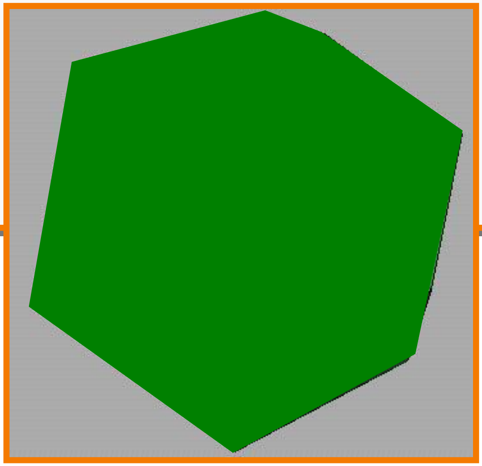
Lighting and Reflectance

COS 426

Ray Casting

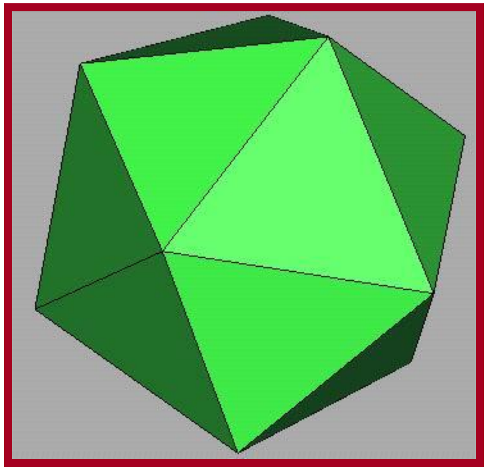
```
R2Image *RayCast(R3Scene *scene, int width, int height)
{
    R2Image *image = new R2Image(width, height);
    for (int i = 0; i < width; i++) {
        for (int j = 0; j < height; j++) {
            R3Ray ray = ConstructRayThroughPixel(scene->camera, i, j);
            R3Rgb radiance = ComputeRadiance(scene,  &ray);
            image->SetPixel(i, j, radiance);
        }
    }
    return image;
}
```



Without Illumination

Ray Casting

```
R3Rgb ComputeRadiance(R3Scene *scene, R3Ray *ray)
{
    R3Intersection intersection = ComputeIntersection(scene, ray);
    return ComputeRadiance(scene, ray, intersection);
}
```

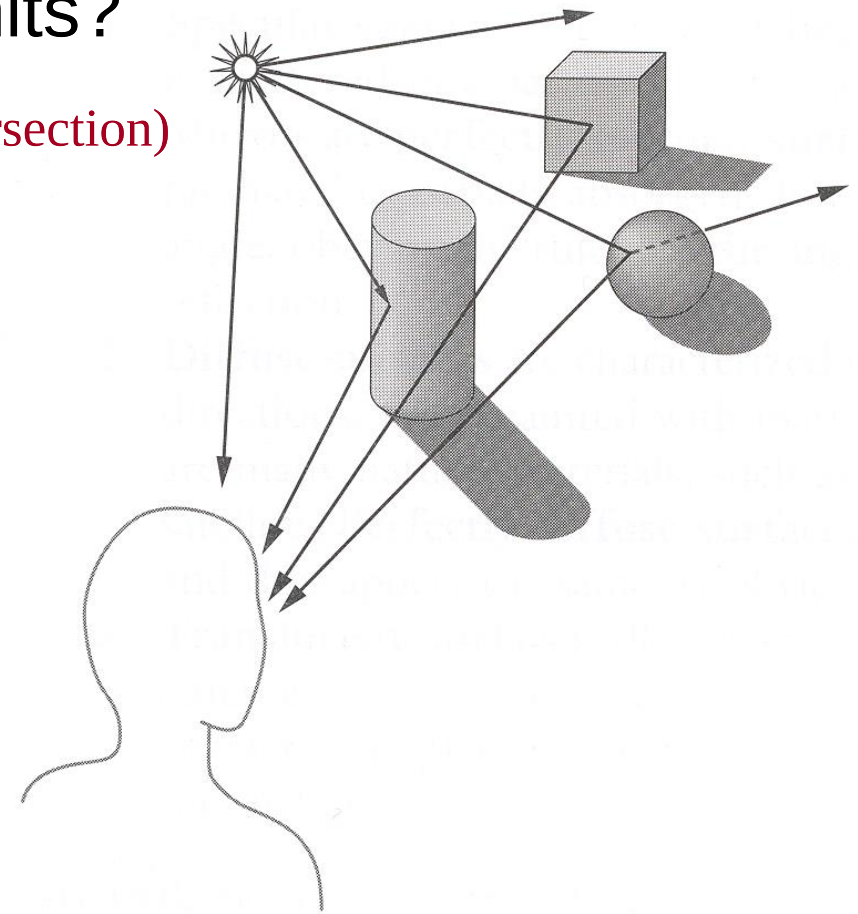


With Illumination

Illumination

- How do we compute radiance for a sample ray once we know what it hits?

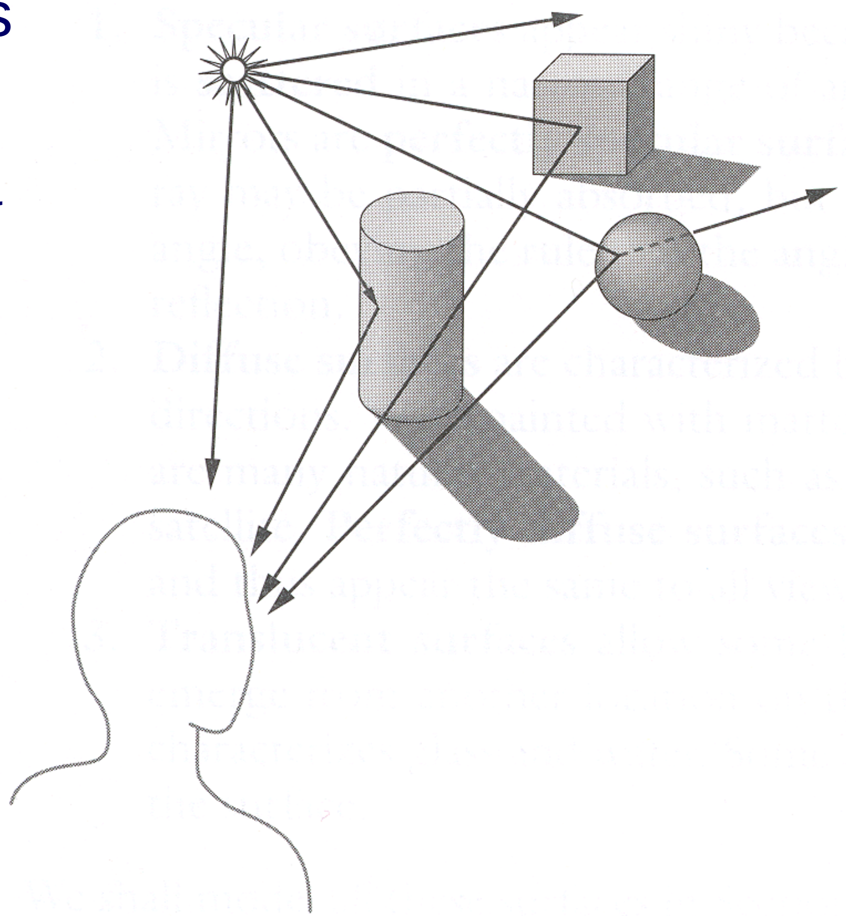
ComputeRadiance(scene, ray, intersection)



Angel Figure 6.2

Goal

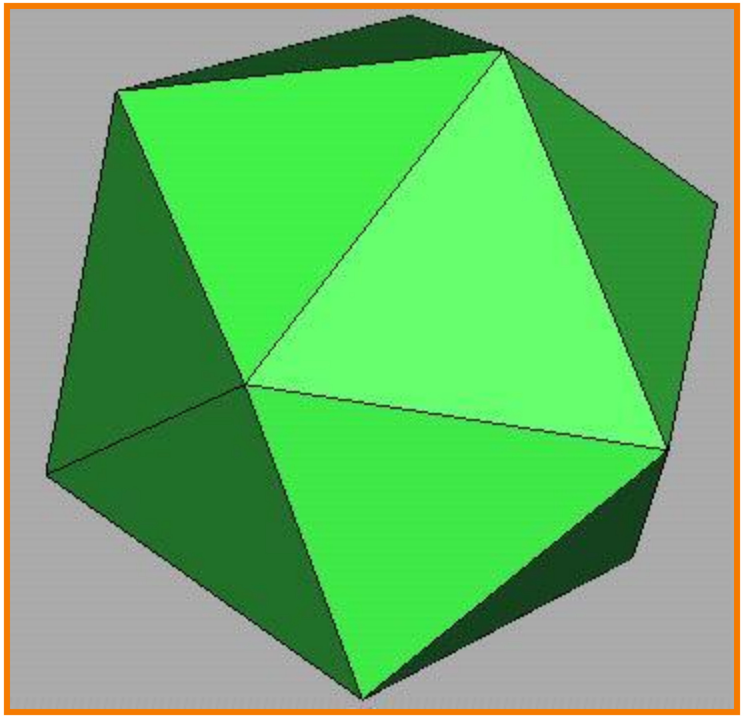
- Must derive computer models for ...
  - Emission at light sources
  - Scattering at surfaces
  - Reception at the camera



- Desirable features …
  - Concise
  - Efficient to compute
  - “Accurate”

Overview

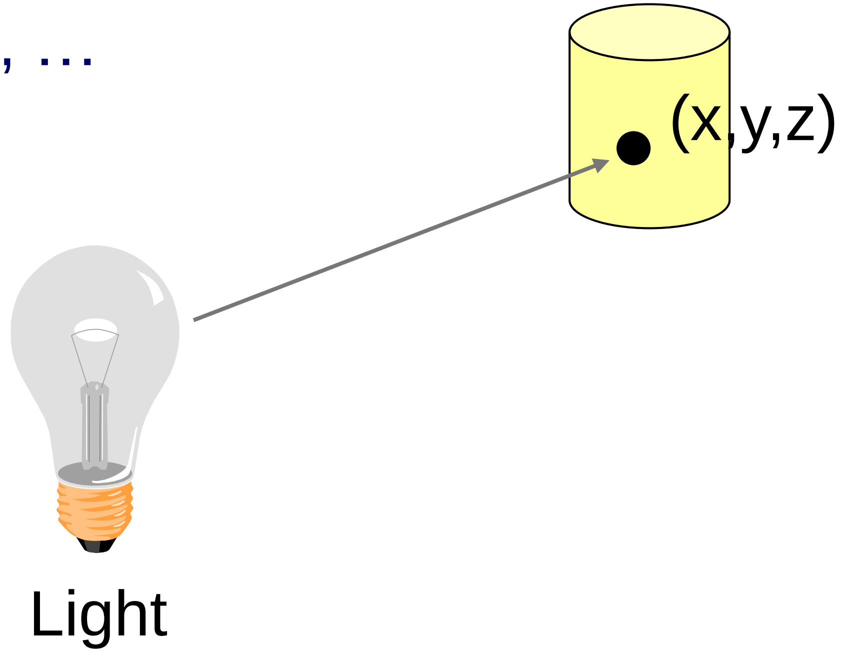
- Direct Illumination
  - Emission at light sources
  - Scattering at surfaces
- Global illumination
  - Shadows
  - Refractions
  - Inter-object reflections



Direct Illumination

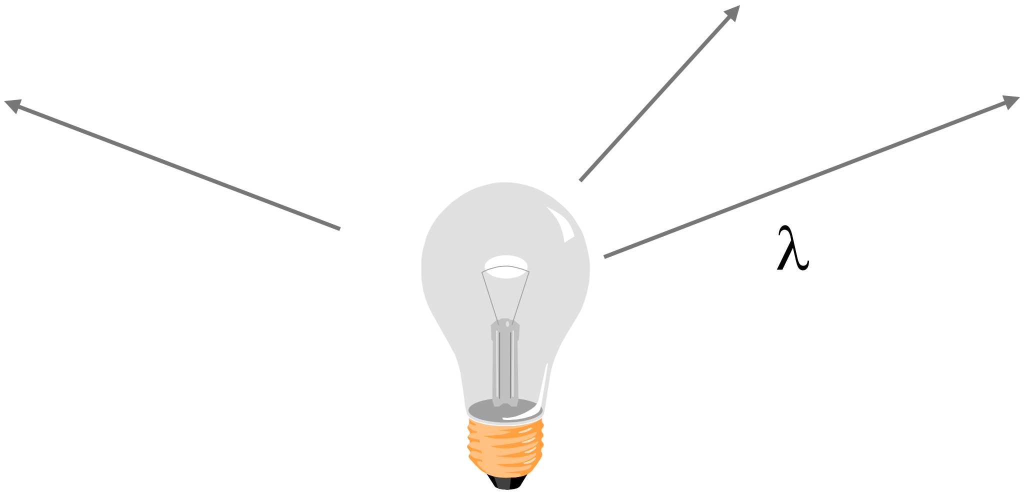
Emission at Light Sources

- "Radiance" of light emitted by a source (or reflected from another surface)
- "Irradiance" $I_L(x,y,z,\theta,\phi,\lambda)$ incident on a surface
  - describes power (energy per unit time) …
  - arriving at location(x,y,z), …
  - from direction (θ,ϕ), …
  - with wavelength λ



