Ray Tracing

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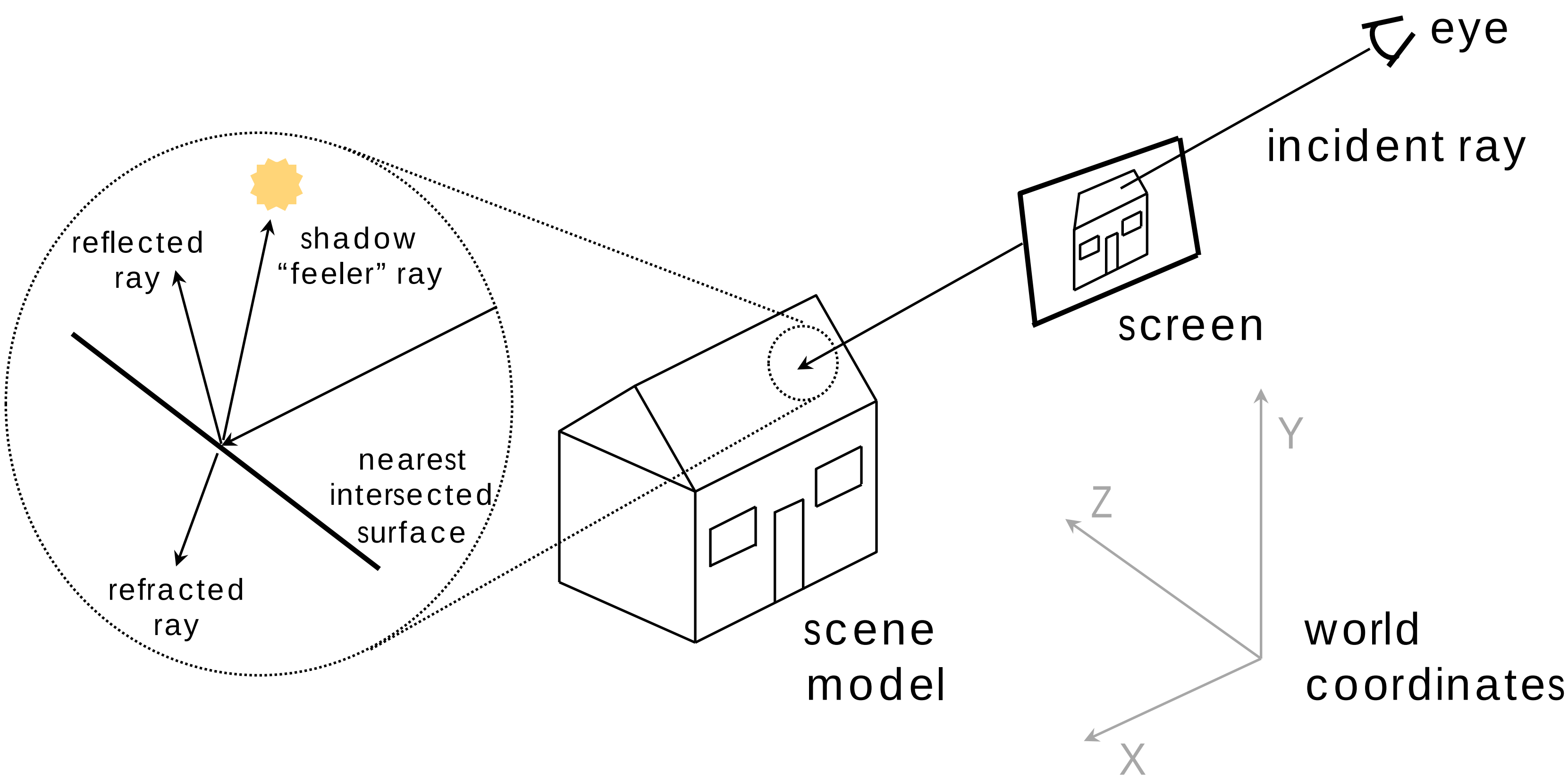
Ray Tracing


eye
incident ray
screen
scene
model
reflected
ray
shadow
“feeler” ray
nearest
intersected
surface
refracted
ray
Y
Z
X
world
coordinates

Ray-Tracing Pseudocode

- For each ray **r** from eye to pixel, color the pixel the value returned by ray_cast(**r**):

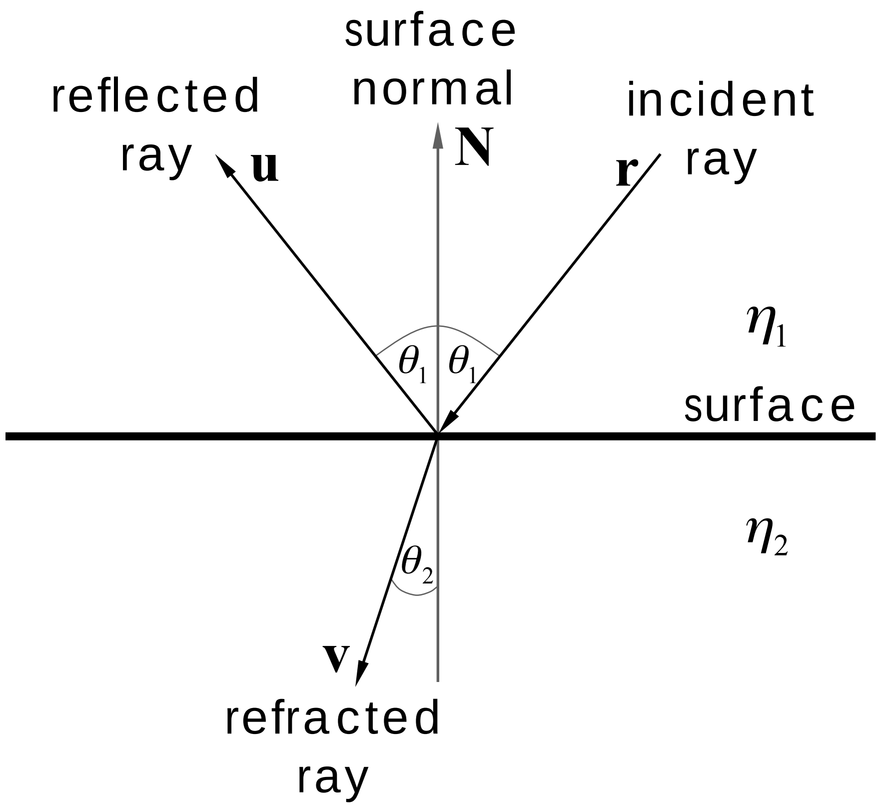
```
ray_cast(r)
{
    s ← nearest_intersected_surface(r);
    p ← point_of_intersection(r, s);
    u← reflect(r, s, p);
    v← refract(r, s, p);
    c ← phong(p, s, r) +
            s.k_reflect × ray_cast(u) +
            s.k_refract × ray_cast(v);
    return(c);
}
```

Pseudocode Explained

- s ← nearest_intersected_surface(**r**);
  - Use geometric searching to find the nearest surface s intersected by the ray **r**
- **p** ← point_of_intersection(**r**, s);
  - Compute **p**, the point of intersection of ray **r** with surface s
- **u**← reflect(**r**, s, **p**); **v**← refract(**r**, s, **p**);
  - Compute the reflected ray **u** and the refracted ray **v** using Snell's Laws

