Global Illumination

Multi-Sampling

Path Tracing

Simple Sampling

- Josef talked about all of the details behind signals and sampling
- For assignment purposes, things will be a bit simpler…

Sampling techniques

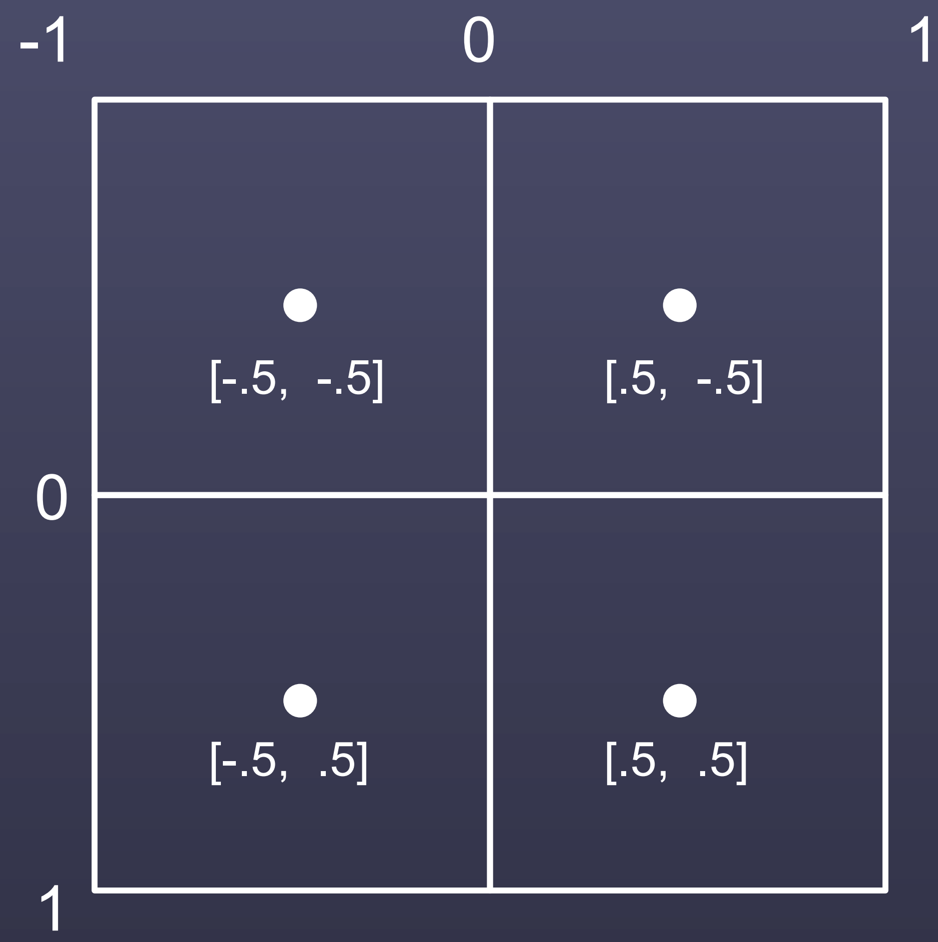
- Uniform
- Random
  - We will focus on this one today
- Jittered
  - This is not much harder than the above (extra credit)

Random Sampling

- You will find that it actually works well enough a lot of the time
- Pick a random point within the area being sampled
- Let’s start by sampling in pixels

2x2 Image

```
for each pixel (i, j)

x = 2.0f *
(j - xres/2.f + 0.5f)/xres;


y = 2.0f *
(i - yres/2.f + 0.5f)/yres;
```



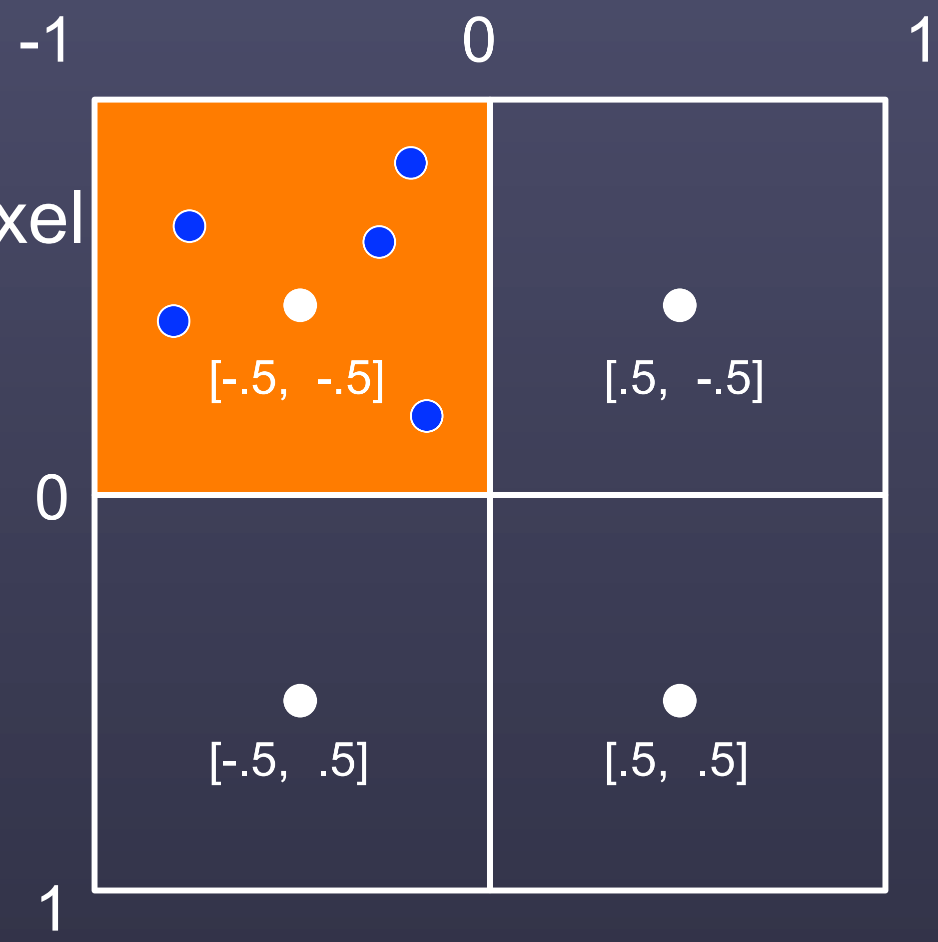
Everything in the range of x = [-1 .. 0], y = [-1 .. 0] falls within the same pixel