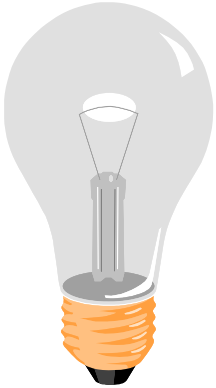
Empirical Models

- Ideally measure radiant energy for “all” situations
    - Too much storage
    - Difficult in practice



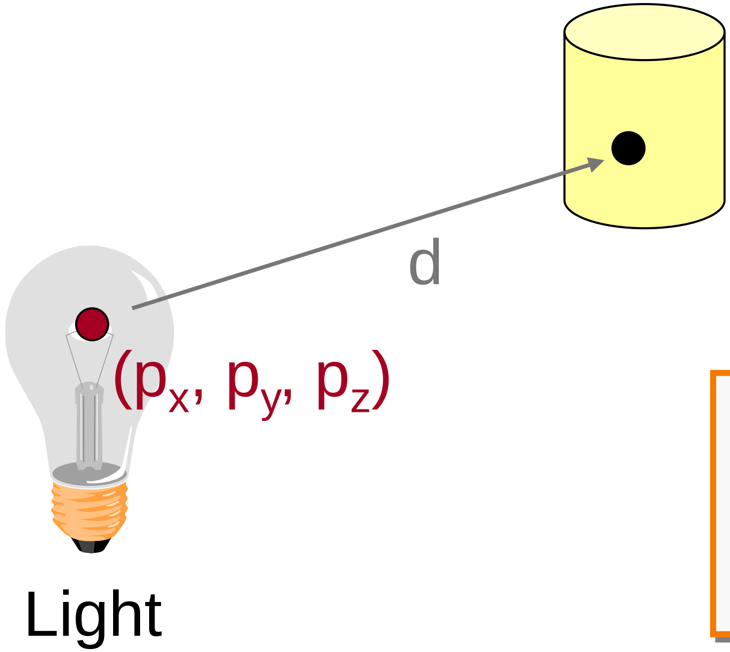
OpenGL Light Source Models

- Simple mathematical models:
  - Point light
  - Spot light
  - Directional light



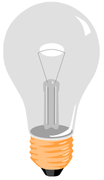
Point Light Source

- Models omni-directional point source
  - intensity (I_0),
  - position (p_x, p_y, p_z),
  - coefficients (c_a, l_a, q_a) for attenuation with distance (d)



$$I_L = \frac{I_0}{c_a + l_a d + q_a d^2}$$

Point Light Source

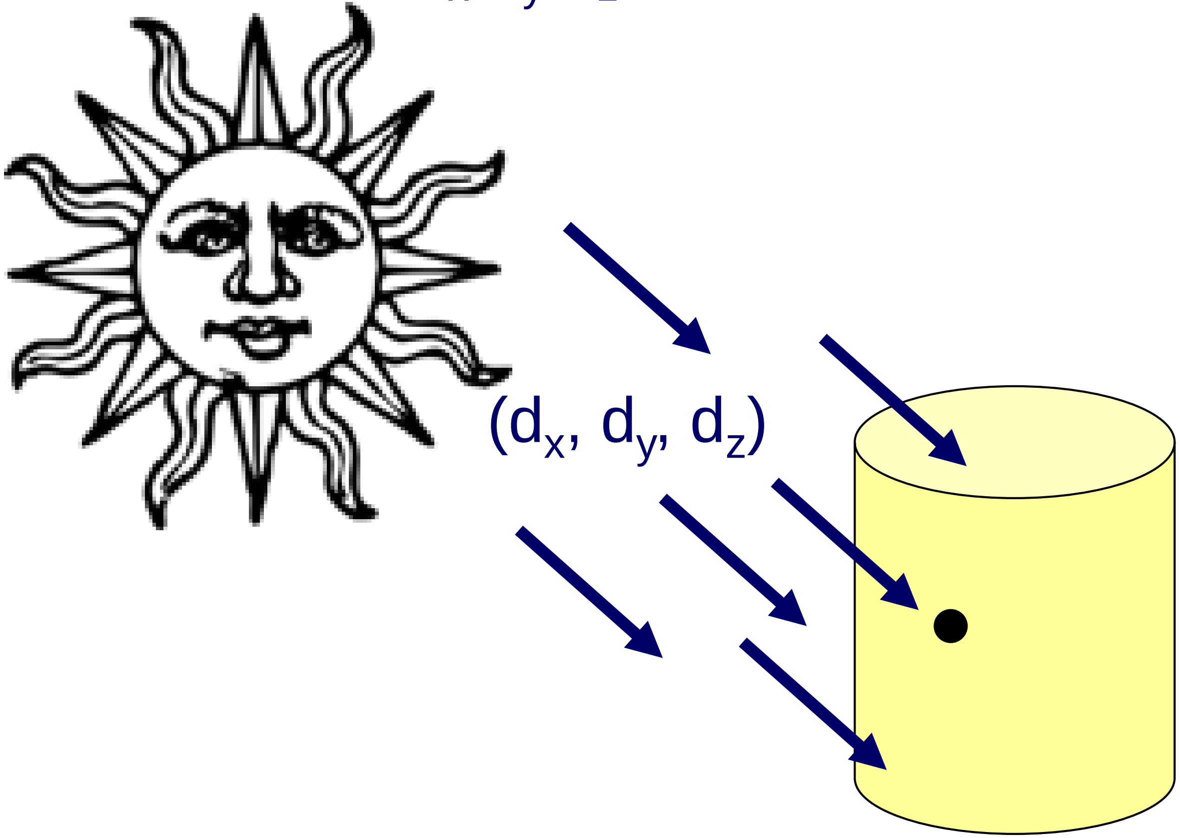


$$I_L = \frac{I_0}{c_a + l_a d + q_a d^2}$$

- Physically-based: “inverse square law”
  - $c_a = l_a = 0$
- Use c_a and $l_a \neq 0$ for (non-physical) artistic effects

Directional Light Source

- Models point light source at infinity
  - intensity (I_0),
  - direction (d_x,d_y,d_z)

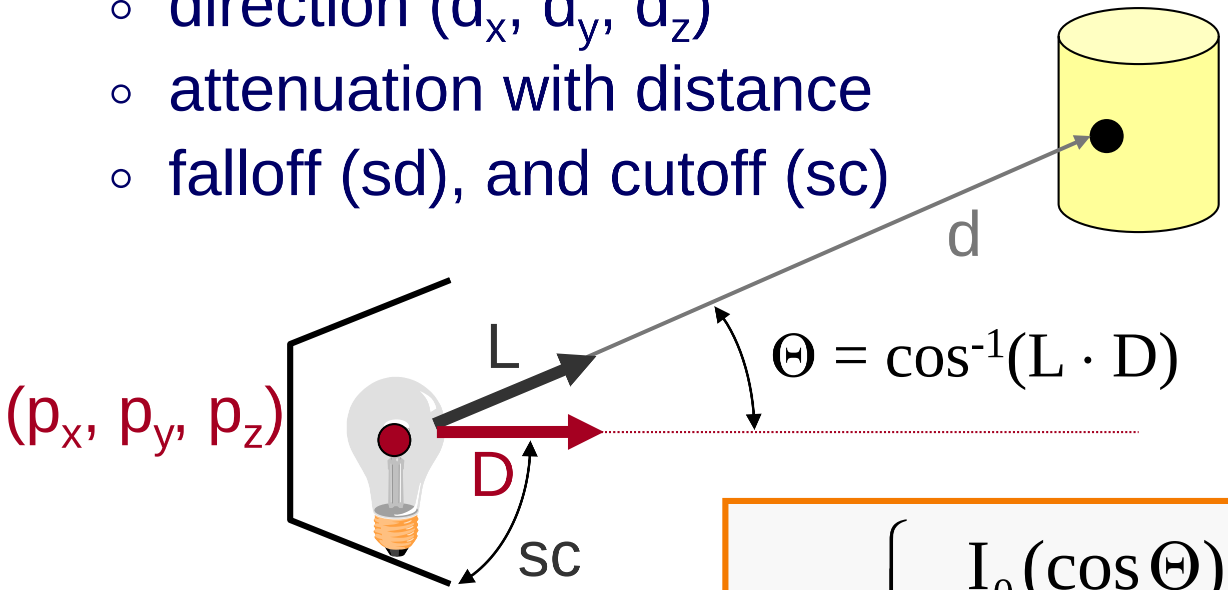


No attenuation with distance

$$I_L = I_0$$

Spot Light Source

- Models point light source with direction
  - intensity (I_0),
  - position (p_x, p_y, p_z),
  - direction (d_x, d_y, d_z)
  - attenuation with distance
  - falloff (sd), and cutoff (sc)

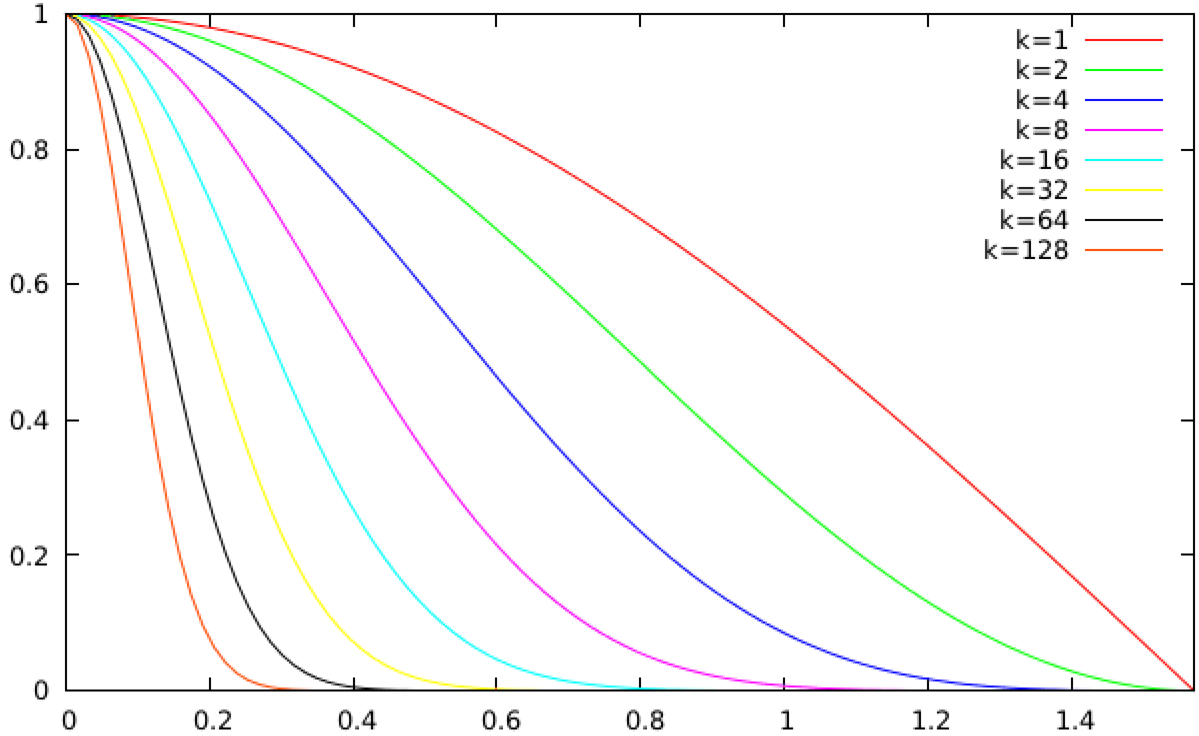


$$I_L = \begin{cases} \dfrac{I_0(\cos\Theta)^{sd}}{c_a + l_a d + q_a d^2} & \text{if } \Theta \le sc, \\ 0 & \text{otherwise} \end{cases}$$

Cosine Lobes

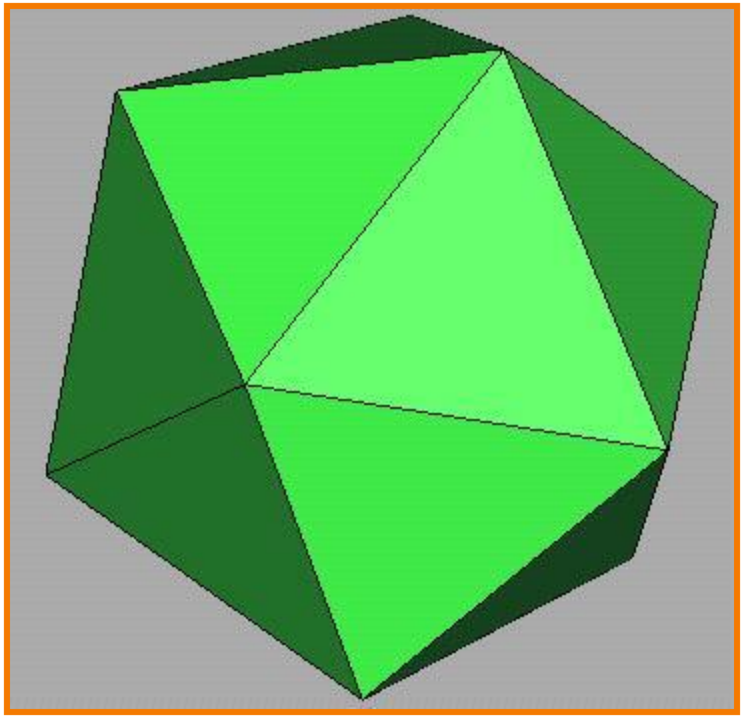
$$(\cos\Theta)^k$$

- Common model for “blob” at origin



Overview

- Direct Illumination
  - Emission at light sources
  - Scattering at surfaces
- Global illumination
  - Shadows
  - Refractions
  - Inter-object reflections



