

# CSC 433/533 Computer Graphics

Joshua Levine  
[josh@email.arizona.edu](mailto:josh@email.arizona.edu)

# Lecture 23 Ray Tracing 4

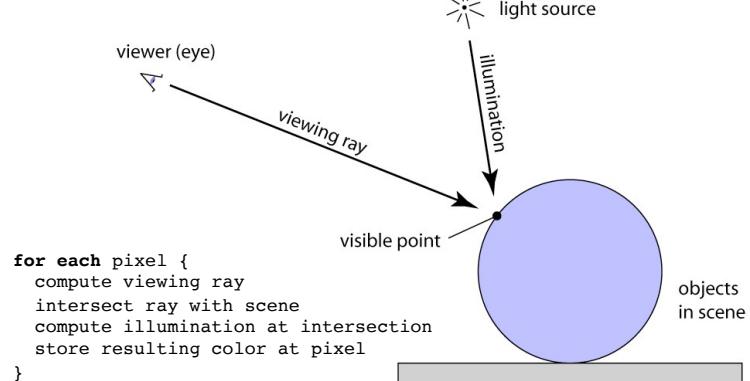
Oct. 7, 2019

## Today's Agenda

- Reminders:
  - A03 questions?
  - WARNING: Midterm in two weeks!
- Goals for today:
  - Wrap up discussion of ray tracing

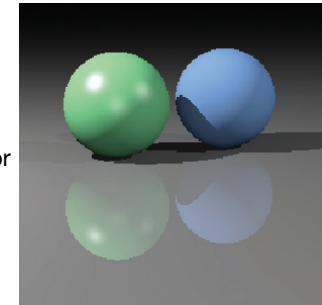
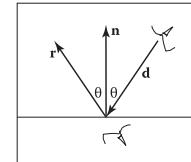
## Last Time

# Ray Tracing Algorithm



# Reflection

- Ideal specular reflection, or mirror reflection, can be modeled by casting another ray into the scene from the hit point
- Direction  $\mathbf{r} = \mathbf{d} - 2(\mathbf{d} \cdot \mathbf{n})\mathbf{n}$
- One can then recursively accumulate some amount of color from whatever object this hits
- color  $c = c + k_m * \text{ray\_cast}()$



# Recursive Ray Tracer

```
Color ray_cast(Ray ray, SurfaceList scene, float near, float far) {  
    ...  
    //initialize color;  compute hit_surf, hit_position;  
    ...  
  
    if (hit_surf is valid) {  
        color = hit_surf.kA * Ia;  
        ...  
    }  
    ...  
  
    return color;  
}
```



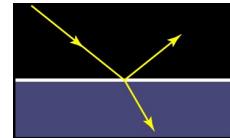
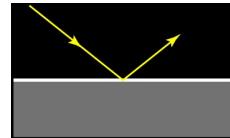
# Simple materials



metal



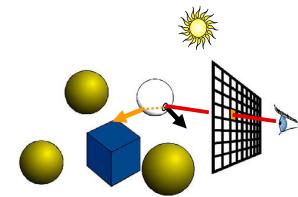
dielectric



## Illuminating Dielectrics

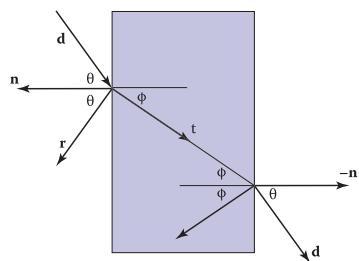
## Translucency (Refraction)

- When a ray hits a dielectric surface, some portion of it transmits through the surface, but bends
- Color of the ray can be modulated by a refraction color



## Snell's Law

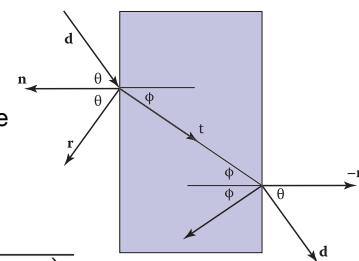
- Governs the angle at which a refracted ray bends
- Computation based on refraction index of original medium,  $n$ , versus new index  $n_t$
- $n_t \sin \theta = n \sin \phi$



