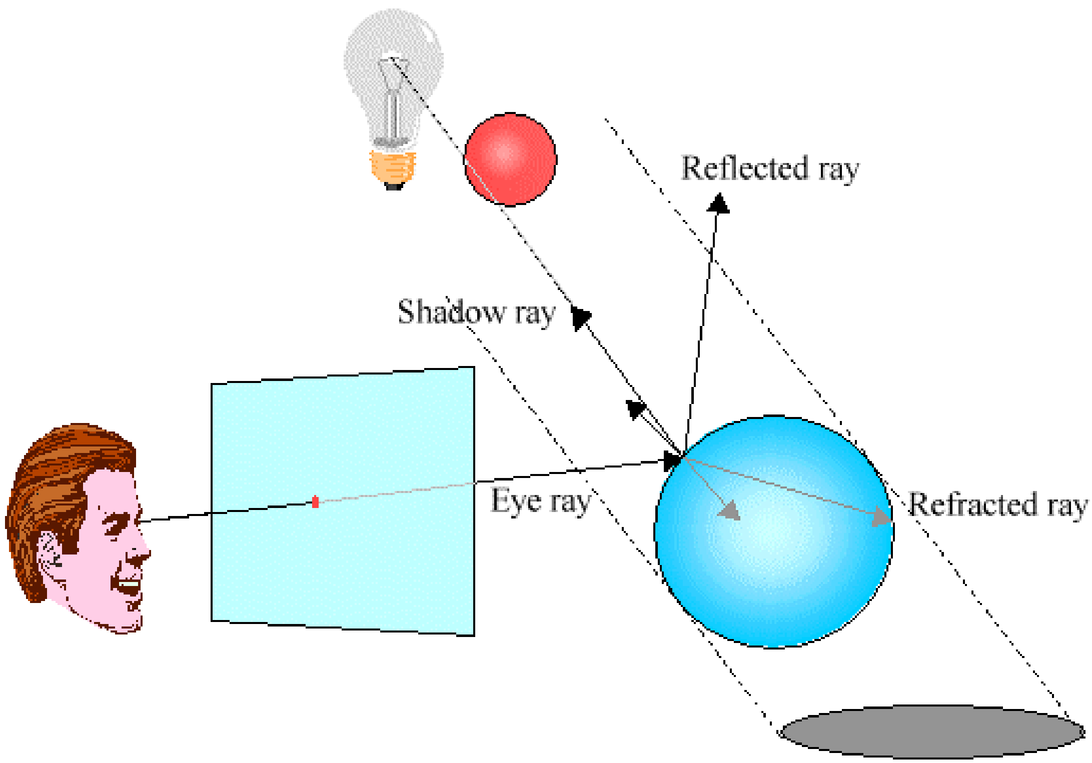
Advanced Ray Tracing

(Recursive) Ray Tracing
Antialiasing
Motion Blur
Distribution Ray Tracing
other fancy stuff

Assumptions

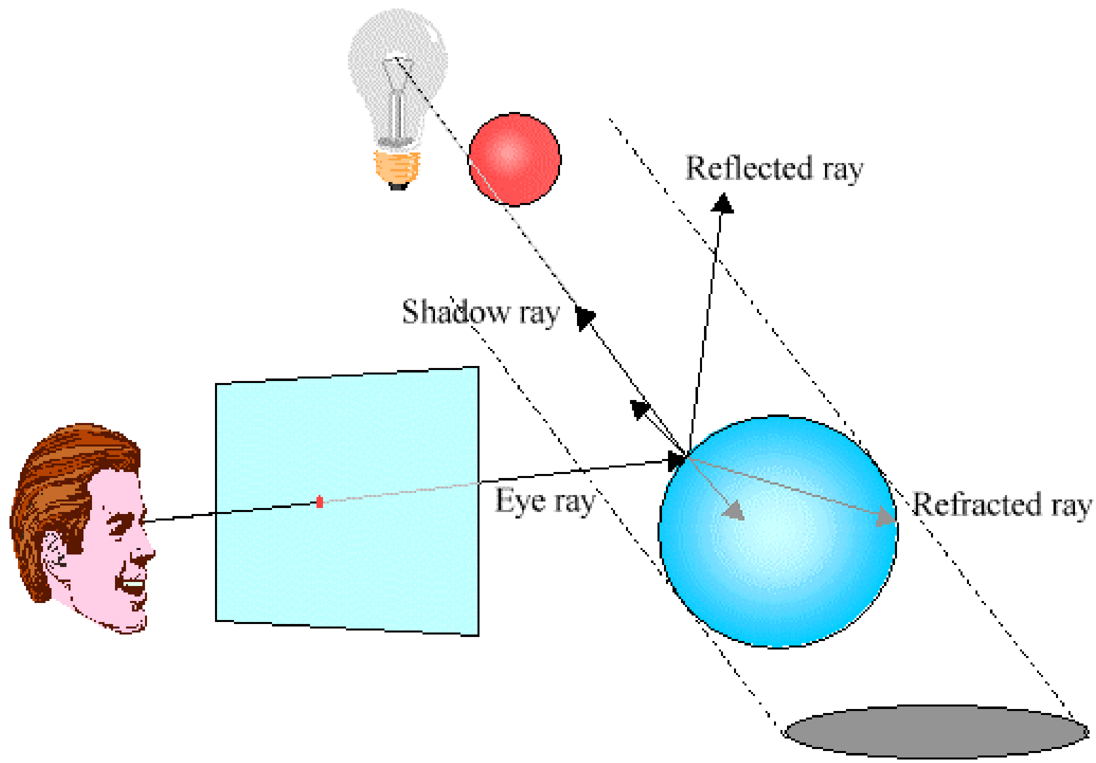
- Simple shading (typified by OpenGL, z-buffering, and Phong illumination model) assumes:
  - direct illumination (light leaves source, bounces at most once, enters eye)
  - no shadows
  - opaque surfaces
  - point light sources
  - sometimes fog
- (Recursive) ray tracing relaxes that, simulating:
  - specular reflection
  - shadows
  - transparent surfaces (transmission with refraction)
  - sometimes indirect illumination (a.k.a. global illumination)
  - sometimes area light sources
  - sometimes fog