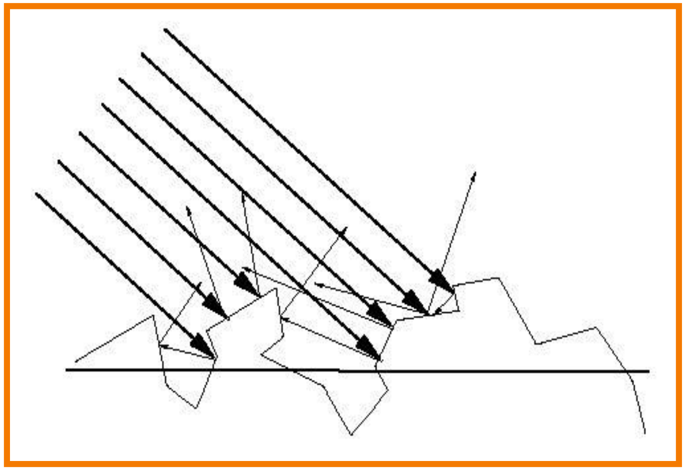
Direct Illumination

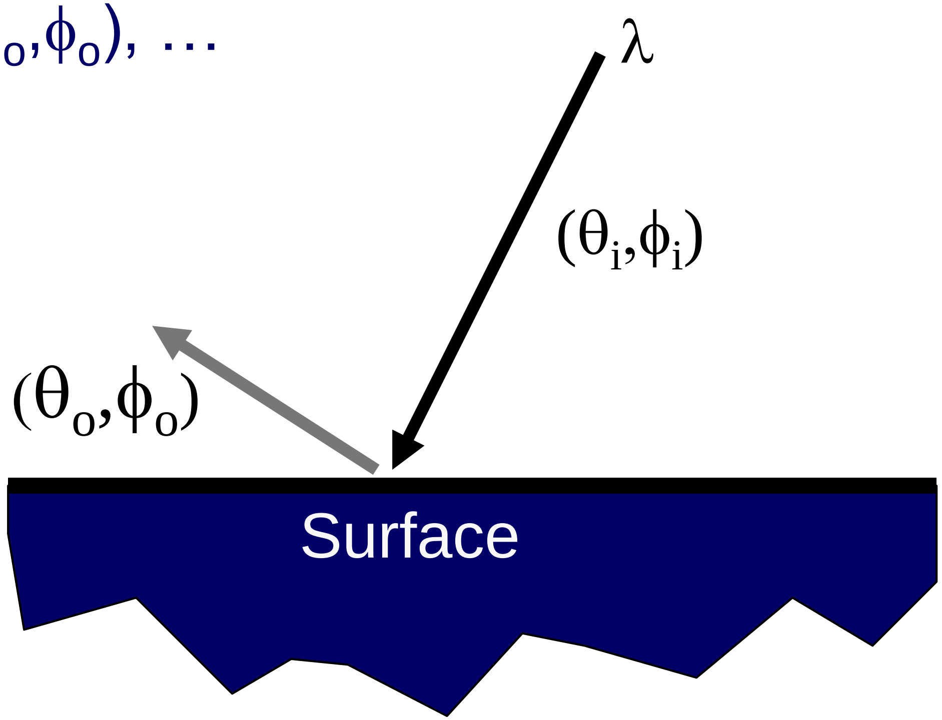
Scattering at Surfaces

Bidirectional **R**eflectance **D**istribution **F**unction

$f_r(\theta_i,\phi_i,\theta_o,\phi_o,\lambda)$ ...

- describes the aggregate fraction of incident energy,
- arriving from direction (θ_i,ϕ_i), ...
- leaving in direction (θ_o,ϕ_o), …
- with wavelength λ

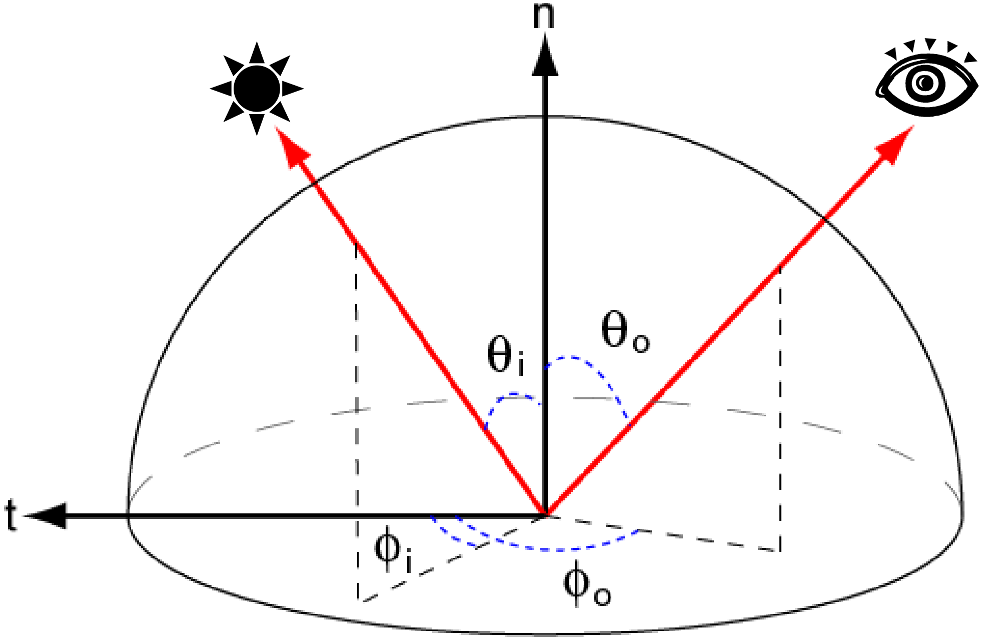




Empirical Models

Ideally measure BRDF for "all" combinations of angles: $\theta_i, \phi_i, \theta_o, \phi_o$

- Difficult in practice
- Too much storage



Parametric Models

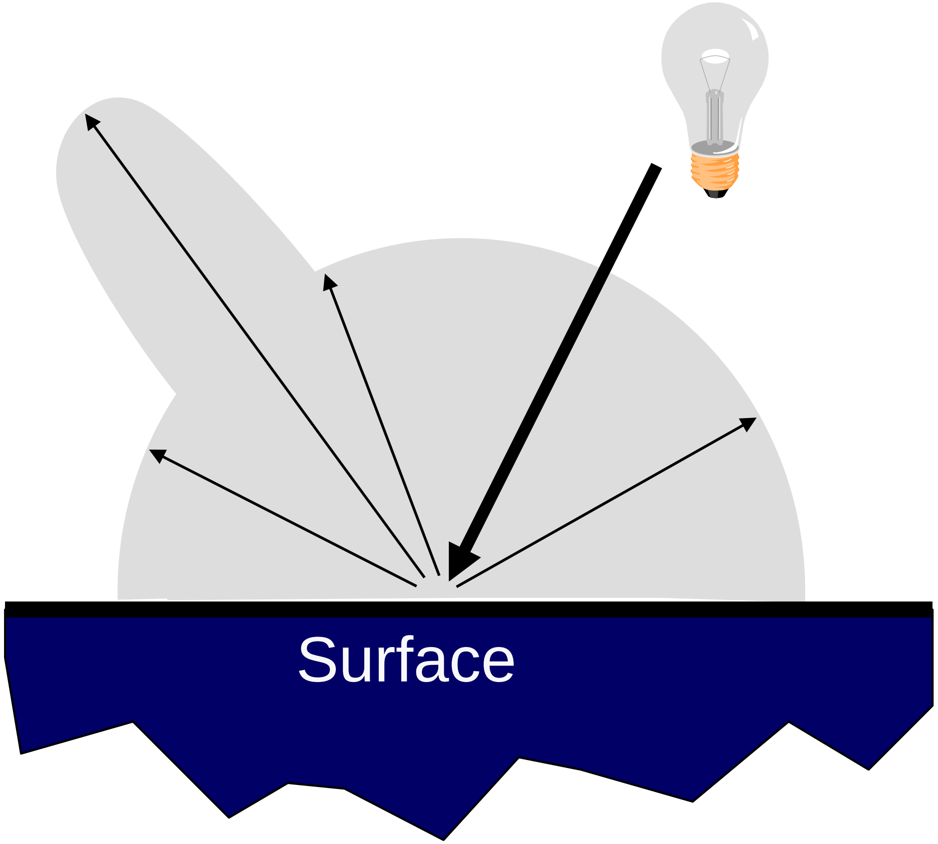
Approximate BRDF with simple parametric function that is fast to compute.

- Phong [75]
- Blinn-Phong [77]
- Cook-Torrance [81]
- He et al. [91]
- Ward [92]
- Lafortune et al. [97]
- Ashikhmin et al. [00]
- etc.

OpenGL Reflectance Model

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

Based on model proposed by Phong



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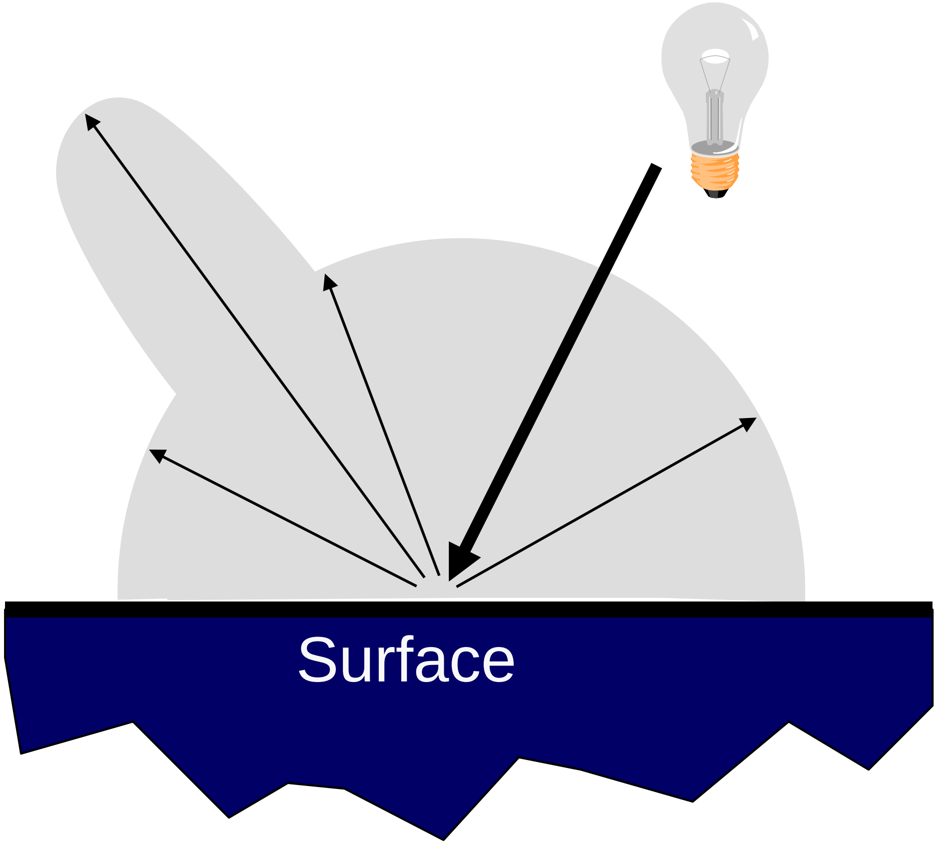
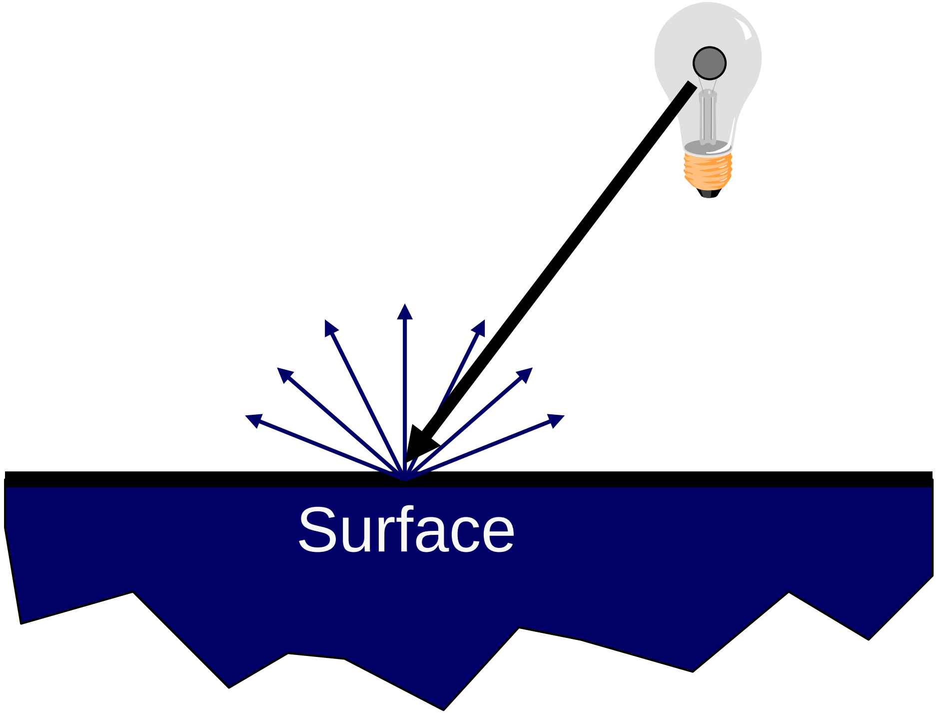
Based on model proposed by Phong