Reflected and Refracted Rays

- Reflected and refracted rays are computed using Snell's Law

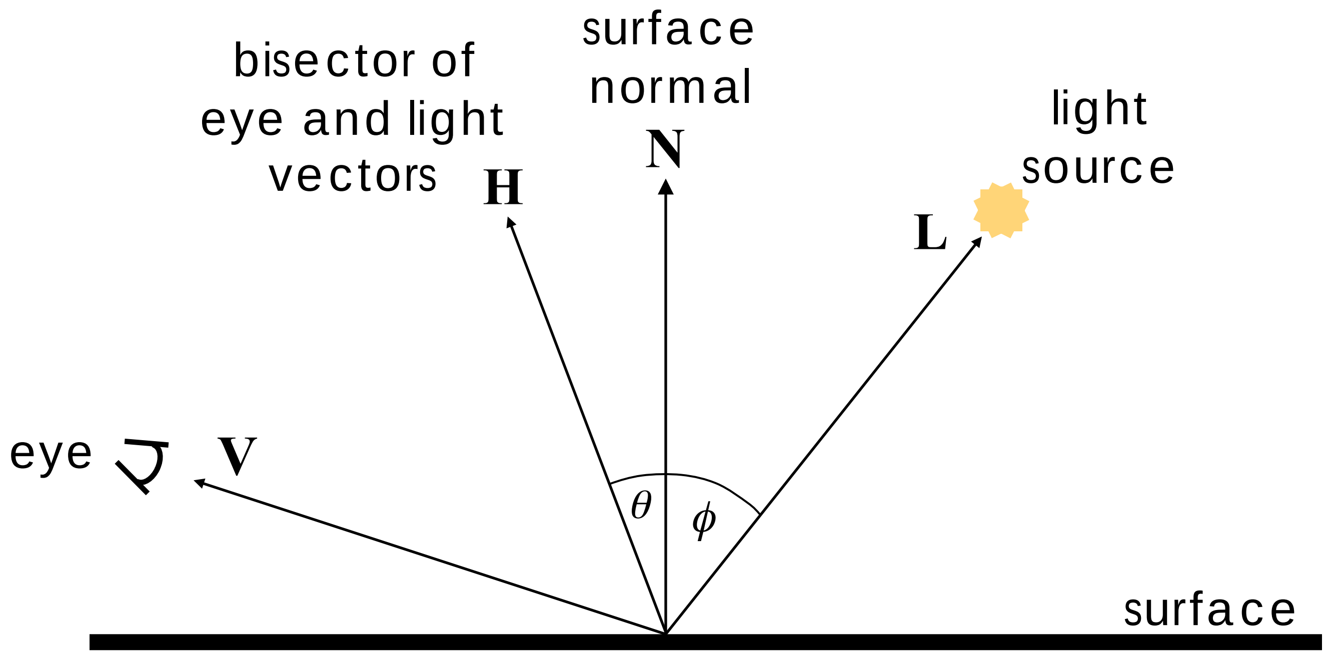


$$\frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{\eta_1}{\eta_2}$$

Pseudocode Explained

- phong(**p**, s, **r**)
  - Evaluate the Phong reflection model for the ray **r** at point **p** on surface s, taking shadowing into account (see next slide)
- $s.k_{reflect} \times$ ray_cast(**u**)
  - Multiply the contribution from the reflected ray **u** by the specular-reflection coefficient $k_{reflect}$ for surface s
- $s.k_{refract} \times$ ray_cast(**v**)
  - Multiply the contribution from the refracted ray **v** by the specular-refraction coefficient $k_{refract}$ for surface s

The Phong Reflection Model



$$R = i_l\left(k_d\cos(\phi) + k_s\cos^c(\theta)\right) + k_d a$$

Set to 0 if shadow “feeler” ray to light source intersects any scene geometry

About Those Calls to ray_cast()...

- The function ray_cast() calls itself *recursively*
- There is a potential for infinite recursion
  - Consider a "hall of mirrors"
- Solution: limit the depth of recursion
  - A typical limit is five calls deep
  - Note that the deeper the recursion, the less the ray's contribution to the image, so limiting the depth of recursion does not affect the final image much

Pros and Cons of Ray Tracing

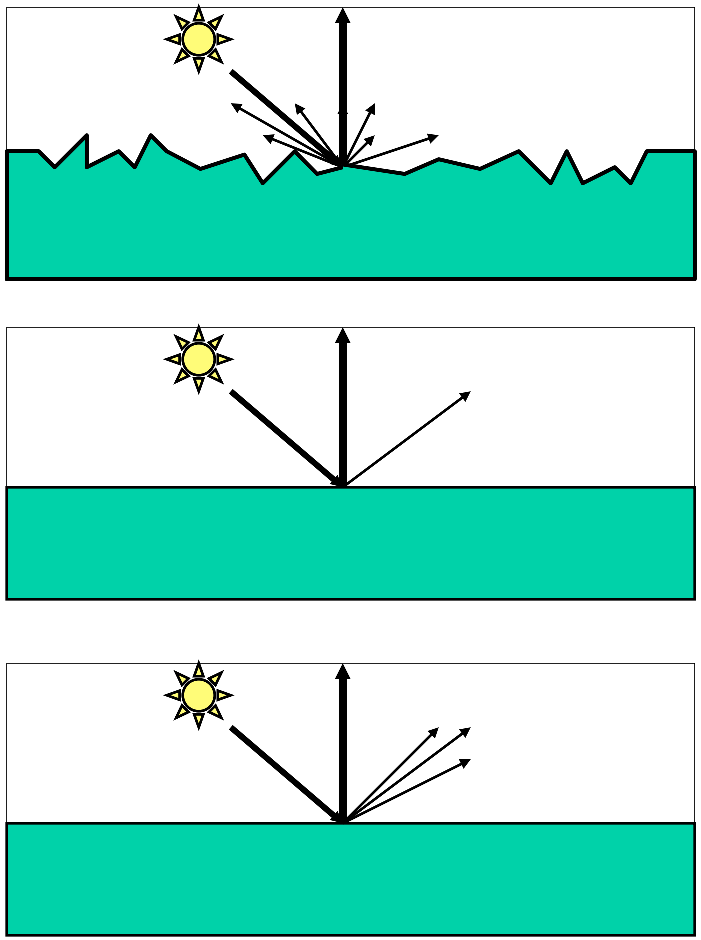
- Advantages of ray tracing
  - All the advantages of the Phong model
  - Also handles shadows, reflection, and refraction
- Disadvantages of ray tracing
  - Computational expense
  - No diffuse inter-reflection between surfaces
  - Not physically accurate
- Other techniques exist to handle these shortcomings, at even greater expense!

An Aside on Antialiasing

- Our simple ray tracer produces images with noticeable “jaggies”
- Jaggies and other unwanted artifacts can be eliminated by antialiasing:
  - Cast multiple rays through each image pixel
  - Color the pixel the average ray contribution
  - An easy solution, but it increases the number of rays, and hence computation time, by an order of magnitude or more

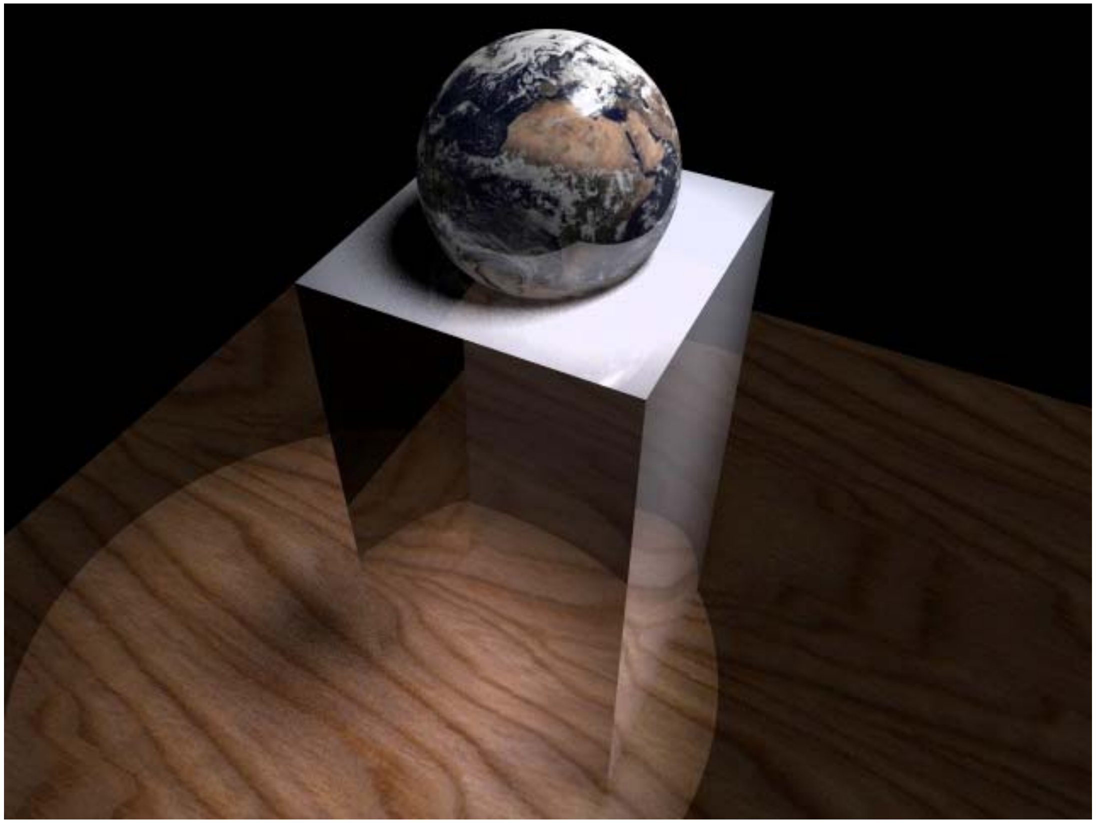
Reflections

- We normally deal with a perfectly diffuse surface.
- With ray-tracing, we can easily handle perfect reflections.
- Phong allows for glossy reflections of the light source.



Reflections

- If we are reflecting the scene or other objects, rather than the light source, then ray-tracing will only handle perfect mirrors.



