M&Ms: Freshmen Experience Ray Tracing

Michael Kazhdan

Outline

- Ray-Tracing
  - Overview
  - Direct Illumination
  - Global Illumination

Geri's Game , *Pixar*

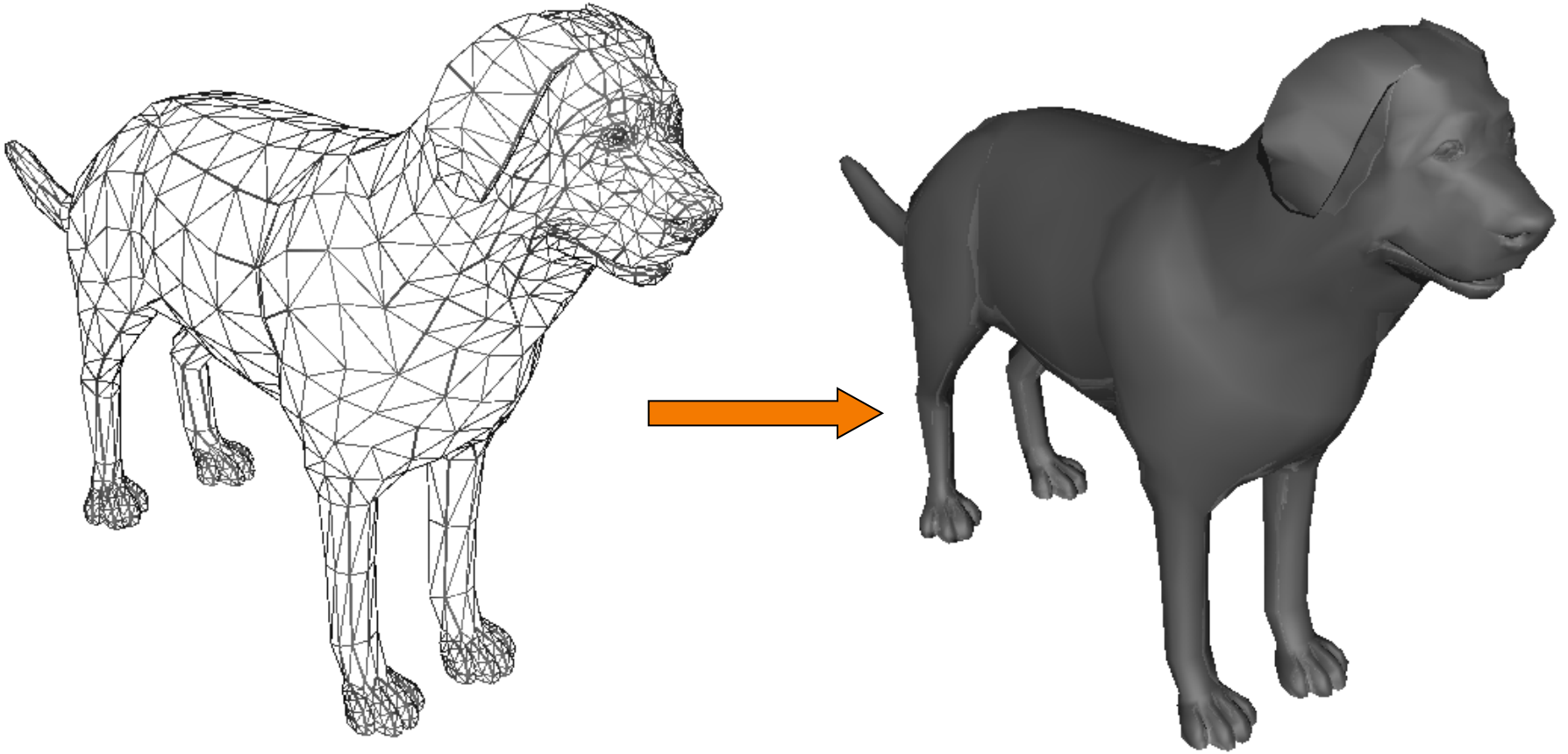
3D Model Representation

In graphics, we often represent the surface of a 3D shape by a set of triangles.

Work by Jim Rygiel for "102 Dalmatians"

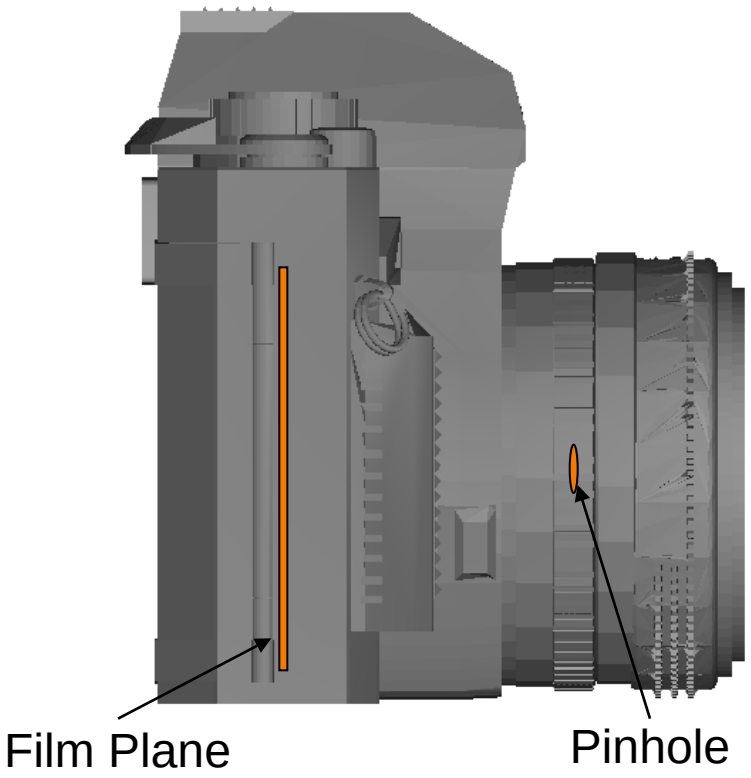
Ray-Tracing

The goal of ray-tracing is to take a collection of geometry representing a 3D scene and render a detailed and credible image.



Traditional Pinhole Camera

- The film sits behind the pinhole of the camera.



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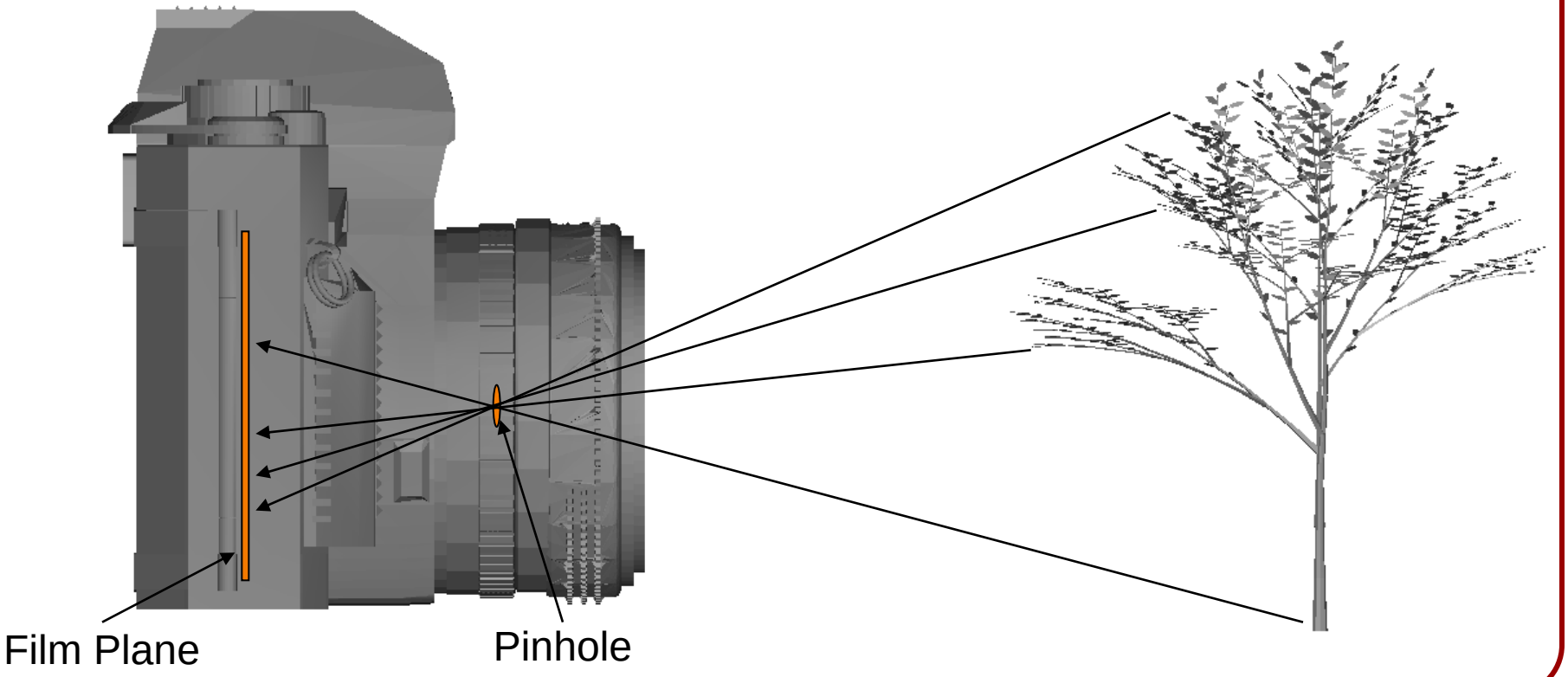
- Rays come in from the outside, pass through the pinhole, and hit the film plane.



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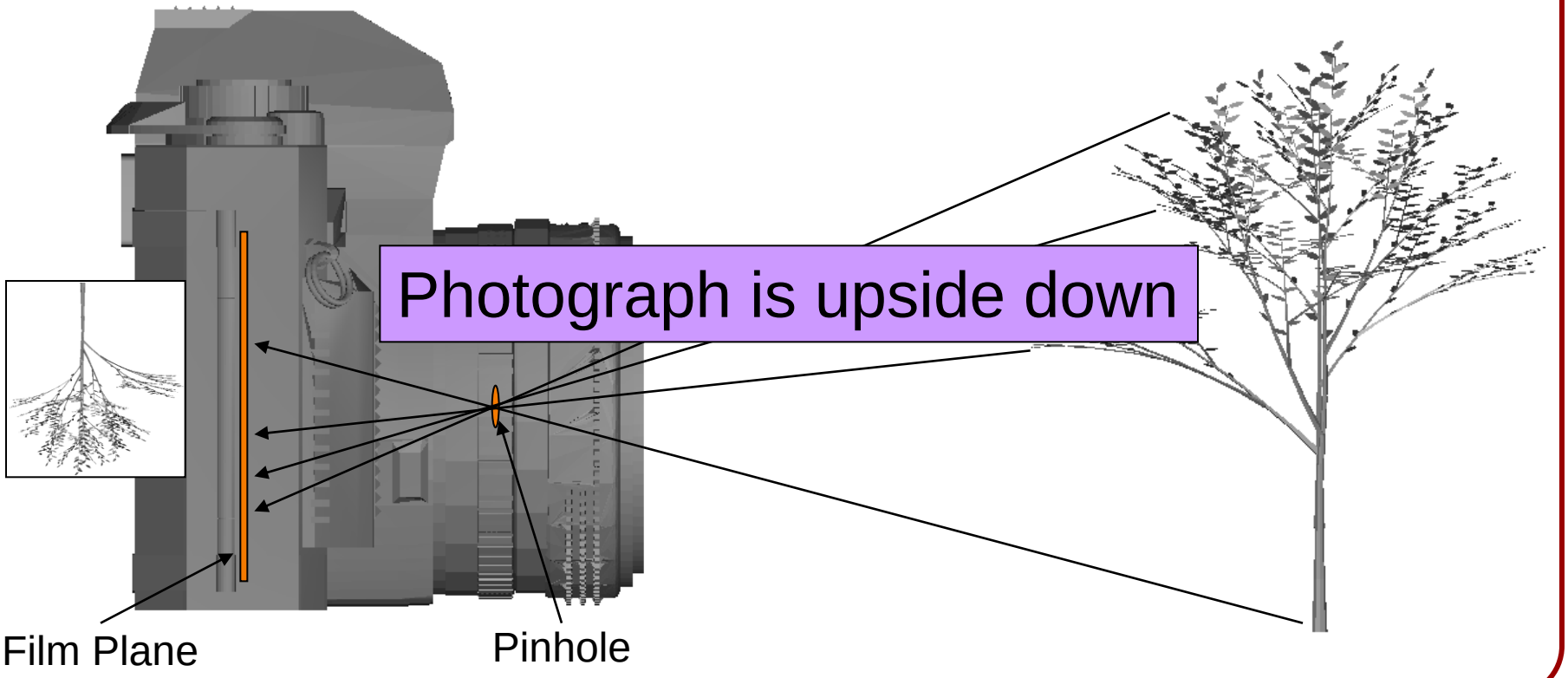

Virtual Camera

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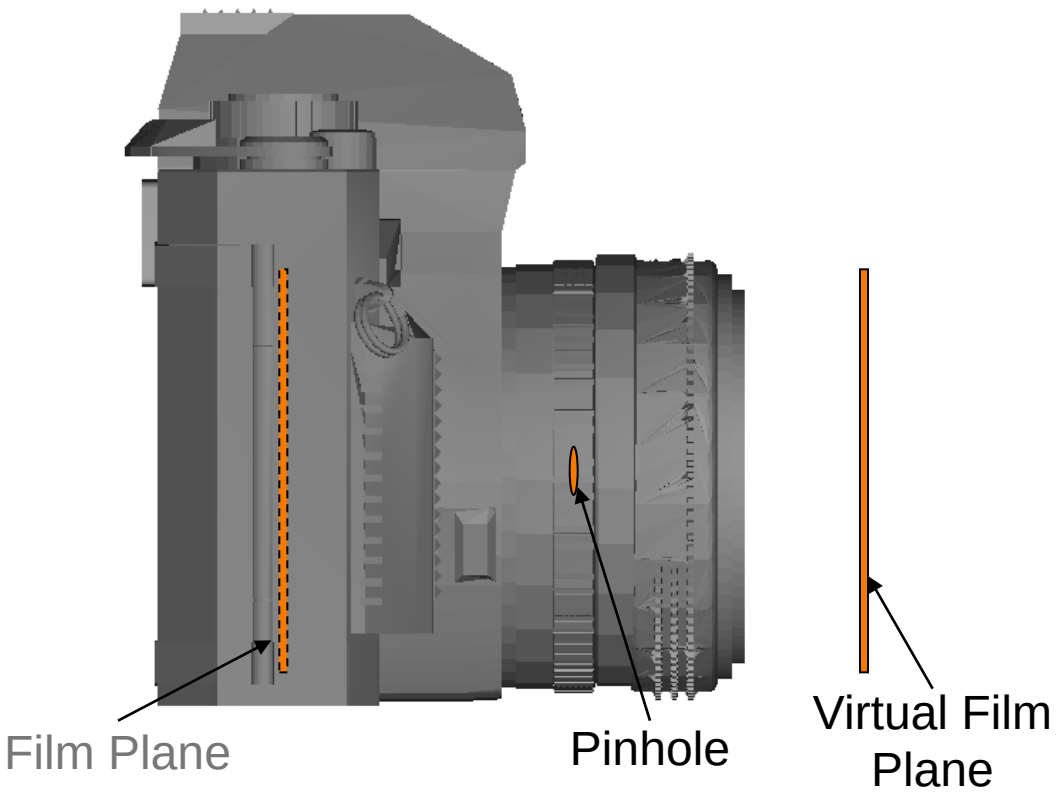

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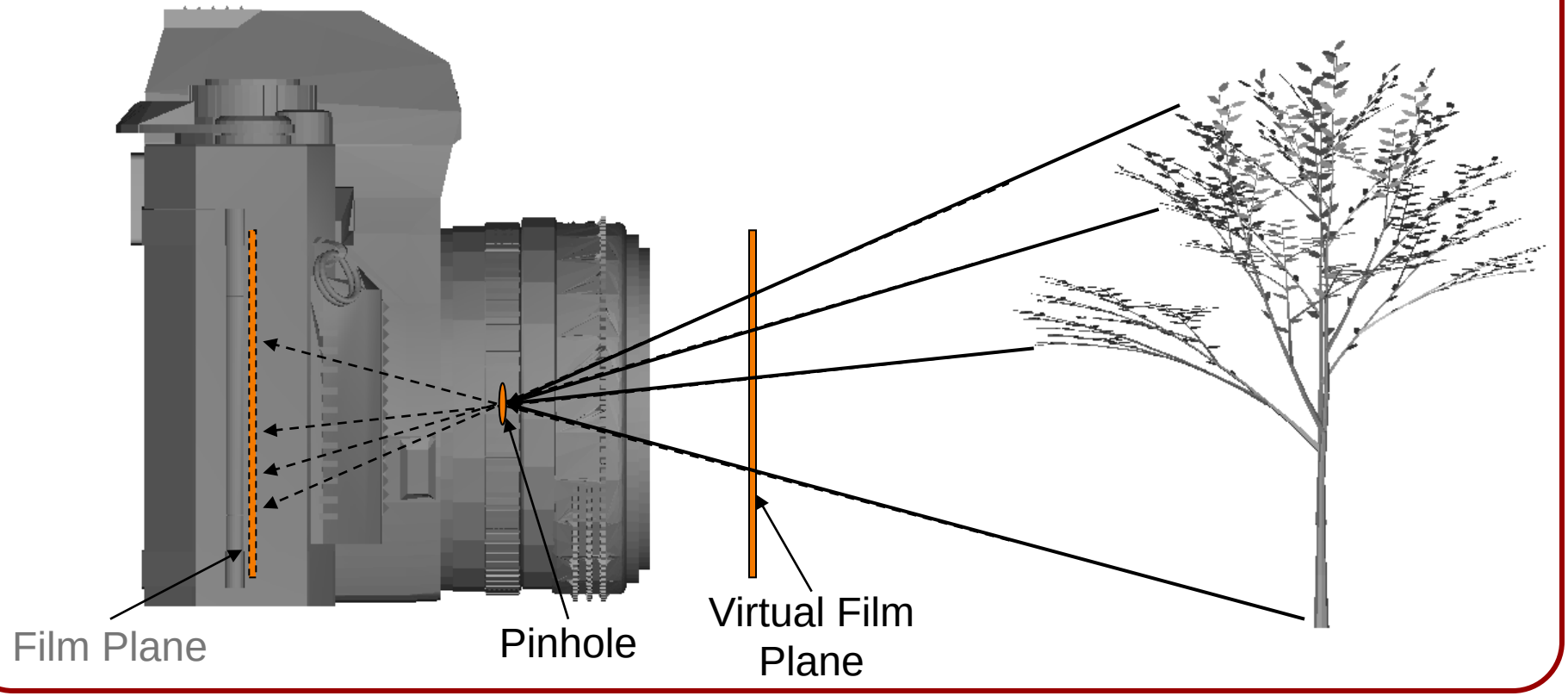