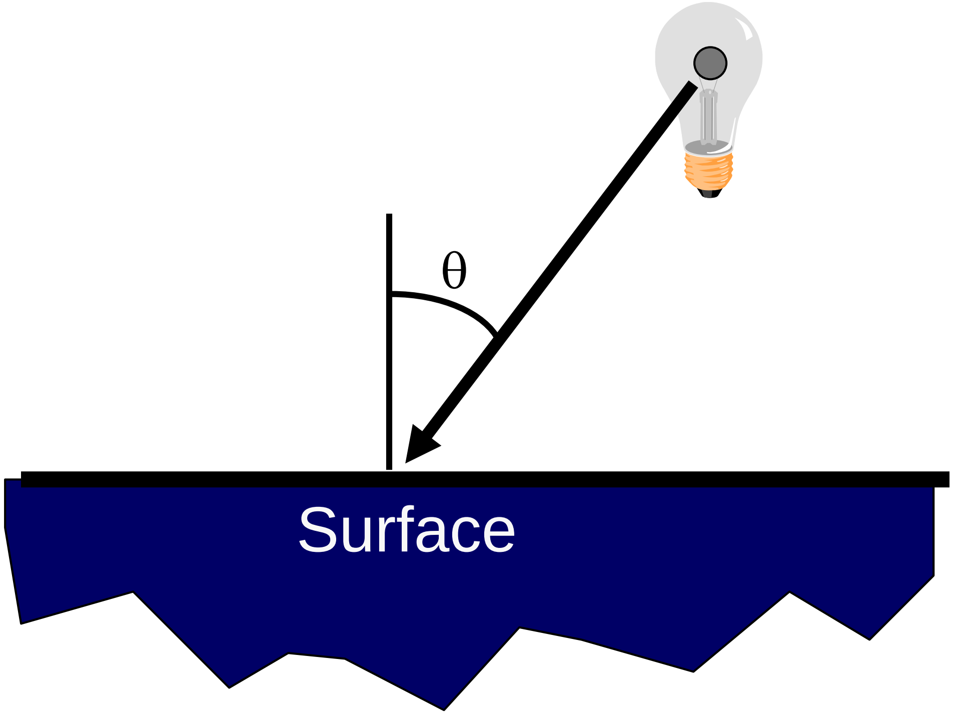
Diffuse Reflection

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



Diffuse Reflection

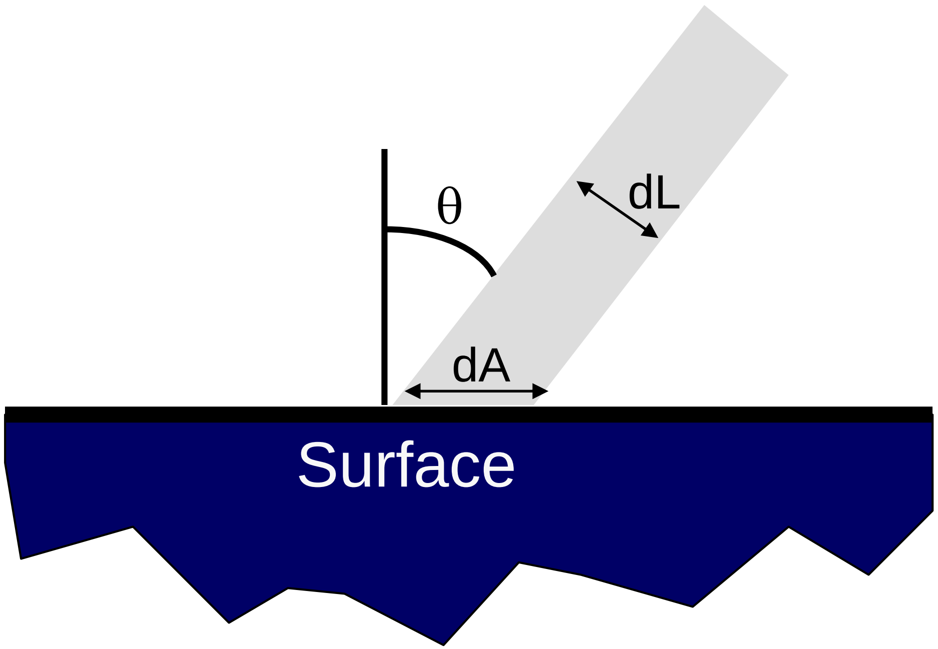
- What is brightness of surface?
  - Depends on angle of incident light



Diffuse Reflection

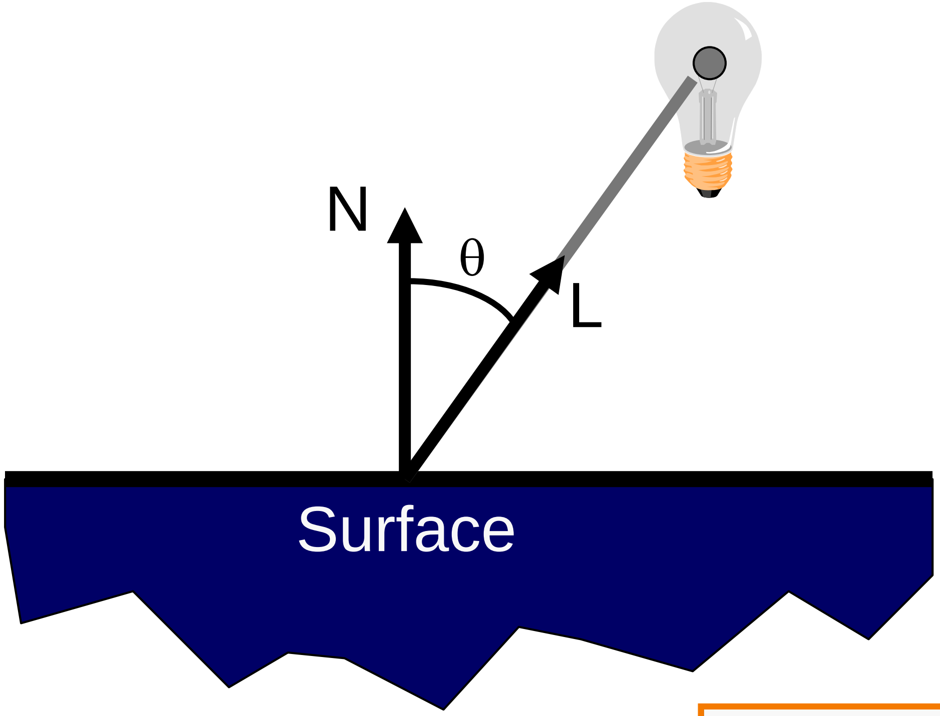
- What is brightness of surface?
  - Depends on angle of incident light

$$dL = dA \cos \Theta$$



Diffuse Reflection

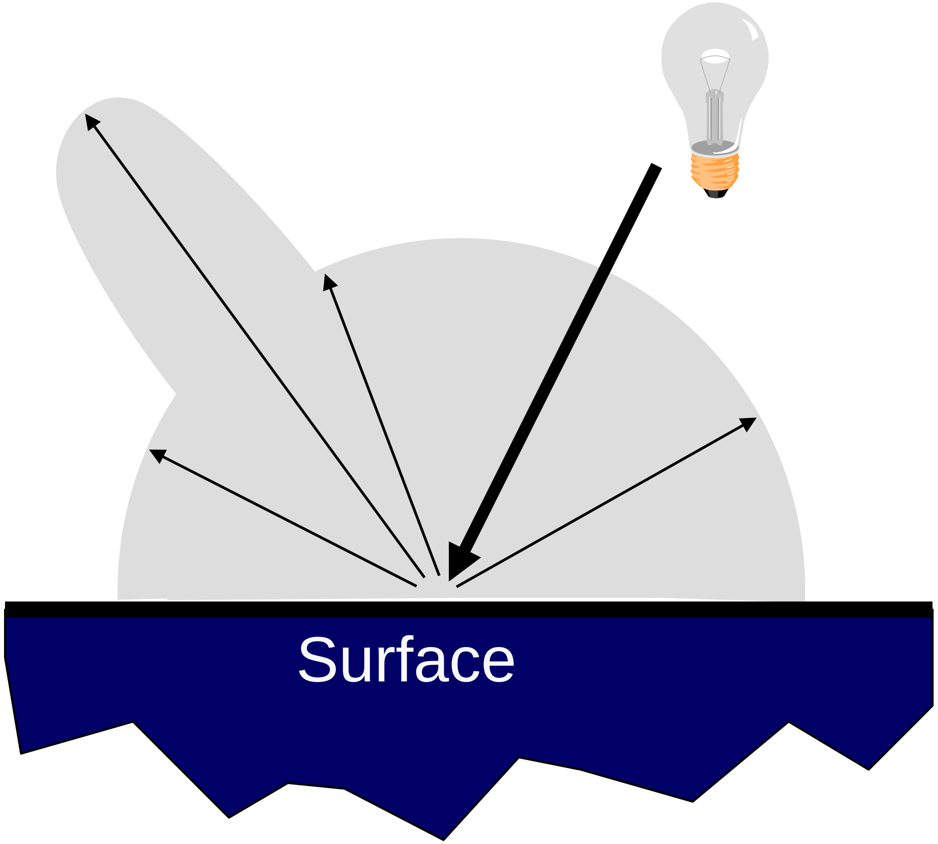
- Lambertian model
  - cosine law (dot product)



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

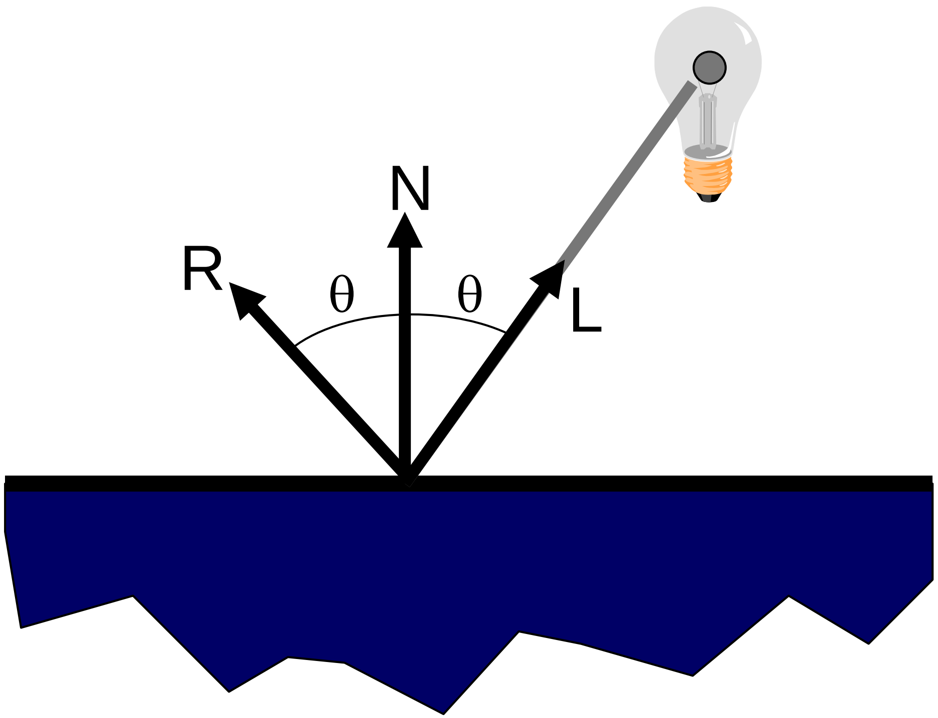
OpenGL Reflectance Model

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



Specular Reflection

- Reflection is strongest near mirror angle
  - Examples: mirrors, metals

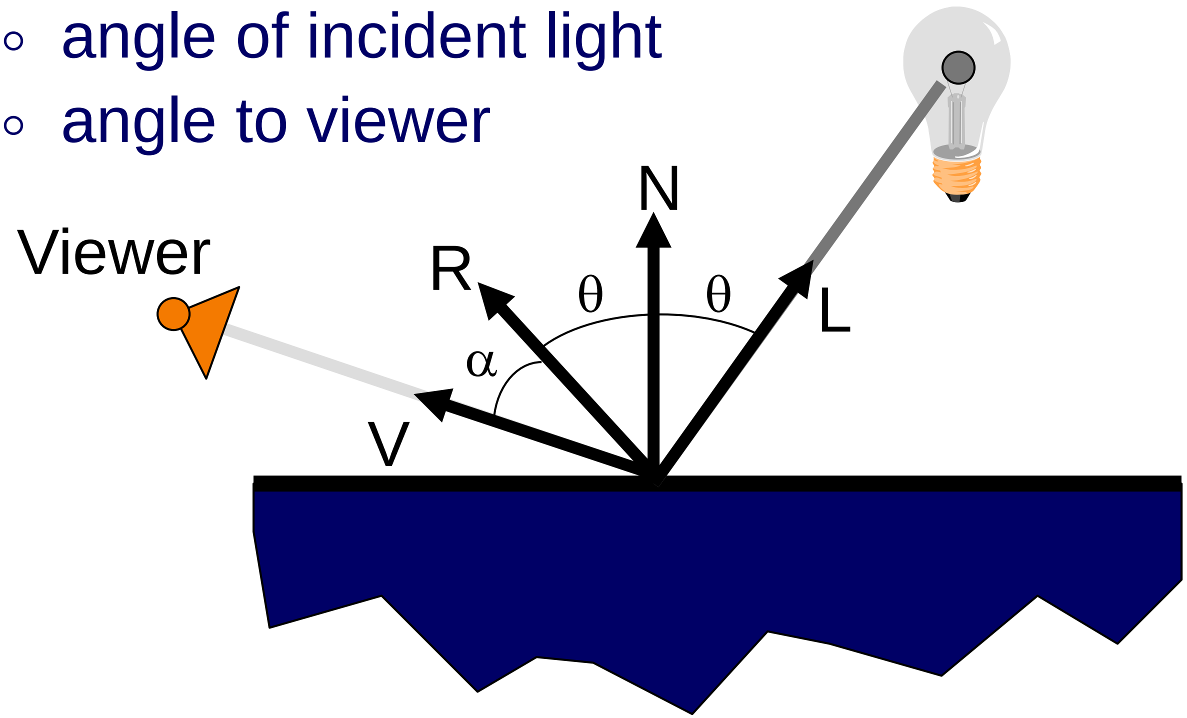


Specular Reflection

How much light is seen?

