Path Tracing

Bridage 2 real-time path tracer

Aalto CS-E5520 Spring 2019
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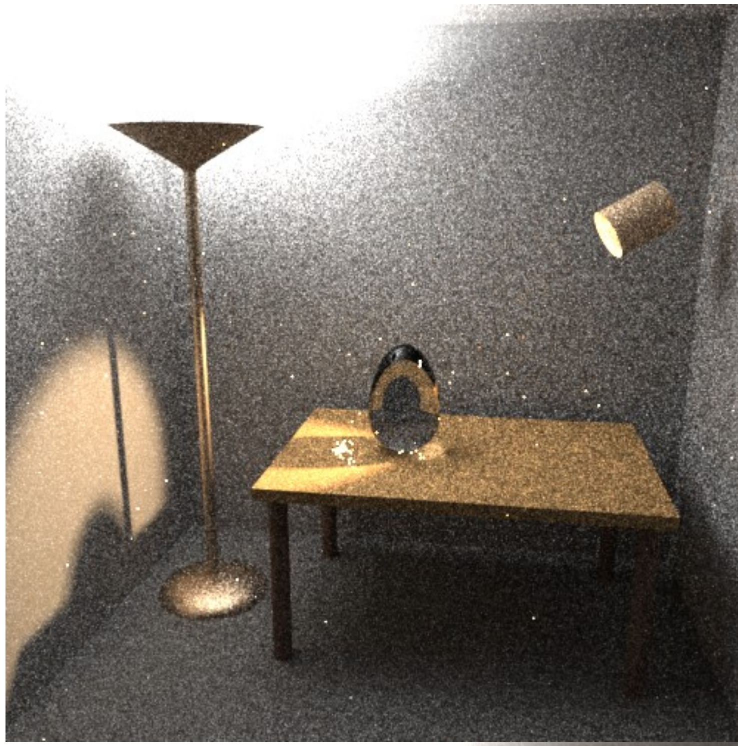
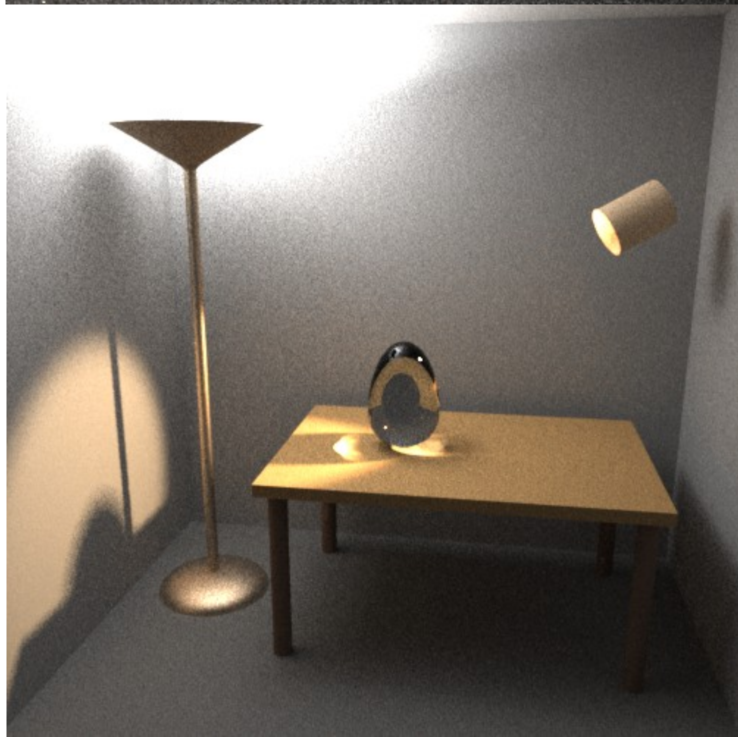
Today

- Path Tracing
  - Intro: nested vs. multidimensional integrals and pixel filtering
  - Recursive sampling of rendering equation using Monte Carlo
  - Direct light sampling
- Bells and whistles





What can it do ~today? (pre-RTX, though)

- Path Tracing + Deep Learning for noise removal

Interactive Reconstruction of Monte Carlo Image Sequences using a Recurrent Denoising Autoencoder

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SIGGRAPH 2017

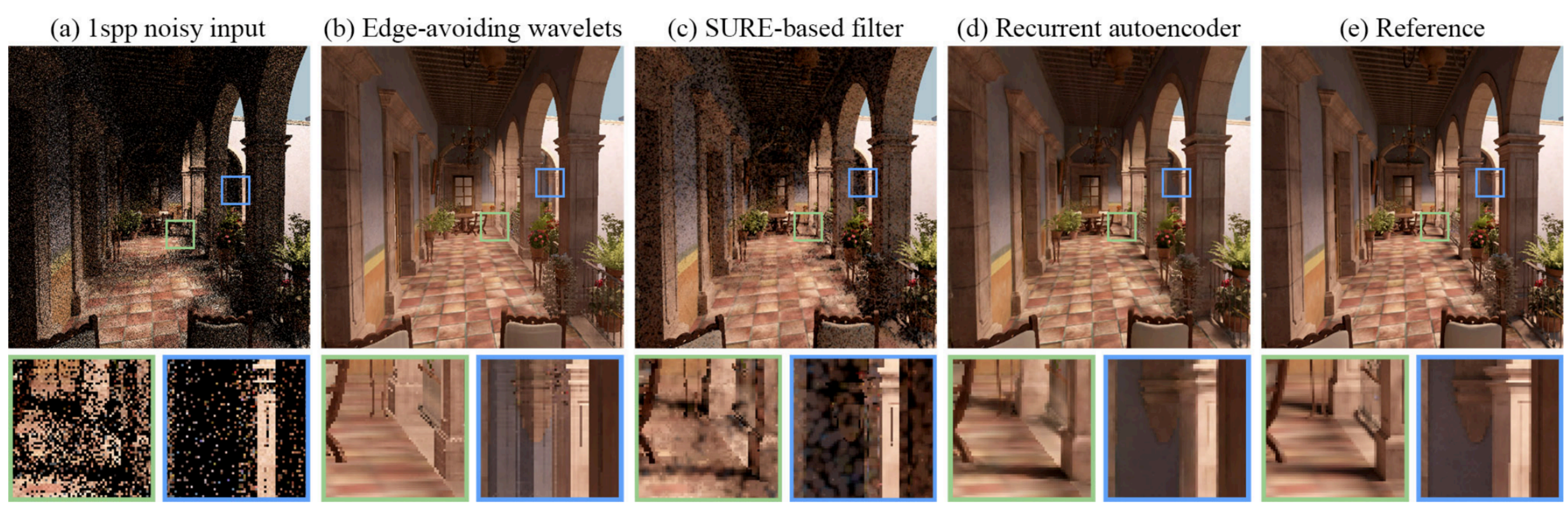


Fig. 1. Left to right: (a) noisy image generated using path-traced global illumination with one indirect inter-reflection and 1 sample/pixel; (b) edge-avoiding wavelet filter [Dammertz et al. 2010] (10.3ms at 720p, SSIM: 0.7737); (c) SURE-based filter [Li et al. 2012] (74.2ms, SSIM: 0.5960); (d) our recurrent denoising autoencoder (54.9ms, SSIM: 0.8438); (e) reference path-traced image with 4096 samples/pixel.

Monte Carlo Integration

$$\int_S f(x)\,\mathrm{d}x \; = E\{\frac{f(x)}{p(x)}\}_p$$

- Distribute samples in integration domain S according to probability density function p(x)
- Then integral equals the expected value of f(x)/p(x)

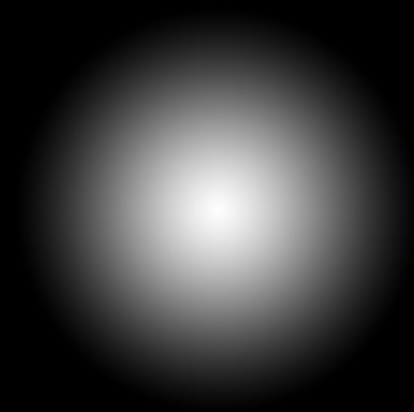
Let’s Go Back to Pixel Filtering

- Remember antialiasing theory from C3100?
- To reduce aliasing, we should ideally...?

Let's Go Back to Pixel Filtering

- Remember antialiasing theory from C3100?
- To reduce aliasing, we should ideally
  1. Low-pass filter the radiance on the image plane before sampling (convolve continuous radiance function + prefilter)
  2. Then sample the low-pass filtered radiance at pixel centers

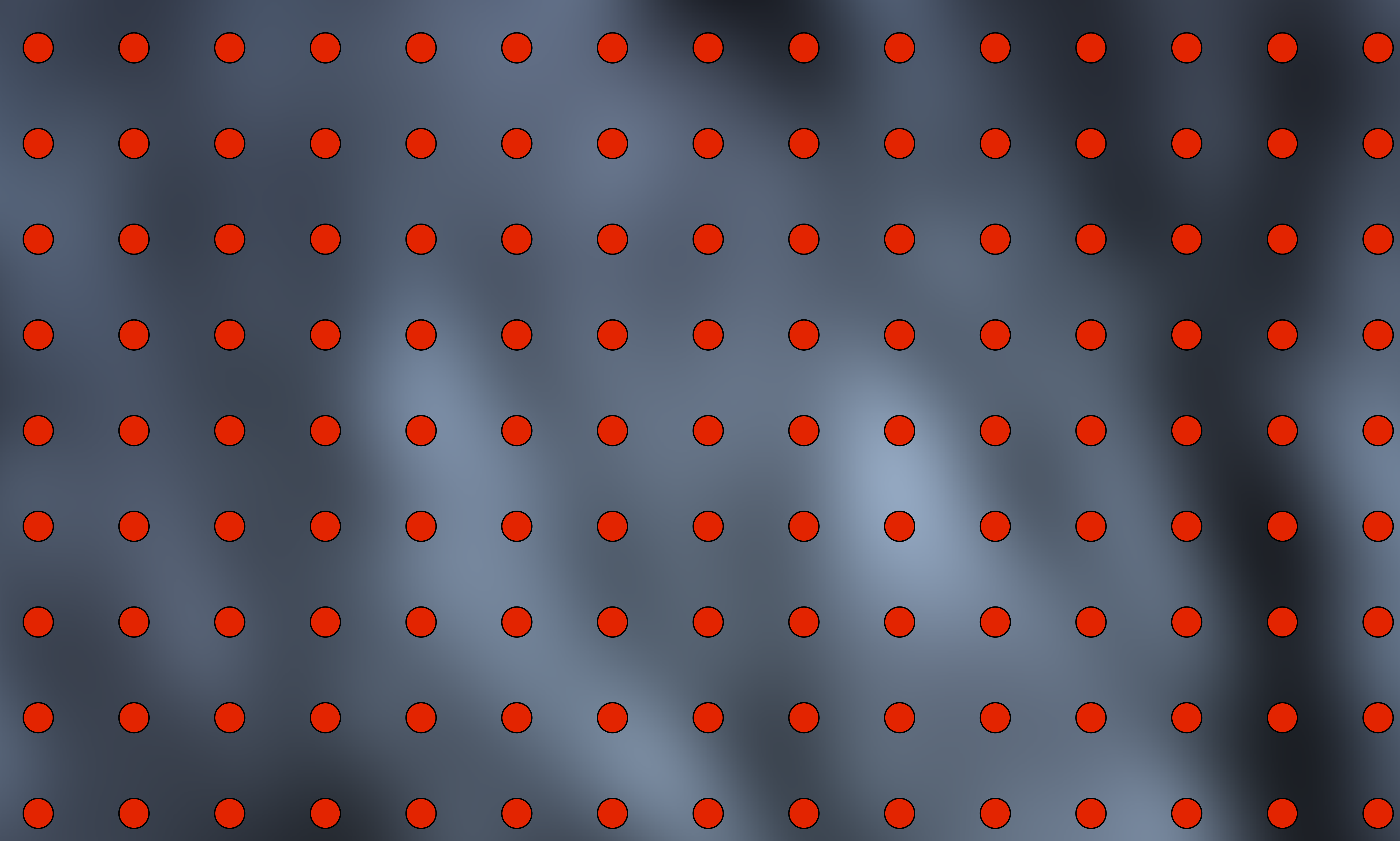
- But we found this was impossible so we turned to supersampling (average many samples in pixel)
  - There is a "proper" way to look at that as well, and here it is..
- (And separate tricks for textures)
  - MIP-maps



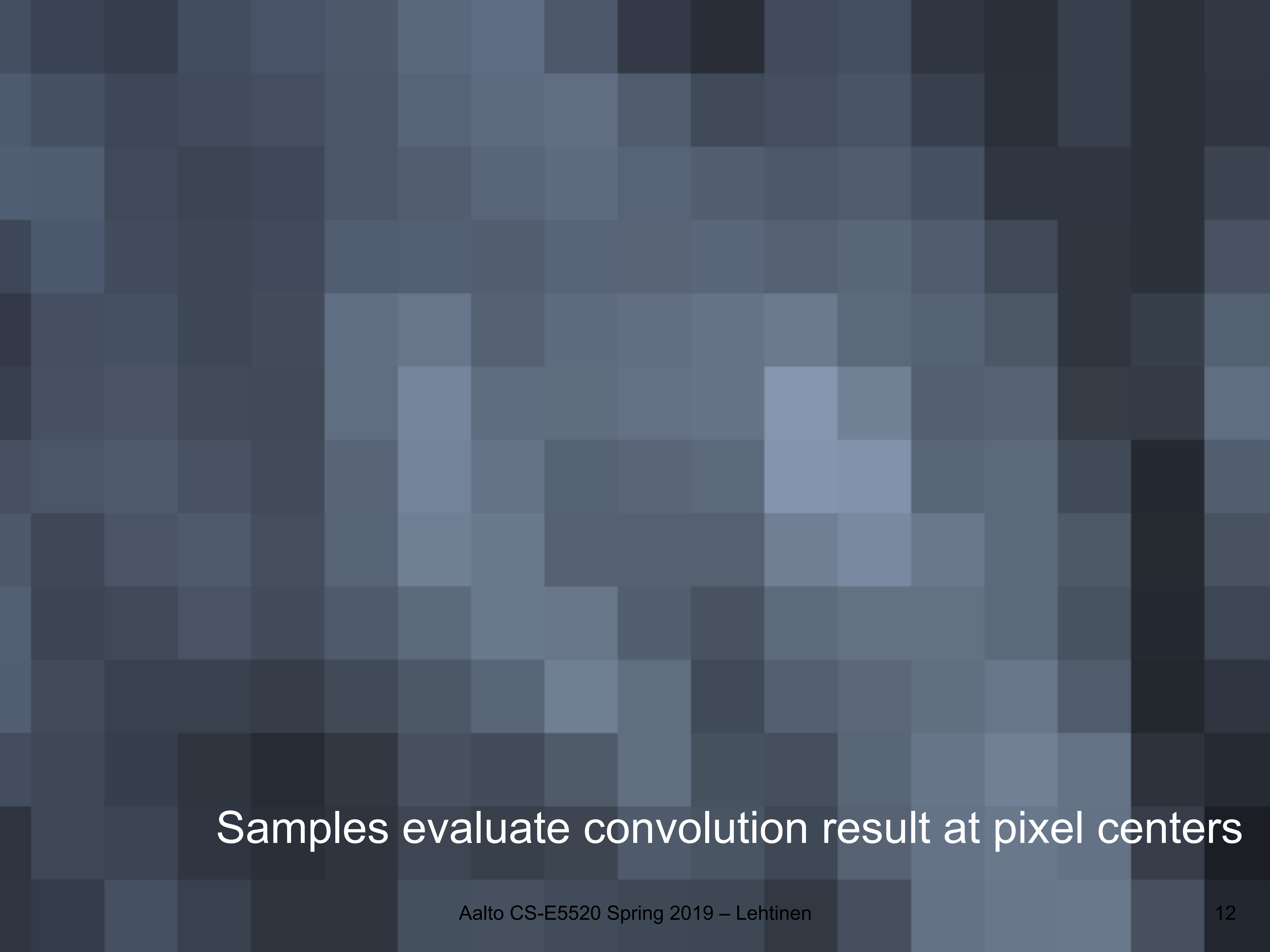
Filter $f(x-x_j, y-y_j)$ centered at pixel (x_j, y_j)

Filter $f(x-x_j, y-y_j)$ centered at pixel (x_j, y_j) times the underlying signal

Low-pass filtered continuous image (convolution of *f* and input image; we can actually never compute this exactly)



Samples at pixel centers



Samples evaluate convolution result at pixel centers

$\int$  $\mathrm{d}x\mathrm{d}y$

i.e., value for pixel at (x_j,y_j) is the integral of the filter times the underlying signal

Pixel Filtering

- Prefilter convolution and sampling can be combined:

$$I_j = \int_{\mathrm{screen}} f(x - x_j, y - y_j)\, L(x, y)\, \mathrm{d}x\, \mathrm{d}y$$

- I_j is the (discrete) intensity/radiance value of jth pixel
- Here x_j, y_j are the center of pixel j, f is the *pixel filter*
  - *Yes, it's just a weighted average*

Filter Normalization

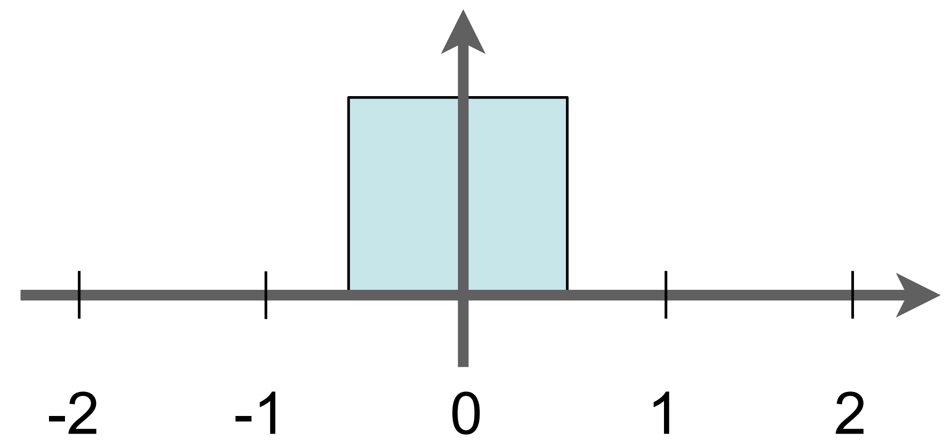
- In practice, we don't care about normalizing the filters analytically, but do it numerically instead

$$I_j = \frac{\int_{\mathrm{screen}} f(x - x_j, y - y_j)\, L(x, y)\, \mathrm{d}x\, \mathrm{d}y}{\int_{\mathrm{screen}} f(x - x_j, y - y_j)\, \mathrm{d}x\, \mathrm{d}y}$$

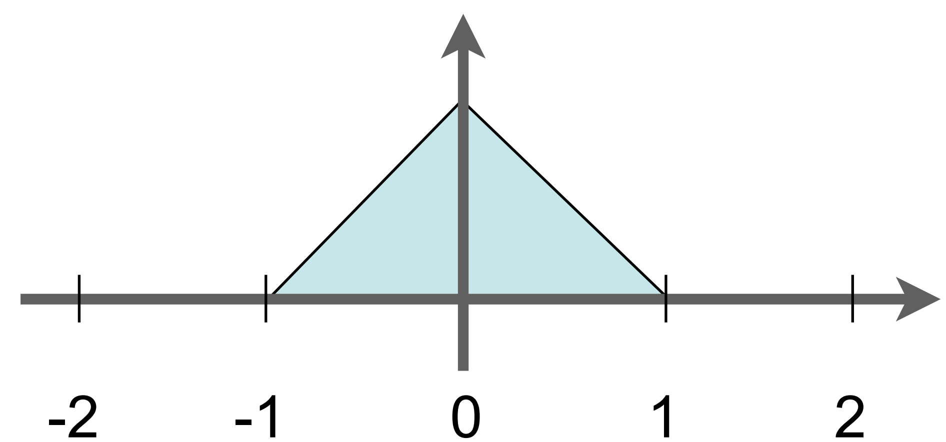
- Intuitive: when we evaluate the above using MC, we sum the "filter weights" from each sample and divide by the sum in the end
  - Note that 1/N cancels out as it's both above and below
  - **IMPORTANT** do it this way; don't rely on $\int f(x, y) = 1$

