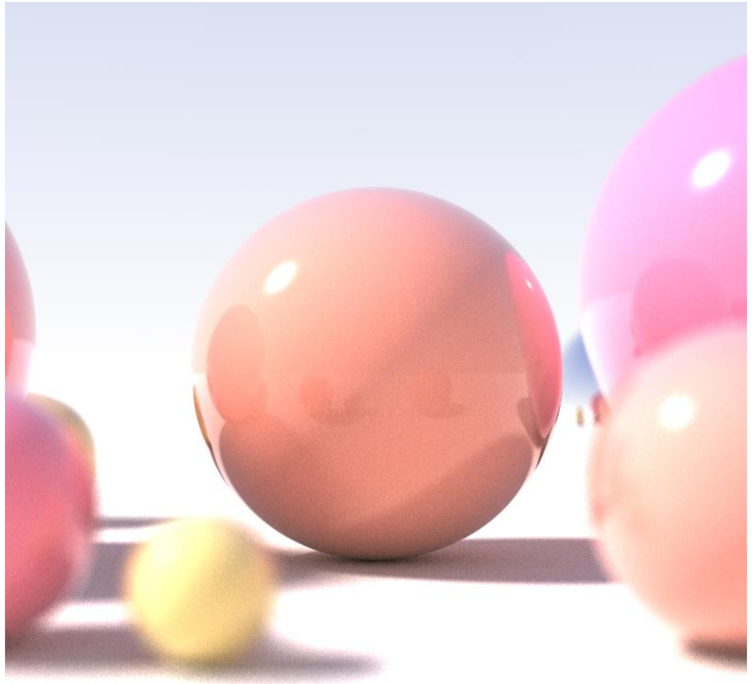
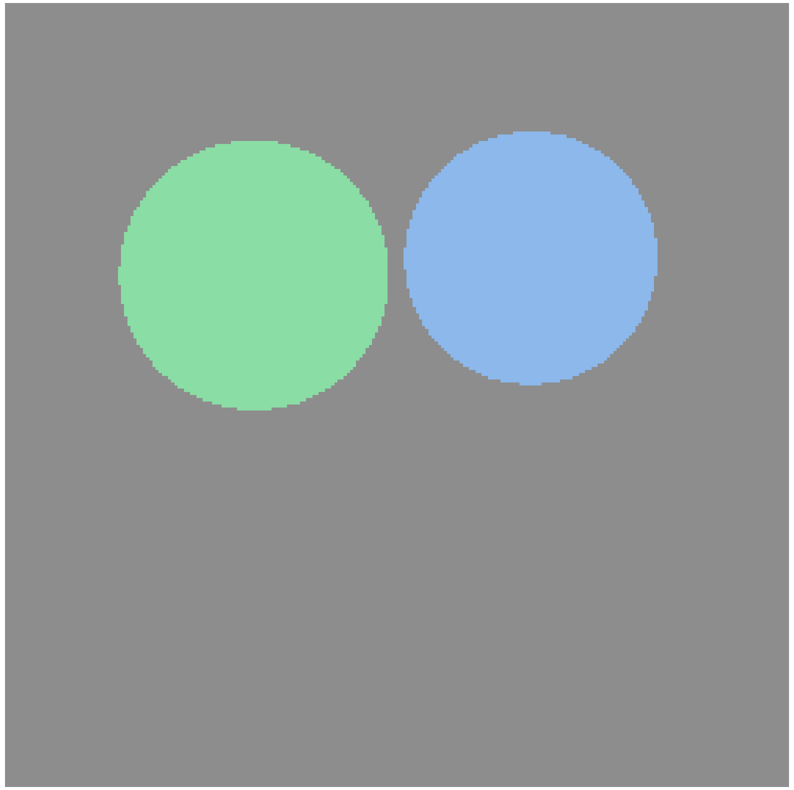
Ray Tracing



Some Slides/Images adapted from Marschner and Shirley and David Levin

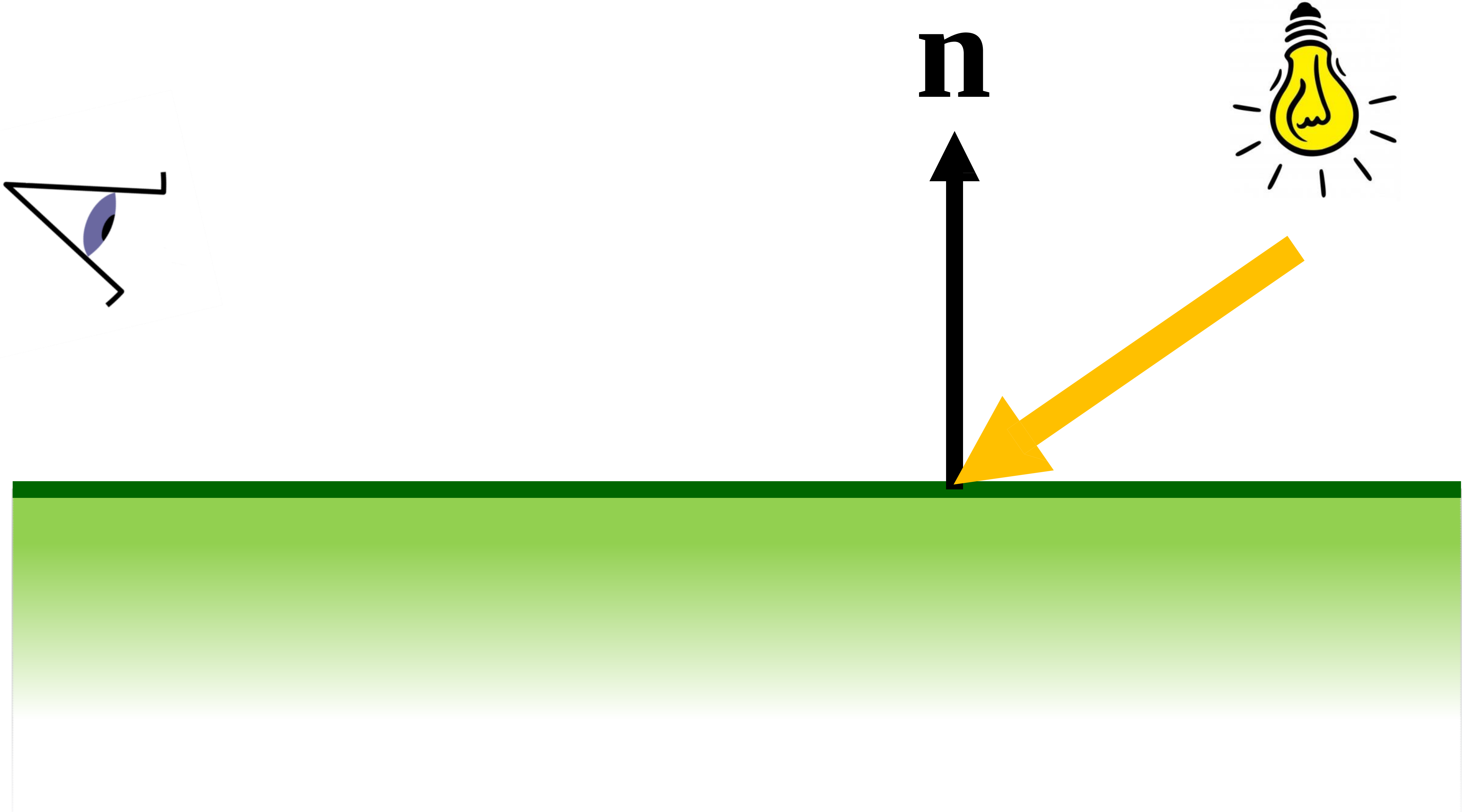
Ray Casting

```
for 0 <= iy < ny
   for 0 <= ix < nx
  {
      ray = camera.getRay(ix, iy);
      firstSurface = scene.intersect(result,ray);
      if (firstSurface)
         image.set(ix, iy, firstSurface.color);
      else
         image.set(ix, iy, background.color);
   }
```

