Ray Tracing
Global Illumination

Wolfgang Heidrich

Course News

Assignment 3 (project)

- Due April 1
- Demos in labs April 2-7

Reading

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

Course Topics for the Rest of the Term

Ray-tracing & Global Illumination

- This week

Parametric Curves/Surfaces

- March 30/April 1
- Taught by Robert Bridson - I will be at a conference

Overview of current research

- April 3/6 (Ivo Ihrke – I am still at conference)

April 8 – Final Q&A (I will be back for that)

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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
  }
}

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Ray-Tracing

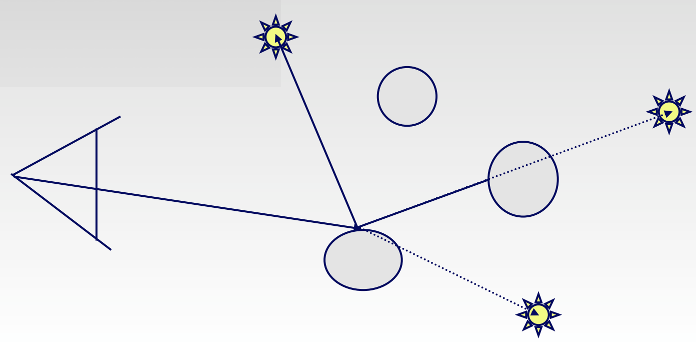
Issues:

- Generation of rays
- Intersection of rays with geometric primitives
- Geometric transformations
- Lighting and shading
- Efficient data structures so we don't have to test intersection with *every* object

Ray-Tracing Shadows

Approach:

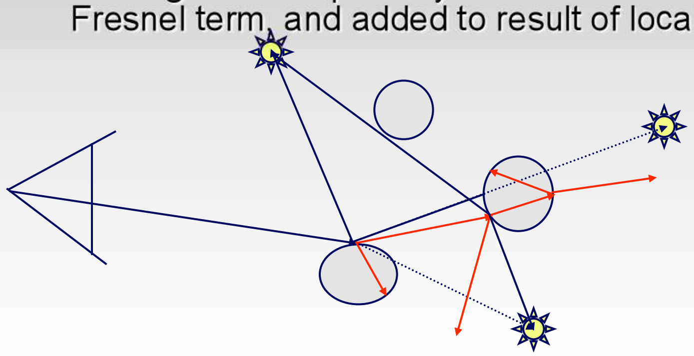
- To test whether point is in shadow, send out <u>*shadow rays*</u> to all light sources
  - *If ray hits another object, the point lies in shadow*



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



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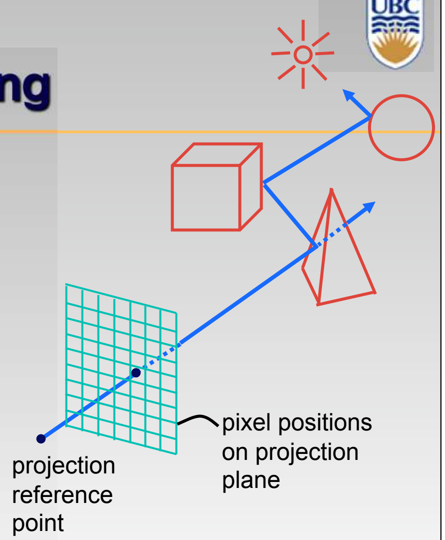
Recursive Ray Tracing

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*



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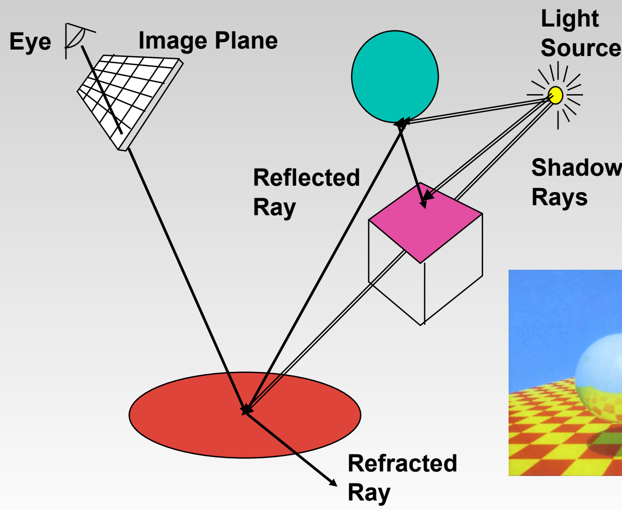
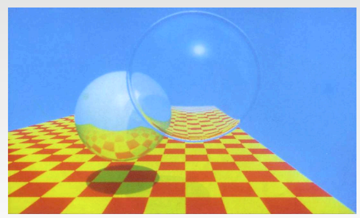
Recursive Ray-Tracing