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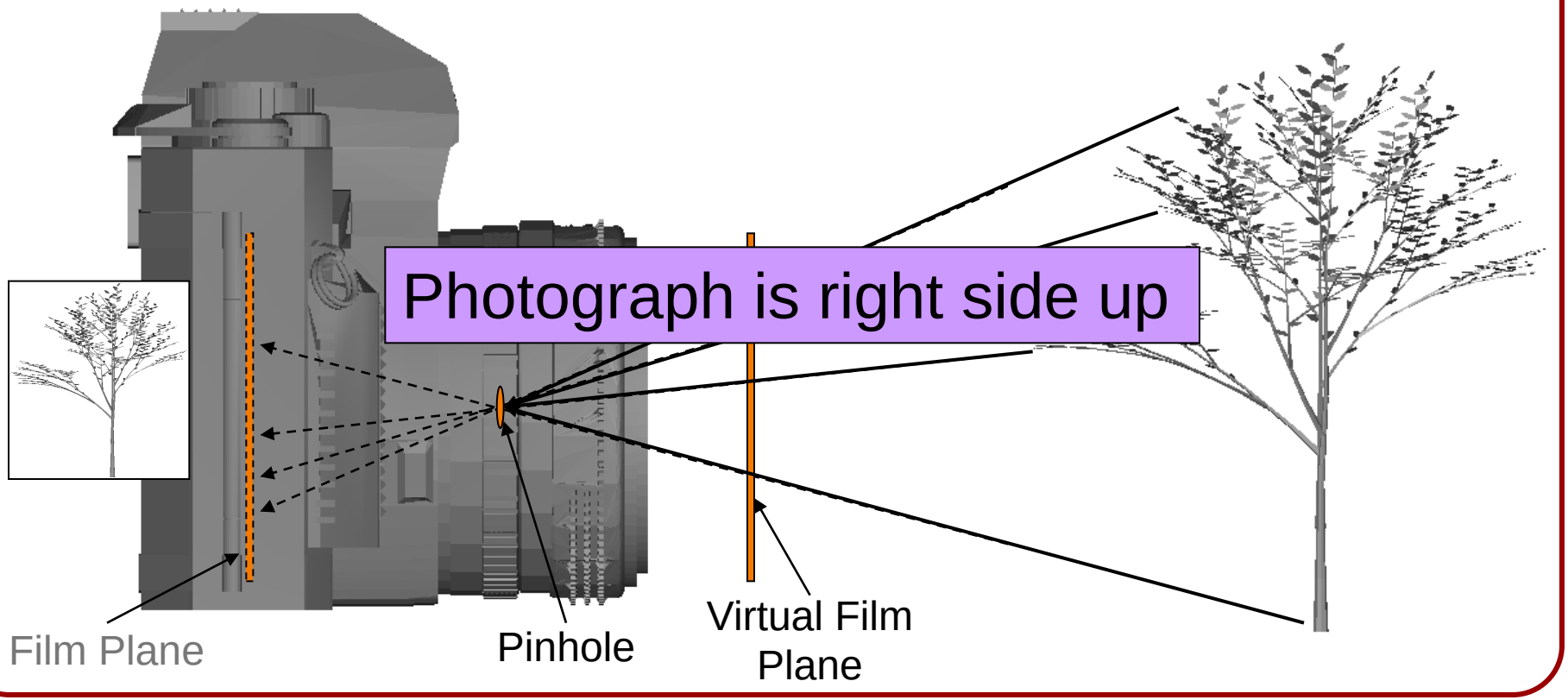
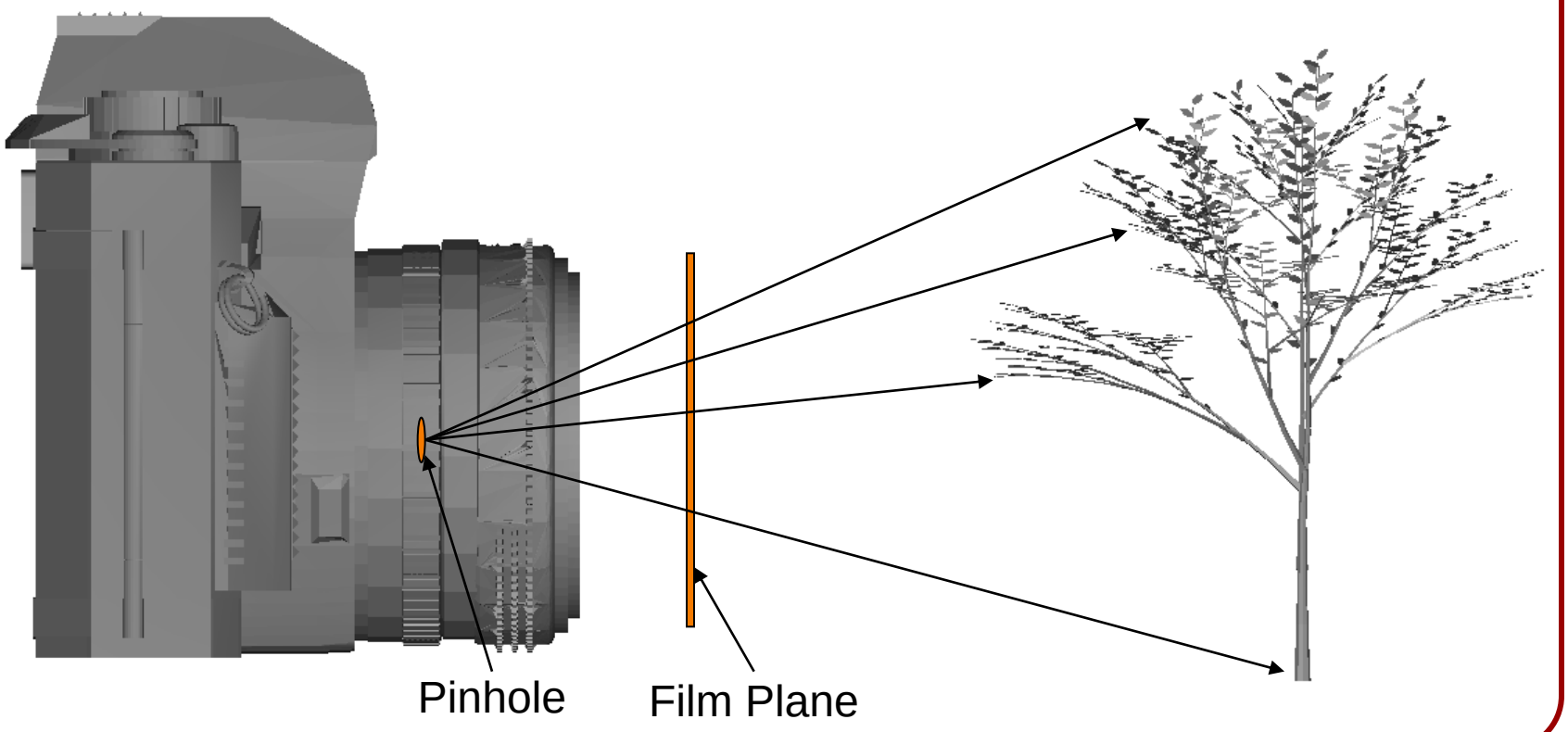


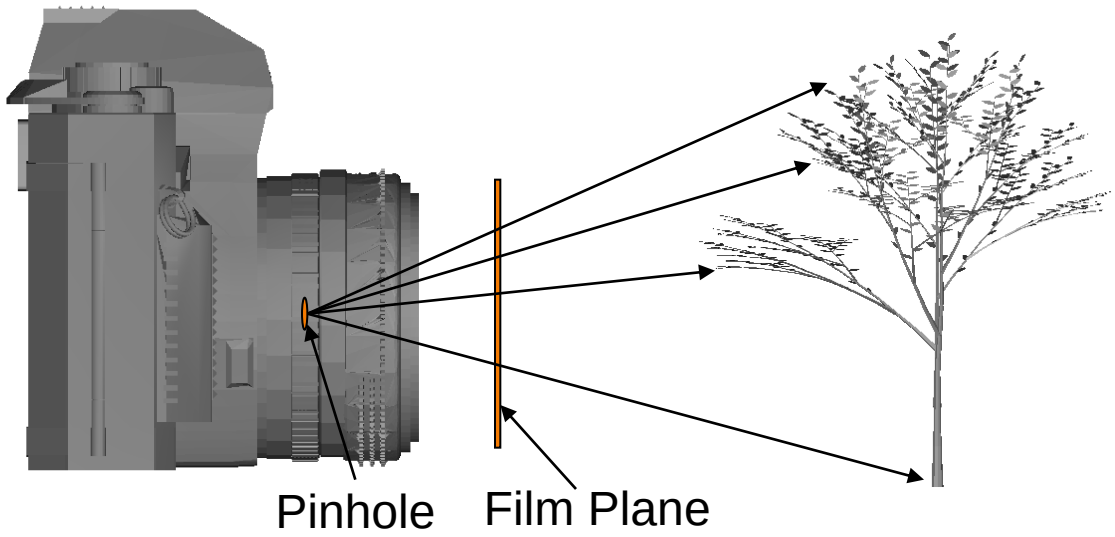
Ray Casting

- We invert the process of image generation by sending rays out from the pinhole.



Ray Casting

- We invert the process of image generation by sending rays out from the pinhole.
- For each pixel in the virtual view screen:
  - Compute the ray from the pinhole, through the pixel
  - Figure out what object in the scene is first hit by the ray
  - Compute the color of the object and assign it to the pixel.



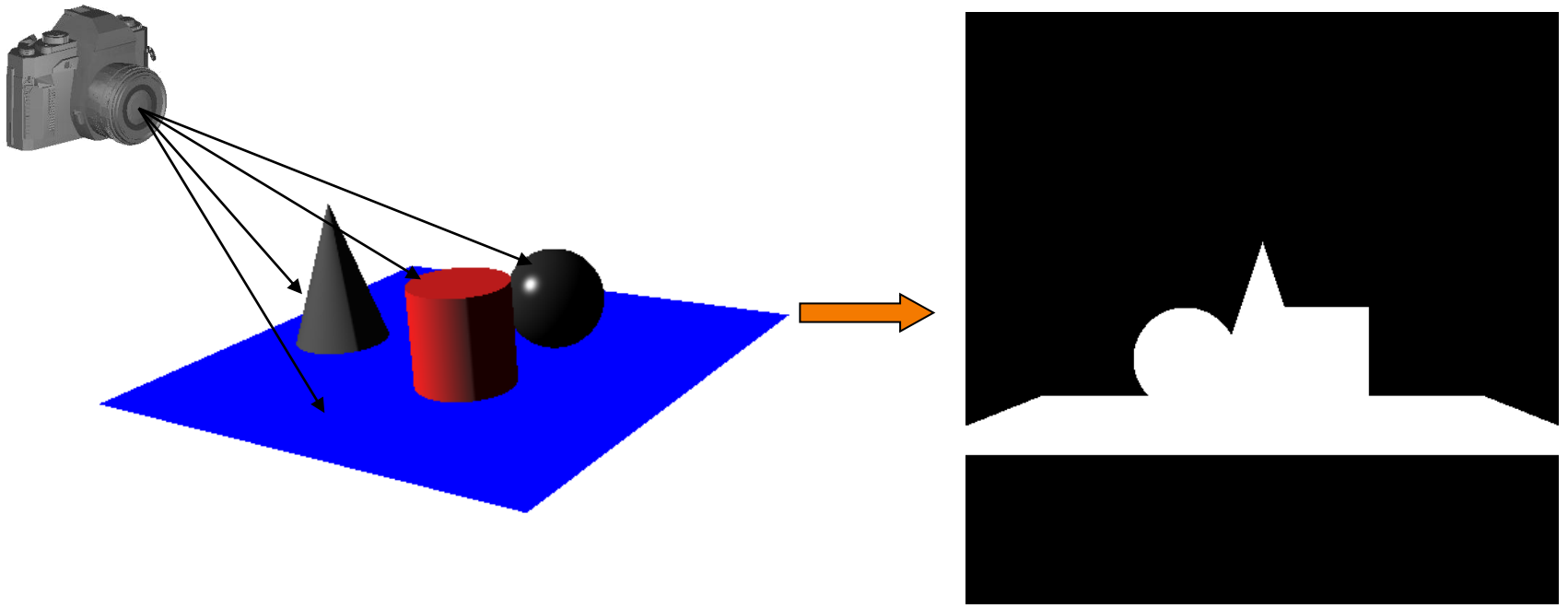
Ray Casting

- 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

- If we ignore the color computation, we can quickly determine the silhouettes of the scene:



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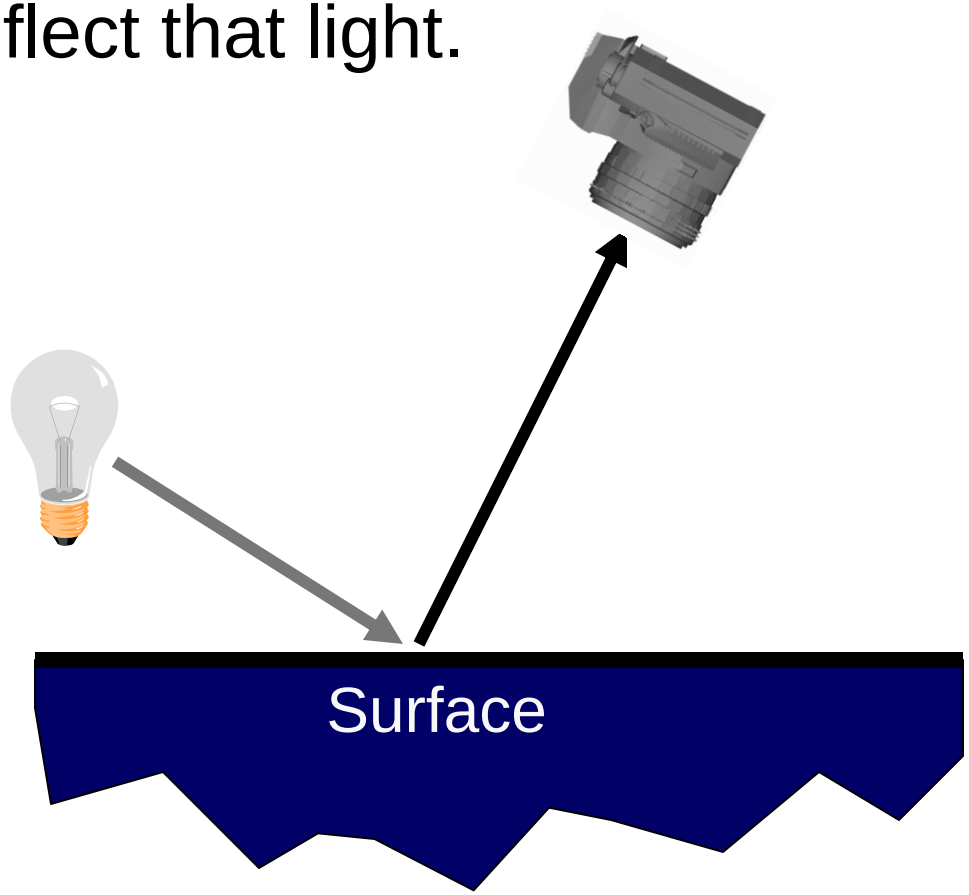
Modeling Surface Reflectance

In practice, the color of the surface is determined by the lights in the scene and the ways in which the different surfaces reflect that light.



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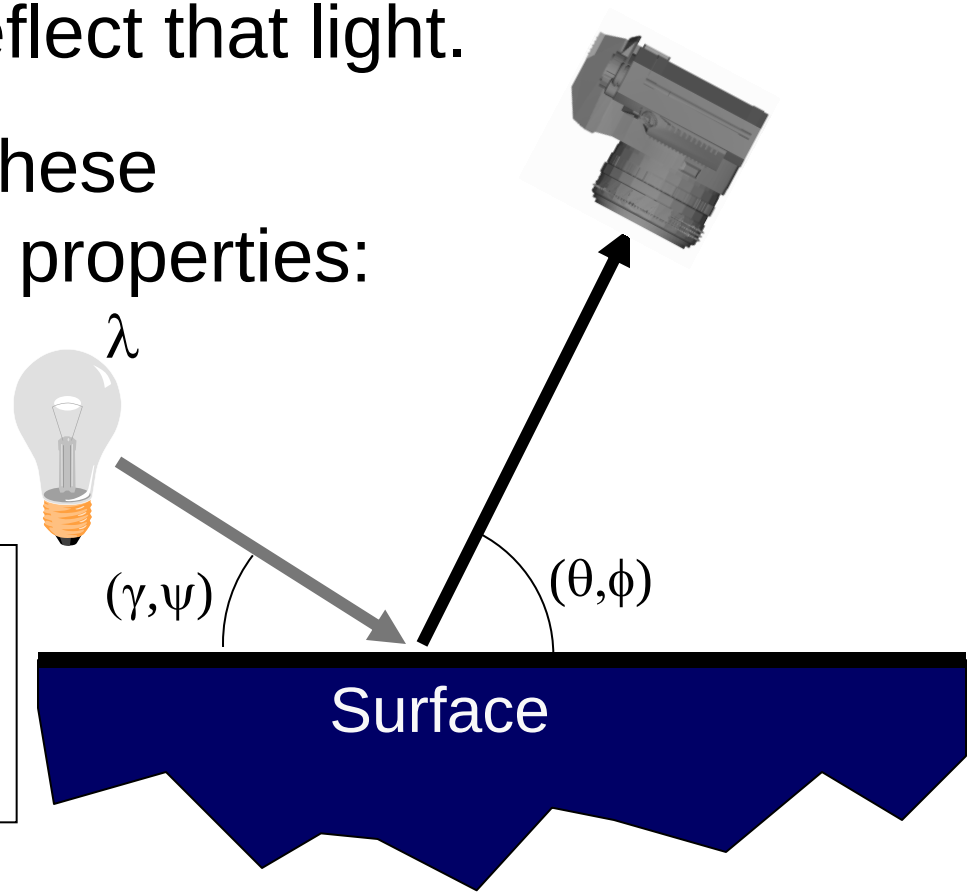
We can try modeling these surface reflectance properties:

$$R_s(\theta, \phi, \lambda, \gamma, \psi)$$



R_s is the fraction of incident light:
- arriving from direction (γ,ψ)
- with wavelength λ
- leaving in direction (θ,ϕ)