## Snell's Law

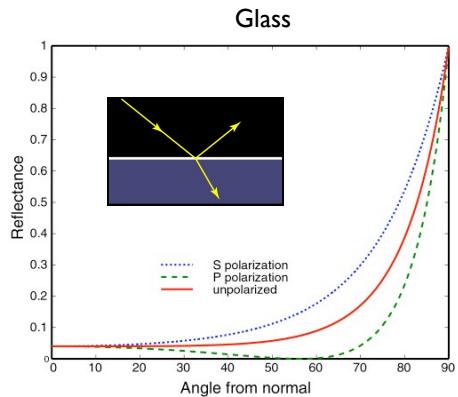
- Working with cosine's are easier because we can use dot products
- Can derive the vector for the refraction direction  $t$  as

$$\begin{aligned} \mathbf{t} &= \frac{n(\mathbf{d} + \mathbf{n} \cos \theta)}{n_t} - \mathbf{n} \cos \phi \\ &= \frac{n(\mathbf{d} - \mathbf{n}(\mathbf{d} \cdot \mathbf{n}))}{n_t} - \mathbf{n} \sqrt{1 - \frac{n^2(1 - (\mathbf{d} \cdot \mathbf{n})^2)}{n_t^2}} \end{aligned}$$



## Specular Reflection from Dielectrics like Glass/Water

- Significant dependence on angle
- About 4% at normal incidence
- Nearly 100% at grazing (rest of the light is transmitted)
- Getting this right has a strong affect on appearance



## Fresnel Equation Models the Reflectivity of Dielectrics

- Can be used to predict how much light reflects from a smooth interface (usually, one material is air/empty space)
- R is the fraction that is reflected
- (1-R) is the fraction that is transmitted

$$F_p = \frac{\eta_2 \cos \theta_1 - \eta_1 \cos \theta_2}{\eta_2 \cos \theta_1 + \eta_1 \cos \theta_2}$$

$$F_s = \frac{\eta_1 \cos \theta_1 - \eta_2 \cos \theta_2}{\eta_1 \cos \theta_1 + \eta_2 \cos \theta_2}$$

$$R = \frac{1}{2} (F_p^2 + F_s^2)$$

## Schlick's Approximation to Fresnel Equations

- A quick hack that works pretty well is to approximate R as

$$R(\theta) = R_0 + (1 - R_0)(1 - \cos \theta)^5$$

- Where  $R_0$  is defined by

$$R_0 = \left( \frac{n_t - 1}{n_t + 1} \right)^2$$

Often, assume n is 1.0 for air

$$F_p = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}$$

$$F_s = \frac{\eta_1 - \eta_2}{\eta_1 + \eta_2}$$

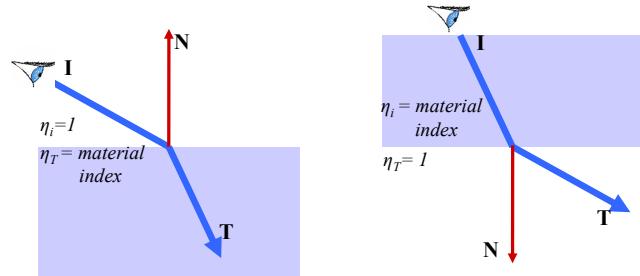
$$R_0 = \left( \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \right)^2$$

## Ray Tracing Dielectrics

- Like a reflective surface, use recursive ray tracing
- But we need two rays:
  - One reflects off the surface (same as mirror ray)
  - The other crosses the surface (computed using Snell's law)
- Both rays do not always exist (e.g. total internal reflection)
- Splitting into two rays creates two recursive paths, sometimes called a **ray tree**
  - Limit recursion with depth

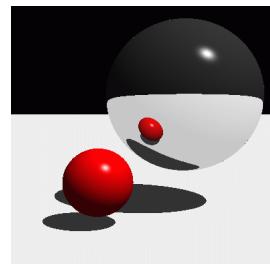
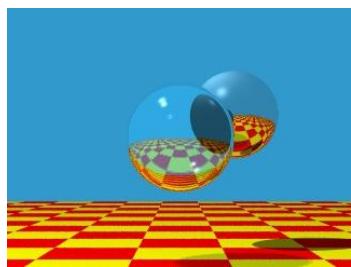
## Refraction and Sidedness of Objects

- Make sure you know whether you're entering or leaving the transmissive material. How? Use normals!
- Intersection transmissive objects are a problem (we will ignore for now)