Sampling a Pixel

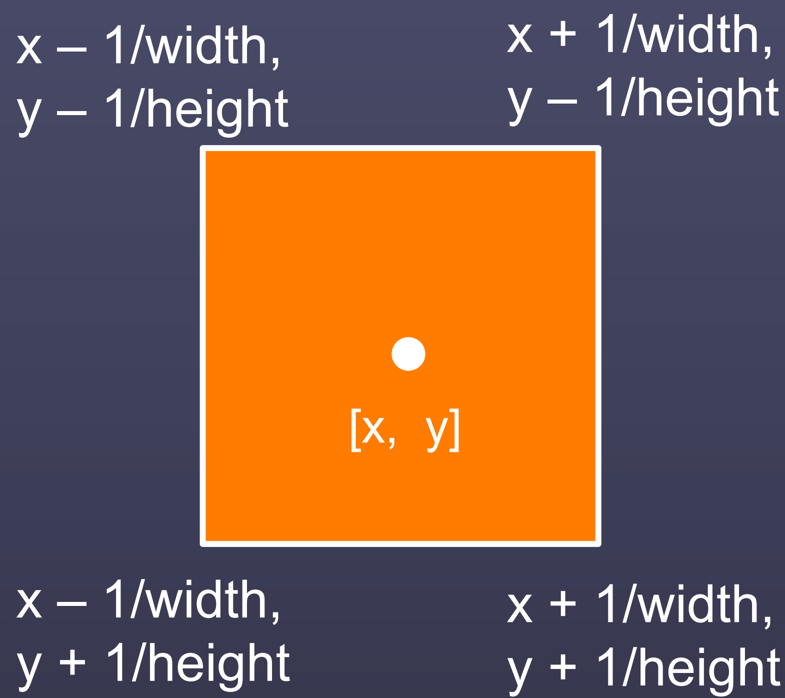
Randomly offset (x, y) within the area of the pixel

Take as many samples as desired

How do we offset?



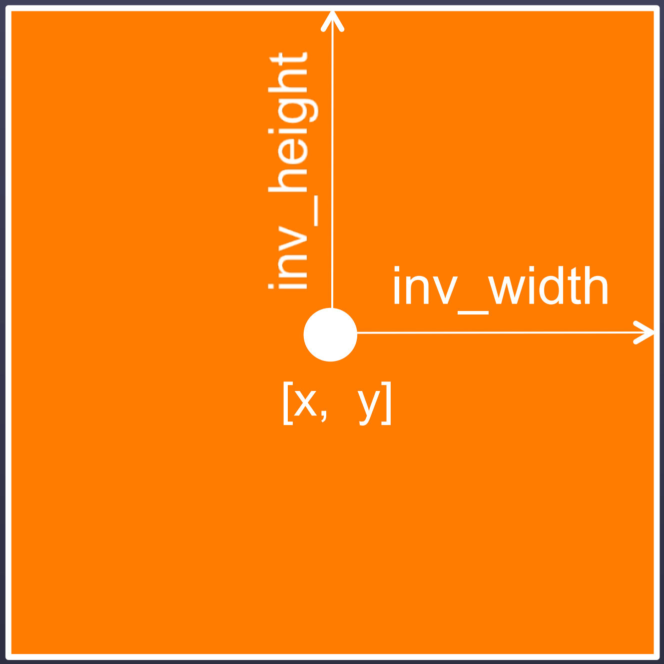
In General




```
inv_width = loadf(0, 2)
inv_height = loadf(0, 5)
```

Random Point in Pixel

```
// value between -1 .. 1
x_off = (trax_rand() - .5f) * 2.f
y_off = (trax_rand() - .5f) * 2.f

x_off *= inv_width
y_off *= inv_height

x += x_off
y += y_off

camera.makeRay(ray, x, y);
```