Ray Types for Ray Tracing



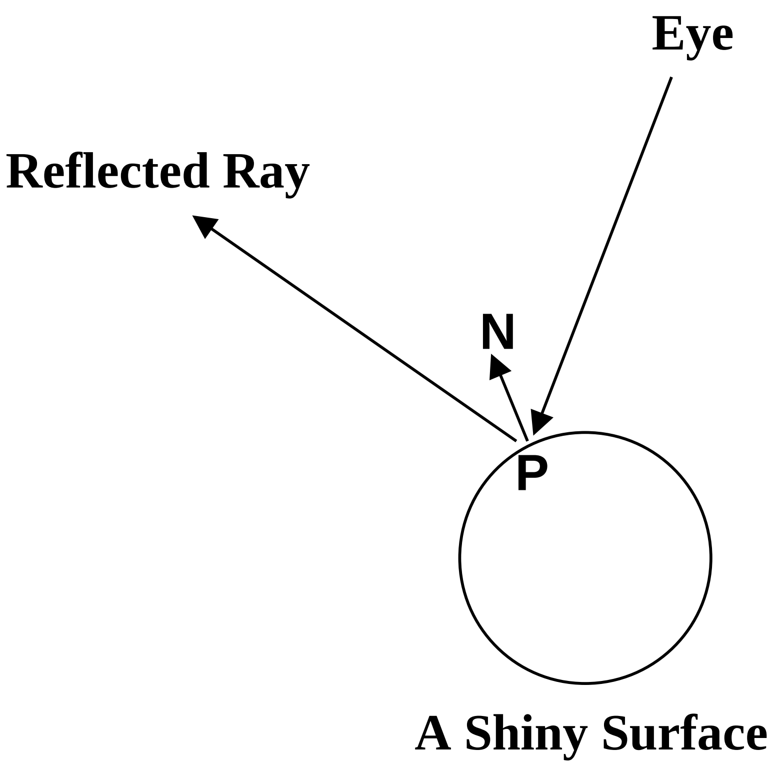
- **We'll distinguish four ray types:**
  - **Eye rays: orginate at the eye**
  - **Shadow rays: from surface point toward light source**
  - **Reflection rays: from surface point in mirror direction**
  - **Transmission rays: from surface point in refracted direction**

Ray Tracing Algorithm



- send ray from eye through each pixel
- compute point of closest intersection with a scene surface
- shade that point by computing shadow rays
- spawn reflected and refracted rays, repeat

Specular Reflection Rays

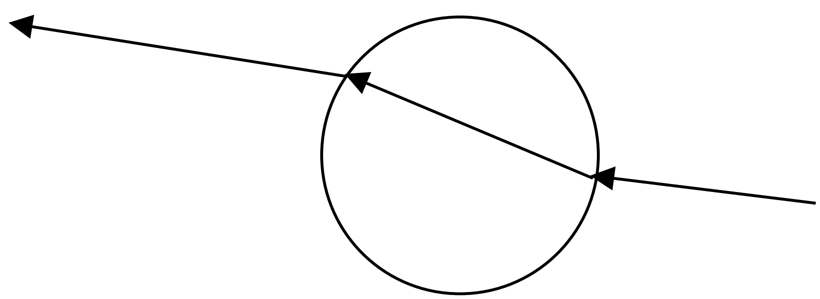


- An eye ray hits a shiny surface
  - We know the direction from which a specular reflection would come, based on the surface normal
  - Fire a ray in this reflected direction
  - The reflected ray is treated just like an eye ray: it hits surfaces and spawns new rays
  - Light flows in the direction opposite to the rays (towards the eye), is used to calculate shading
  - It's easy to calculate the reflected ray direction

Note: arrowheads show the direction in which we're *tracing the rays*, not the direction the light travels.

Specular Transmission Rays

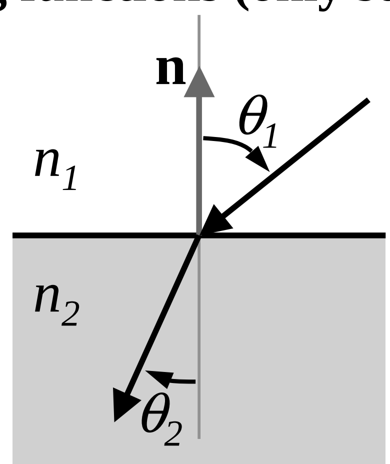
- **To add transparency:**
  - **Add a term for light that's coming from within the object**
  - **These rays are refracted (bent) when passing through a boundary between two media with different refractive indices**
  - **When a ray hits a transparent surface fire a *transmission ray* into the object at the proper refracted angle**
  - **If the ray passes through the other side of the object then it bends again (the other way)**