Jason Bryan, cis782, Ohio State, 2000

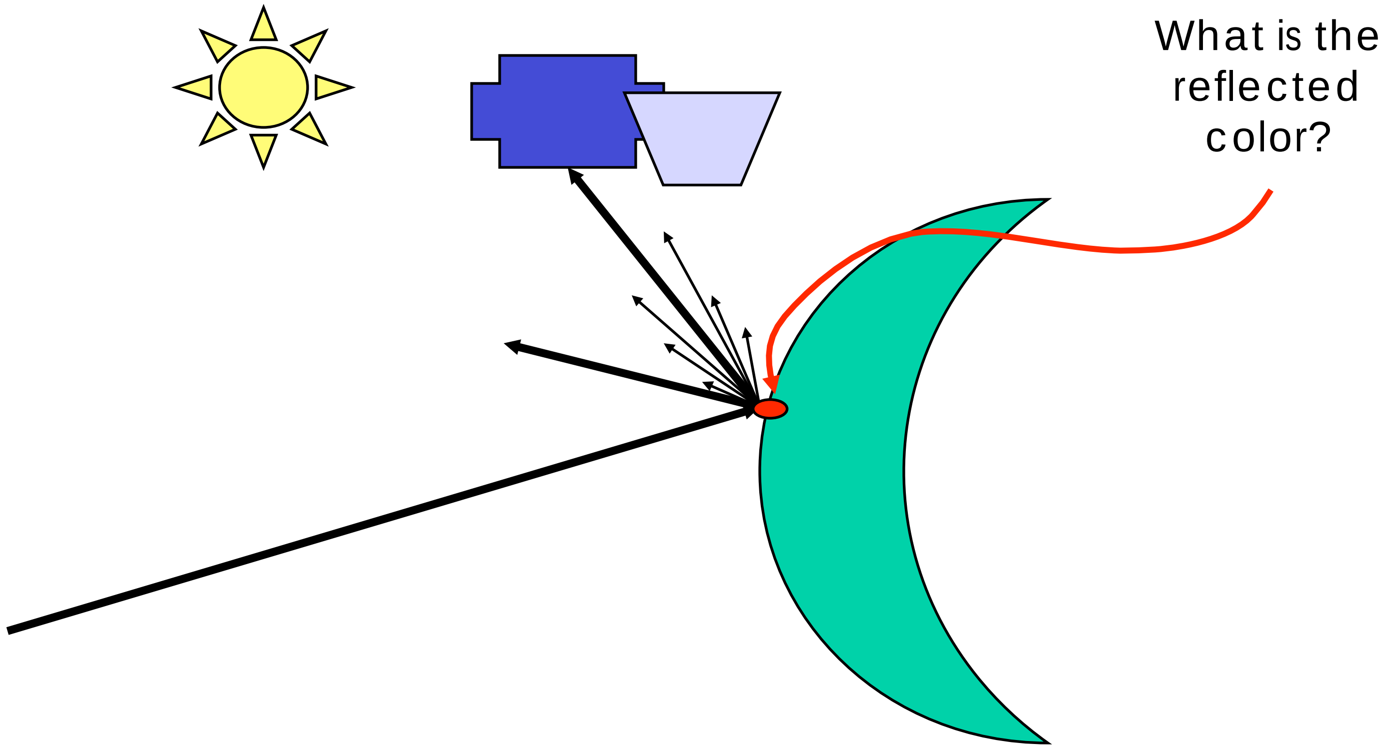
Reflections

- Glossy reflections blur the reflection.

Jason Bryan, cis782, Ohio State, 2000

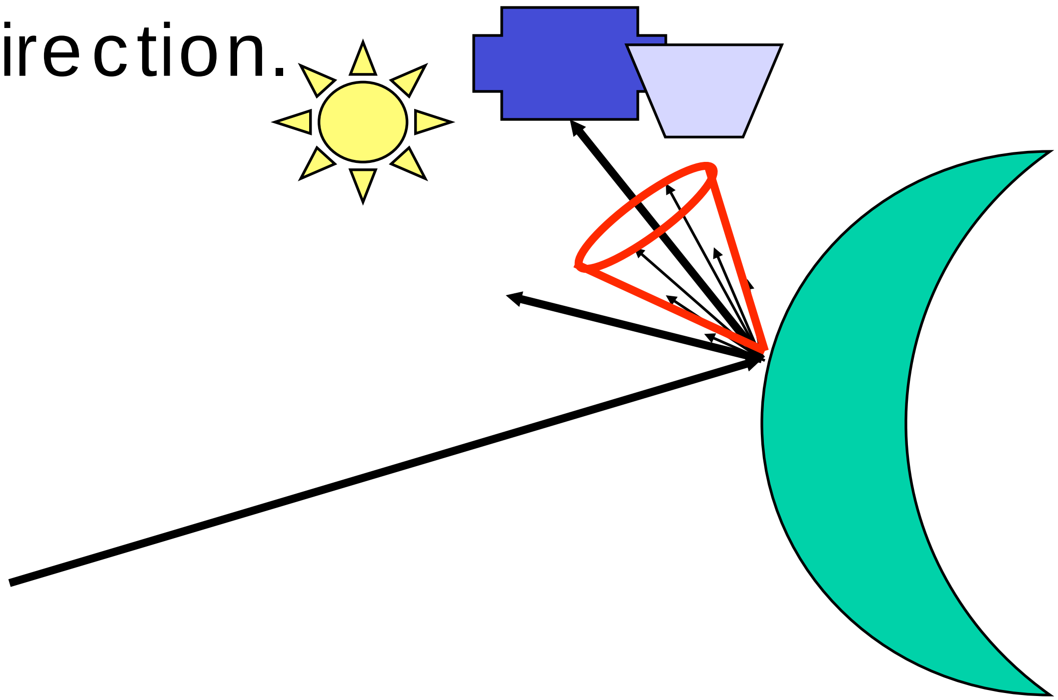
Reflections

- Mathematically, what does this mean?



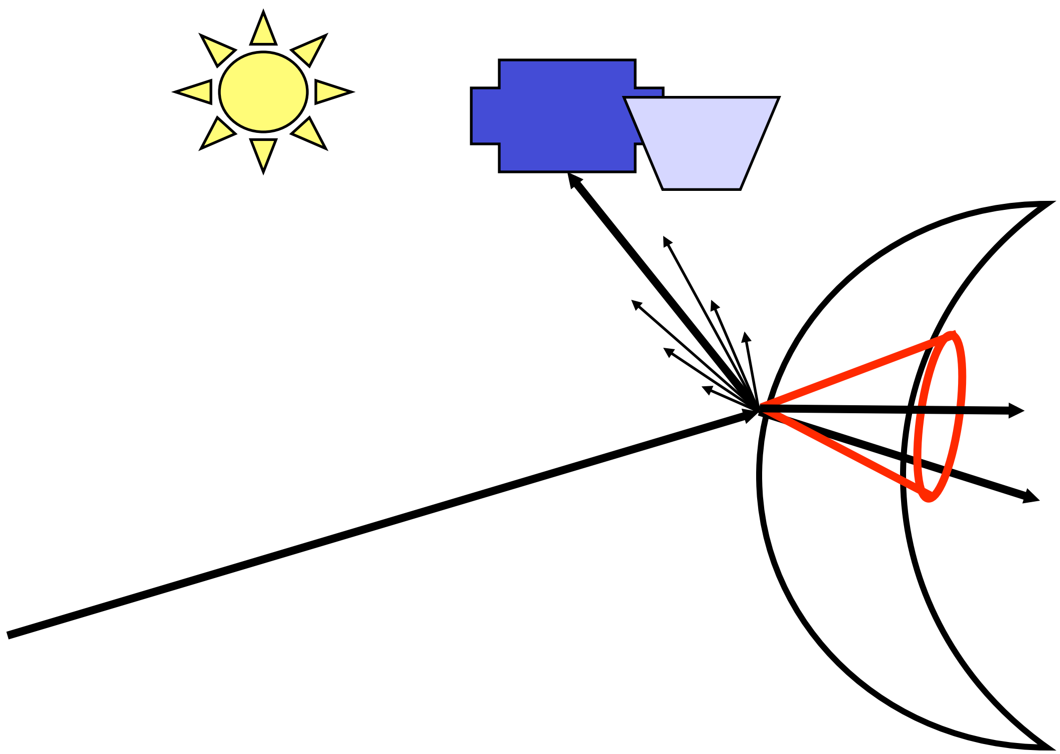
Glossy Reflections

- We need to integrate the color over the reflected cone.
- Weighted by the reflection coefficient in that direction.