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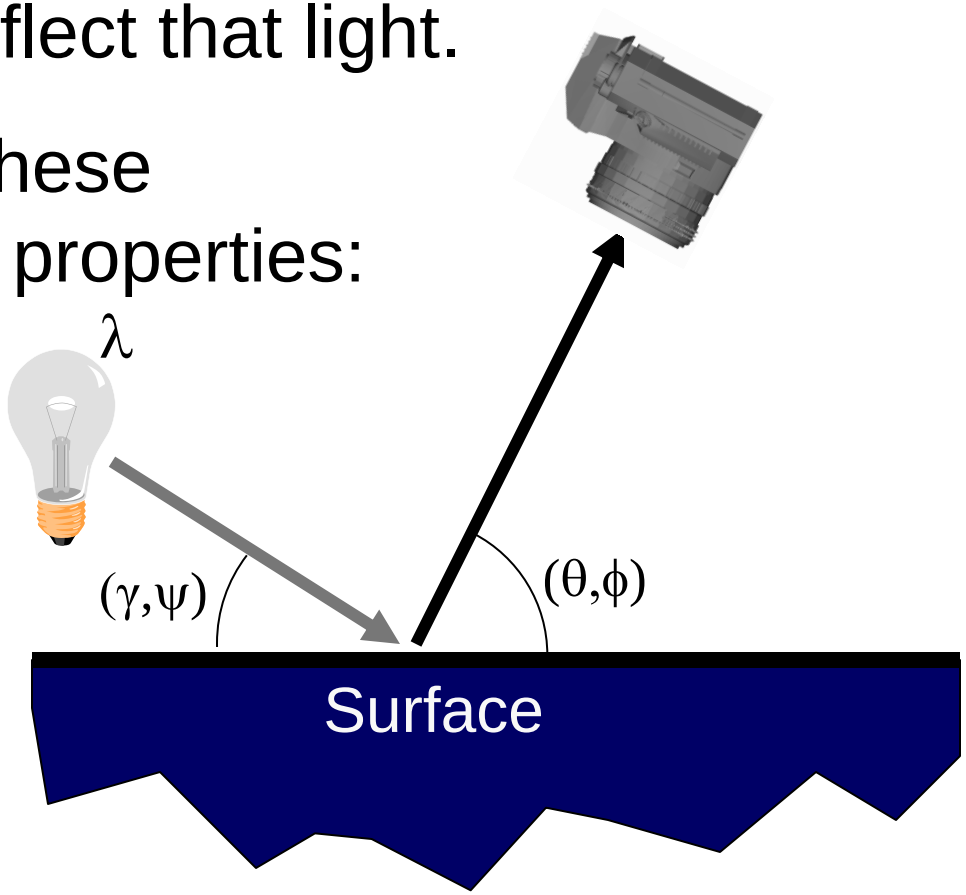
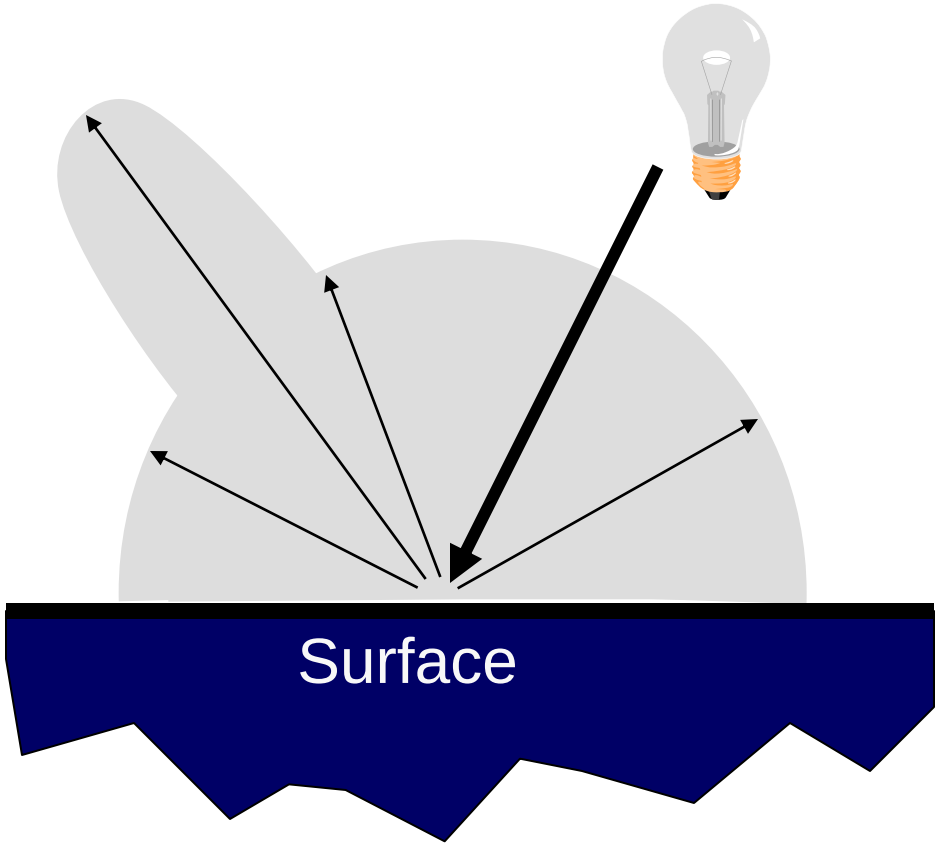
- Too much storage
- Difficult in practice



Simple Reflectance Model

- Simple analytic model:
  - diffuse reflection +
  - specular reflection +
  - emission +
  - “ambient”

Based on model proposed by Phong



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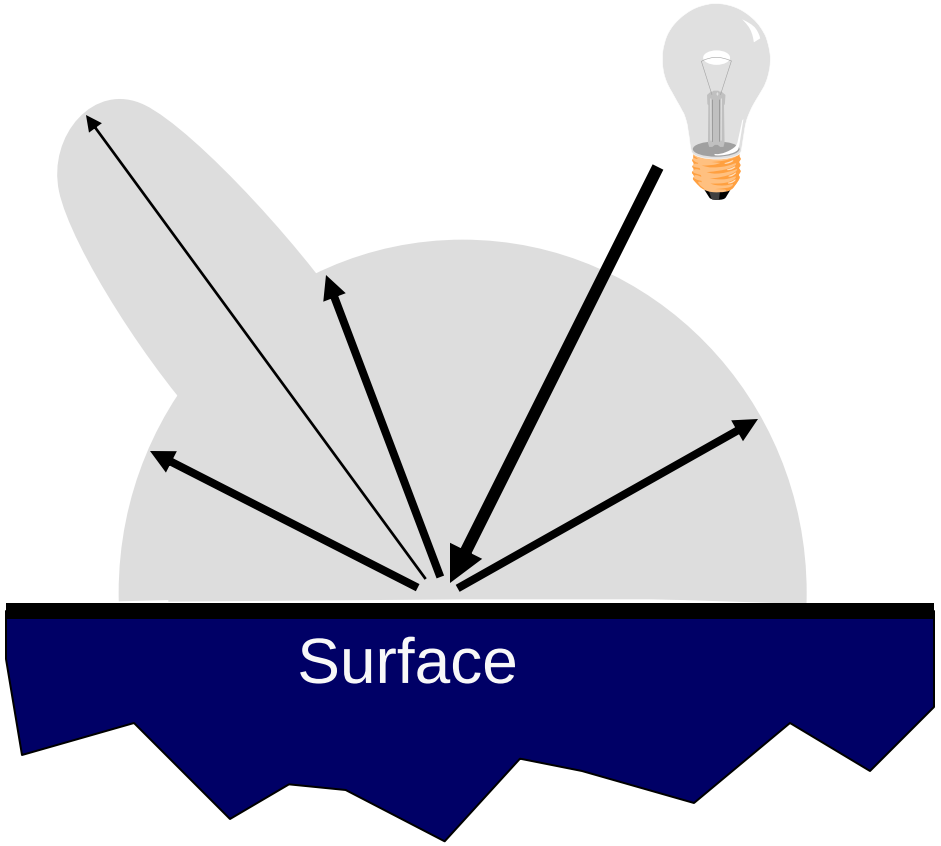
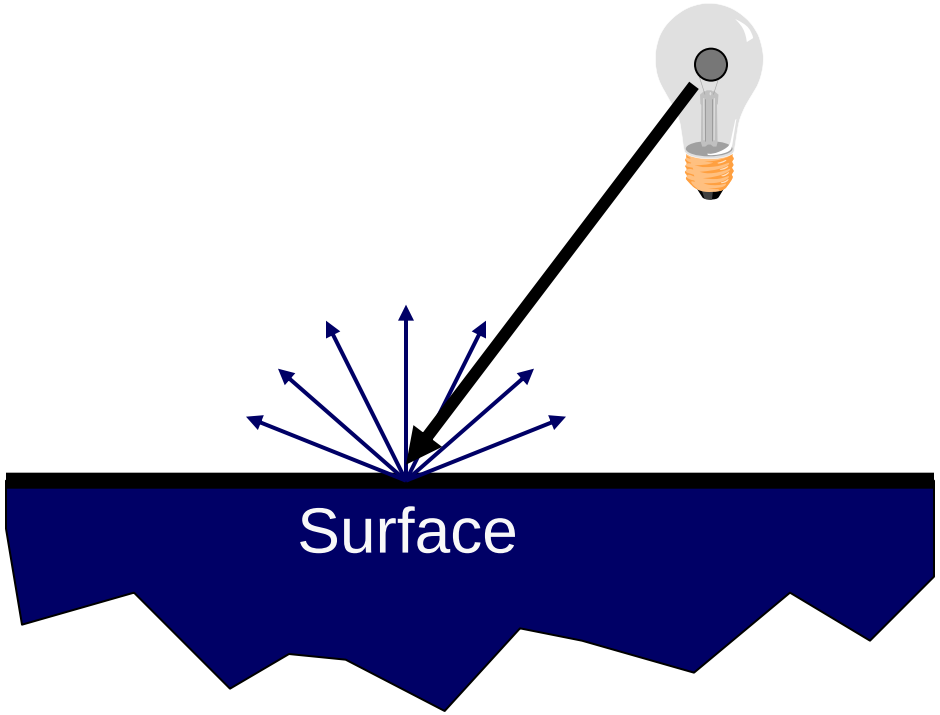


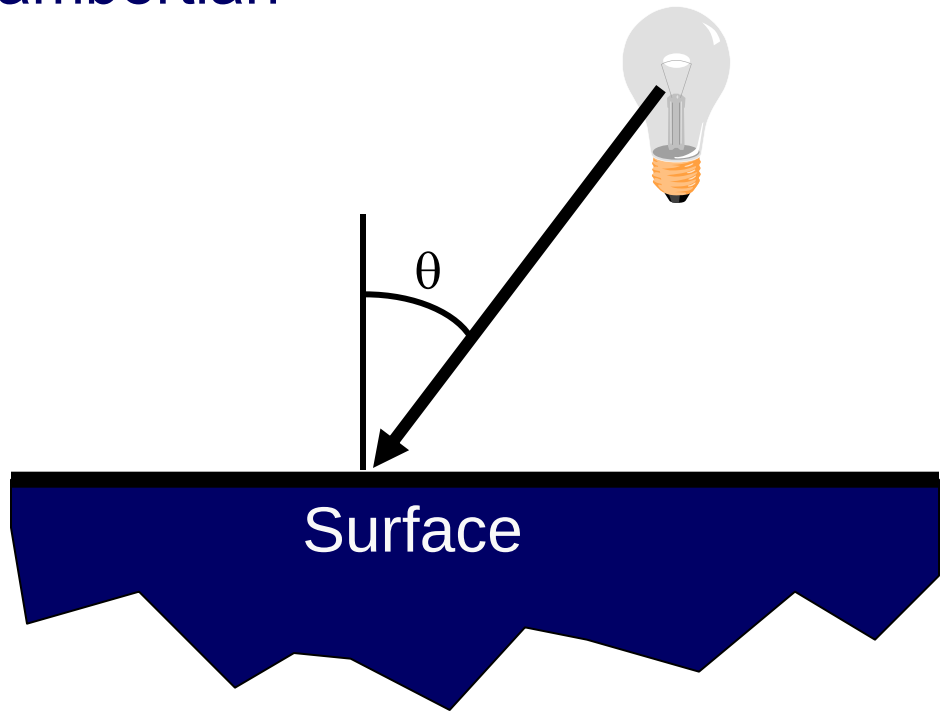
Diffuse Reflection

- Assume surface reflects equally in all directions
  - Examples: chalk, clay



Diffuse Reflection

- How much light is reflected?
  - Depends on angle of incident light
  - aka “Lambertian”



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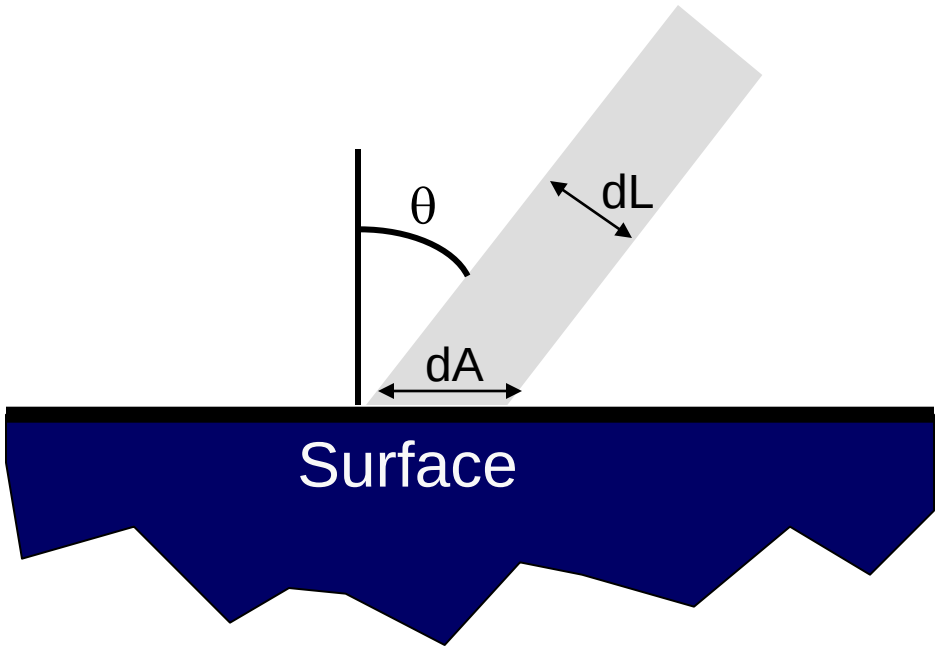
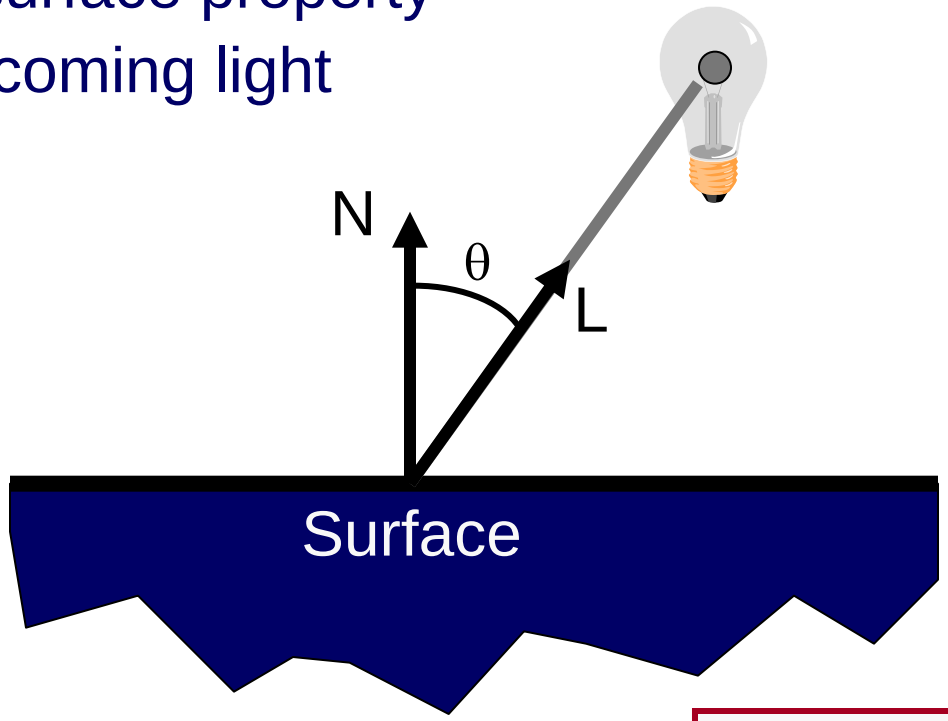
$$dL = dA\cos\Theta$$



Think of a flashlight!