Common Pixel Filters, 1D profiles

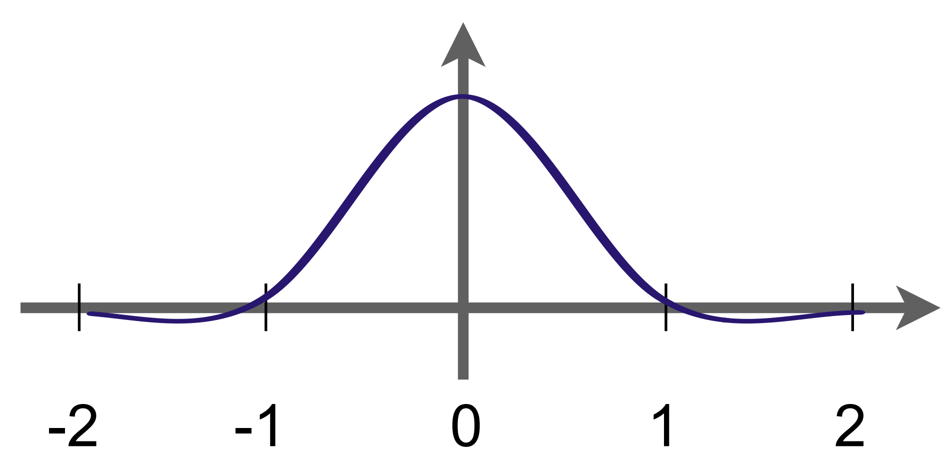
$$f_{\text{box}}(x) = \begin{cases} 1, & -0.5 \le x \le 0.5 \\ 0, & \text{otherwise} \end{cases}$$



$$f_{\text{tent}}(x) = \begin{cases} x+1, & -1 \le x \le 0 \\ 1-x, & 0 \le x \le 1 \\ 0, & \text{otherwise} \end{cases}$$



$$f_{\text{M-N}}(x) = \frac{1}{6} \begin{cases} 7|x|^3 - 12|x|^2 + \frac{16}{3} & |x| < 1 \\ -\frac{7}{3}|x|^3 + 12|x|^2 - 20|x| + \frac{32}{3} & 1 \le |x| \le 2 \\ 0, & \text{otherwise} \end{cases}$$



Mitchell-Netravali filter with A=1/3, B=1/3

Extension to 2D

- "Tensor product" or "separable" filters are constructed from the 1D filters by multiplication

$$f(x, y) = f(x) f(y)$$

- You can also use a non-separable pyramid as a 2D filter, but there seems to be little point
- OK, one more: Gaussian

$$f^{\sigma}_{\mathrm{Gaussian}}(x) = \exp\{-\frac{x^2}{2\sigma^2}\}$$

  – Notes: sigma controls width; not normalized to unit integral!
  – Never drops to zero. We usually cut the filter at 3*sigma or so.

Down to Business: AO

- What if each value of the original image is an integral?
- In assignment 1 you compute, for each primary hit P

$$\int_\Omega V(P,\omega)\cos\theta\,\mathrm{d}\omega$$

  using Monte Carlo integration
  - V is a function that is 1 if the ray of a certain length is unblocked, 0 if it is blocked

Let’s Combine Pixel Filter with AO

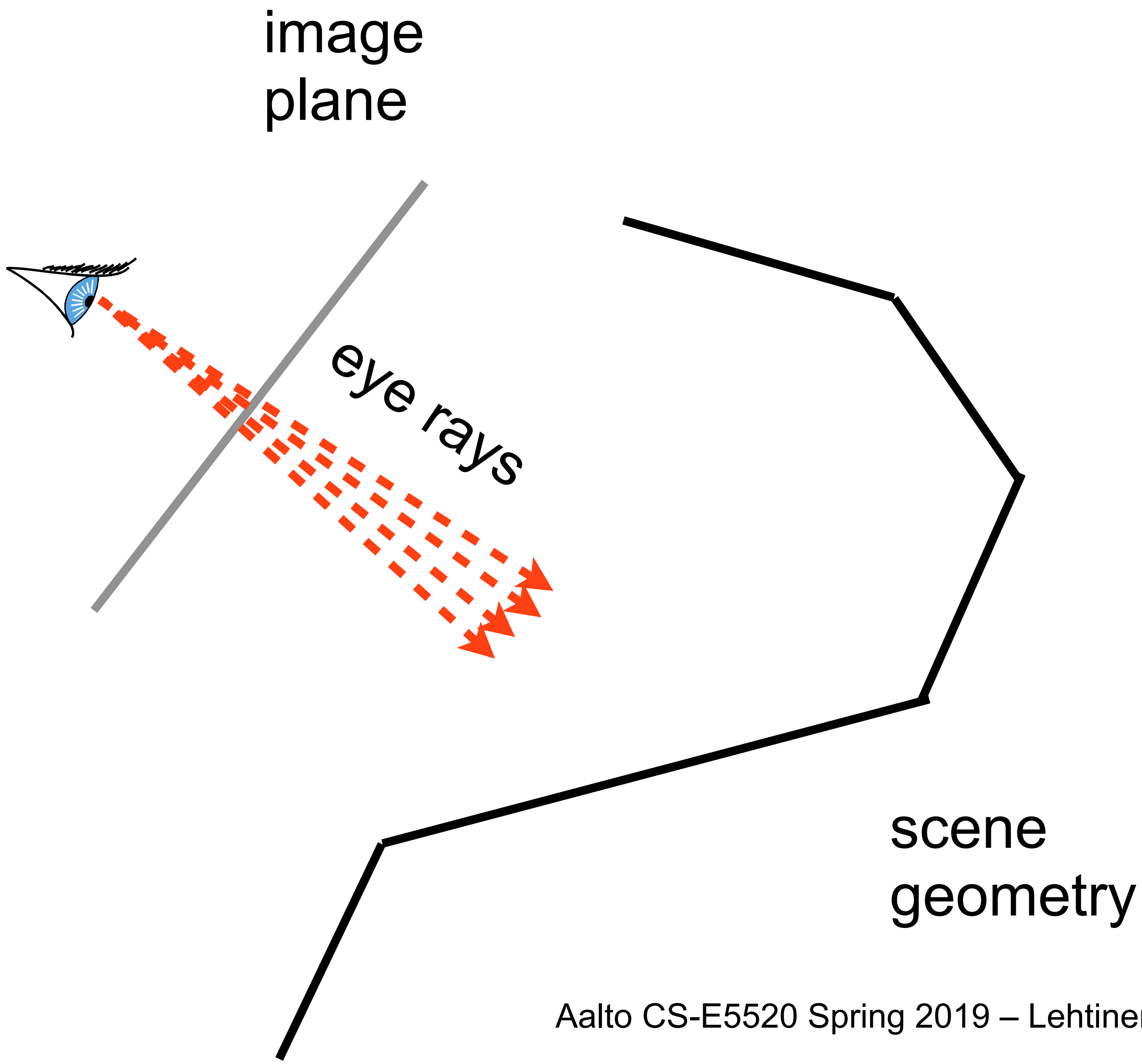
- Each pixel value given by

$$I_j = \int_{\text{screen}} f(x - x_j, y - y_j) \left(\int_\Omega V(P(x,y),\omega) \cos\theta \mathrm{d}\omega \right) \mathrm{d}x\,\mathrm{d}y$$

- (Normalization not shown)
- Two nested 2D integrals
  - Outer one over the screen (2D)
  - Inner one over the hemisphere at the point P hit by ray through image coordinages x,y
    - Again, 2D (hemisphere)

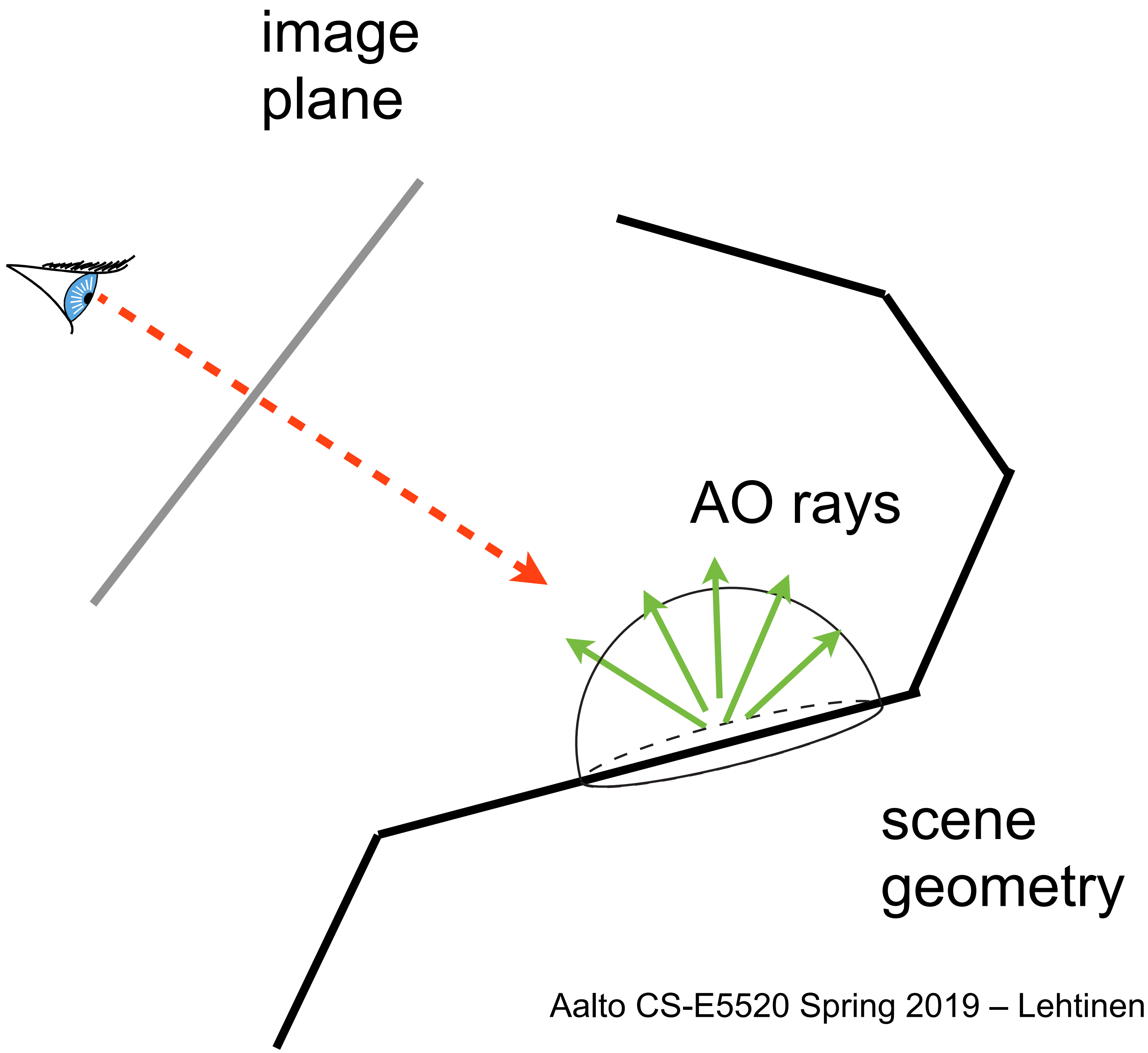
Outer Integral

$$I_j = \int_{\text{screen}} f(x - x_j, y - y_j) \left(\int_\Omega V(P(x,y),\omega) \cos\theta \mathrm{d}\omega \right) \mathrm{d}x\,\mathrm{d}y$$



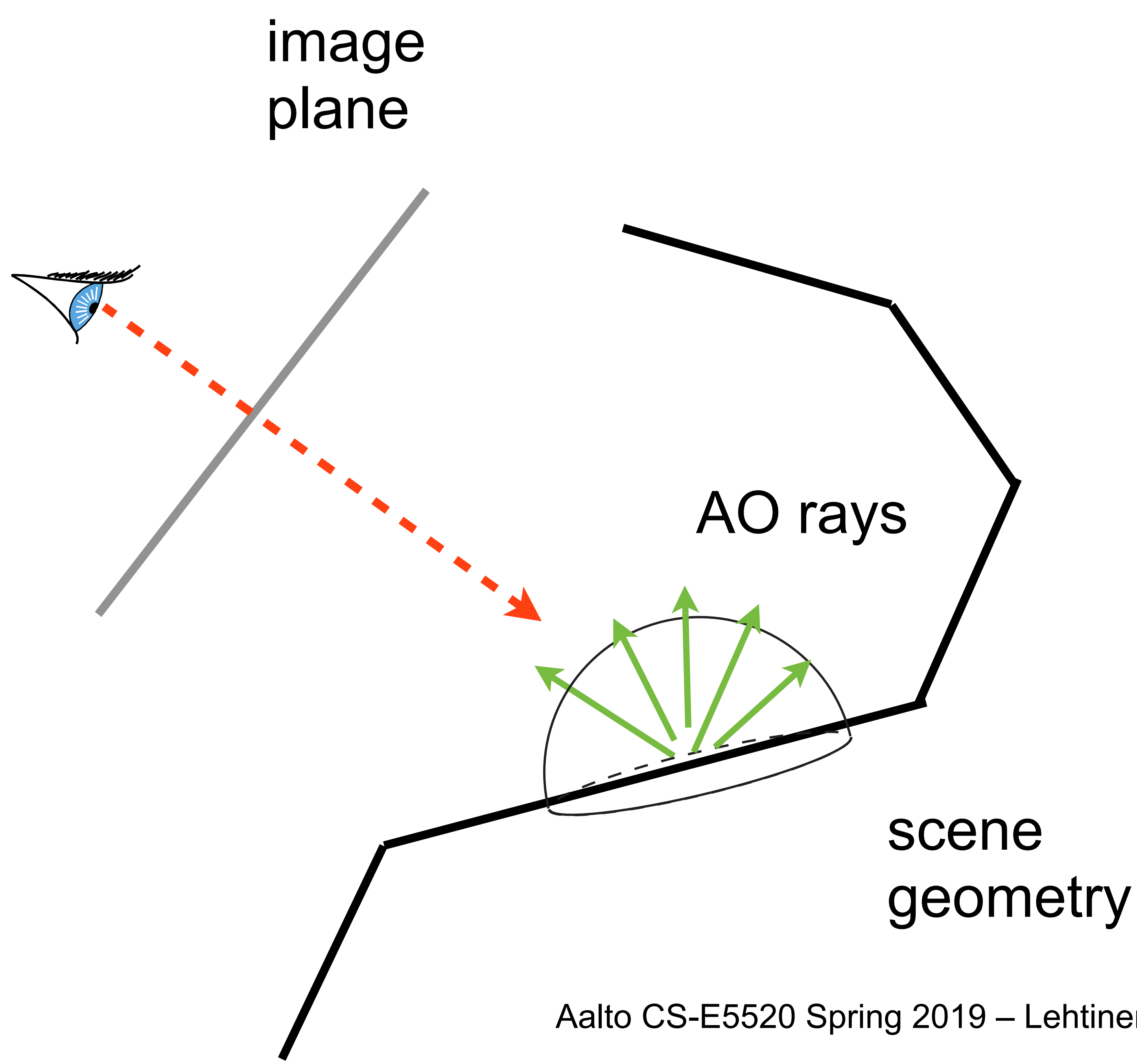
Inner Integral, for each eye ray

$$I_j = \int_{\text{screen}} f(x - x_j, y - y_j) \left(\int_\Omega V(P(x,y),\omega) \cos\theta \mathrm{d}\omega \right) \mathrm{d}x\, \mathrm{d}y$$



Inner Integral, for each eye ray

$$I_j = \int_{\text{screen}} f(x - x_j, y - y_j) \left(\int_\Omega V(P(x,y), \omega) \cos\theta \mathrm{d}\omega \right) \mathrm{d}x \, \mathrm{d}y$$



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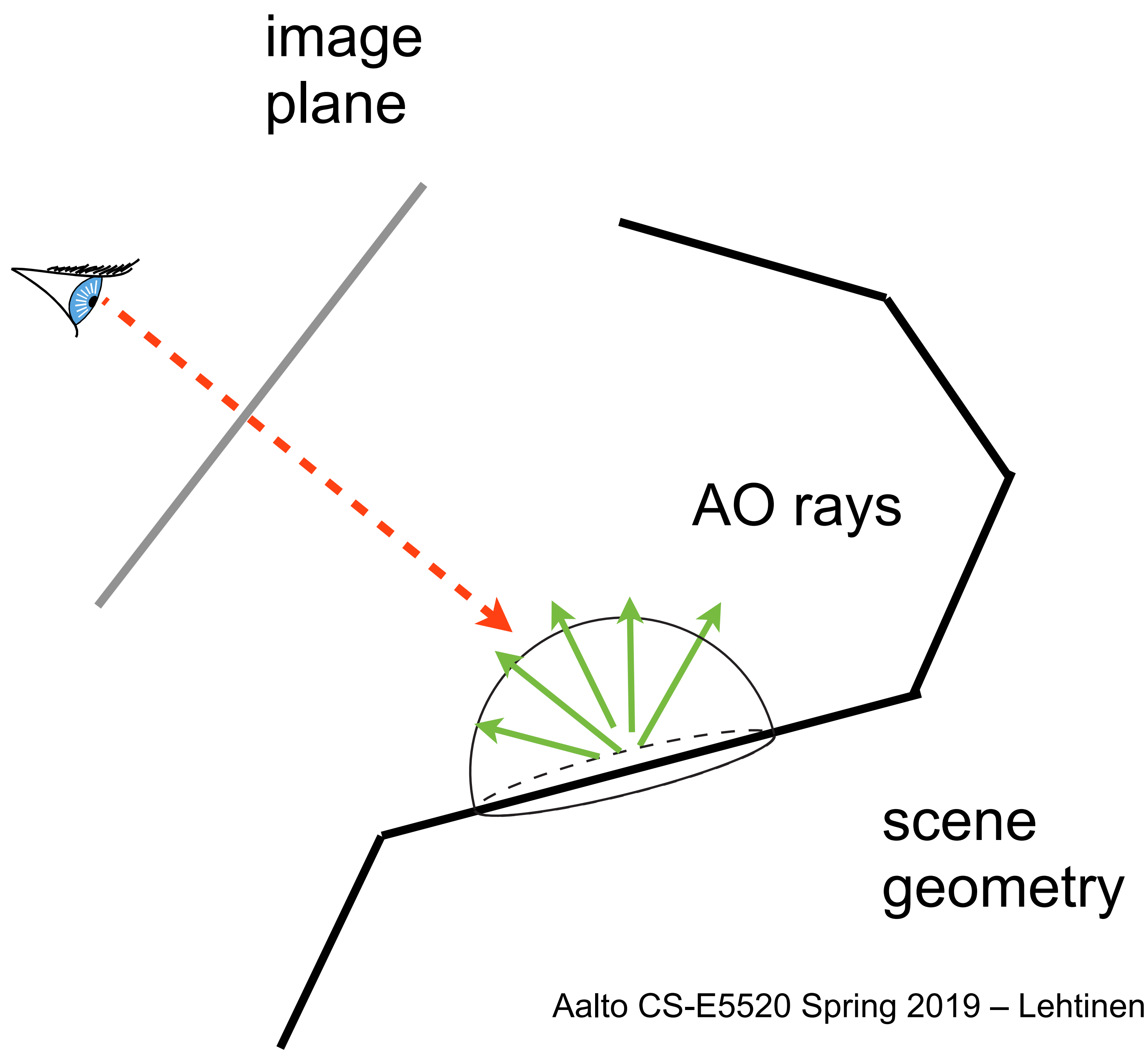