Filtering

- Box
  - We will focus on this one today
- Triangle
  - More difficult than the above, but not terribly (requires samples outside pixel)
- Gaussian
  - Same infrastructure as triangle filter, different math

Box Filter

- Simply means all samples are weighted equally
- For each sample, add ray contribution to the color of the pixel
  - Pixel will likely end up with > 1 intensity
- Then divide color by num_samples
  - then clamp to 0 .. 1

Putting it all together

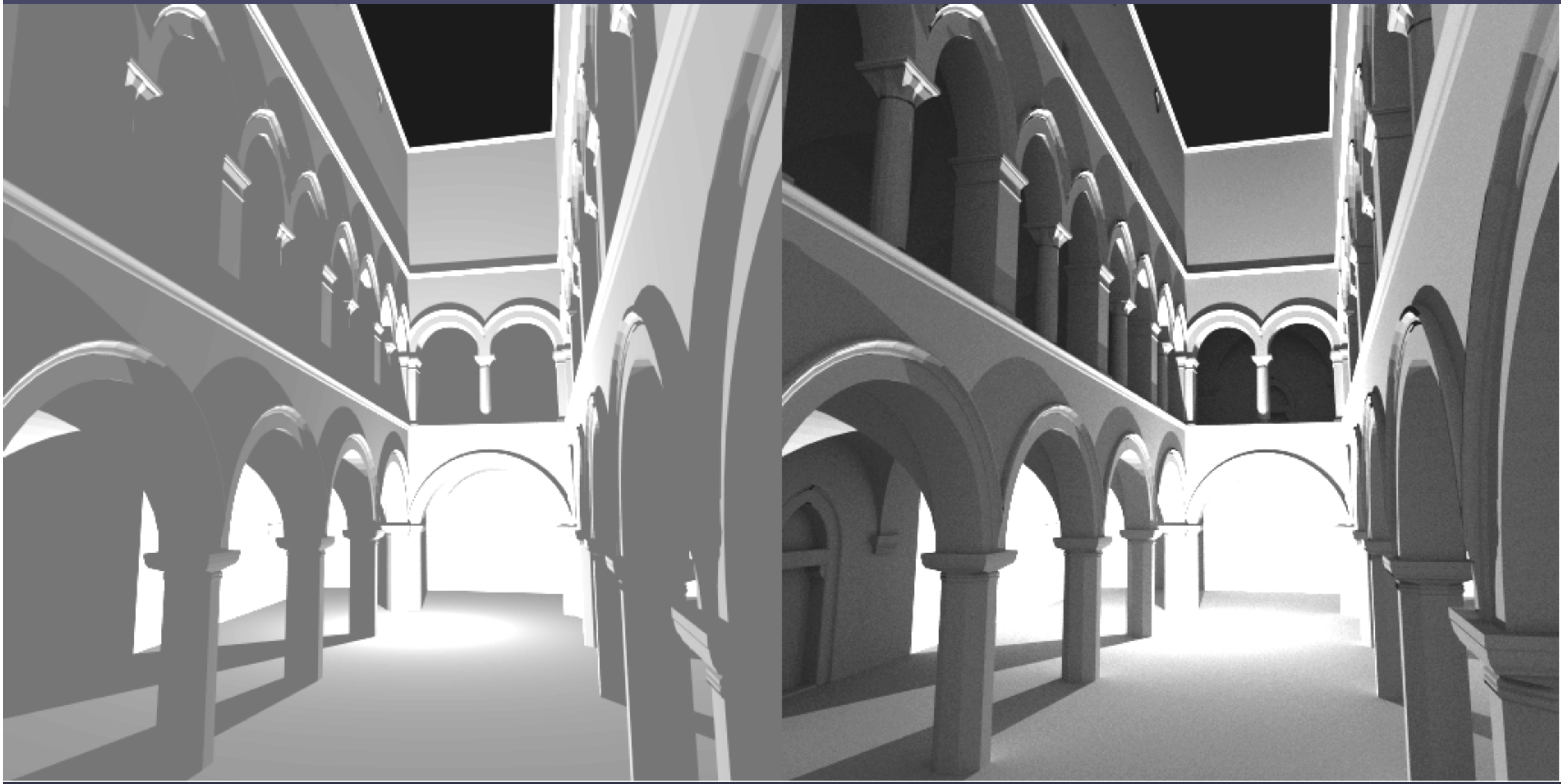
```
for(pixels)
  for(num_samples)
     camera.makeRay(ray, x, y) // x and y
                                 have been
                                 randomly
                                 permuted
     bvh.intersect(hit, ray)
     result += shade(...) // +=, not =

  result /= num_samples  // box filter
  image.set(i, j, result);
```

Global Illumination

- So far, we have looked at light from specific sources
  - Light source
  - Reflections
  - Refractions

- In reality, it isn't this simply
  - Still using "ambient" term for everything not in direct light

