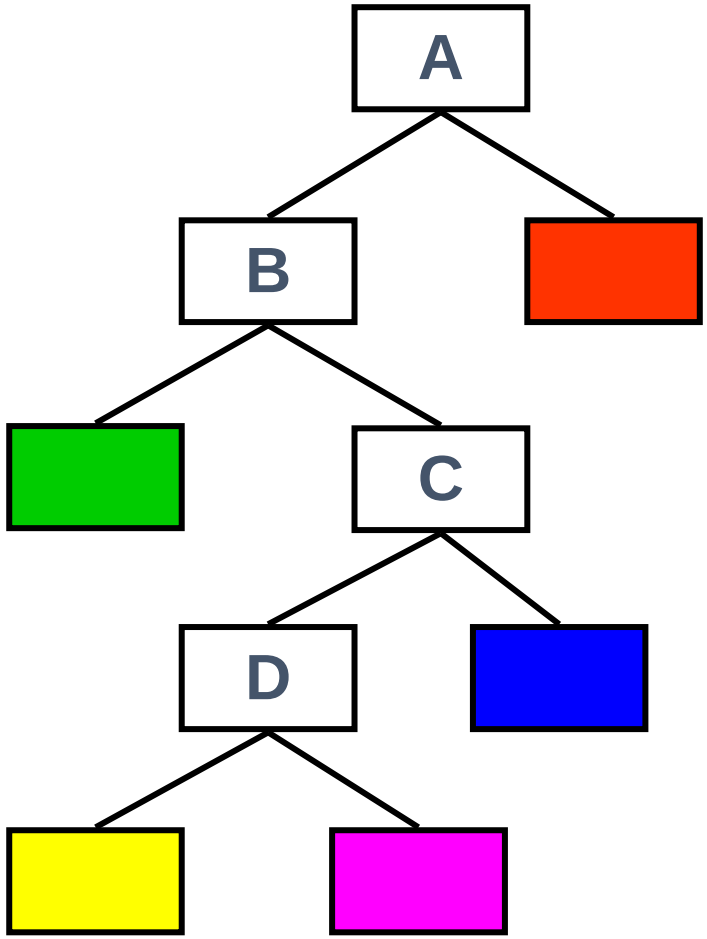
Kd Tree





Kd Tree





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