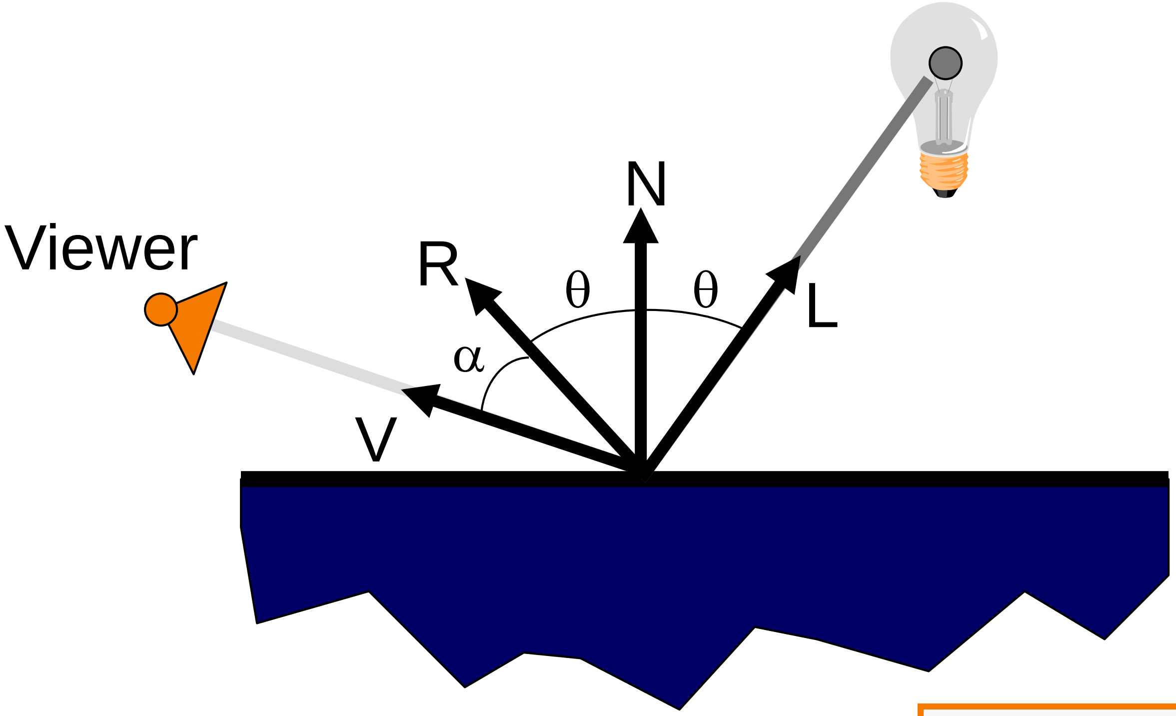
Depends on:

- angle of incident light
- angle to viewer



Specular Reflection

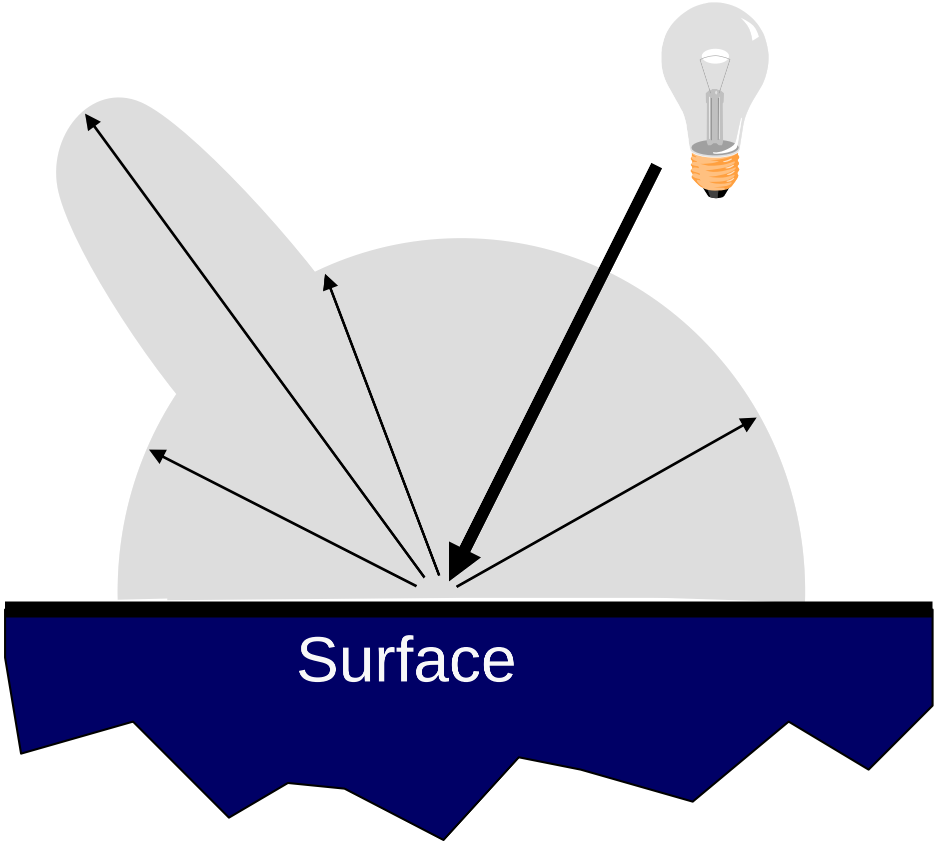
- Phong Model
  - $(\cos\alpha)^n$ This is a (vaguely physically-motivated) hack!



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

OpenGL Reflectance Model

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



Emission

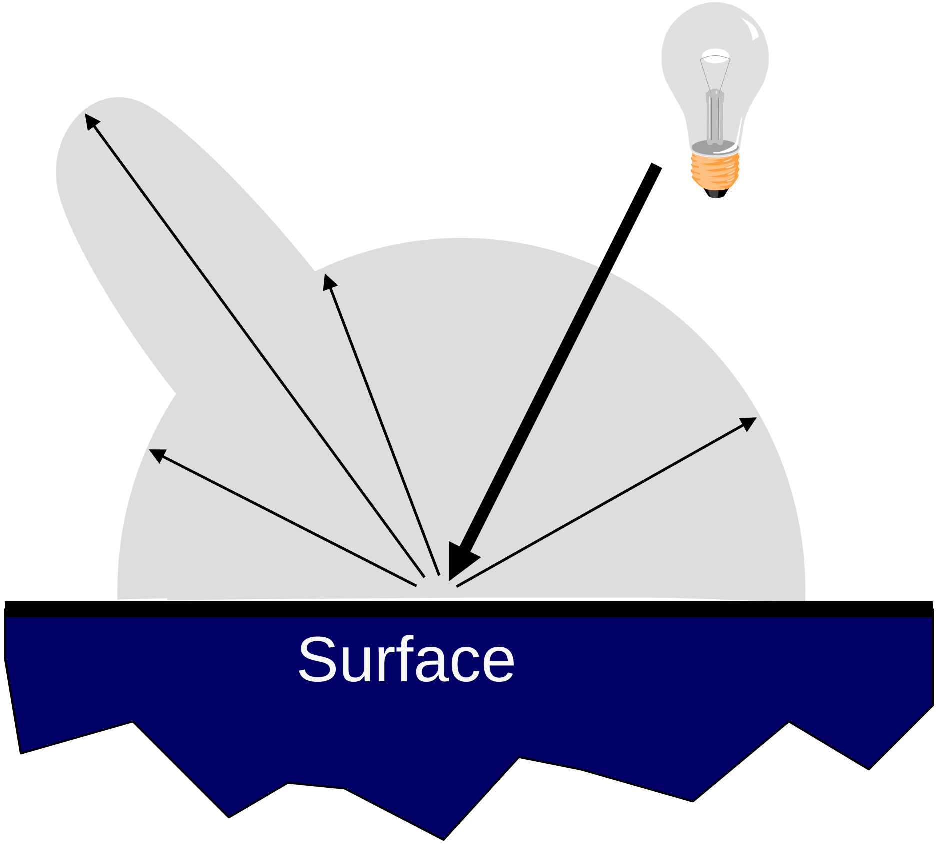
Represents light emanating directly from surface

- Note: does not automatically act as light source! Does not affect other surfaces in scene!

Emission $\neq 0$

OpenGL Reflectance Model

- Simple analytic model:
  - diffuse reflection +
  - specular reflection +
  - emission +
  - "ambient"