Whitted, 1980

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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;
```

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Recursive Ray-Tracing

What rays need to be traced?

- Materials with diffuse/Phong reflection component:
  - *Shadow rays to each light source (binary visibility only)*
- Materials with mirror reflection component:
  - *Reflection ray (i.e. recursion)*
- Materials with transmissive component:
  - *Refraction ray (recursion)*

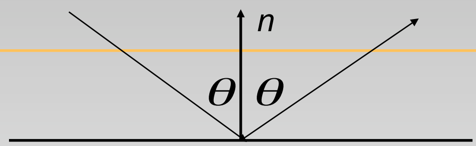
In practice, materials can have any combination of the above components

Algorithm Termination Criteria

Termination criteria

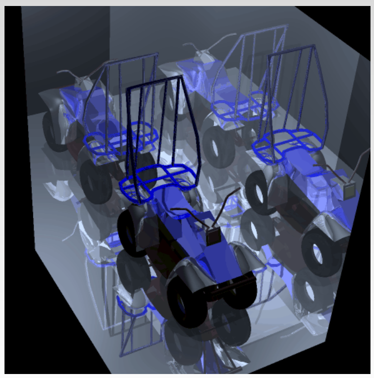
- No intersection
- Reach maximal depth
  - *Number of bounces*
- Contribution of secondary ray attenuated below threshold
  - *Each reflection/refraction attenuates ray*

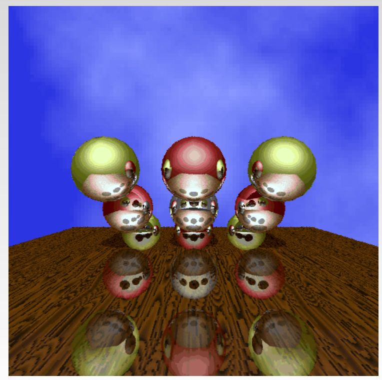
Reflection



Mirror effects

- Perfect specular reflection





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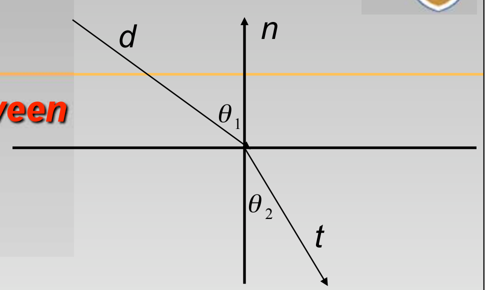
Refraction

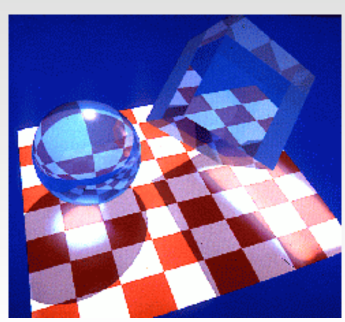


Happens at interface between transparent object and surrounding medium

- 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



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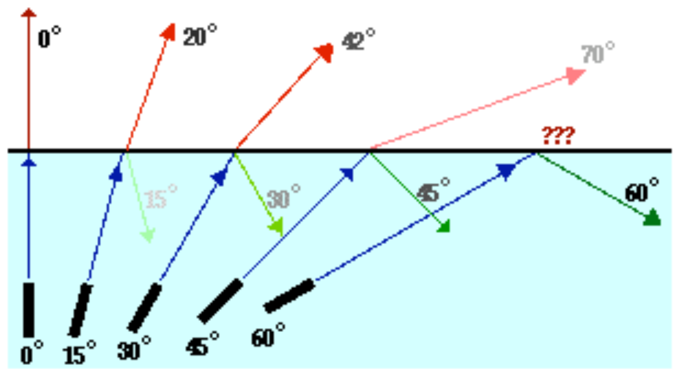
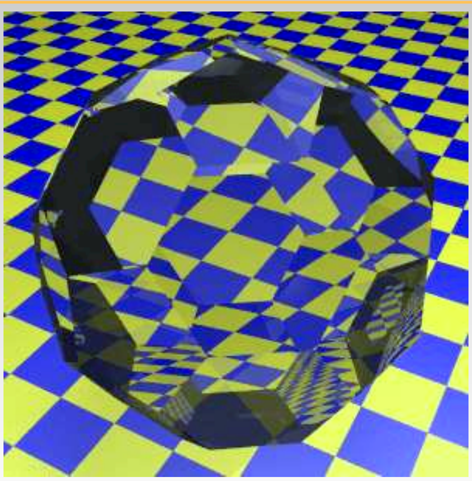