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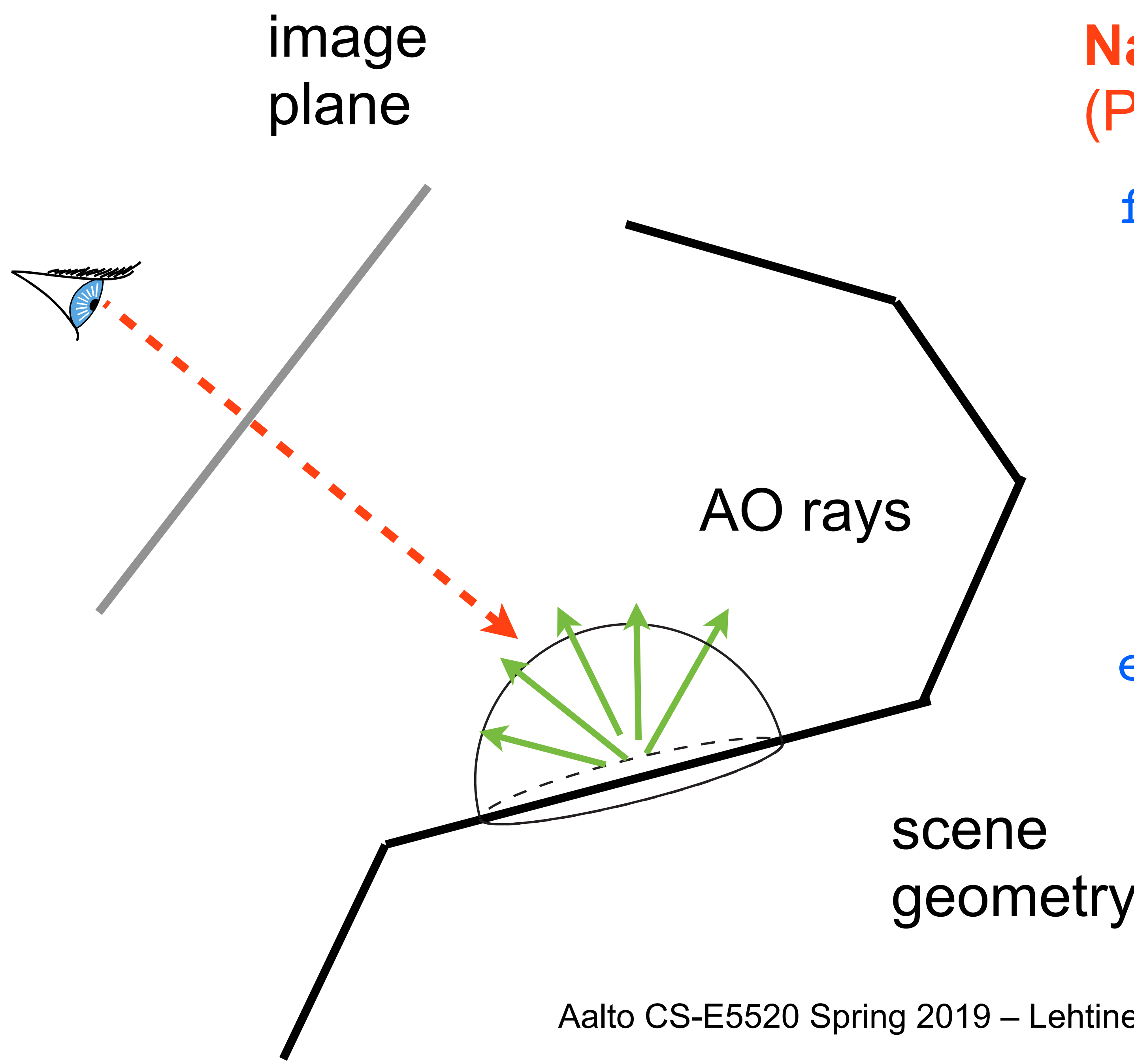

Naive MC implementation:
(PDFs, accumulation not shown)

```
for i=1 to #eyerays
  pick (x,y)
  P=castray(x,y)
  for j=1 to #aorays
    // shoot rays from P
    // etc
  end
end
```

Inner Integral, for each eye ray

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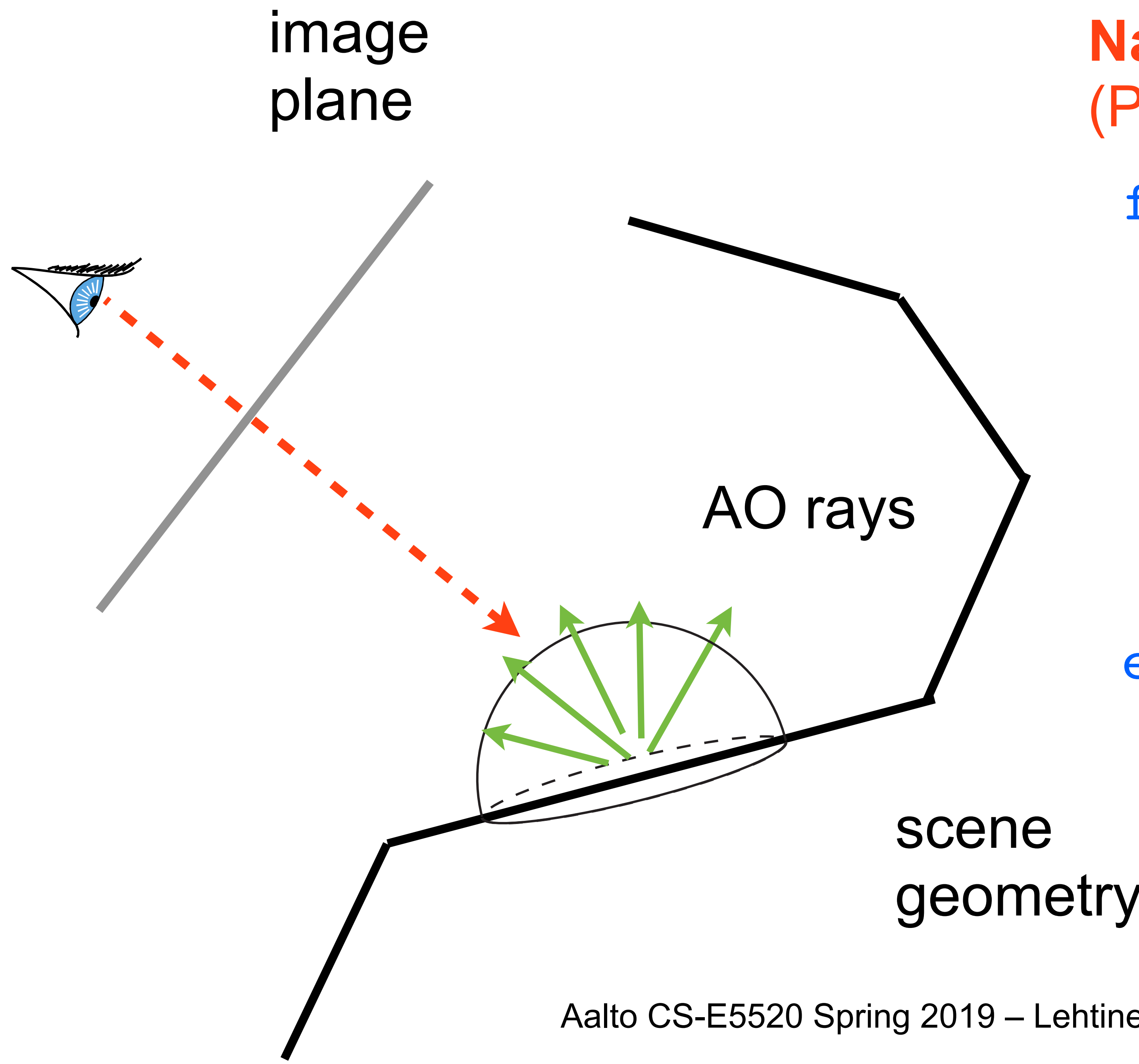

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    // etc
  end
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```

Although you do this in assn1, it makes little sense

Problems

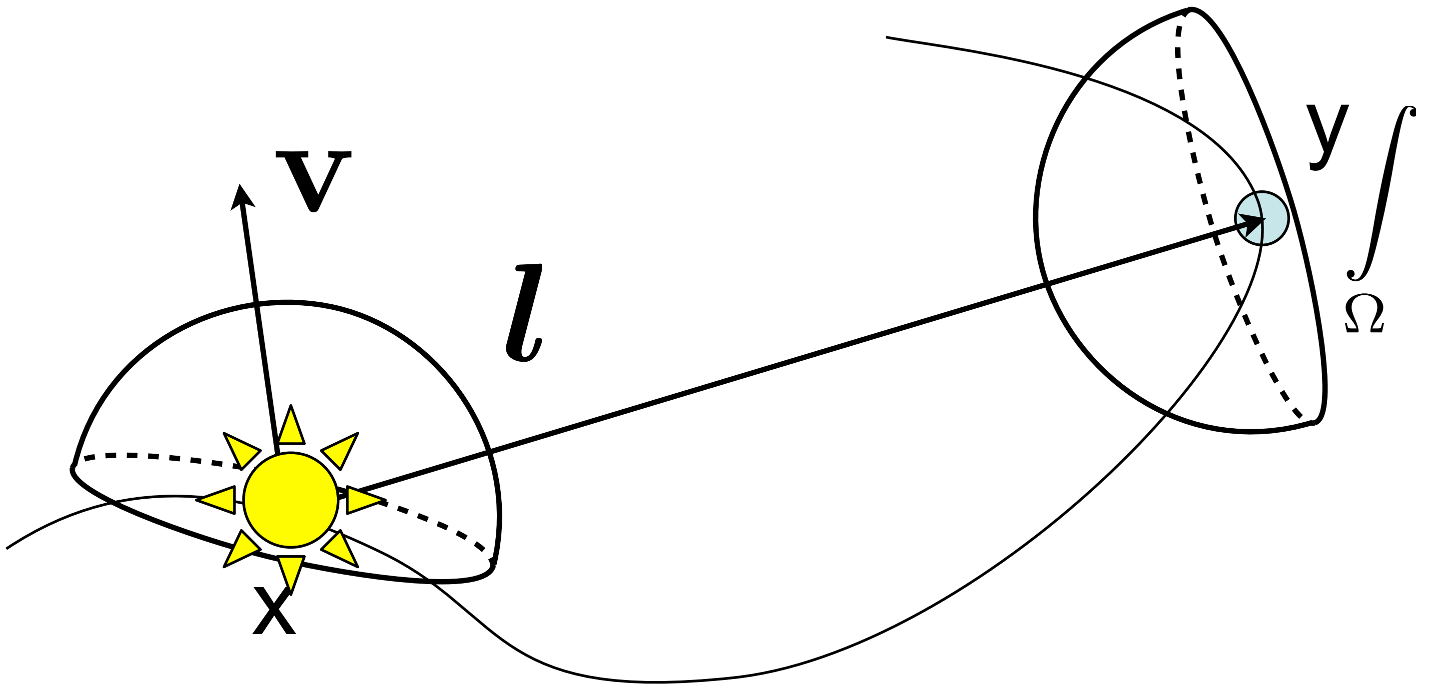
- Difficult to control number of rays cast in the pixel
  - You have two knobs to tweak
- What if we had even further integrals...?

Recap: Rendering Equation

$$L(x \to \mathbf{v}) = \int_\Omega L(x \leftarrow \mathbf{l})\, f_r(x, \mathbf{l} \to \mathbf{v})\ \cos\theta\, \mathrm{d}\mathbf{l}$$

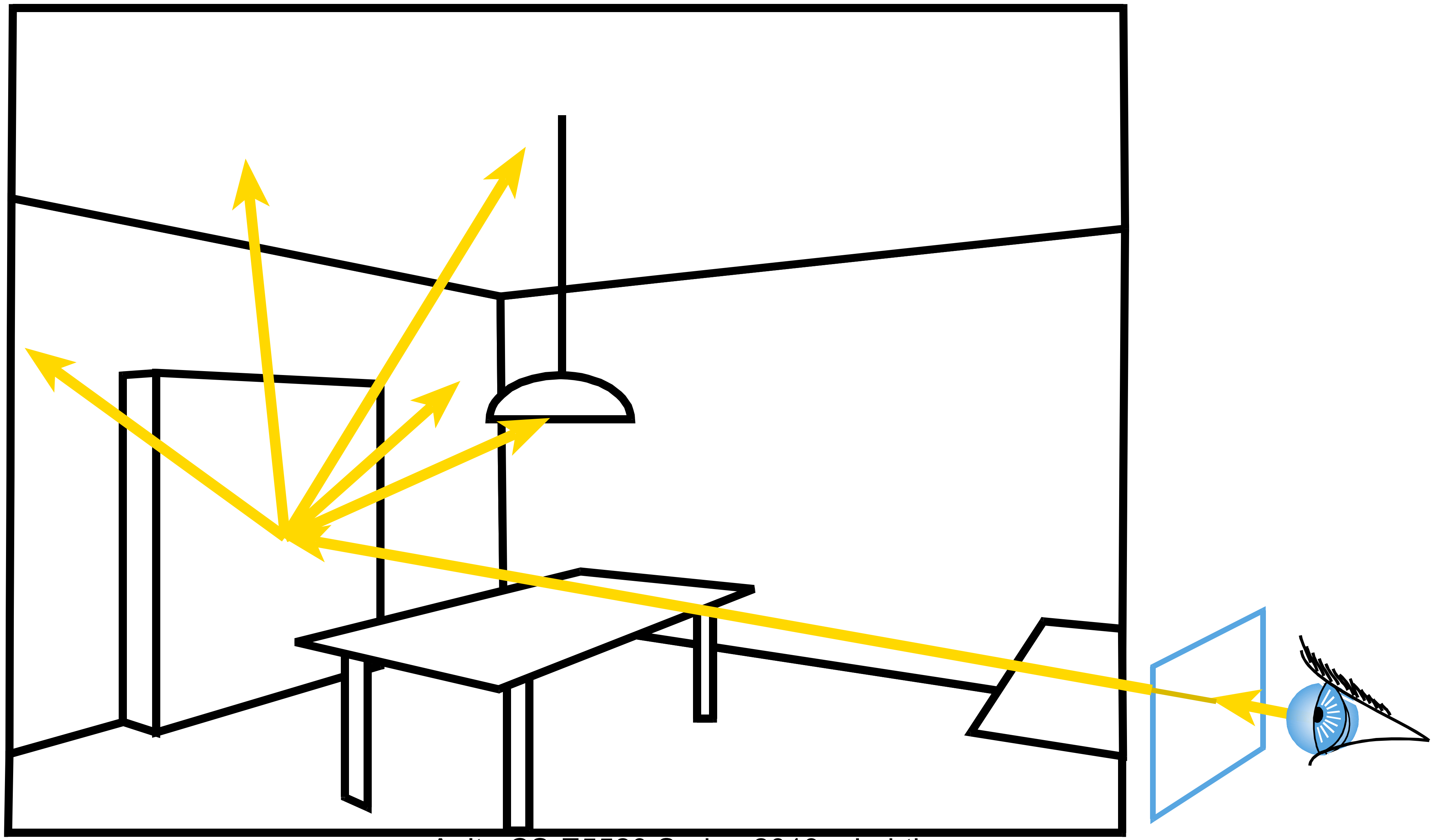
$$+\ E(x \to \mathbf{v})$$

to know incoming radiance, must know outgoing radiance elsewhere => recursion!



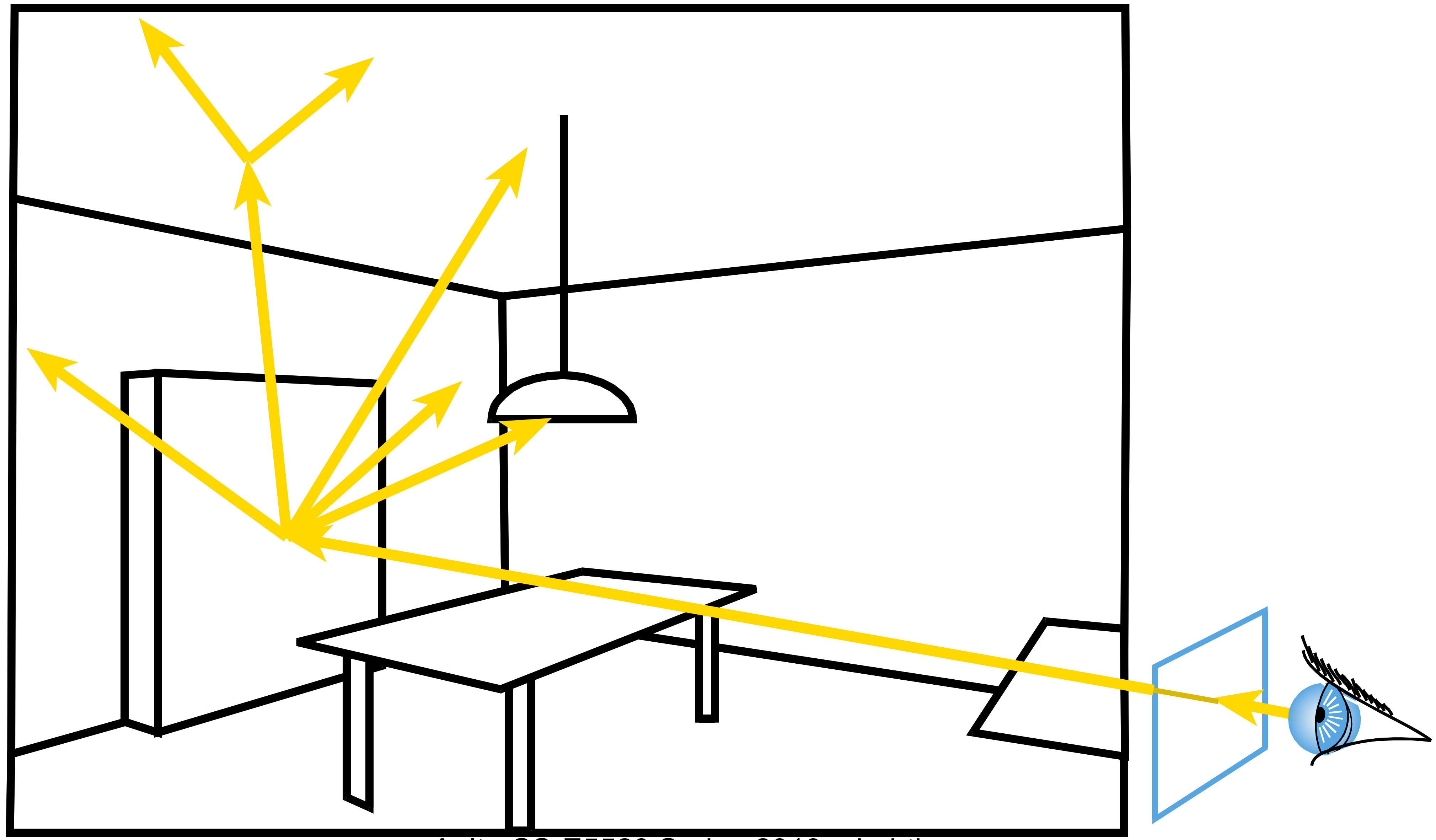
“Monte-Carlo Ray Tracing”

- Cast a ray from the eye through each pixel
- Cast N random rays from the hit point to evaluate hemispherical integral using random sampling



“Monte-Carlo Ray Tracing”