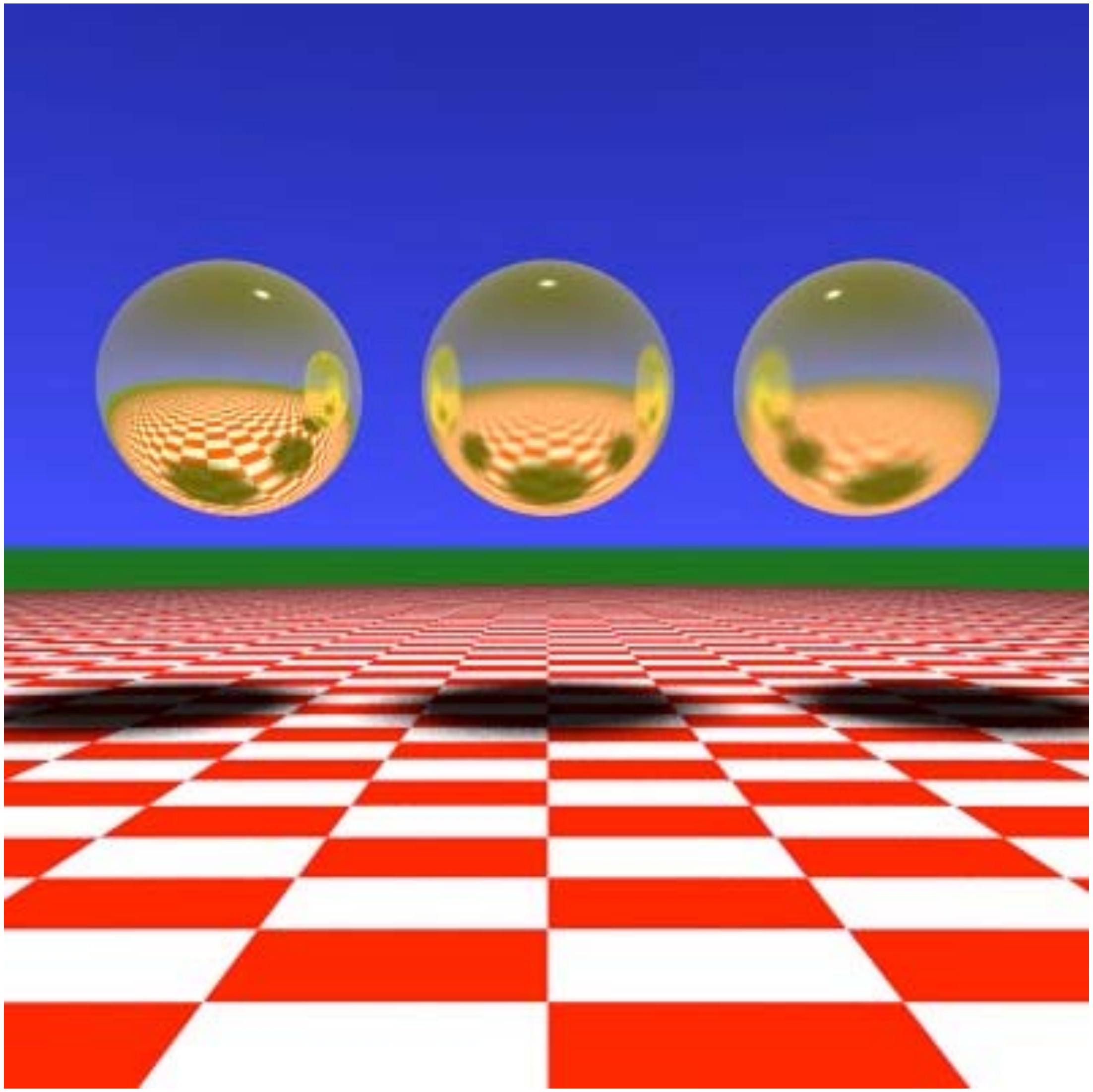


Translucency

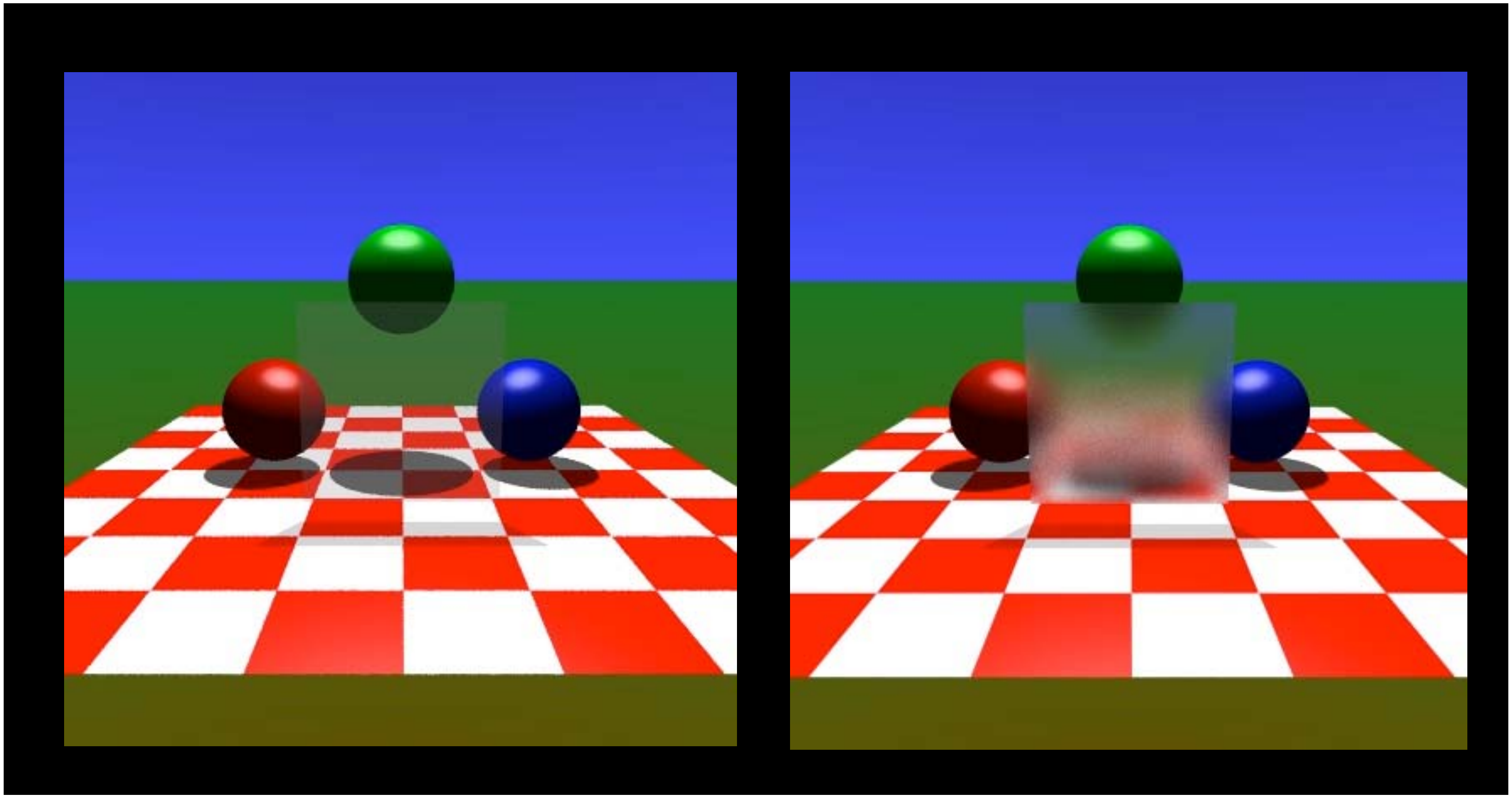
- Likewise, for blurred refractions, we need to integrate around the refracted angle.