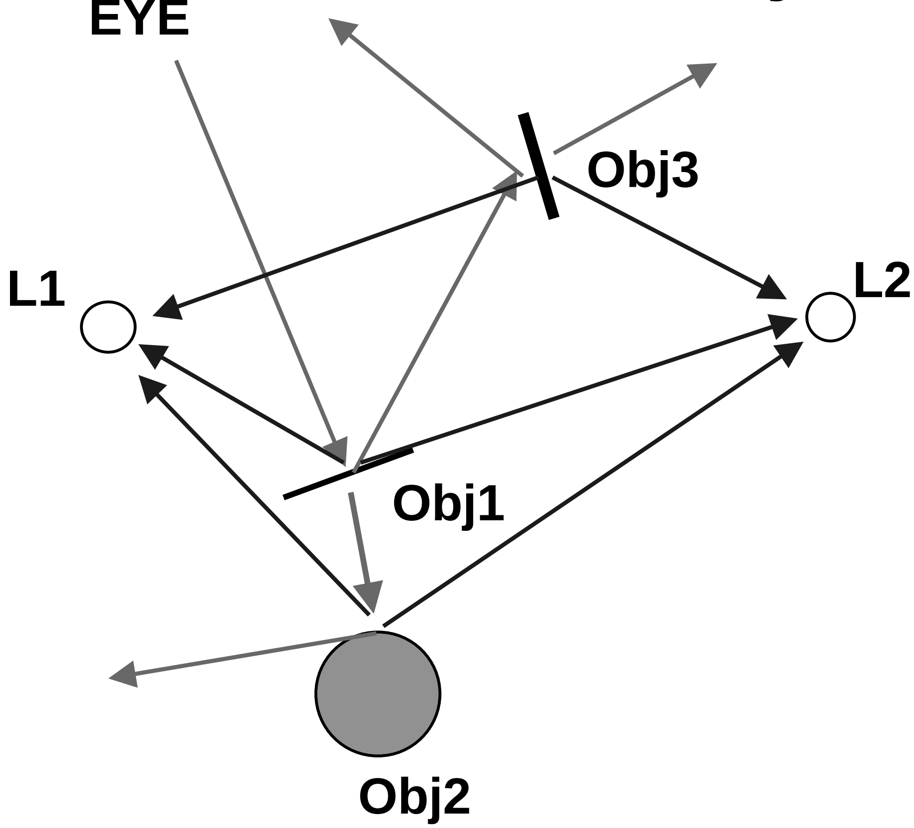
Refraction

- **Refraction:**
  - **The bending of light due to its different velocities through different materials**
  - **rays bend toward the normal when going from sparser to denser materials (e.g. air to water), away from normal in opposite case**
- **Refractive index:**
  - **Light travels at speed *c/n* in a material of refractive index *n***
    - » ***c* is the speed of light in a vacuum**
    - » ***c* varies with wavelength, hence rainbows and prisms**
  - **Use Snell's law** $n_1 \sin \theta_1 = n_2 \sin \theta_2$ **to derive refracted ray direction**
    - » **note: ray dir. can be computed without trig functions (only sqrts)**

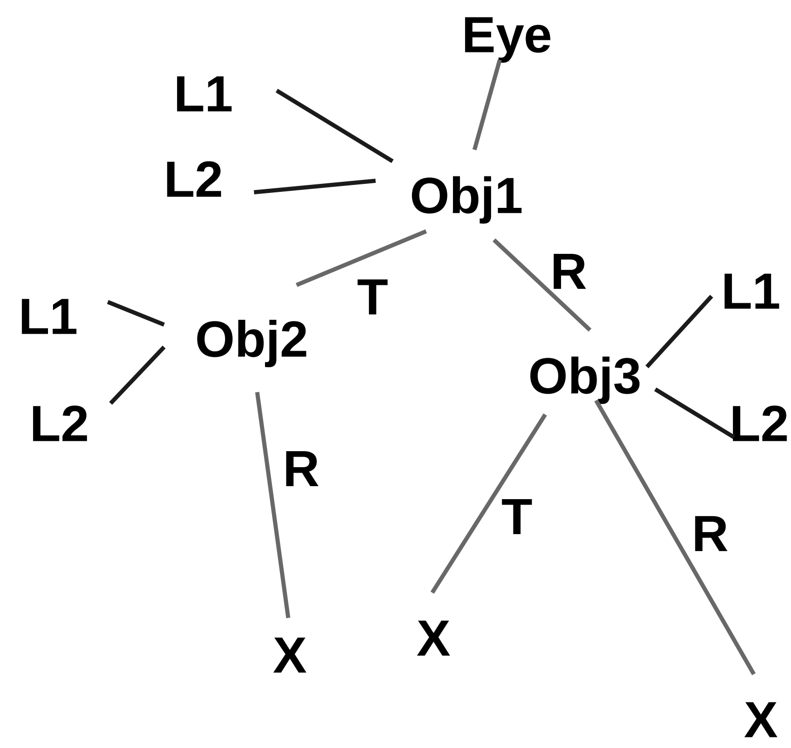
MATERIAL	INDEX OF REFRACTION
air/cacuum	1
water	1.33
glass	about 1.5
diamond	2.4



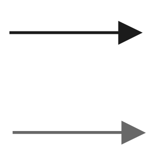
Ray Genealogy



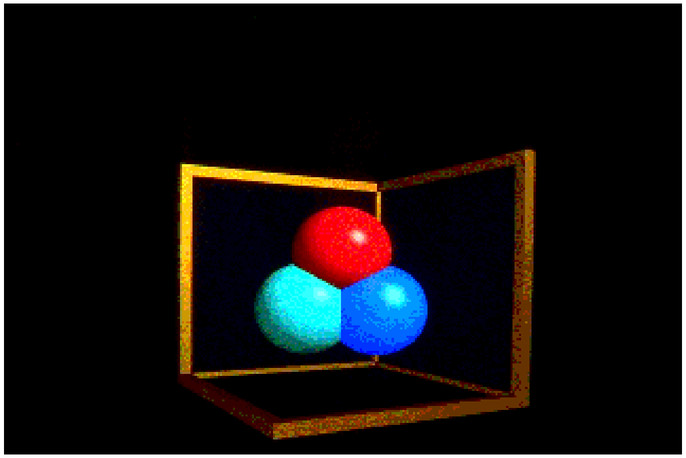
RAY PATHS (BACKWARD)