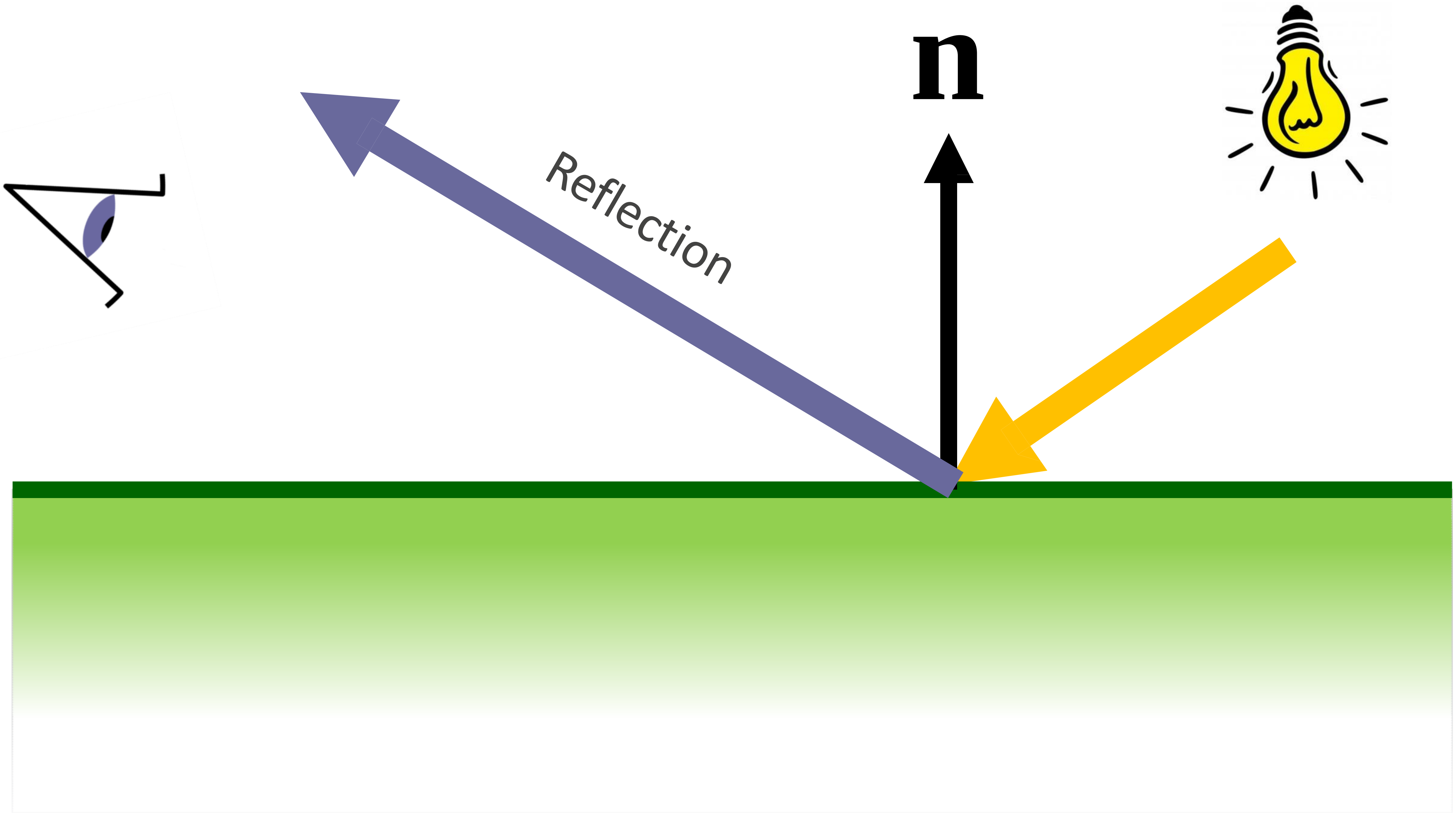


Light and Surfaces

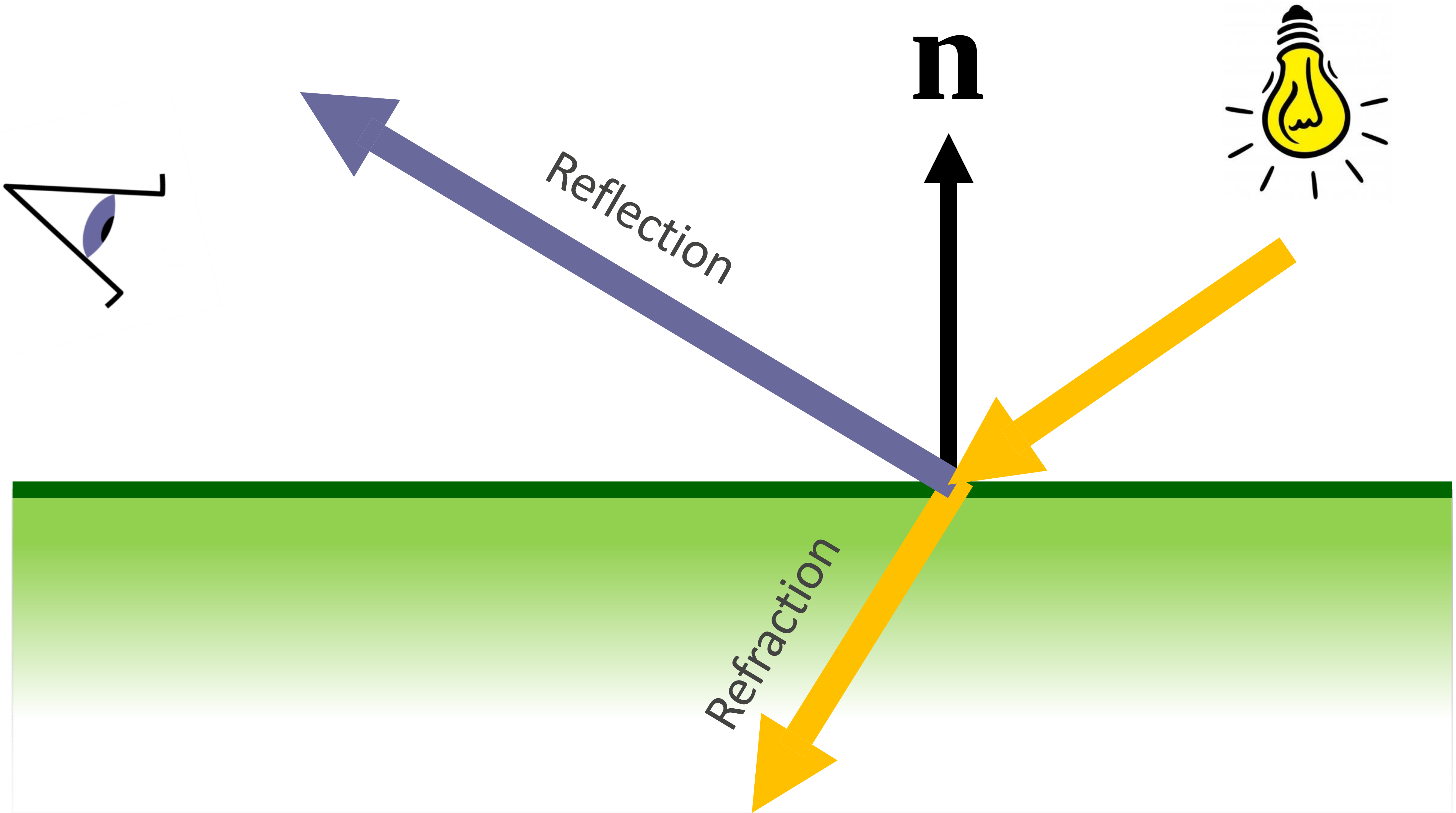
Light and Surfaces



Light and Surfaces

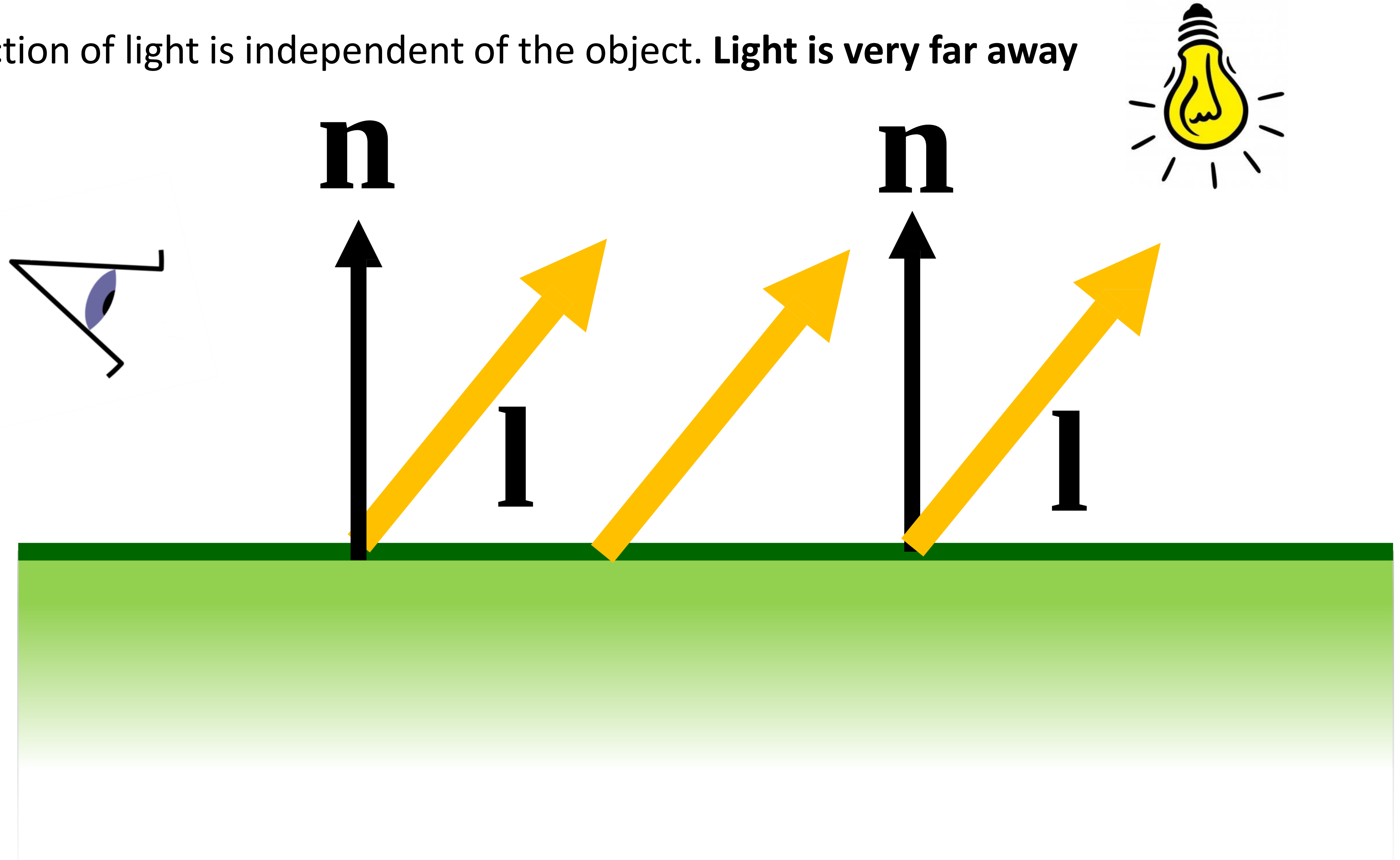


Light and Surfaces



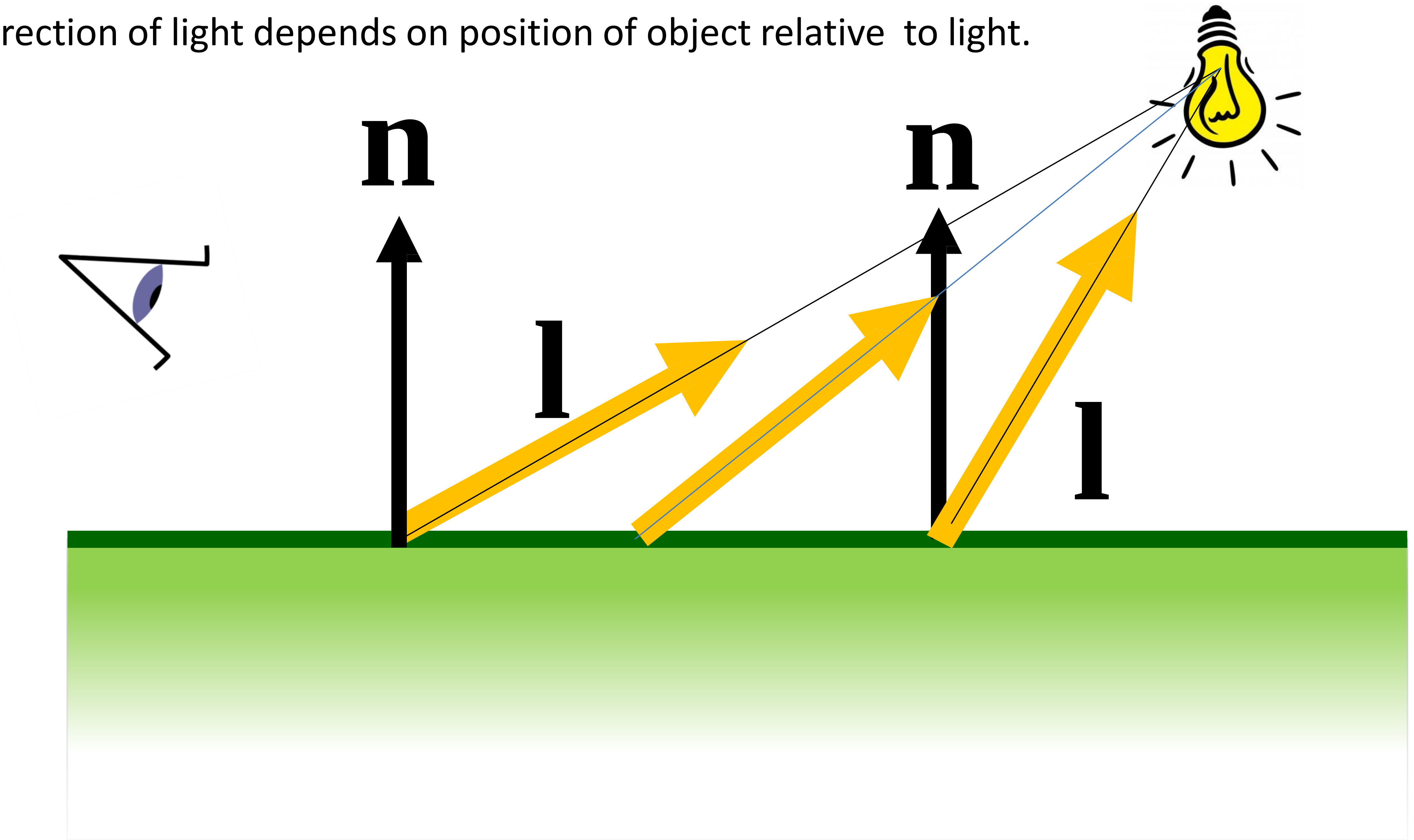
Directional Light

Direction of light is independent of the object. **Light is very far away**



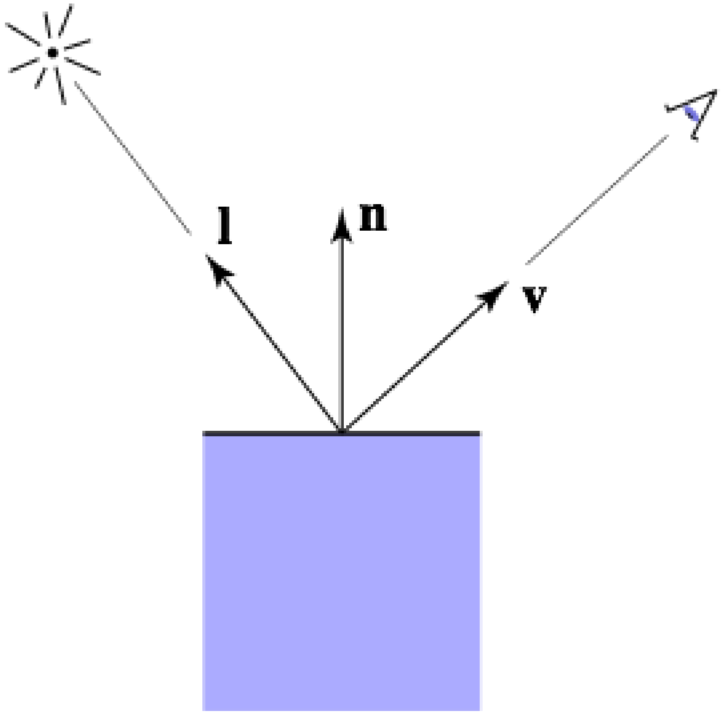
Point Light

Direction of light depends on position of object relative to light.



Shading

- Compute light reflected toward camera
- Inputs:
  - – eye direction
  - – light direction
    (for each of many lights)
  - – surface normal
  - – surface parameters
    (color, shininess, …)



Computing the Normal at a Hit Point

- Polygon normal: cross product of two non-collinear edges.

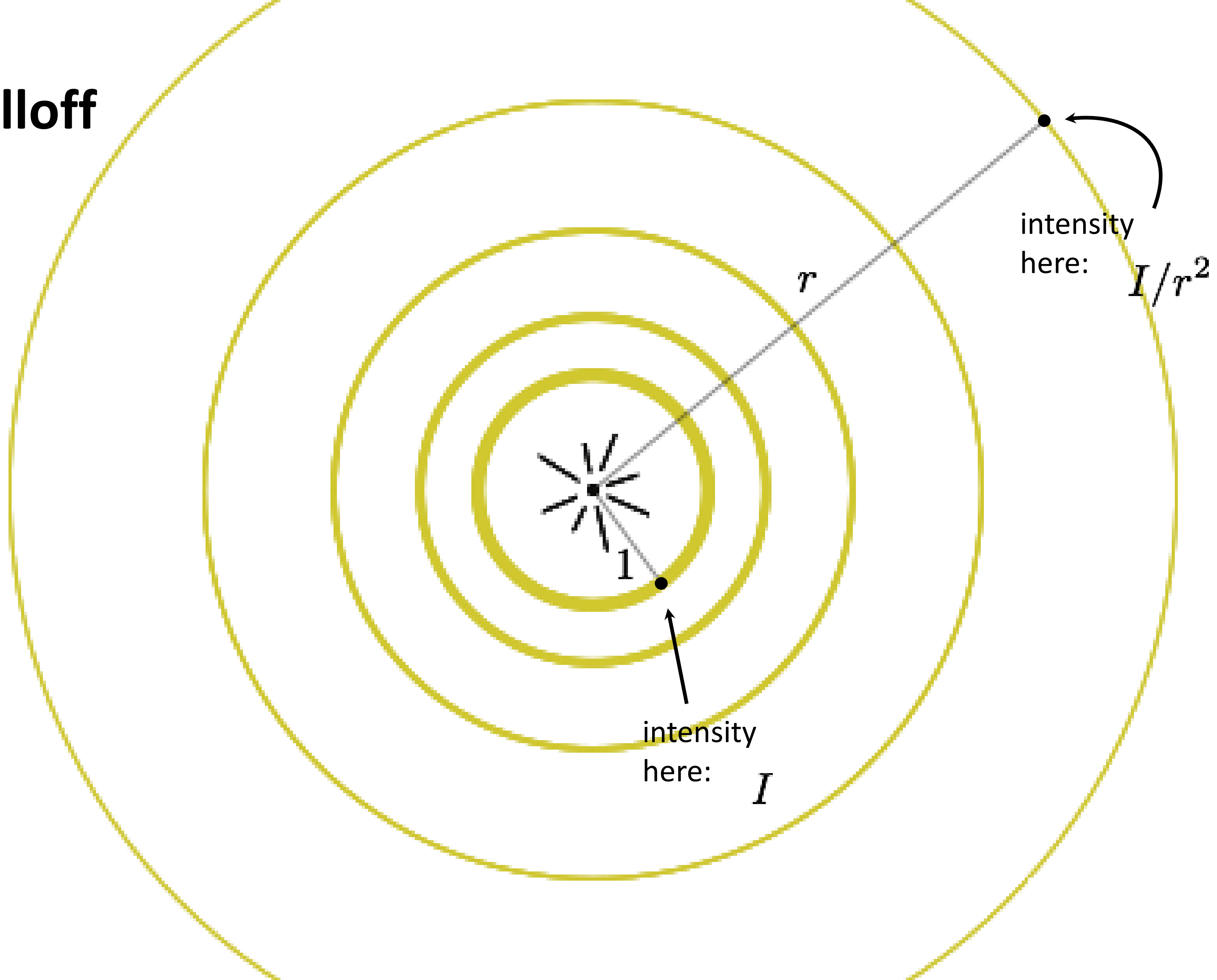
- Implicit surface normal $f(p)=0$:

  gradient(f)(p).

- Explicit parametric surface $f(a,b)$:

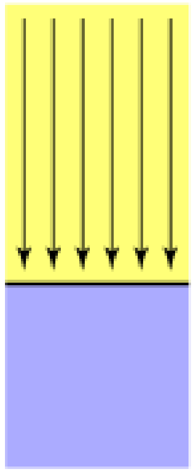
$$\delta f(s,b)/ \delta s \; X \; \delta f(a,t)/ \delta t.$$

Light falloff

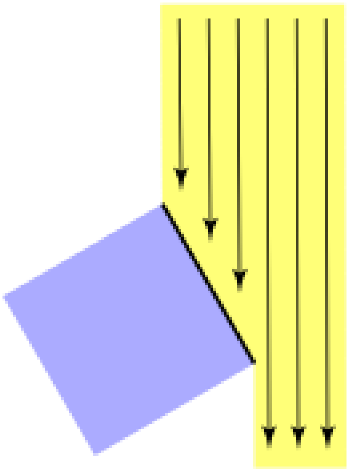


Diffuse reflection

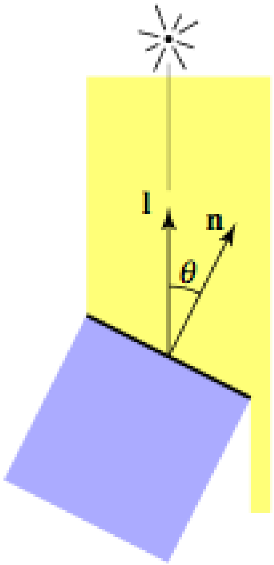
- Light is scattered uniformly in all directions
  - the surface color is the same for all viewing directions
- Lambert's cosine law



Top face of cube receives a certain amount of light



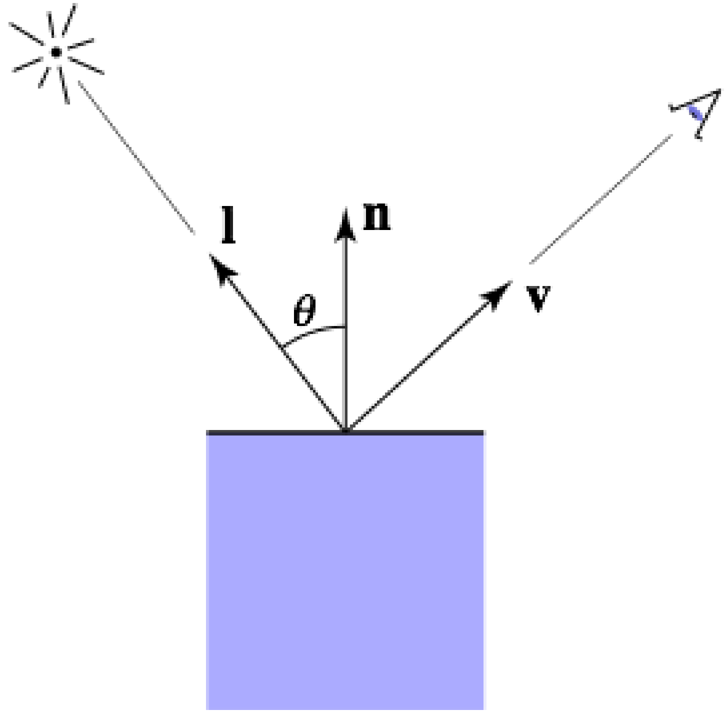
Top face of 60º rotated cube intercepts half the light



In general, light per unit area is proportional to $\boxed{\cos\theta = l \bullet n}$

Lambertian shading

Shading independent of view direction



illumination from source

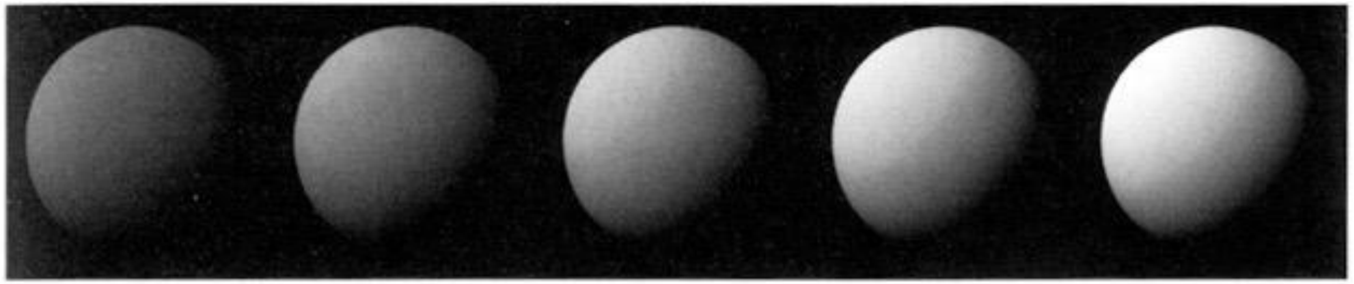
$$L_d = k_d \, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{l})$$

diffuse coefficient

diffusely reflected light

Lambertian shading

Produces a matte appearance



$k_d \longrightarrow$

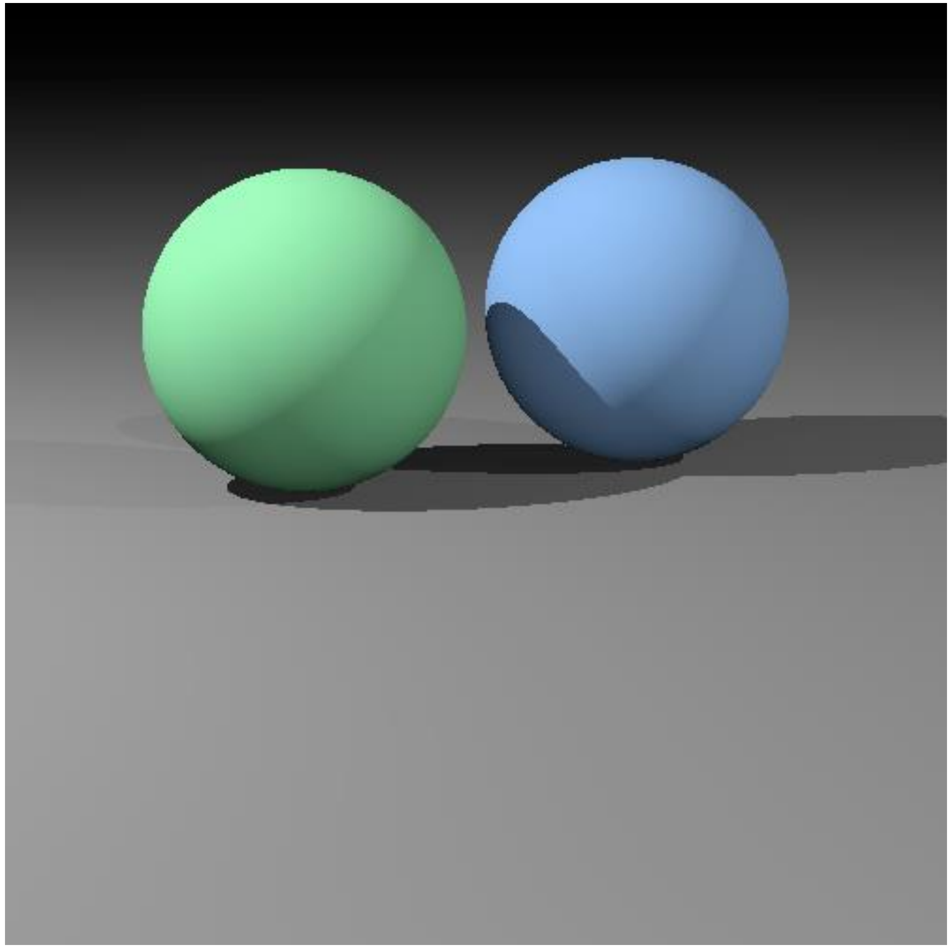


Image without shading

```
for 0 <= iy < ny
   for 0 <= ix < nx
  {
      ray = camera.getRay(ix, iy);
      firstSurface = scene.intersect(result,ray);
      if (firstSurface)
         image.set(ix, iy, firstSurface.color);
      else
         image.set(ix, iy, background.color);
   }
```