Total Internal Reflection

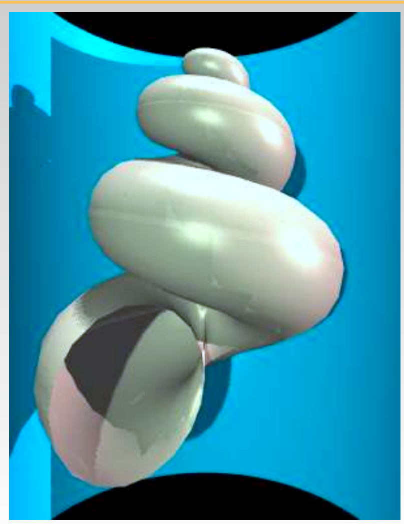
As the angle of incidence increases from 0 to greater angles ...



...the refracted ray becomes dimmer (there is less refraction)
...the reflected ray becomes brighter (there is more reflection)
...the angle of refraction approaches 90 degrees until finally a refracted ray can no longer be seen.

Ray-Tracing Example Images





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Ray-Tracing Terminology

Terminology:

- Primary ray: ray starting at camera
- Shadow ray
- Reflected/refracted ray
- Ray tree: all rays directly or indirectly spawned off by a single primary ray

Note:

- Need to limit maximum depth of ray tree to ensure termination of ray-tracing process!

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Ray-Tracing

Issues:

- Generation of rays
- Intersection of rays with geometric primitives
- Geometric transformations
- Lighting and shading
- Efficient data structures so we don't have to test intersection with *every* object

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Ray Tracing

Data Structures

- Goal: reduce number of intersection tests per ray
- Lots of different approaches:
  - *(Hierarchical) bounding volumes*
  - *Hierarchical space subdivision*
    - Oct-tree, k-D tree, BSP tree

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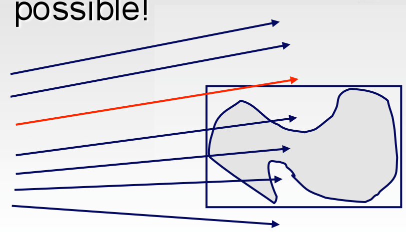