Global Illumination



Global Illumination

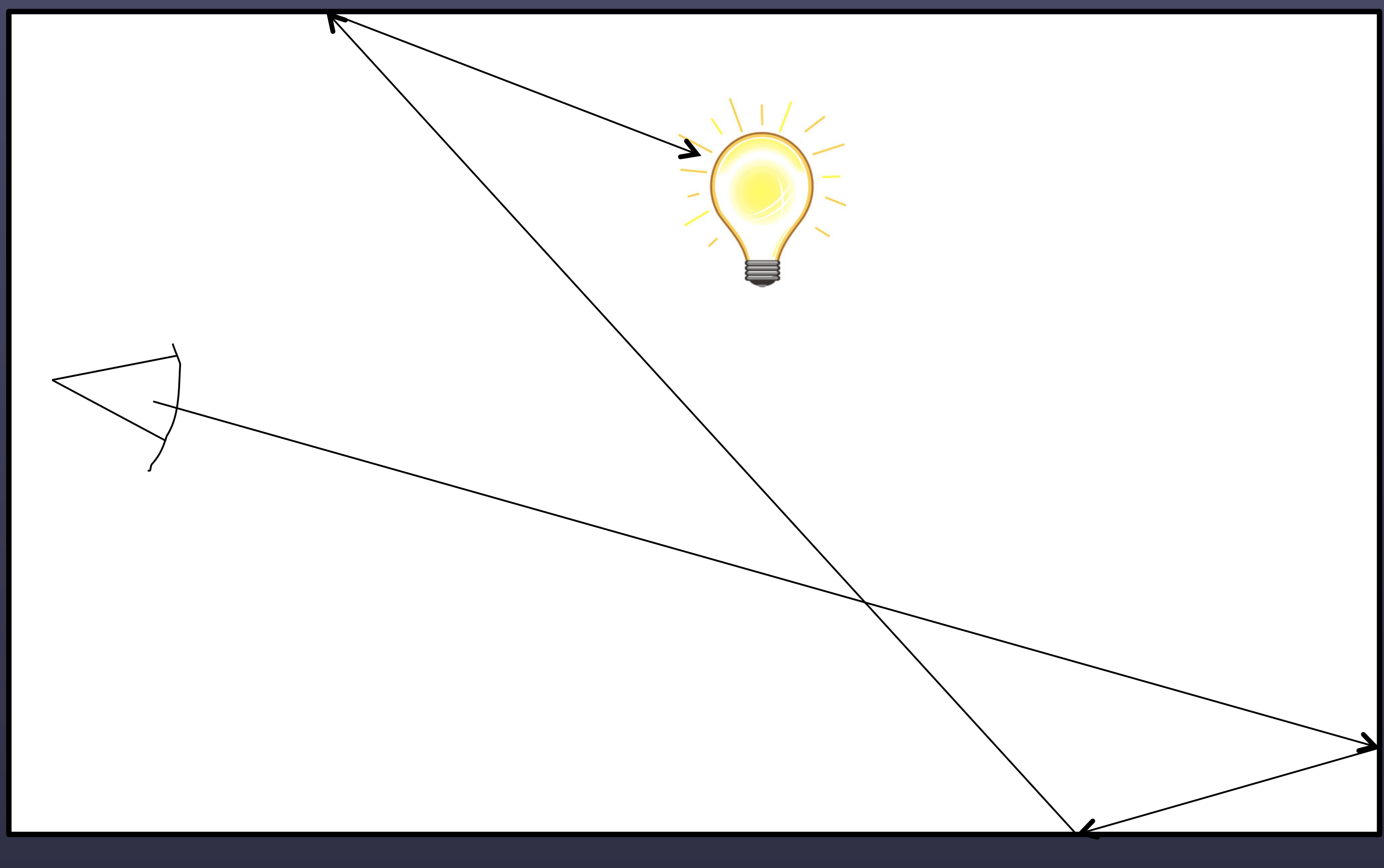
- Metropolis
- Ambient Occlusion
- Photon Mapping
- Path Tracing
  - arguably the most straight-forward
- Others…

Path Tracing

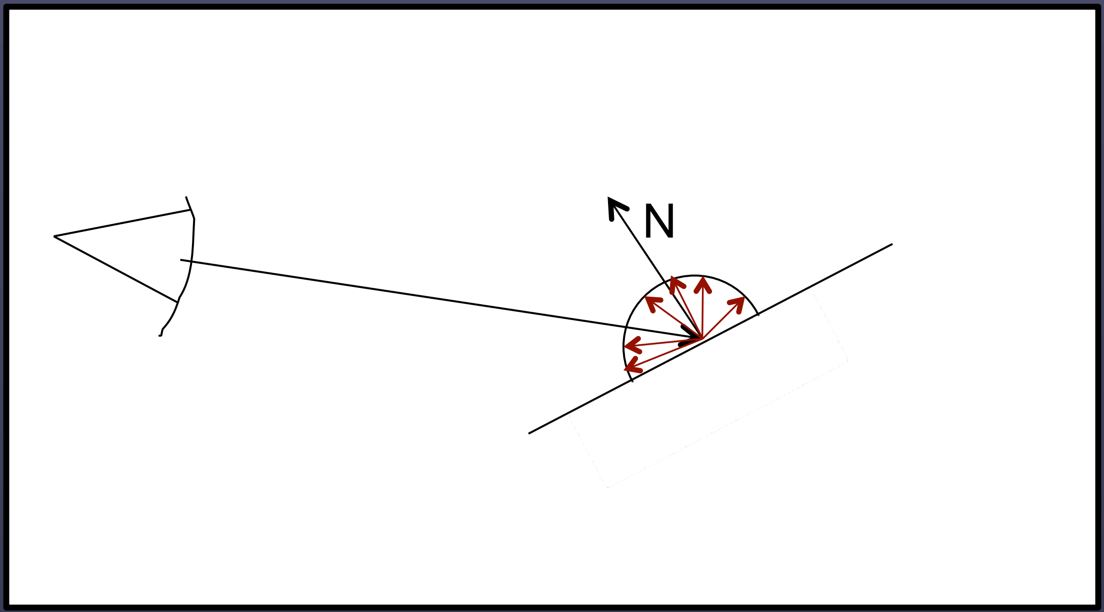
- Pure path tracing is the most naïve solution to global illumination
  - Also the most elegant (my opinion)

