Progressive Photon Mapping

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Gulfstream interior

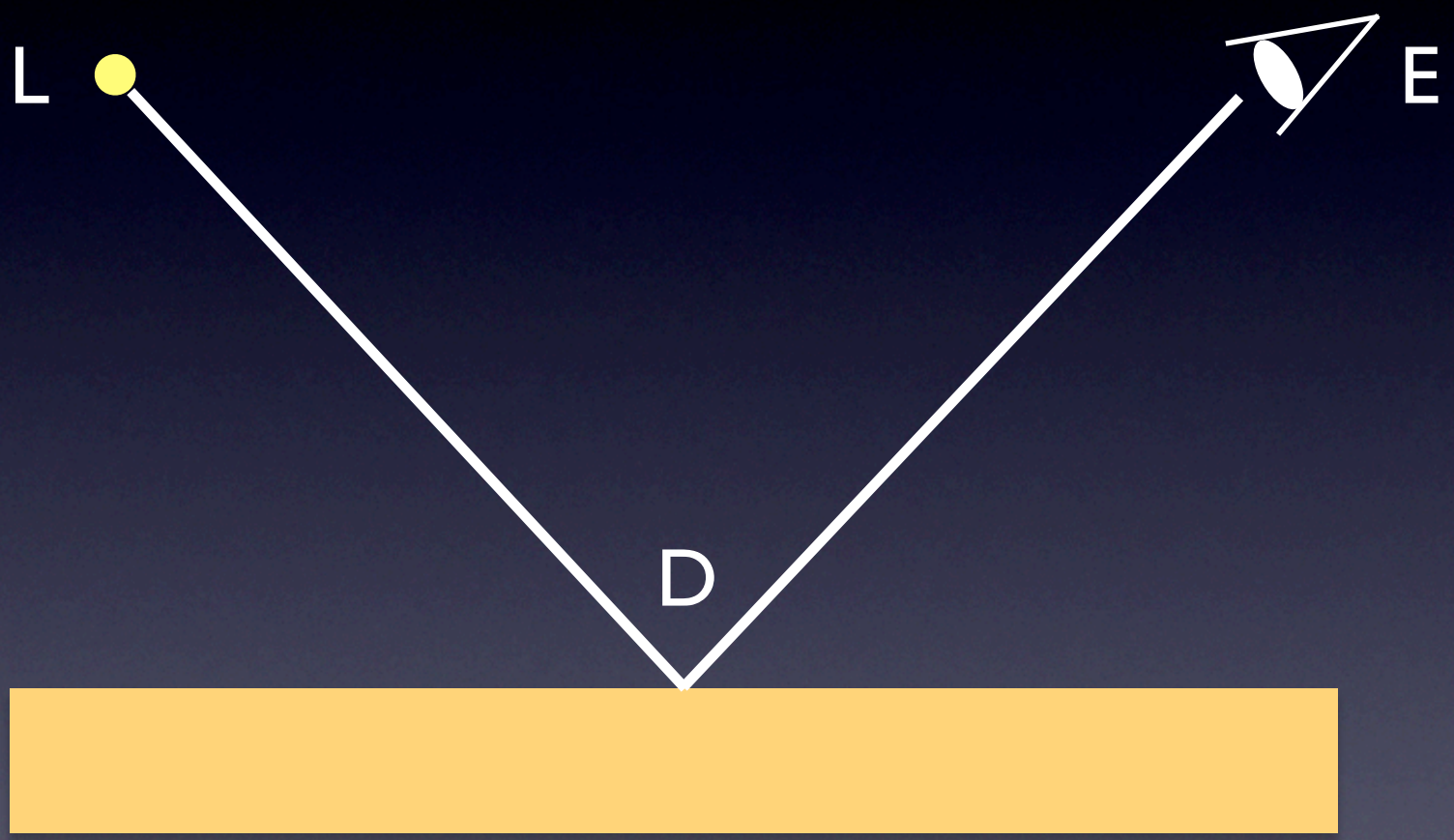
Global Illumination Algorithms

- Biased methods
  - Irradiance Caching [Ward 88]
  - Photon Mapping [Jensen 95]
  - Density Estimation [Shirley 95]
  - Instant Radiosity [Keller 97]
  - Lightcuts [Walter 05]