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



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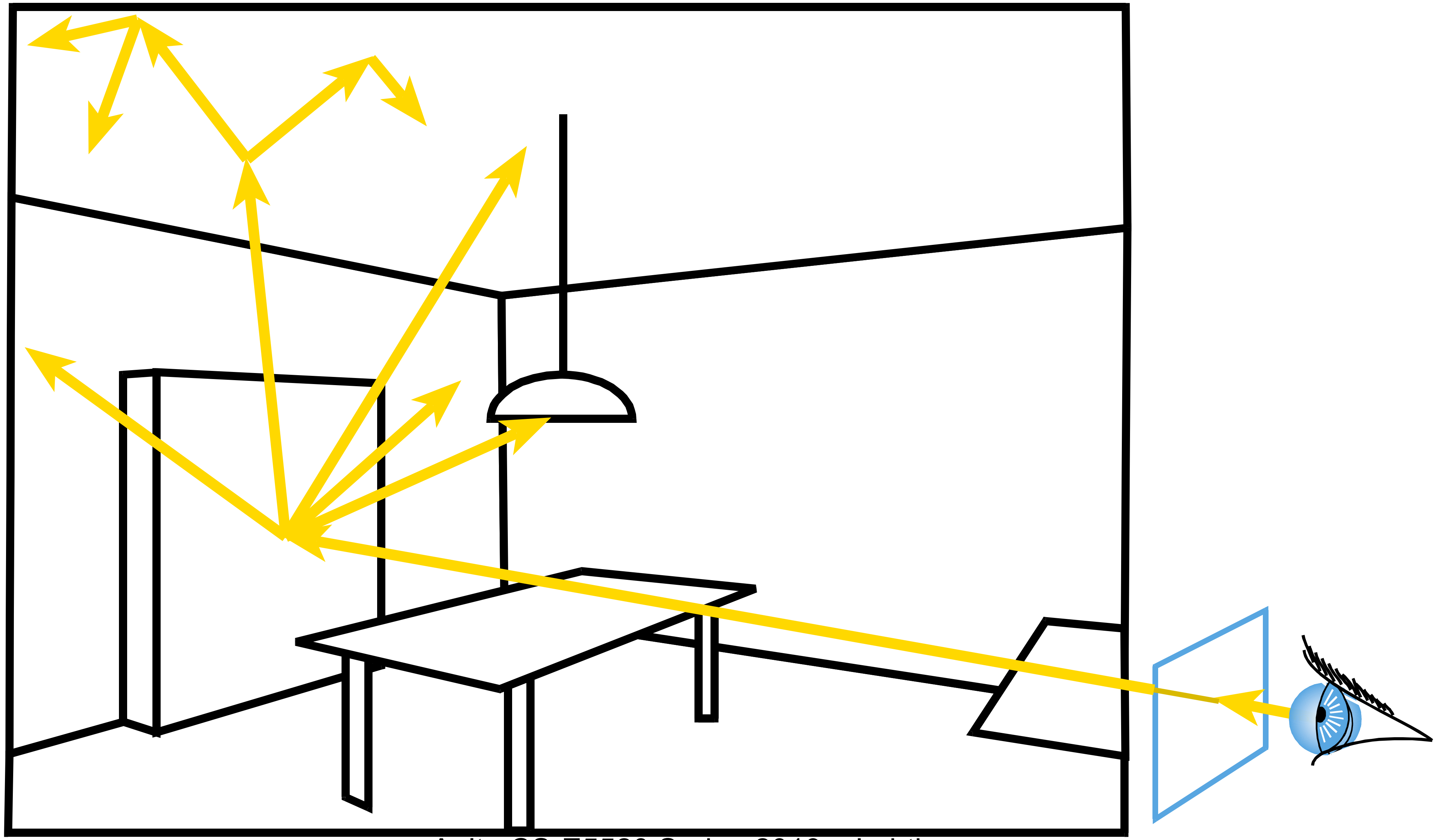

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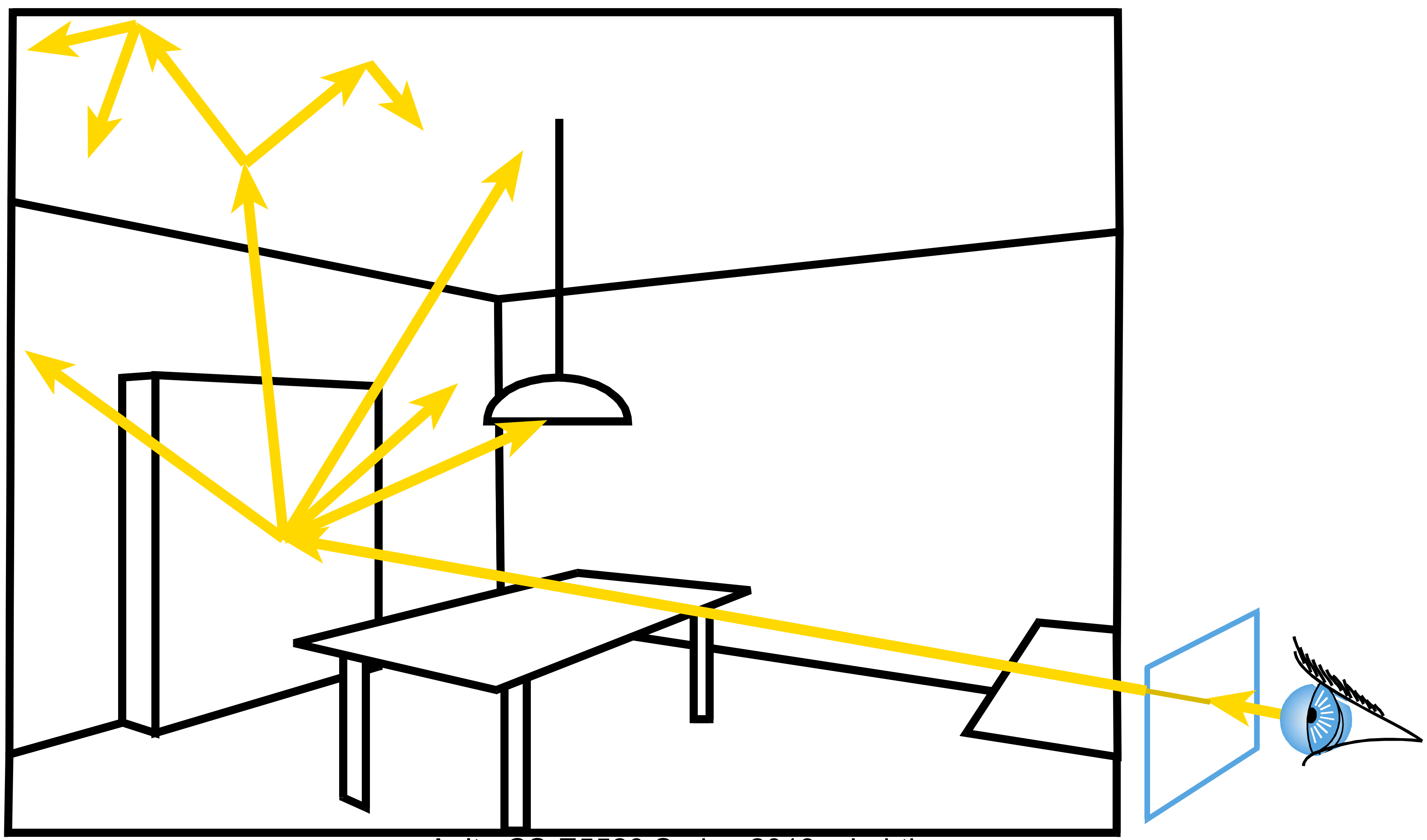
Combinatorial explosion!



Combinatorial Explosion

- Sample indirect illumination with 100 rays
- Each ray results in N more rays.. grows exponentially
- For N=100
  - 1 eye ray
  - 100 indirect rays at primary hit
  - 10 000 indirect rays at the secondary hits
  - 1 000 000 at the tertiary hits
  - You get the picture

Back to AO: Better Way

- Rather than 2D x 2D, one integral over 4D domain:

$$I_j = \int_{\text{screen}\times\Omega} g(x, y, \omega)\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\omega$$

with integrand

$$g(x, y, \omega) = f(x - x_j, y - y_j)\,V(P(x, y), \omega)\,\cos\theta$$

Back to AO: Better Way

- Rather than 2D x 2D, one integral over 4D domain:

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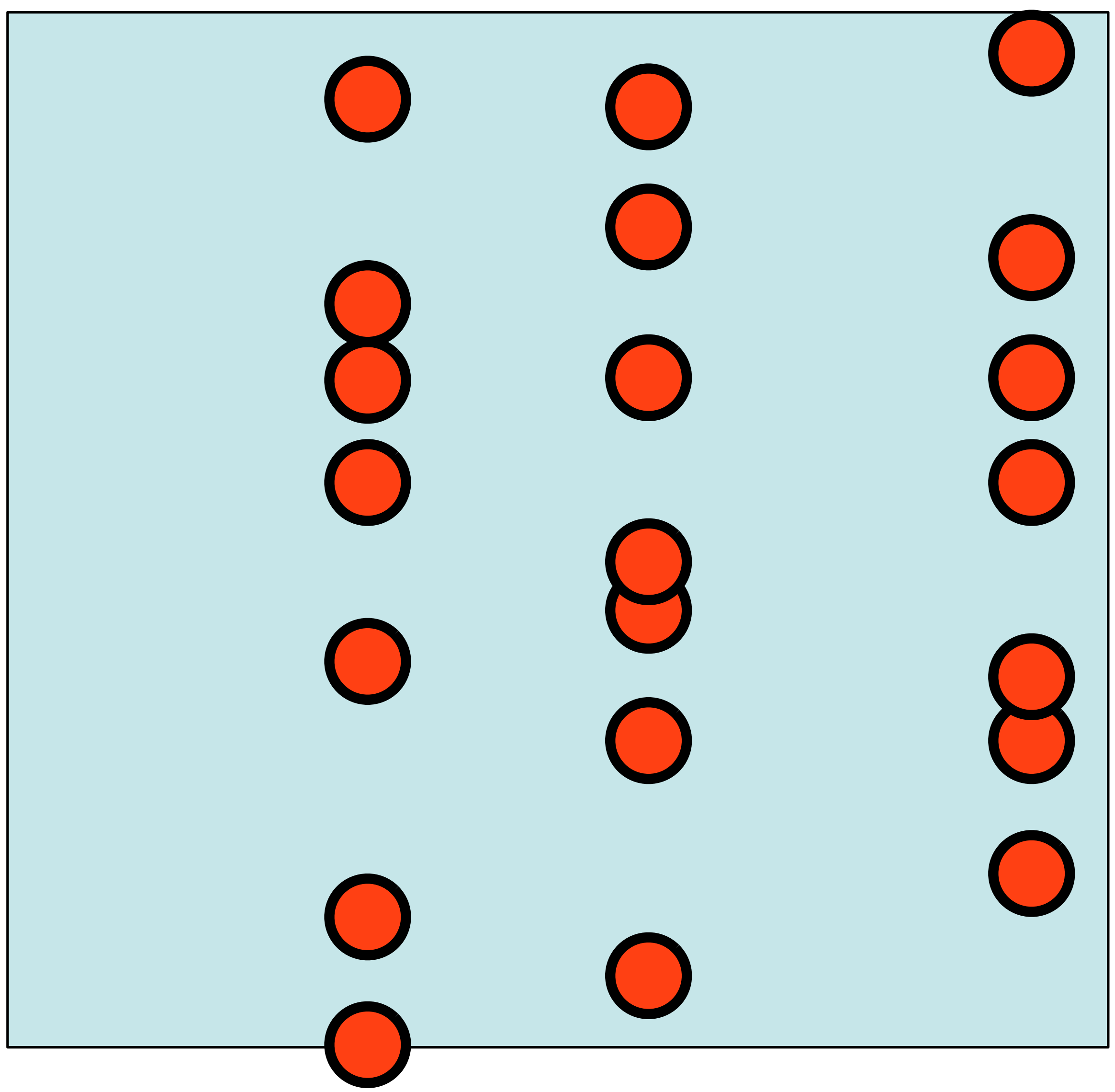
with integrand

$$g(x, y, \omega) = f(x - x_j, y - y_j)\, V(P(x, y), \omega)\, \cos\theta$$

- This is strictly equivalent; just another point of view
  – *Think of 1D vs. 2D integrals*

Nested 1D + 1D, naive

$$\int \left(\int f(x, y) \mathrm{d}y \right) \mathrm{d}x$$

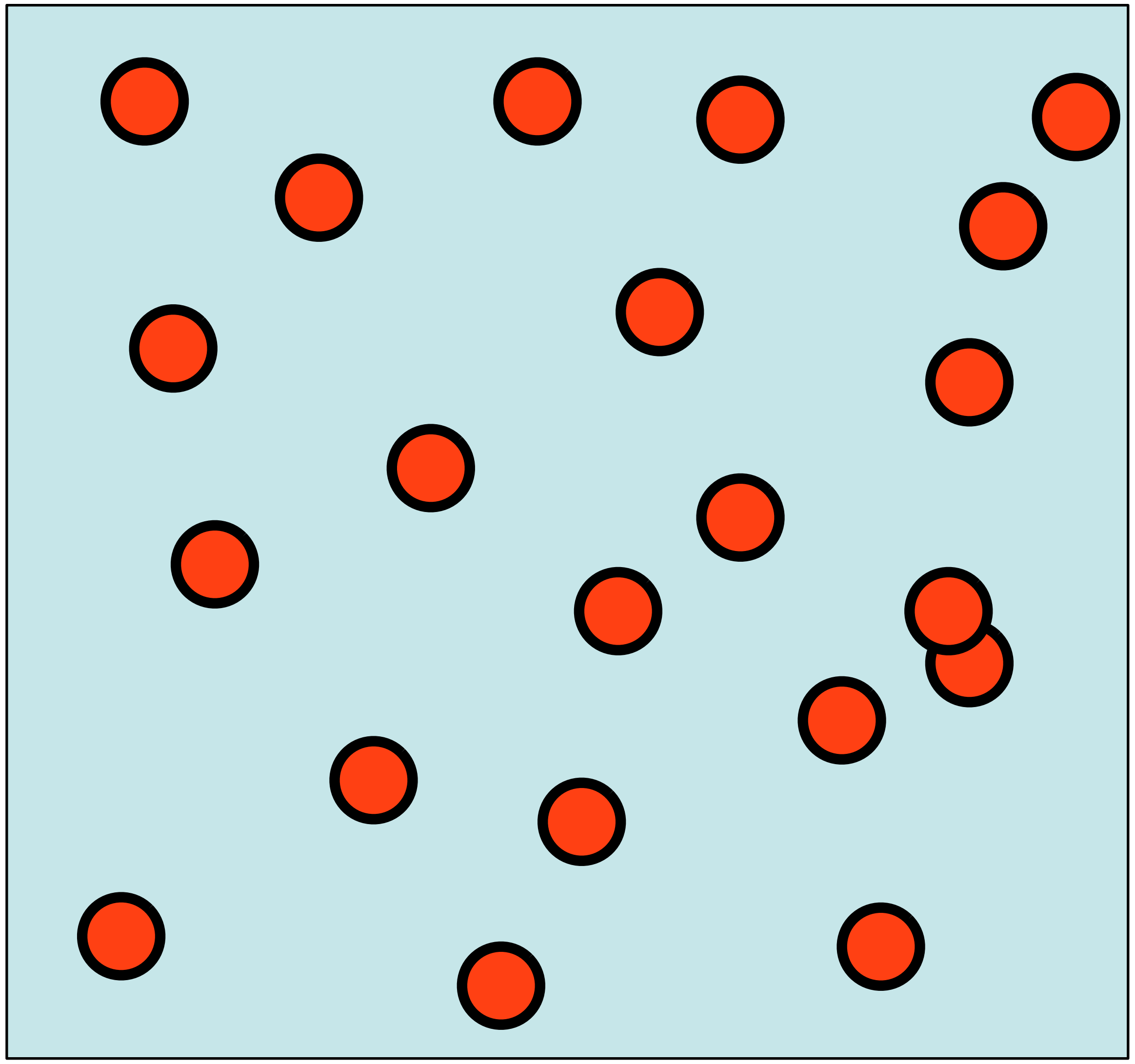


First pick x,
then pick a
bunch of ys

Repeat

Nested 1D + 1D, treat as 2D

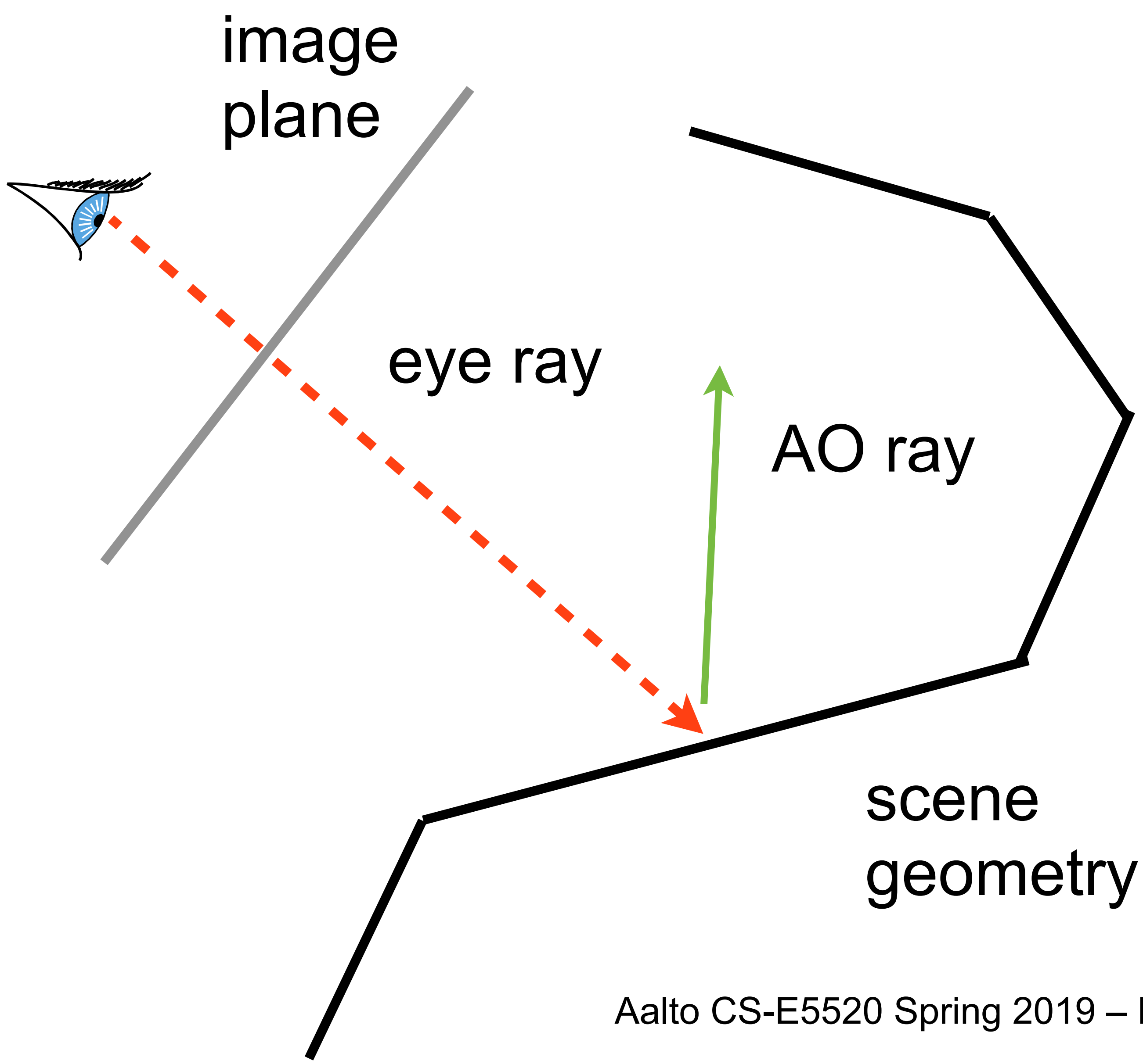
$$\int \left(\int f(x,y) \mathrm{d}y \right) \mathrm{d}x = \int \int f(x,y)\, \mathrm{d}x \mathrm{d}y$$