- Path tracing for Lambertian shading
  1. Cast a ray from the camera
  2. Multiply attenuation by material
     - From that point, cast exactly 1 ray in a random direction
  3. Repeat step 2 until light source is hit
  4. Final color = attenuation * emitted light

Path Tracing



Random reflection direction



•Pick a random direction on the normal hemisphere

•How?

Orthonormal basis

- First, we need to find a set of orthogonormal axes based on the normal
  - This will be sort of like a "camera"

- Set the `Z` axis in our new basis equal to the normal
  - Find any `X` and `Y` orthogonal to `Z` and unit length ("orthonormal")
  - How?

Orthonormal basis

- Remember, cross product returns a vector that is perpendicular to both input vectors

```
Vector Z = normal;
cross(N, any vector)
```

Pick one of (1, 0, 0), (0, 1, 0), (0, 0, 1)

- This result will be perpendicular to the normal
  - But what if the vector we pick is parallel to the normal?
  - Result will be zero vector

Orthonormal basis

- Choose axis with smallest component in normal

```
if(N.x < N.y && N.x < N.z)
   { axis = vec(1.0f, 0.0f, 0.0f); }
 else if (N.y < N.z)
   { axis = vec(0.0f, 1.0f, 0.0f); }
 else
   { axis = vec(0.0f, 0.0f, 1.0f); }
```

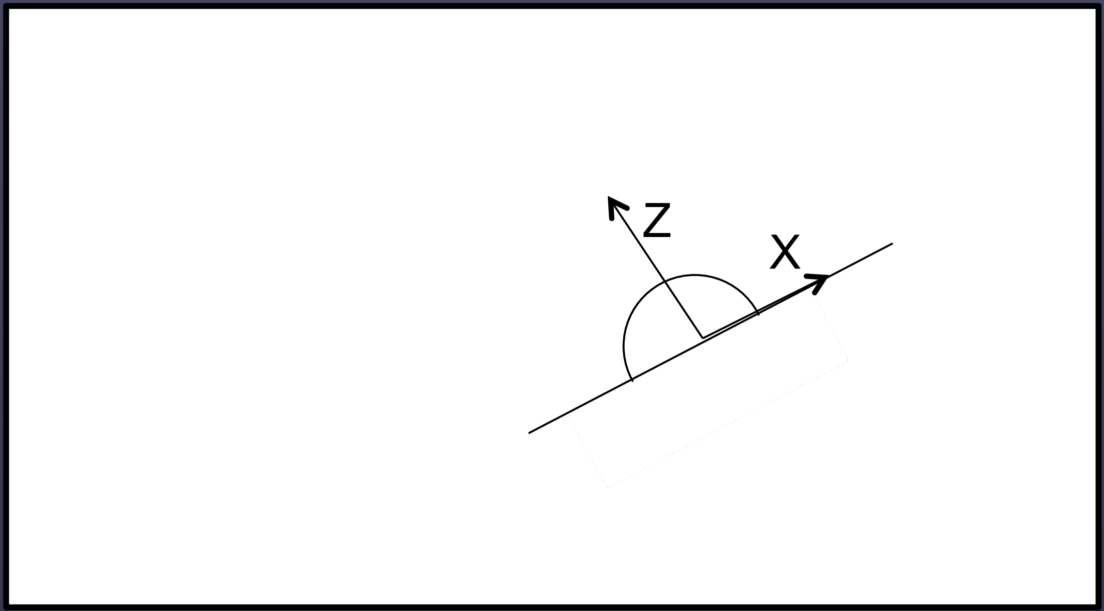
Orthonormal basis

- Last axis is cross product of other two

```
X = normal.cross(axis).normalize()
Y = normal.cross(X)
```

- Now we have a new axis system
  - X and Y are tangent to the surface
  - Z is normal to the surface