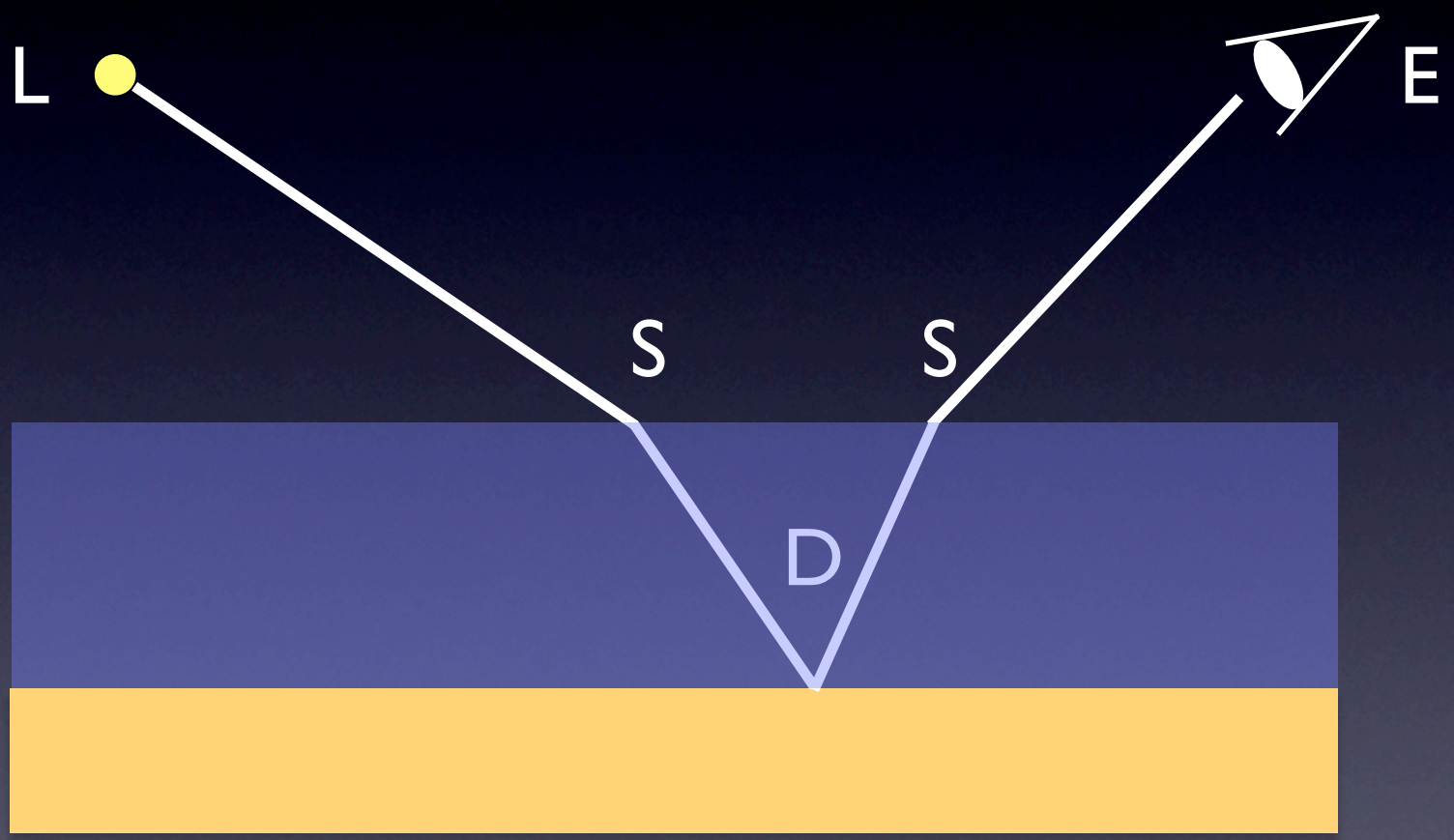
Global Illumination Algorithms

- Unbiased methods
  - Path Tracing [Kajiya 86]
  - Bidirectional Path Tracing [Lafortune 93][Veach 95]
  - Light Tracing [Dutré93]
  - Metropolis Light Transport [Veach 97]