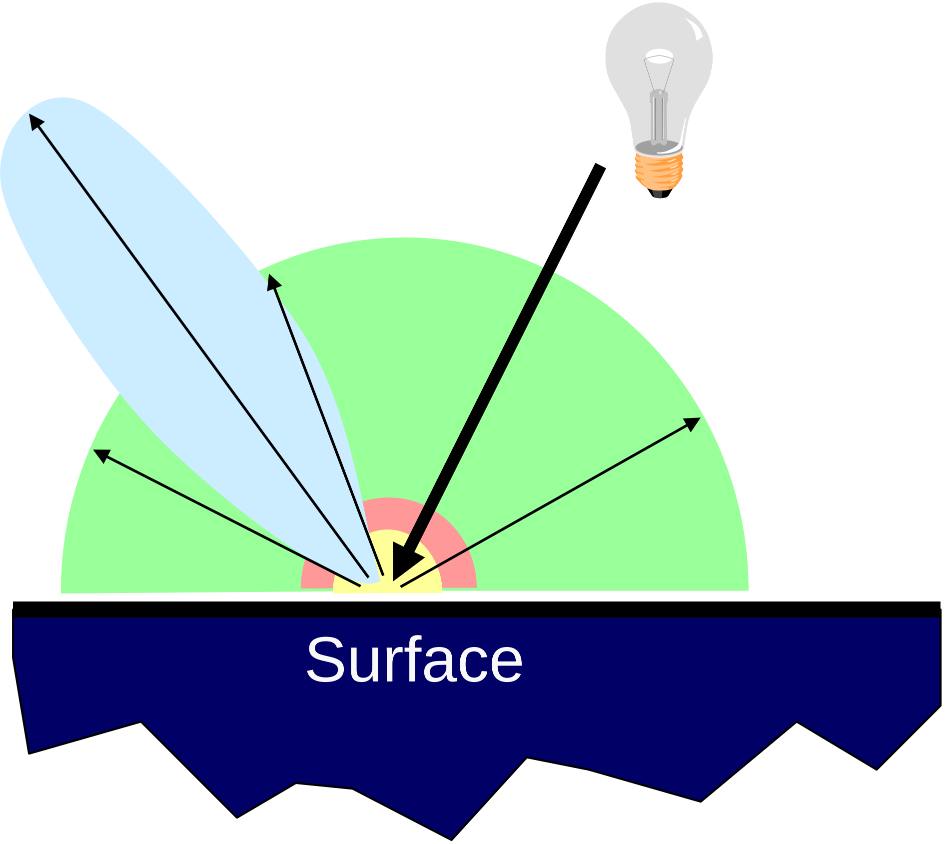
Ambient Term

Represents reflection of all indirect illumination

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

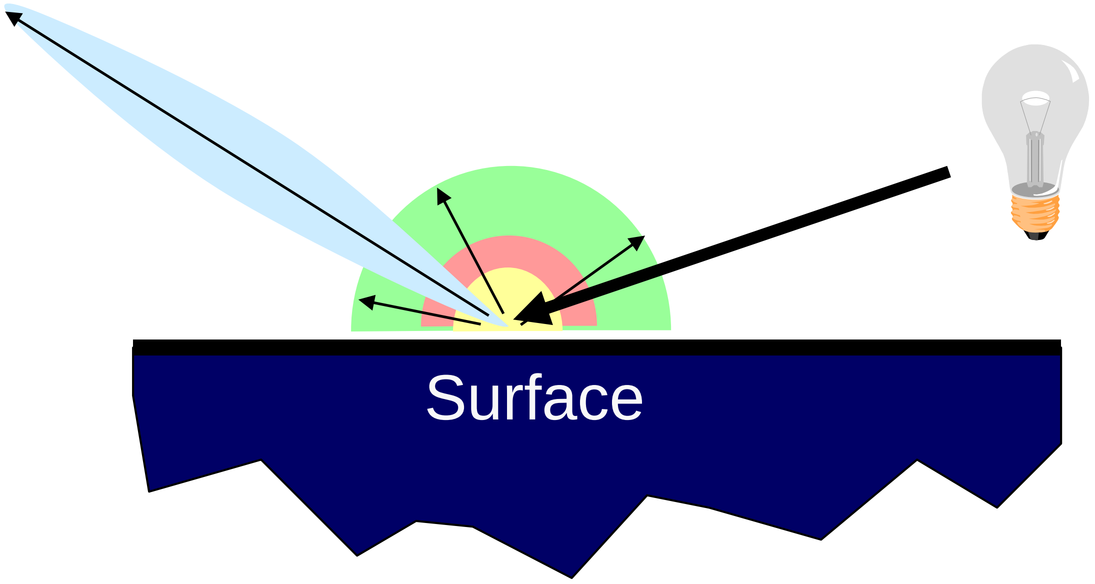
OpenGL Reflectance Model

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



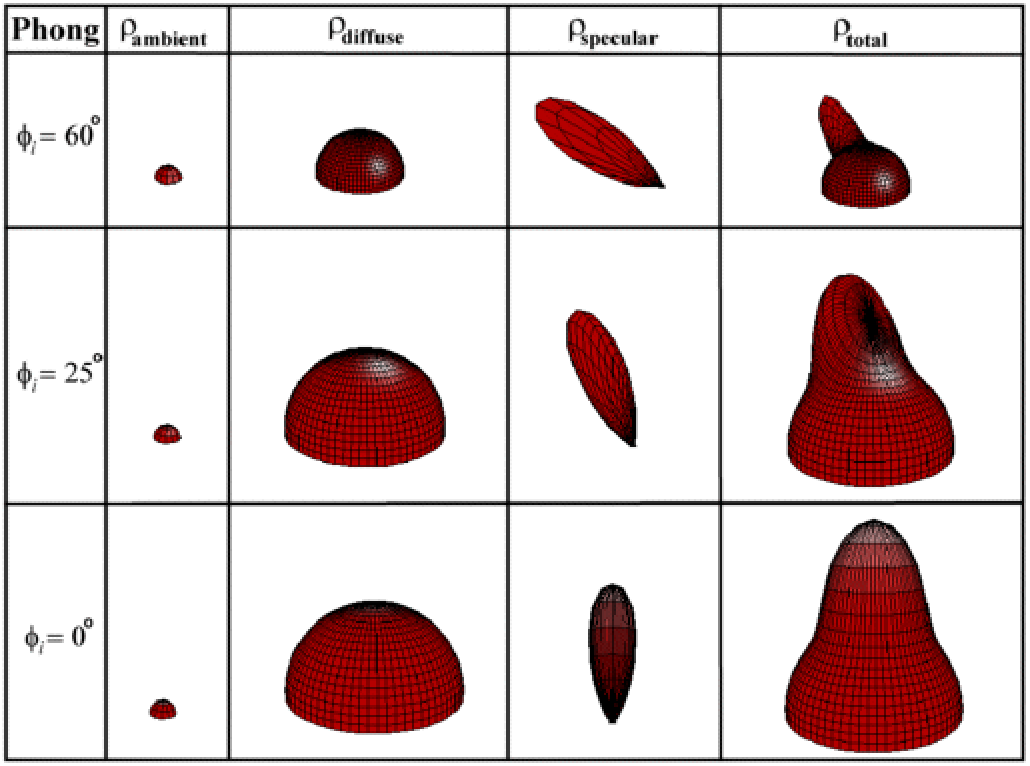
OpenGL Reflectance Model

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



OpenGL Reflectance Model

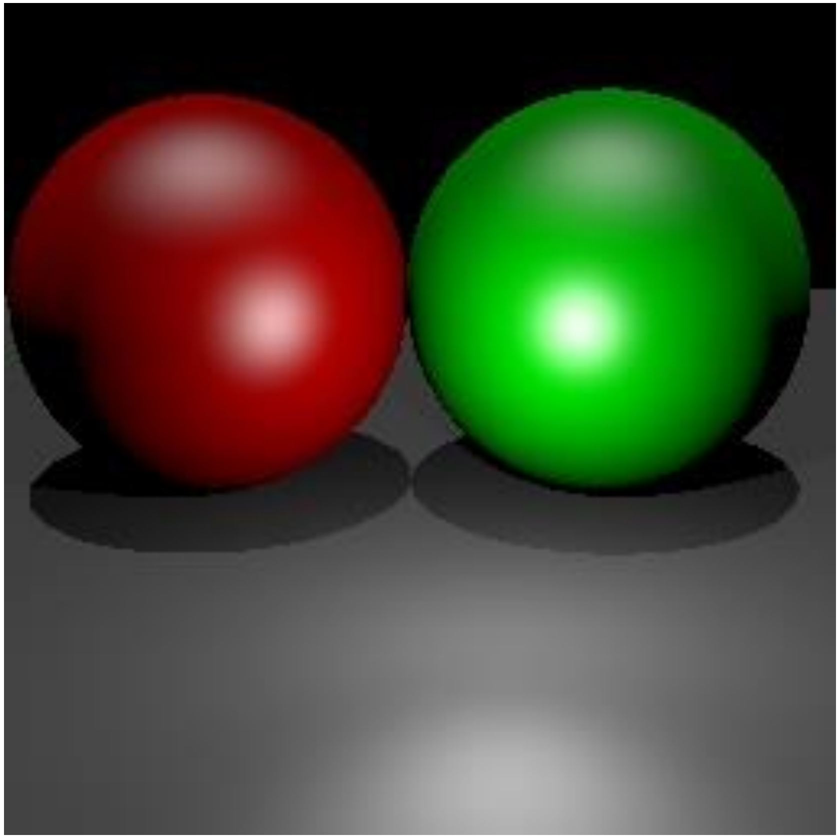
Sum diffuse, specular, emission, and ambient



Leonard McMillan, MIT

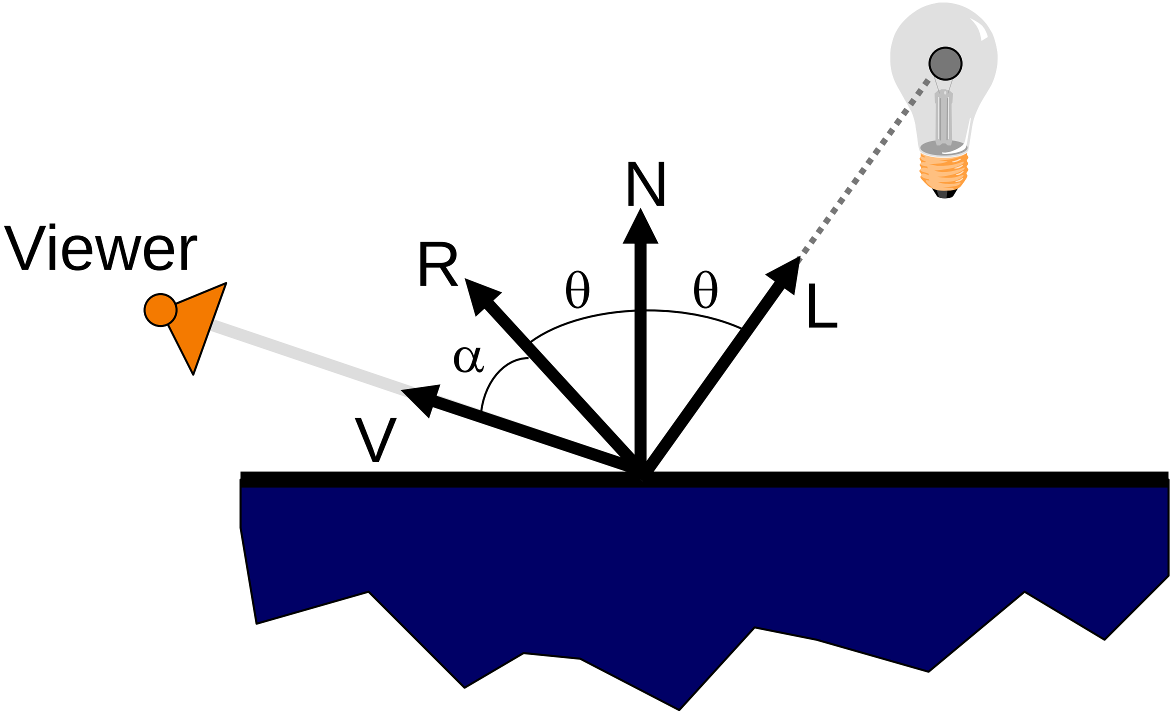
OpenGL Reflectance Model

Good model for plastic surfaces, …



Direct Illumination Calculation

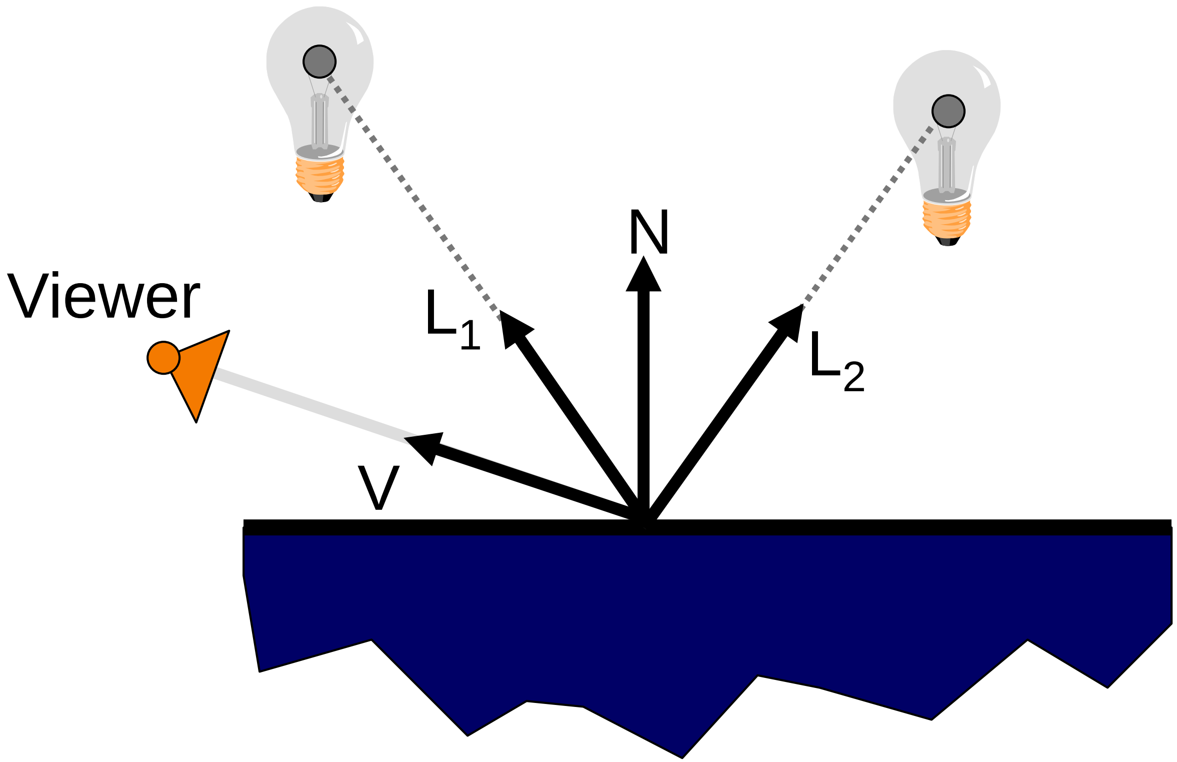
Single light source:



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

Direct Illumination Calculation

Multiple light sources:



Note: all of the *K* and *I* are RGB colors

$$I = I_E + K_A I_{AL} + \sum_L \left(K_D (N \cdot L_i) + K_S (V \cdot R_i)^n \right) I_L$$

Overview

- Direct Illumination
  - Emission at light sources
  - Scattering at surfaces

- Global illumination
  - Shadows
  - Transmissions
  - Inter-object reflections

Global Illumination

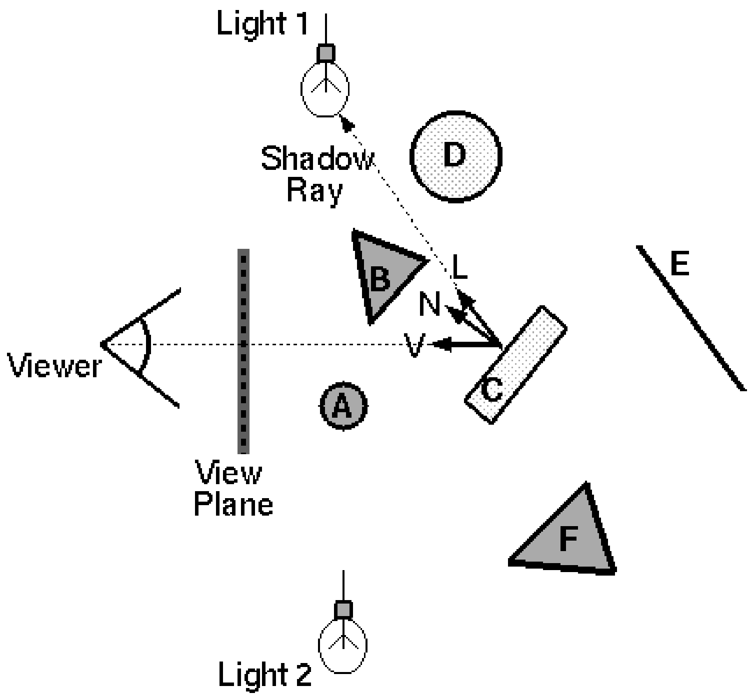
Global Illumination

Greg Ward

Ray Casting (last lecture)