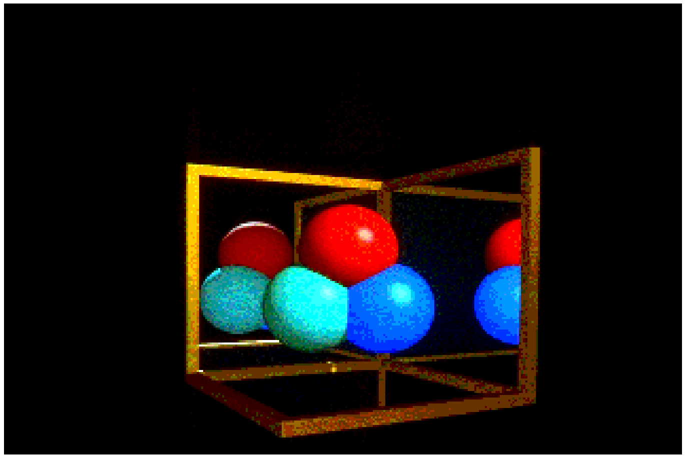
RAY TREE



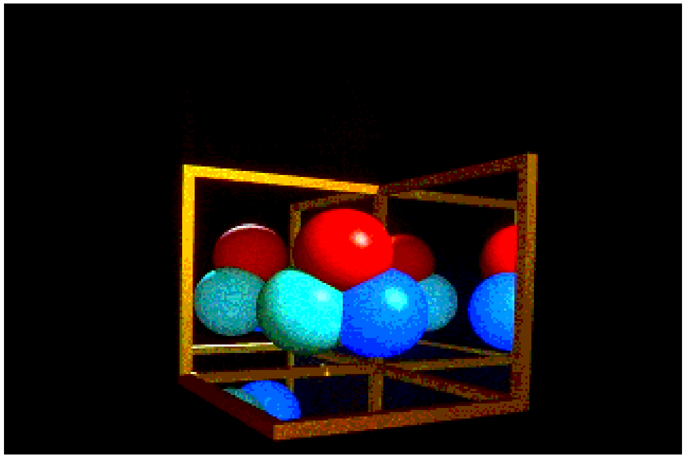
Ray Casting vs. Ray Tracing



Ray Casting -- 1 bounce



Ray Tracing -- 2 bounce



Ray Tracing -- 3 bounce

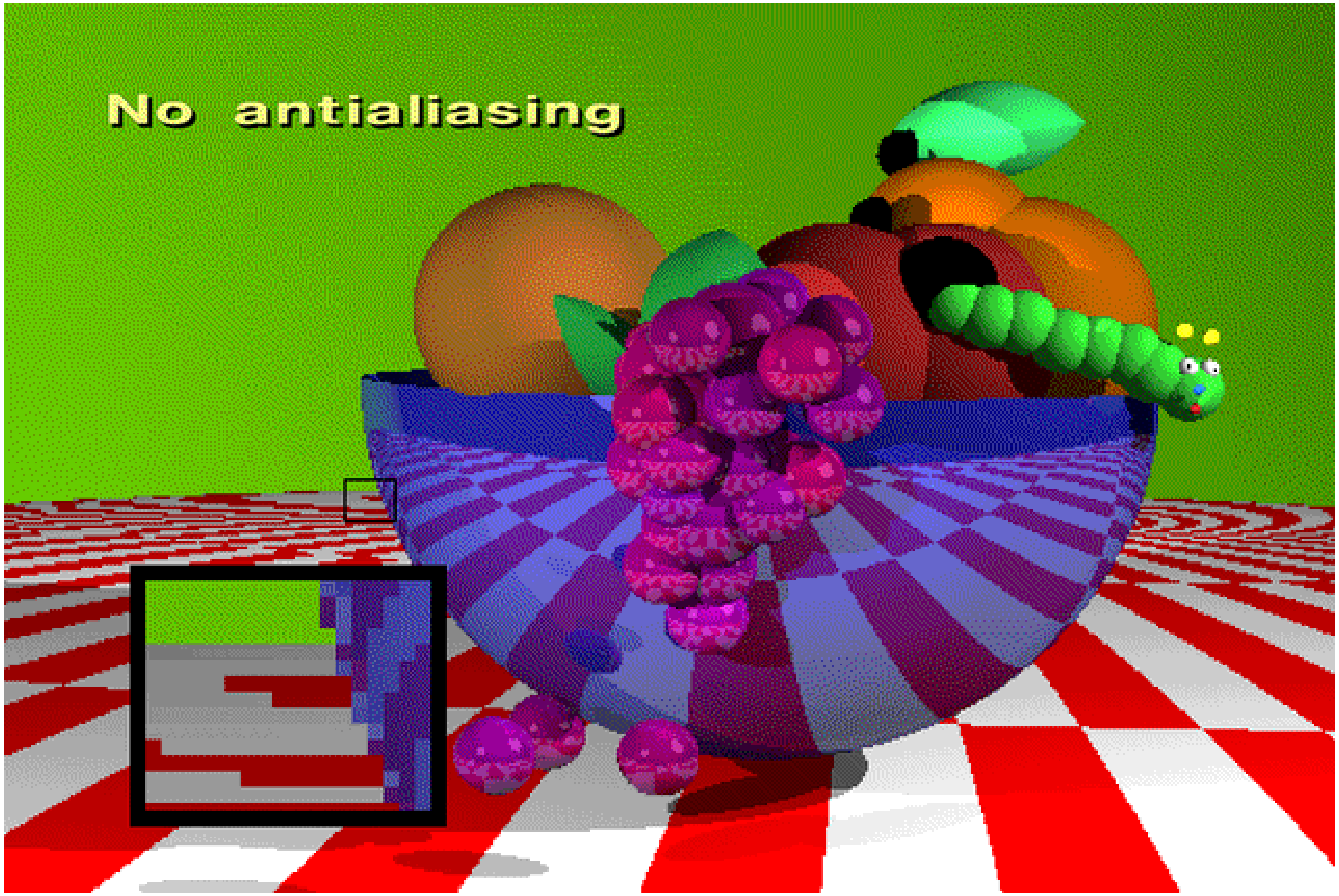
Writing a Simple Ray Tracer

```
Raytrace()          // top level function
   for each pixel x,y
      color(pixel) = Trace(ray_through_pixel(x,y))


Trace(ray)          // fire a ray, return RGB radiance
   object_point = closest_intersection(ray)
   if object_point return Shade(object_point, ray)
   else return Background_Color
```