Bounding Volumes

Idea:

- Rather than testing every ray against a potentially very complex object (e.g. triangle mesh), do a quick *conservative* test first which eliminates most rays
  - *Surround complex object by simple, easy to test geometry (typically sphere or axis-aligned box)*
    - Want to make bounding volume as tight as possible!



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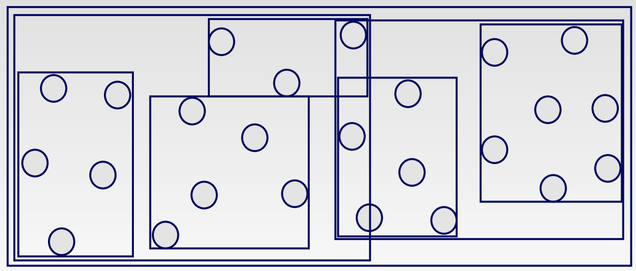
Hierarchical Bounding Volumes

Extension of previous idea:

- Use bounding volumes for groups of objects



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Spatial Subdivision Data Structures

Bounding Volumes:

- Find simple object completely enclosing complicated objects
  - *Boxes, spheres*
- Hierarchically combine into larger bounding volumes

Spatial subdivision data structure:

- Partition the whole space into cells
  - *Grids, oct-trees, (BSP trees)*
- Simplifies and accelerates traversal
- Performance less dependent on order in which objects are inserted

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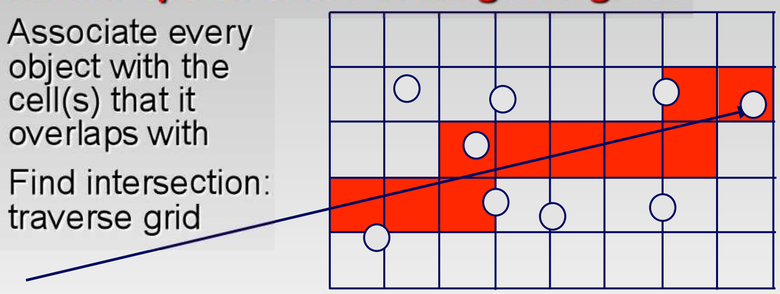
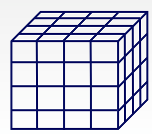
Regular Grid

Subdivide space into rectangular grid:

- Associate every object with the cell(s) that it overlaps with
- Find intersection: traverse grid



In 3D: regular grid of cubes (voxels):



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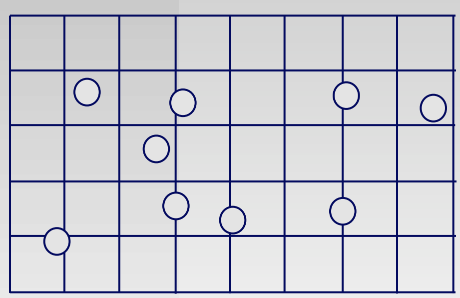