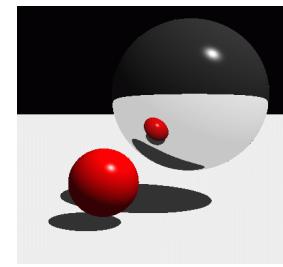
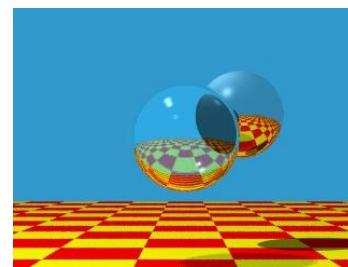


## Distribution Ray Tracing

### Reality Check: Do These Pictures Look Real?

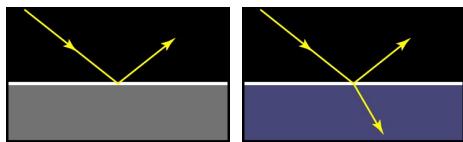


### What's Wrong?

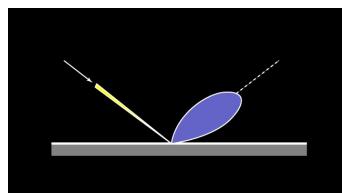


- No surface is a perfect mirror because no surface is perfectly smooth

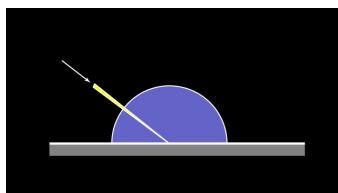
## What have we modeled?



ideal specular (mirror)

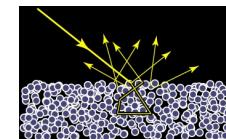
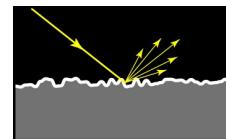


glossy specular

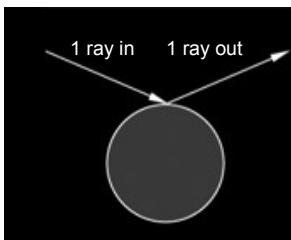


Lambertian

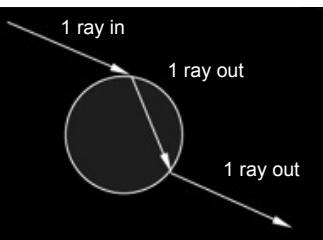
## Most Surfaces have Microgeometry



## Ideal Reflection/Refraction



Perfectly specular  
(mirror) reflection

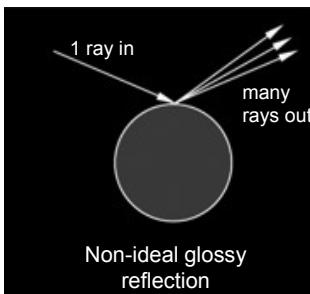


Perfectly specular  
refraction

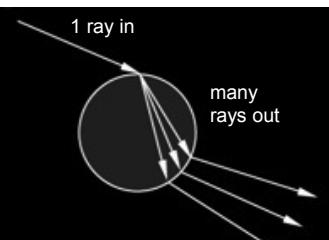
Adapted from [blender.org](https://blender.org)

## Non-Ideal Reflection/Refraction

- Can approximate the microgeometry



Non-ideal glossy  
reflection

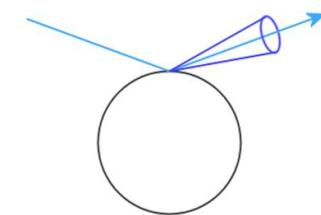
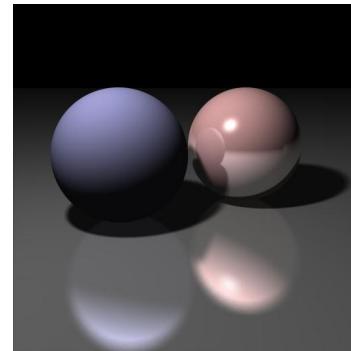


Non-ideal refraction

Adapted from [blender.org](https://blender.org)