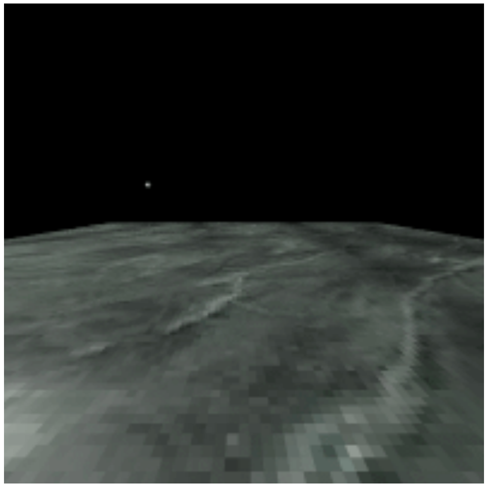
Translucency



Translucency



Translucency



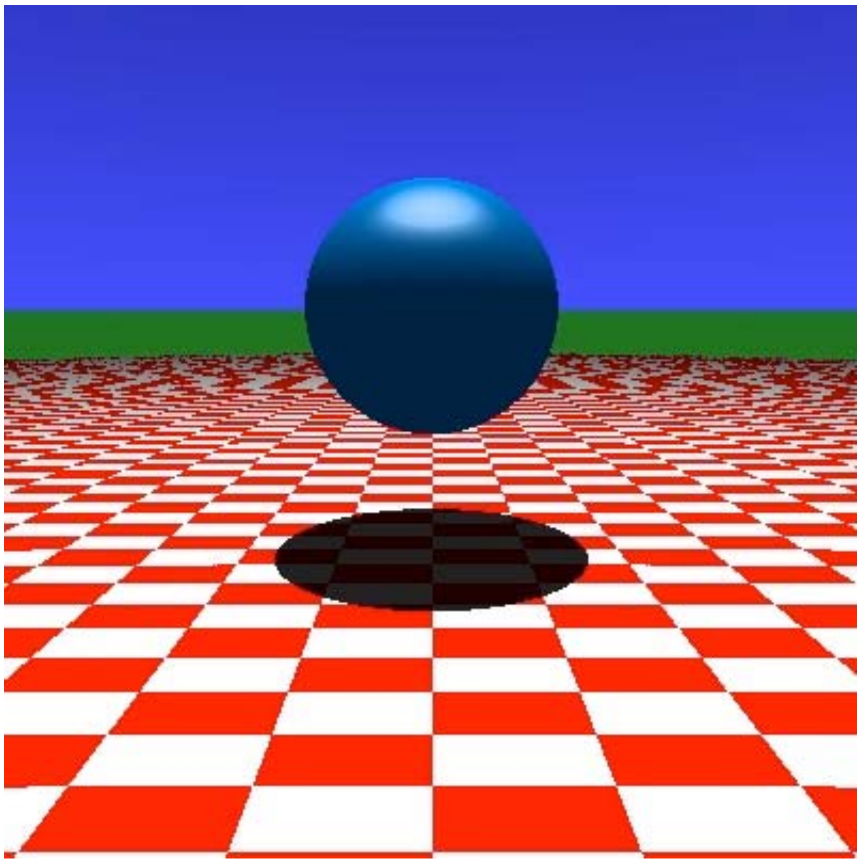
Calculating the integrals

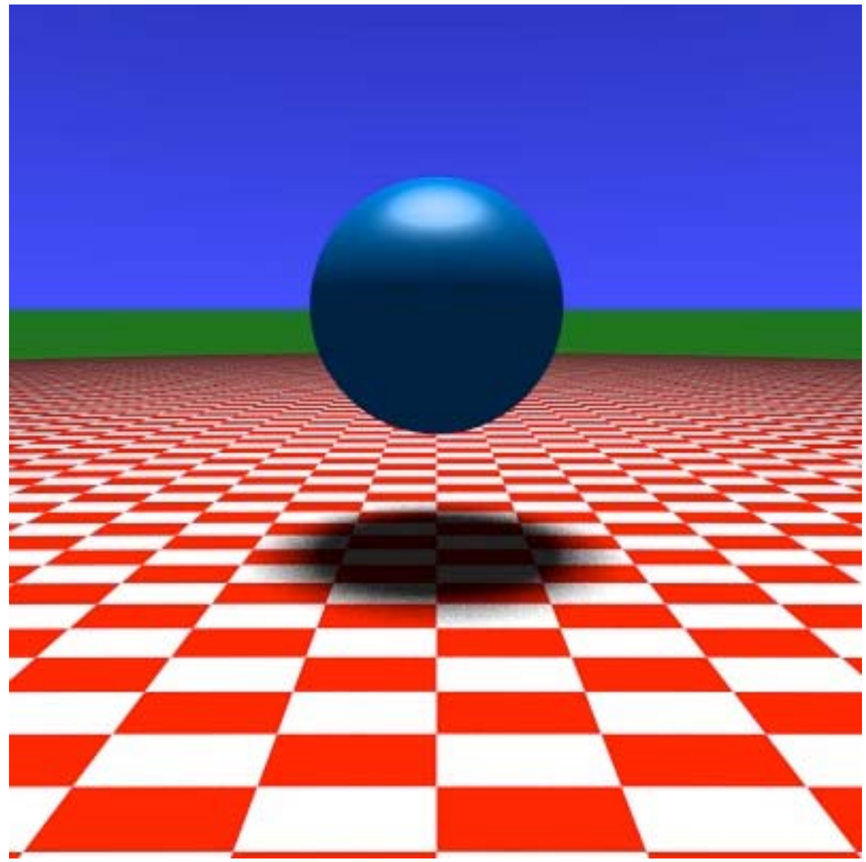
- How do we calculate these integrals?
  - Two-dimensional of the angles and ray-depth of the cone.
  - Unknown function -> the rendered scene.
- Use Monte-Carlo integration

Shadows

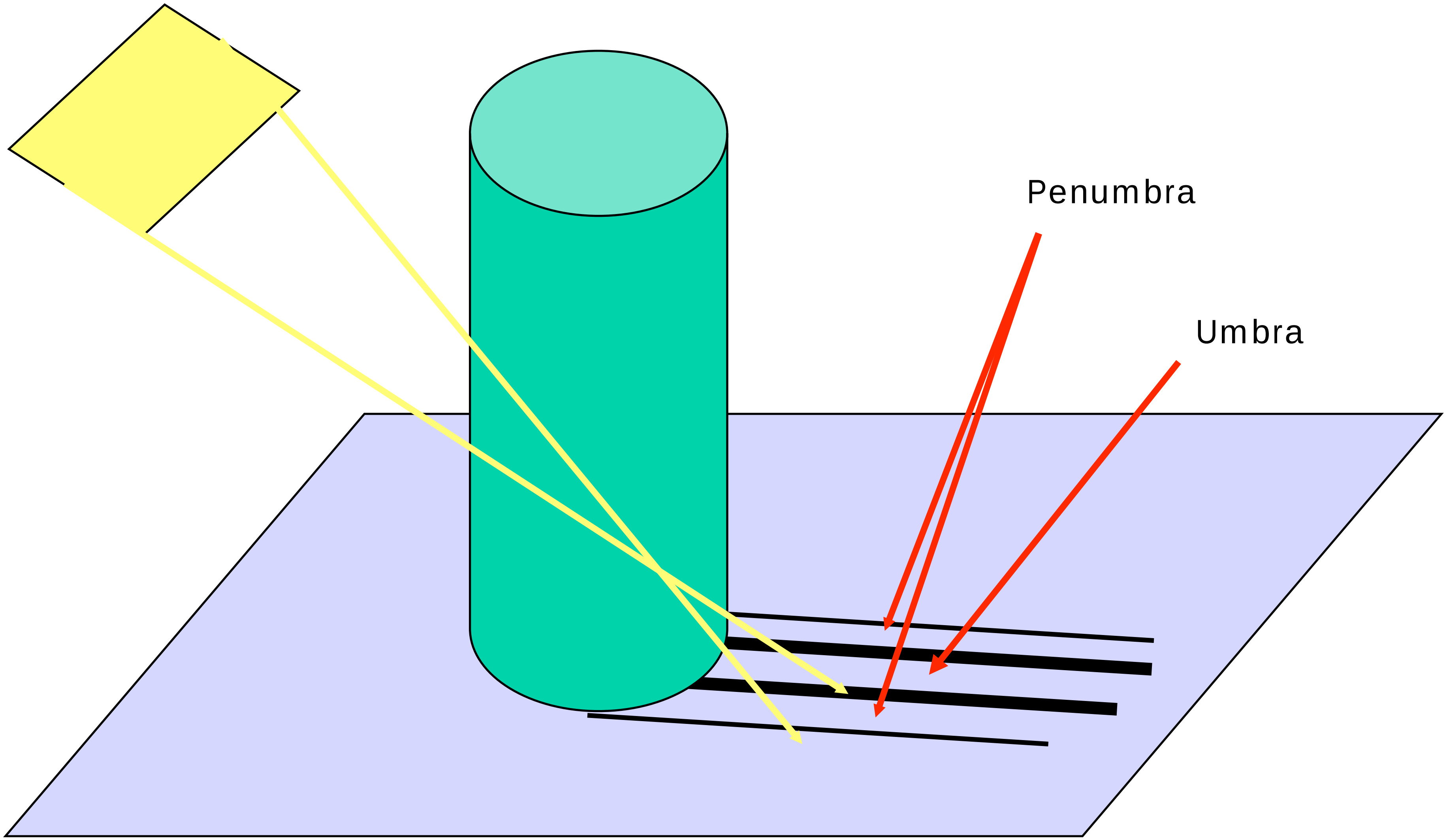
- Ray tracing casts shadow feelers to a point light source.
- Many light sources are illuminated over a finite area.
- The shadows between these are substantially different.
- Area light sources cast soft shadows
  - Penumbra
  - Umbra