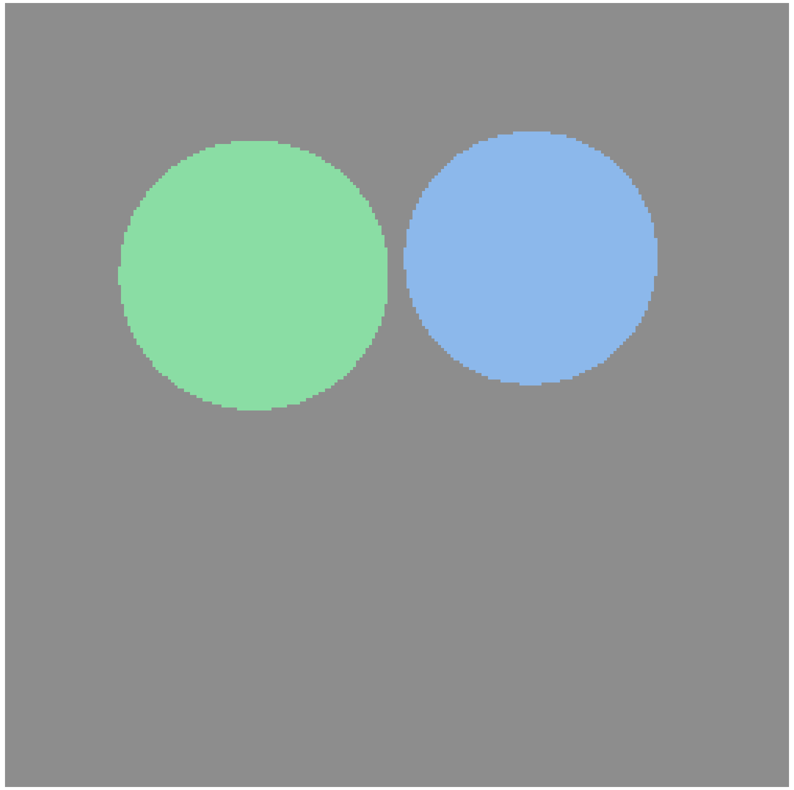
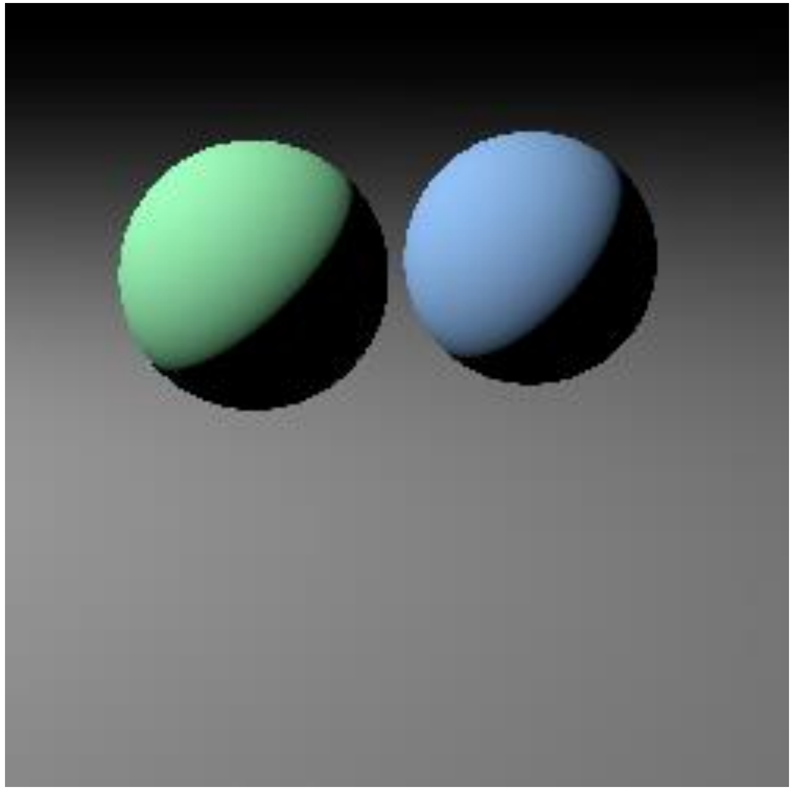


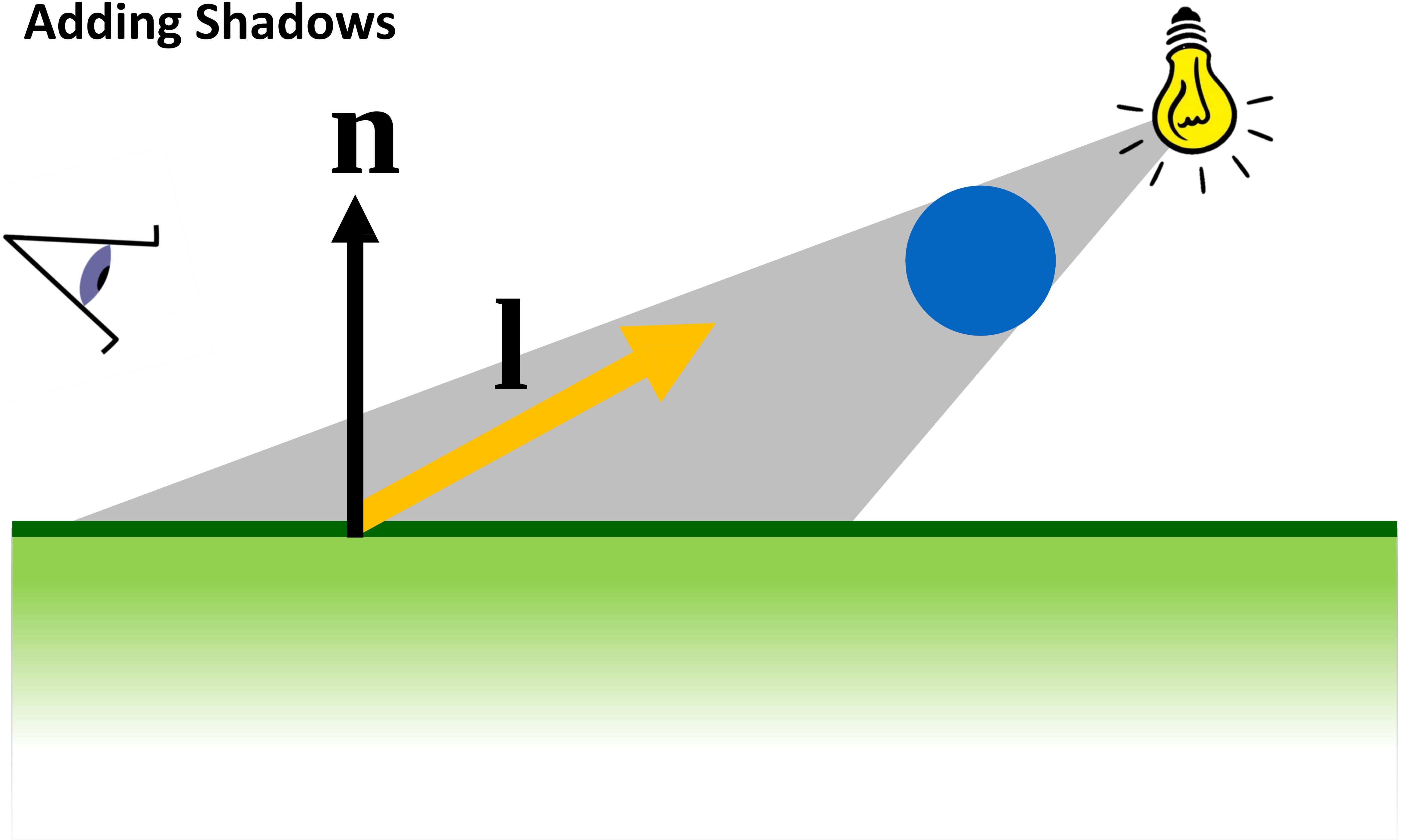
Image with shading

```
for 0 <= iy < ny
   for 0 <= ix < nx
  {
      ray = camera.getRay(ix, iy);
      firstSurface = scene.intersect(result,ray);
      image.set(ix, iy,
               firstSurface.shade(ray,light,result.point,
                     result.normal);
      else
         image.set(ix, iy, background.color);
   }
```

```
Surface.shade(ray,light,point,normal) {
        l=light.pos-position;
        it= surface.k*light.intensity*max(0,normal.l);
        return surface.color*it;
}
```



Adding Shadows

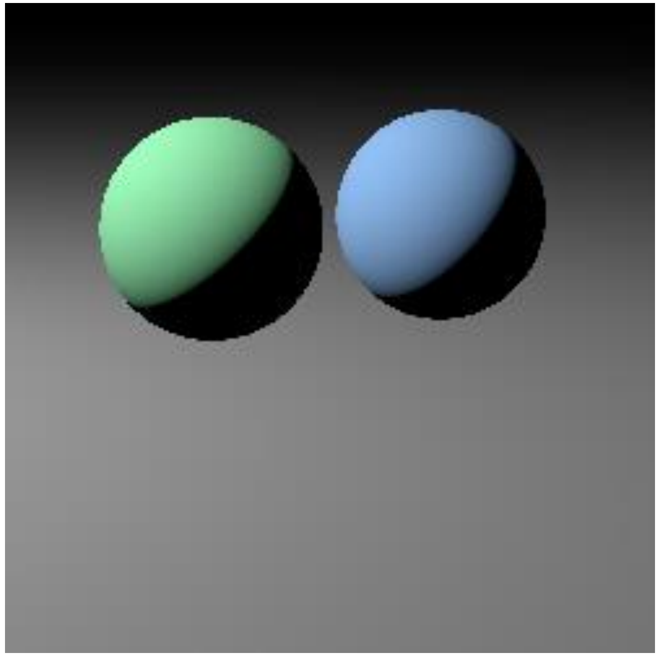


Shadows

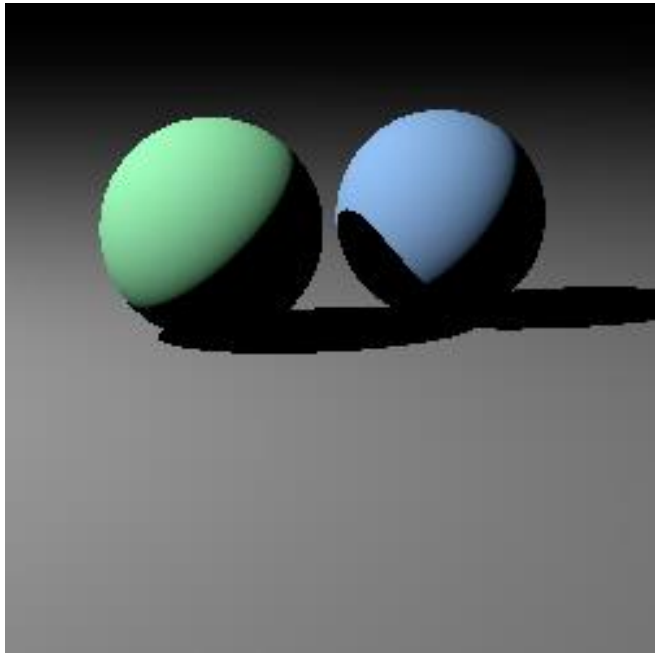
- Surface is only illuminated if nothing blocks its view of the light.
- With ray tracing it's easy to check if a point in the scene is in shadow.

  just shoot a ray from the point to the light and intersect it with the scene!

```
Surface.shade(ray,light,point,normal) {
        l=light.pos-position;
        shadowray=(point,l);
        if  !scene.intersect(result,shadowray)
        {
            it= surface.k*light.intensity*
                max(0,normal.l);
            return surface.color*it;
        }
        else
            return black;
}
```



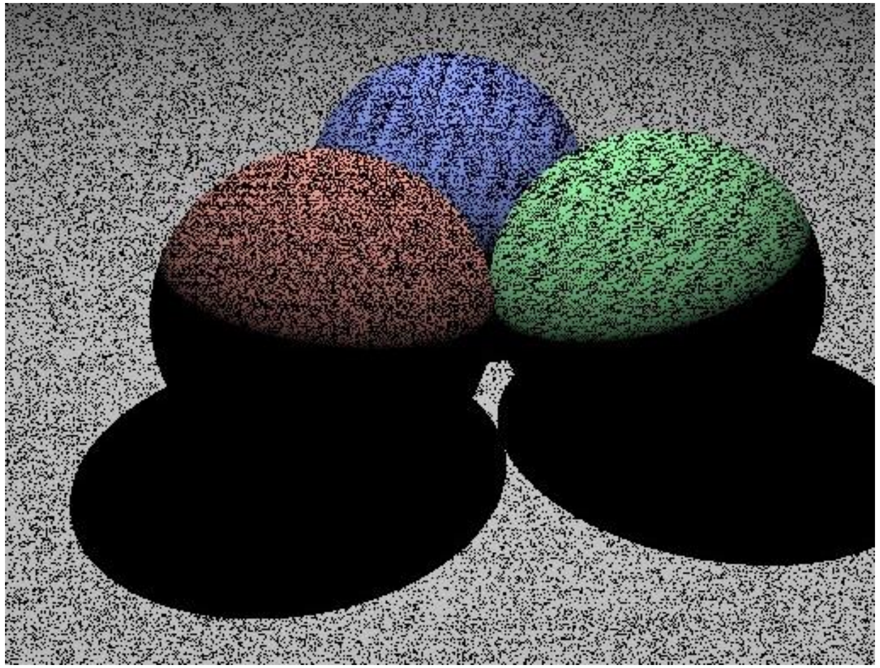
Without shadows



With shadows

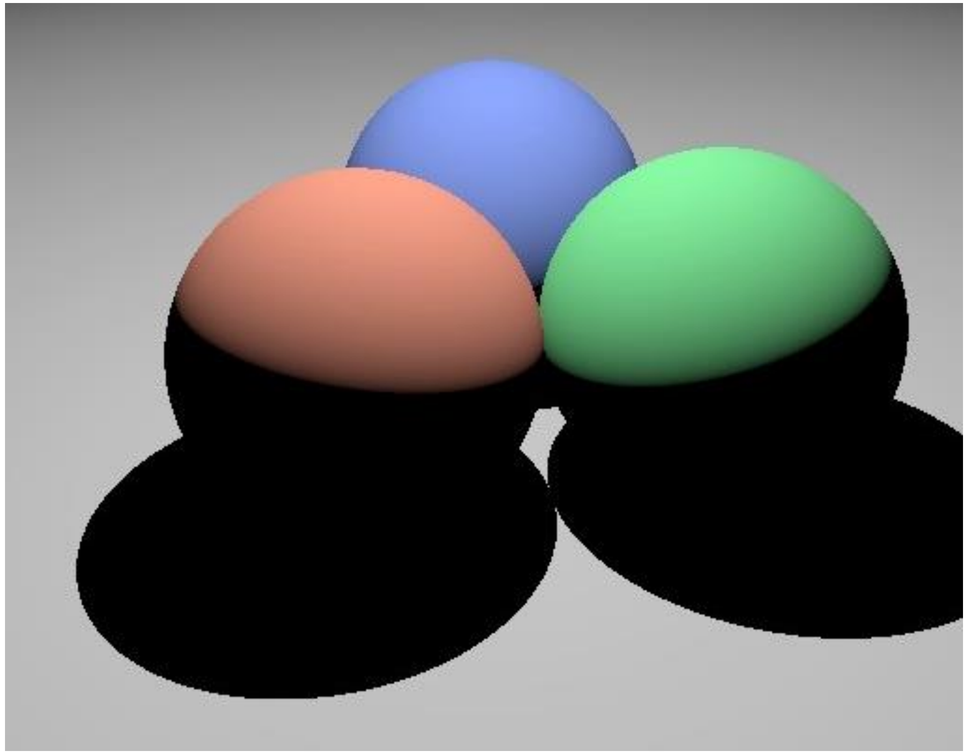
Classic shadow error

What’s going on?