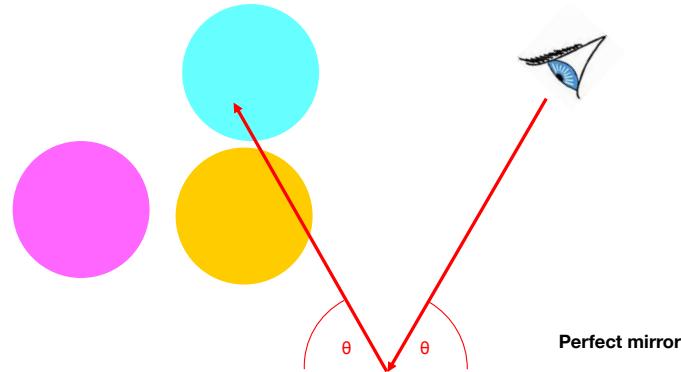


## Approach: Distribution Glossy Reflection by Randomly Sampling Rays



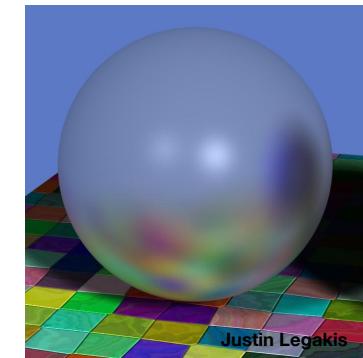
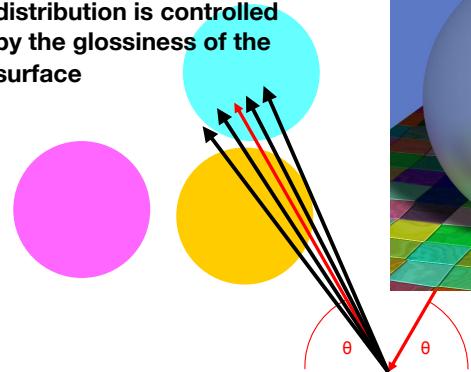
<https://graphics.stanford.edu/wiki/cs148-11-fall/RaytracingResults>  
<http://www.baylee-online.net/Projects/Raytracing/Algorithms/Glossy-Reflection-Transmission>

## Ideal Reflection: One Ray Per Bounce



## Glossy Reflection: Compute Many Rays per Bounce and Average

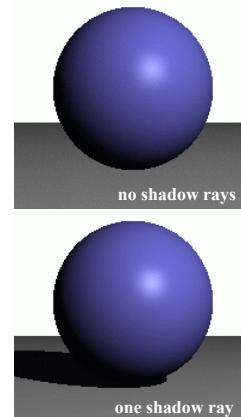
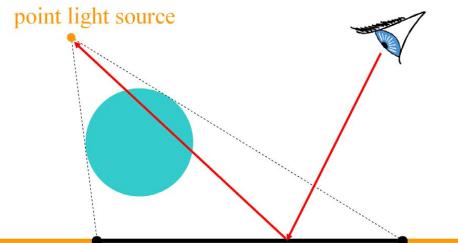
Variation in this distribution is controlled by the glossiness of the surface



# Other Uses of Distribution Ray Tracing

## Problem: Hard Shadows

- One shadow ray per intersection per point light source



## Distributed Ray Tracing

Robert L. Cook  
Thomas Porter  
Loren Carpenter  
Computer Division  
Lucasfilm Ltd.

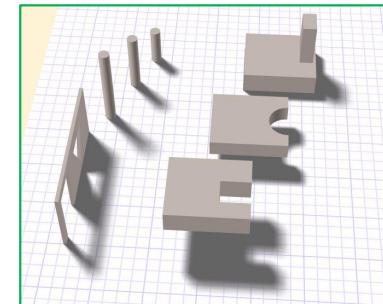
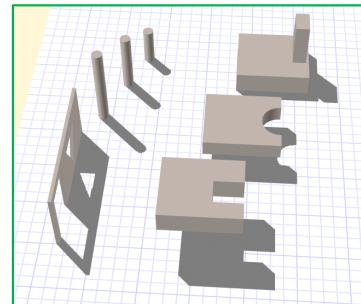
### Abstract

Ray traced images are sharp because ray directions are determined precisely from geometry. Fuzzy phenomena would seem to require large numbers of additional samples per ray. By distributing the rays rather than adding more of them, however, fuzzy phenomena can be rendered with no additional rays beyond those required for spatially oversampled ray tracing. This approach provides correct and easy solutions to some previously unsolved problems.