Diffuse Reflection

- Lambertian model
  - cosine law (dot product)
  - K_D is surface property
  - I_L is incoming light



$$I_D = K_D(N \bullet L)I_L$$

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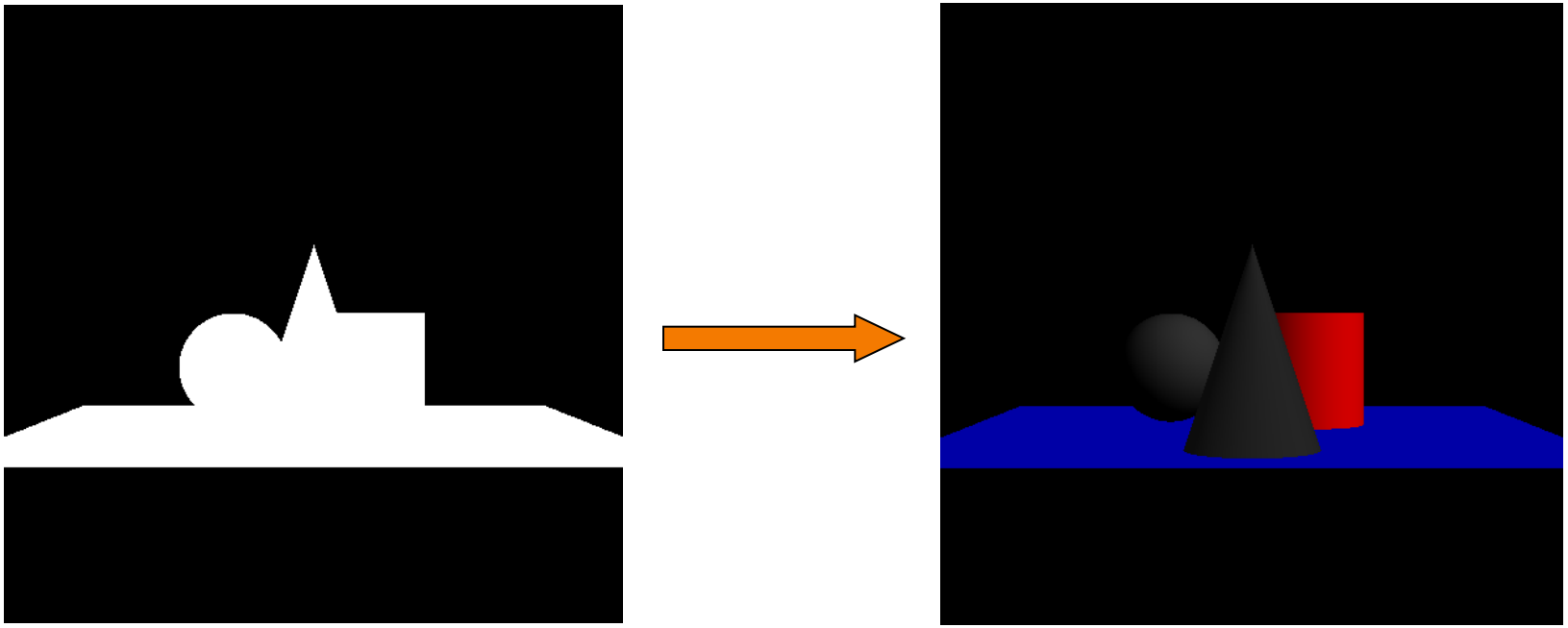

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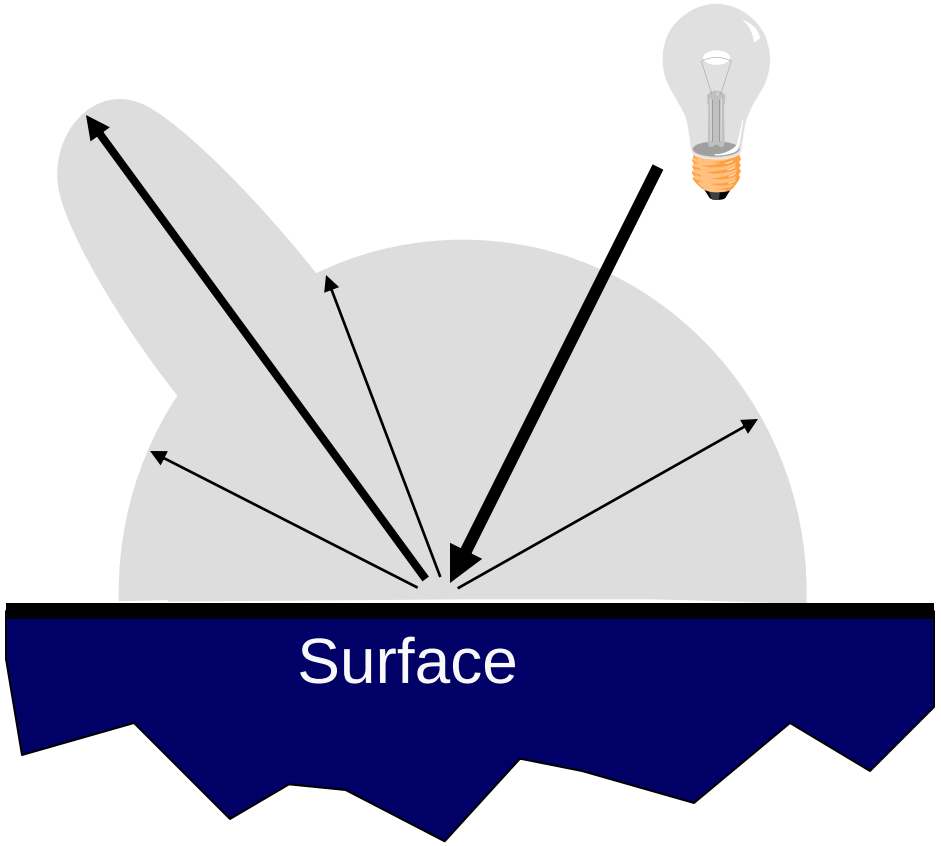

Specular Reflection

- Reflection is strongest near mirror angle
  - Examples: metals, shiny apples

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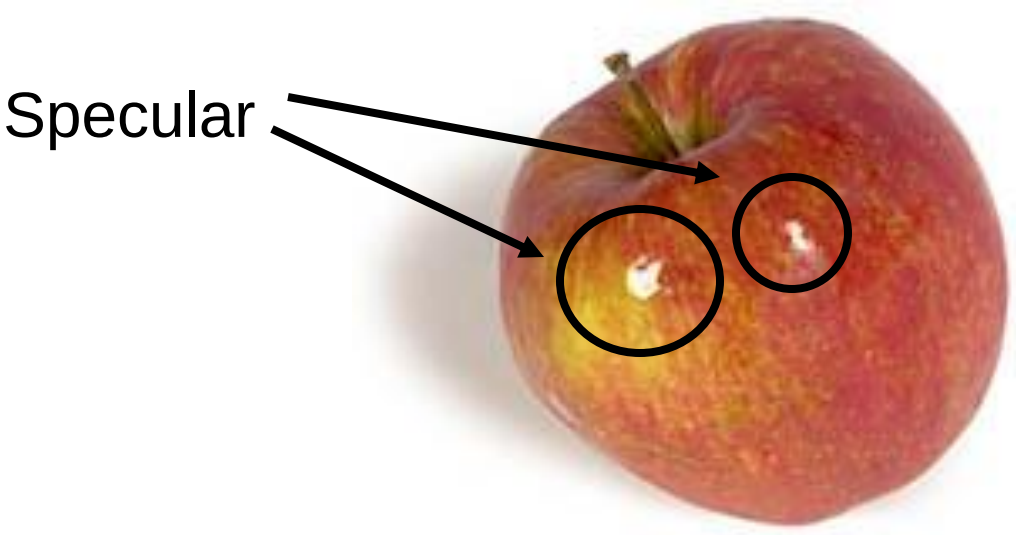
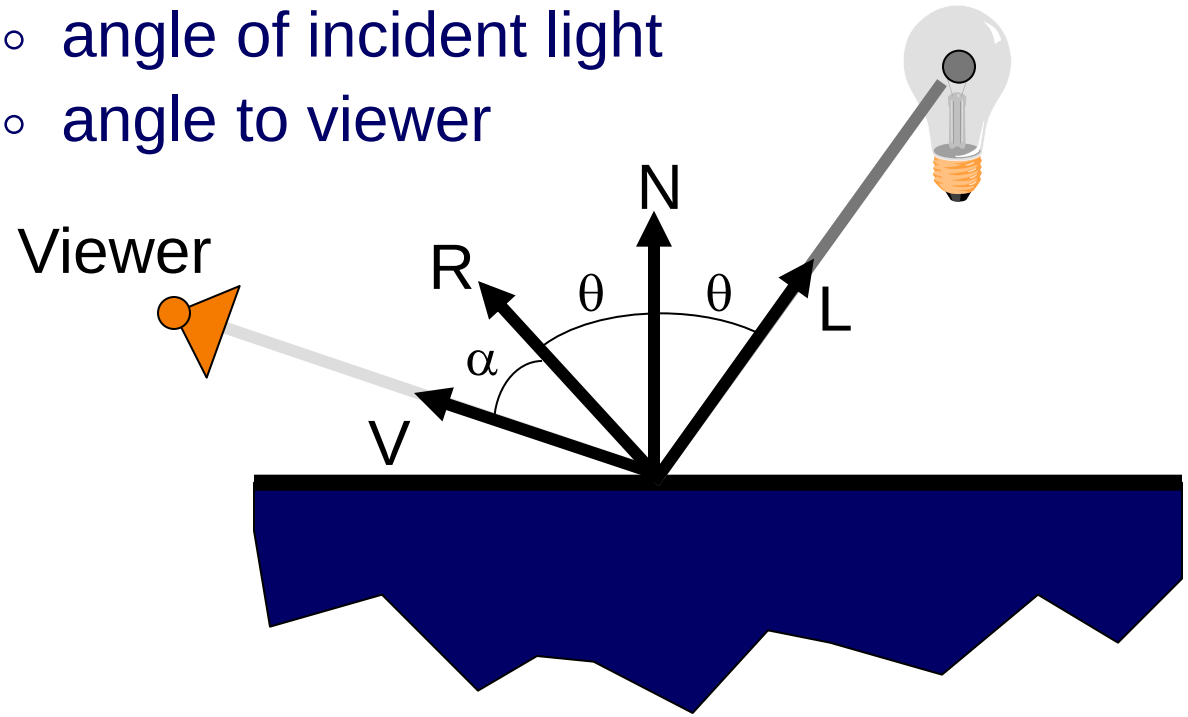


Specular Reflection

How much light is seen?

Depends on:

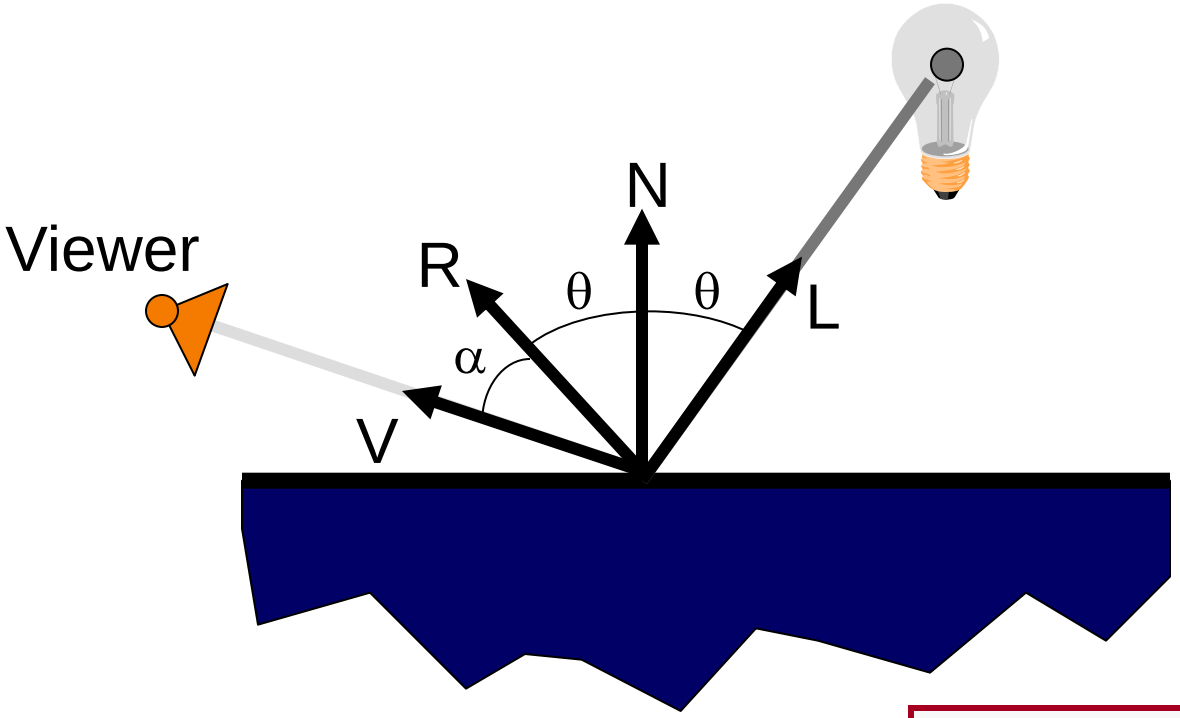
- angle of incident light
- angle to viewer



Specular Reflection

- Phong Model
  - $\cos(\alpha)^n$

This is a physically-motivated hack!



$$I_S = K_S (V \bullet R)^n I_L$$

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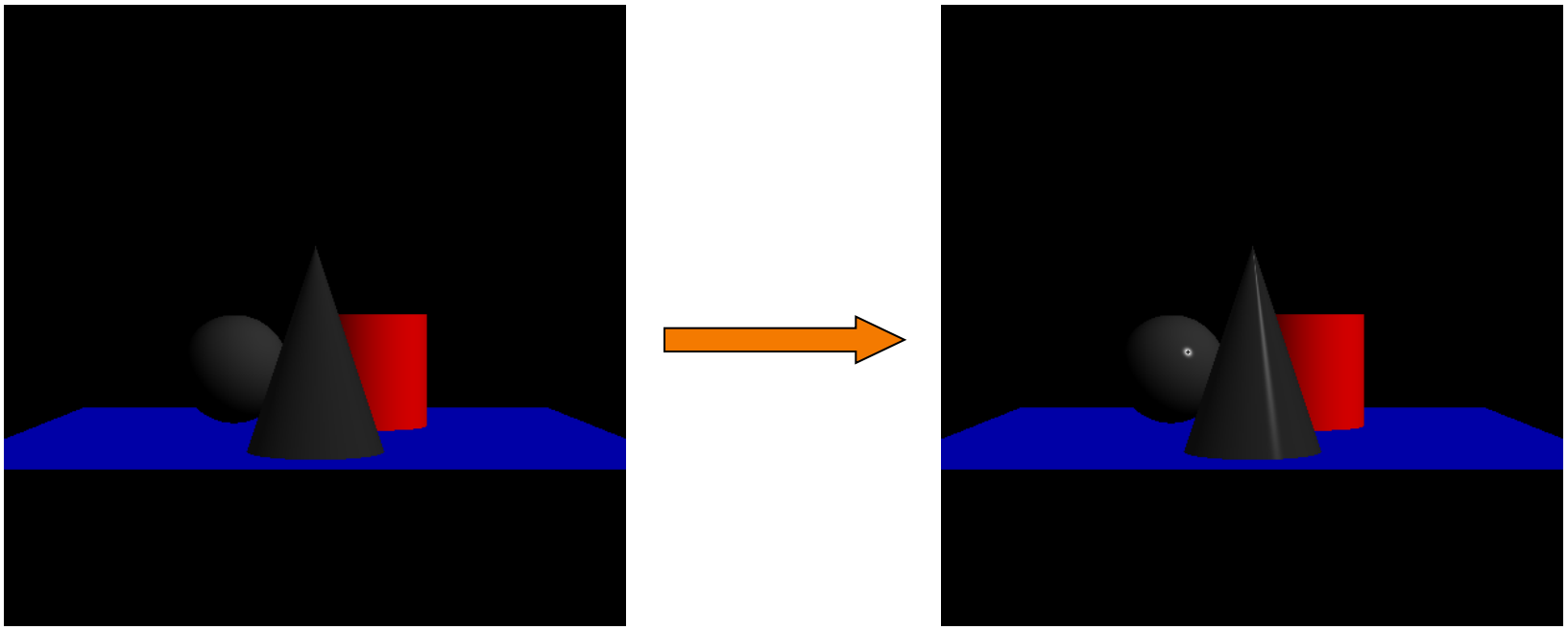

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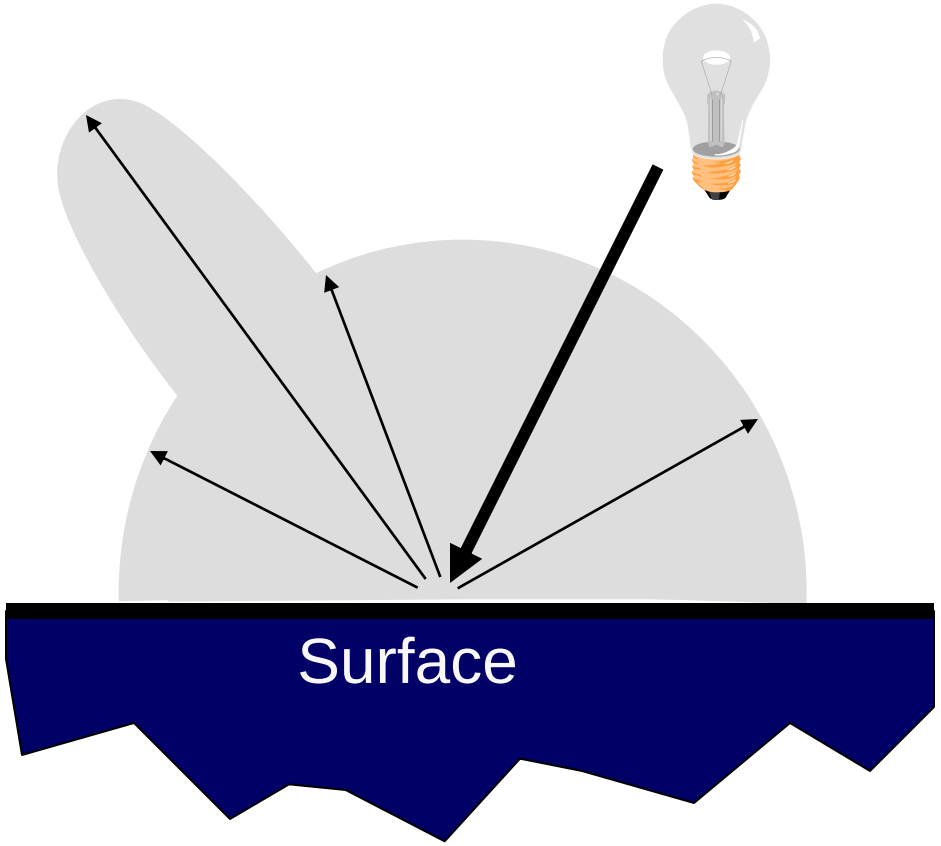
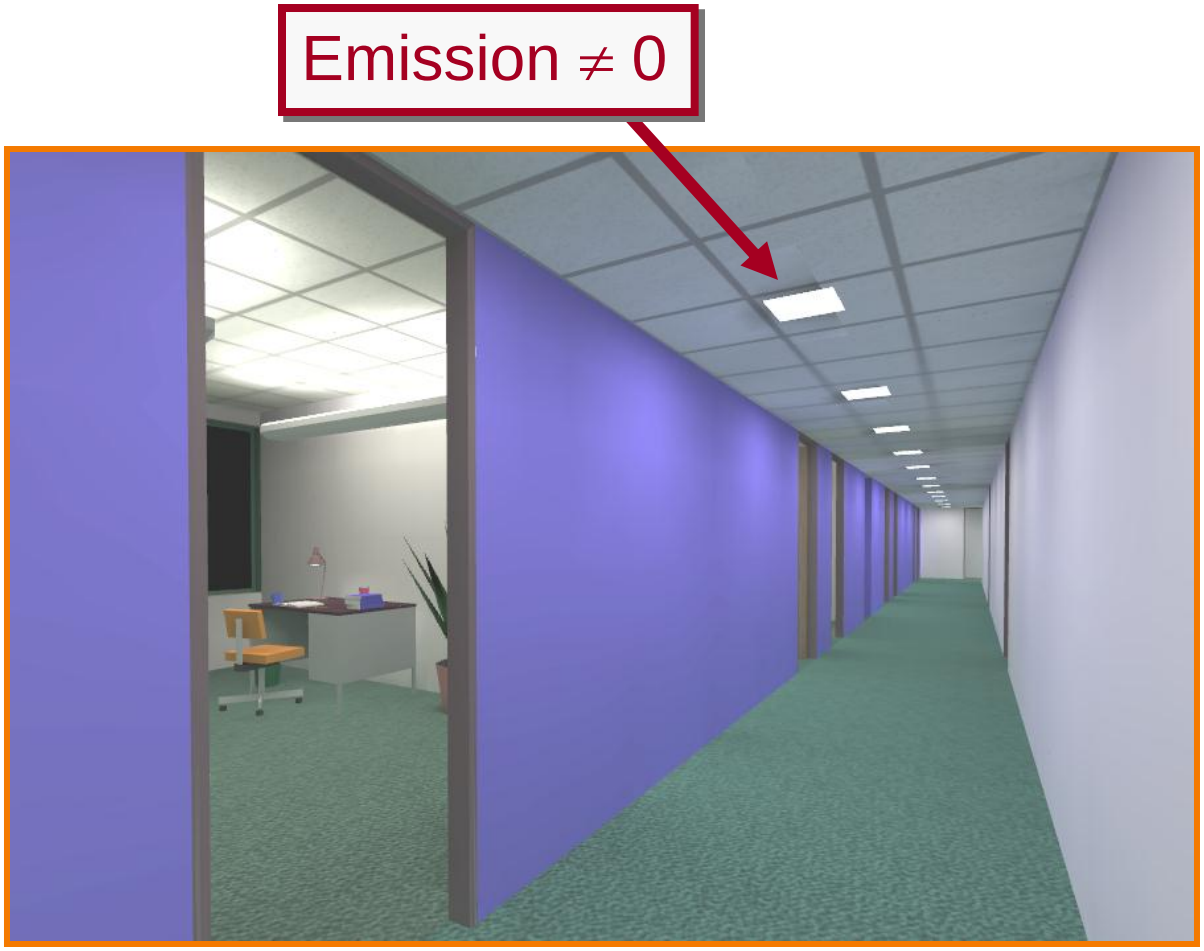