Classic shadow error

Start shadow rays just outside surface



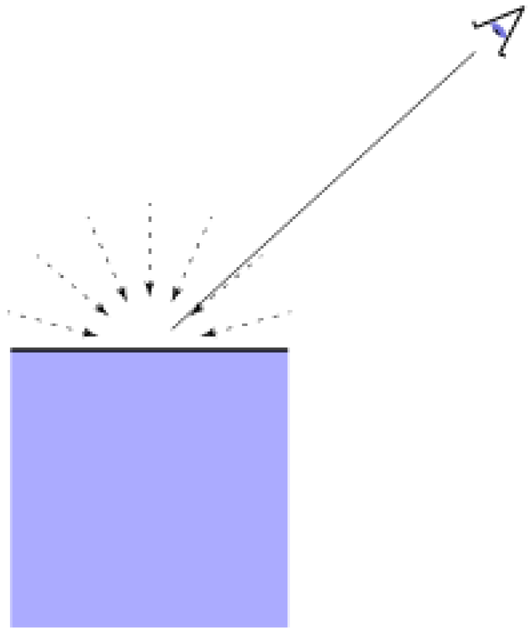
Multiple lights

- Important to fill in black shadows
- Just loop over lights, add contributions
- Ambient shading
  - black shadows are not really right
  - one solution: dim light at camera
  - alternative: add a constant “ambient” color to the shading…

Ambient shading

Shading that does not depend on anything

– add constant color to account for disregarded illumination and fill in black shadows



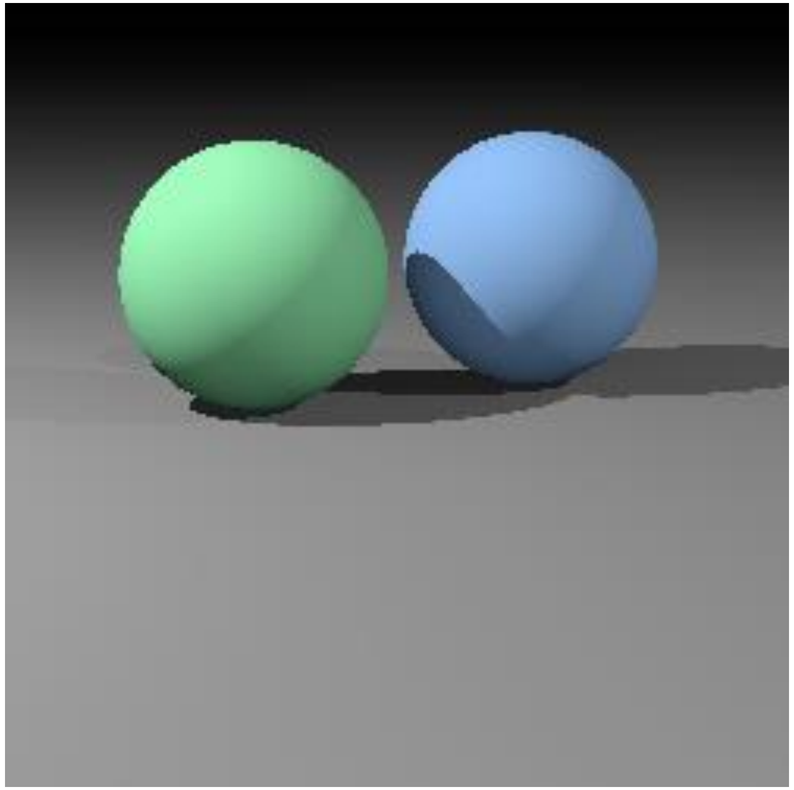
$$L_a = k_a\, I_a$$

ambient coefficient

reflected ambient light

Image with multiple lights

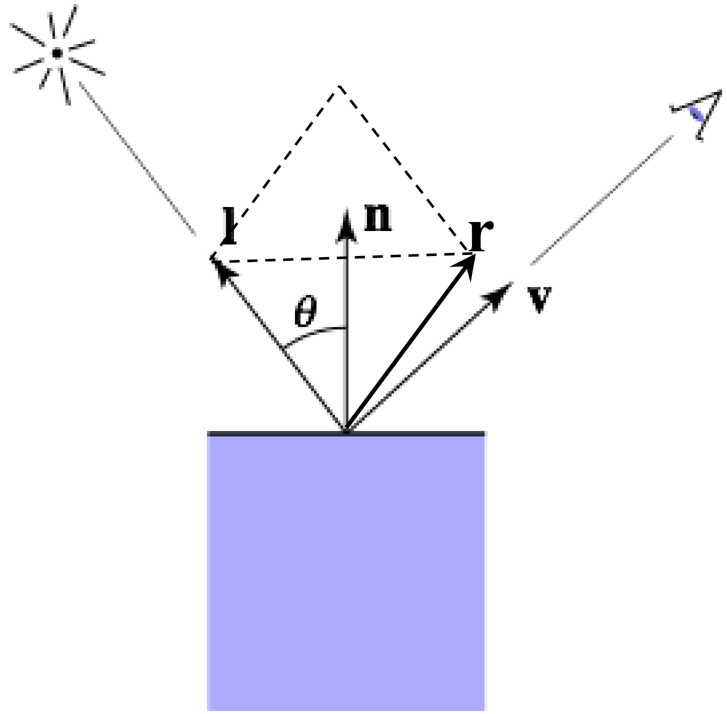
```
shade(ray, lights, point, normal) {
   result = ambient;
   for light in lights {
         l=light.pos-position;
         shadowray=(point+ε*normal,l);
         if  !scene.intersect(result,shadowray)
         {
               it= surface.k*light.intensity*max(0,normal.l);
               result+= surface.color*it;
         }
   }
   return result;
}
```



Mirror reflection

Intensity depends on view direction

– reflects incident light from mirror direction



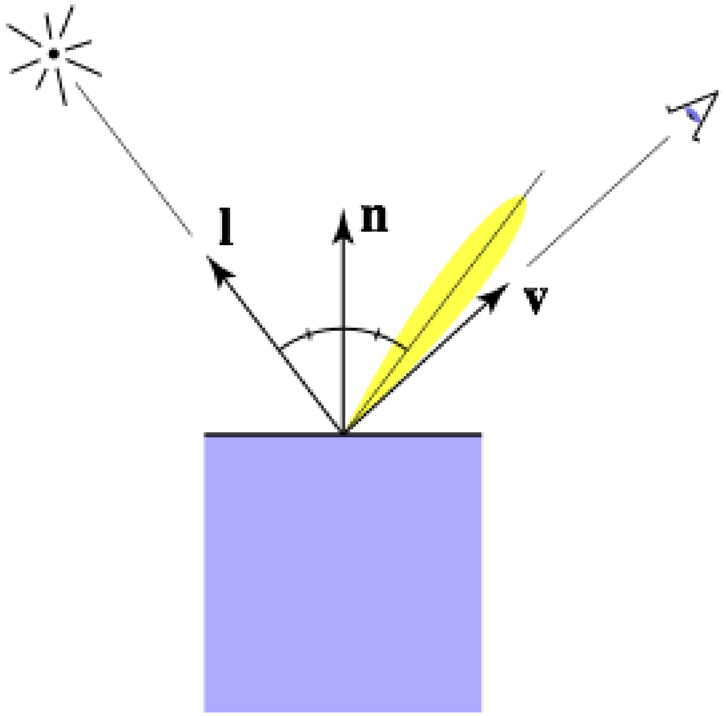
$$\mathbf{r} = 2(\mathbf{n}.\mathbf{l})\mathbf{n} - \mathbf{l}$$

Specular shading (Phong)

Intensity depends on view direction

– bright near mirror configuration

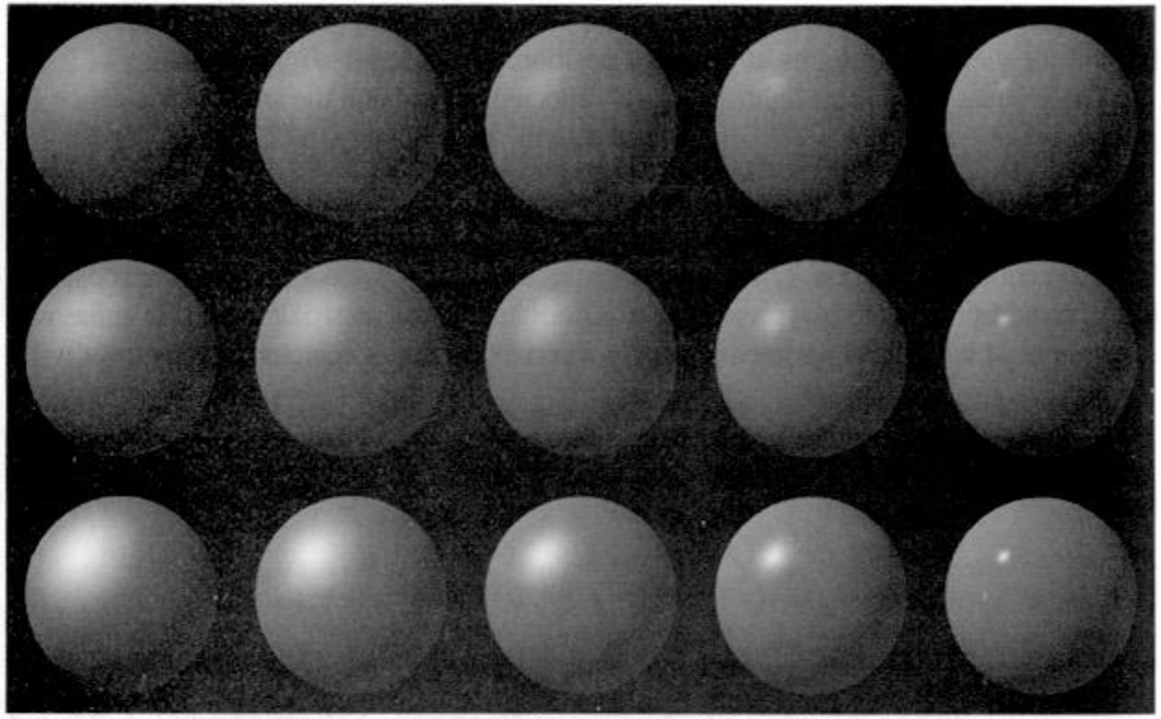
$$k_s * I_s * \boxed{(\mathbf{v}.\mathbf{r})^{shiny}}$$