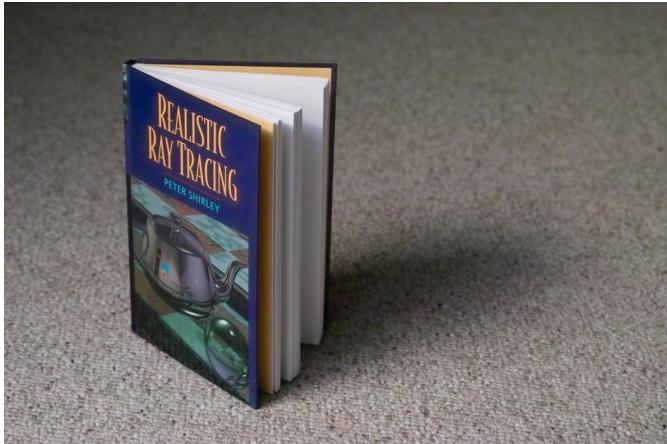
Ray traced images are sharp because ray directions are determined precisely from geometry. Fuzzy phenomena would seem to require large numbers of additional samples per ray. By distributing the rays rather than adding more of them, however, fuzzy phenomena can be rendered with no additional rays beyond those required for spatially oversampled ray tracing. This approach provides correct and easy solutions to some previously unsolved problems.

This approach has not been possible before because of aliasing. Ray tracing is a form of point sampling and, as such, has been subject to aliasing artifacts. This aliasing is not inherent, however, and ray tracing can be filtered as effectively as any analytic method[4]. The filtering does incur the expense of additional rays, but it is not

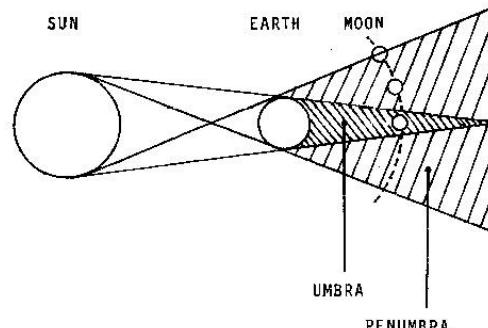
## Soft Shadows



## Soft Shadows



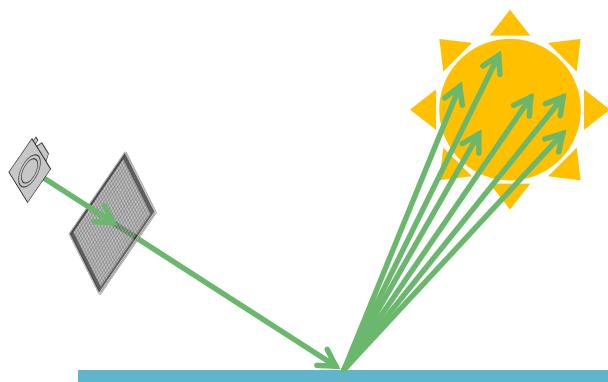
## What Causes Soft Shadows



<http://user.online.be/felixverbelen/funec1.jpg>

Lights aren't all point sources

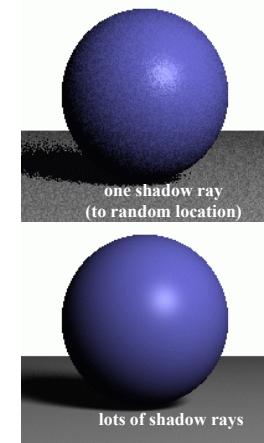
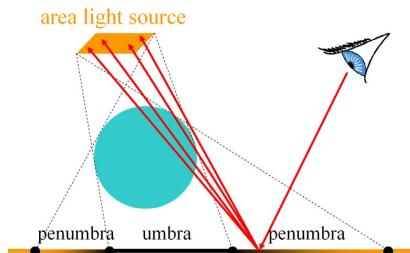
## Distribution Soft Shadows



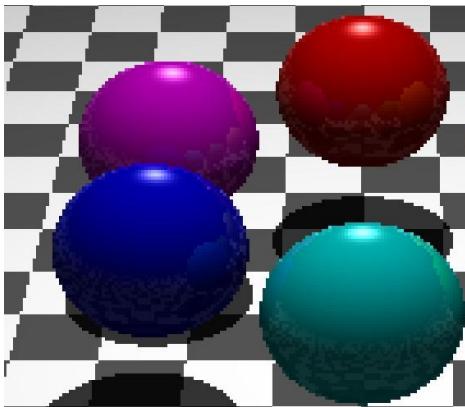
Randomly sample light rays

## Computing Soft Shadows

- Model light sources as spanning an area
- Sample random positions on area light source and average rays