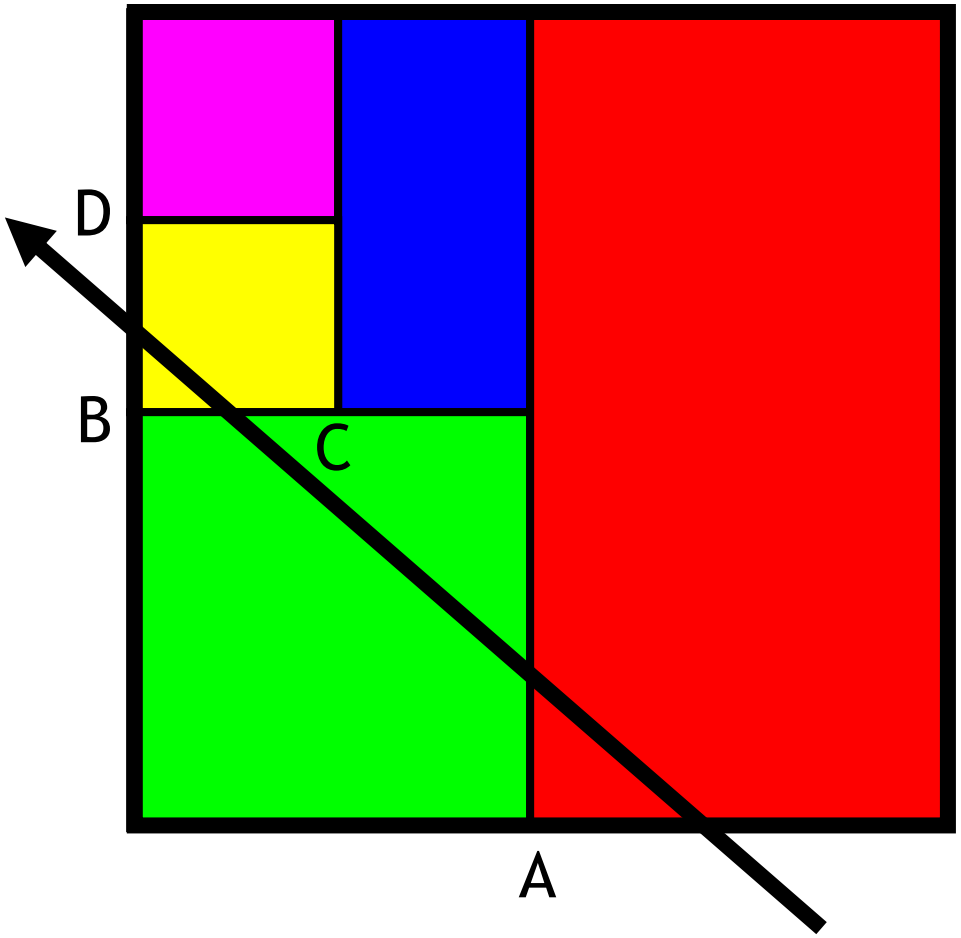
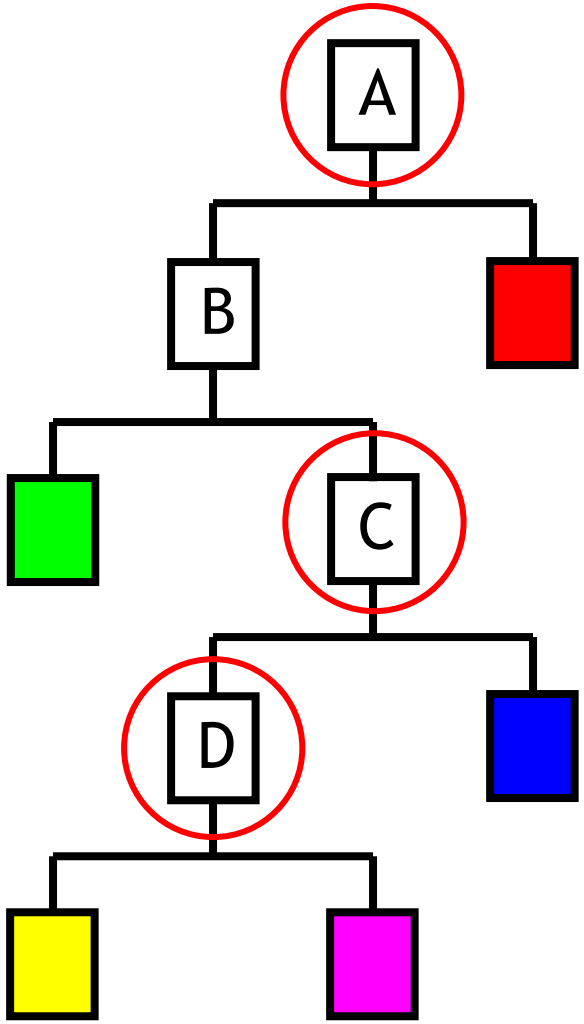
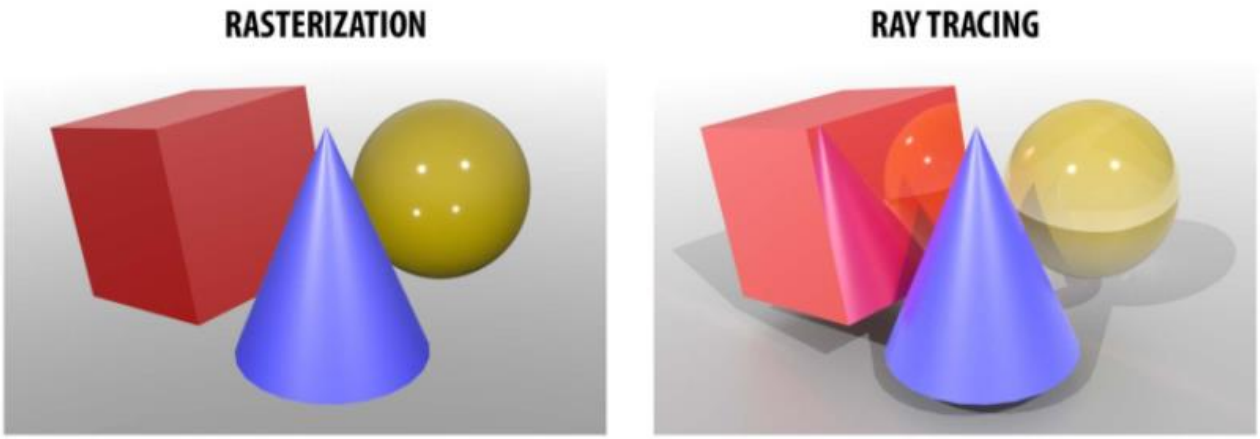