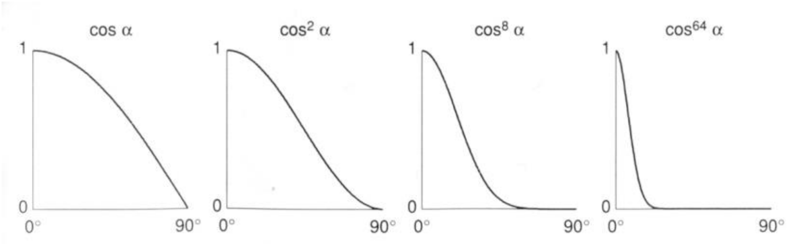
Phong model

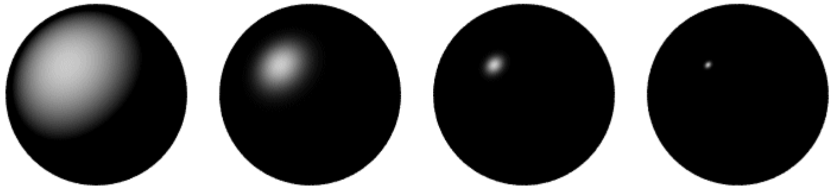
Increasing *shiny* narrows the lobe

k_s

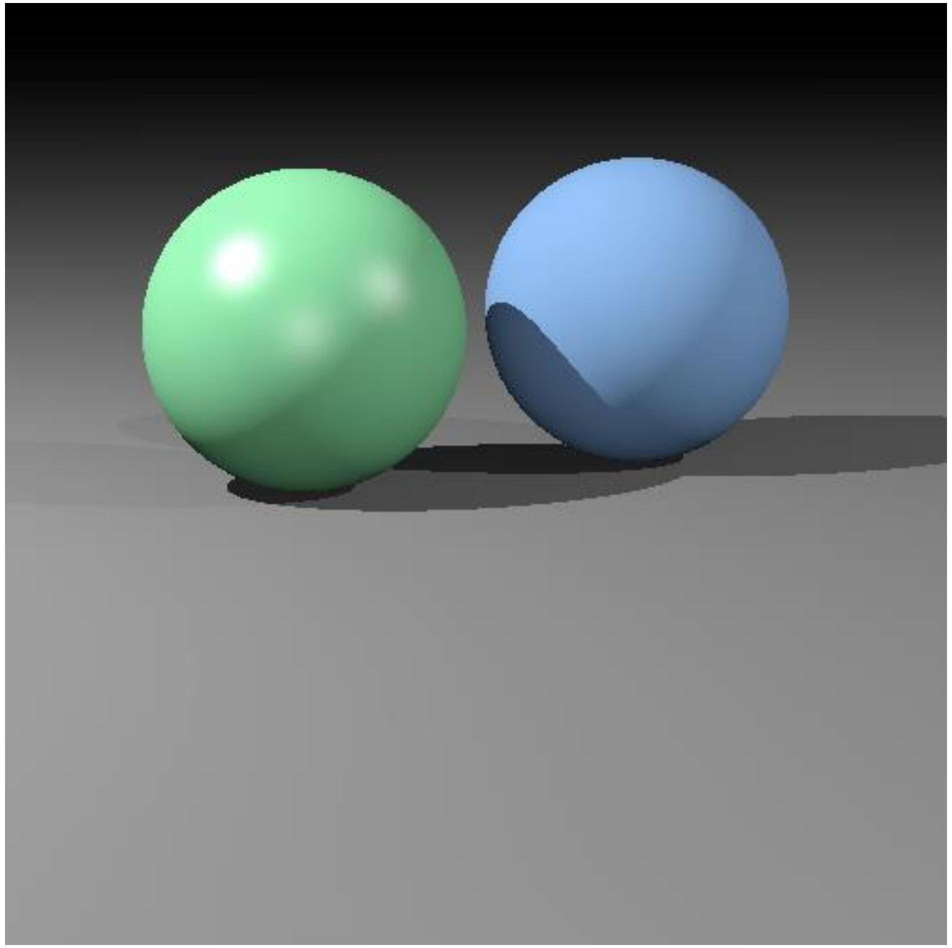


shiny



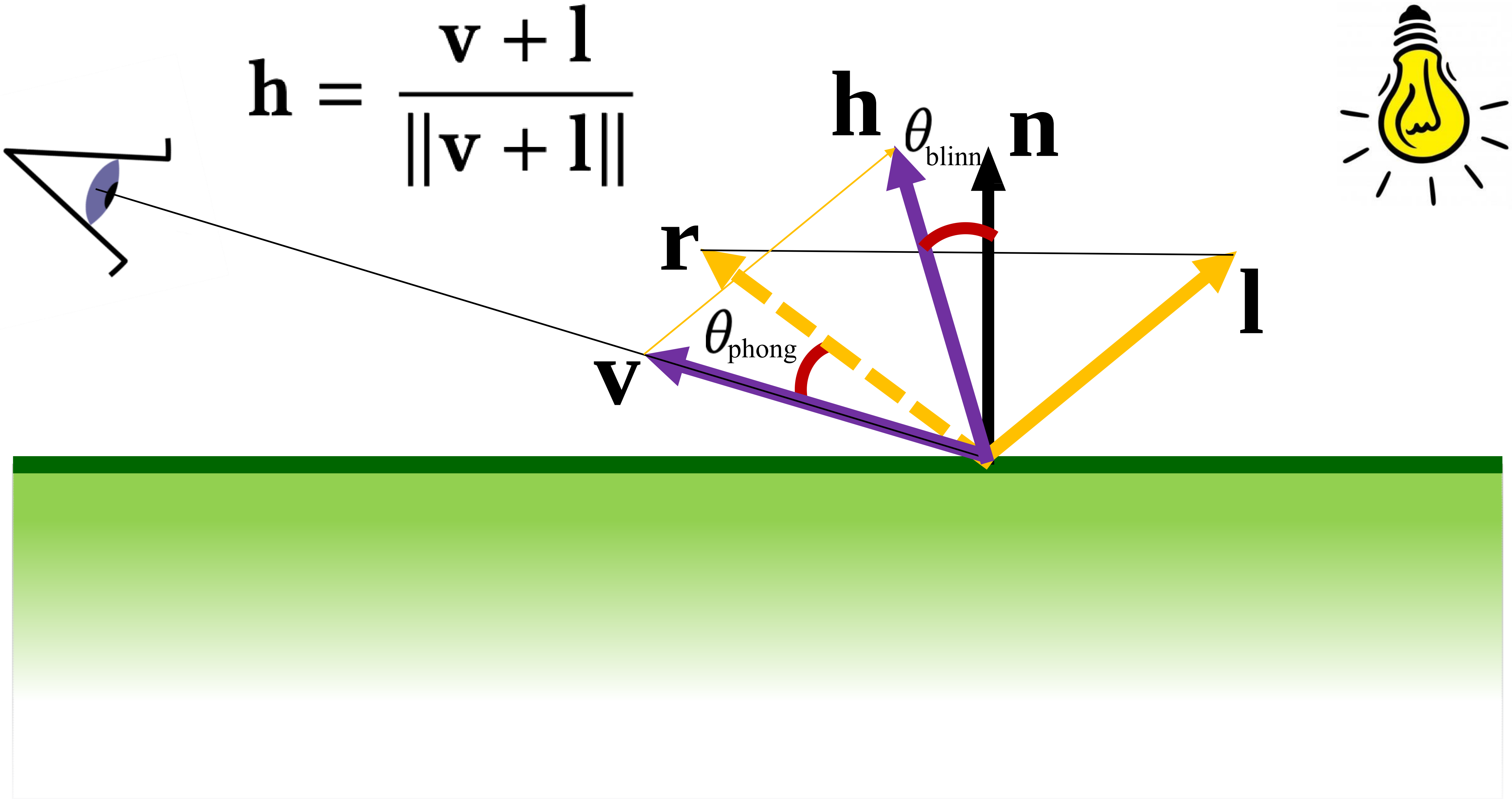


Diffuse + Specular (Phong) shading

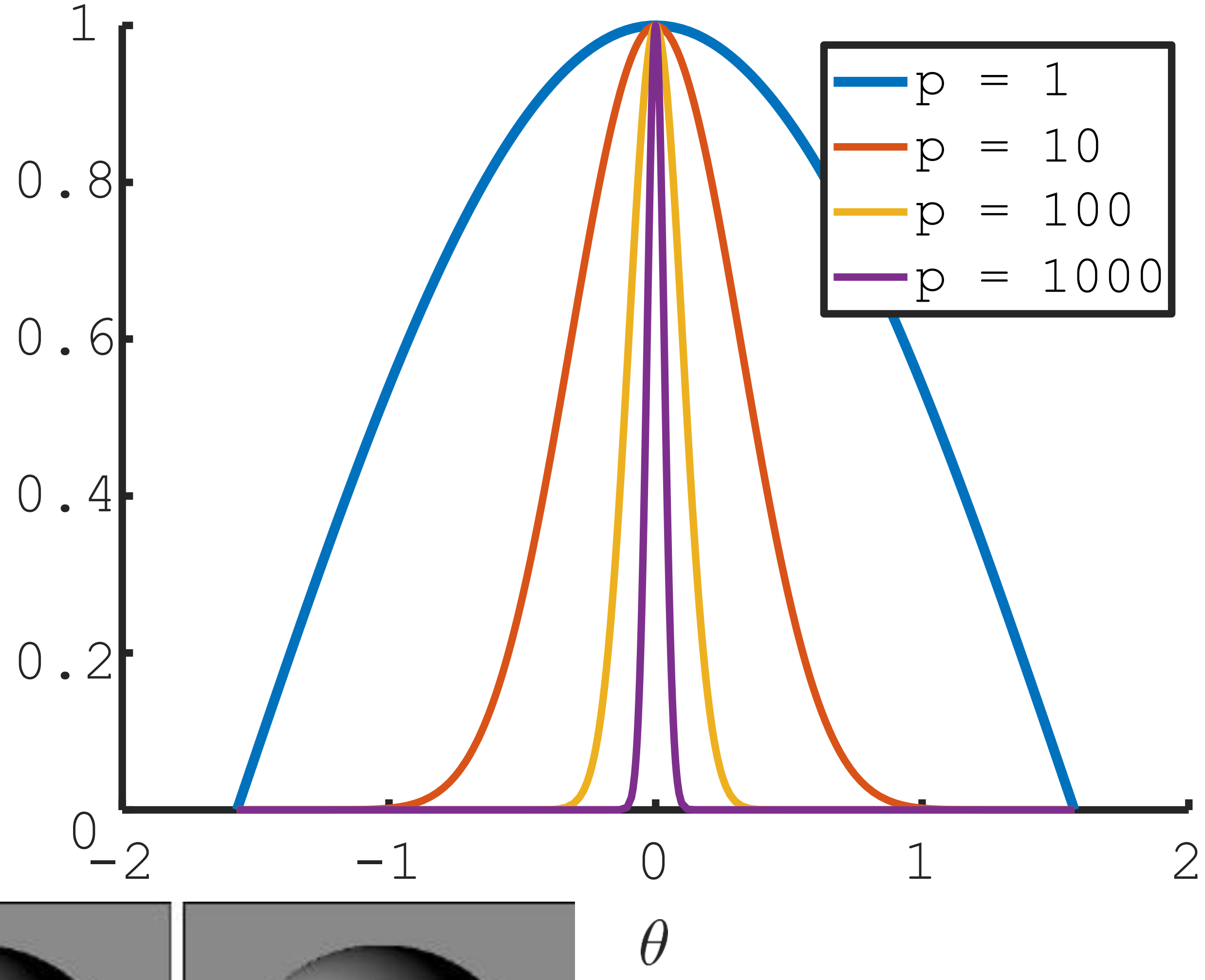


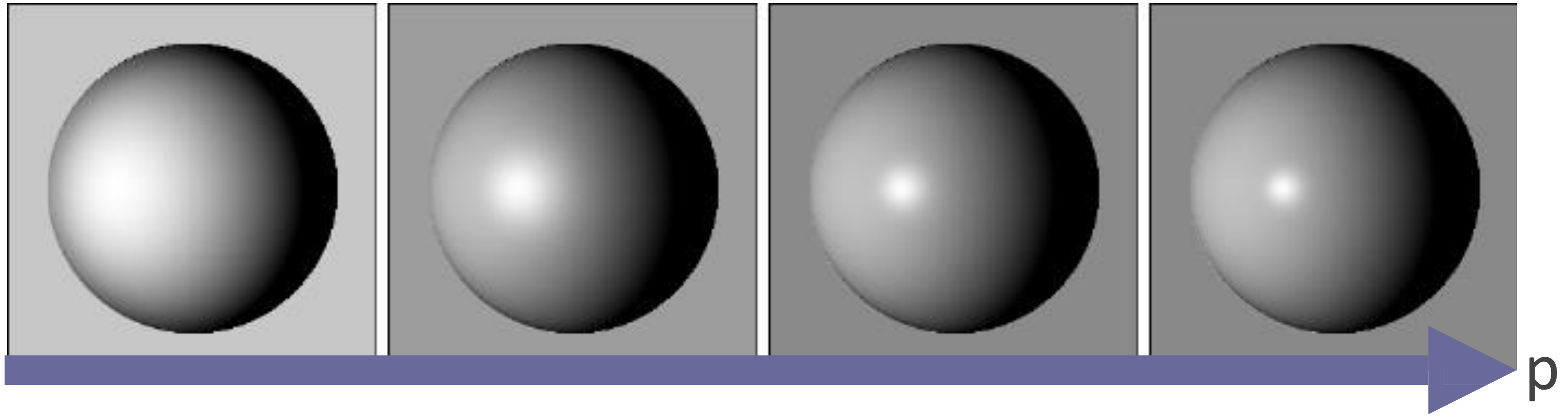
Specular Shading (Blinn)

$$\mathbf{h} = \frac{\mathbf{v} + \mathbf{l}}{\|\mathbf{v} + \mathbf{l}\|}$$

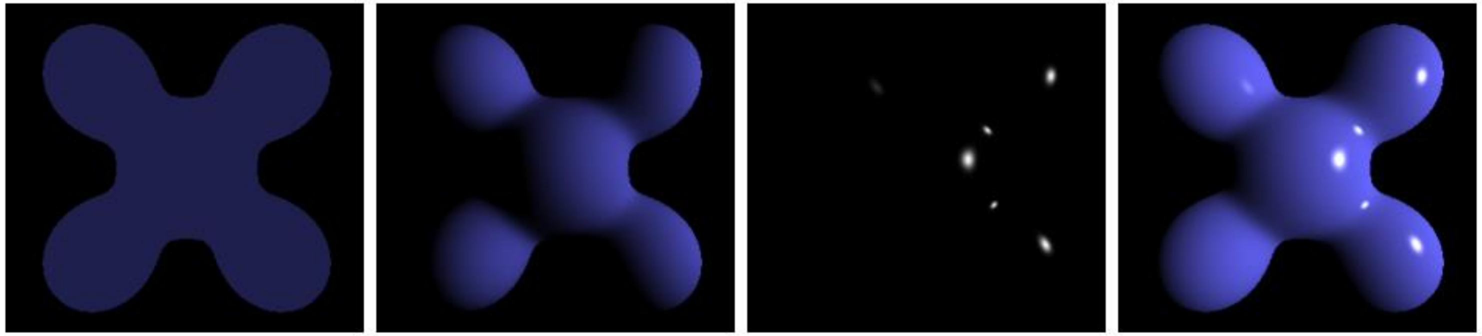


$$L = k_s \, I \, \max(0, \mathbf{n} \cdot \mathbf{h})^p$$





Local Illumination



- Usually include ambient, diffuse, Phong in one model

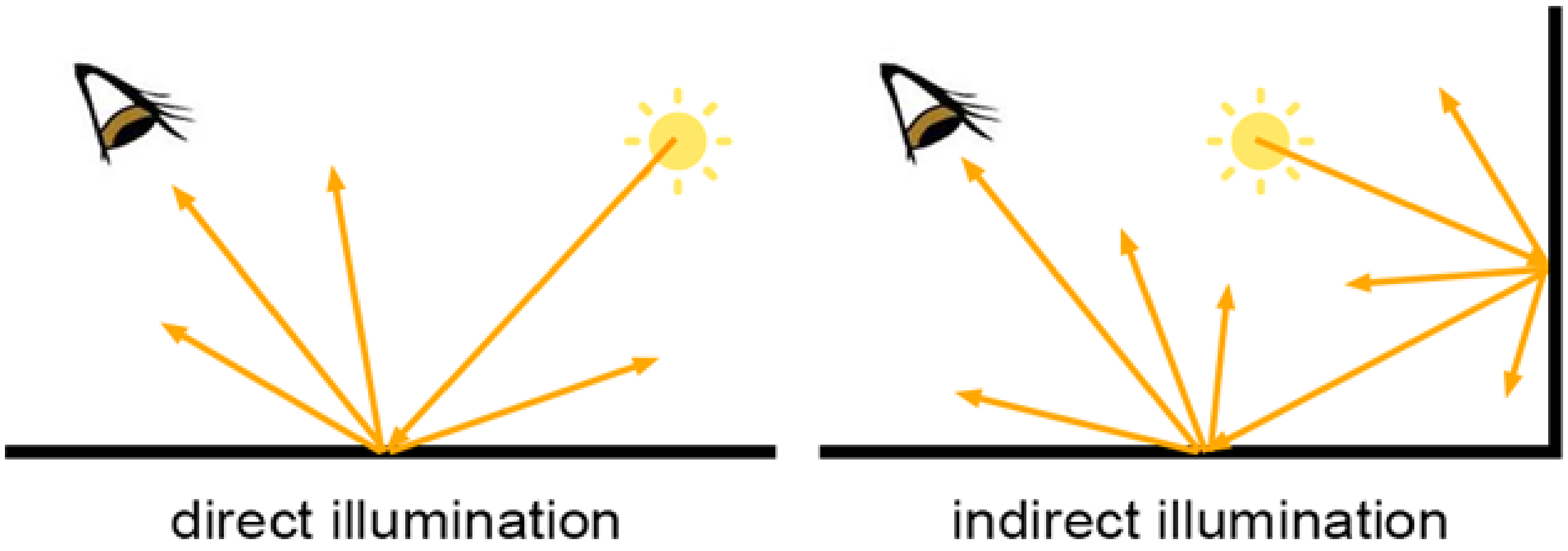
$$\begin{aligned} L &= L_a + L_d + L_s \\ &= k_a\, I_a + k_d\, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{l}) + k_s\, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{h})^p \end{aligned}$$

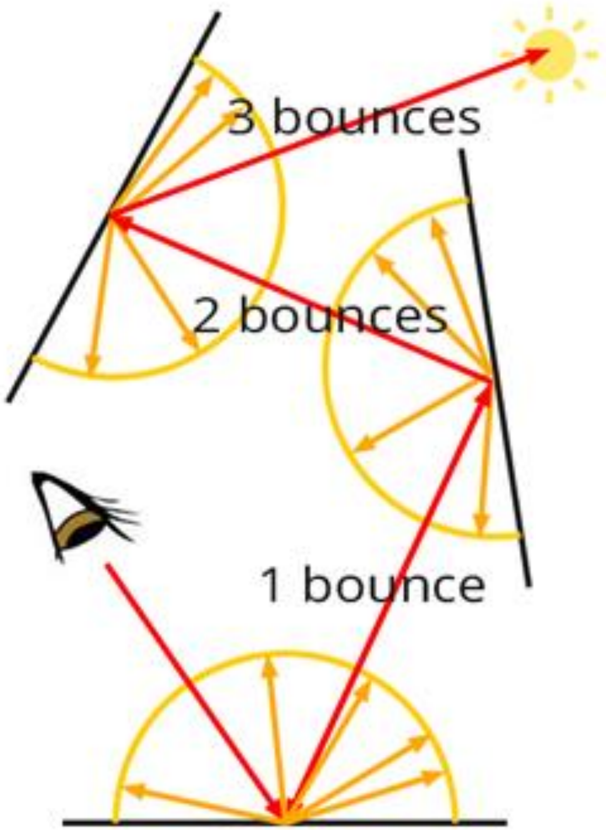
- The final result is the sum over many lights

$$L = L_a + \sum_{i=1}^{N} [(L_d)_i + (L_s)_i]$$

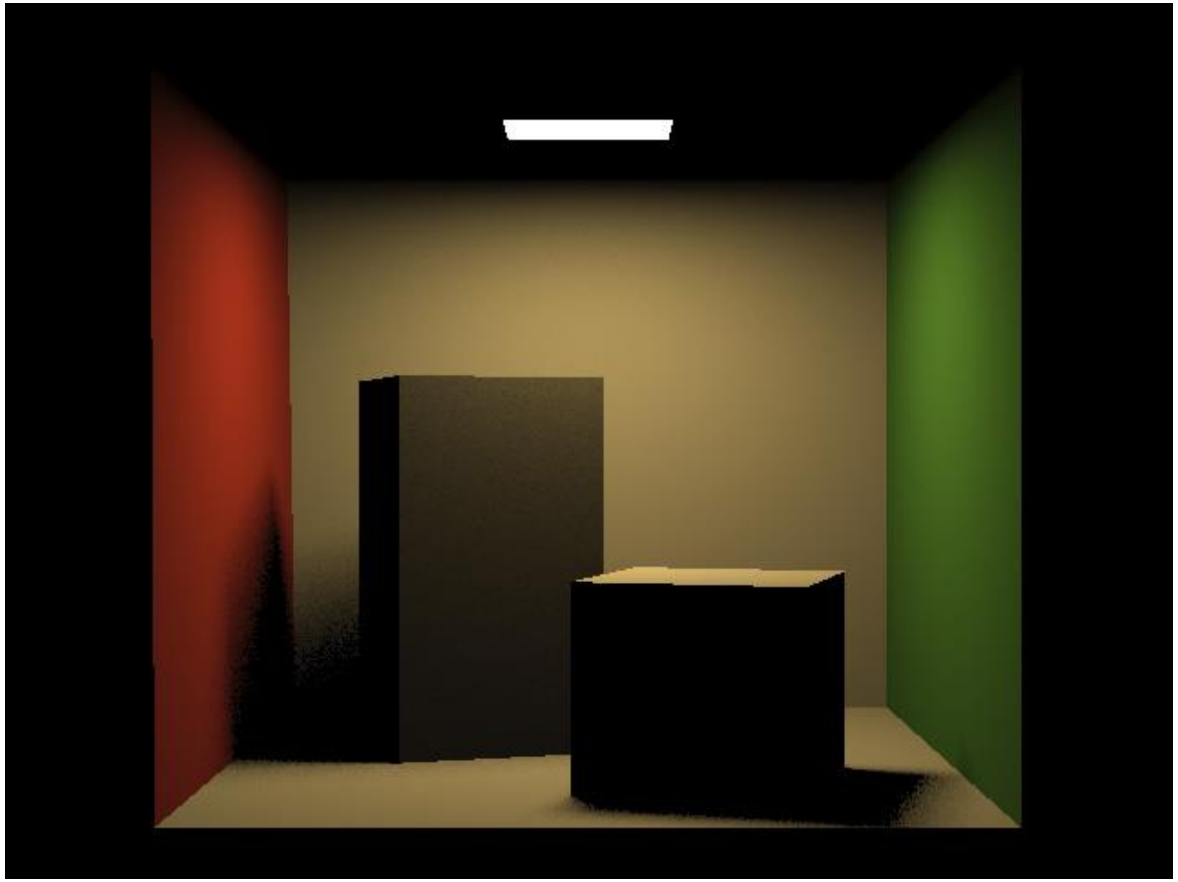
$$L = k_a\, I_a + \sum_{i=1}^{N} \left[k_d\, (I_i/r_i^2) \max(0, \mathbf{n} \cdot \mathbf{l}_i) + k_s\, (I_i/r_i^2) \max(0, \mathbf{n} \cdot \mathbf{h}_i)^p \right]$$

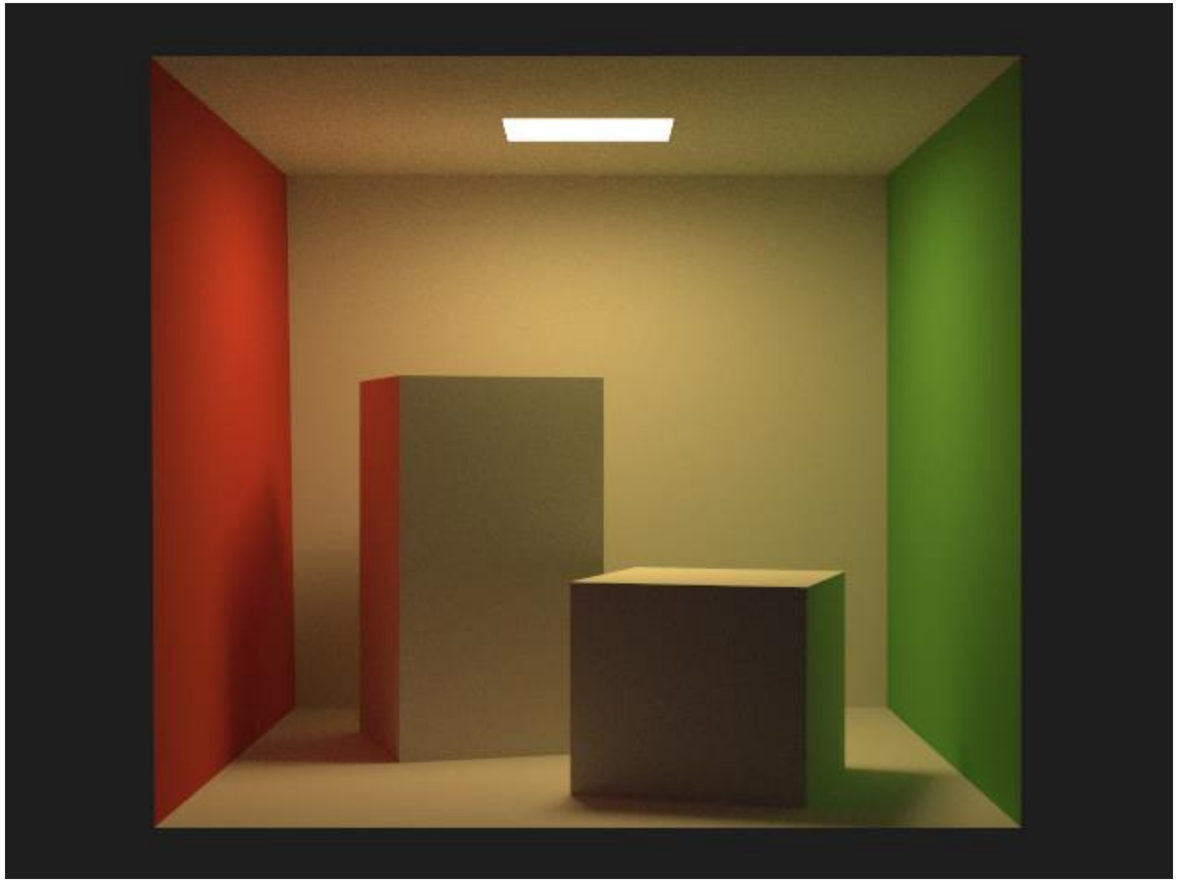
Direct Illumination
…no Global Effects so far





Direct vs. Indirect Illumination





http://www.deluxerender.com/2017/01/the-cornell-box-a-renderers-rite-of-pathage/
https://en.wikipedia.org/wiki/Cornell_box

Local vs. Global Illumination

Local Illumination Models

- e.g. Phong, Blinn.
- Model source from a light reflected once off a surface towards the eye.
- Indirect light is included with an ad hoc “ambient” term which is normally constant across the scene.