Soft Shadows





Soft Shadows



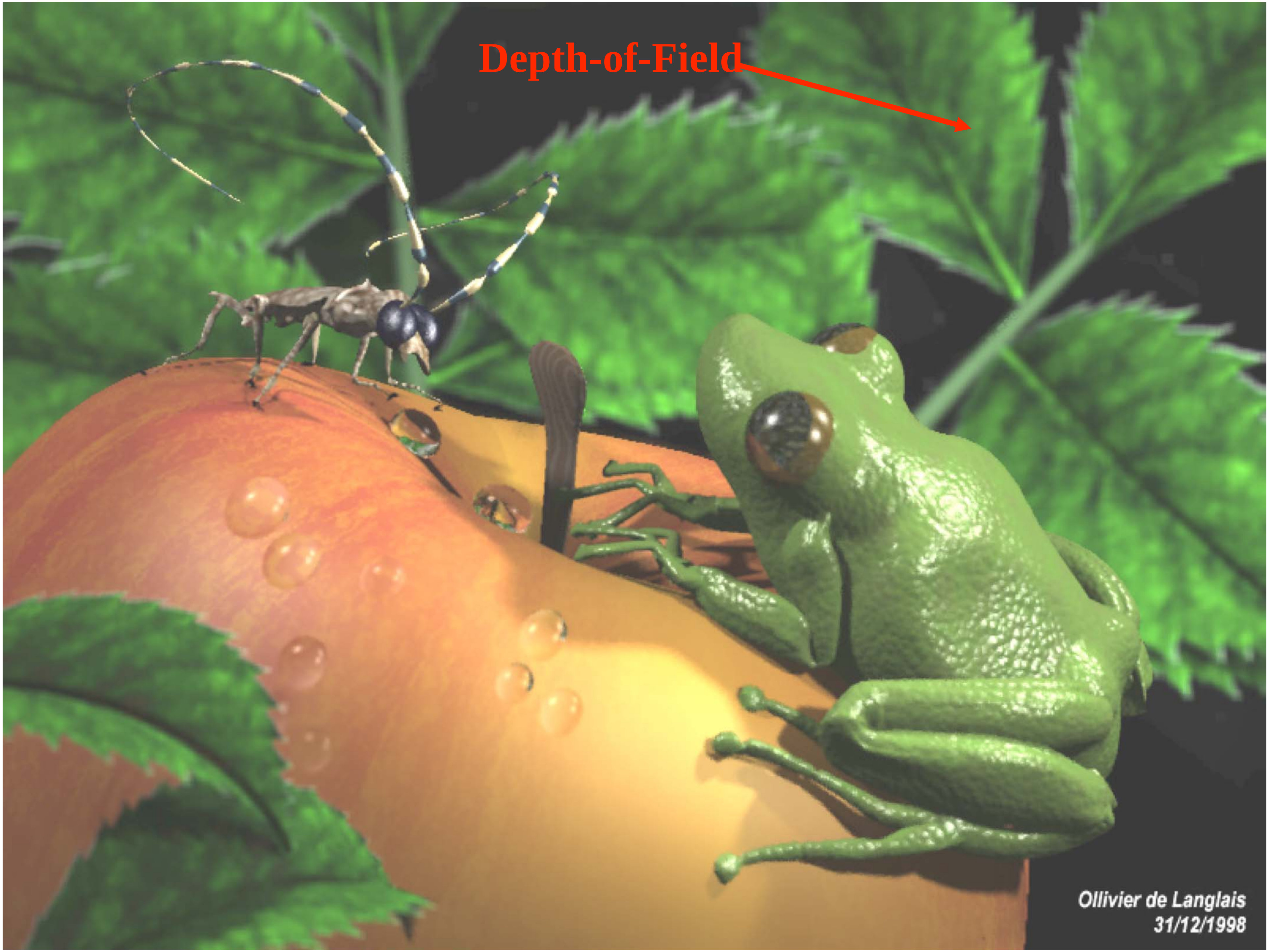
Soft Shadows

- Umbra – No part of the light source is visible.
- Penumbra – Part of the light source is occluded and part is visible (to a varying degree).

- Which part? How much? What is the Light Intensity reaching the surface?

Camera Models

- Up to now, we have used a pinhole camera model.
- These has everything in focus throughout the scene.
- The eye and most cameras have a larger lens or aperature.


Depth-of-Field
Ollivier de Langlais
31/12/1998

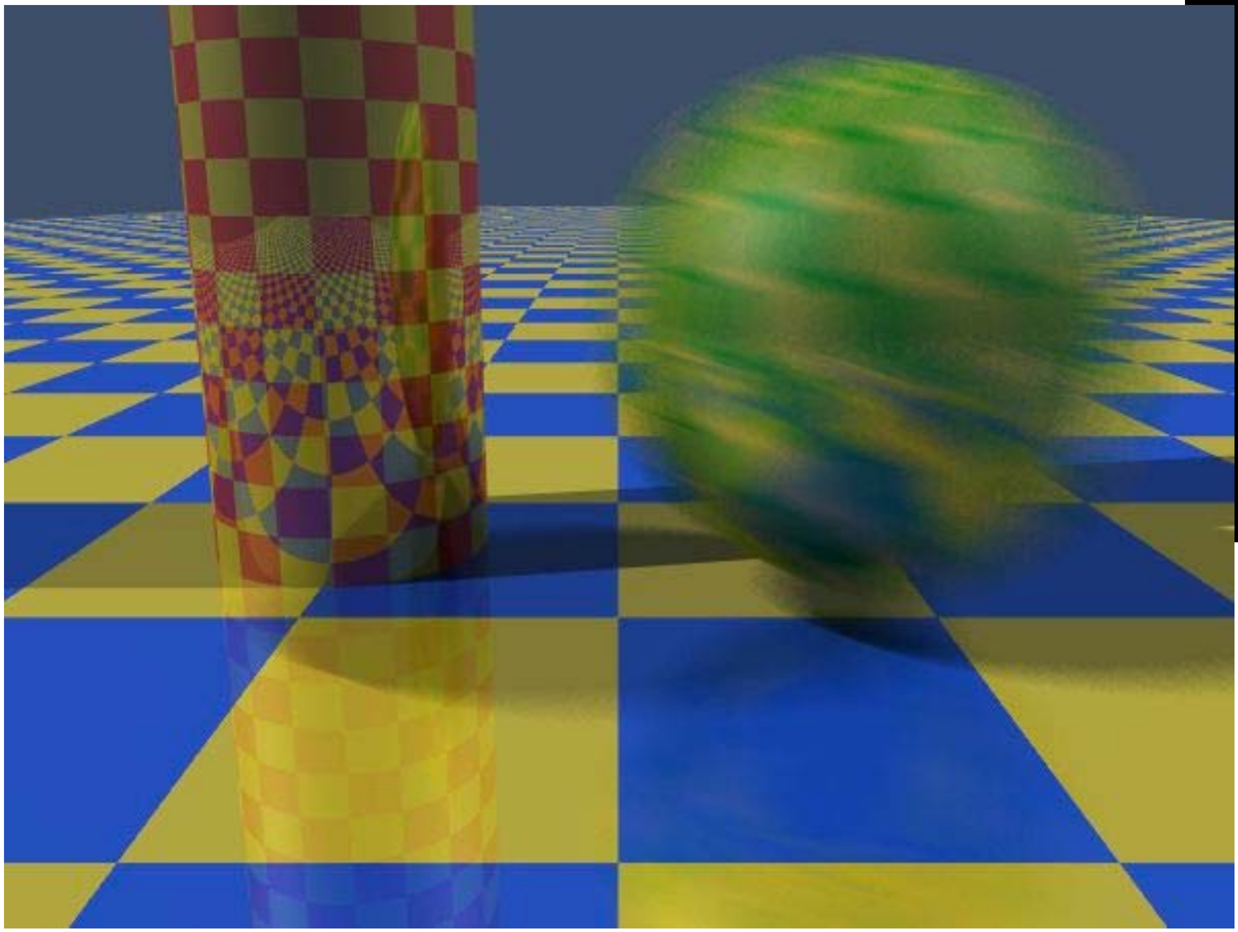
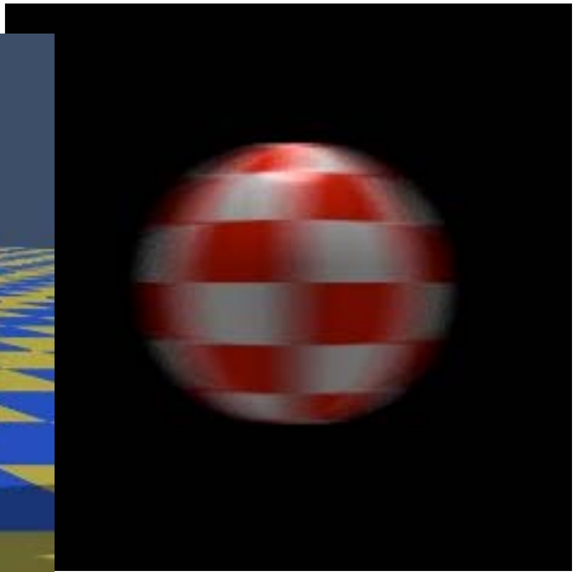
Depth of Field