Draw 2D samples (x,y) from 2D pdf

Visually: One sample is Two Rays

$$I_j = \int_{\text{screen}\times\Omega} g(x,y,\omega)\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\omega$$

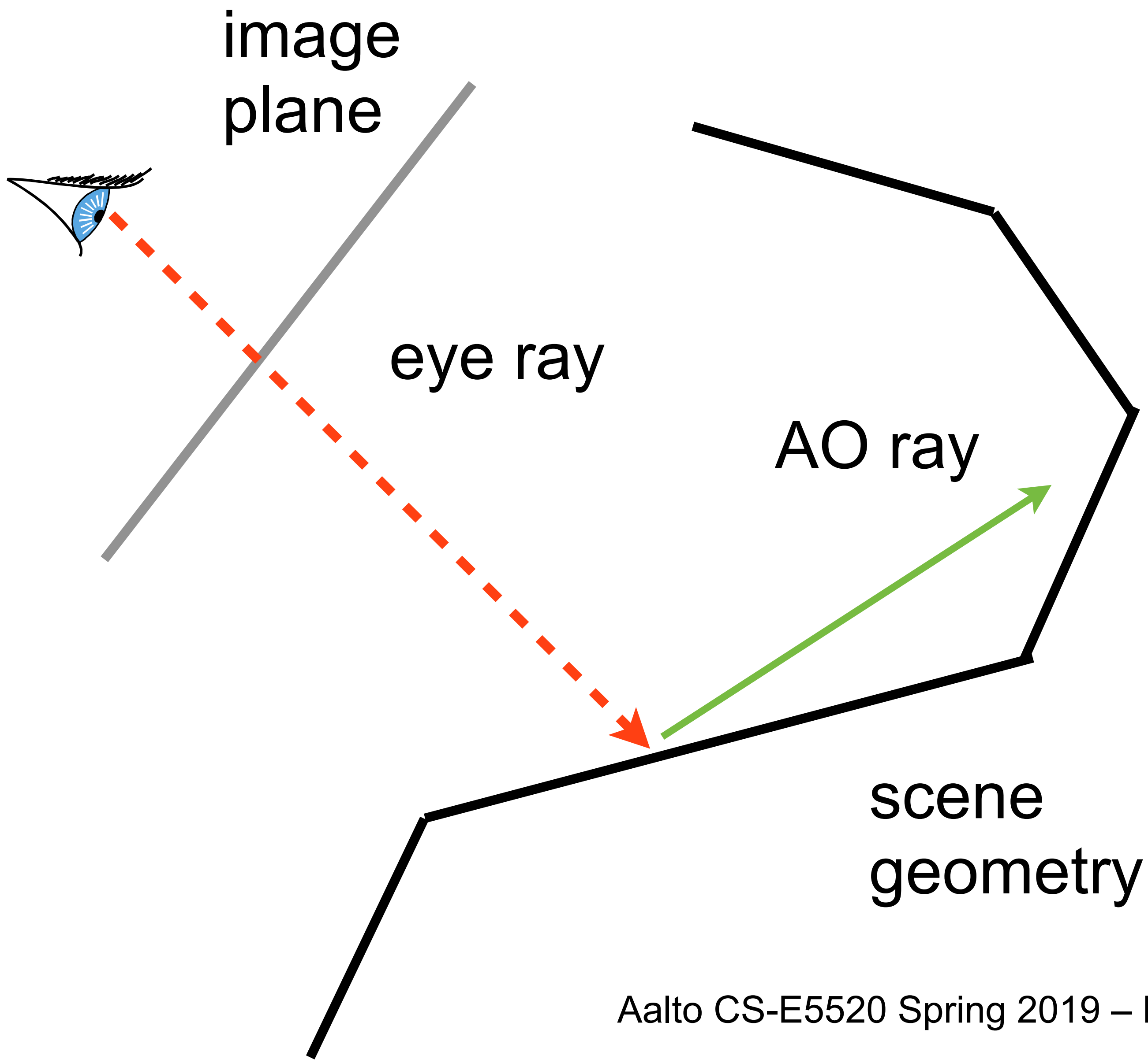


Better MC implementation:

```
res = 0
for i=1 to #samples
  pick sample (x,y,w_out)
  pdf=p(x,y)*p(w_out)
  P=castray(x,y)
  V=castray(P,w_out)
  res += g(x,y,V)/pdf
end
res = res/#samples
```

Visually: One sample is Two Rays

$$I_j = \int_{\text{screen}\times\Omega} g(x,y,\omega)\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\omega$$



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  V=castray(P,w_out)
  res += g(x,y,V)/pdf
end
res = res/#samples
```

Implementation Details

- Naturally, if your pixel filters overlap, you use the same samples for updating all the pixels with nonzero filter responses

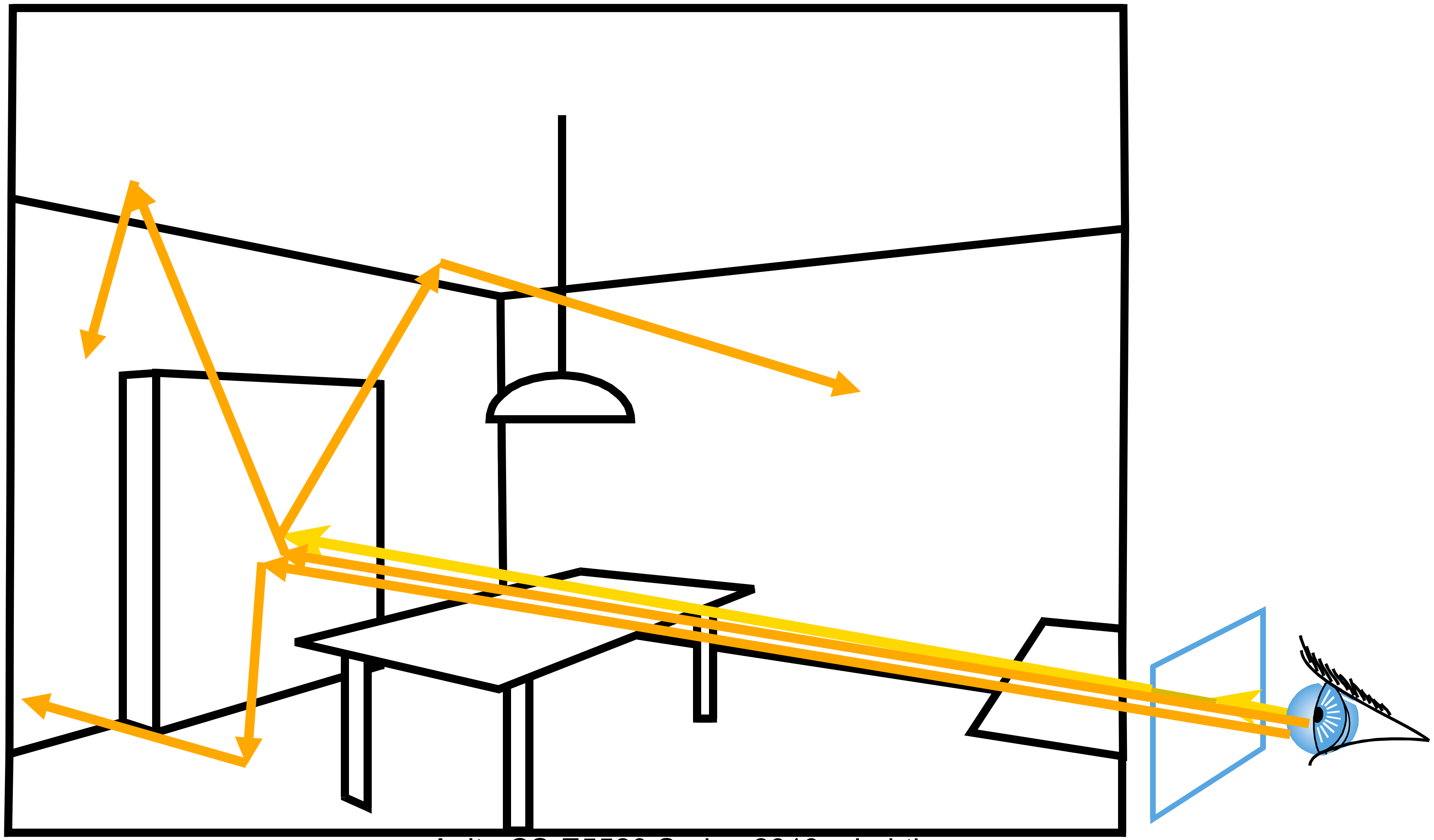
```
res[k] = weight[k] = 0 for all pixels k
for each pixel k
  for i=1 to #samplesperpixel
    pick sample (x,y,omega)          // e.g. 4D Sobol'
    pdf=p(x,y)*p(omega)              // usually p(x,y) == 1
    P=castray(x,y)                   // find primary hit
    V=castray(P,omega).length()>D    // evaluate AO shadow term
    for each pixel j where f_j(x,y) is nonzero
      res[j] += f_j(x,y)*cos(theta)*V/pdf
      weight[j] += f_j(x,y)/p(x,y)
    end
  end
end
res[k] = res[k]/weight[k]
```

Filter of *j*th pixel

$$f_j(x,y) = f(x - x_j, y - y_j)$$

Monte Carlo Path Tracing

- Trace only one secondary ray per recursion
  - Otherwise number of rays explodes!
- But send many primary rays per pixel (antialiasing)



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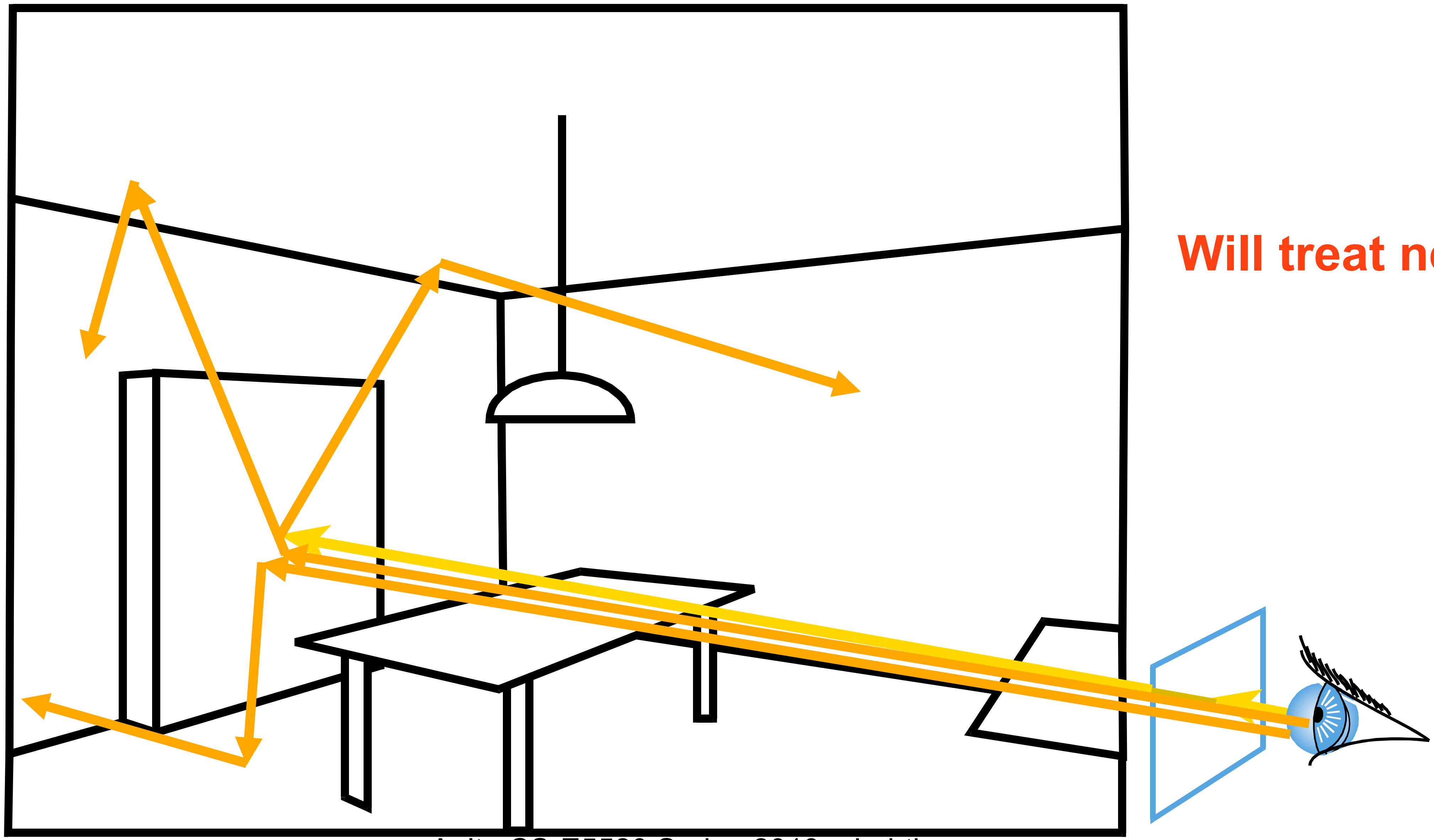
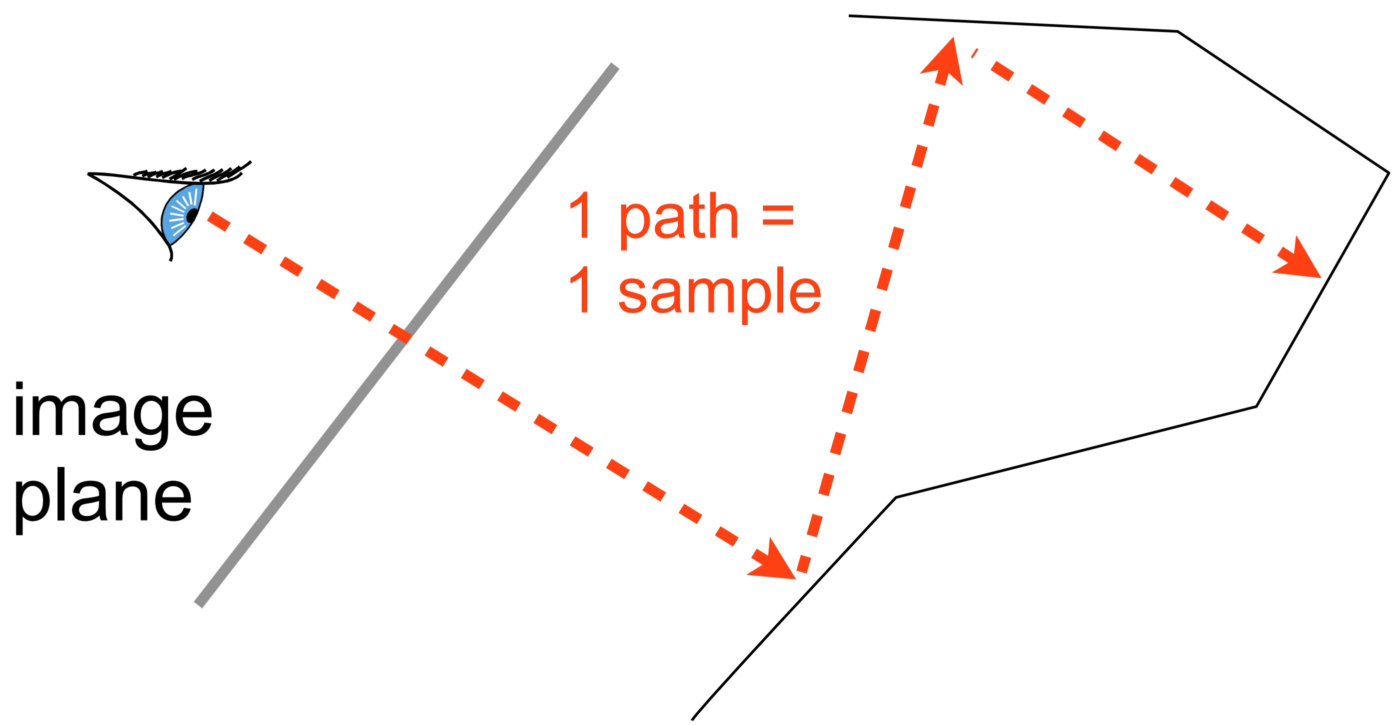


Will treat next time!

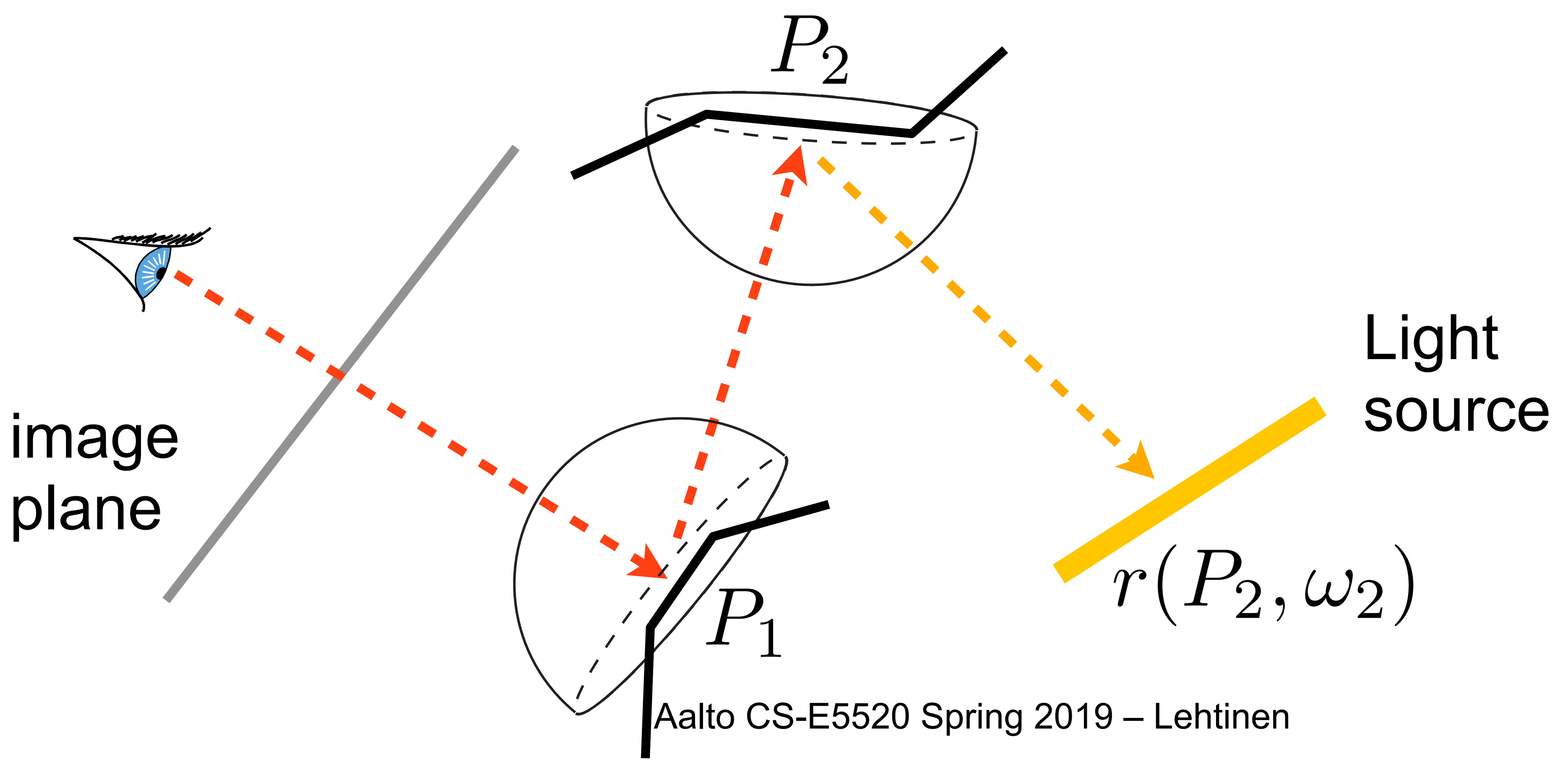
Monte Carlo Path Tracing

- The idea is just the same as before with AO+filter
  - Instead of thinking about nested integrals over hemispheres at each bounce, let's think of one integral over the Cartesian product of all the hemispheres
  - For n bounces, the domain is $\text{screen} \times \underbrace{\Omega \times \ldots \times \Omega}_{n \text{times}}$
  - Each sample is a *path* = *sequence of rays*



Example: 1 Indirect Bounce

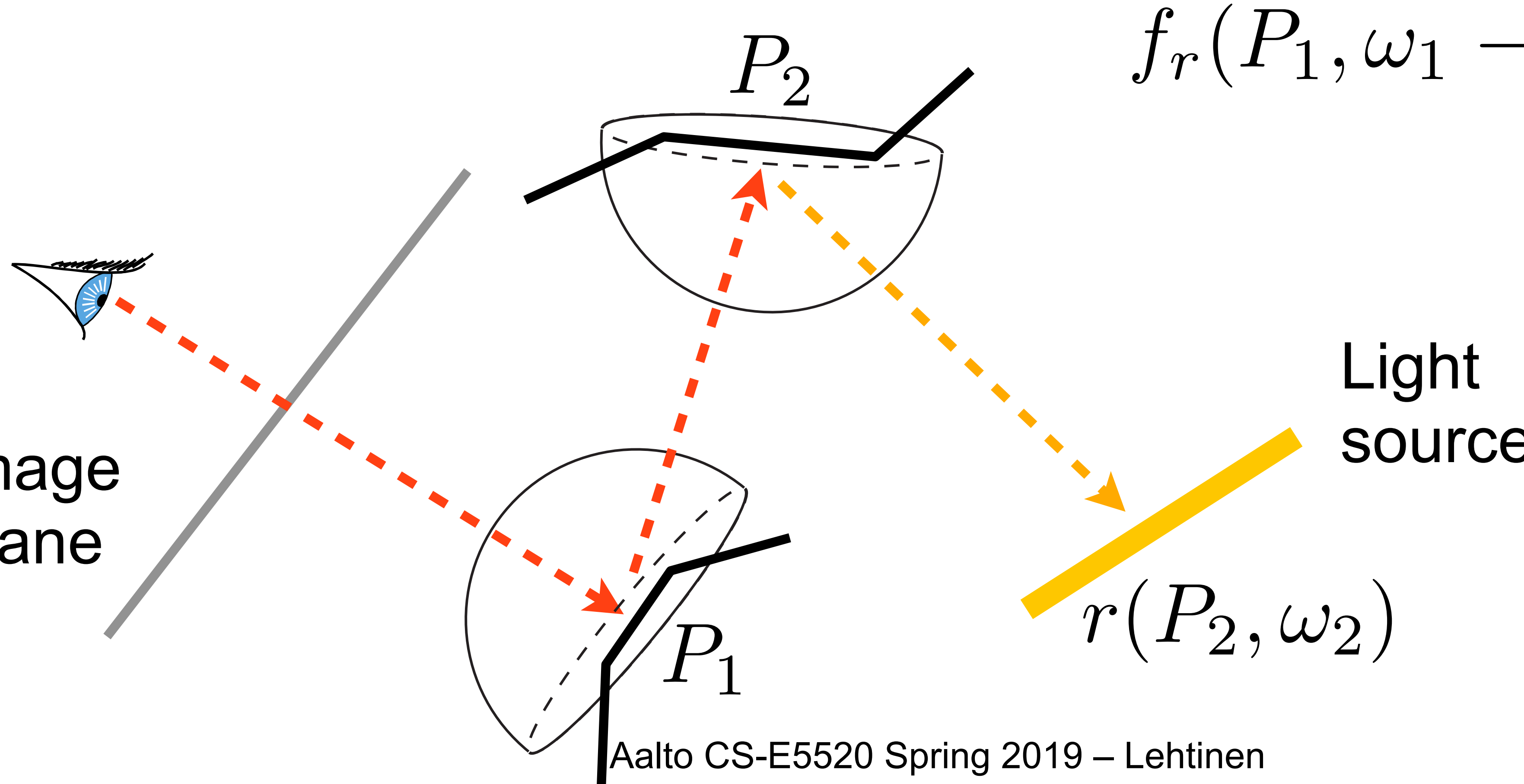
- Nested version (P_1, P_2 are ray hit points)



Example: 1 Indirect Bounce

- Nested version (P_1, P_2 are ray hit points)

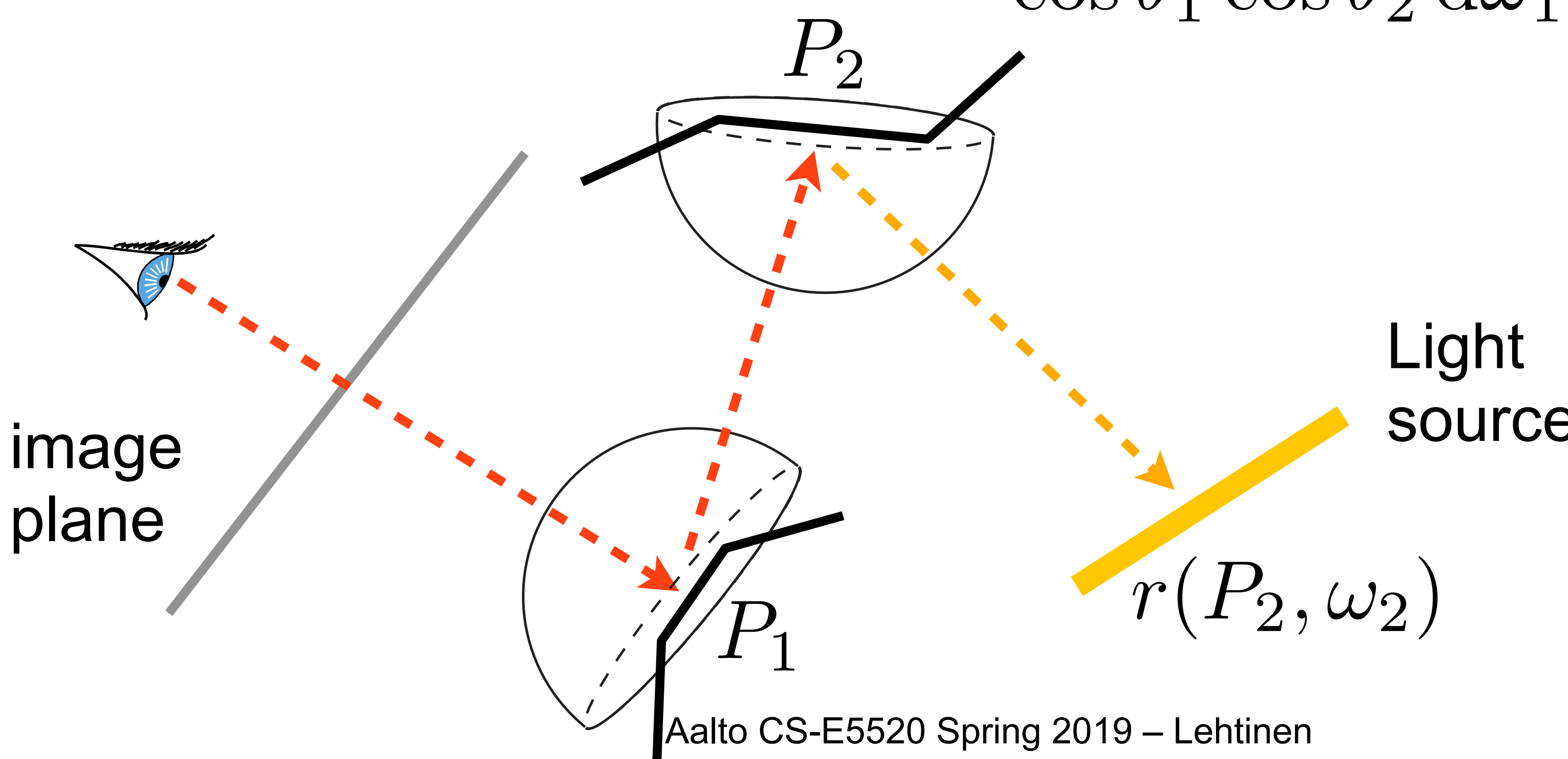
$$L_2(x,y) = \int_{\Omega(P_1)} \overbrace{\left[\int_{\Omega(P_2)} E(r(P_2,\omega_2) \to P_2) f_r(P_2, \omega_2 \to -\omega_1) \cos\theta_2 \mathrm{d}\omega_2\right]}^{L(P_1 \leftarrow \omega_1)} f_r(P_1, \omega_1 \to \mathrm{eye}) \cos\theta_1 \mathrm{d}\omega_1$$



Example: 1 Indirect Bounce

- Flat version, 4D integral

$$L_2(x,y) = \int_{\Omega(P_1)\times\Omega(P_2)} E(r(P_2,\omega_2) \to P_2) \times$$
$$f_r(P_2,\omega_2 \to -\omega_1) f_r(P_1,\omega_1 \to \text{eye}) \times$$
$$\cos\theta_1 \cos\theta_2 \, \mathrm{d}\omega_1 \mathrm{d}\omega_2$$



This really is just as simple as going from two nested 1D integrals to a 2D area integral!

Full Solution

- The full lighting solution is a sum over paths of all lengths

$$L(x,y) = \sum_{i=0}^{\infty} L_i(x,y), \qquad \text{with } L_0(x,y) = E(P_1 \leftarrow \text{eye})$$

- Notice how we've "unwrapped" the recursive rendering equation into a sum of terms
  - n bounce lighting is an integral over $\text{screen} \times \underbrace{\Omega \times \ldots \times \Omega}_{n \text{times}}$
  - This is really the same as directly evaluating the terms of the Neumann series E + TE + TTE + ...

Sampling Paths

- "Local path sampling" proceeds bounce to bounce, always importance sampling according to local BRDF
- That is, for each sample (path):
  - First sample screen (x, y), then trace ray
  - At primary hit, choose outgoing direction ω_1, trace ray
  - At secondary hit, choose outgoing direction ω_2
  - Apply local PDFs at each step.. justification below

- Denote the full path $\bar{x} = (x, y, \omega_1, \omega_2, \ldots)$
  - Then $p(\bar{x}) = p(x, y)\, p(\omega_1)\, p(\omega_2) \ldots$
  - (This assumes independent choices at each bounce)
  - Easy to implement

Brute Force Path Tracing, Eye Part

$$L(x \to \mathbf{v}) = \int_\Omega L(x \leftarrow \mathbf{l})\, f_r(x, \mathbf{l} \to \mathbf{v})\, \cos\theta \,\mathrm{d}\mathbf{l}$$

$$+\ E(x \to \mathbf{v})$$