Ray Tracing v.s. Rasterization

- Rasterization is **more friendly to hardware** and usually has higher parallelism
- But when we need to **interact with other triangles**, it is much more difficult to simulate effects such as reflection, refraction, shadows, and global illumination
  - Need specialized algorithms

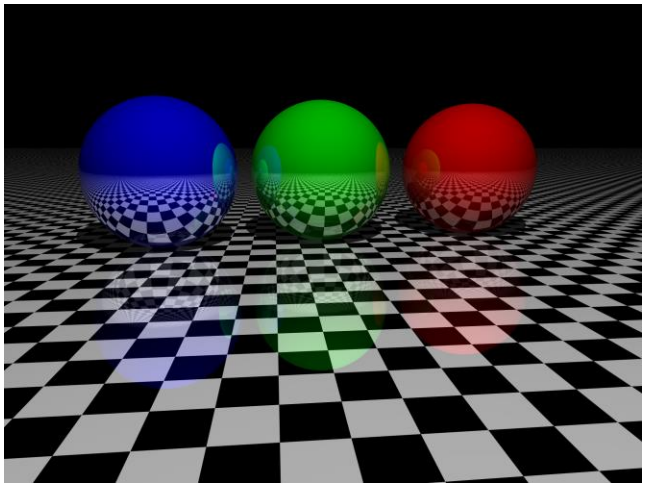


Ray Tracing v.s. Rasterization

- **Transparency**
  - **Rasterization**
    - Render the object in order (distant objects first) and blend with the previous result in the color buffer
  - **Ray-tracing:**
    - Trace a secondary (refracted) ray through the object's surface

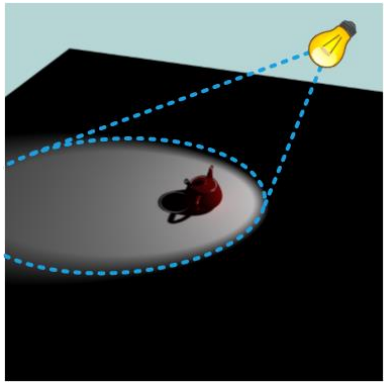
Ray Tracing v.s. Rasterization

- **Reflection**
  - **Rasterization**
    - Render the scene into an environment map
    - Look up the environment map in the fragment shader
  - **Ray-tracing:**
    - Trace a secondary (reflected) ray from the object's surface



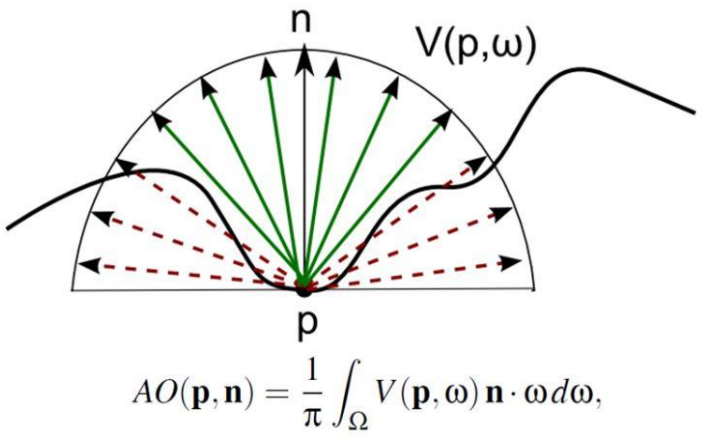
Ray Tracing v.s. Rasterization

- **Shadow**
  - **Rasterization**
    - Render a **shadow map** to record the closest surface from each light
    - Look up the map to determine whether a surface point is in shadow or not in the second pass
  - **Ray-tracing**
    - Trace a shadow ray to see if the lighting direction is occluded