Emission

- Represents light eminating directly from polygon



Emission

$$I = I_E$$

Emission ≠ 0

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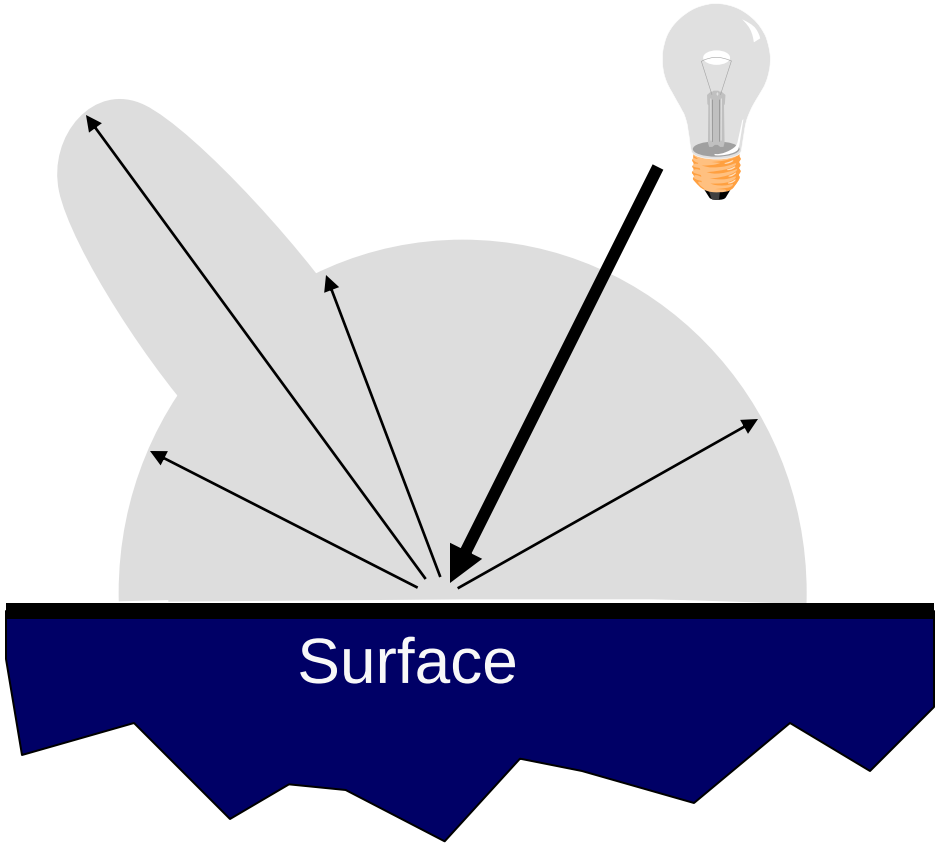
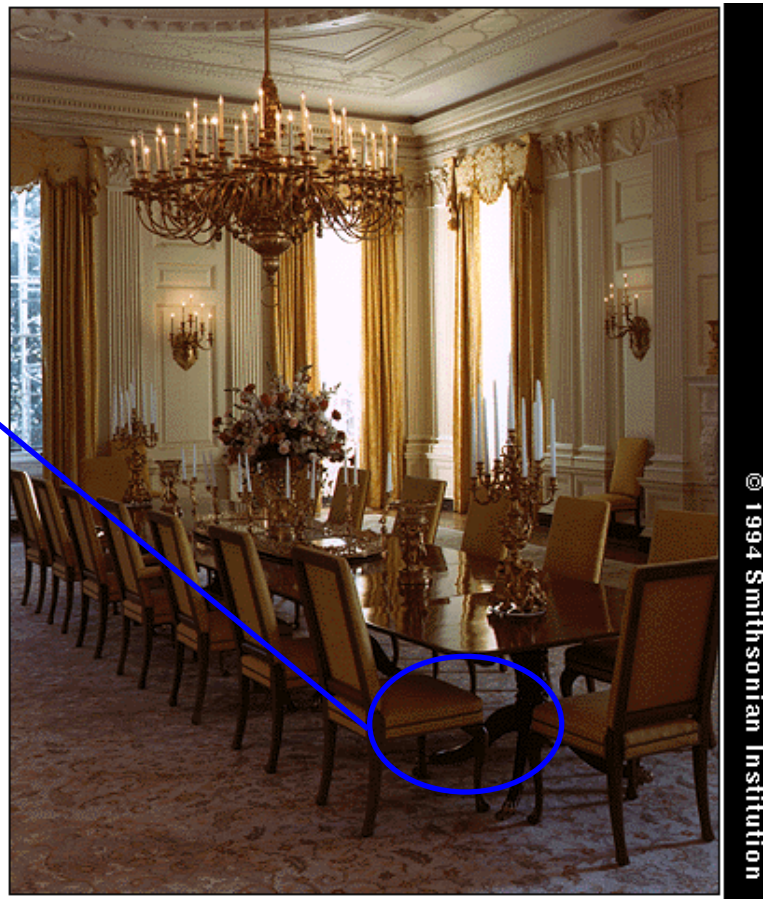


Ambient Term

Represents reflection of all indirect illumination

- Locations that are not directly illuminated are still not black because after light rays bounce around the scene, they eventually reach these positions.



This is a total hack (avoids complexity of global illumination)!

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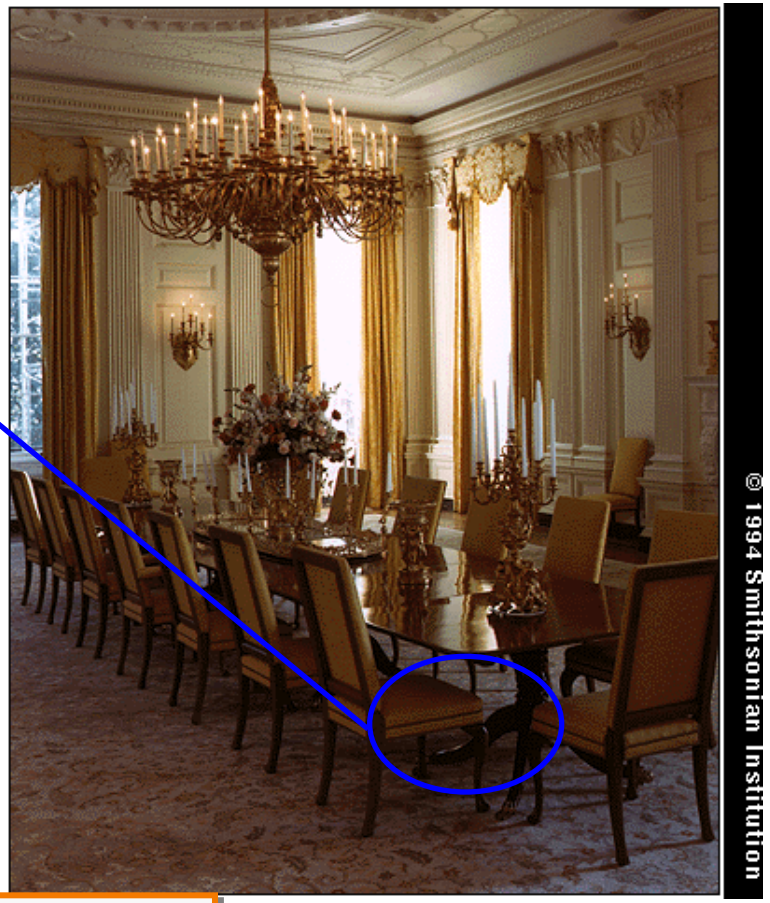

$$I_A = K_A I_{AL}$$

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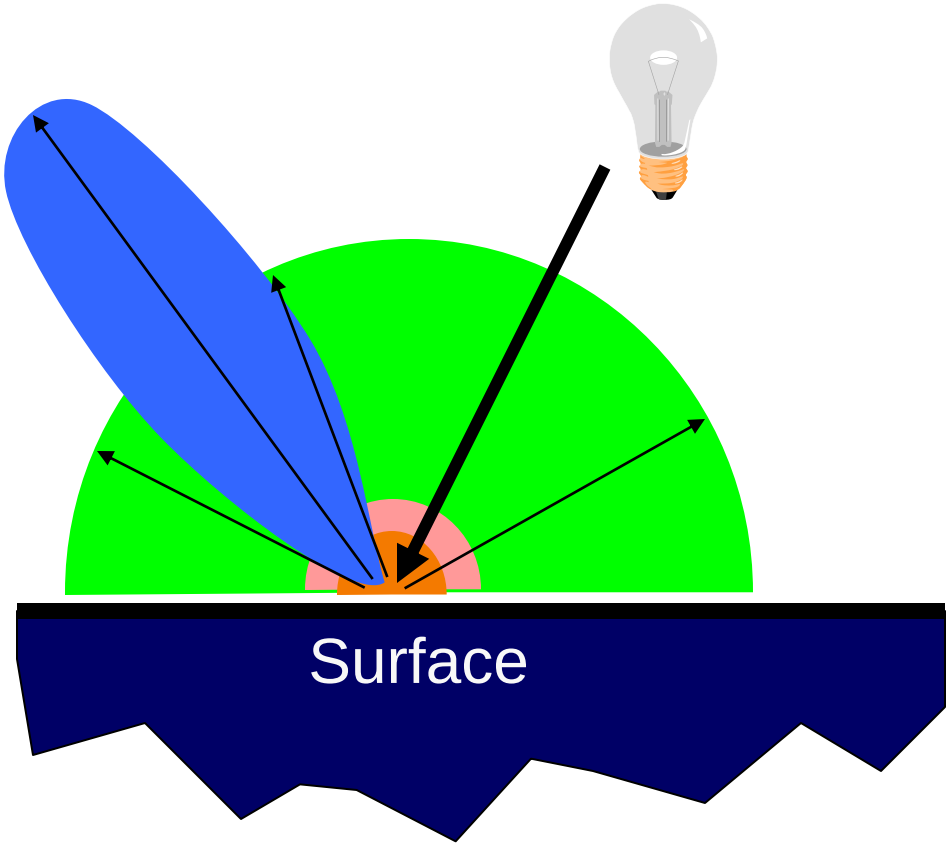

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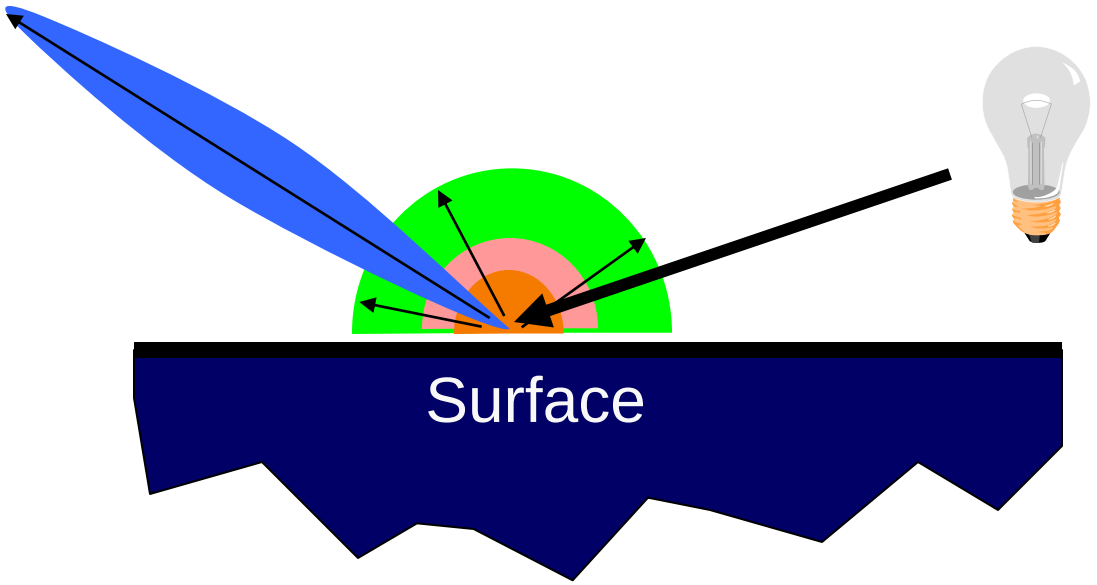
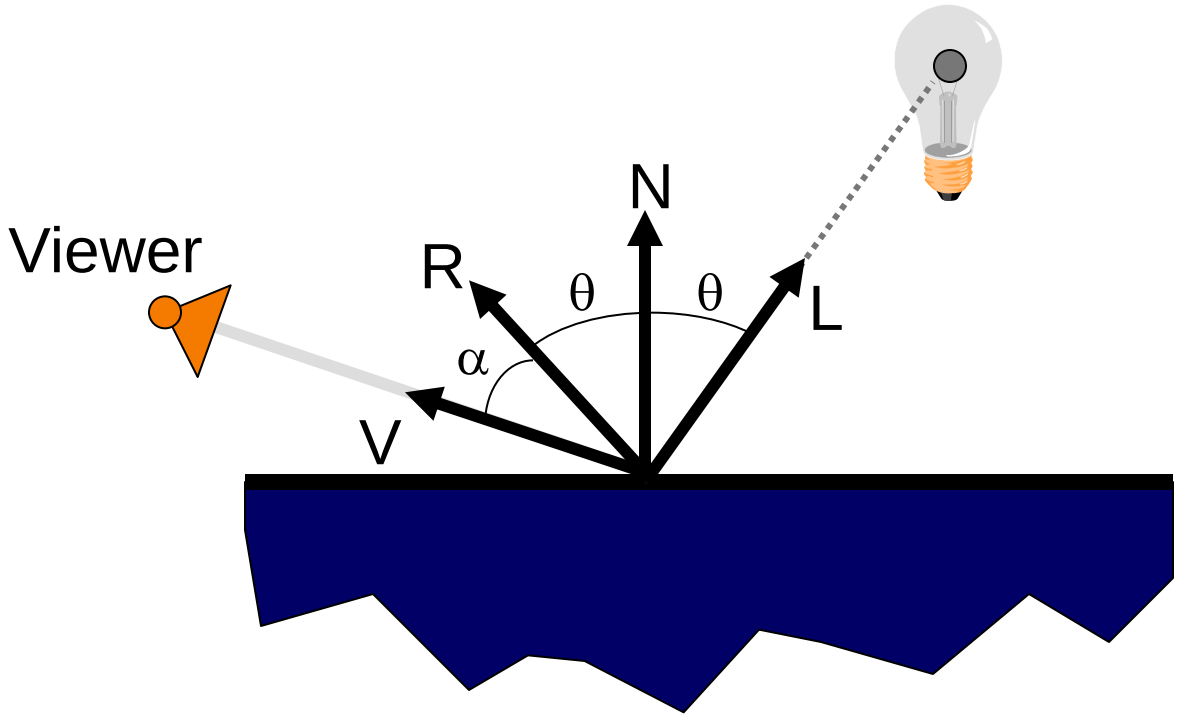


Surface Illumination Calculation

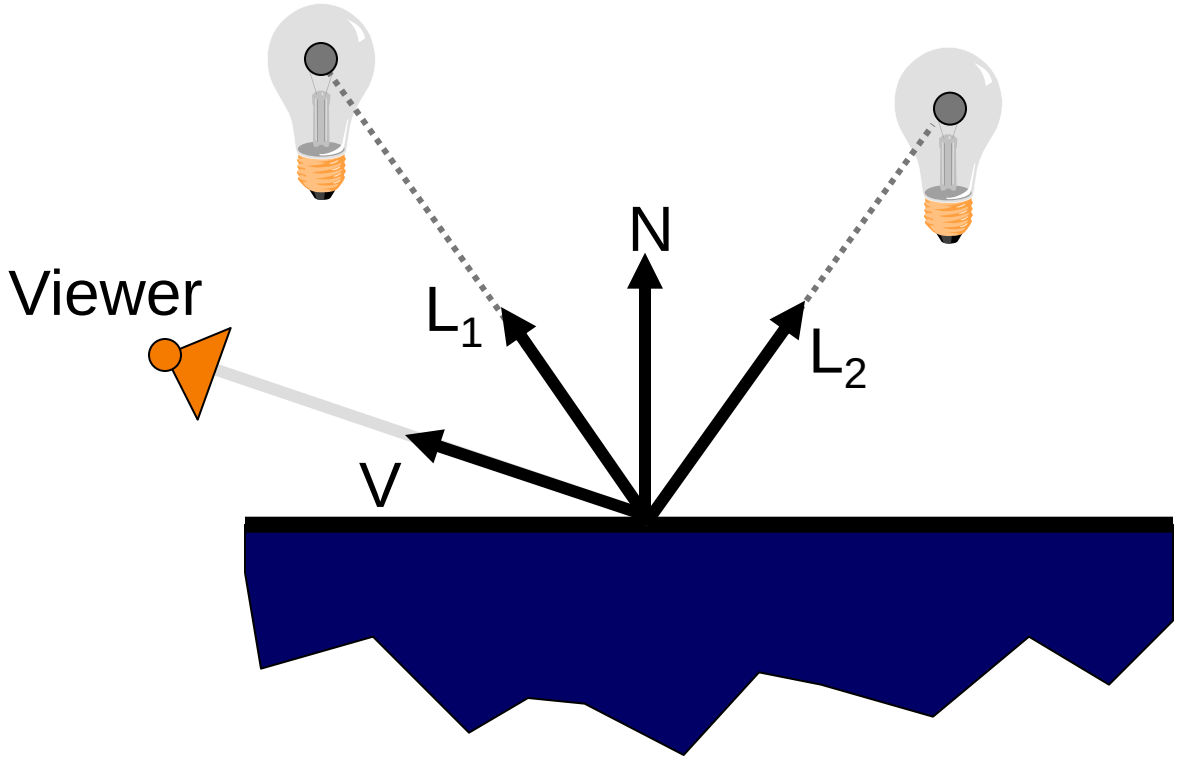
- Single light source :



$$I = I_E + K_A I_{AL} + K_D (N \bullet L) I_L + K_S (V \bullet R)^n I_L$$

Surface Illumination Calculation

- Multiple light sources:



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Shadows

- Shadow term tells if light sources are blocked
  - Cast ray towards each light source L_i. If the ray is blocked, do not consider the contribution of the light.