Global Illumination Models

- e.g. recursive ray tracing (incomplete model).
- Try to measure light propagation in the scene.
- Model interaction between objects, other objects, and their environment

Path Tracing

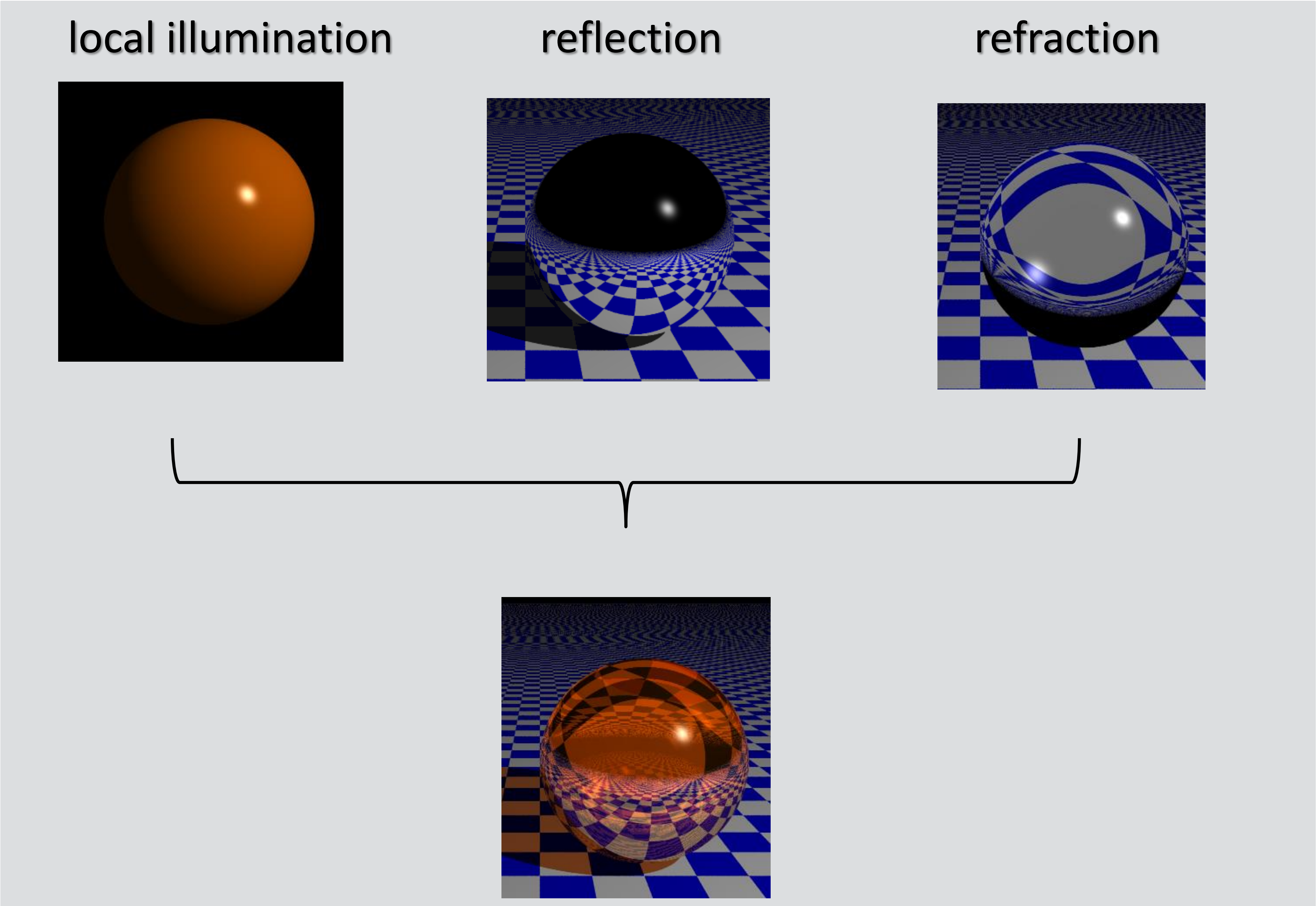
- A ray from a light L can bounce of any number of specular S and diffuse objects D before entering the eye E. The paths from E to L for eg. can be

  E-D-L, E-S-D-D-S-S-D-S-L, E-D-D-S-D-S-L…

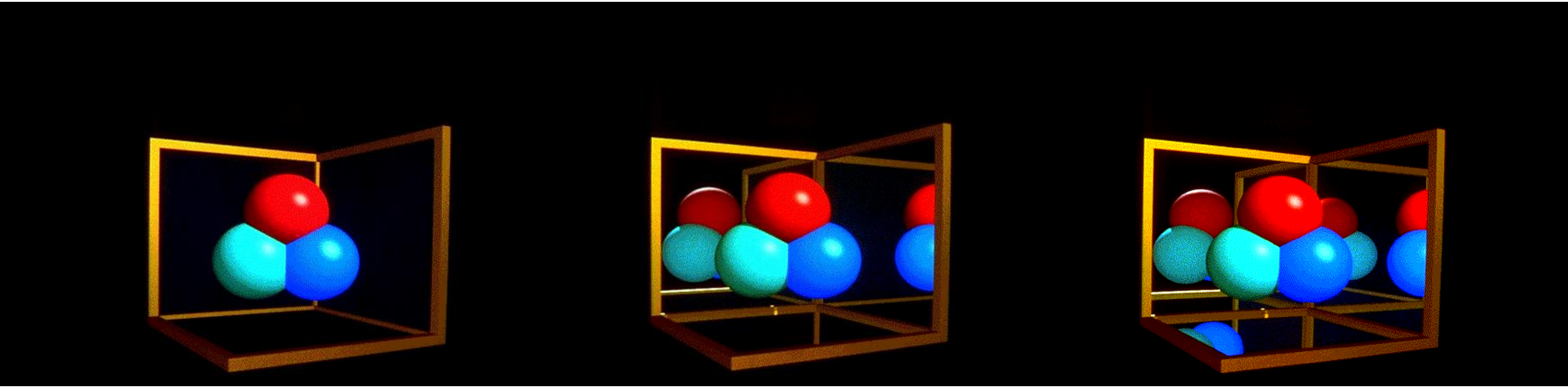
- Rays are infinitely thin
- Don’t disperse

- Ray Tracing model shiny objects exhibiting multiple reflections, i.e. paths of the form

  $E - S^* - D^+ – L.$

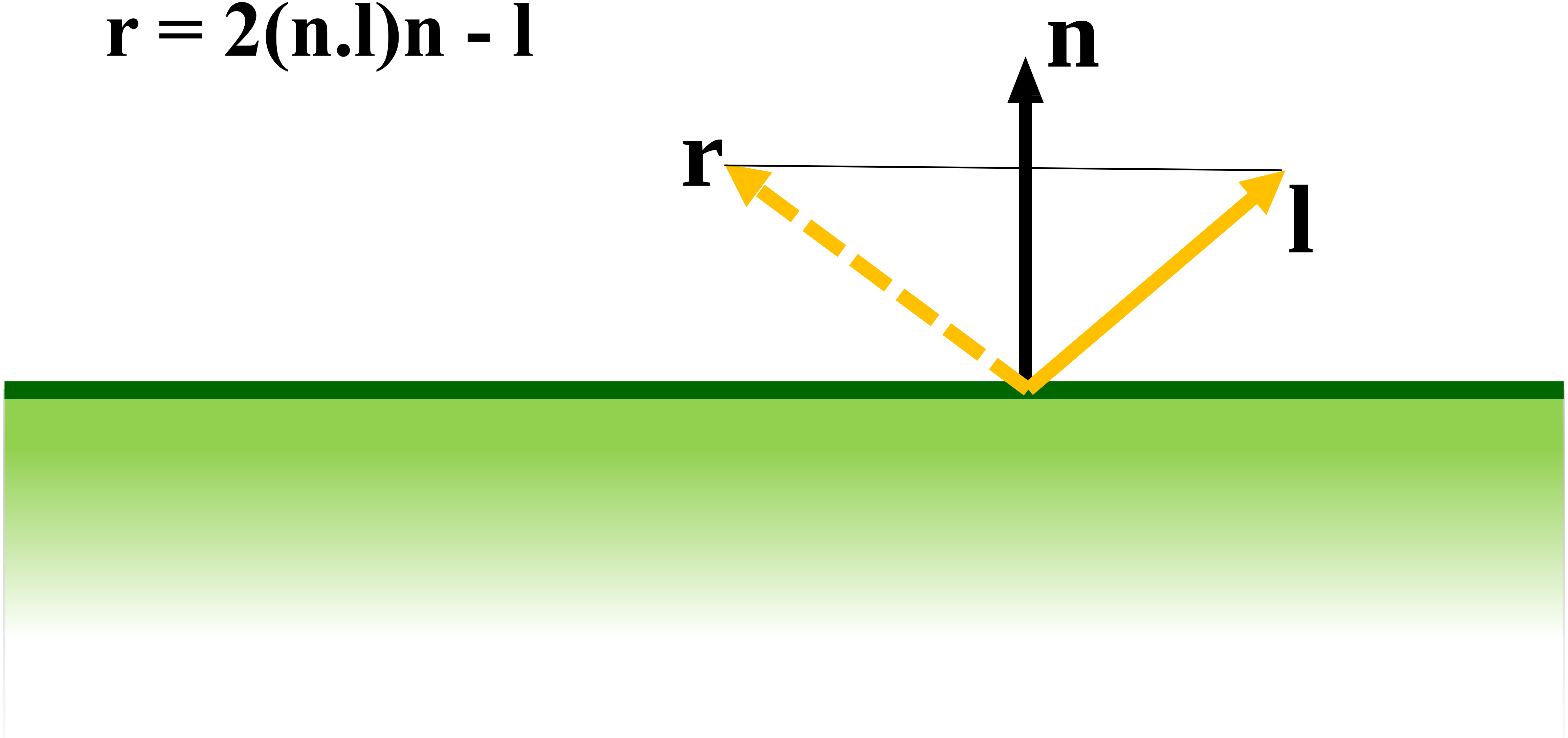

local illumination
reflection
refraction

Ray Tracing recursion



Reminder: reflected ray

$$r = 2(n.l)n - l$$



Ray Tracing

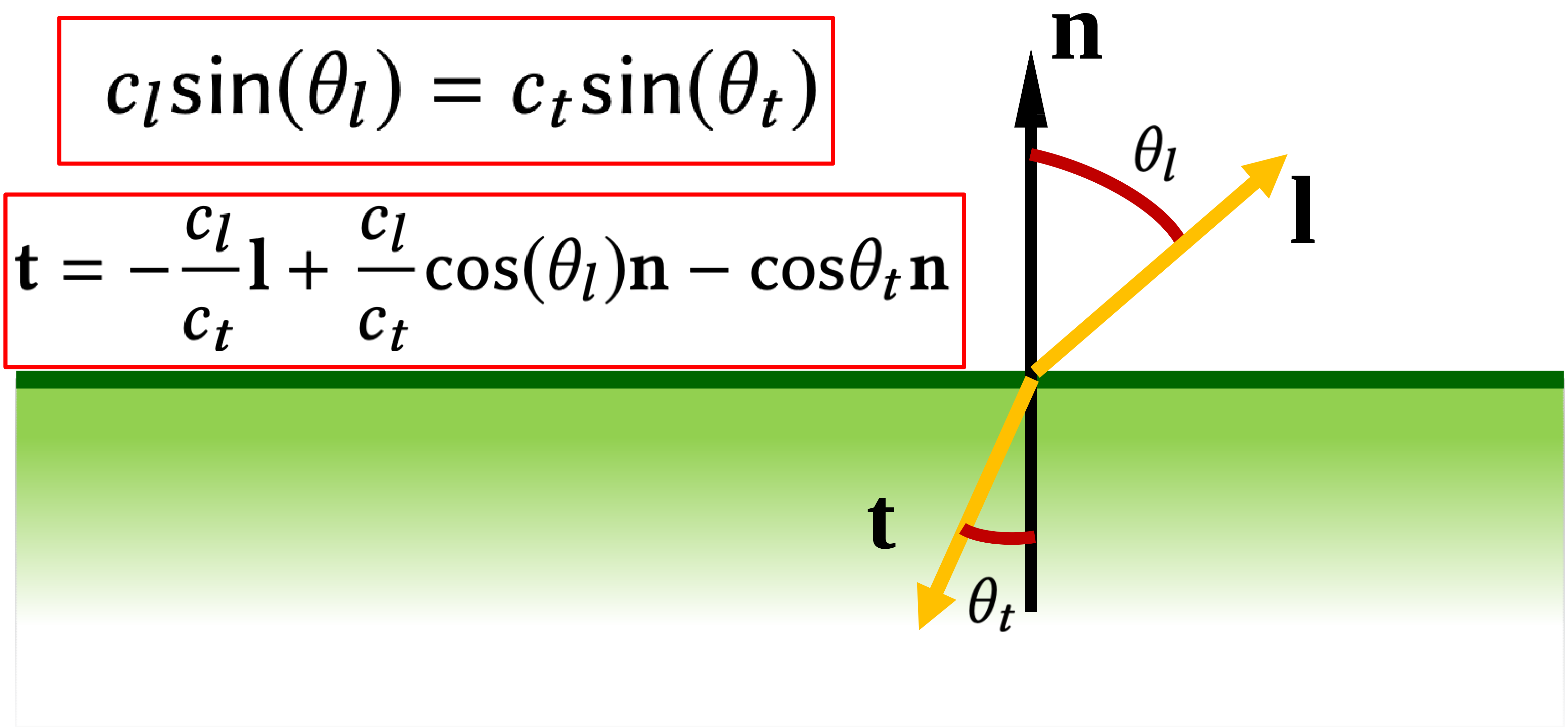
```
for each pixel in the image {
      pixel colour = rayTrace(viewRay, 0)
}
```

```
colour rayTrace(Ray, depth) {
      for each object in the scene {
            if(Intersect ray with object) {
                  colour = shading model
                  if(depth < maxDepth)
                  colour +=rayTrace(reflectedRay,depth+1)
            }
      }
      return colour
}
```

Refraction (Snell's Law)

$$\boxed{c_l \sin(\theta_l) = c_t \sin(\theta_t)}$$

$$\boxed{\mathbf{t} = -\frac{c_l}{c_t}\mathbf{l} + \frac{c_l}{c_t}\cos(\theta_l)\mathbf{n} - \cos\theta_t \mathbf{n}}$$

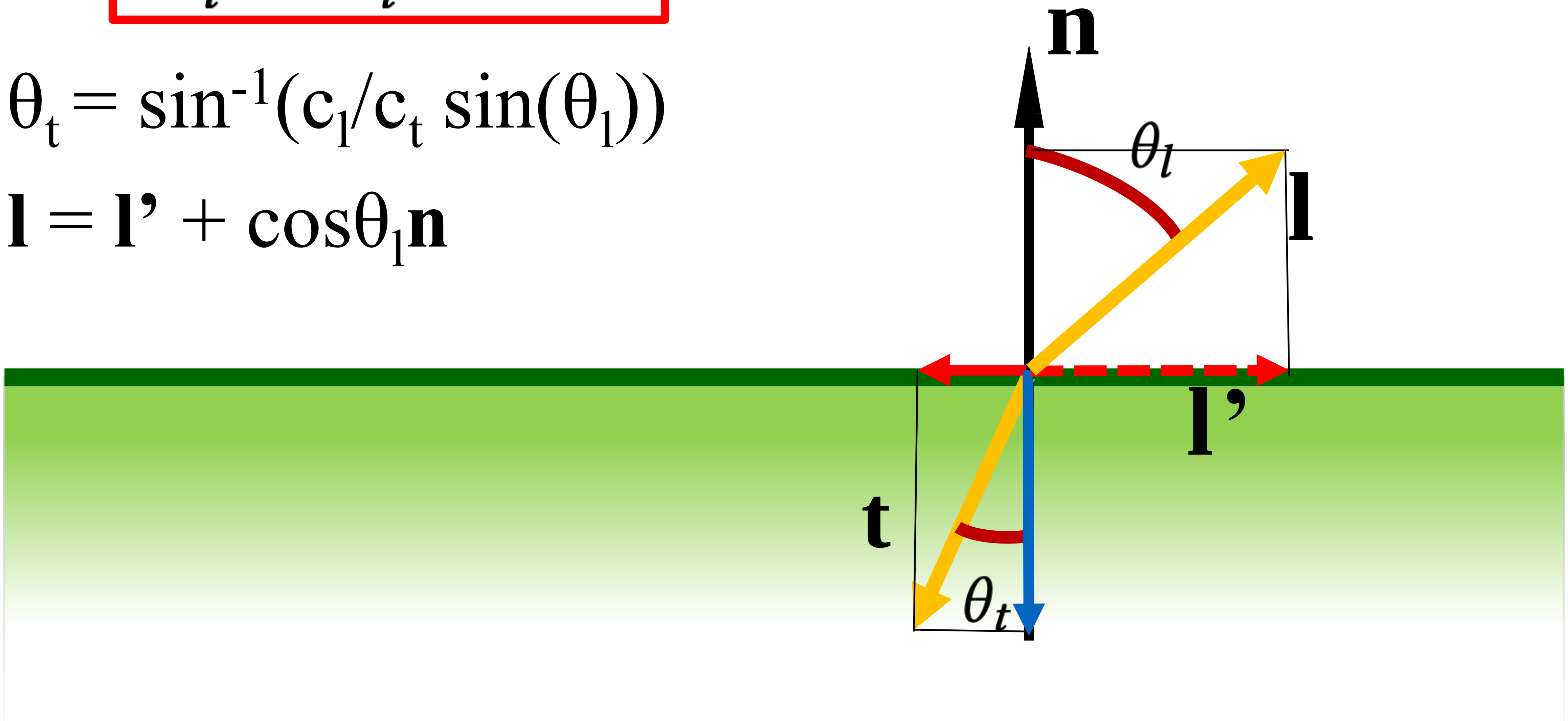


Refraction (Snell's Law)

$$\mathbf{t} = \boxed{-\frac{c_l}{c_t}\mathbf{l} + \frac{c_l}{c_t}\cos(\theta_l)\mathbf{n}}\boxed{-\cos\theta_t\mathbf{n}}$$