Writing a Simple Ray Tracer (Cont.)

```
Shade(point, ray)              /* return radiance along ray */
   radiance = black;           /* initialize color vector */
   for each light source
      shadow_ray = calc_shadow_ray(point,light)
      if !in_shadow(shadow_ray,light)
         radiance += phong_illumination(point,ray,light)
   if material is specularly reflective
      radiance += spec_reflectance *
        Trace(reflected_ray(point,ray)))
   if material is specularly transmissive
      radiance += spec_transmittance *
        Trace(refracted_ray(point,ray)))
   return radiance


Closest_intersection(ray)
   for each surface in scene
      calc_intersection(ray,surface)
   return the closest point of intersection to viewer
   (also return other info about that point, e.g., surface
     normal, material properties, etc.)
```

Problem with Simple Ray Tracing: Aliasing



Aliasing

- **Ray tracing gives a color for every possible point in the image**
- **But a square pixel contains an *infinite* number of points**
  - **These points may not all have the same color**
  - **Sampling: choose the color of one point (center of pixel)**
  - **This leads to *aliasing***
    - **jaggies**
    - **moire patterns**
  - **aliasing means one frequency (high) masquerading as another (low)**
    - **e.g. wagon wheel effect**

- **How do we fix this problem?**

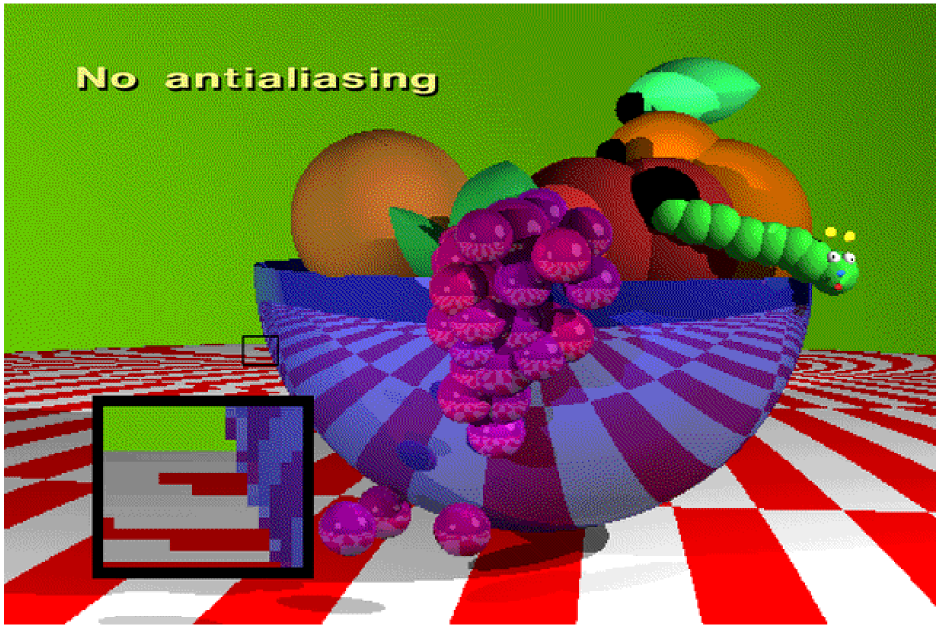
Antialiasing

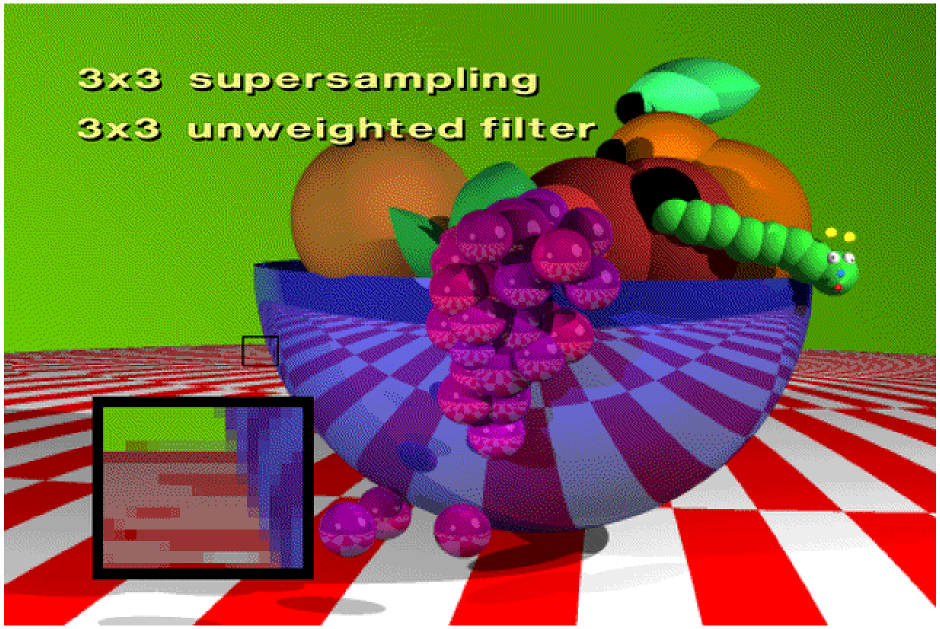
- **Supersampling**
  - **Fire more than one ray for each pixel (e.g., a 3x3 grid of rays)**
  - **Average the results using a filter**
  - **Can be done *adaptively***
    - » **divide pixel into 2x2 grid, trace 5 rays (4 at corners, 1 at center)**
    - » **if the colors are similar then just use their average**
    - » **otherwise recursively subdivide each cell of grid**
    - » **keep going until each 2x2 grid is close to uniform or limit is reached**
    - » **filter the result**

Adaptive Supersampling: Making the World a Better Place

- **Is adaptive supersampling the answer?**
  - **Areas with fairly constant appearance are sparsely sampled (good)**
  - **Areas with lots of variability are heavily sampled (good)**
- **But alas...**
  - **even with massive supersampling visible aliasing is possible when the sampling grid interacts with regular structures**
  - **problem is, objects tend to be almost aligned with sampling grid**
  - **noticeable beating, moire patterns, etc… are possible**
- **So use *stochastic sampling***
  - **instead of a regular grid, subsample randomly (or pseudo)**
  - **adaptively sample *statistically***
  - **keep taking samples until the color estimates converge**
  - **jittering: perturb a regular grid**