LDE Path



LSDSE Path



Progressive Photon Mapping

First algorithm for computing *all* types of light transport with arbitrary accuracy

Progressive Photon Mapping

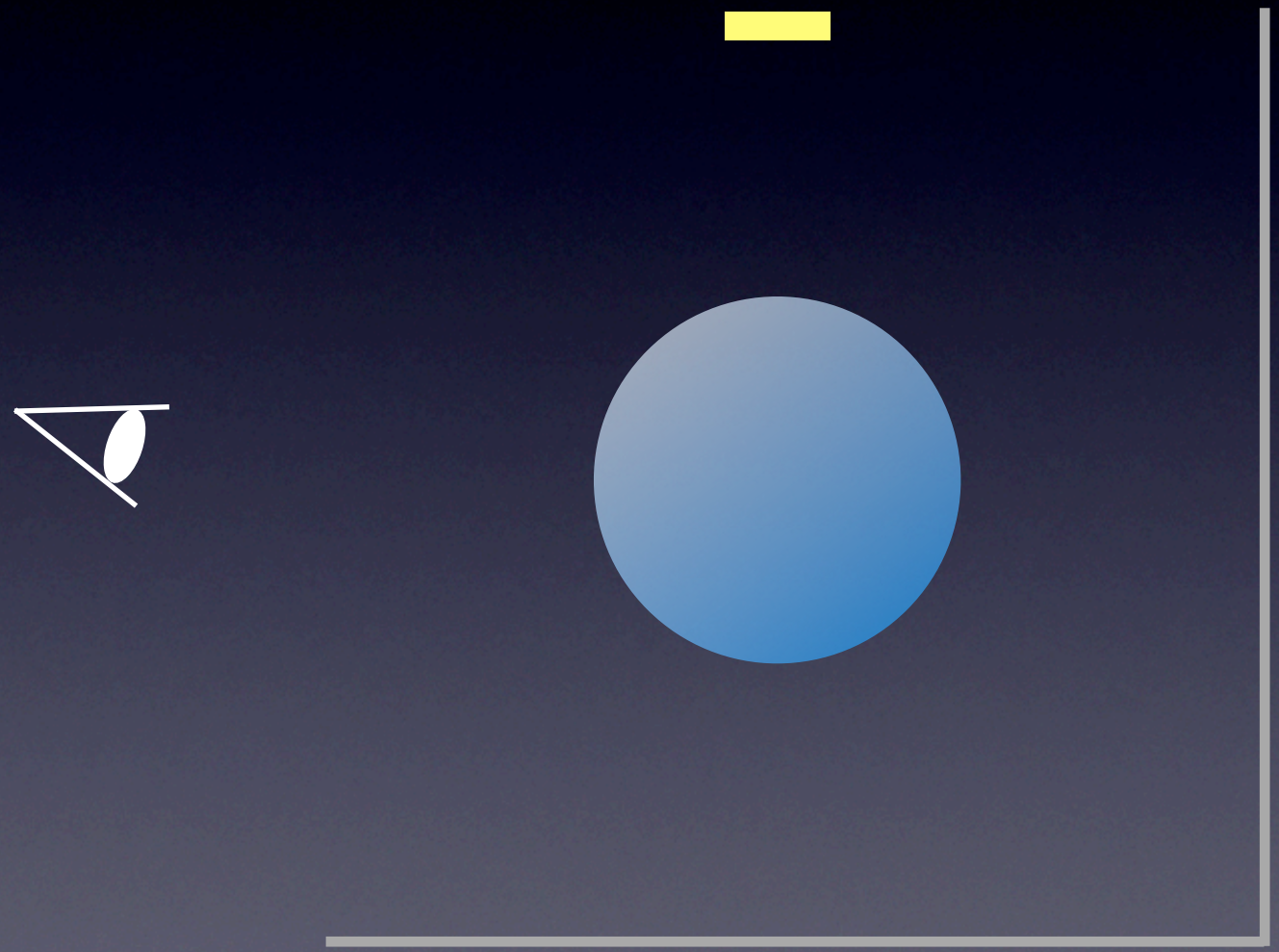
- New formulation of photon mapping
  - Robust for *any* light path including SDS path
  - Arbitrary accuracy using finite memory
  - New progressive radiance estimation algorithm
  - Easy to implement