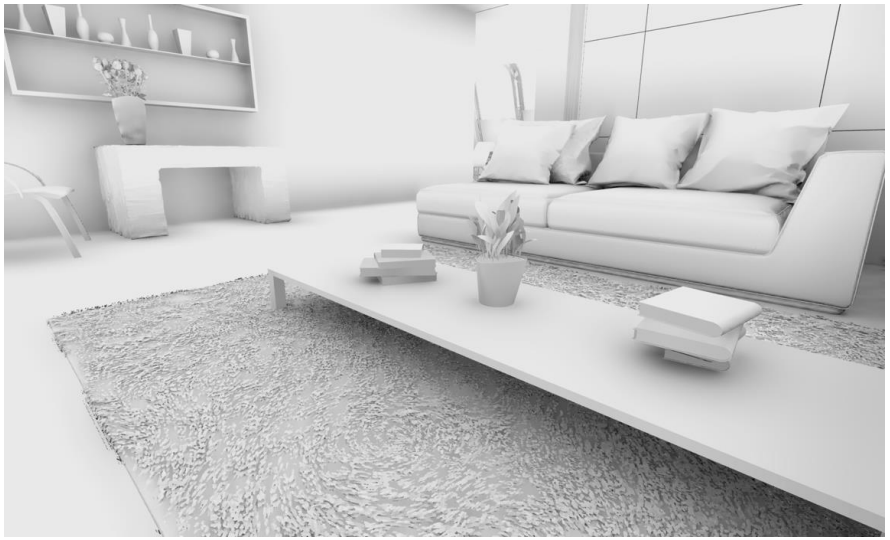


Ray Tracing v.s. Rasterization

- **Ambient occlusion**
  - **Rasterization**
    - Use the **depth map** to find nearby occluders in screen space
  - **Ray-tracing**
    - Trace shadow rays to see if a direction is occluded

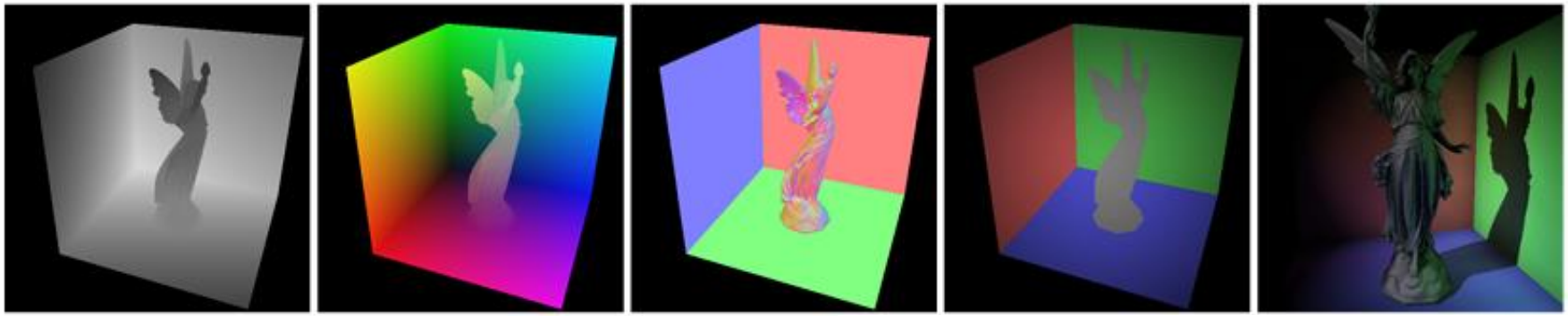


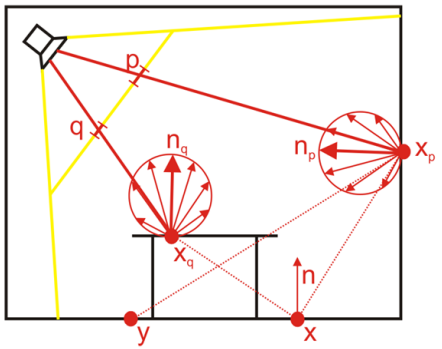
$$AO(\mathbf{p},\mathbf{n}) = \frac{1}{\pi}\int_{\Omega} V(\mathbf{p},\omega)\,\mathbf{n}\cdot\omega\, d\omega,$$

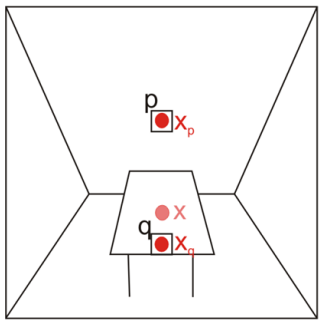


Ray Tracing v.s. Rasterization

- **Global illumination**
  - **Rasterization**
    - Render the direct lighting result from the light view
    - Use the results in the first pass to render indirect lighting