Orthonormal basis



Y not drawn in 2D example

Hemisphere sampling

- Pick a random vector on the unit hemisphere defined by our new basis
- Option 1:
  - Define the “hemicube” (half cube) on the surface
  - Randomly pick points inside the cube until we get one that is inside the hemisphere
  - Will be uniformly distributed (actually a bad thing)
- Option 2:
  - Randomly pick points on the unit disc
  - Project out to hemisphere
  - Not uniformly distributed (more later)

Hemisphere sampling

- Pick random point inside the unit disc:

```
do
    {
      u = trax_rand()
      v = trax_rand()
      u *= 2.0f;
      u -= 1.0f;
      v *= 2.0f;
      v -= 1.0f;
      u_2 = u * u;
      v_2 = v * v;
    }
while((u_2 + v_2) >= 1.0f);
```

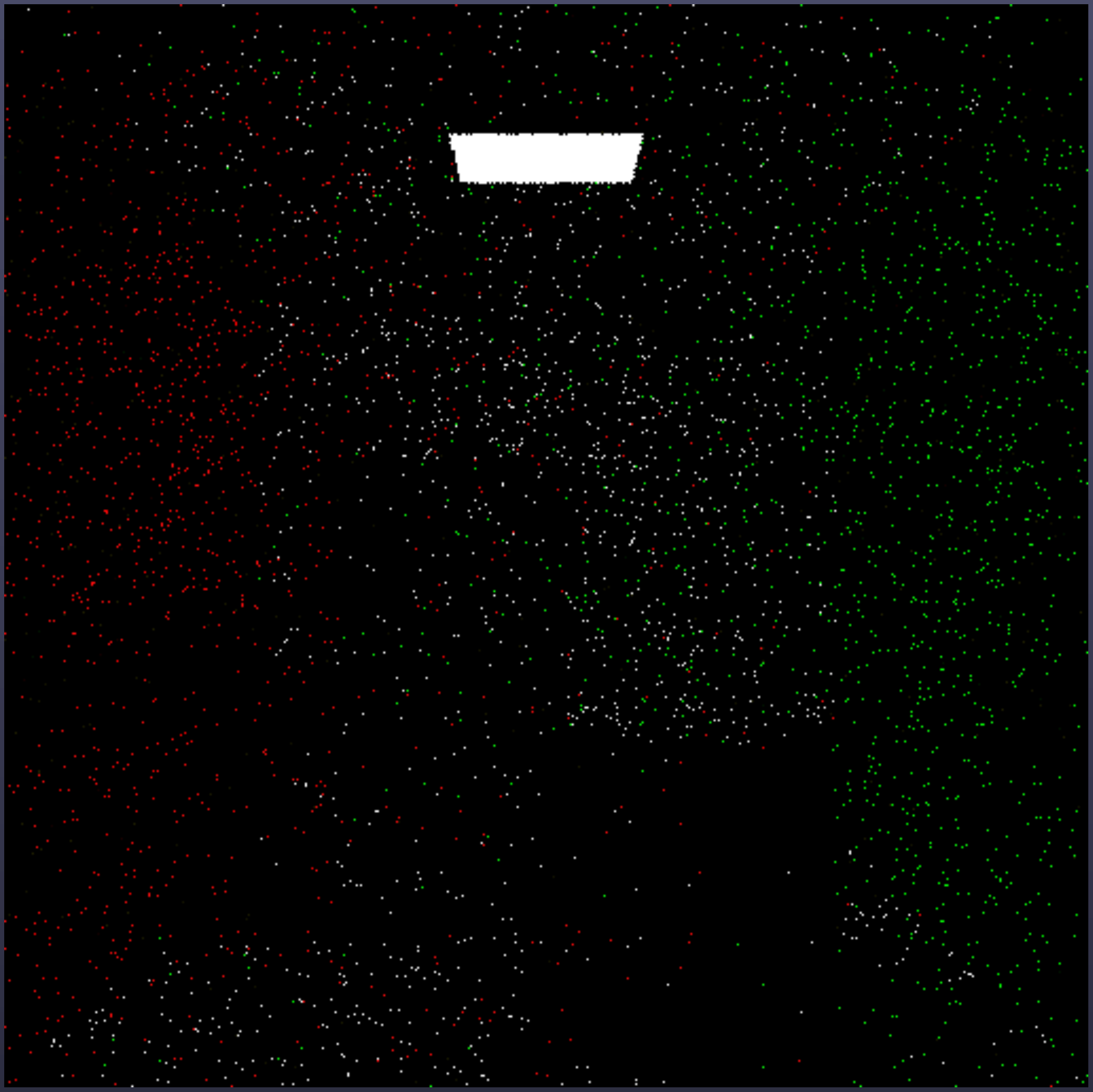
Path Tracing

- We now have a vector (u, v) on the (X, Y) plane
- Need to project up Z axis to make unit length (this will be a point on unit hemisphere)
- We know length needs to be 1.0
  - $w = \text{sqrt}(1 – u^2 – v^2)$
- refDir = (X * u) + (Y * v) + (normal * w)

Cosine weighting

- This generates samples weighted more heavily towards the normal
- Specifically, weighted by the cosine of the angle between the reflected ray and the normal
- Lambertian shading says we should multiply incoming light by cosine of angle
  - With samples cosine-weighted, we don’t need to