Supersampling



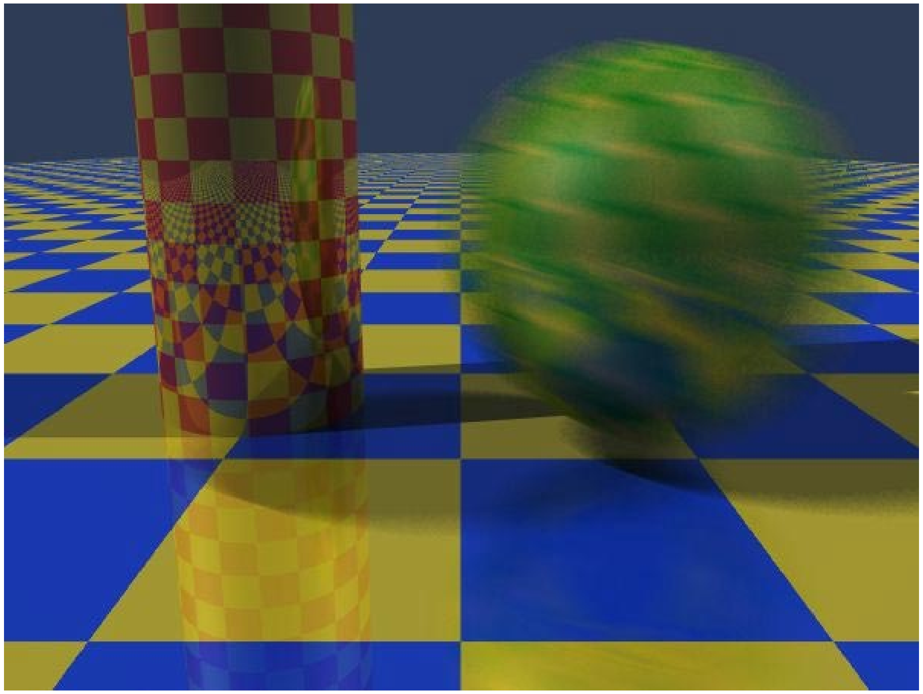


Temporal Aliasing

- **Aliasing happens in time as well as space**
  - **the sampling rate is the frame rate, 30Hz for NTSC video, 24Hz for film**
  - **fast moving objects move large distances between frames**
  - **if we point-sample time, objects have a jerky, strobed look**
- **To avoid temporal aliasing we need to filter in time too**
  - **so compute frames at 120Hz and average them together (with appropriate weights)?**
  - **fast-moving objects become blurred streaks**
- **Real media (film and video) automatically do temporal anti-aliasing**
  - **photographic film integrates over the exposure time**
  - **video cameras have persistence (memory)**
  - **this shows up as *motion blur* in the photographs**

Motion Blur

- Apply stochastic sampling to time as well as space
- Assign a time as well as an image position to each ray
- The result is still-frame motion blur and smooth animation
- This is an example of distribution ray tracing



The Classic Example of Motion Blur

- From Foley et. al. Plate III.16
- Rendered using distribution ray tracing at 4096x3550 pixels, 16 samples per pixel.
- Note motion-blurred reflections and shadows with penumbrae cast by extended light sources.

Distribution Ray Tracing

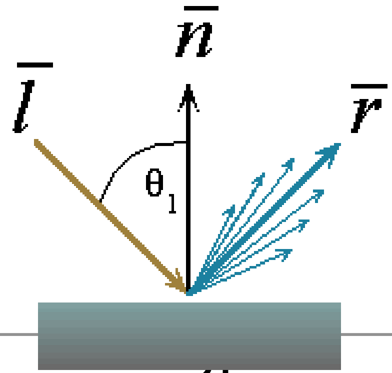
- **distribute rays throughout a pixel to get spatial antialiasing**
- **distribute rays in time to get temporal antialiasing (motion blur)**
- **distribute rays in reflected ray direction to simulate gloss**
- **distribute rays across area light source to simulate penumbras (soft shadows)**
- **distribute rays throughout lens area to simulate depth of field**
- **distribute rays across hemisphere to simulate diffuse interreflection (radiosity)**

- **a.k.a. "distributed ray tracing" or stochastic ray tracing**
- **a form of numerical integration**

- **aliasing is replaced by less visually annoying noise!**
- **powerful idea! (but can get slow)**

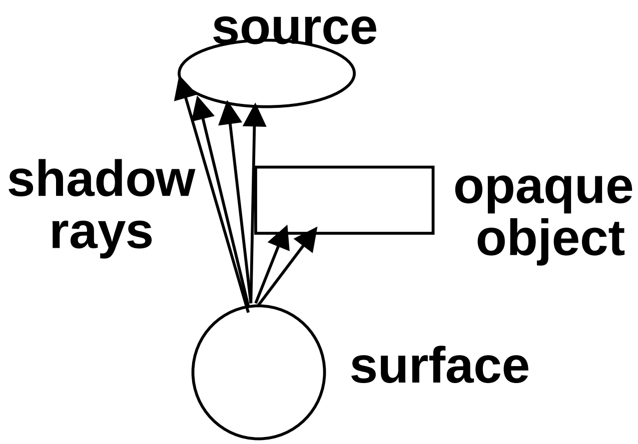
Gloss and Highlights

- Simple ray tracing spawns only one reflected ray
- But Phong illumination models a cone of rays
  - Produces fuzzy highlights
  - Change fuzziness (cone width) by varying the shininess parameter
- Can we generate fuzzy highlights?
  - Yes: via shadow rays
  - But there's a catch
    - » we can't light reflected from the fuzzy highlight onto other objects
- A more accurate model is possible using stochastic sampling
  - Stochastically sample rays within the cone
  - Sampling probability drops off sharply away from the specular angle
  - Highlights can be soft, blurred reflections of other objects