Depth-of-Field

- Details

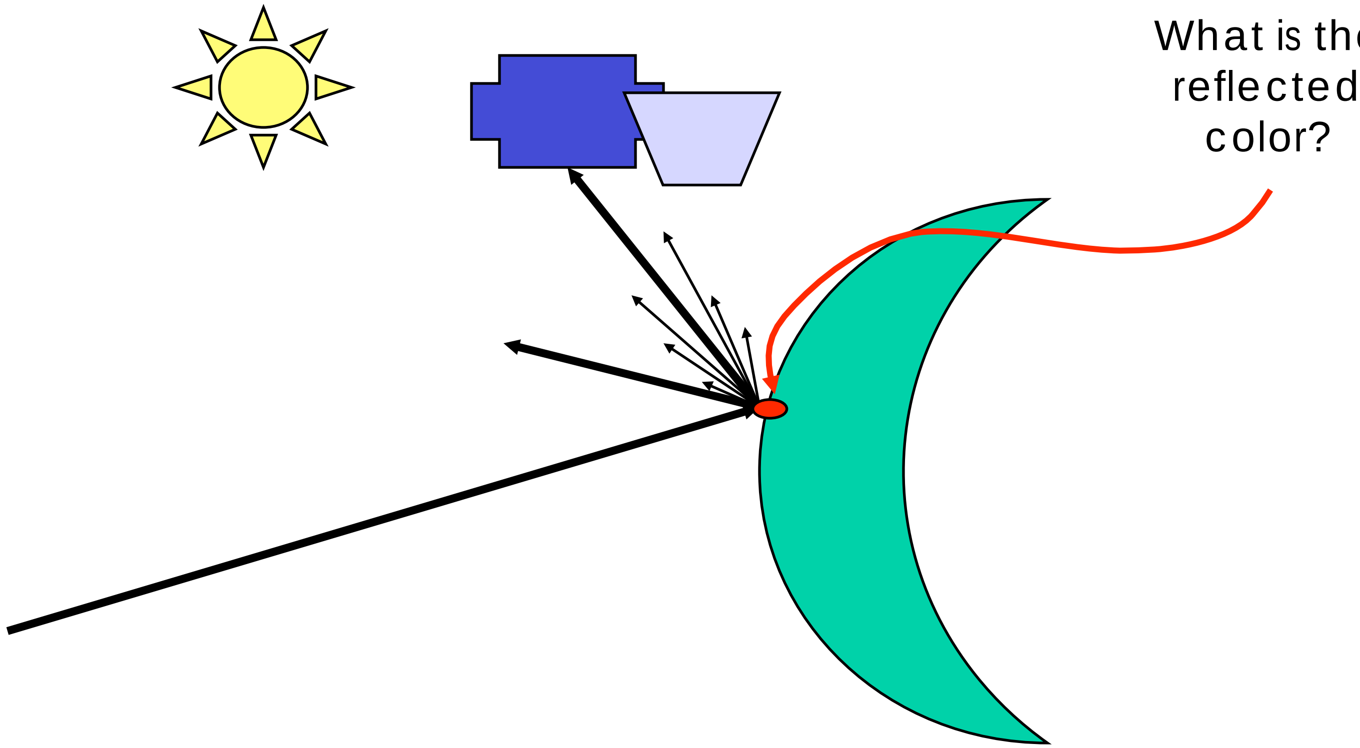
Motion Blur

- Integrate (or sample) over the frame time.

Rendering the Scene

- So, we ask again, what is the color returned for each pixel?



Rendering a Scene

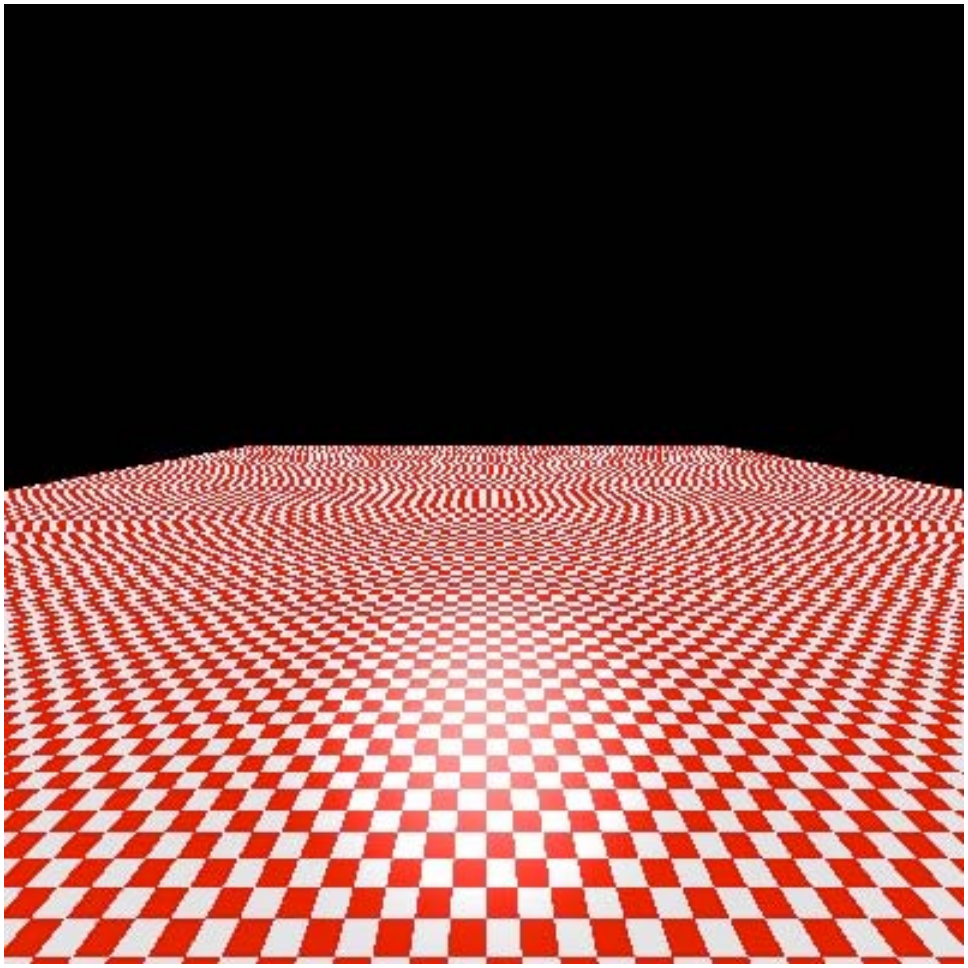
- For each frame
  - Generate samples in time and average (t):
    - For each Pixel (nxn)
      - Sample the Camera lens (lxl)
        - Sample the area light source for illumination (sxs)
        - Recursively sample the reflected direction cone (rxr).
        - Recursively sample the refracted direction cone (axa).
- Total complexity ***O*** *(p*p*t*l*l*s*s*r*r*a*a)!!!!!*
- *Where p is the number of rays cast in the recursion – n^2 primary rays, $3n^2$ secondary, …*
- If we super-sample on a fine sub-pixel grid, it gets even worse!!!

Rendering a Scene

- If we only sample the 2D integrals with a *mxm* grid, and time with 10 samples, we have a complexity of $\boldsymbol{O}(m^9p^2)$.