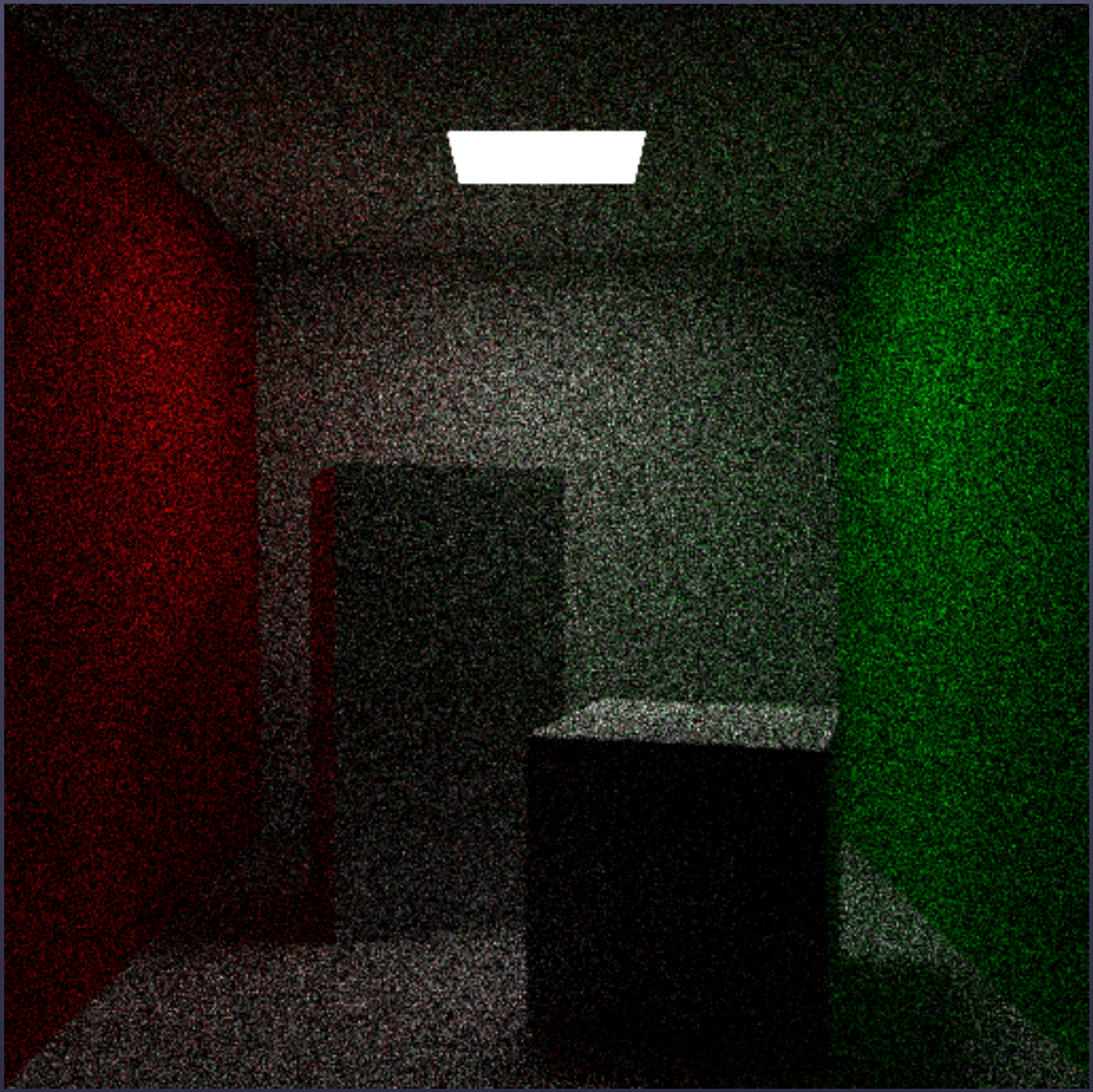
Path Tracing



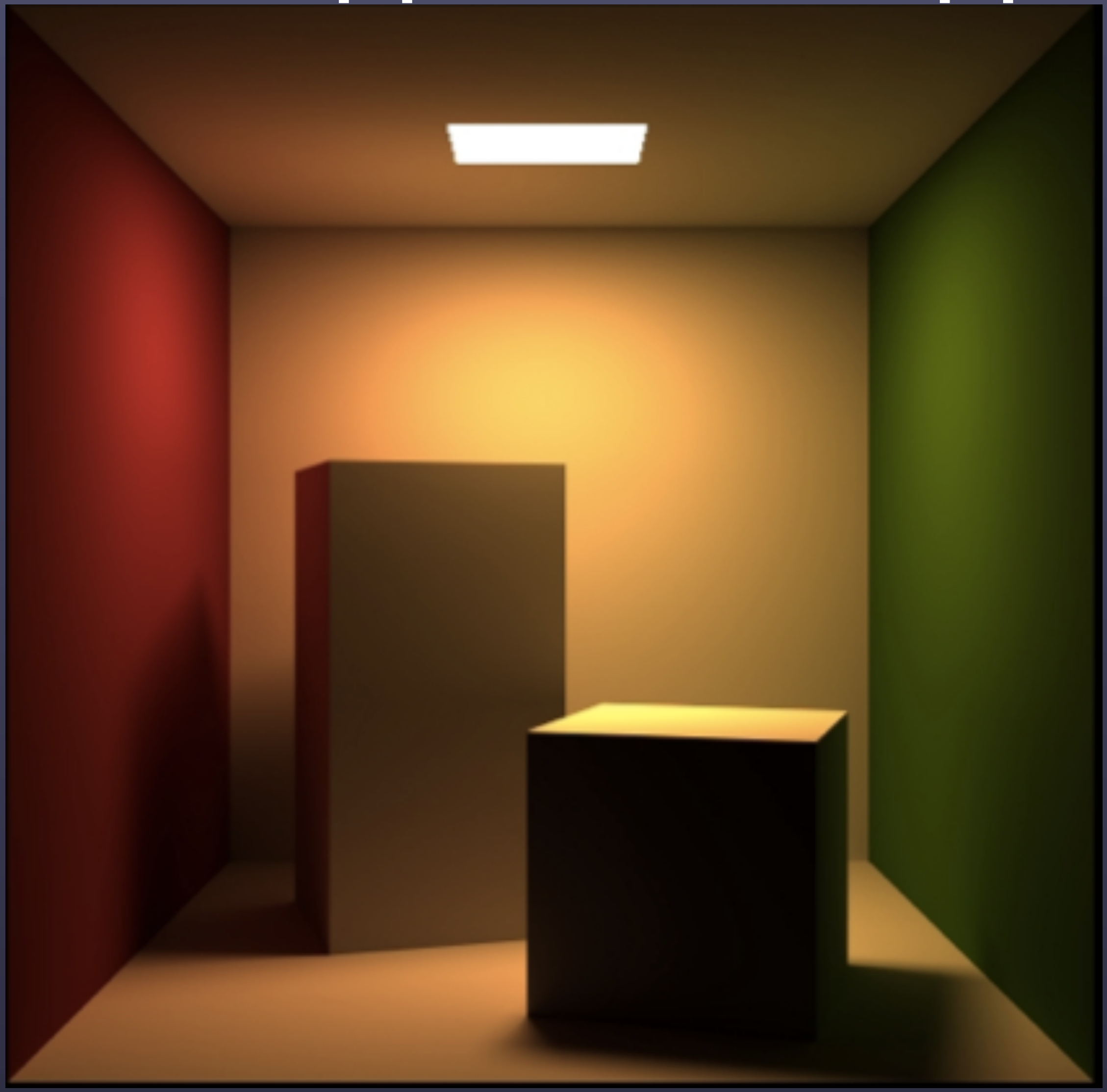
Path Tracing

- Obviously we need more than 1 sample per pixel
- With more samples, the image begins to converge to the “correct” result
  - In practice, requires more than is reasonable
  - Unless you have hours, even days to wait

100 samples per pixel



100k spp, tone mapped



Sampling

- Two techniques:
    1. Take multiple GI samples per hit point
    2. Take 1 GI sample per hit point, increase samples per pixel
- Option 2 will provide anti-aliasing at the same time
    - But we also may not need that many primary ray samples
- Option 1 muddies implementation a bit

Path Length

- In an enclosed space, a path may bounce forever
- Need some way of terminating “useless” paths
  - Russian roulette
  - Max depth
  - Min attenuation

Attenuation

- Every time a ray bounces, it is attenuated by that material (loses energy)
- Start with attenuation (color) of (1, 1, 1), multiply it by color of hit material on each bounce
- If total energy becomes less than small amount, kill the path

Importance sampling

- Probabilistically, most paths of light will not hit a light source
- These paths don't contribute anything to the image, and are wasted work
- With point light sources, no light will be found whatsoever
- Kajia path tracing combines pure path tracing with direct Lambertian shading

Kajia path tracing

```
...
for each sample
  attenuation = Color(1.f, 1.f, 1.f)
  Ray r = cameraRay(…)
  while(depth < max_depth) {
      HitRecord hit
      bvh.intersect(hit, ray)
      result += shade(…) * attenuation
      attenuation *= mat_color
      r = hemiRay(…)
      depth++
  }
```

Kajia path tracing

- The previous pseudo code doesn’t stop when hitting a light
- In TRaX, we will never hit the light (point lights only)
  – Pure path tracing won’t work with point lights
- Must not be recursive!

Kajia path tracing

- Kajia path tracing samples a random light source directly (not all of them)
  - We only have one anyway
- Sampling light sources directly does not account for visible intensity of light
  - May be obscured slightly
  - May be far away
  - Can't handle transparent materials

Pure Path Tracing

- Automatically solves various problems
  - Caustics
  - Visible intensity of light sources
- Simplifies architecture
  - No longer need “Light” objects (use emissive term in material)
- Requires bajillions of samples to converge
  - Probability of path hitting a light source is low

Pure Path Tracing

Total energy in the scene will be low – based on probability of hitting a light…

Need some kind of tone mapping to bring things in to reasonable range

Tone-Mapped

Exact same information as previous image

Free caustics