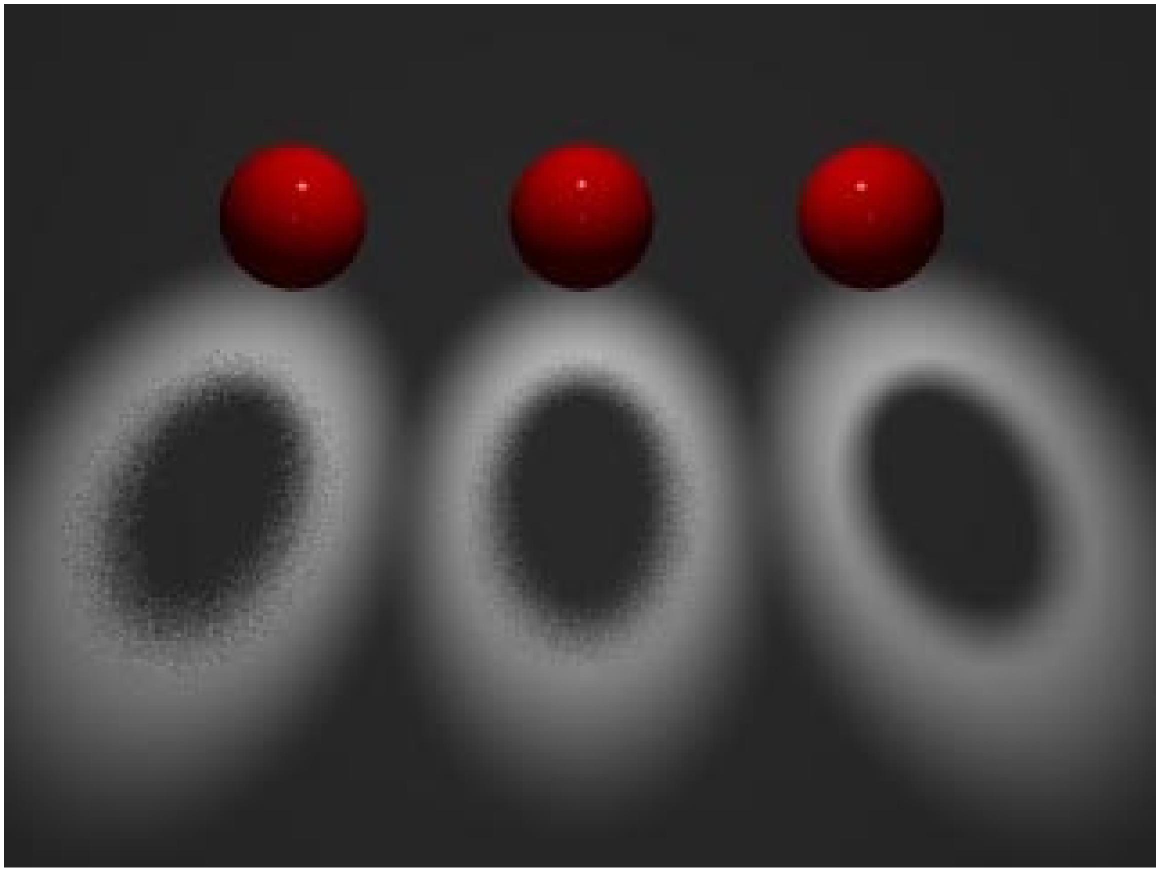


Soft Shadows

- **Point light sources produce sharp shadow edges**
  - **the point is either shadowed or not**
  - **only one ray is required**
- **With an extended light source the surface point may be partially visible to it (*partial eclipse*)**
  - **only part of the light from the sources reaches the point**
  - **the shadow edges are softer**
  - **the transition region is the *penumbra***
- **Distribution ray tracing can simulate this:**
  - **fire shadow rays from random points on the source**
  - **weight them by the brightness**
  - **the resulting shading depends on the fraction of the obstructed shadow rays**

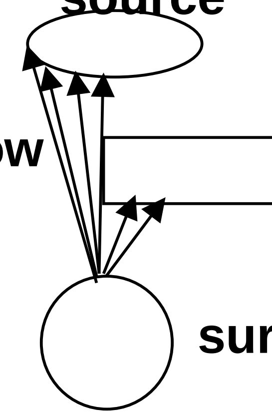


Soft Shadows



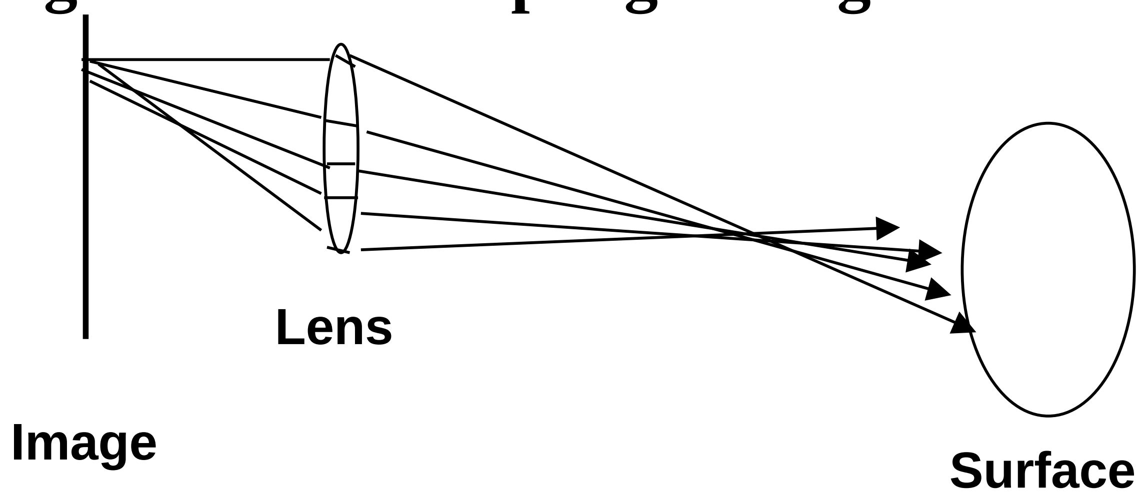
fewer rays,
more noise

more rays,
less noise



Depth of Field

- The pinhole camera model only approximates real optics
  - real cameras have lenses with focal lengths
  - only one plane is truly in focus
  - points away from the focus project as disks
  - the further away from the focus the larger the disk
- the range of distance that appear in focus is the *depth of field*
- simulate this using stochastic sampling through different parts of the lens



