Ray-Tracing Soft Shadows
Global Illumination

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Course News

Homework 8
- Ray-tracing, global illumination
- Discussed today, tomorrow in labs

Assignment 3 (project)
- Due Friday!!
- Demos in labs starting this Friday
- Demos are MANDATORY(!)

Reading
- Chapter 10 (ray tracing), except 10.8-10.10
- Chapter 14 (global illumination)

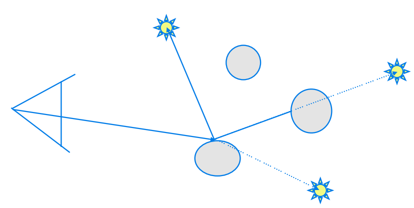
Ray-Tracing

Basic Algorithm (Whithead):

for every pixel p_i {
  Generate ray r from camera position through pixel p_i
    p_i= background color
  for every object o in scene {
    if(r intersects o && intersection is closer than previously found intersections)
      Compute lighting at intersection point, using local normal and material properties; store result in p_i
  }
}

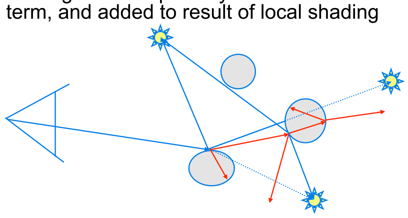
Ray-Tracing Shadows

Approach:
- To test whether point is in shadow, send out <u>*shadow rays*</u> to all light sources
  - *If ray hits another object, the point lies in shadow*



Ray-Tracing Reflections/Refractions

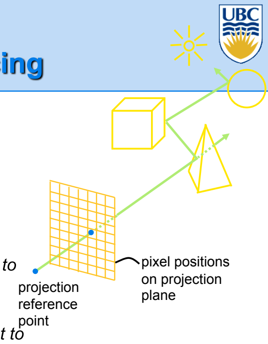
Approach:
- Send rays out in reflected and refracted direction to gather incoming light
- That light is multiplied by local surface color and Fresnel term, and added to result of local shading



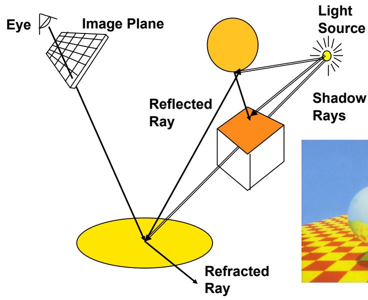
Recursive Ray Tracing

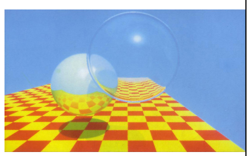
Ray tracing can handle
- Reflection (chrome)
- Refraction (glass)
- Shadows

Spawn secondary rays
- Reflection, refraction
  - *If another object is hit, recurse to find its color*
- Shadow
  - *Cast ray from intersection point to light source, check if intersects another object*



Recursive Ray-Tracing





Whitted, 1980

Recursive Ray-Tracing Algorithm

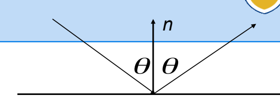
```
RayTrace(r,scene)
obj := FirstIntersection(r,scene)
if (no obj)  return BackgroundColor;
else begin
   if ( Reflect(obj) ) then
      reflect_color := RayTrace(ReflectRay(r,obj));
   else
      reflect_color := Black;
  if ( Transparent(obj) ) then
      refract_color := RayTrace(RefractRay(r,obj));
   else
      refract_color := Black;
  return Shade(reflect_color,refract_color,obj);
end;
```


Algorithm Termination Criteria

Termination criteria

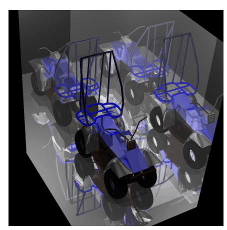
- No intersection
- Reach maximal depth
  - *Number of bounces*
- Contribution of secondary ray attenuated below threshold
  - *Each reflection/refraction attenuates ray*