```
for each pixel
 Lout = 0, w=0
 for i=1 to #samples
  generate xi,yi inside pixel with p(x,y)
  ray_i = generatecameraray(xi,yi)
  Lout += f(xi,yi) * trace(ray_i)/p(x,y)
  w += f(xi,yi)/p(x,y)
 endfor
 L(pixel) = Lout/w
endfor
```

(Assuming, for simplicity, that only one pixel filter is nonzero. Look back a few slides for full treatment.)

Brute Force Path Tracing

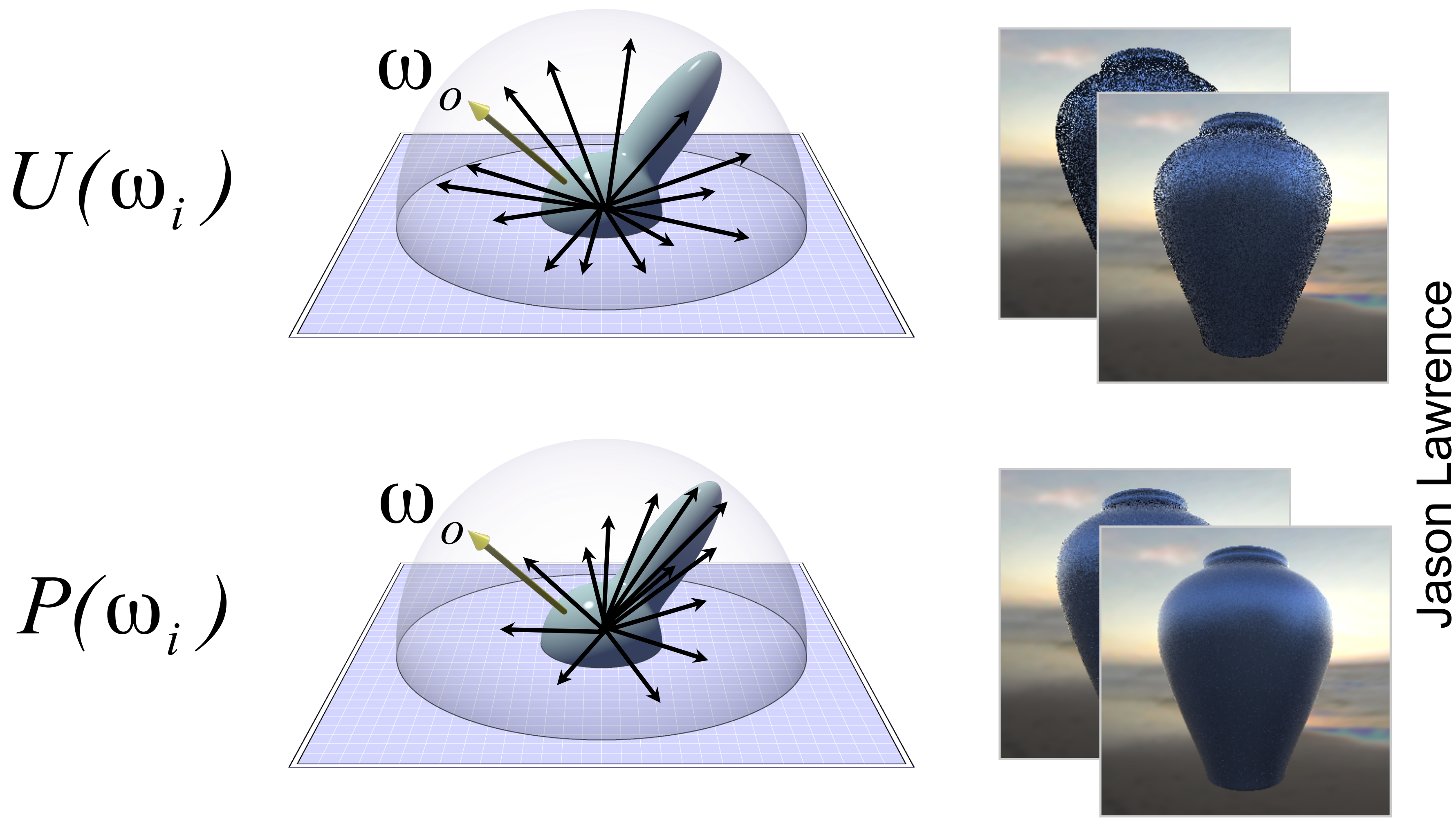
$$L(x \rightarrow \mathbf{v}) = \int_\Omega L(x \leftarrow \mathbf{l})\, f_r(x, \mathbf{l} \rightarrow \mathbf{v})\, \cos\theta \,\mathrm{d}\mathbf{l}$$

$$+ E(x \rightarrow \mathbf{v})$$