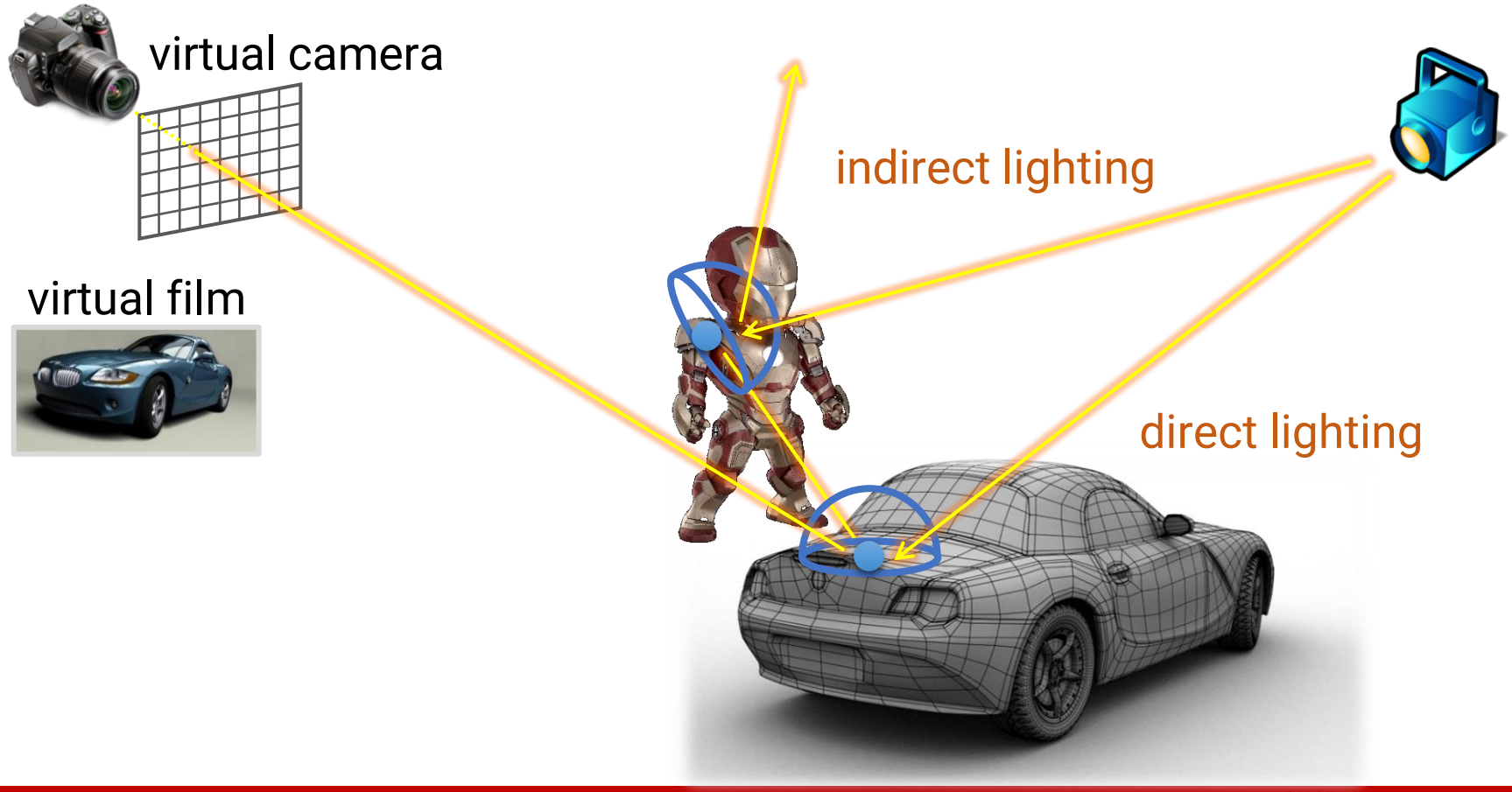






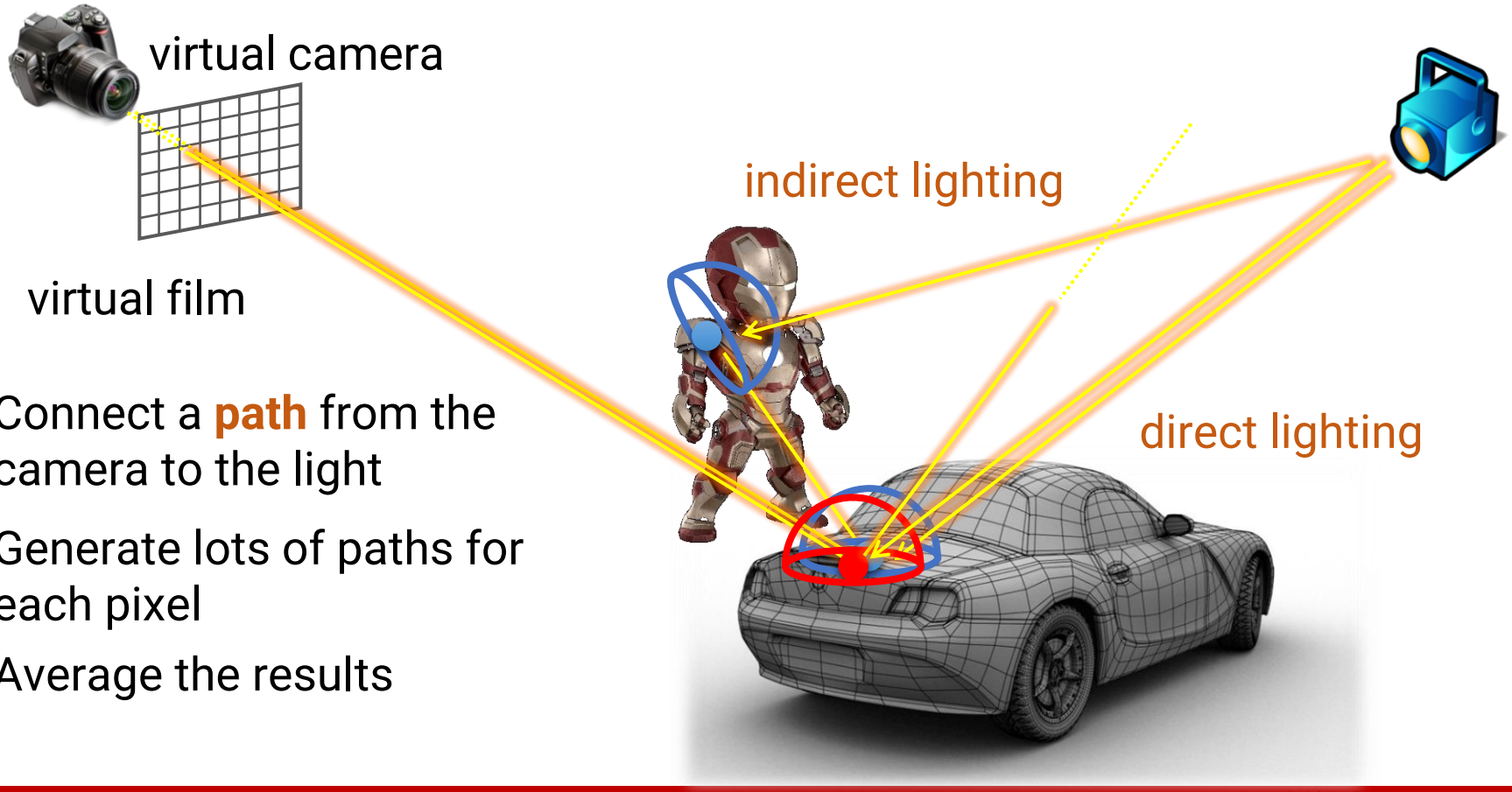
Ray Tracing v.s. Rasterization

- **Global illumination**
  - **Ray-tracing**



Ray Tracing v.s. Rasterization

- **Global illumination**
  - **Ray-tracing: path tracing**



Connect a **path** from the camera to the light

Generate lots of paths for each pixel

Average the results

Ray Tracing v.s. Rasterization

- **Problems with ray tracing**
  - Ray tracing is more general
  - However, its simulator usually has a slow convergence rate and produces lots of noise when samples are not enough
- Solution
  - More rays
  - Filtering

Real-time Ray Tracing

- Recently some GPU ray tracers achieve real-time frame rates by incorporating filtering techniques
  - NVIDIA OptiX
    - https://developer.nvidia.com/rtx/ray-tracing/optix
  - Unreal Engine
    - https://docs.unrealengine.com/5.1/en-US/hardware-ray-tracing-in-unreal-engine/
  - DirectX
    - https://microsoft.github.io/DirectX-Specs/d3d/Raytracing.html
- It is believed to replace rasterization in the future
  - Not that sure now …

Real-time Ray Tracing

- Unreal Engine Ray Tracing Demo
  - https://www.youtube.com/watch?v=J3ue35ago3Y

Any Questions?