Photon Mapping

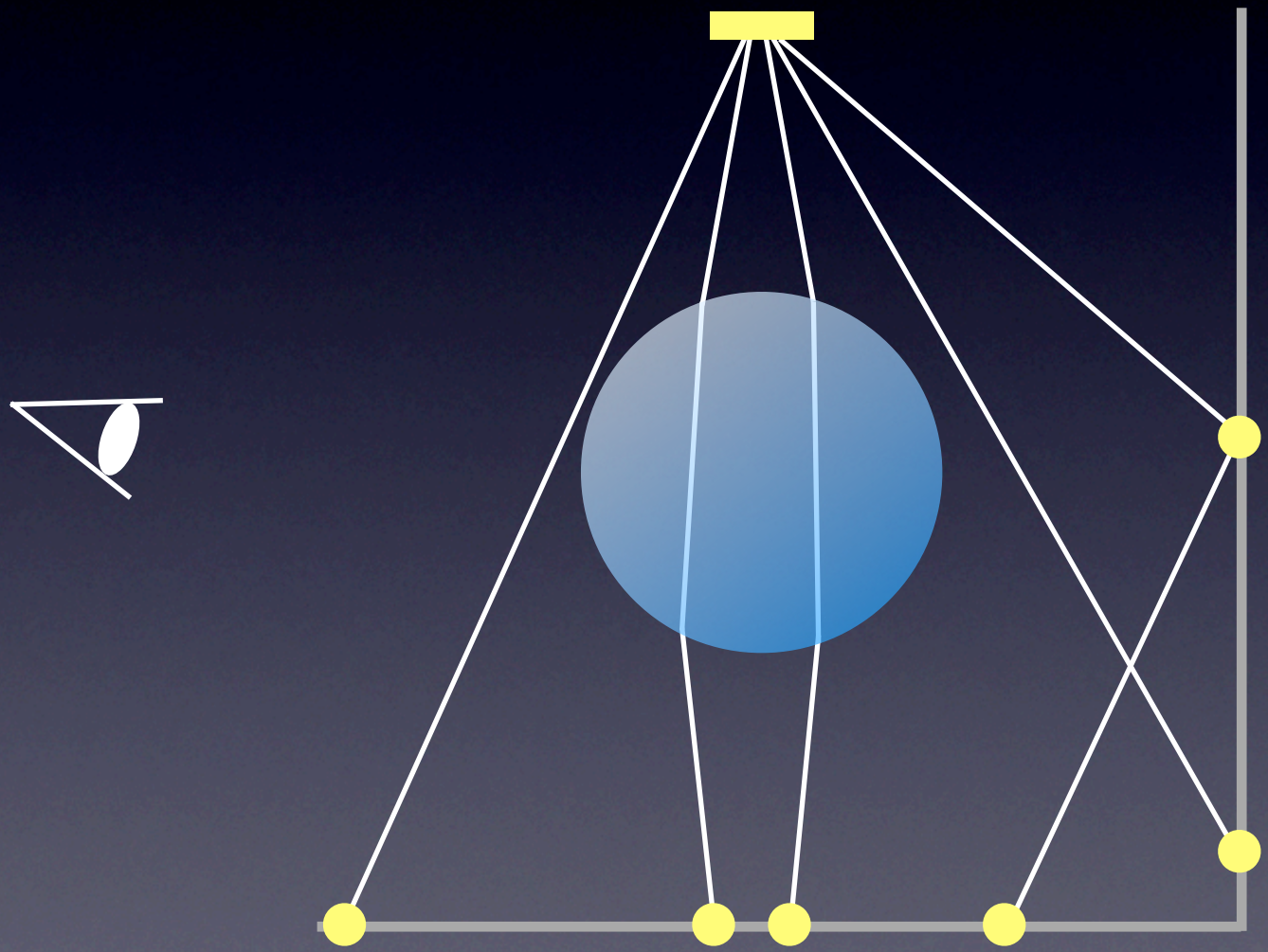
Photon Mapping

- 2 pass method
  - 1st pass: photon tracing
  - 2nd pass: rendering using the photon map