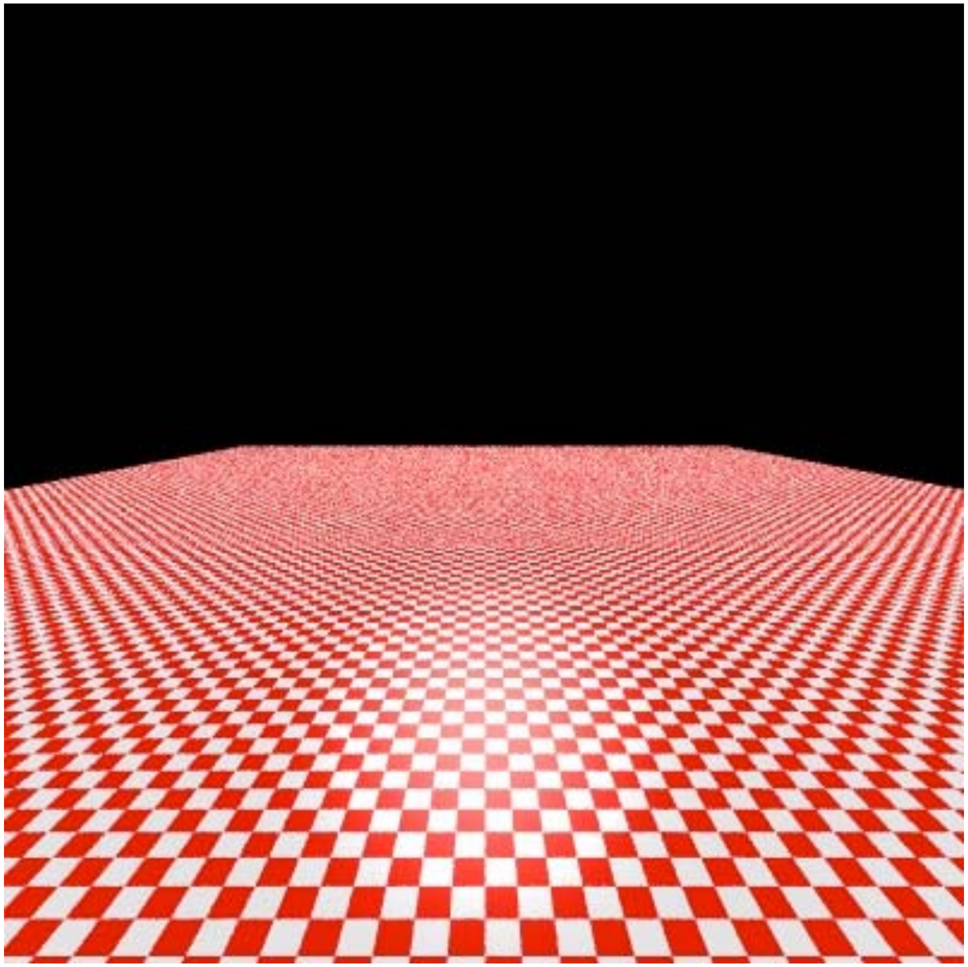
Supersampling

- 1 sample per pixel



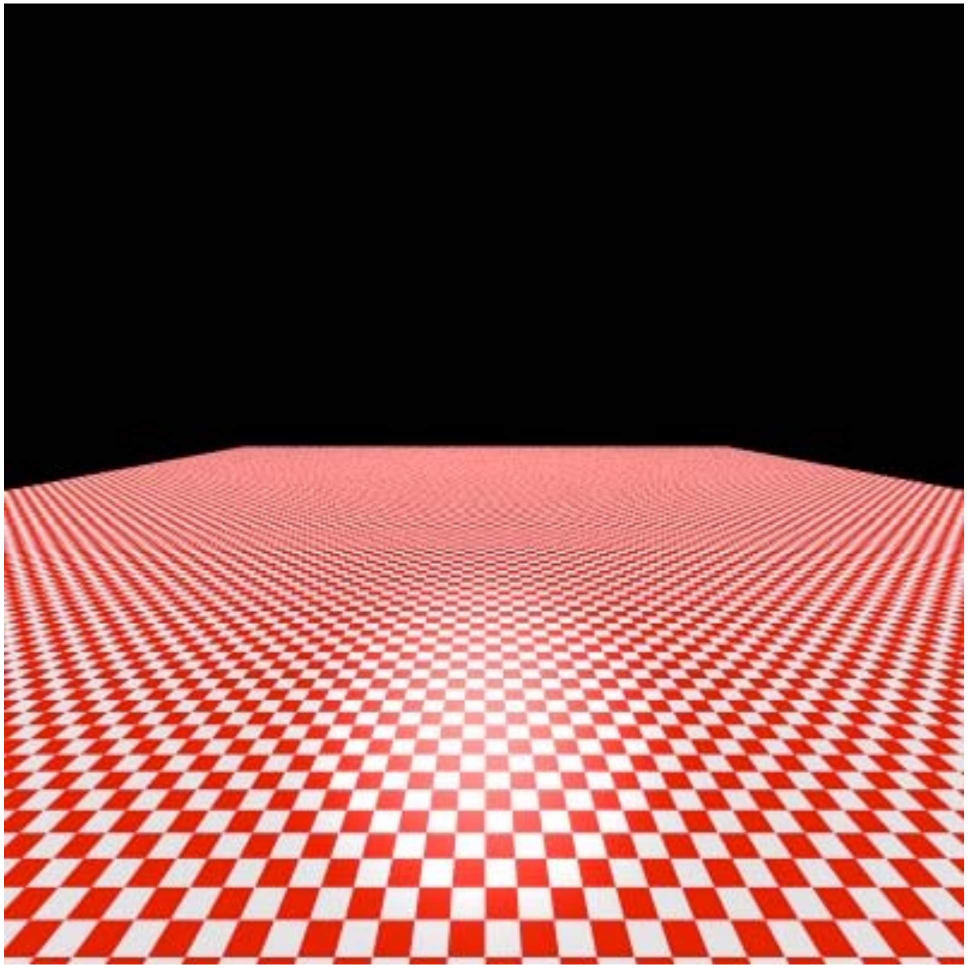
Supersampling

- 16 samples per pixel



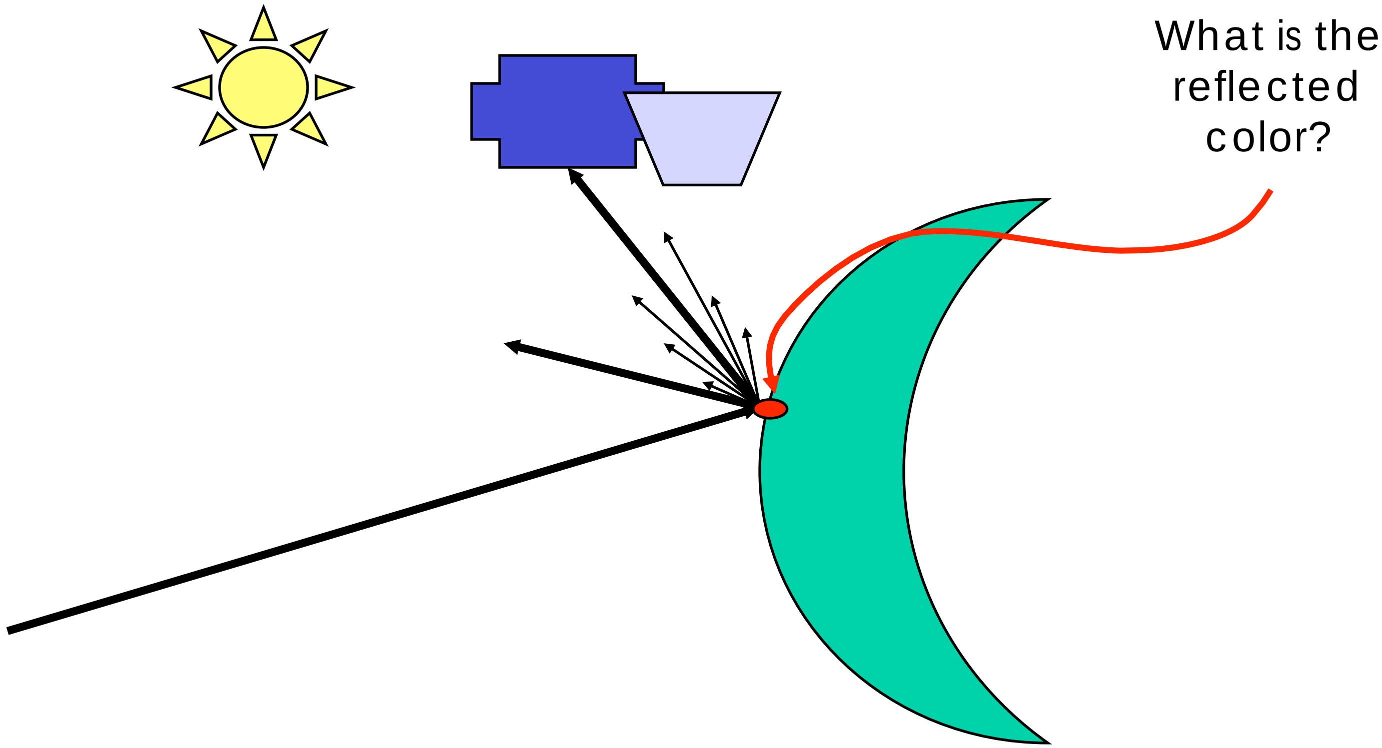
Supersampling

- 256 samples per pixel



Rendering the Scene

- So, we ask a third time, what is the color returned for each pixel?



Rendering the Scene

- If we were to write this as an integral, each pixel would take the form:

$$\int\int\int\int\int\int\int\int f(\theta_{reflect}, r_{reflect}, x_{light}, y_{light}, \theta_{refract}, r_{refract}, lens_x, lens_y, time, u, v)\, d\theta\, dr\, dx\, dy\, d\theta\, dr\, dl_x\, dl_y\, dt\, du\, dv$$

- Someone try this in Matlab!!!

Rendering the scene

- So, what does this tell us?
- Rather than compute a bunch of 2D integrals everywhere, use Monte-Carlo integration to compute this one integral.

Distributed Ray-Tracing

- Details of how Monte-Carlo integration is used in DRT.