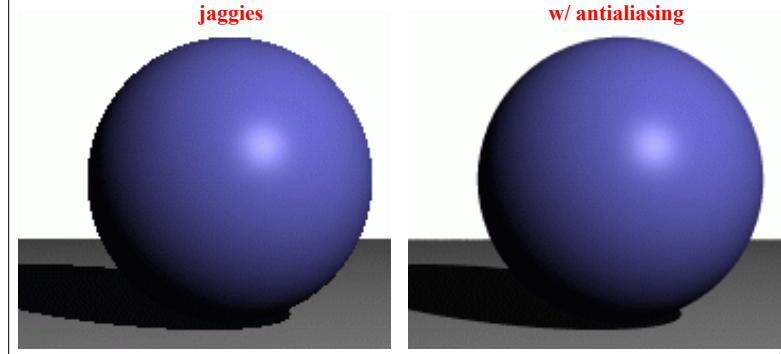
## Problem: Aliasing



<http://www.hackification.com/2008/08/31/experiments-in-ray-tracing-part-8-anti-aliasing/>

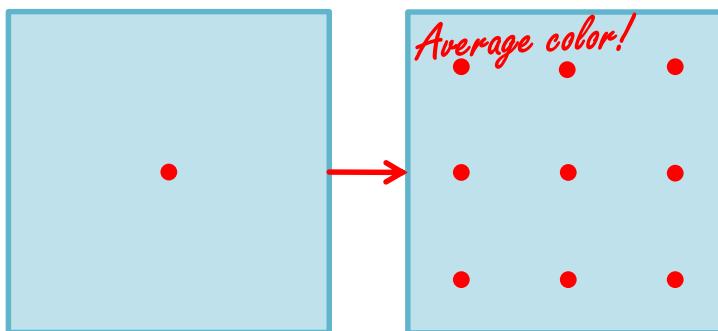
## Antialiasing w/ Supersampling

- Cast multiple rays per pixel, average result



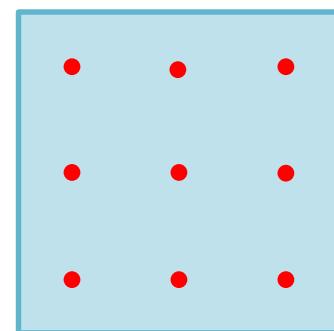
49

## Distribution Antialiasing



Multiple rays per pixel

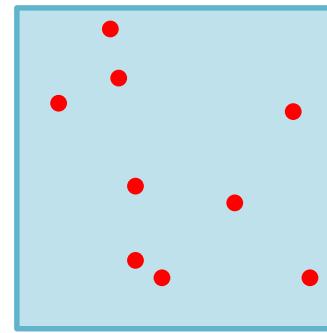
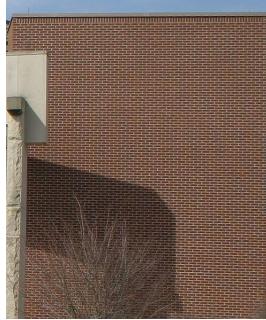
## Distribution Antialiasing w/ Regular Sampling



[http://upload.wikimedia.org/wikipedia/commons/f/fb/Moir%C3%A9\\_pattern\\_of\\_bricks\\_small.jpg](http://upload.wikimedia.org/wikipedia/commons/f/fb/Moir%C3%A9_pattern_of_bricks_small.jpg)