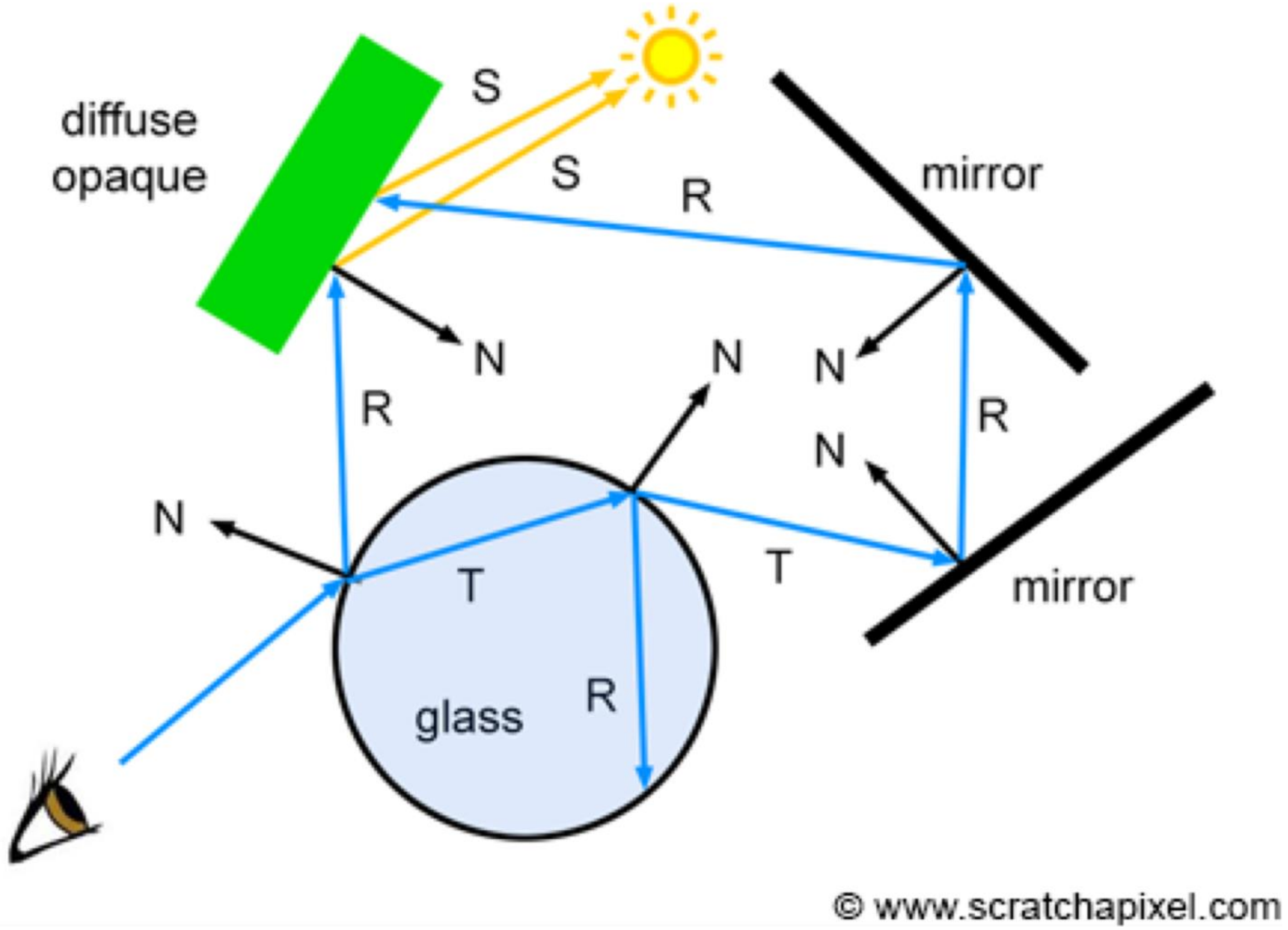
$$\theta_t = \sin^{-1}(c_l/c_t \sin(\theta_l))$$

$$\mathbf{l} = \mathbf{l'} + \cos\theta_l\mathbf{n}$$



```
colour rayTrace(Ray, depth) {
    for each object in the scene {
        if(Intersect ray with object) {
            colour = shading model
            if(depth < maxDepth) {
                colour +=
                    rayTrace(reflectedRay,depth+1)
                colour +=
                    rayTrace(refractedRay,depth+1)
            }
        }
    }
    return colour
}
```

Ray Spawning



https://www.scratchapixel.com/lessons/3d-basic-rendering/ray-tracing-overview/light-transport-ray-tracing-whitted

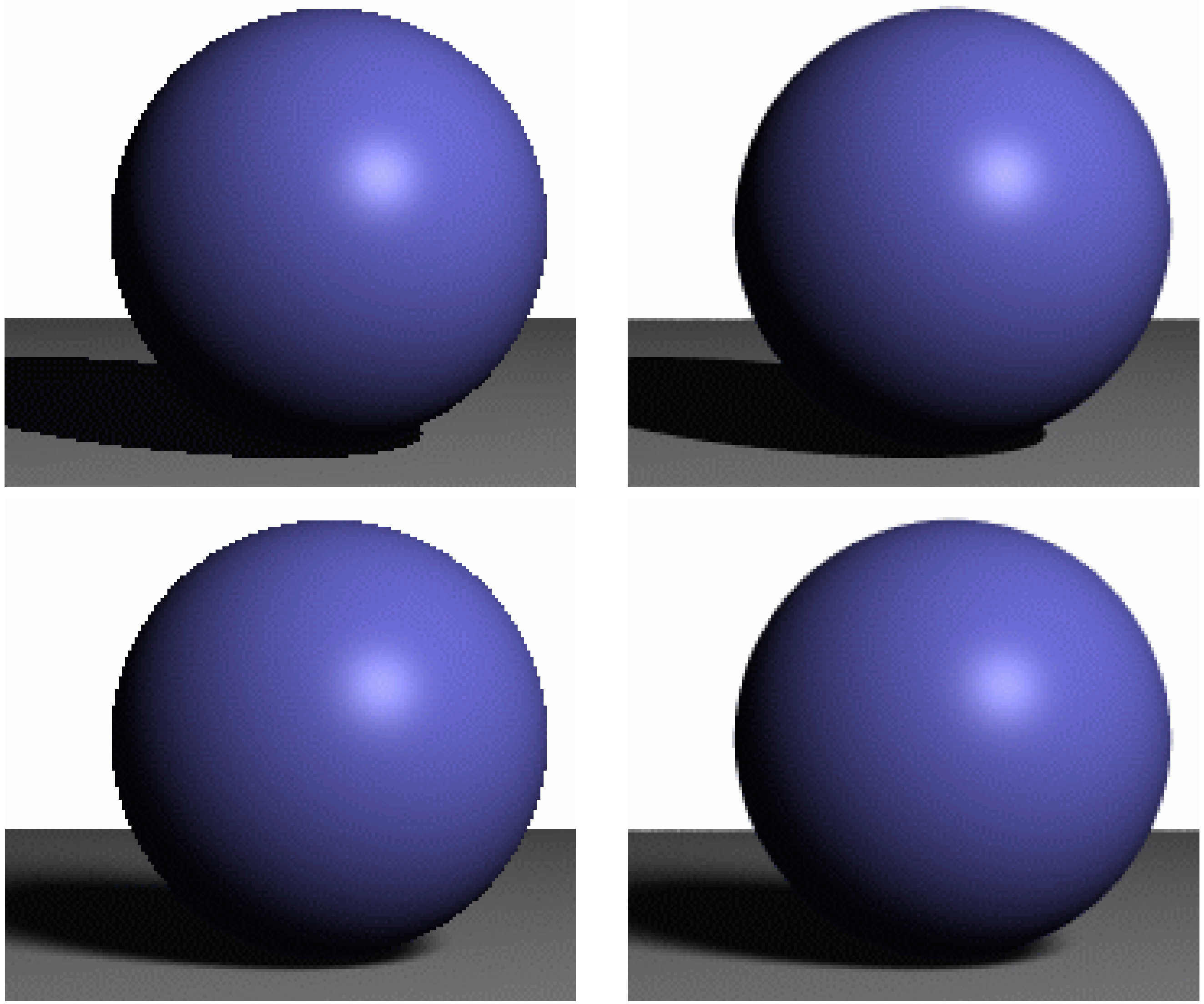
Ray Tracing supersampling

jaggies

w/ antialiasing

point light

area light



Ray Tracing

- Unifies in one framework
  - Hidden surface removal
  - Shadow computation
  - Reflection of light
  - Refraction of light
  - Global **specular** interaction

Assignment #3 tasks

`PointLight::direction` in `src/PointLight.cpp`

Compute the direction to a point light source and its *parametric* distance from a query point.

`DirectionalLight::direction` in `src/DirectionalLight.cpp`

Compute the direction to a direction light source and its *parametric* distance from a query point (infinity).

`src/raycolor.cpp`

Make use of `first_hit.cpp` to shoot a ray into the scene, collect hit information and use this to return a color value.

`src/blinn_phong_shading.cpp`

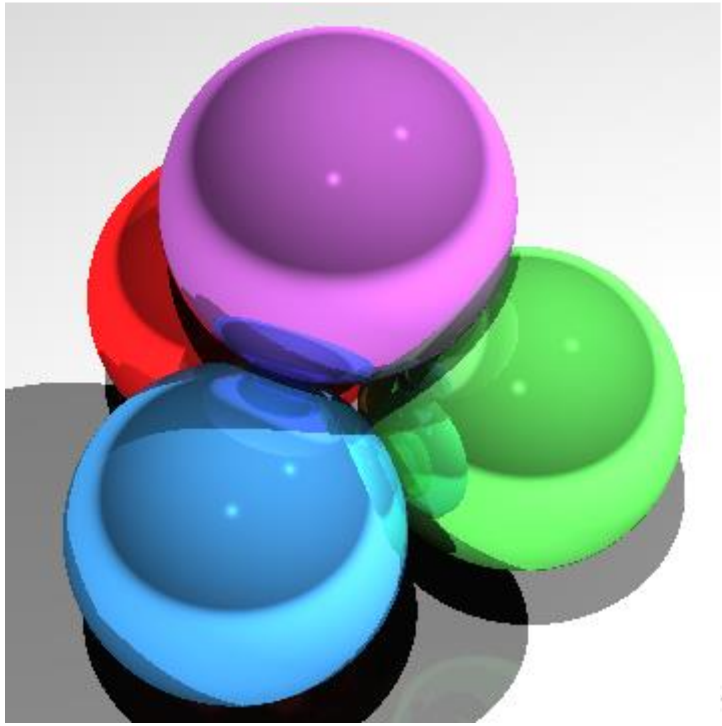
Compute the lit color of a hit object in the scene using Blinn-Phong shading model. This function should also shoot an additional ray to each light source to check for shadows.

`src/reflect.cpp`

Given an "incoming" vector and a normal vector, compute the mirror reflected "outgoing" vector.

`src/creative.json`

Be creative! Design a scene using any of the available Object types (spheres, planes, triangles, triangle soups), Light types (directional, point), Material parameters, colors (materials and/or lights), and don't forget about the camera parameters.

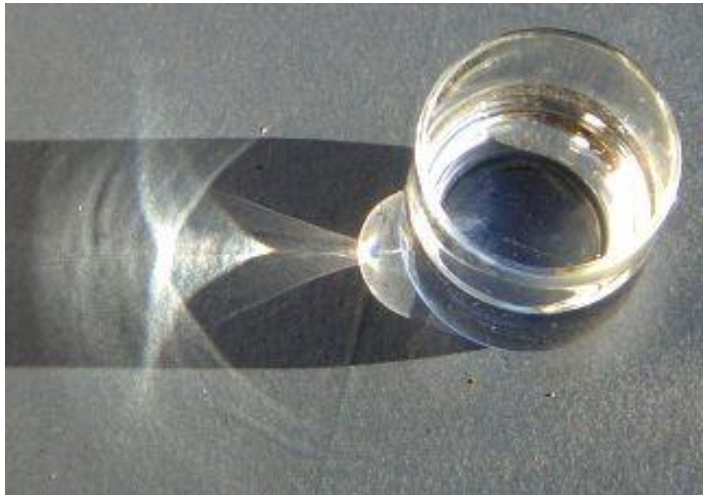


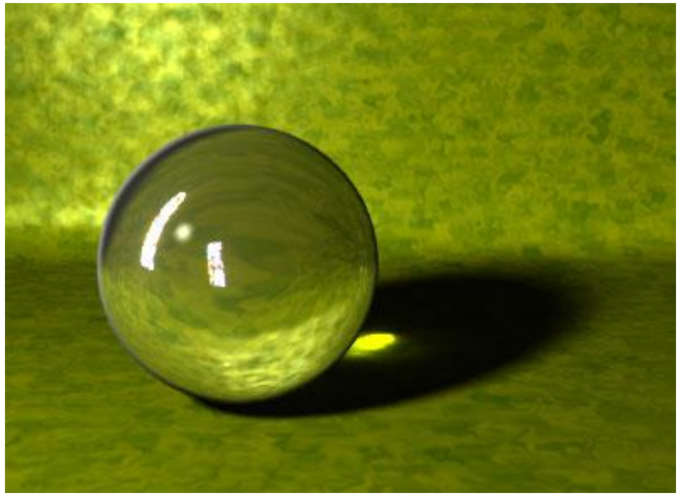
Ray Tracing Deficiencies

- Intersection computation time can be long (solution: **bounding volumes**).
- Recursive algorithm can lead to exponential complexity (solution: stochastic sampling).
- Ignores light transport mechanisms involving diffuse surfaces.

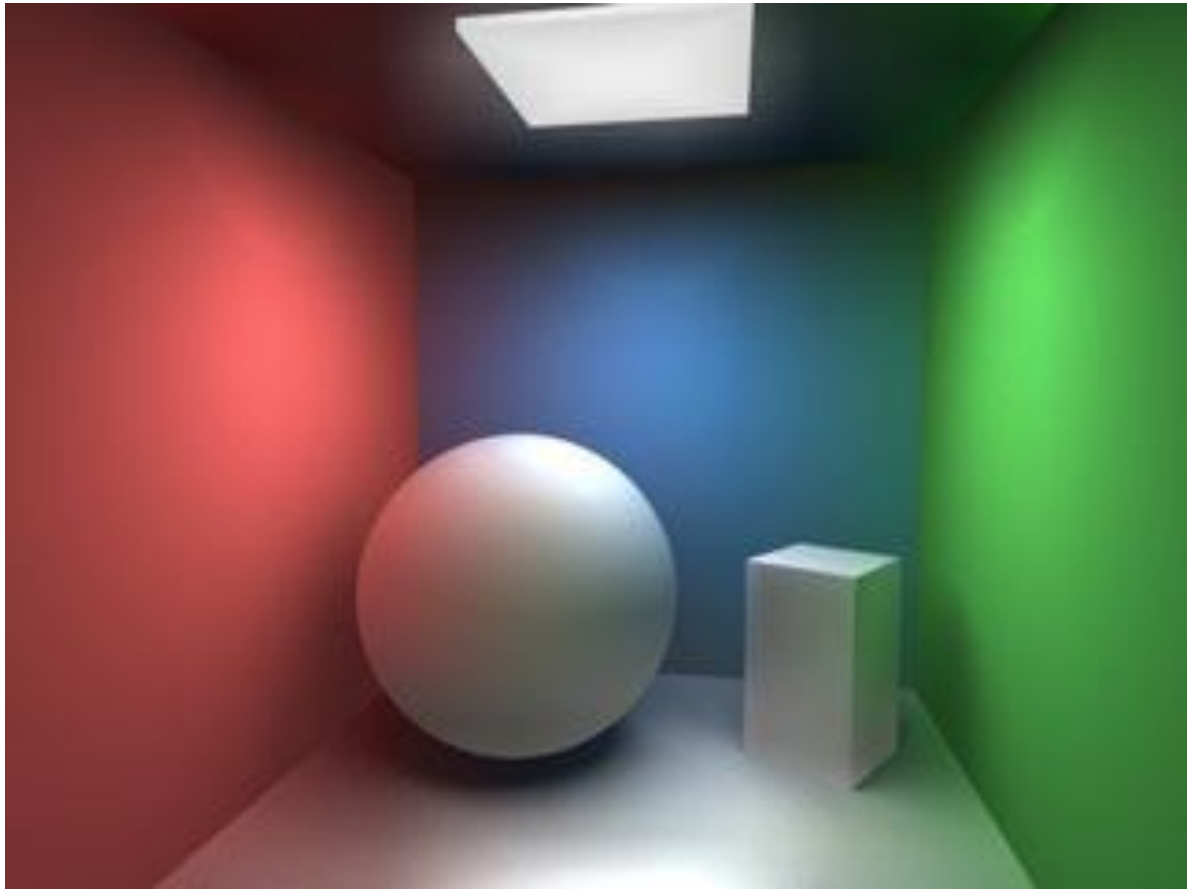
Ray Tracing Improvements: Caustics

- Transport E – S – S – S - D – S – S – S - L
- Trace from the light to the surfaces and then from the eye to the surfaces
- “shower” scene with light and then collect it
- “Where does light go?” vs “Where does light come from?”
- Good for caustics





Radiosity: E – D – D – D - L



The Rendering Equation

$$L_o(x, \vec{w}) = L_e(x, \vec{w}) + \int_\Omega f_r(x, \vec{w}', \vec{w}) L_i(x, \vec{w}')(\vec{w}' \cdot \vec{n}) \mathrm{d}\vec{w}'$$

scarier version found here: https://en.wikipedia.org/wiki/Rendering_equation
research paper found here: https://dl.acm.org/doi/10.1145/15886.15902