Creating a Regular Grid

Steps:

- Find bounding box of scene
- Choose grid resolution in x, y, z
- Insert objects
- Objects that overlap multiple cells get referenced by all cells they overlap



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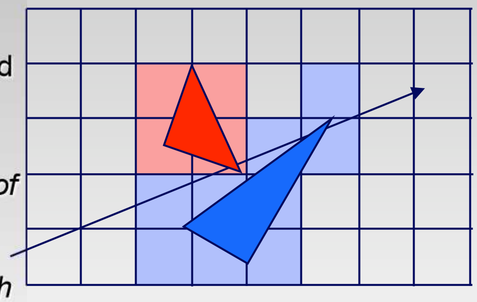
Grid Traversal

Traversal:

- Start at ray origin
- While no intersection found
  - *Go to next grid cell along ray*
  - *Compute intersection of ray with all objects in the cell*
  - *Determine closest such intersection*
  - ***Check if that intersection is inside the cell***
  - *If so, terminate search*



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Traversal

Note:

- This algorithm calls for computing the intersection points multiple times (once per grid cell)
- In practice: store intersections for a (ray, object) pair once computed, reuse for future cells

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Regular Grid Discussion

Advantages?

- Easy to construct
- Easy to traverse

Disadvantages?

- May be only sparsely filled
- Geometry may still be clumped

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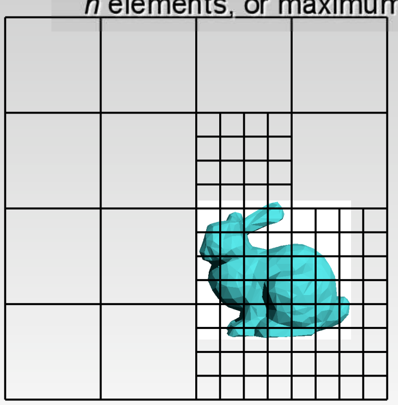
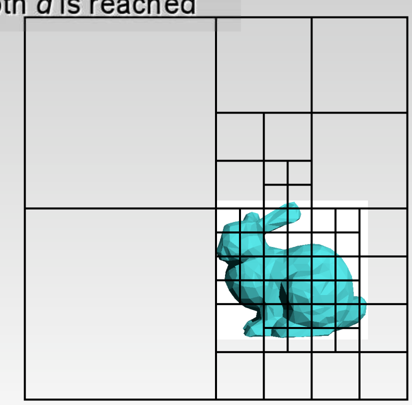
Adaptive Grids

- Subdivide until each cell contains no more than *n* elements, or maximum depth *d* is reached



Nested Grids



Octree/(Quadtree)