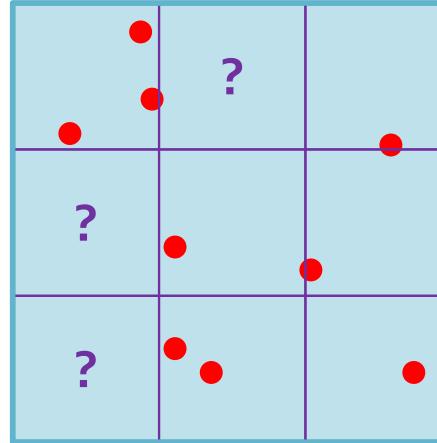
Multiple rays per pixel

## Distribution Antialiasing w/ Random Sampling



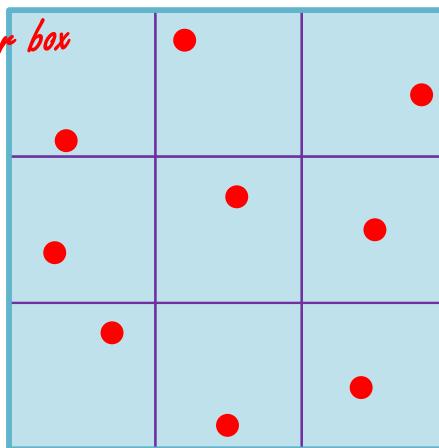
Remove Moiré patterns

## Random Sampling Could Miss Regions Without Enough Sampling



## Stratified (Jittered) Sampling

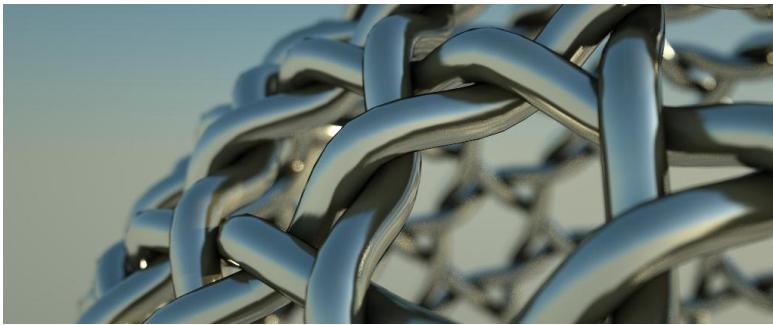
*One ray per box*



## Problem: Focus Real Lenses Have Depth of Field

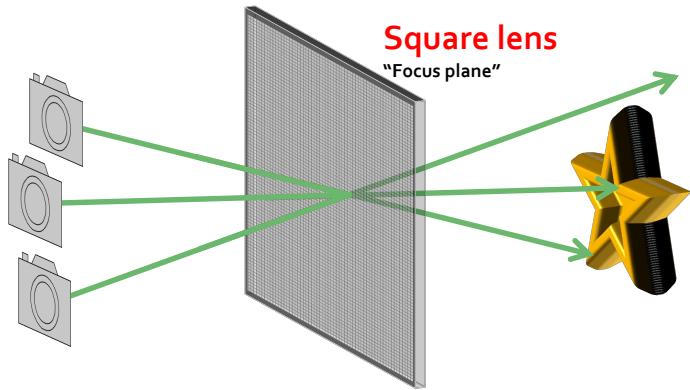


## Problem: Focus Real Lenses Have Depth of Field



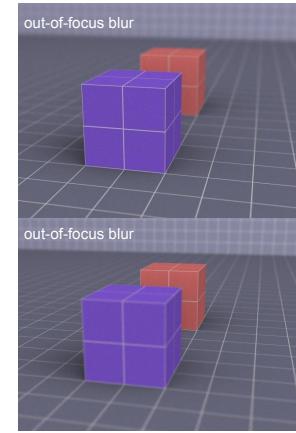
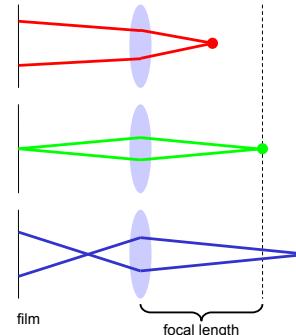
<http://liam887.files.wordpress.com/2010/08/weaver.jpg>

## Distribution Depth of Field



## Depth of Field

- Multiple rays per pixel, sample lens aperture



## Problem: Exposure Time Real Sensors Take Time to Acquire

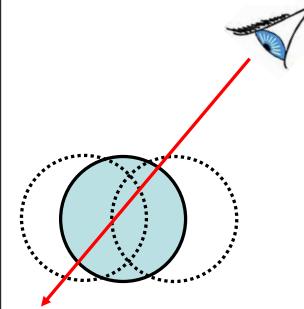


## Problem: Exposure Time Real Sensors Take Time to Acquire



## Motion Blur

- Sample objects temporally over a time interval



Rob Cook

## Lec13 Required Reading

- FOOG, Ch. 23
- Check out recommended reading for some additional references

## Reminder: Assignment 03

Assigned: Wednesday, Sept. 25  
Written (Past) Due: Monday, Oct. 7, 4:59:59 pm  
Program Due: Wednesday, Oct. 9, 4:59:59 pm