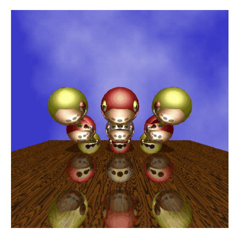
Reflection



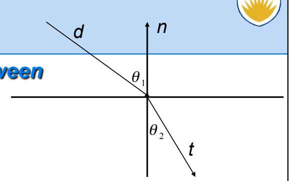
Mirror effects

- Perfect specular reflection





Refraction

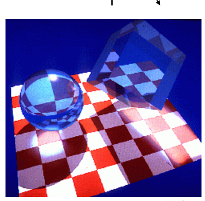


Happens at interface between transparent object and surrounding medium

- E.g. glass/air boundary

Snell's Law

- $c_1 \sin\theta_1 = c_2 \sin\theta_2$
- Light ray bends based on refractive indices c_1, c_2



Area Light Sources

So far:

- All lights were either point-shaped or directional
  - *Both for ray-tracing and the rendering pipeline*
- Thus, at every point, we only need to compute lighting formula and shadowing for ONE light direction

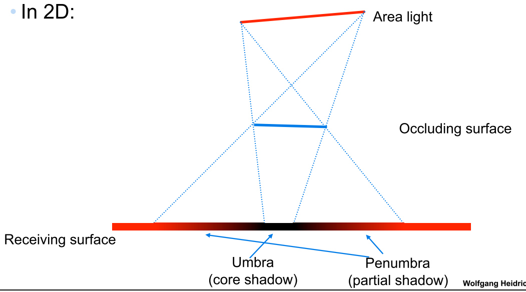
In reality:

- All lights have a finite area
- Instead of just dealing with one direction, we now have to integrate over all directions that go to the light source

Area Light Sources

Area lights produce soft shadows:

- In 2D:



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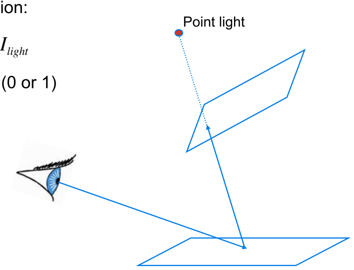
Area Light Sources

Point lights:

- Only one light direction:

$$I_{reflected} = \rho \cdot V \cdot I_{light}$$

- V is visibility of light (0 or 1)
- ρ is lighting model (e.g. diffuse or Phong)



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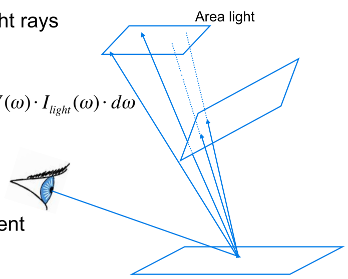
Are Light Sources

Area Lights:

- Infinitely many light rays
- Need to integrate over all of them:

$$I_{reflected} = \int_{\substack{light\\directions}} \rho(\omega)\cdot V(\omega)\cdot I_{light}(\omega)\cdot d\omega$$

- Lighting model visibility and light intensity can now be different for every ray!



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Integrating over Light Source

Rewrite the integration

- Instead of integrating over directions

$$I_{reflected} = \int_{\substack{light\\directions}} \rho(\omega)\cdot V(\omega)\cdot I_{light}(\omega)\cdot d\omega$$

we can integrate over points on the light source

$$I_{reflected}(q) = \int_{s,t} \frac{\rho(p-q)\cdot V(p-q)}{|p-q|^2}\cdot I_{light}(p)\cdot ds\cdot dt$$

where q: point on reflecting surface, p= F(s,t) is a point on the area light

- *We are integrating over p*
- *Denominator: quadratic falloff!*

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Integration

Problem:

- Except for the simplest of scenes, either integral is **not solvable analytically**!
- This is mostly due to the visibility term, which could be arbitrarily complex depending on the scene

So:

- Use numerical integration
- Effectively: approximate the light with a whole number of point lights

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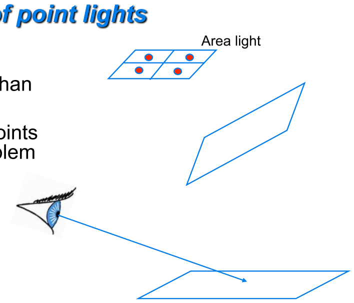
Numerical Integration