Trace primary rays from camera

- Direct illumination from unblocked lights only

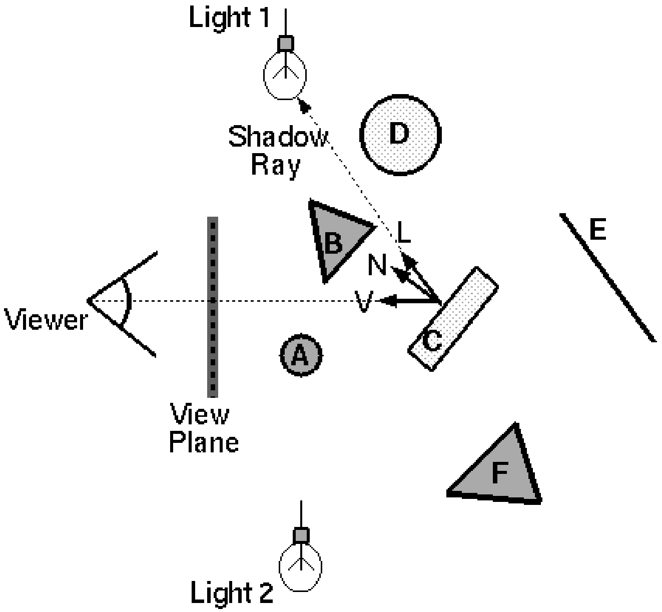


$$I = I_E + K_A I_{AL} + \sum_L \left(K_D (N \cdot L_i) + K_S (V \cdot R_i)^n \right) I_L$$

Shadows

Shadow term tells if light sources are blocked

- Cast ray towards each light source
- S_L = 0 if ray is blocked, S_L = 1 otherwise



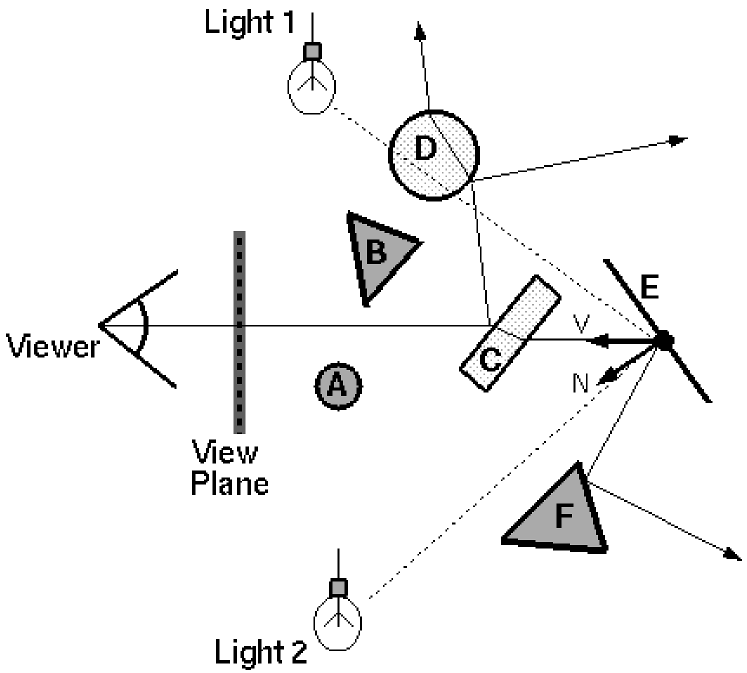
Shadow Term

$$I = I_E + K_A I_{AL} + \sum_L \left(K_D (N \cdot L_i) + K_S (V \cdot R_i)^n \right) S_L I_L$$

Recursive Ray Tracing

Also trace secondary rays from hit surfaces

- Mirror reflection and transparency

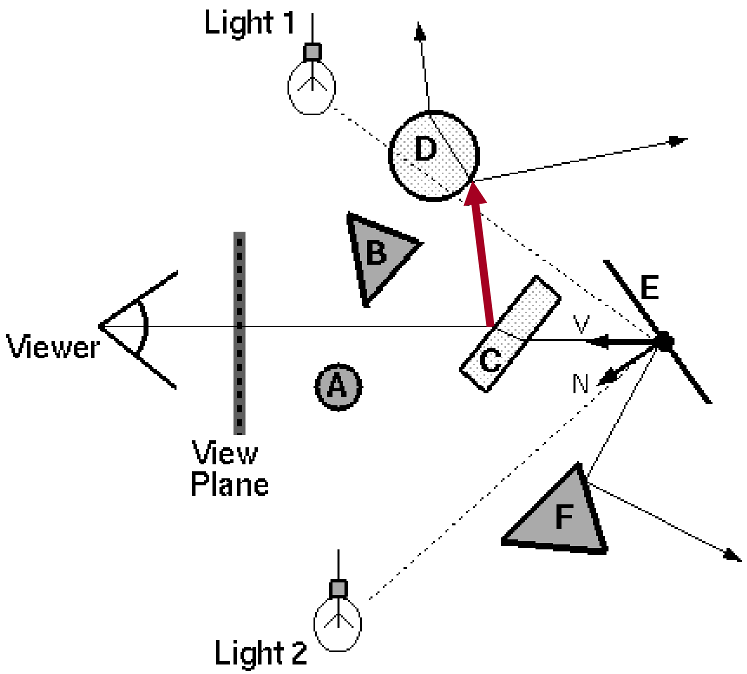


$$I = I_E + K_A I_{AL} + \sum_L \left(K_D (N \cdot L_i) + K_S (V \cdot R_i)^n \right) S_L I_L + K_S I_R + K_T I_T$$

Mirror reflections

Trace secondary ray in mirror direction

- Evaluate radiance along secondary ray and include it into illumination model



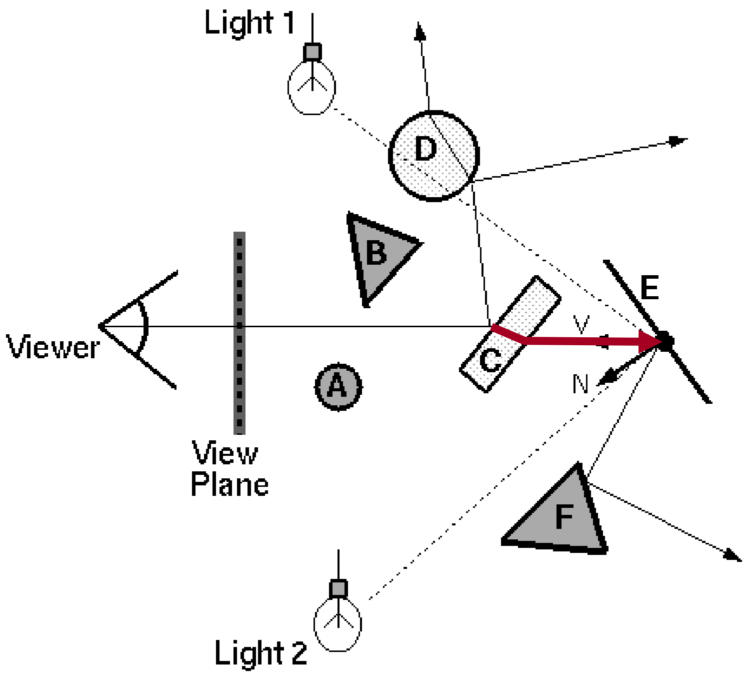
Radiance for mirror reflection ray

$$I = I_E + K_A I_{AL} + \sum_L \left(K_D (N \cdot L_i) + K_S (V \cdot R_i)^n \right) S_L I_L + K_S I_R + K_T I_T$$

Transparency

Trace secondary ray in direction of refraction

- Evaluate radiance along secondary ray and include it into illumination model



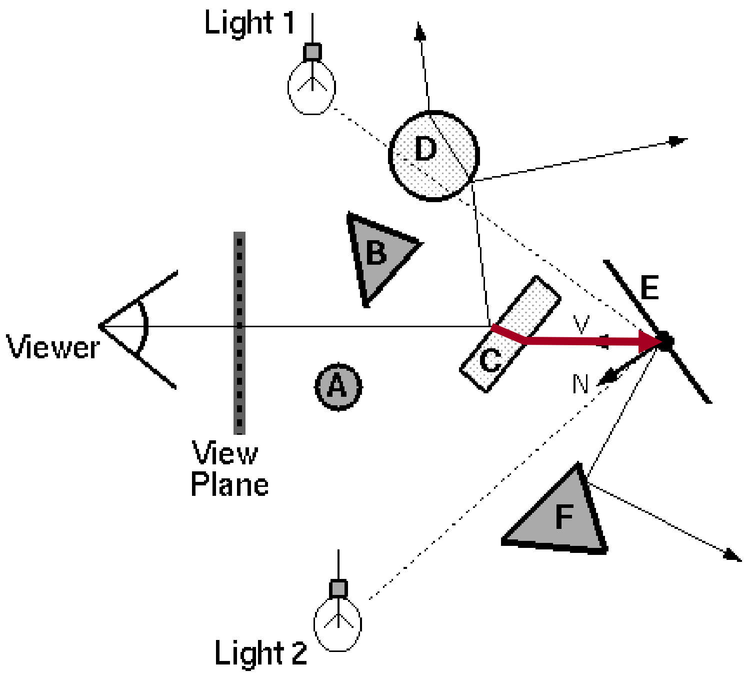
Radiance for refraction ray

$$I = I_E + K_A I_{AL} + \sum_L \left(K_D (N \cdot L_i) + K_S (V \cdot R_i)^n\right) S_L I_L + K_S I_R + K_T I_T$$

Transparency

Transparency coefficient is fraction transmitted

- $K_T = 1$ for translucent object, $K_T = 0$ for opaque
- $0 < K_T < 1$ for object that is semi-translucent



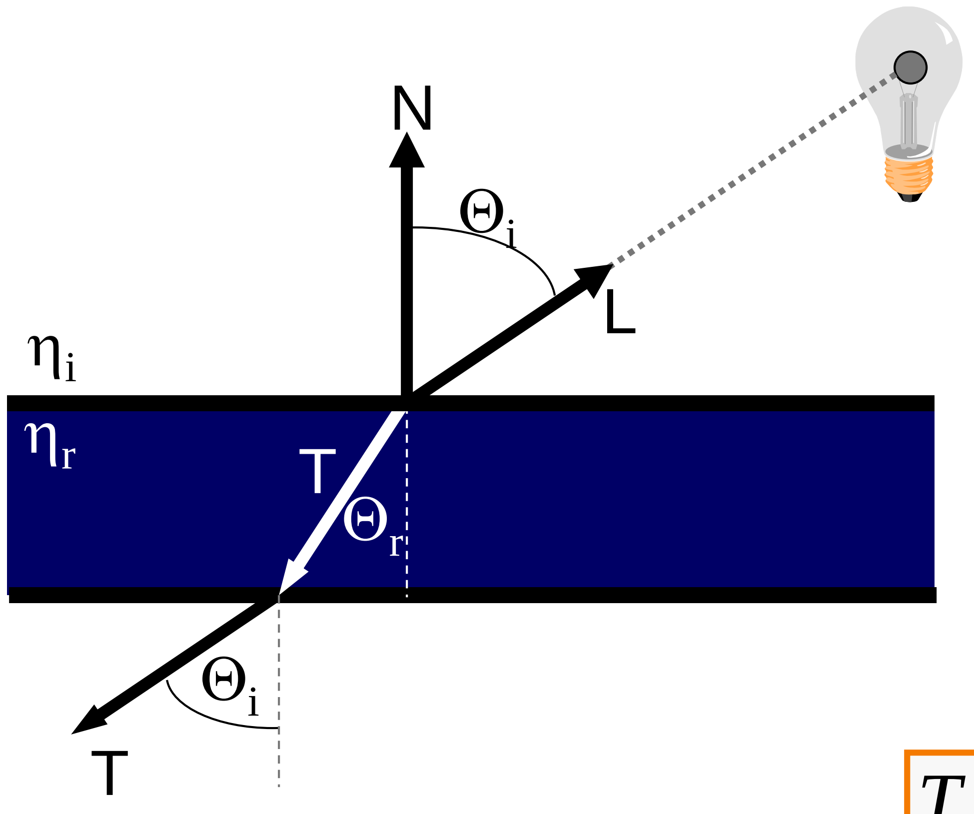
Transparency Coefficient

$$I = I_E + K_A I_{AL} + \sum_L \left(K_D (N \cdot L_i) + K_S (V \cdot R_i)^n \right) S_L I_L + K_S I_R + K_T I_T$$

Refractive Transparency

For thin surfaces, can ignore change in direction

- Assume light travels straight through surface

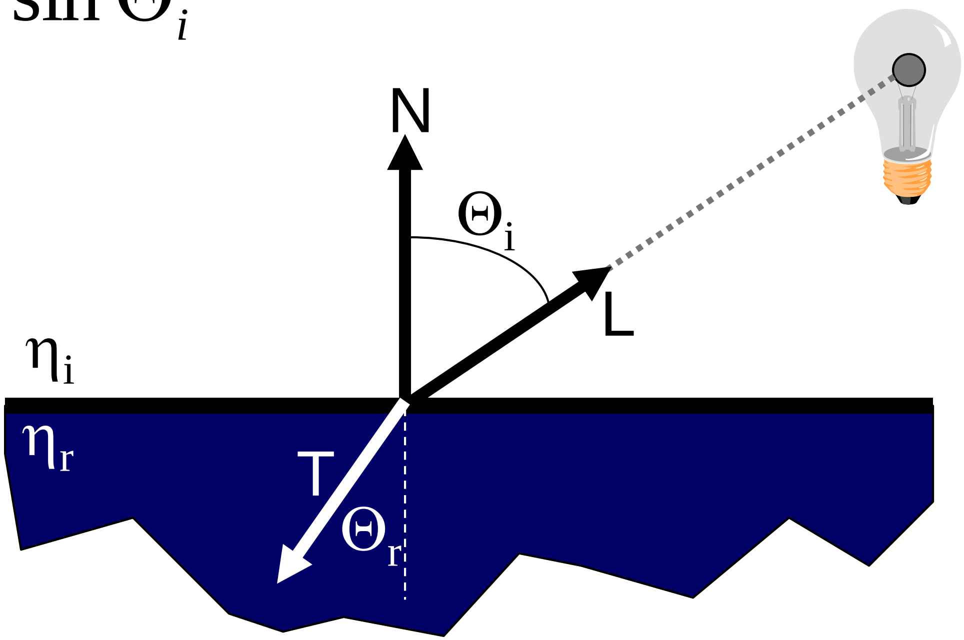


$$T \cong -L$$

Refractive Tranparency

For solid objects, apply Snell's law:

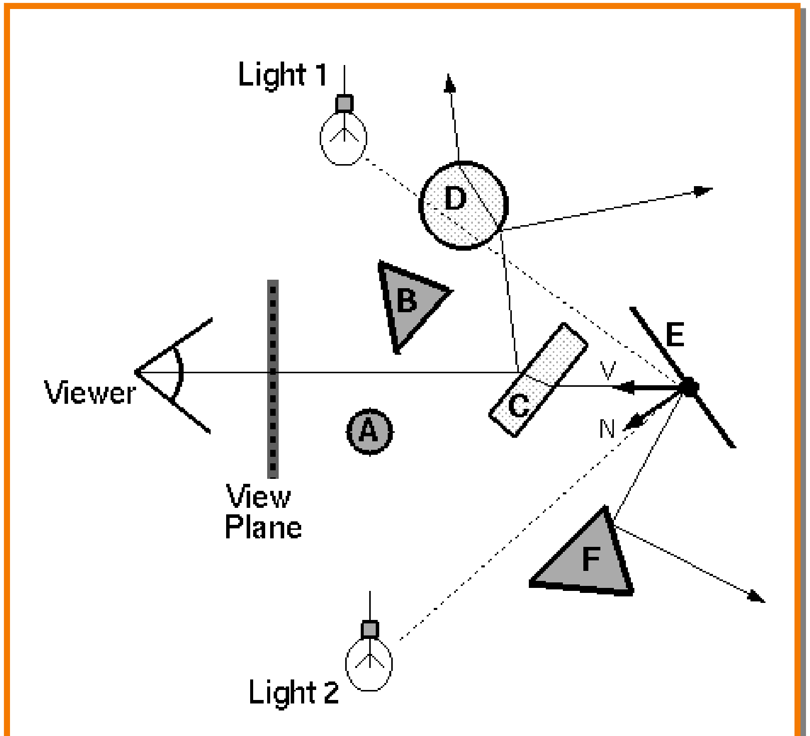
$$\eta_r \sin \Theta_r = \eta_i \sin \Theta_i$$



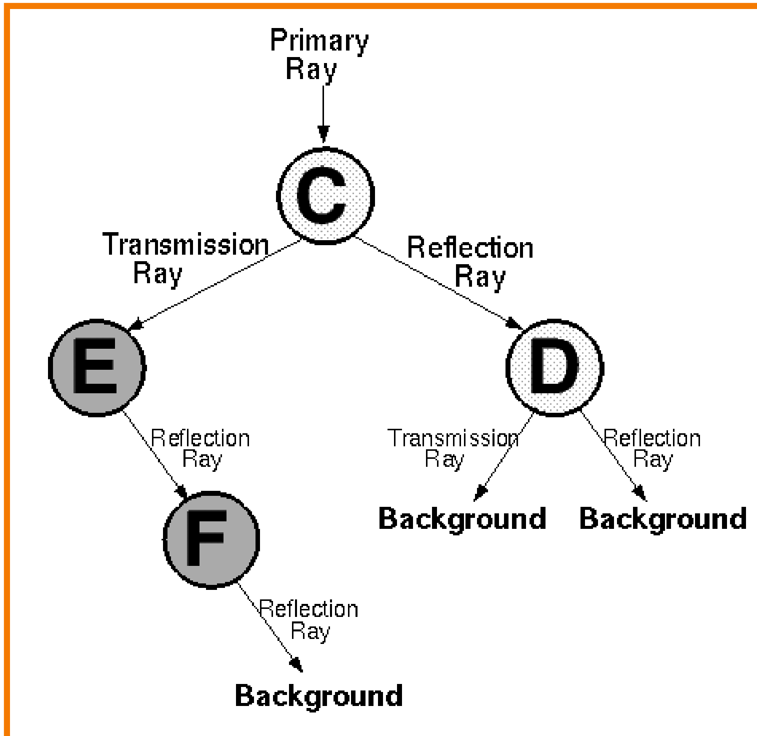
$$T = \left(\frac{\eta_i}{\eta_r}\cos\Theta_i - \cos\Theta_r\right)N - \frac{\eta_i}{\eta_r}L$$

Recursive Ray Tracing

Ray tree represents illumination computation



Ray traced through scene

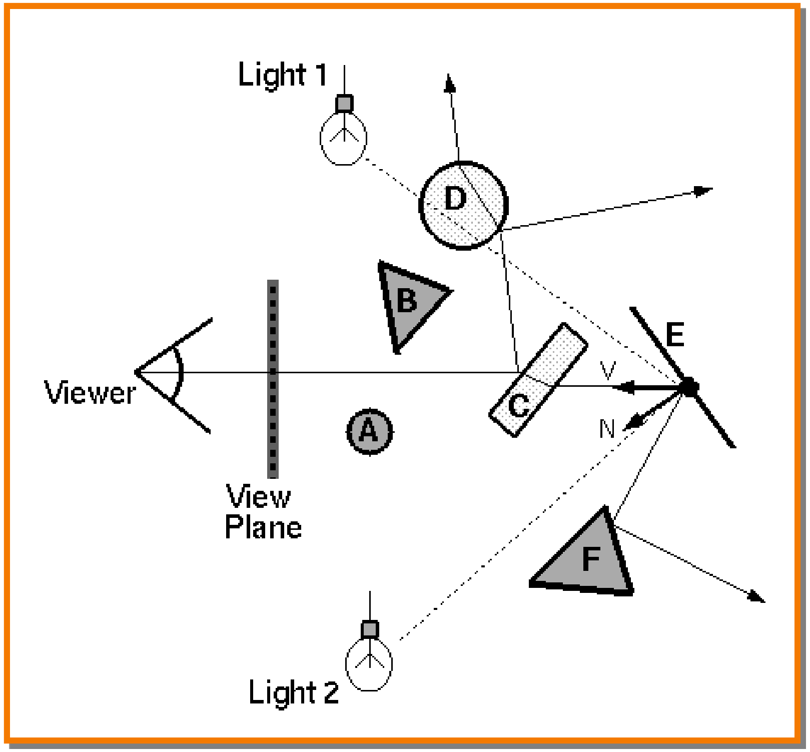


Ray tree

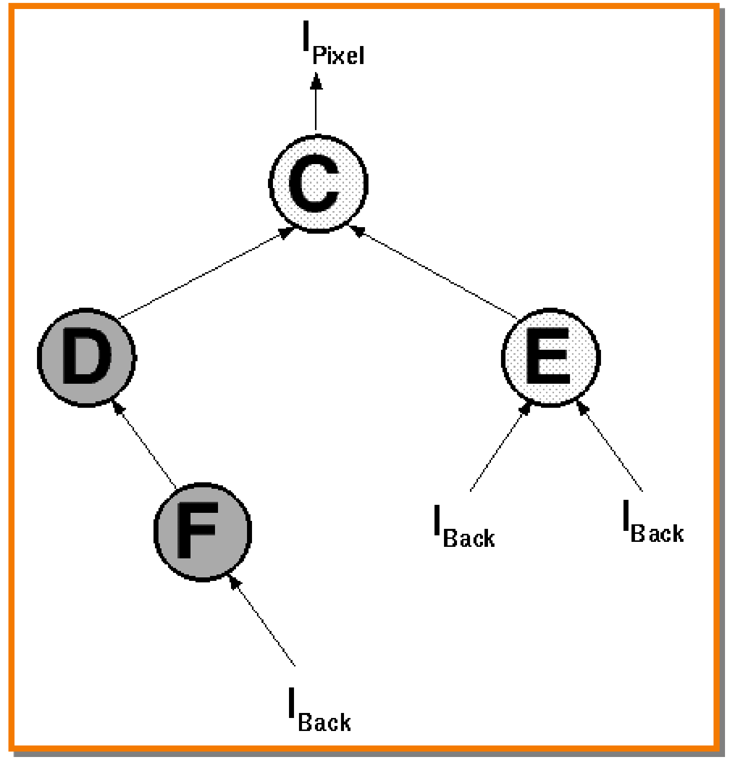
$$I = I_E + K_A I_{AL} + \sum_L \left(K_D (N \cdot L_i) + K_S (V \cdot R_i)^n \right) S_L I_L + K_S I_R + K_T I_T$$

Recursive Ray Tracing

Ray tree represents illumination computation



Ray traced through scene



Ray tree

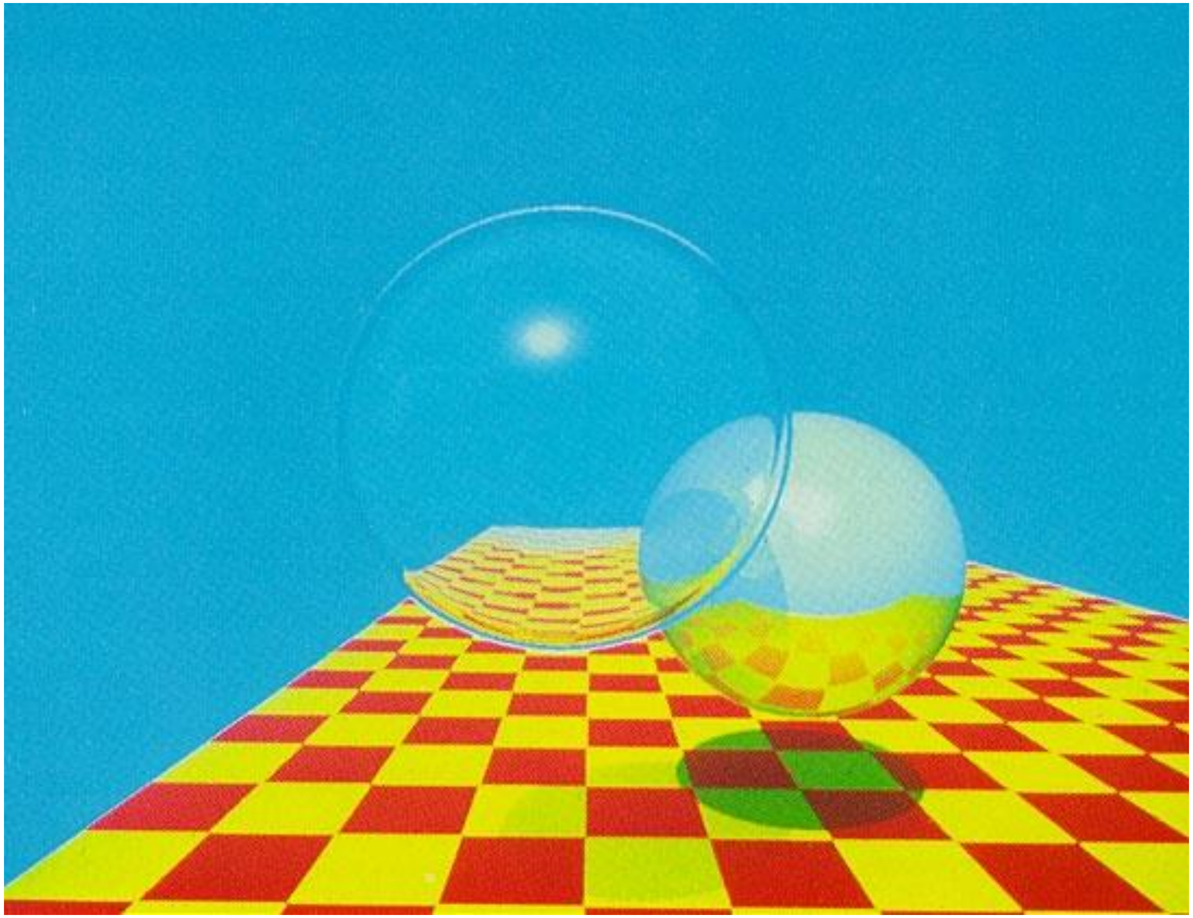
$$I = I_E + K_A I_{AL} + \sum_L \left(K_D (N \cdot L_i) + K_S (V \cdot R_i)^n \right) S_L I_L + K_S I_R + K_T I_T$$

Recursive Ray Tracing

ComputeRadiance is called recursively

```
R3Rgb ComputeRadiance(R3Scene *scene, R3Ray *ray, R3Intersection& hit)
{
    R3Ray specular_ray = SpecularRay(ray, hit);
    R3Ray refractive_ray = RefractiveRay(ray, hit);
    R3Rgb radiance = Phong(scene, ray, hit) +
                     Ks * ComputeRadiance(scene, specular_ray) +
                     Kt * ComputeRadiance(scene, refractive_ray);
    return radiance;
}
```

Example



Turner Whitted, 1980

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

More on global illumination next time!

Example from Production

This scene has 400 virtual lights

Pixar