```
trace(ray)
 hit = intersect(scene, ray)
 result = emission(hit,-dir(ray))  // 0 if no light
 // sample outgoing direction
 [w,pdf] = sampleReflection(hit,dir(ray))
 // recursively estimate incoming radiance, apply BRDF
 result += BRDF(hit,-dir(ray),w)*
           cos(theta)*
           trace(ray(hit,w))/pdf
 return result
// when we apply the PDF like this, we are implicitly
// multiplying them for all bounces like shown before
```

Notes

- `sampleReflection()` chooses a direction with which to estimate reflectance integral for indirect part
  - I.e. importance sample according to BRDF

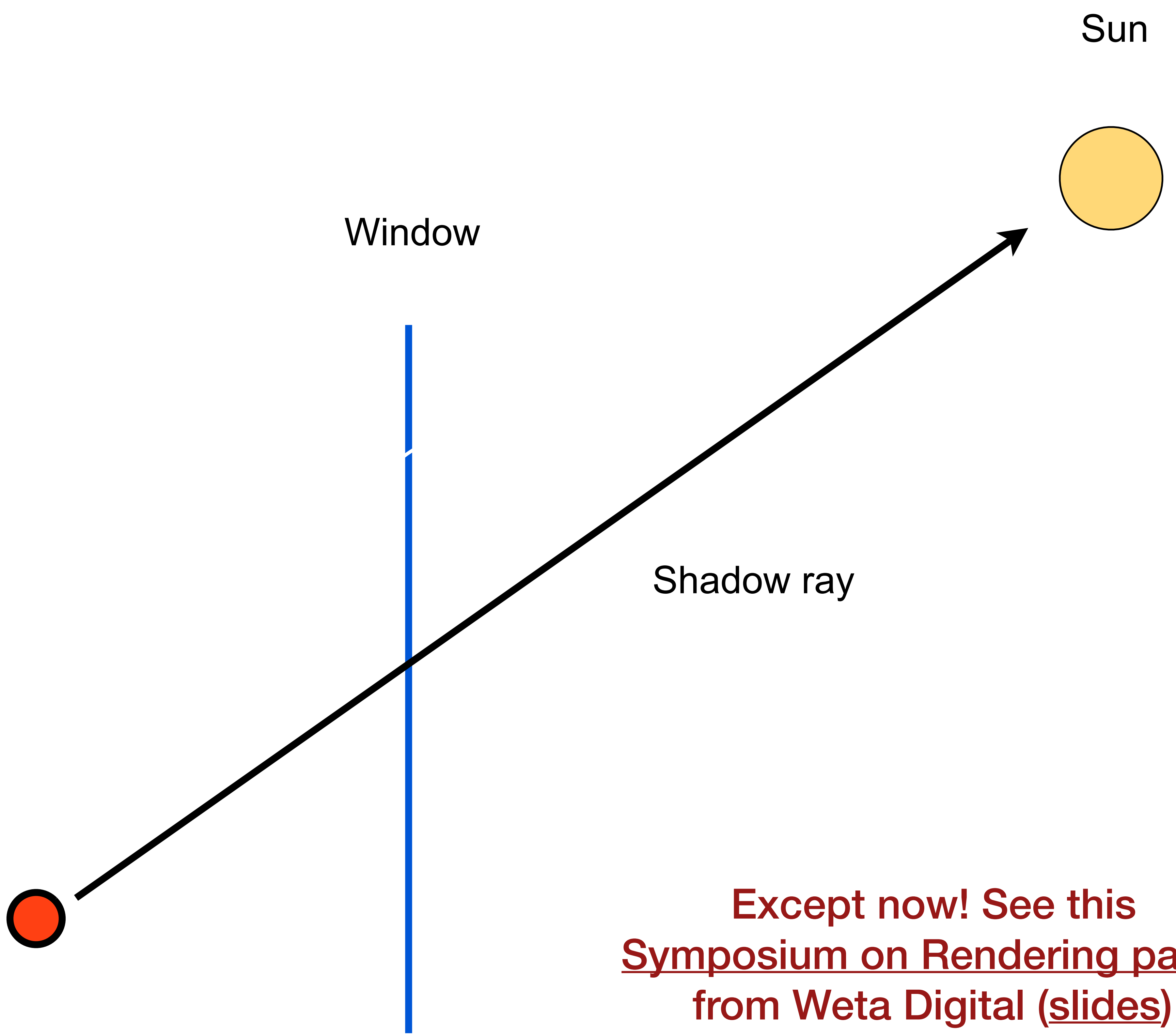


Why “Brute Force”?

- We’re waiting for the sampler to hit the light on its own
  - Often not a good idea
  - But sometimes we can’t do too much else
  - Think of an architectural model where all the light comes through several specular bounces through windows

- In simple cases we can help by adding an explicit direct light sampling step to each bounce

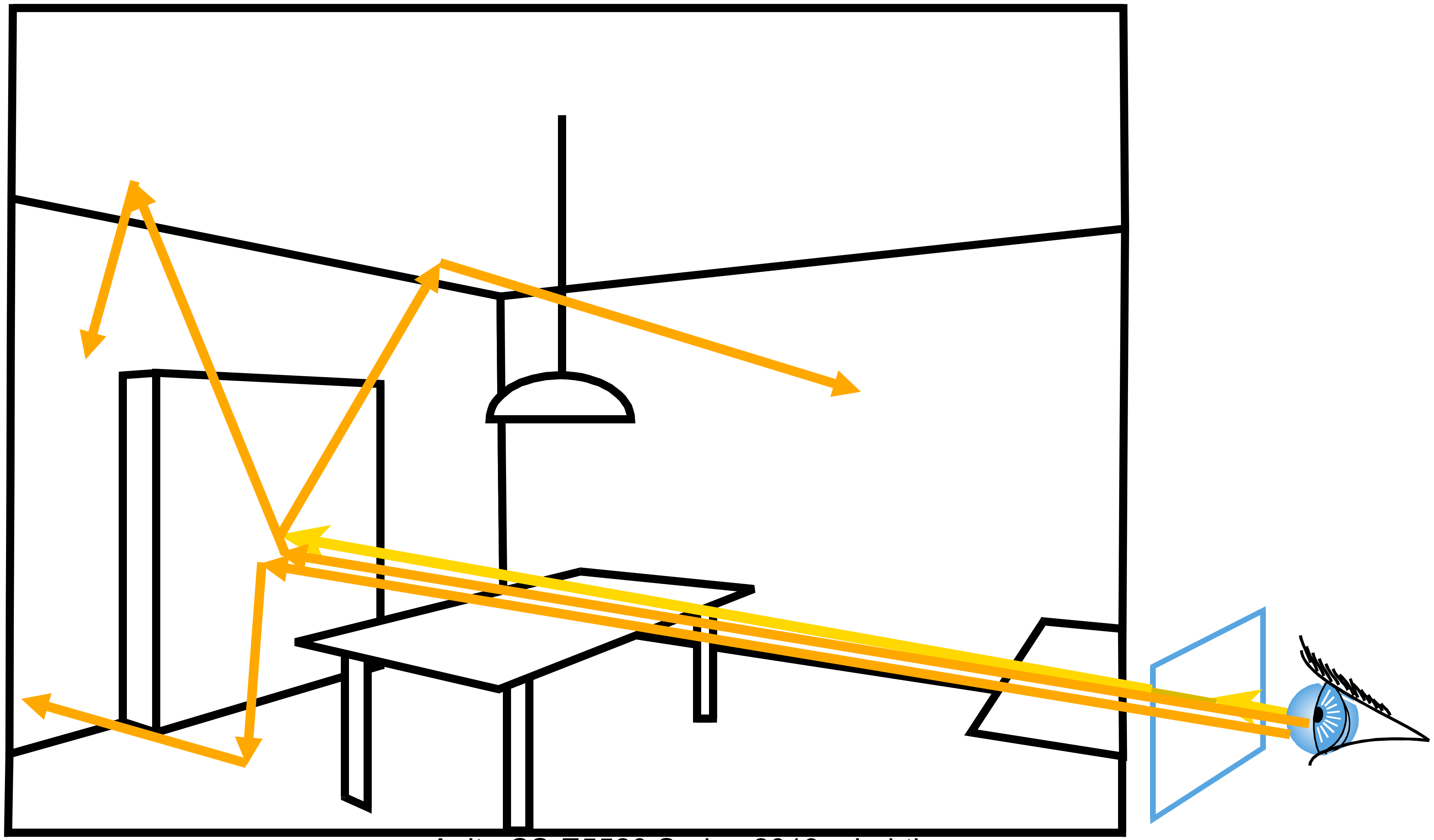
~~This Doesn't Work!~~



Except now! See this
Symposium on Rendering paper
from Weta Digital (slides)

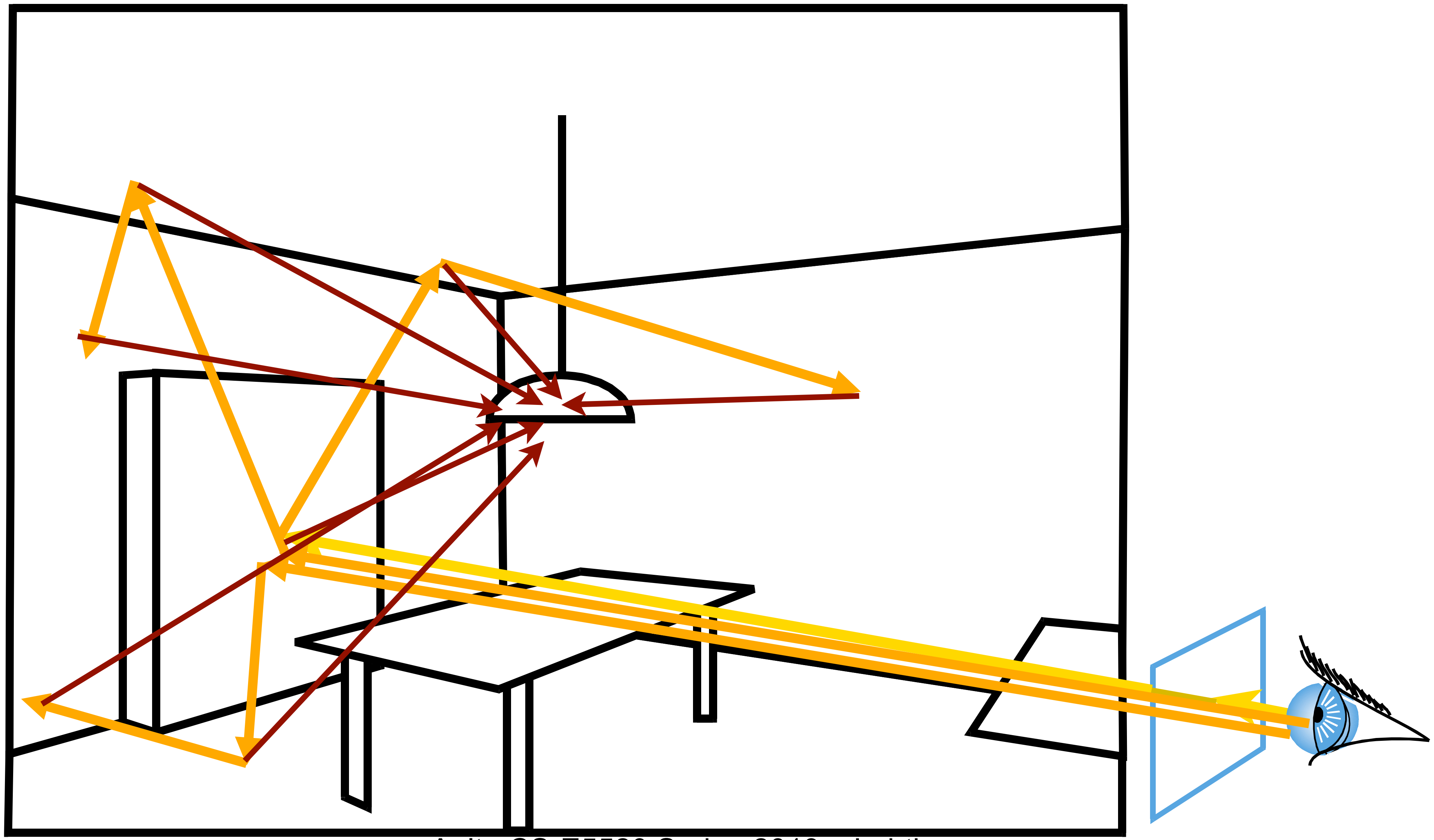
Brute Force Path Tracing

- Trace only one secondary ray per recursion
  - Otherwise number of rays explodes!
- But send many primary rays per pixel (antialiasing)



Path Tracing w/ Light Sampling

- At each hit, also sample a light and shoot a shadow ray
- The standard way of doing path tracing
- Also called “next event estimation”



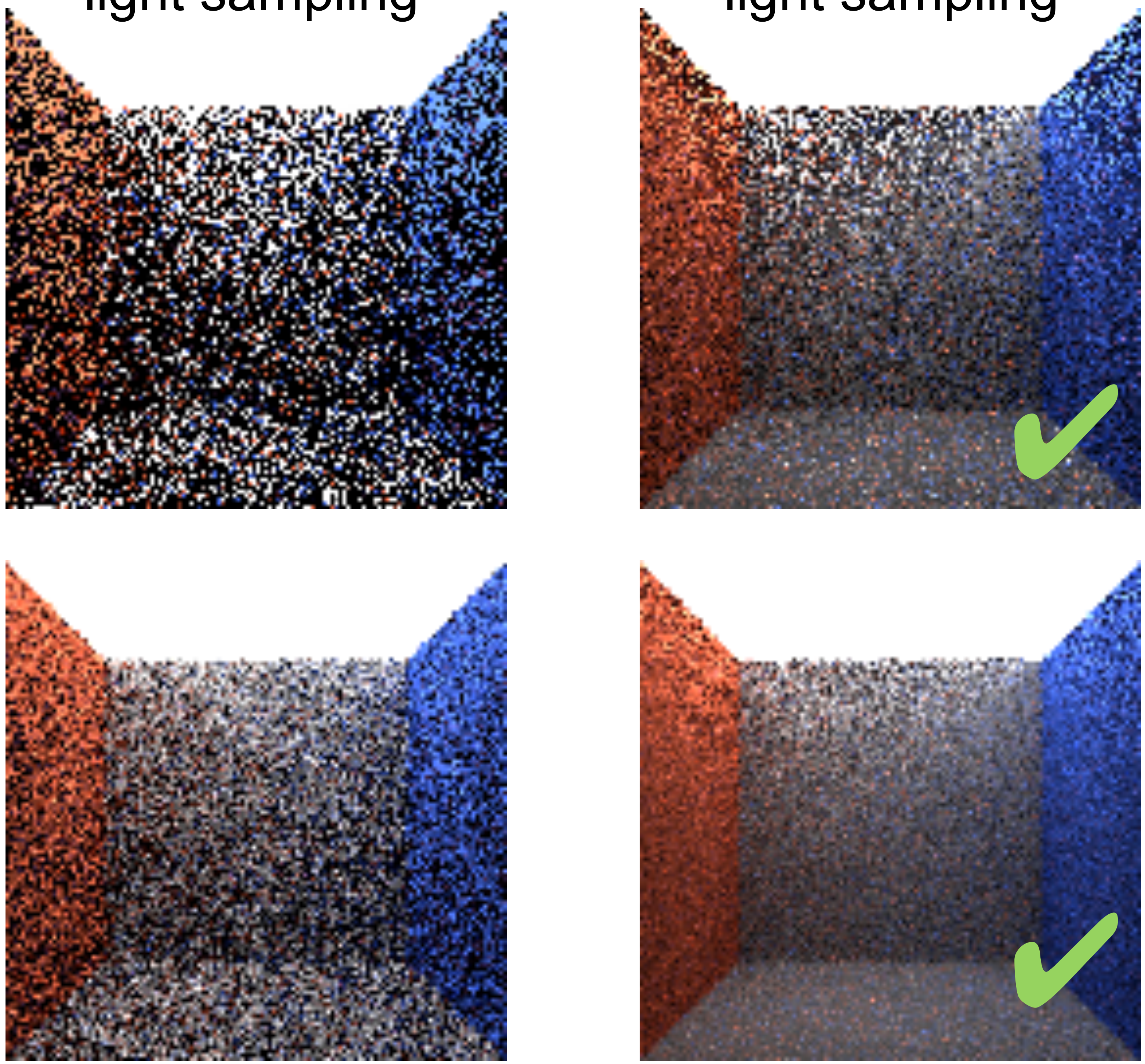
Importance of Sampling the Light

Without explicit light sampling

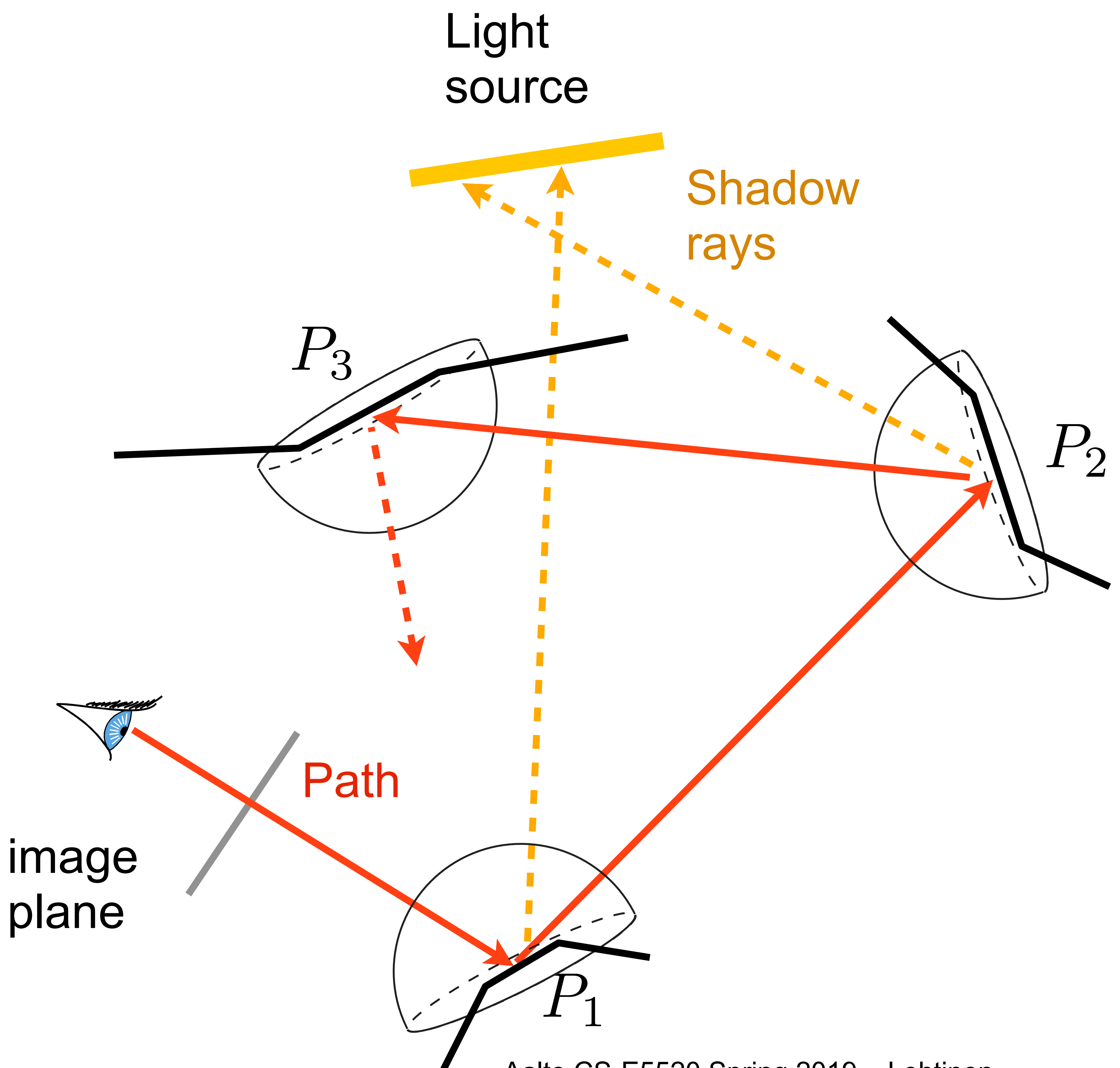
With explicit light sampling

1 path per pixel

4 paths per pixel



Path Tracing w/ Light Sampling



Interpretation of Shadow Rays

- Recall: the full lighting solution is a sum over paths of all lengths

$$L(x,y) = \sum_{i=0}^{\infty} L_i(x,y), \qquad \text{with } L_0(x,y) = E(P_1 \leftarrow \text{eye})$$

- Notice how we've "unwrapped" the recursive rendering equation into a sum of terms
  - n bounce lighting is an integral over $\text{screen} \times \underbrace{\Omega \times \ldots \times \Omega}_{n\text{times}}$ (brute force PT)
  - But now we've replaced the final hemisphere with lights by solid-angle-to-area conversion: $\text{screen} \times \omega \times \omega \ldots \times \text{lights}$

Path Tracing Pseudocode

$$L(x \rightarrow \mathbf{v}) = \int_{\Omega} L(x \leftarrow \mathbf{l})\, f_r(x, \mathbf{l} \rightarrow \mathbf{v})\, \cos\theta \,\mathrm{d}\mathbf{l}$$

$$+\ E(x \rightarrow \mathbf{v})$$

```
trace(ray)
 hit = intersect(scene, ray)
 if ray is from camera // only add “very direct” light here
  result = emission(hit,-dir(ray))
 [y,pdf1] = sampleLightsource()     // pick shadow ray dest.
 // G(hit,y) contains the usual cosine/r^2 of the
 // hemisphere-to-area variable change
 result += V(hit,y)*E(y,y->hit)*BRDF*cos*G(hit,y)/pdf1
 [w,pdf] = sampleReflection(hit,dir(ray)) // like before
 result += BRDF(hit,-dir(ray),w)*
           cos(theta)*
           trace(ray(hit,w))/pdf
 return result
```

Notes 2

- `sampleLightsource`() picks a point on the light source and evaluates its PDF
  - You're doing this in the first part of your radiosity assignment
  - ..and we saw this already on the first MC lecture
  - We're (again) applying the solid angle-to-area variable change (i.e. we're integrating over the surface of the light source)

- When you have multiple light sources, you pick *one* at random, and build this into the PDF
  - Simple: just multiply the light source $p(y)$ with the probability of picking that particular light source

Picking Lights

- It makes sense to importance sample the light you pick
- E.g. doesn’t make sense to sample dim, far-away lights as often as bright, nearby ones!

One Small Problem

One Small Problem

- Yes, it doesn't terminate if you just keep going
  - Fortunately, there's still something we can do!

Russian Roulette

- The usual MC estimate is $E\{\frac{f(x)}{p(x)}\}_p$
  - f/p is a random variable because x is a random variable

Russian Roulette

- The usual MC estimate is $E\{\frac{f(x)}{p(x)}\}_p$
  - *f*/*p* is a random variable because *x* is a random variable
- Let's multiply this by another specially constructed random variable R
  - R(x)=0 with probability $\alpha(x)$, and $R = 1/(1-\alpha)$ otherwise
  - Also assume α and *x* are uncorrelated (independent). Then:

$$E\{\frac{R \cdot f(x)}{p(x)}\} = E\{R\}\, E\{\frac{f(x)}{p(x)}\} = E\{\frac{f(x)}{p(x)}\}$$

This step requires independence

Russian Roulette: What is Going On?

- R(x)=0 with probability $\alpha(x)$, and $R = 1/\alpha$ otherwise

$$E\{\frac{R \cdot f(x)}{p(x)}\} = E\{R\}\, E\{\frac{f(x)}{p(x)}\} = E\{\frac{f(x)}{p(x)}\}$$

- *We've given ourselves permission to sometimes replace the value of the integrand with zero without introducing bias to the result*
  - When we don't set it to zero, we multiply the result by $1/\alpha$
- This means, for instance, that we can probabilistically terminate light paths without tracing them to infinity

Path Tracing w/ RR

$$L(x \to \mathbf{v}) = \int_\Omega L(x \leftarrow \mathbf{l})\, f_r(x, \mathbf{l} \to \mathbf{v})\, \cos\theta \, \mathrm{d}\mathbf{l}$$

$$+ \; E(x \to \mathbf{v})$$