The Rendering Equation

$$\boxed{L_o(x, \vec{w})} = \boxed{L_e(x, \vec{w})} + \boxed{\int_\Omega f_r(x, \vec{w}', \vec{w}) L_i(x, \vec{w}')(\vec{w}' \cdot \vec{n}) \mathrm{d}\vec{w}'}$$

outgoing light at position **x** and direction **w**

emitted light at position **x** and direction **w**

and

reflected light at position **x** and direction **w**

The Rendering Equation

$$\boxed{L_o(x,\vec{w})} = \boxed{L_e(x,\vec{w})} + \boxed{\int_\Omega \boxed{f_r(x,\vec{w}',\vec{w})}\,\boxed{L_i(x,\vec{w}')}(\vec{w}'\cdot\vec{n})\,\mathrm{d}\vec{w}'}$$

the reflected light at position **x** and direction **w**

is the integral over all possible directions **w'**

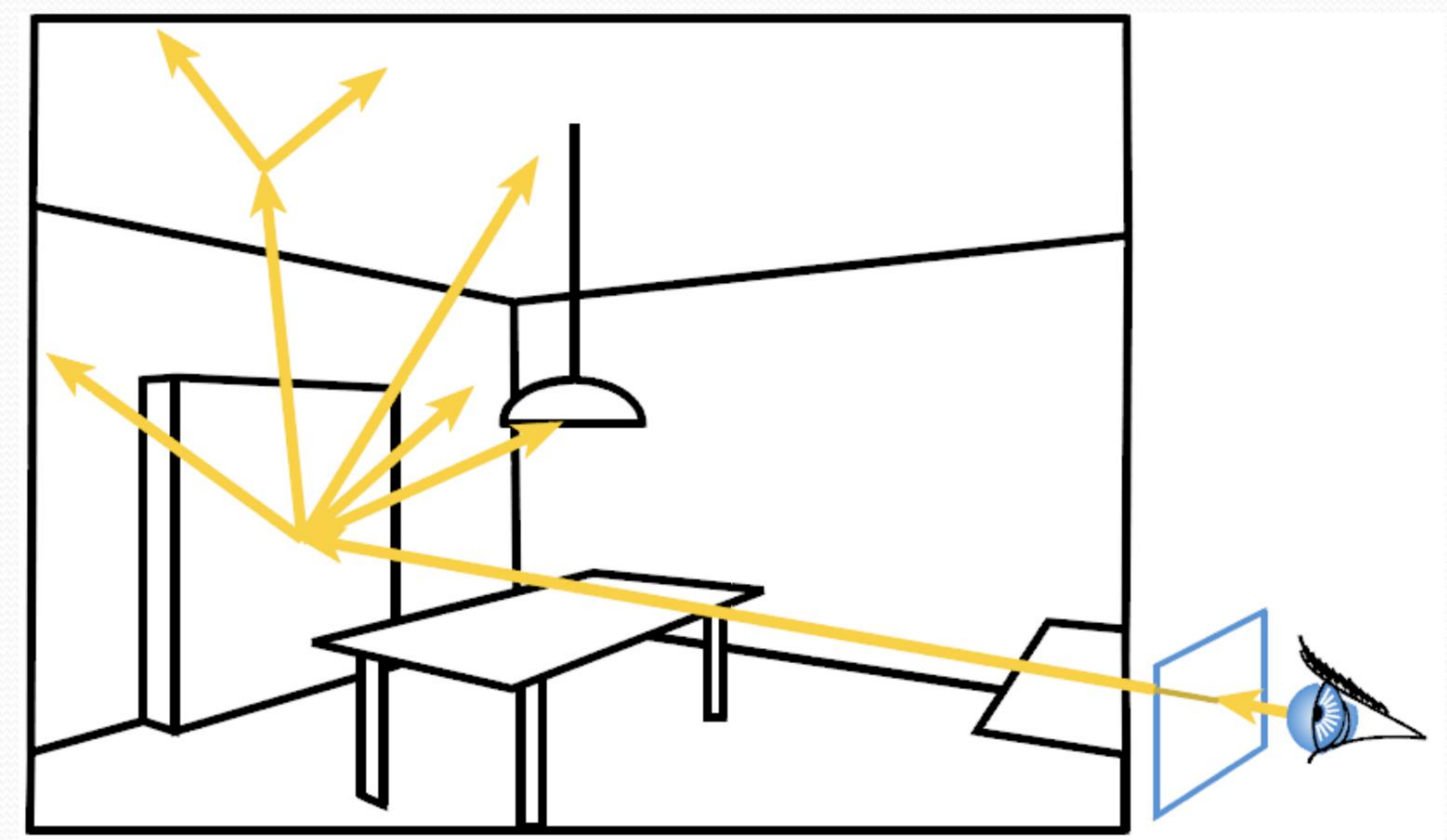
the incoming light from all directions

times

BRDF:
a function describing how light is reflected at an opaque surface

Monte Carlo Methods

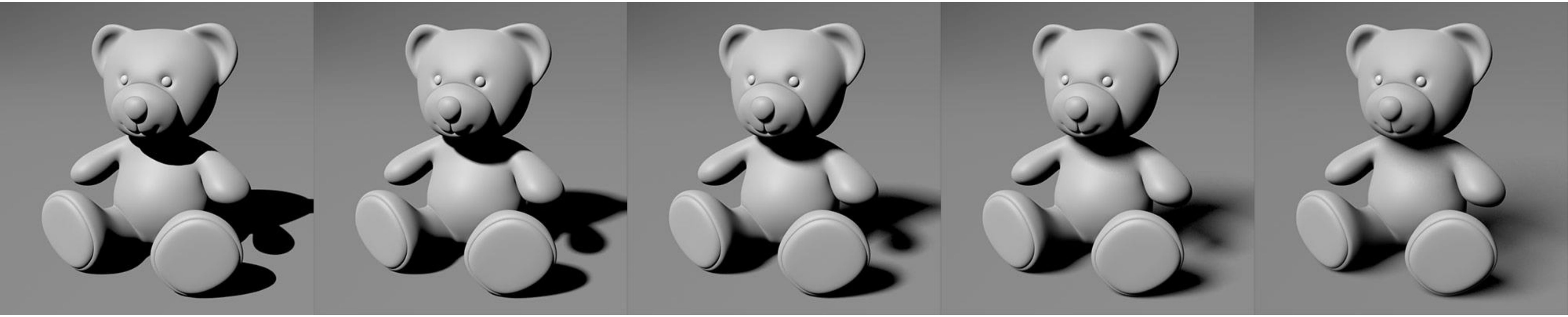
Rely on random sampling to “solve” rendering equation



http://courses.cs.tau.ac.il/Computer-Graphics/10a/lectures/05a-RayTracingAdv.pdf

Area Light

Hard v soft shadows

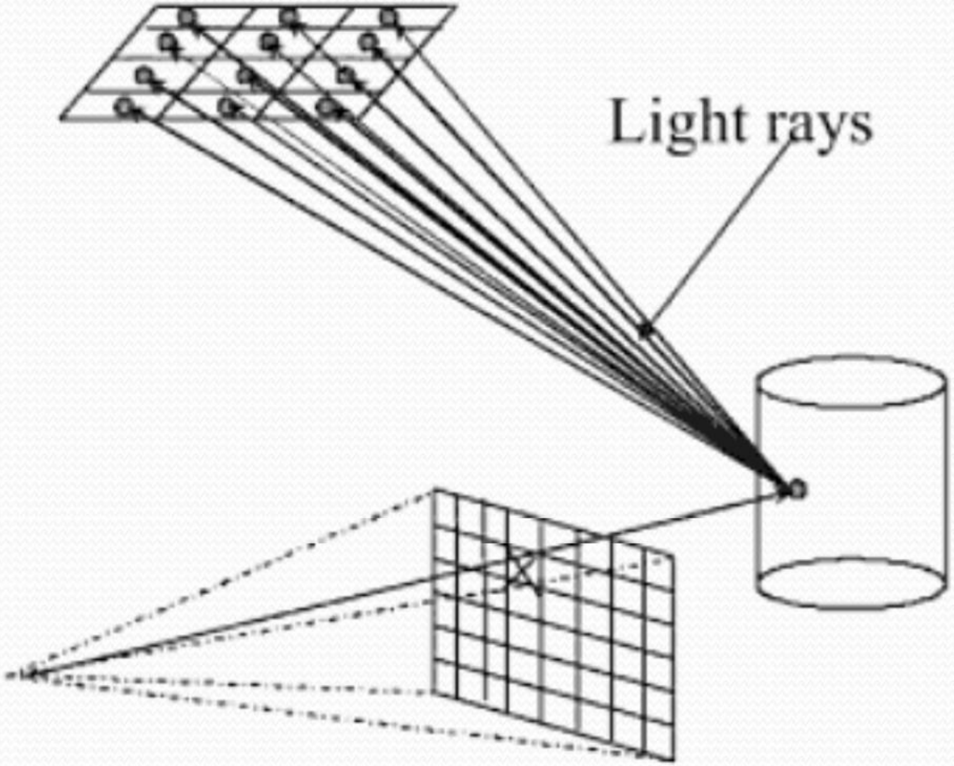


Hard shadow

More realistic soft shadows

Area Light

- Disadvantages of the simple uniform method:
  - Very time consuming
  - If the grid resolution is low, artifacts appear in the shadows.

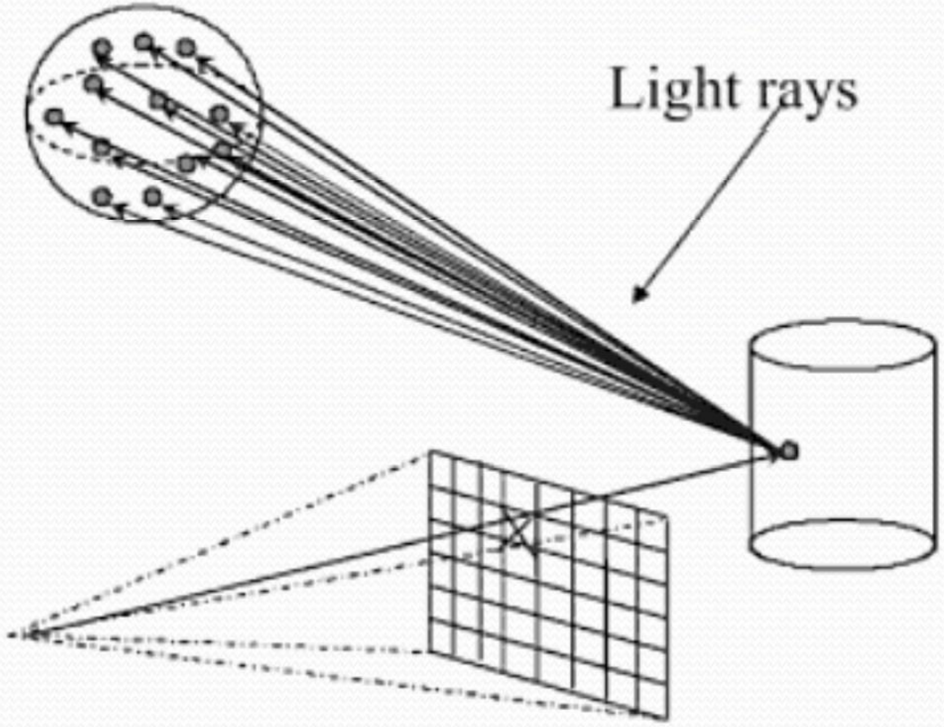


http://courses.cs.tau.ac.il/Computer-Graphics/10a/lectures/05a-RayTracingAdv.pdf

Area Light

Monte-Carlo Area light

- Light is modeled as a sphere
- Highest intensity in the middle. Gradually fade out.
- Shoot n rays to random points in the sphere
- Average their value.



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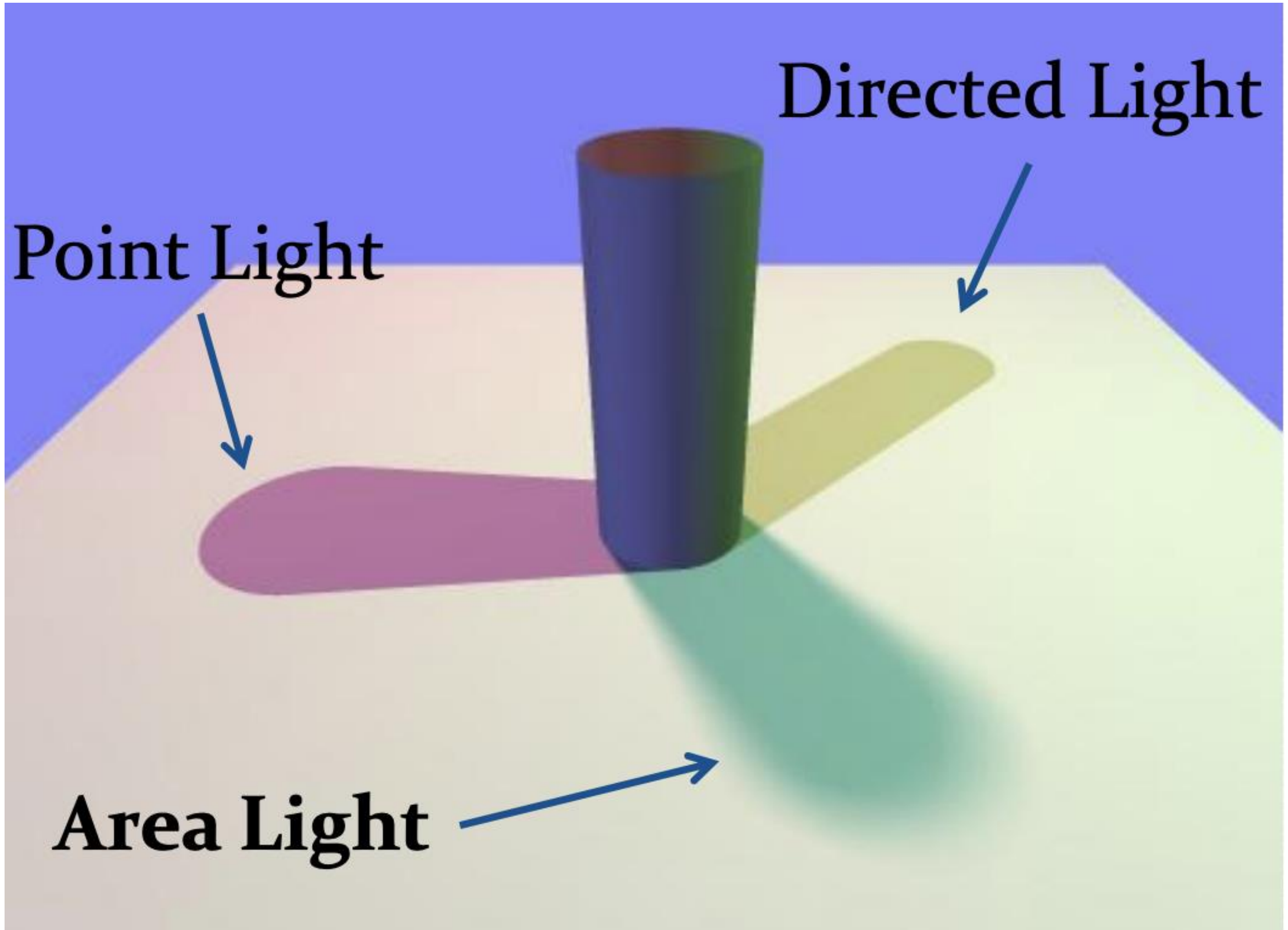
Area Light

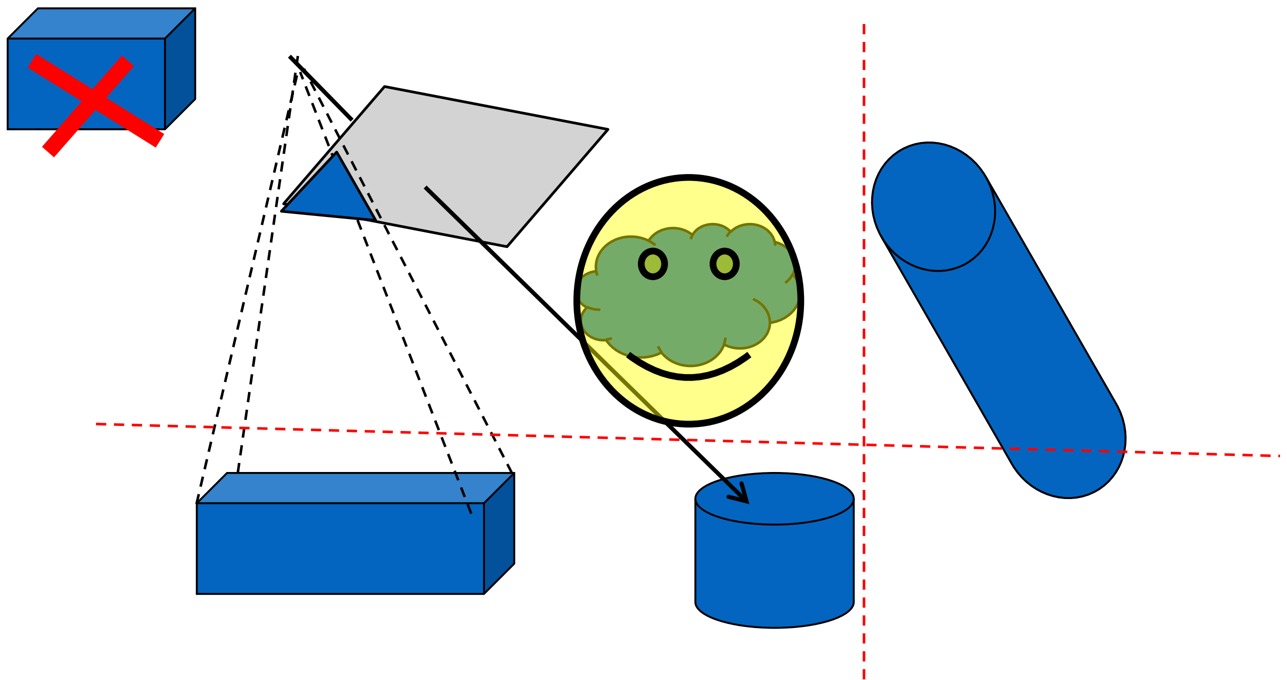


http://courses.cs.tau.ac.il/Computer-Graphics/10a/lectures/05a-RayTracingAdv.pdf

Ray Intersection: Efficiency Considerations

Speed-up the intersection process.

- Ignore object that clearly don't intersect.
- Use proxy geometry.
- Subdivide and structure space hierarchically.
- Project volume onto image to ignore entire sets of rays.



Faster Intersections for Ray Tracing