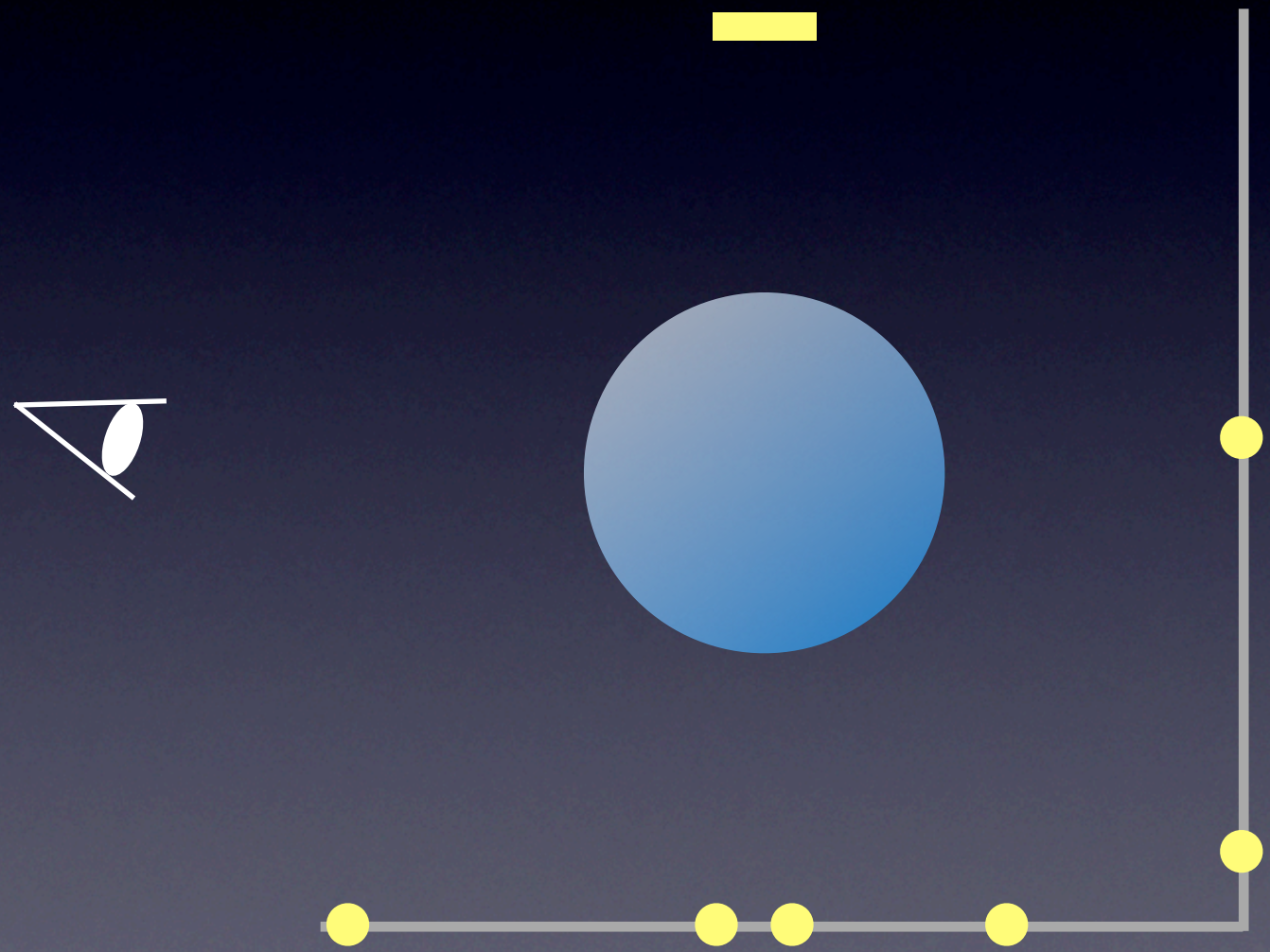
Photon Mapping - 1st Pass



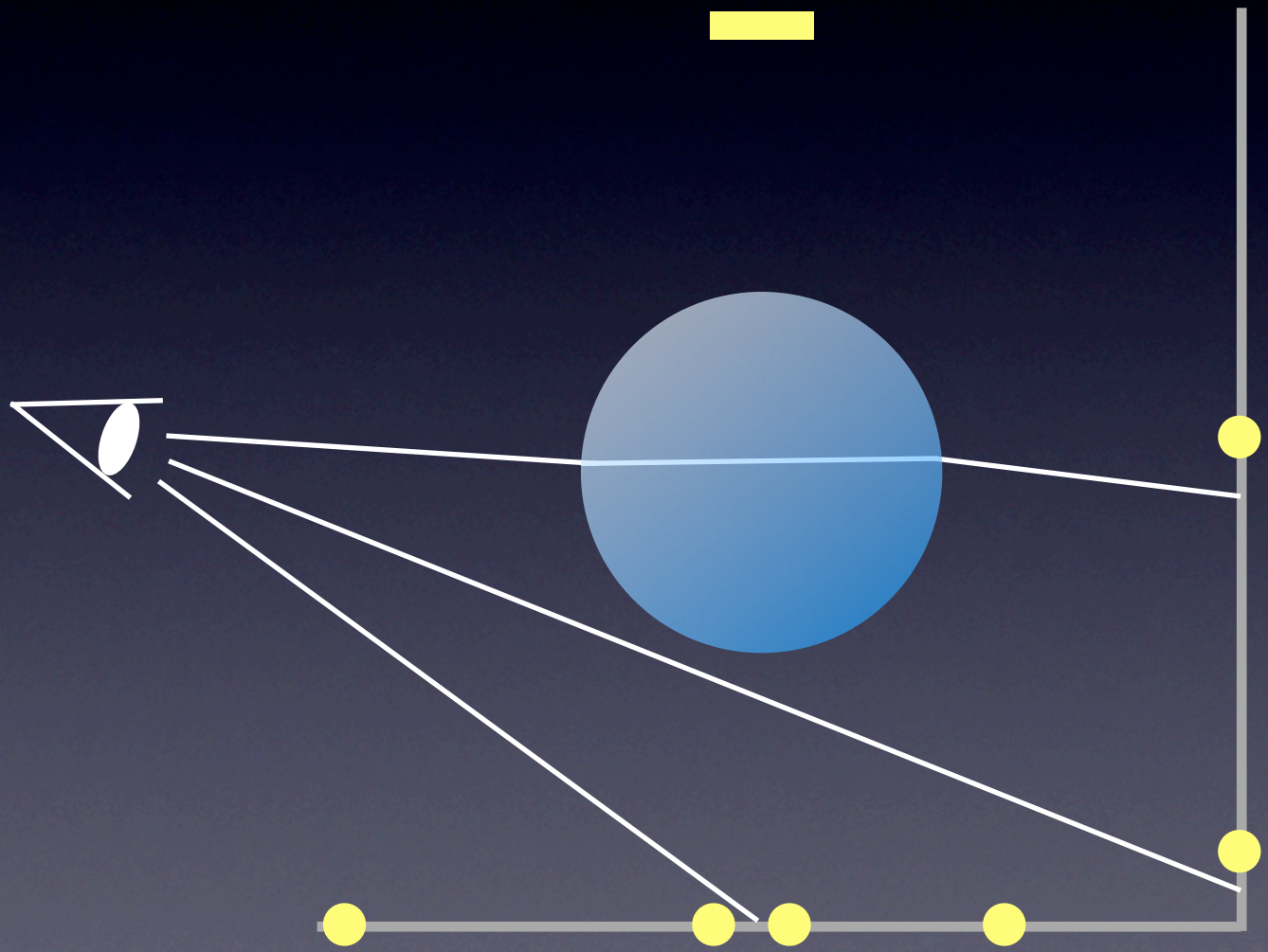
Photon Mapping - 1st Pass



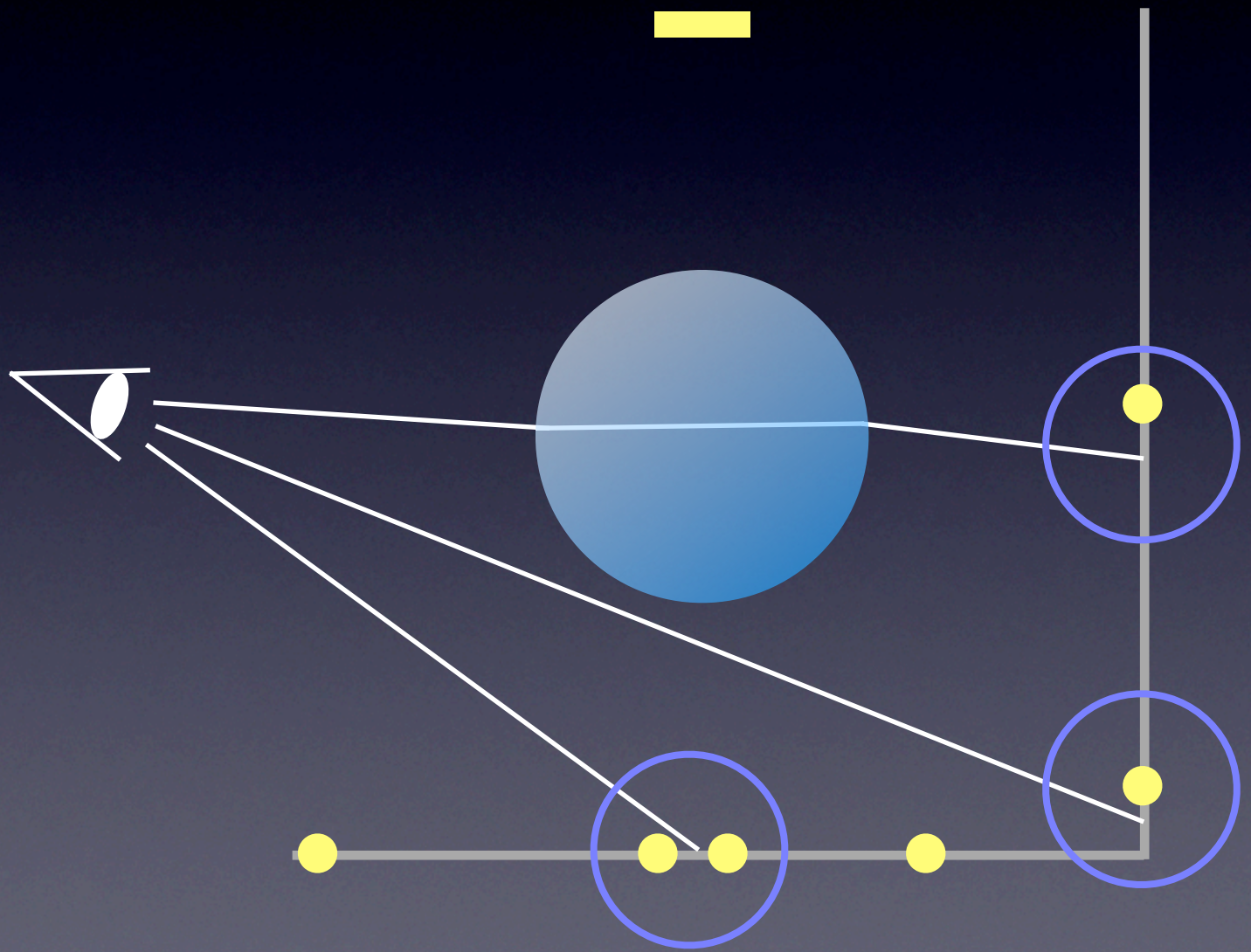
Photon Mapping - 2nd Pass



Photon Mapping - 2nd Pass



Photon Mapping - 2nd Pass



Radiance Estimate

$$L\left(x,\vec{\omega}\right) \approx \sum_{p=1}^{K} \frac{f_r\left(x,\vec{\omega},\vec{\omega}_p\right)\phi_p\left(x_p,\vec{\omega}_p\right)}{\pi r^2}$$

Convergence of Photon Mapping

10k photons 100k photons 1M photons 10M photons

Convergence of Photon Mapping

$$L\left(x,\vec{\omega}\right) = \lim_{K\to\infty, r\to 0} \sum_{p=1}^{K} \frac{f_r\left(x,\vec{\omega},\vec{\omega}_p\right)\phi_p\left(x_p,\vec{\omega}_p\right)}{\pi r^2}$$

- Converges to the correct solution with an infinite number of photons
- Requires infinite density of photons

Multiple Photon Maps

- Average images with different photon maps
- Combine results from several photon maps [Christensen 2004]