Beyond Ray Tracing

- **Ray tracing ignores the diffuse component of incident illumination**
  - **to achieve this component requires sending out rays from each surface point for the whole visible hemisphere**
  - **this is the *branching factor* of the recursive ray tree**
- **Even if you could compute such a massive problem there is a conceptual problem:**
  - **you will create loops:**
    - » **point A gets light from point B**
    - » **point B also gets light from point A**

Doing it *Really* Right (or trying)

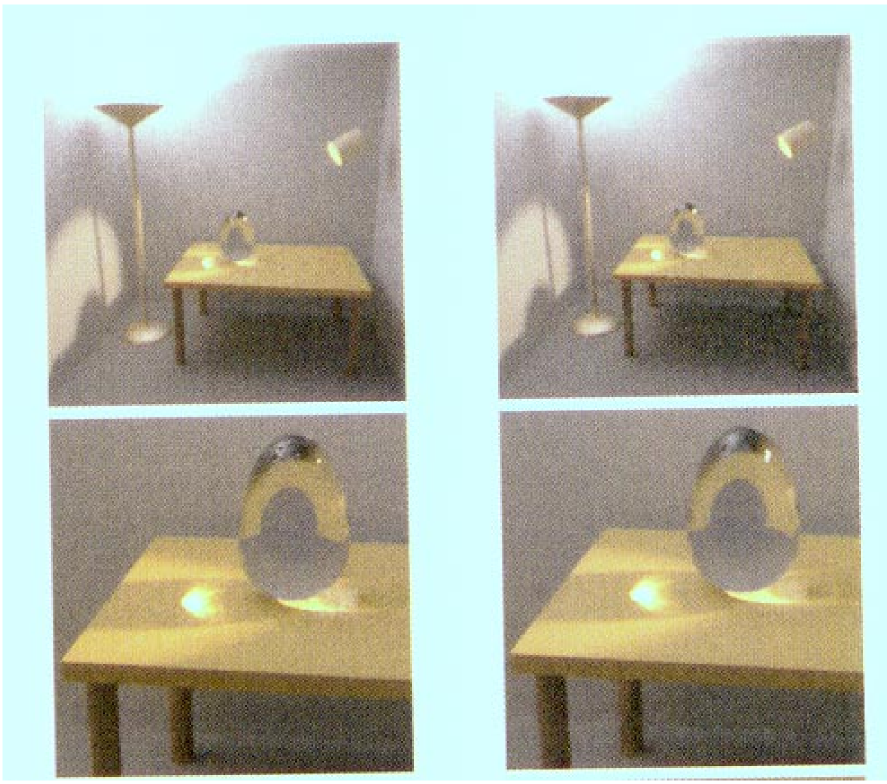
- The real solution is to solve simultaneously for incoming and outgoing light at all surface points
  - this is a massive integral equation
- *Radiosity* (in 15-463) deals with the easy case of purely diffuse scenes
- Or, you can sample many, many complete paths from light source to camera
  - Metropolis Light Transport (Veach and Guibas, Siggraph 1997)

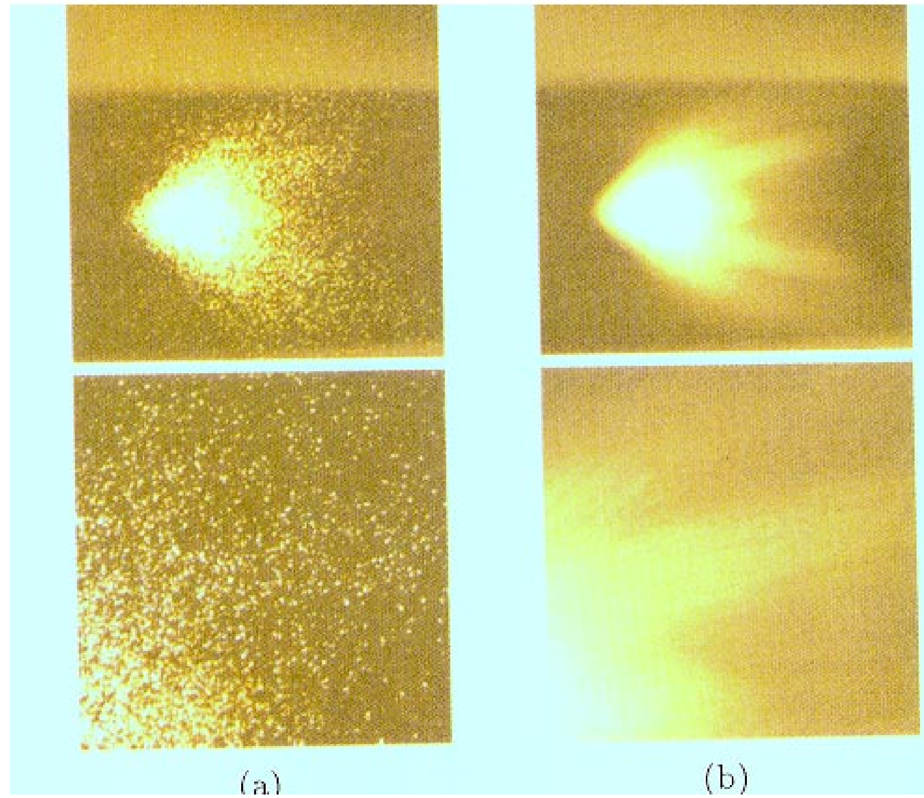
Diffuse Illumination

(b) Metropolis light transport with an average of 250 mutations per pixel [the same computation time as (a)].

From Veach and Guibas, Siggraph '97

Caustics





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