```
trace(ray)
 hit = intersect(scene, ray)
 if ray is from camera // only add "very direct" light here
  result = emission(hit,-dir(ray))
 [y,pdf1] = sampleLightsource()     // pick shadow ray dest.
 result += E(y,y->hit)*BRDF*cos*G(hit,y)/pdf1
 [w,pdf] = sampleReflection(hit,dir(ray))
 // russian roulette with alpha=0.5
 terminate = uniformrandom() < 0.5
 if !terminate
  result += BRDF(hit,-dir(ray),w)*
            cos(theta)*
            trace(ray(hit,w))/pdf/0.5   // 1/0.5 =mult. by 2!
 return result
```

“Path Space”

- Earlier we wrote n-bounce lighting as a simultaneous integral over n hemispheres
- We can just as well integrate over surfaces instead
  - We just need to add in the geometry terms like before
    - $1/r^2$, visibility, the other cosine
- The space of paths of length n is then simply

$$\underbrace{S \times \ldots \times S}_{n \text{ times}}$$

  with S being the set of 2D surfaces of the scene
- See Eric Veach’s PhD

What Does It Look Like?

- Jacco Bikker's Brigade Real Time GPU Path Tracer (video)
  - Multiple GPUs + post processing for removing noise
  - A few years old already, but gets the point across

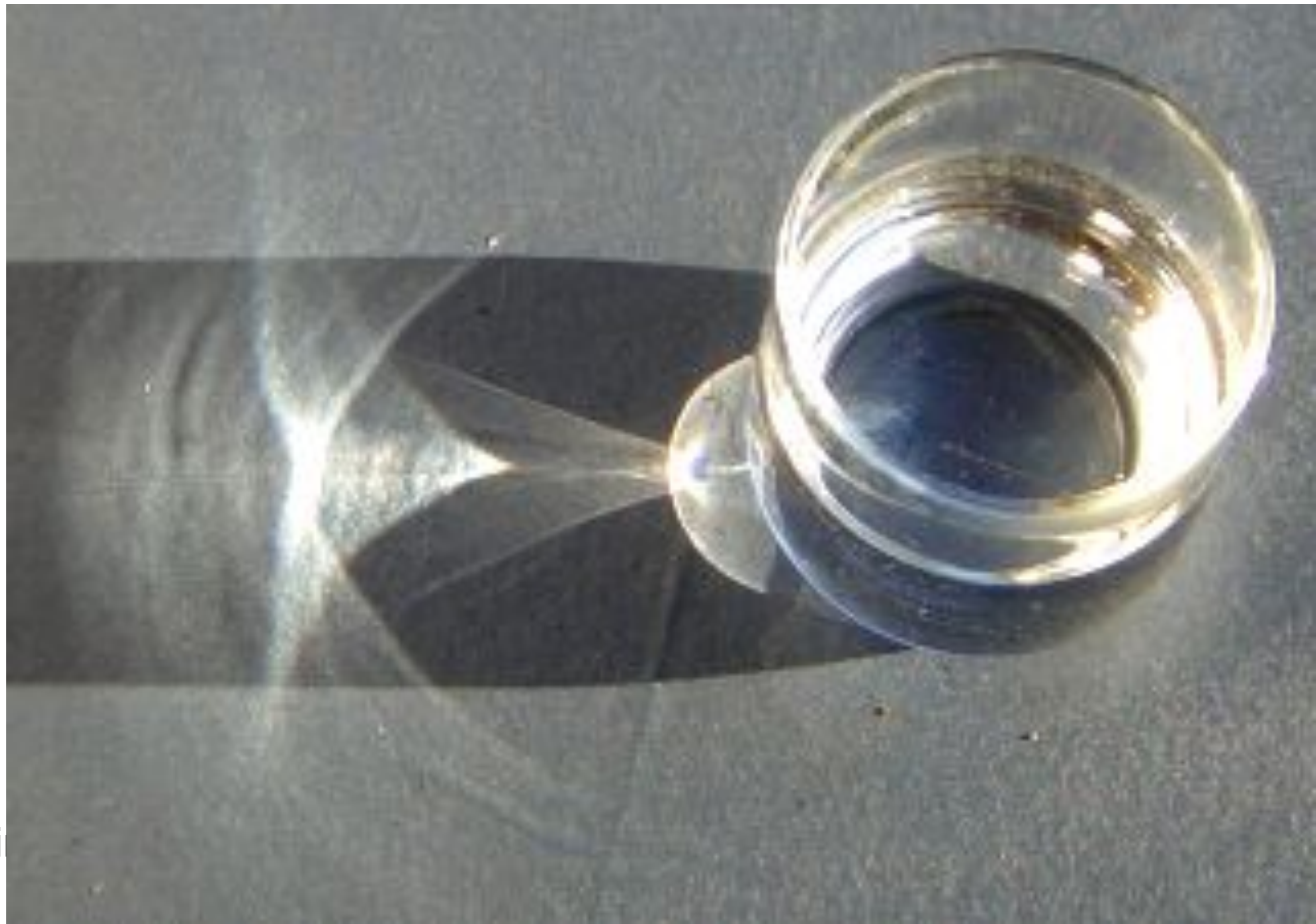
- See http://raytracey.blogspot.co.nz/2012/08/real-time-path-traced-brigade-demo-at.html

Bigger Picture

- We are shooting rays from the camera, propagating them along, and kind of hoping we will find light
  - Actively try to hit it by the light source samples

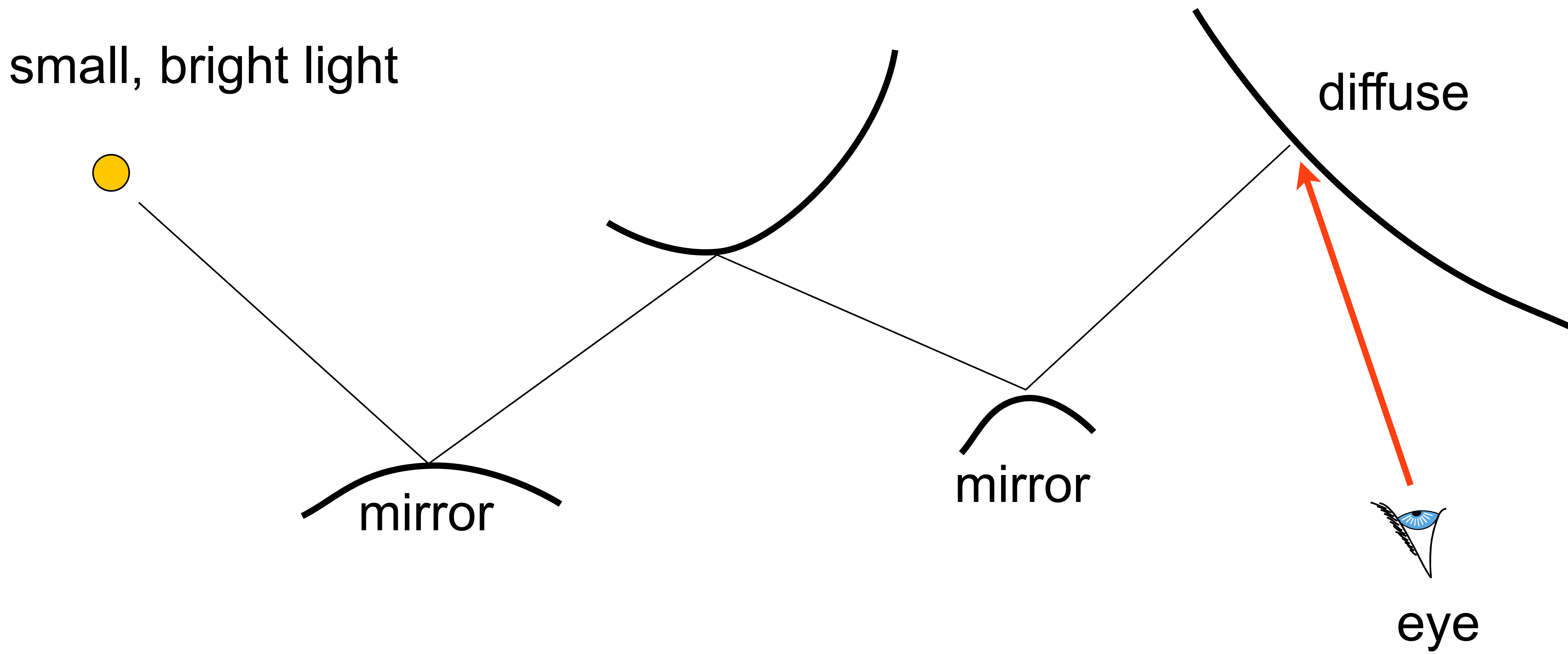
- What about more difficult cases?
  - In a *caustic*, the light propagates through a series of specular refractions and reflections before hitting a diffuse surface

wikipedia



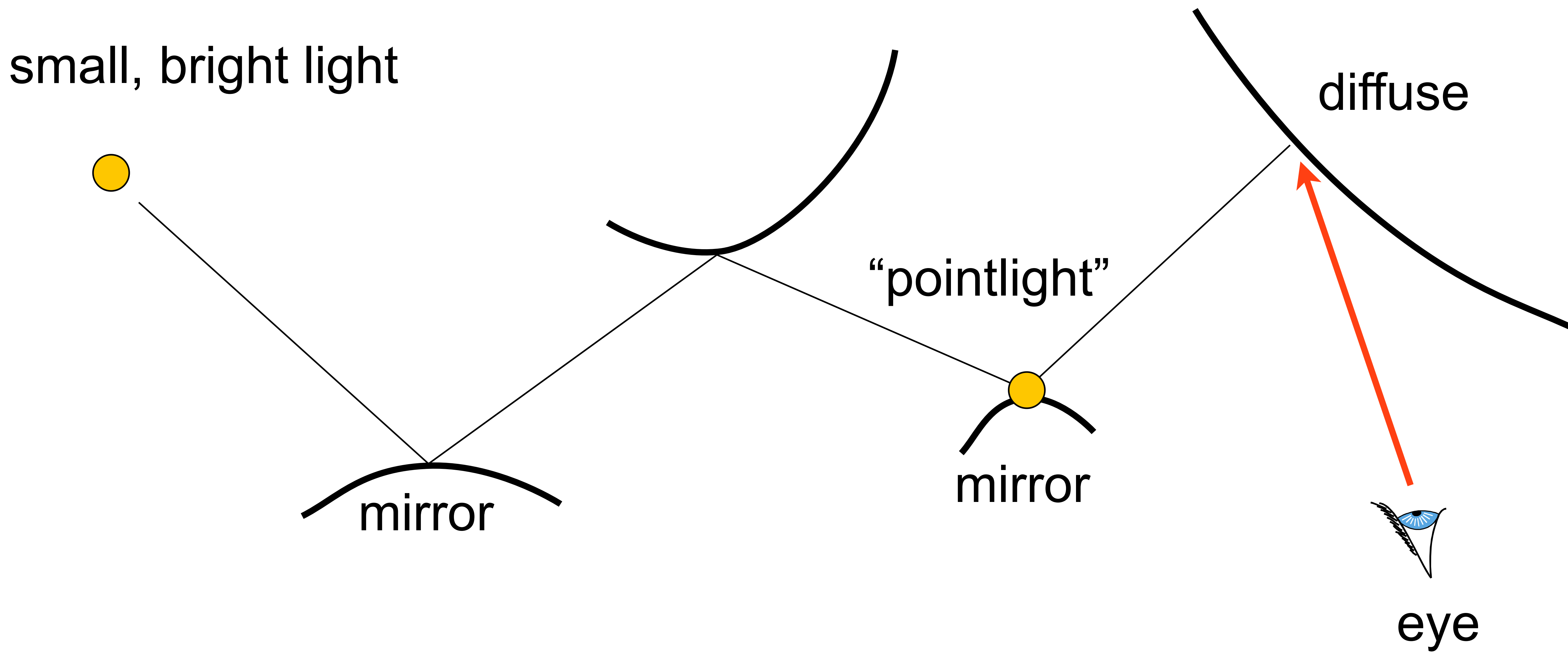
Problem With Caustics

- Think of an almost pointlike light shining through a sequence of curved mirrors onto a receiver



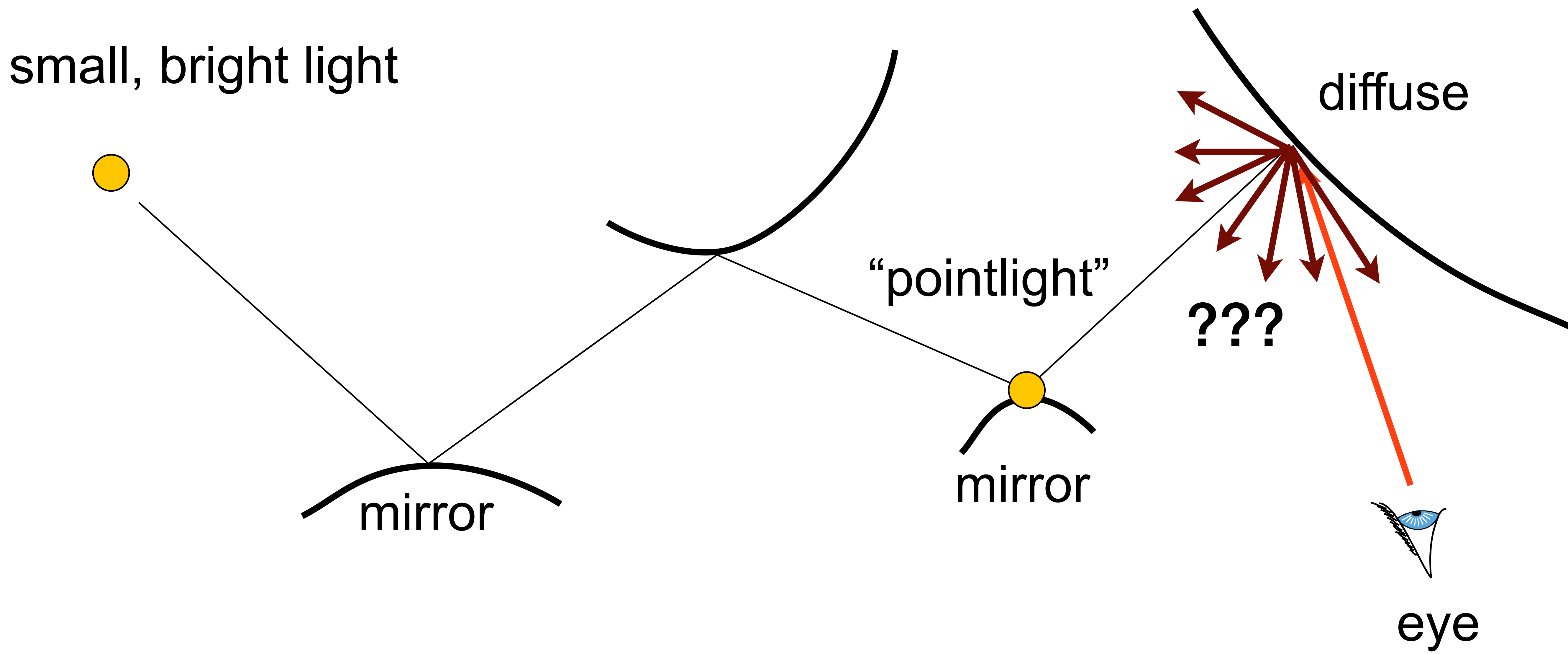
Problem With Caustics

- The point hit by the eye ray effectively sees a pointlight in the direction of the last mirror



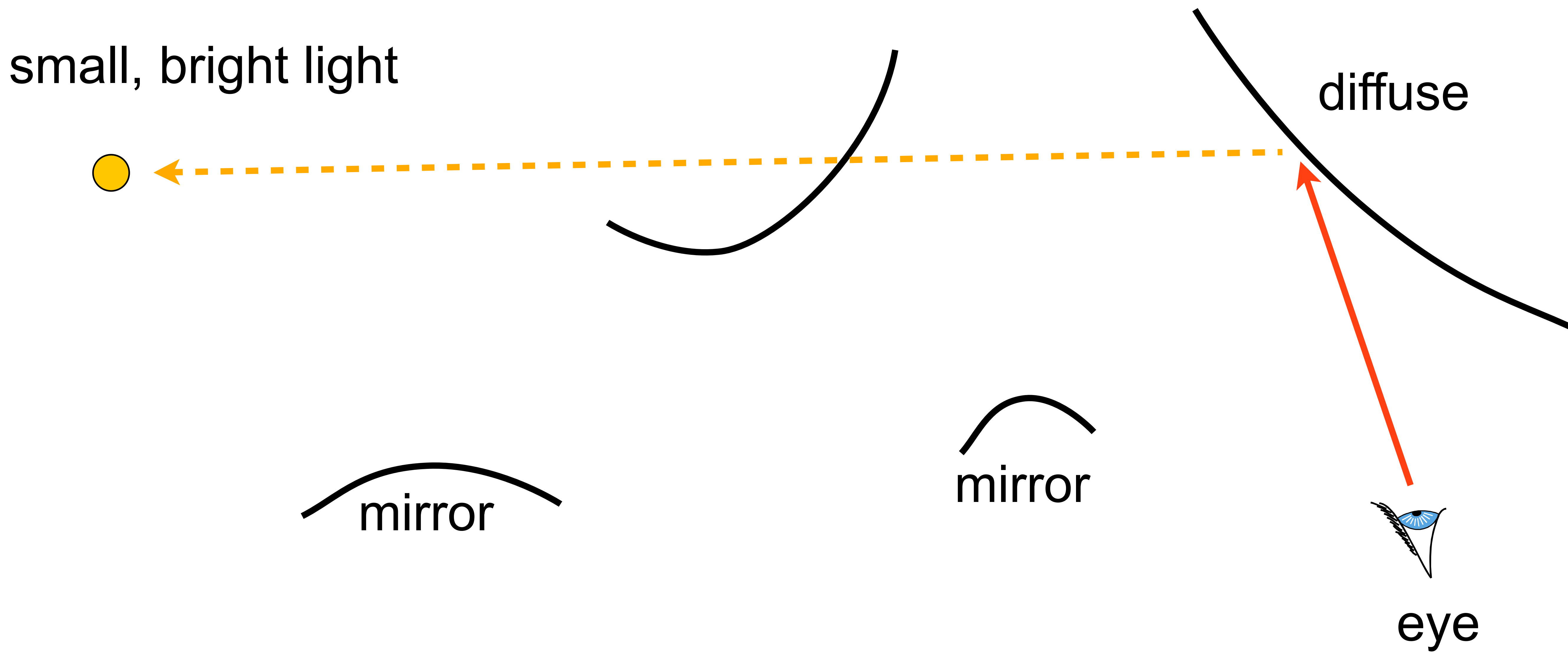
Problem With Caustics

- The point hit by the eye ray effectively sees a pointlight in the direction of the last mirror
  - How does the cosine importance sampler know that?



Problem With Caustics

- All we can do is shoot shadow rays towards the light
  - Not very helpful here!



Problem With Caustics

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To be continued…