Regular grid of point lights

- Problem: will see 4 hard shadows rather than as soft shadow
- Need LOTS of points to avoid this problem



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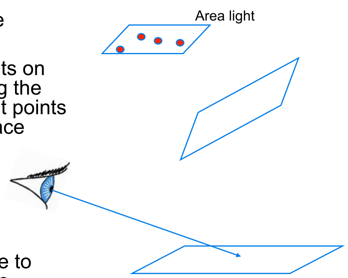
Monte Carlo Integration

Better:

- Randomly choose the points
- Use different points on light for computing the lighting in different points on reflecting surface
- This produces random noise
- Visually preferable to structured artifacts



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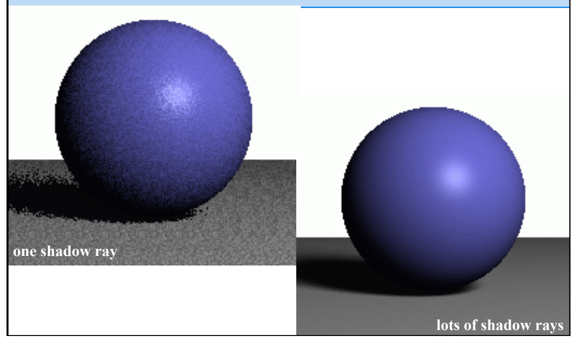
Monte Carlo Integration



Monte Carlo Integration

Formally:

- Approximate integral with finite sum

$$I_{reflected}(q) = \int_{s,t} \frac{\rho(p-q)\cdot V(p-q)}{|p-q|^2}\cdot I_{light}(p)\cdot ds\cdot dt$$

$$\approx \frac{A}{N}\sum_{i=1}^{N}\frac{\rho(p_i-q)\cdot V(p_i-q)}{|p_i-q|^2}\cdot I_{light}(p_i)$$

where

- *The p_i are randomly chosen on the light source*
  - With equal probability!
- *A is the total area of the light*
- *N is the number of samples (rays)*

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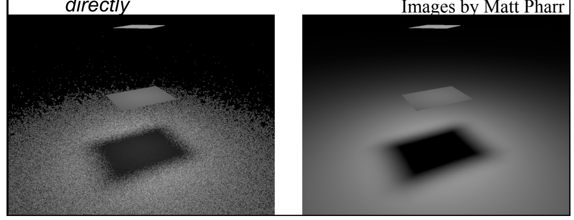
Sampling

Sample directions vs. sample light source

- Most directions do not correspond to points on the light source
  - *Thus, variance will be higher than sampling light directly*

Images by Matt Pharr



Monte Carlo Integration

Note:

- This approach of approximating lighting integrals with sums over randomly chosen points is much more flexible than this!
- In particular, it can be used for global illumination
  - *Light bouncing off multiple surfaces before hitting the eye*

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Global Illumination

So far:

- Have considered only light directly coming form the light sources
  - *As well as mirror reflections, refraction*

In reality:

- Light bouncing off diffuse and/or glossy surfaces also illuminates other surfaces
  - *This is called global illumination*

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Direct Illumination

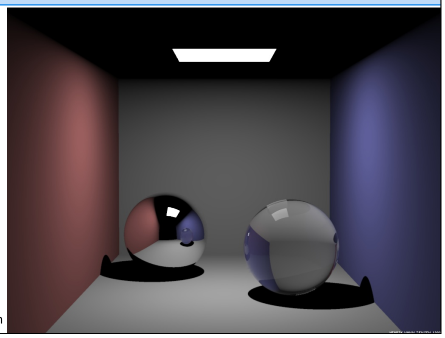


Image by
Henrik Wann Jensen

Global Illumination

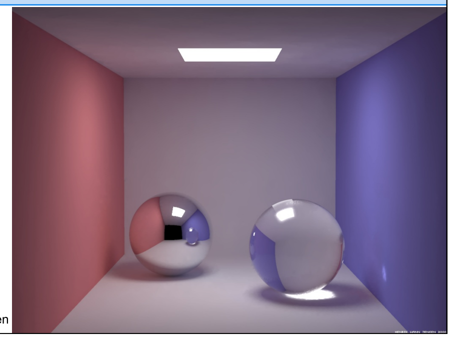


Image by
Henrik Wann Jensen

Rendering Equation

Equation guiding global illumination:

$$L_o(x,\omega_o) = L_e(x,\omega_o) + \int_\Omega \rho(x,\omega_i,\omega_0) L_i(\omega_i)\, d\omega_i$$

$$= L_e(x,\omega_o) + \int_\Omega \rho(x,\omega_i,\omega_0) L_o(R(x,\omega_i),-\omega_i)\, d\omega_i$$

Where

- ρ is the reflectance from ω_i to ω_o at point x
- L_o is the outgoing (I.e. reflected) radiance at point x in direction ω_i
  - *Radiance is a specific physical quantity describing the amount of light along a ray*
  - *Radiance is constant along a ray*
- L_e is the emitted radiance (=0 unless point x is on a light source)
- R is the "ray-tracing function". It describes what point is visible from x in direction ω_i

Rendering Equation

Equation guiding global illumination:

$$L_o(x,\omega_o) = L_e(x,\omega_o) + \int_\Omega \rho(x,\omega_i,\omega_0) L_i(\omega_i)\, d\omega_i$$

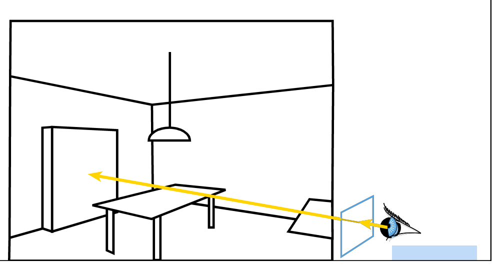
$$= L_e(x,\omega_o) + \int_\Omega \rho(x,\omega_i,\omega_0) L_o(R(x,\omega_i),-\omega_i)\, d\omega_i$$

Note:

- The rendering equation is an integral equation
- This equation cannot be solved directly
  - *Ray-tracing function is complicated!*
  - *Similar to the problem we had computing illumination from area light sources!*

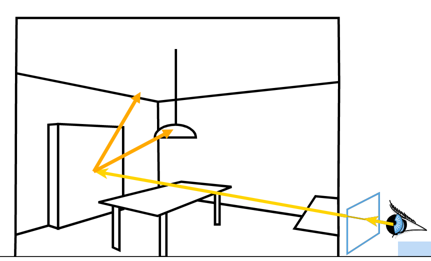
Ray Casting

- Cast a ray from the eye through each pixel
- The following few slides are from Fred Durand (MIT)



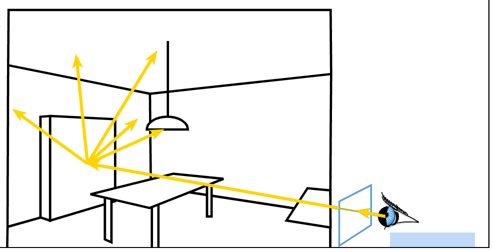
Ray Tracing

- Cast a ray from the eye through each pixel
- Trace secondary rays (light, reflection, refraction)



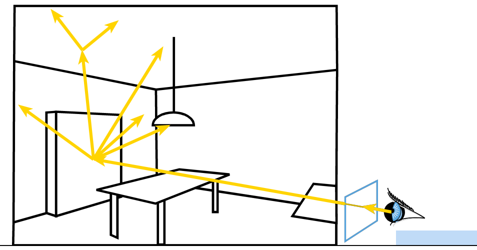
Monte Carlo Ray Tracing

- Cast a ray from the eye through each pixel
- Cast random rays from the visible point
  - *Accumulate radiance contribution*