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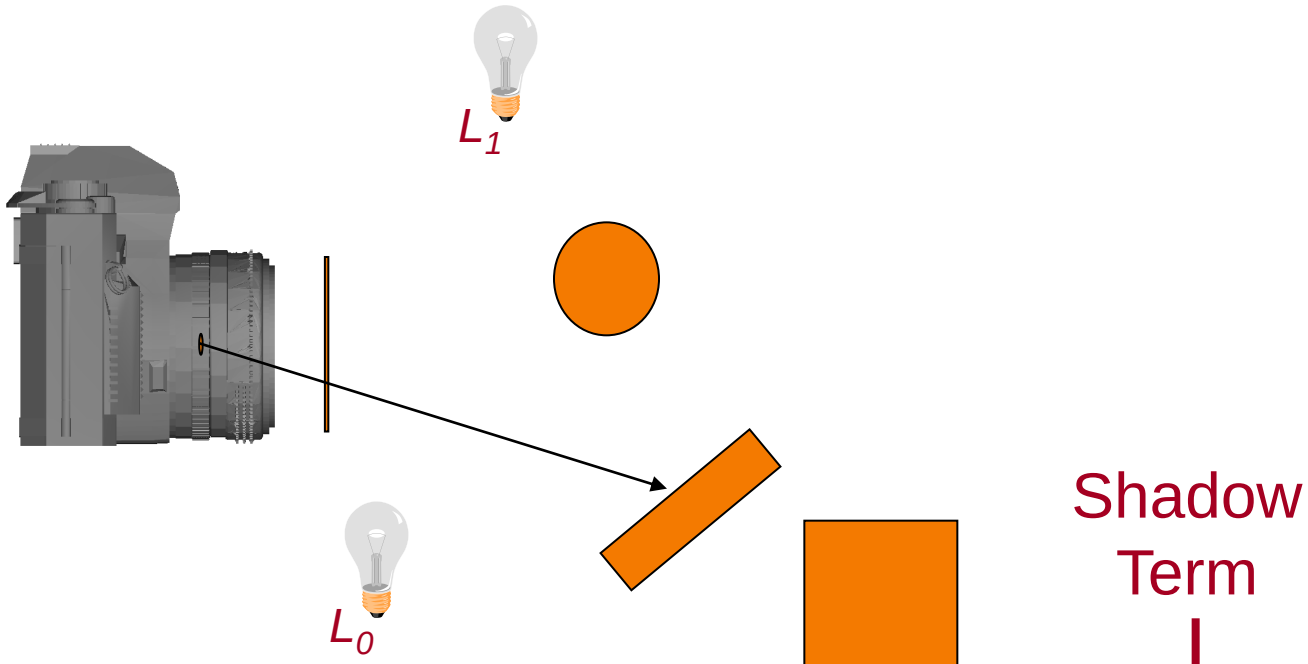

$$I = I_E + K_A I_A + \sum_L (K_D (N \bullet L) + K_S (V \bullet R)^n) I_L S_L$$

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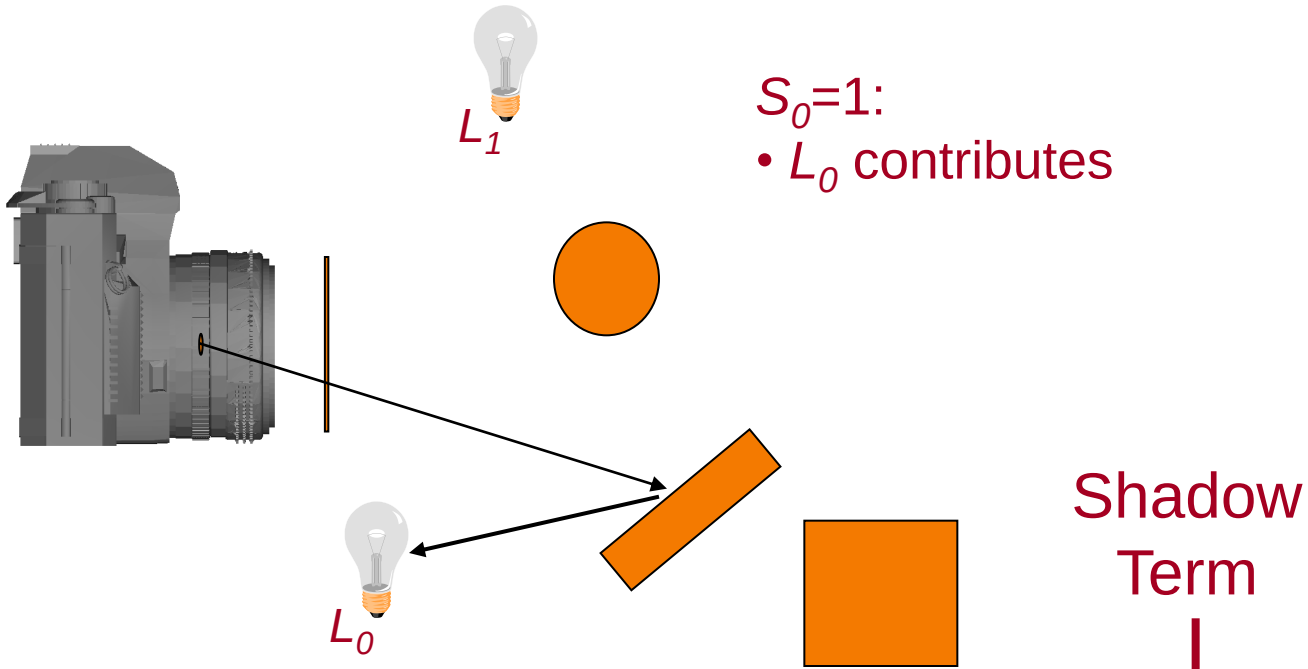

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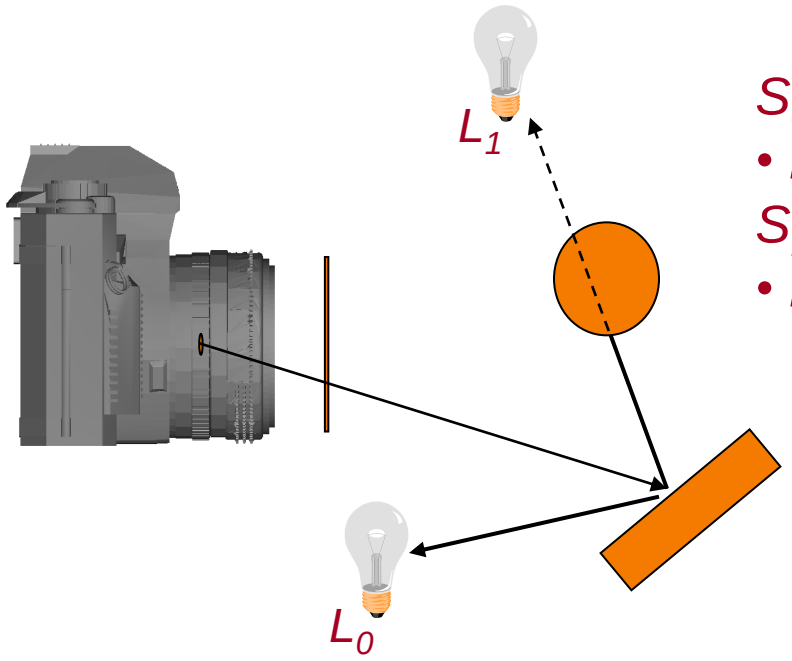

S_0=1:
- L_0 contributes

S_1=0:
- L_1 does not contribute

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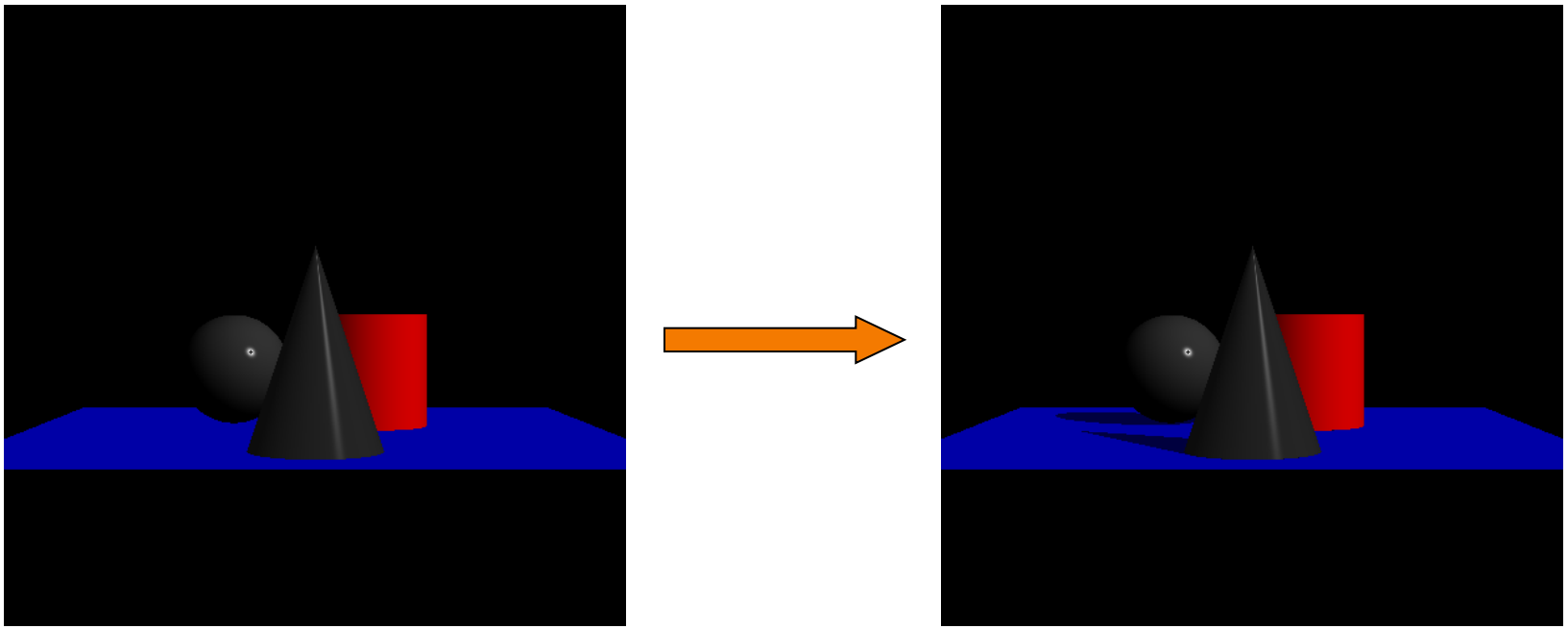
Ray Casting

- Trace primary rays from camera
  - Direct illumination from unblocked lights only



Recursive Ray Tracing

- Also trace secondary rays from hit surfaces
  - Consider contributions from:
    1. Reflected Rays
    2. Refracted Rays

Mirror Reflections

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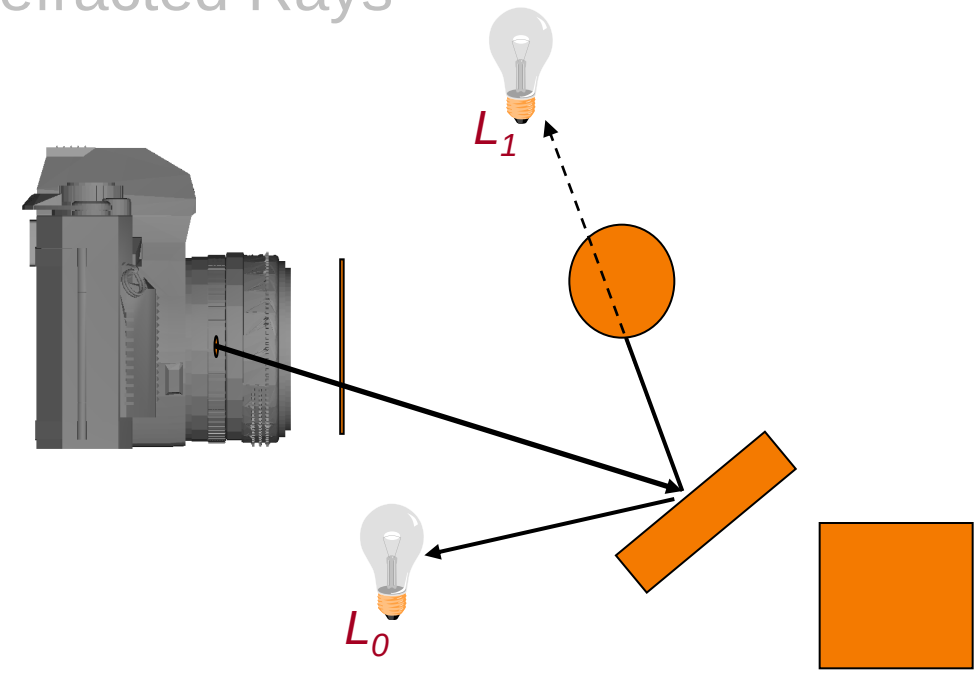

Radiance for mirror reflection ray

$$I = I_E + K_A I_A + \sum_L (K_D (N \bullet L) + K_S (V \bullet R)^n) I_L S_L + K_S I_R$$

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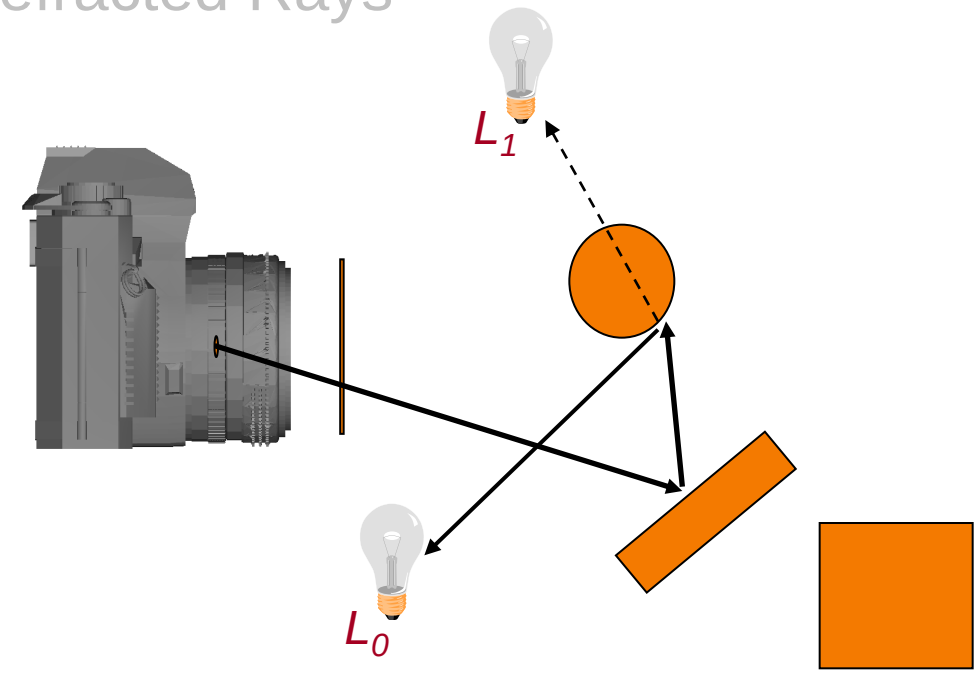

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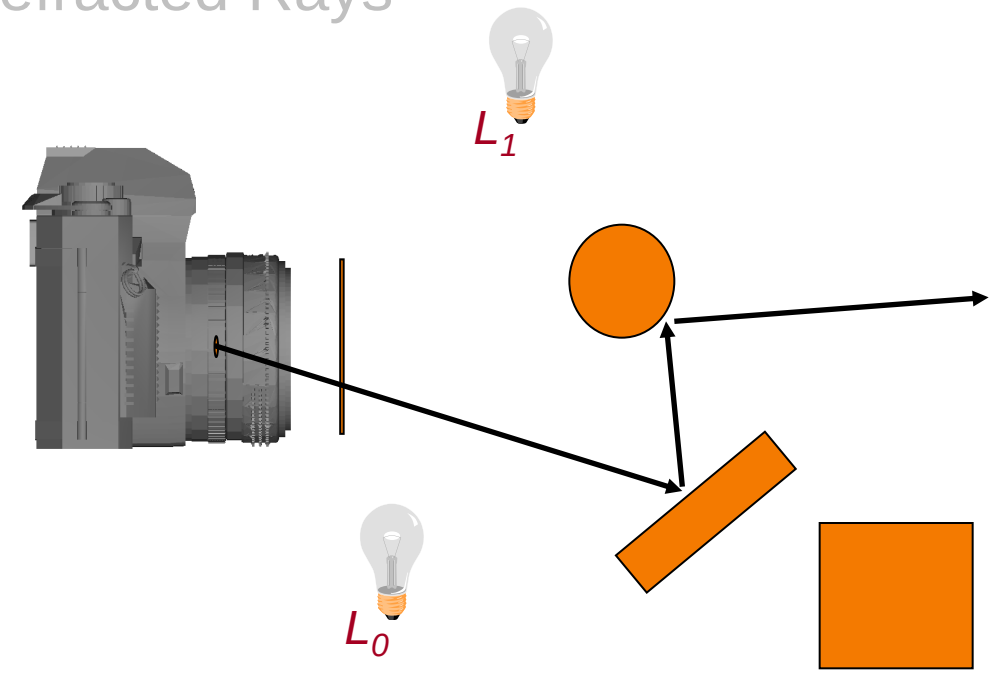