- This slide and the next are curtsey of Fredo Durand at MIT

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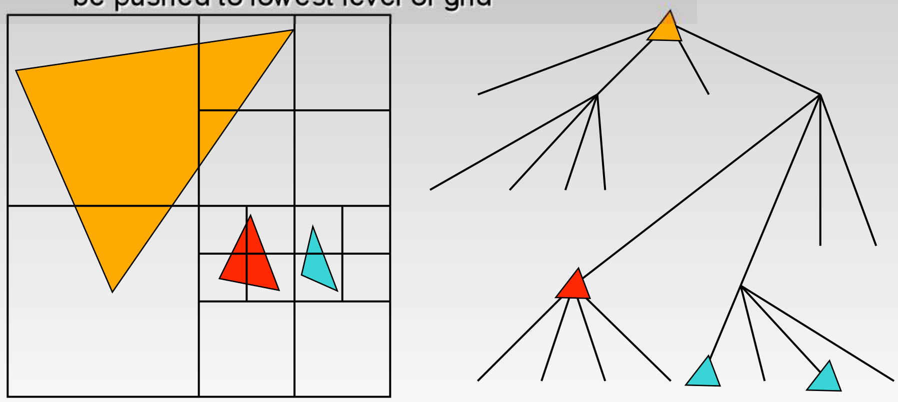
Primitives in an Adaptive Grid

- Can live at intermediate levels, or be pushed to lowest level of grid



Octree/(Quadtree)

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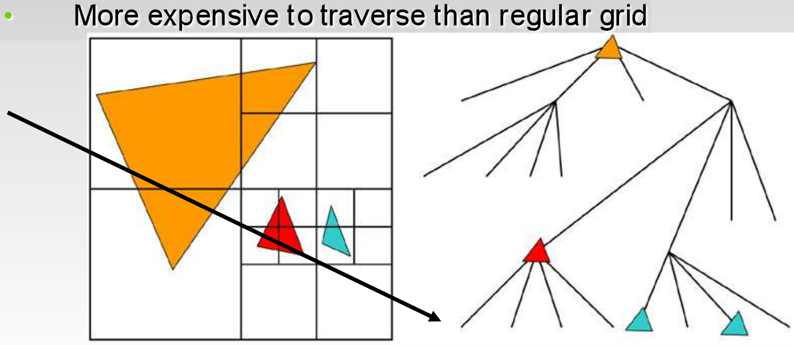
Adaptive Grid Discussion

Advantages

- Grid complexity matches geometric density

Disadvantages

- More expensive to traverse than regular grid



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Coming Up...

Friday:

- More global illumination

Monday/Wednesday:

- Curves & surfaces

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Soft Shadows & Global Illumination

CPSC 314

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

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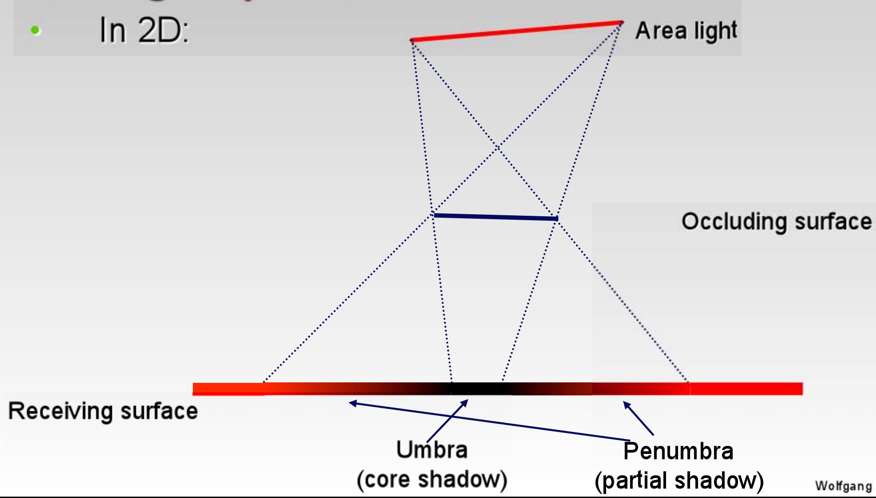
Area Light Sources

Area lights produce soft shadows:

- In 2D:



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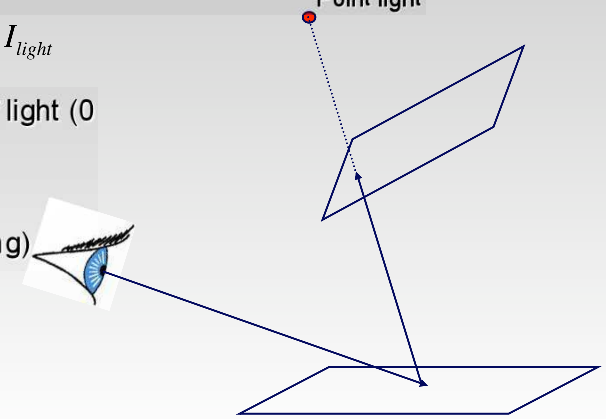
Area Light Sources

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)



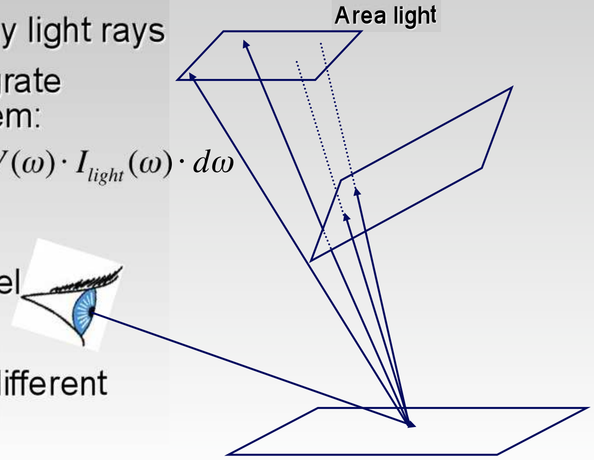
Are Light Sources

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!



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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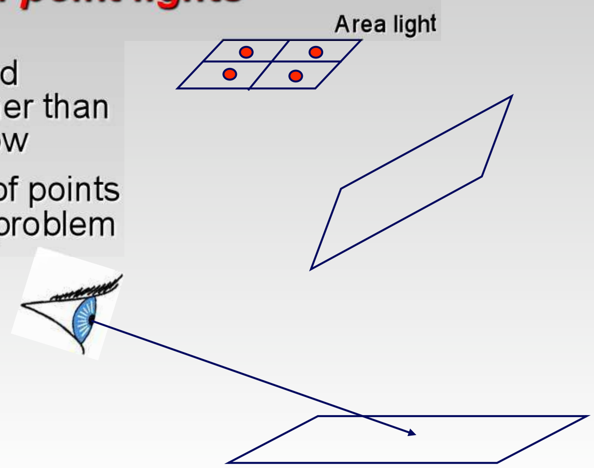