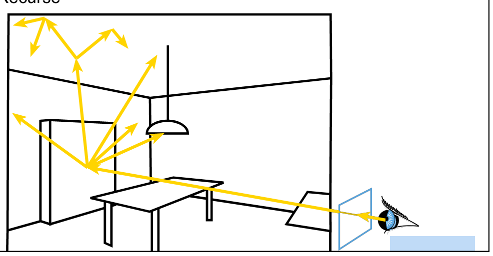
Monte Carlo Ray Tracing

- Cast a ray from the eye through each pixel
- Cast random rays from the visible point
- Recurse



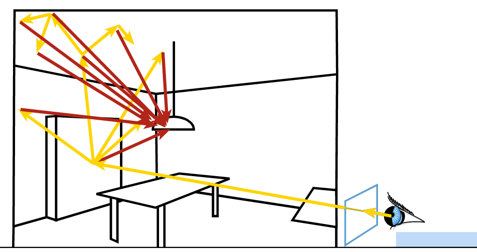
Monte Carlo

- Cast a ray from the eye through each pixel
- Cast random rays from the visible point
- Recurse



Monte Carlo

- Systematically sample primary light



Monte Carlo Path Tracing

In practice:

- Do not branch at every intersection point
  - *This would have exponential complexity in the ray depth!*
- Instead:
  - *Shoot some number of primary rays through the pixel (10s-1000s, depending on scene!)*
  - *For each pixel and each intersection point, make a single, random decision in which direction to go next*

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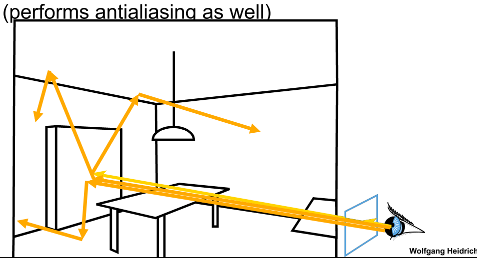
Monte Carlo Path Tracing

- Trace only one secondary ray per recursion
- But send many primary rays per pixel
- (performs antialiasing as well)



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How to Sample?

Simple sampling strategy:

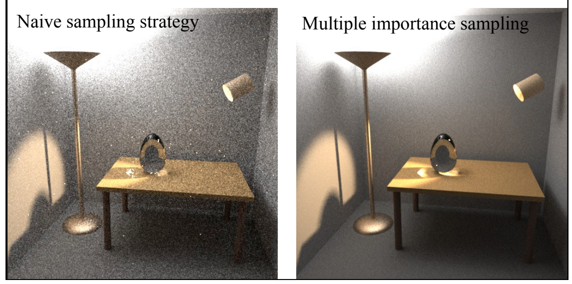
- At every point, choose between all possible reflection directions with equal probability
- This will produce very high variance/noise if the materials are specular or glossy
- Lots of rays are required to reduce noise!

Better strategy: importance sampling

- Focus rays in areas where most of the reflected light contribution will be found
- For example: if the surface is a mirror, then only light from the mirror direction will contribute!
- Glossy materials: prefer rays near the mirror direction

How to Sample?

- Images by Veach & Guibas



How to Sample?

Sampling strategies are still an active research area!

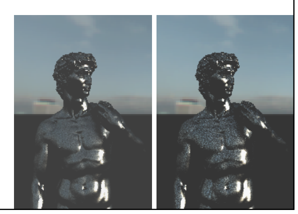
- Recent years have seen drastic advances in performance
- Lots of excellent sampling strategies have been developed in statistics and machine learning
  - *Many are useful for graphics*

How to Sample?

Objective:

- Compute light transport in scenes using stochastic ray tracing
  - *Monte Carlo, Sequential Monte Carlo*
  - *Metropolis*

[Burke, Ghosh, Heidrich '05]
[Ghosh, Heidrich '06],
[Ghosh, Doucet, Heidrich '06]



How to Sample?

- E.g: importance sampling (left) vs. Sequential Monte Carlo (right)

More on Global Illumination

This was a (very) quick overview

- More details in CPSC 514 (Computer Graphics: Rendering)
- Not offered this year, but in 2008/9

Coming Up…

Next Week:

- Global illumination

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