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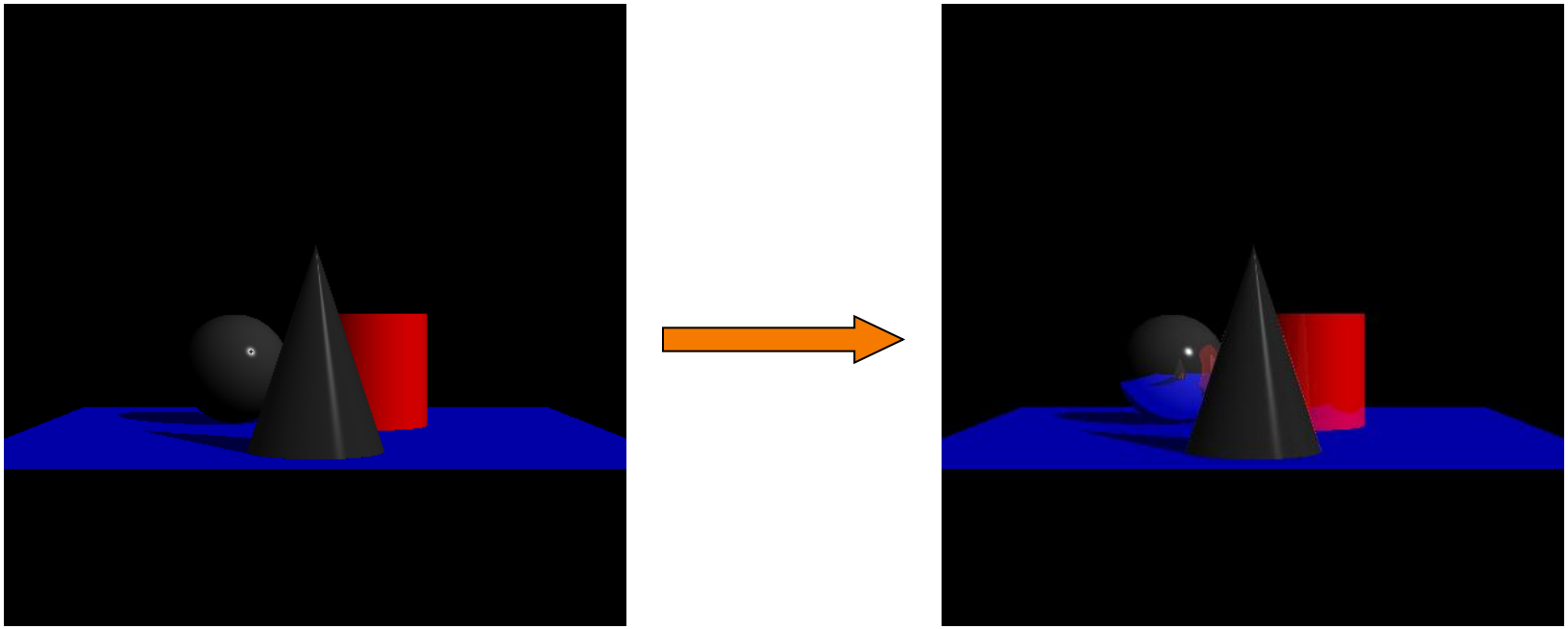
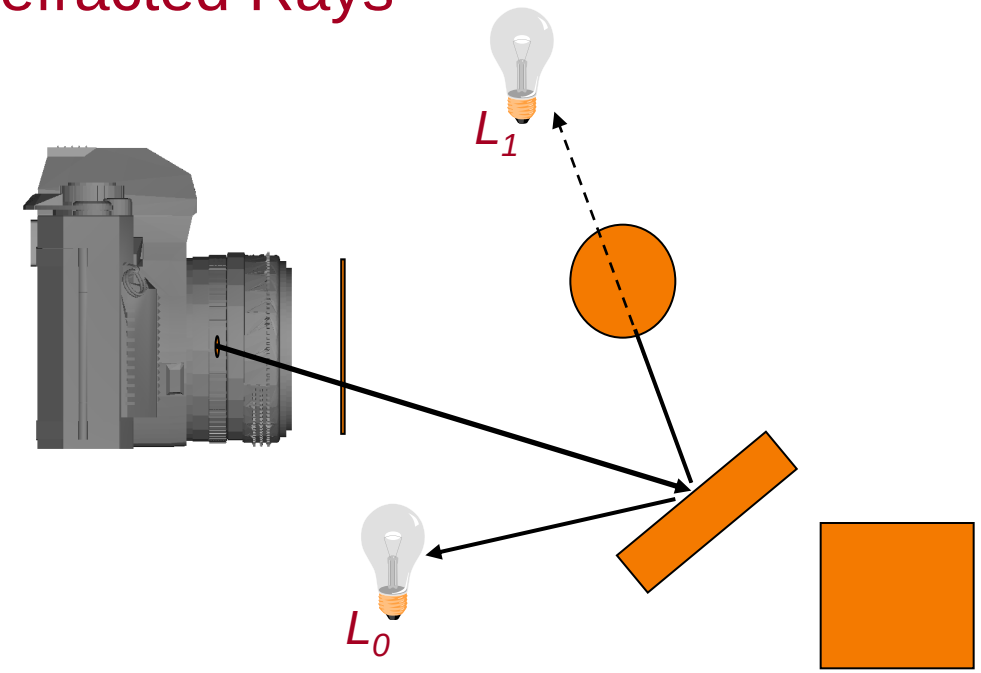


Transparent Refraction

- Also trace secondary rays from hit surfaces
  - Consider contributions from:
    1. Reflected Rays
    2. Refracted Rays



Radiance for refraction ray

$$I = I_E + K_A I_A + \sum_L (K_D (N \bullet L) + K_S (V \bullet R)^n) I_L S_L + K_S I_R + K_T I_T$$

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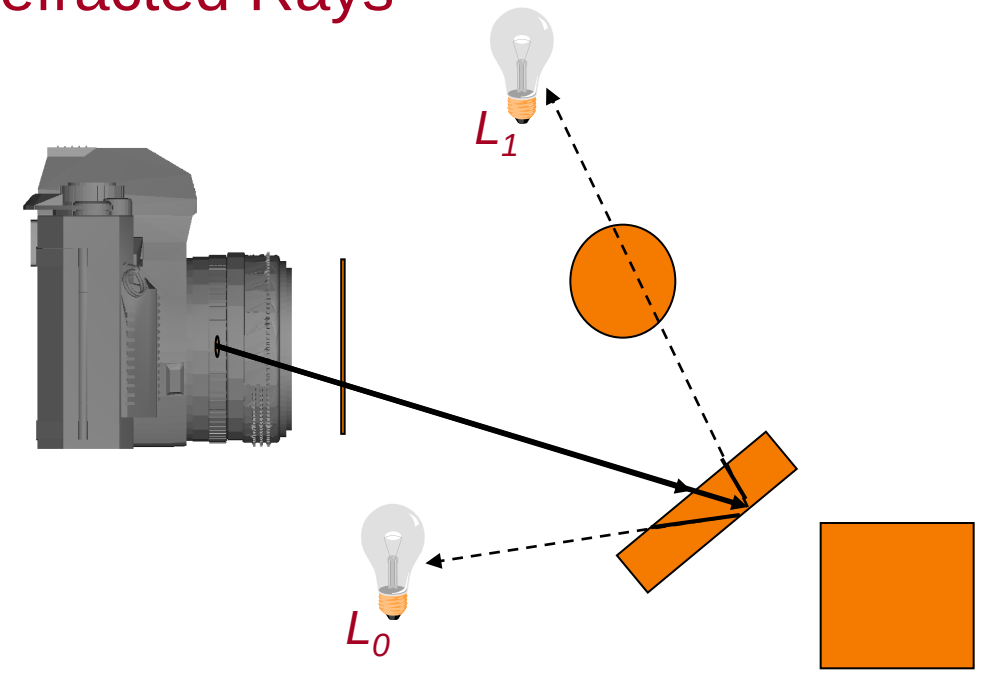

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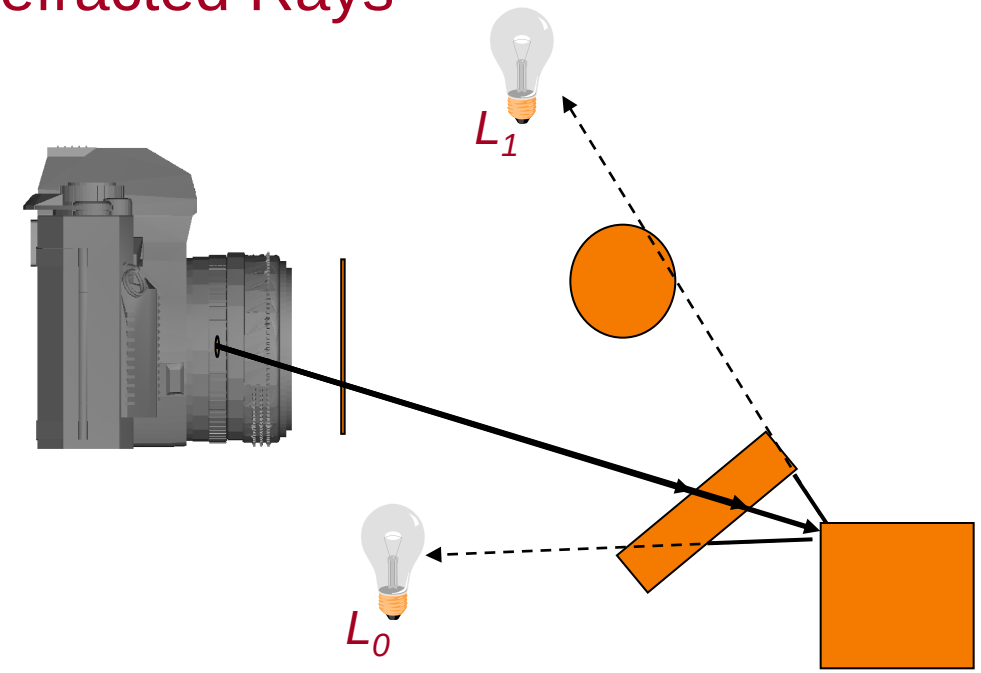

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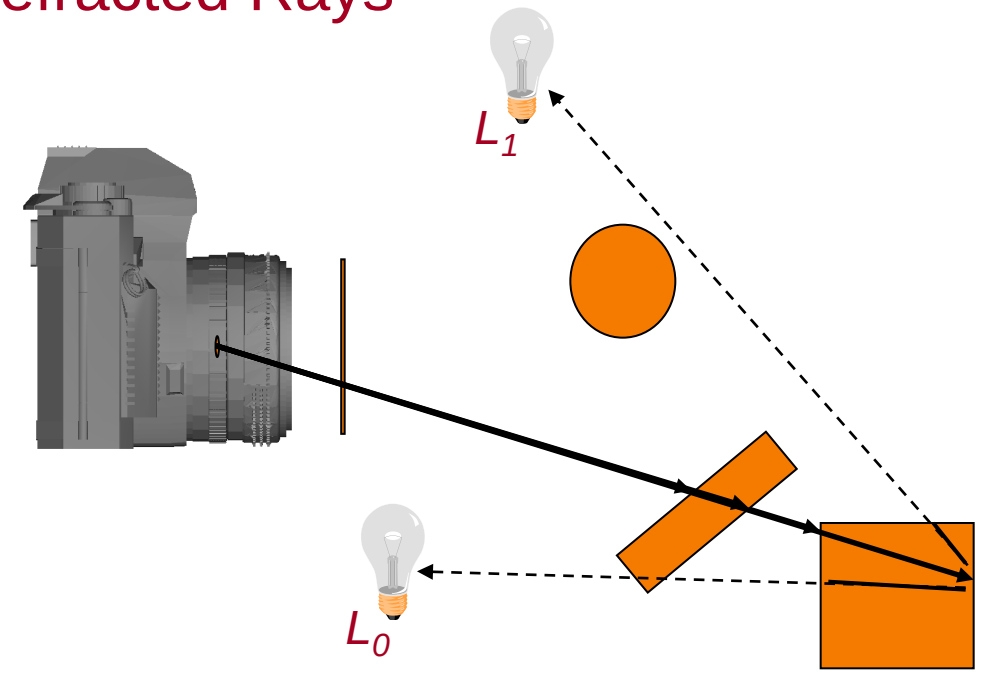

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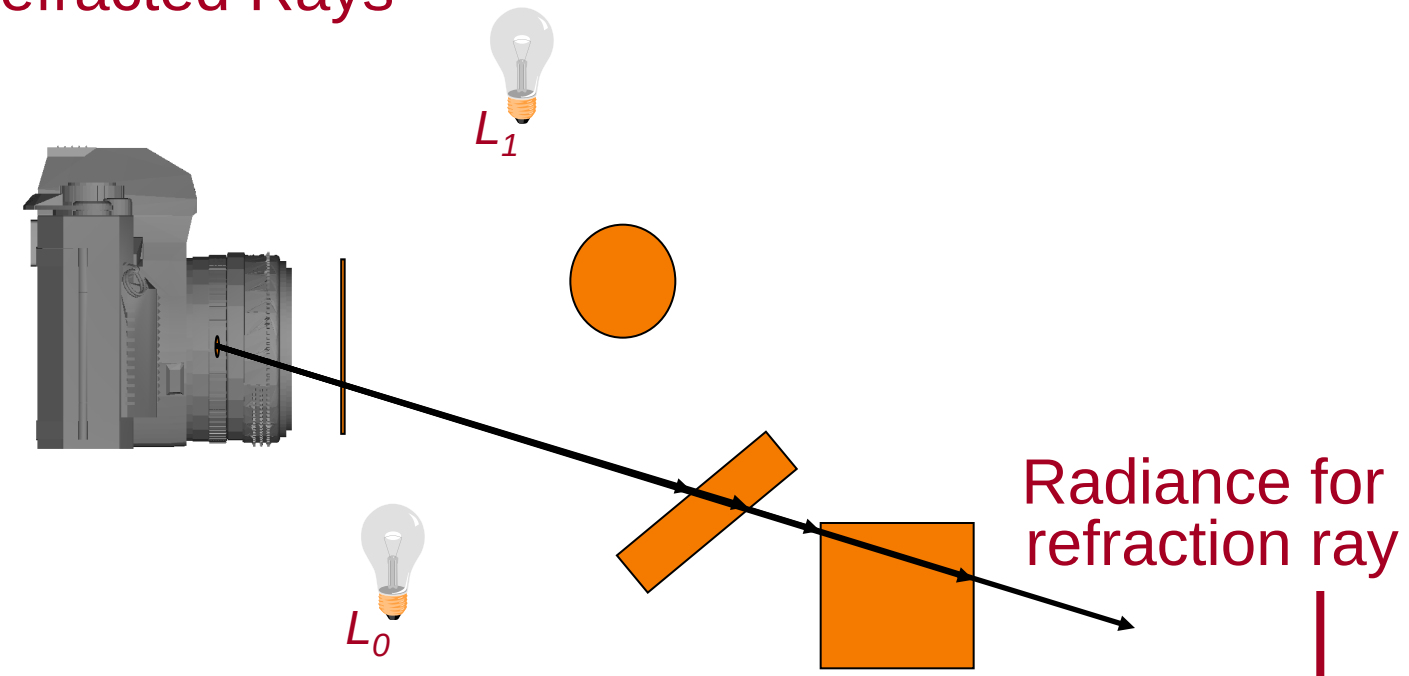

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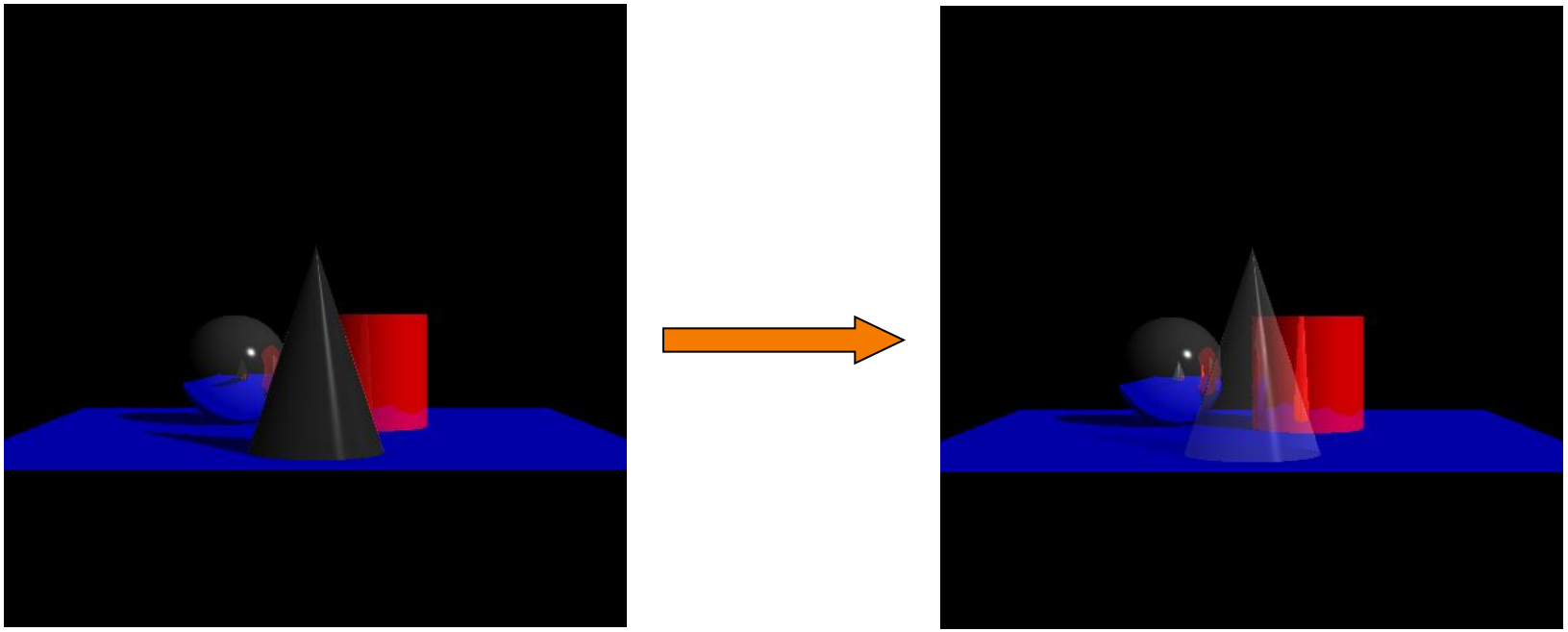
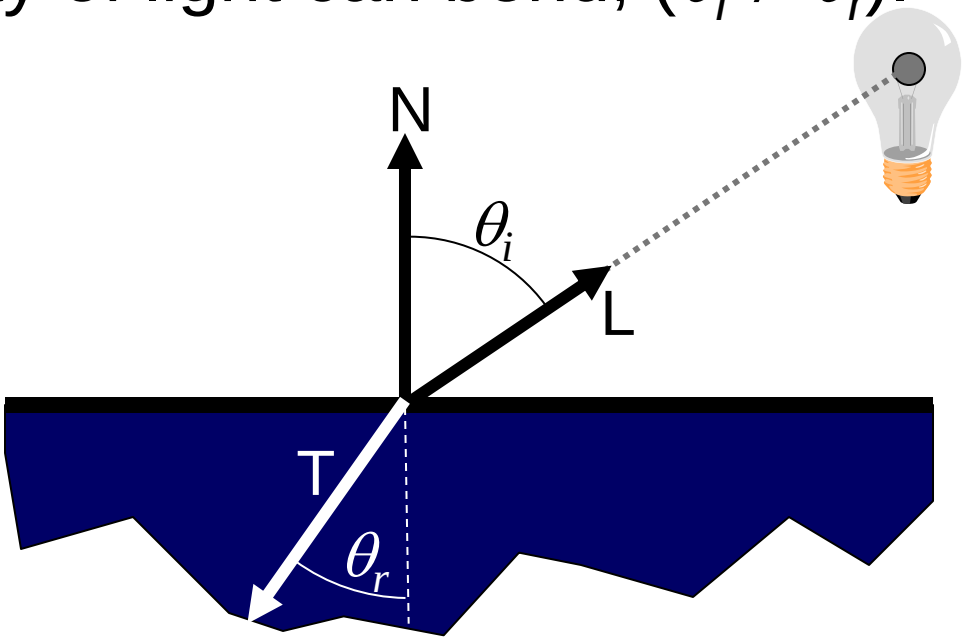


Transparent Refraction

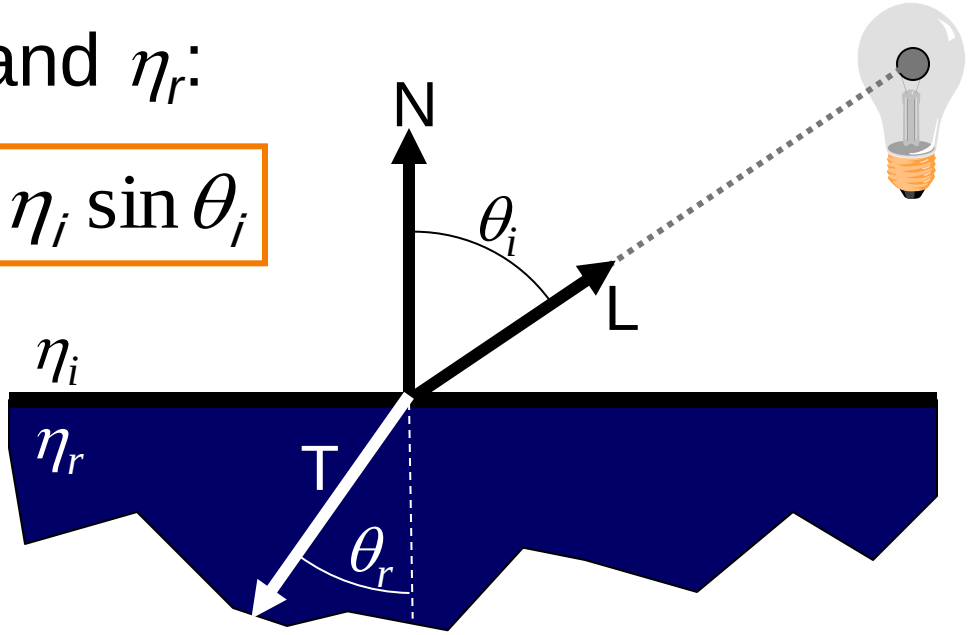
- When a light of light passes through a transparent object, the ray of light can bend, ($\theta_i \neq \theta_r$).