Numerical Integration

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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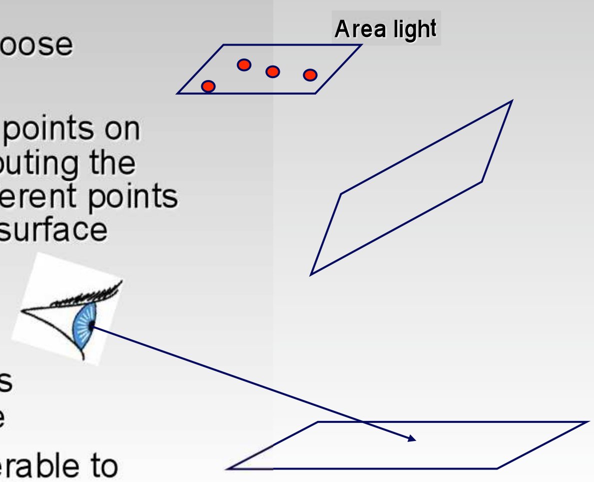
Monte Carlo Integration

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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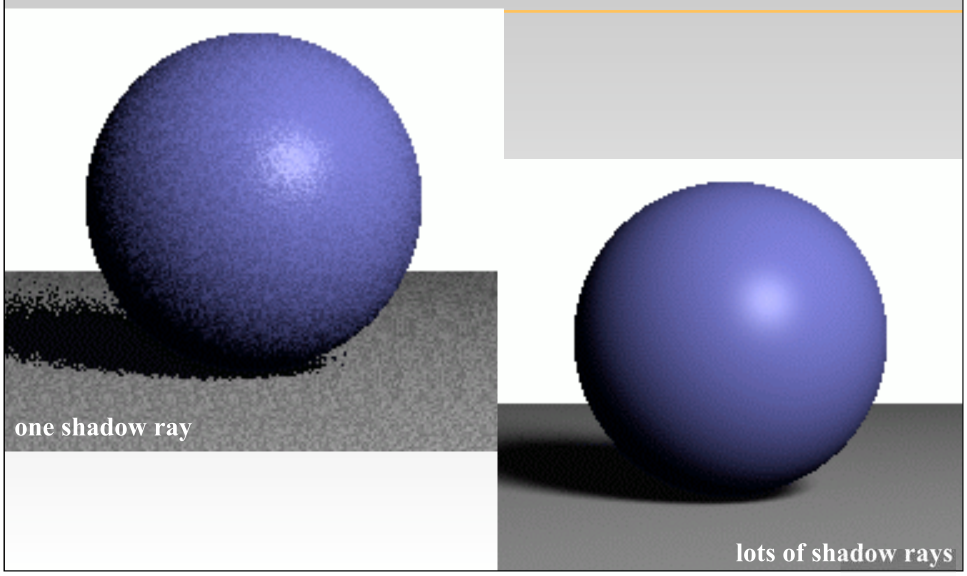
Monte Carlo Integration



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

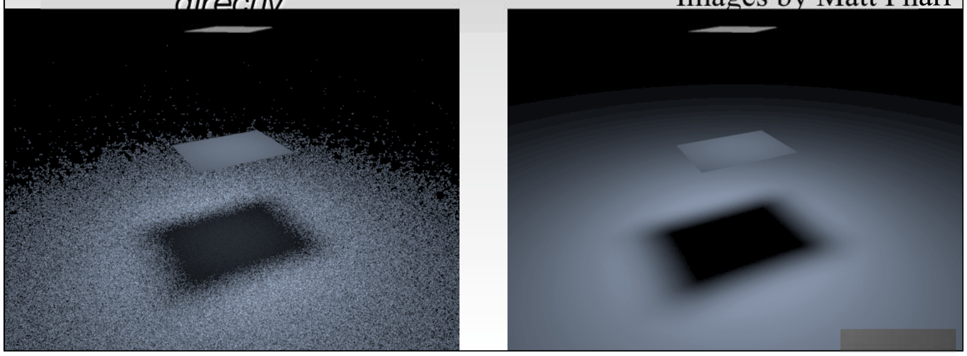
- *The p_i are randomly chosen on the light source*
  - With equal probability!
- *A is the total area of the light*
- *N is the number of samples (rays)*

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

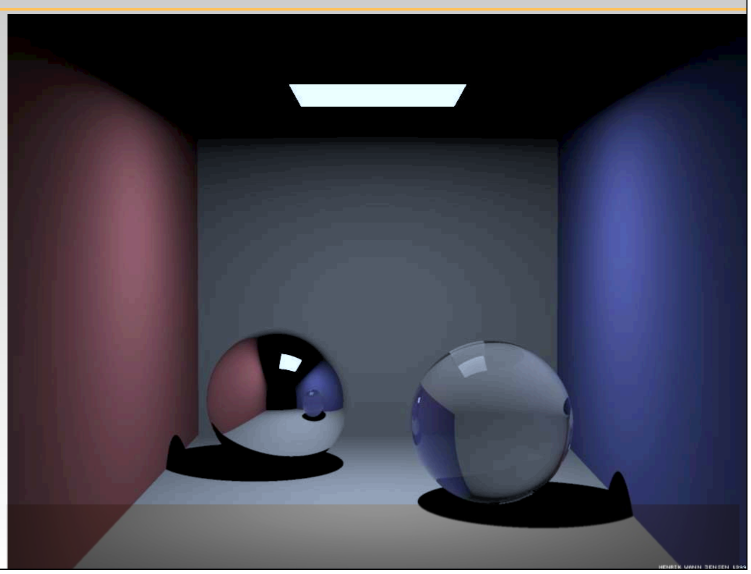
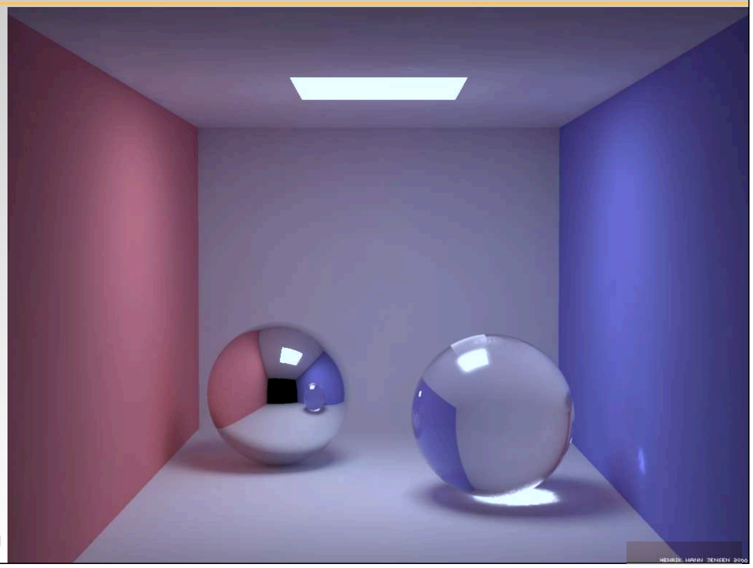


Image by
Henrik Wann Jensen

Global Illumination



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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_ρ 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

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!*

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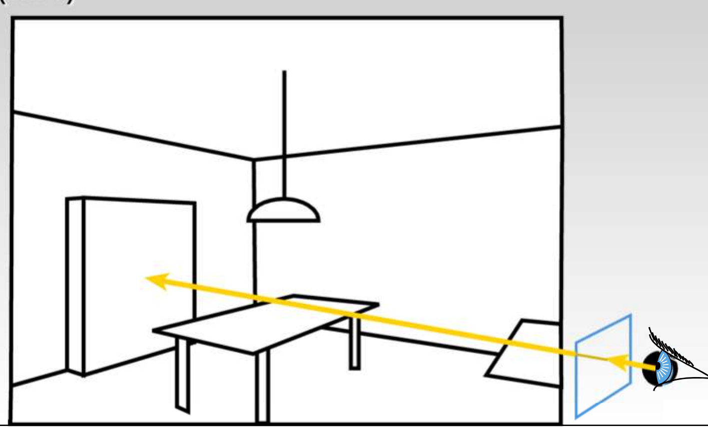
Ray Casting

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



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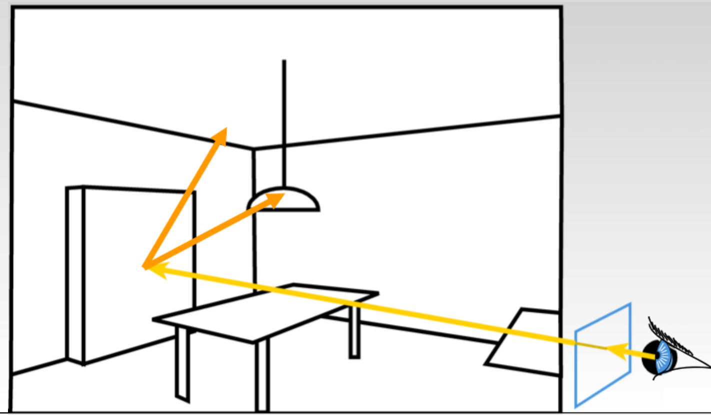
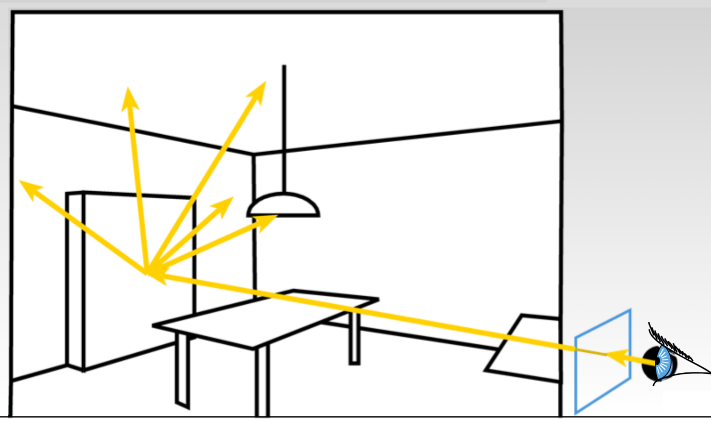
Ray Tracing

- 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*



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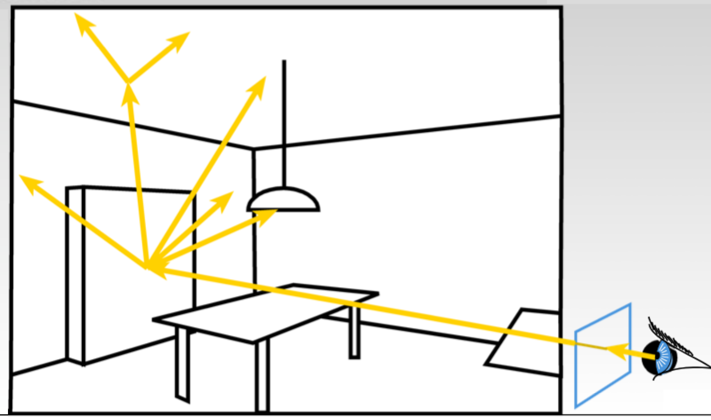
Monte Carlo Ray Tracing

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



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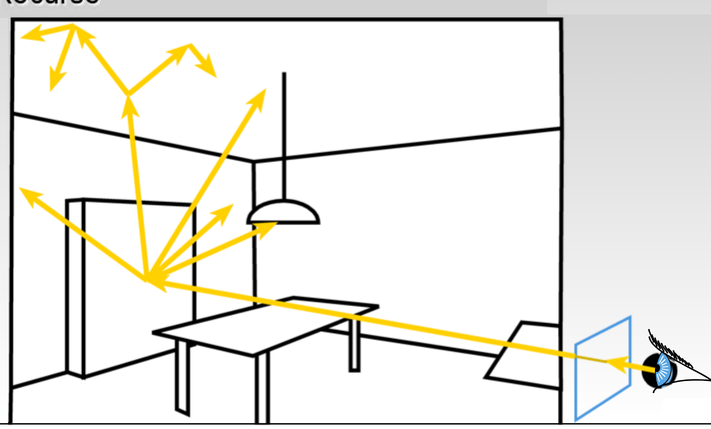
Monte Carlo

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



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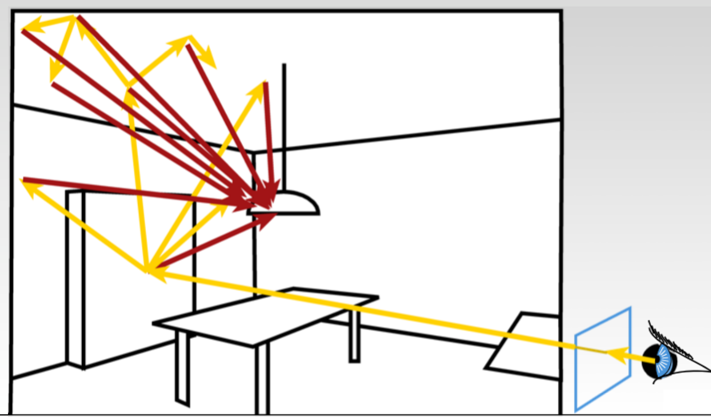
Monte Carlo

- Systematically sample primary light



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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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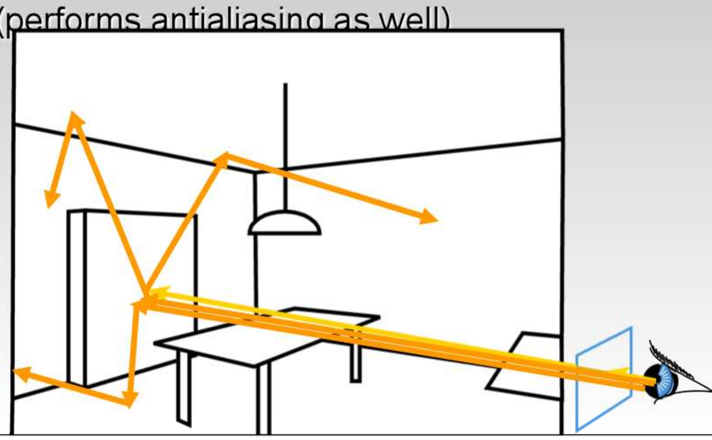
Monte Carlo Path Tracing

- 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

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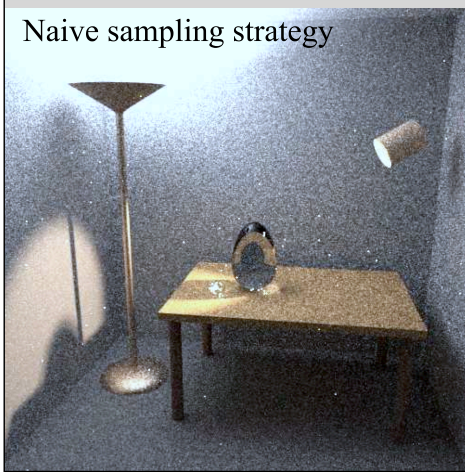
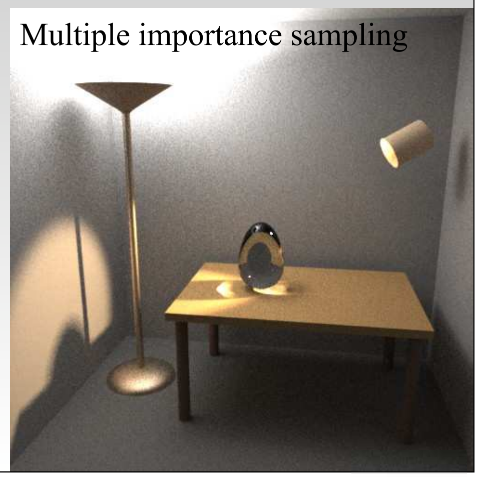
How to Sample?

- 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*

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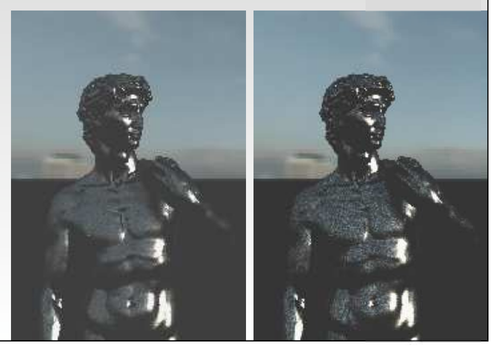
How to Sample?

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)

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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

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Coming Up

Tuesday:

- Color

Thursday:

- Curves & surfaces

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