Snell's Law

- The way that light bends is determined by the indices of refraction of the internal and external materials η_i and η_r:

$$\eta_r \sin\theta_r = \eta_i \sin\theta_i$$



The index of refraction of air is η=1.

Snell's Law

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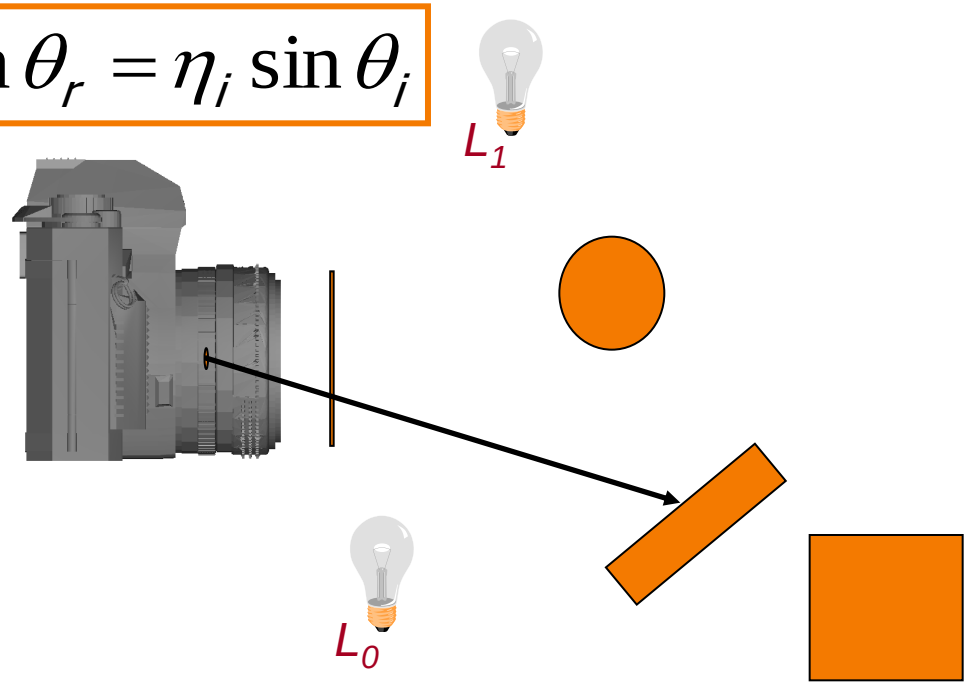

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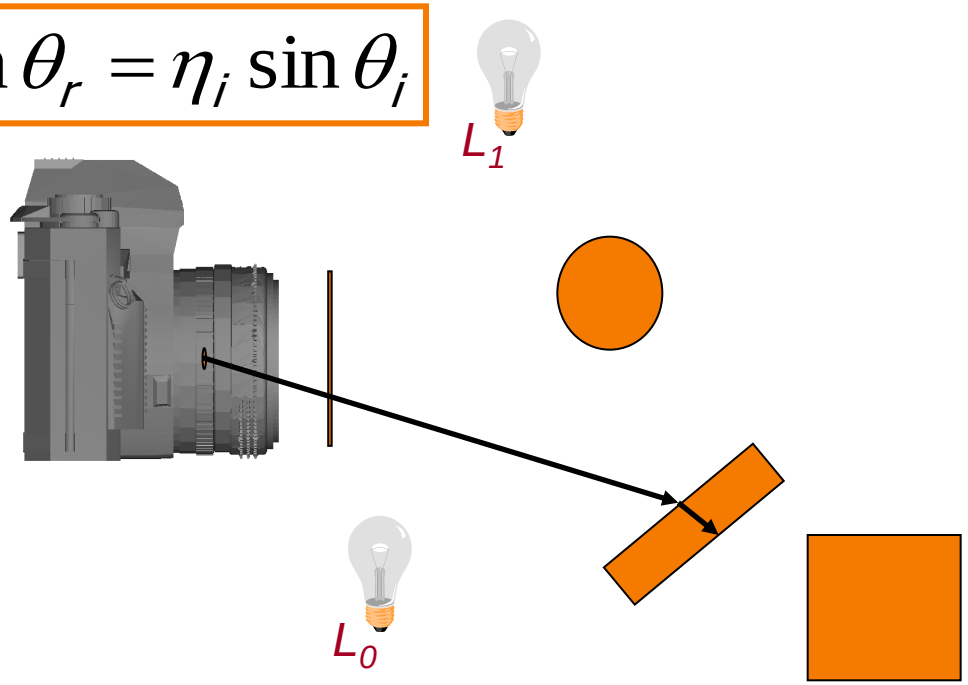

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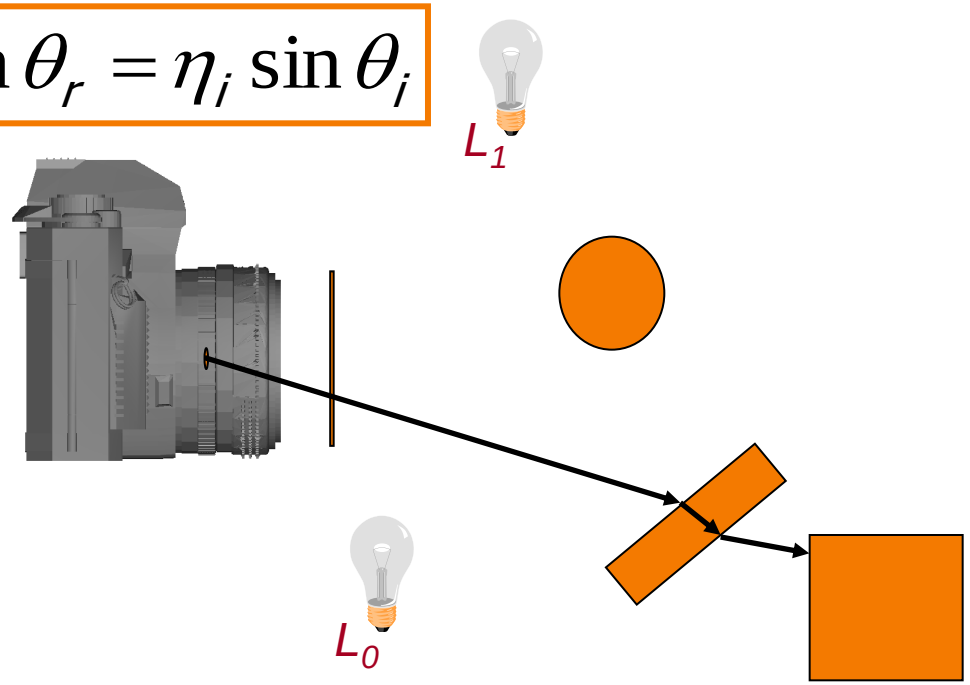

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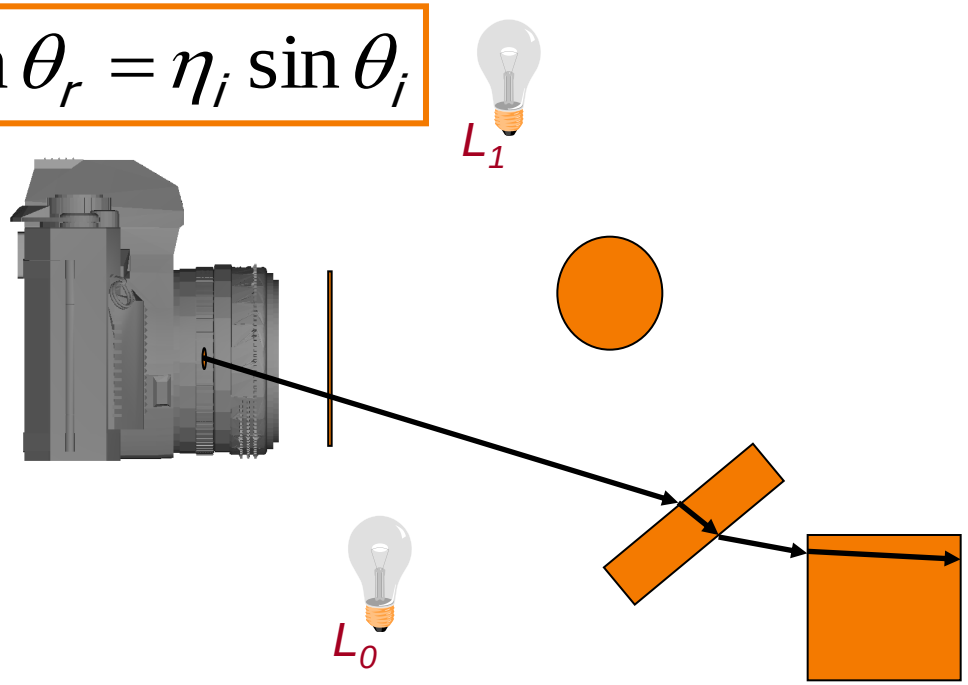

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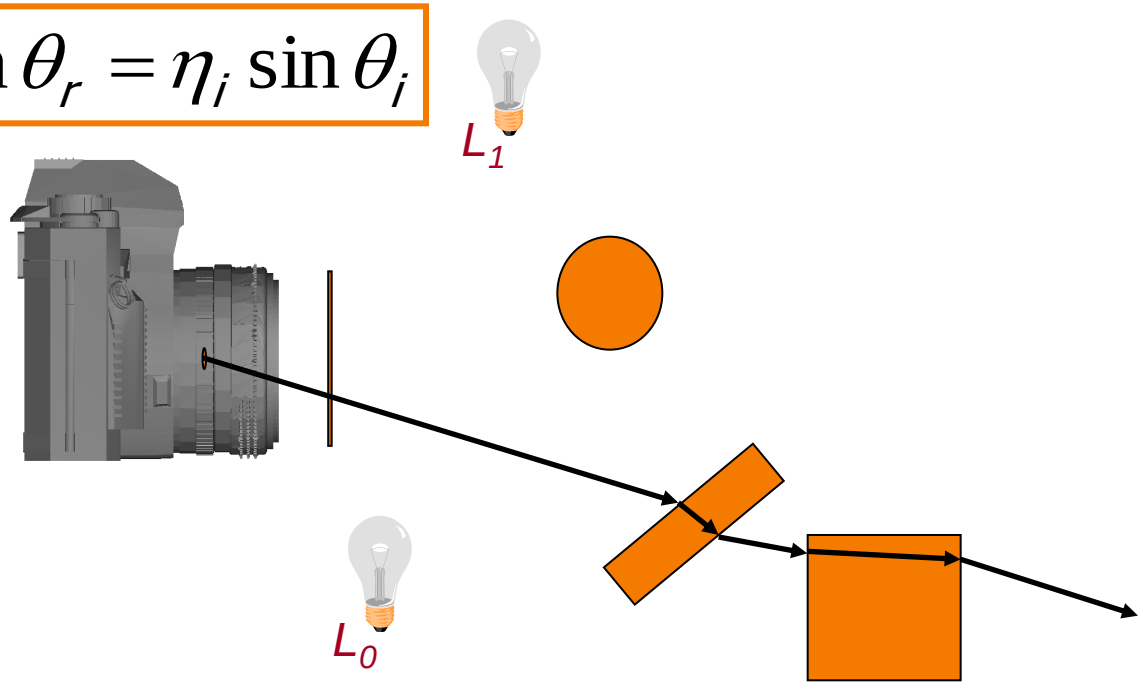

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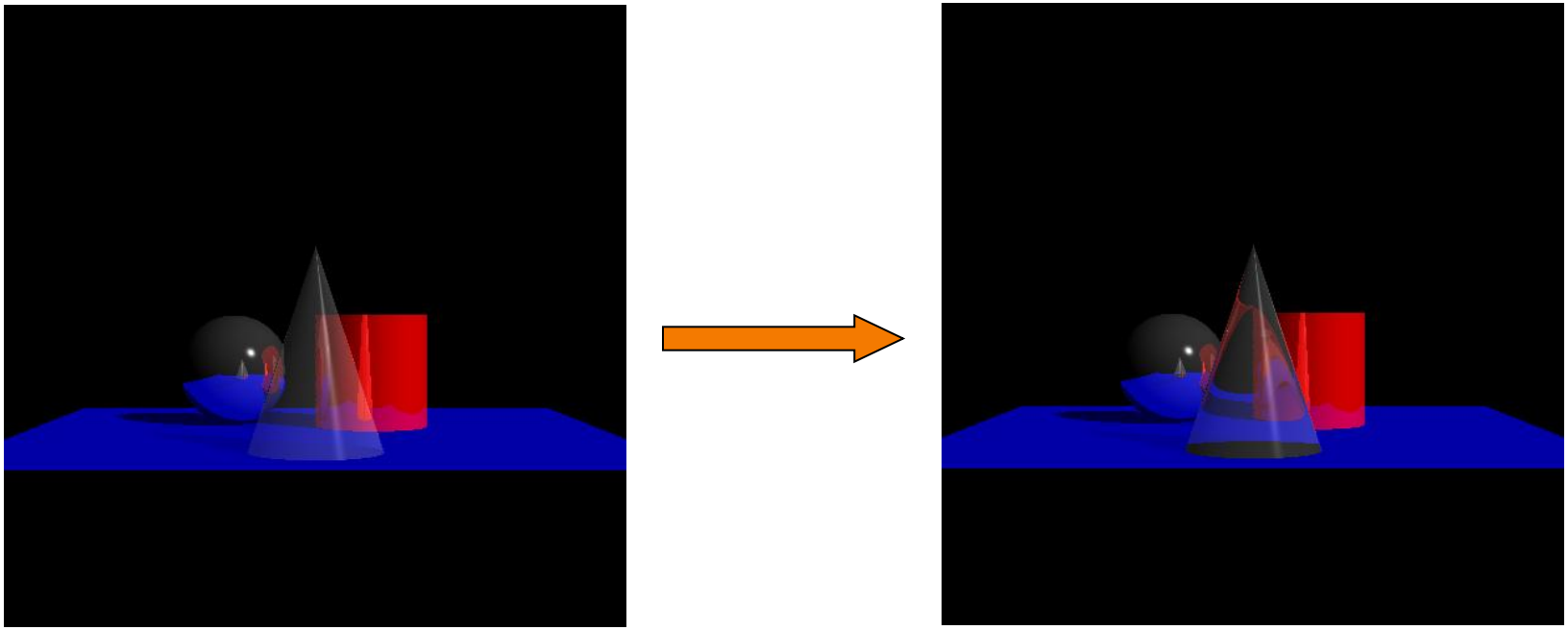
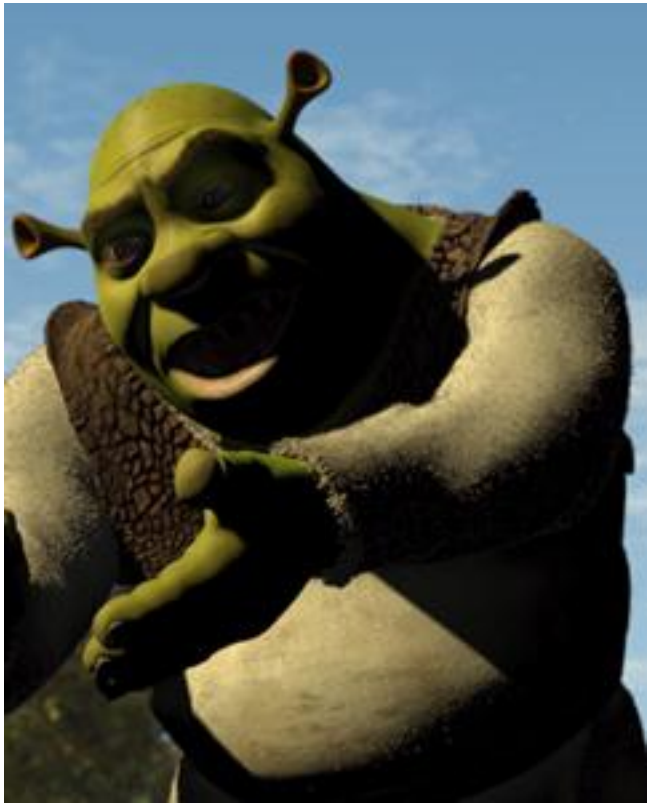


Summary

- Ray casting (direct illumination)
  - Usually use simple analytic approximations for light source emission and surface reflectance
- Recursive ray tracing (global illumination)
  - Incorporate shadows, mirror reflections, and pure refractions

All of this is an approximation so that it is practical to compute

Summary



direct illumination

global illumination

Global illumination makes a big difference!

PDI/Dreamworks