- Give a smoother but incorrect result that lacks fine-scale details

Progressive Photon Mapping

Progressive Photon Mapping

- Multi-pass method
  - Initial pass:
    points generation for radiance estimates
  - Refinement pass:
    - photon tracing
    - progressive radiance estimate

Key Idea

- Progressive radiance estimation
  - New density estimation algorithm
  - Converges to the correct value

Progressive Radiance Estimate

Progressive Radiance Estimate

$$\boxed{L_0\left(x,\vec{\omega}\right)} = \sum_{p=1}^{\boxed{N_0}} \frac{f_r\left(x,\vec{\omega},\vec{\omega}_p\right)\phi_p\left(x_p,\vec{\omega}_p\right)}{\pi\boxed{R_0^2}}$$

Progressive Radiance Estimate

$$\boxed{L_0\left(x,\vec{\omega}\right)} = \sum_{p=1}^{\boxed{N_0}} \frac{f_r\left(x,\vec{\omega},\vec{\omega}_p\right)\phi_p\left(x_p,\vec{\omega}_p\right)}{\pi\boxed{R_0^2}}$$

$$\boxed{L_1\left(x,\vec{\omega}\right)} = \sum_{p=1}^{\boxed{N_1}} \frac{f_r\left(x,\vec{\omega},\vec{\omega}_p\right)\phi_p\left(x_p,\vec{\omega}_p\right)}{\pi\boxed{R_1^2}}$$

Progressive Radiance Estimate

$$L_0(x,\vec{\omega}) = \sum_{p=1}^{N_0} \frac{f_r(x,\vec{\omega},\vec{\omega}_p)\,\phi_p(x_p,\vec{\omega}_p)}{\pi R_0^2}$$

$$L_1(x,\vec{\omega}) = \sum_{p=1}^{N_1} \frac{f_r(x,\vec{\omega},\vec{\omega}_p)\,\phi_p(x_p,\vec{\omega}_p)}{\pi R_1^2}$$

$$\vdots$$

$$L_i(x,\vec{\omega}) = \sum_{p=1}^{N_i} \frac{f_r(x,\vec{\omega},\vec{\omega}_p)\,\phi_p(x_p,\vec{\omega}_p)}{\pi R_i^2}$$

$$\vdots$$

Progressive Radiance Estimate

$$L_i\left(x,\vec{\omega}\right)=\sum_{p=1}^{N_i}\frac{f_r\left(x,\vec{\omega},\vec{\omega}_p\right)\phi_p\left(x_p,\vec{\omega}_p\right)}{\pi R_i^2}$$

$$\lim_{i\to\infty} L_i\left(x,\vec{\omega}\right)=L\left(x,\vec{\omega}\right)$$

$$R_{i+1}<R_i$$

$$N_{i+1}>N_i$$

Progressive Radiance Estimate

- Assume the density of photons is uniform within the disc

$$\frac{N_i + M_i}{\pi {R_i}^2} = \frac{N_{i+1}}{\pi {R_{i+1}}^2}$$

Progressive Radiance Estimate

- Keep a fraction α of newly added photons M_i

$$\frac{N_i + M_i}{\pi {R_i}^2} = \frac{N_{i+1}}{\pi {R_{i+1}}^2}$$

$$\boxed{N_{i+1} = N_i + \alpha M_i}$$

Progressive Radiance Estimate

- Solve the quadratic equation for R_{i+1}

$$\frac{N_i + M_i}{\pi {R_i}^2} = \frac{N_{i+1}}{\pi {R_{i+1}}^2}$$

$$N_{i+1} = N_i + \alpha M_i$$

$$\frac{N_i + M_i}{\pi {R_i}^2} = \frac{N_i + \alpha M_i}{\pi {R_{i+1}}^2}$$

Progressive Radiance Estimate

- Solve the quadratic equation for R_{i+1}

$$\frac{N_i + M_i}{\pi {R_i}^2} = \frac{N_{i+1}}{\pi {R_{i+1}}^2}$$

$$N_{i+1} = N_i + \alpha M_i$$

$$R_{i+1} = R_i \sqrt{\frac{N_i + \alpha M_i}{N_i + M_i}}$$

Progressive Radiance Estimate

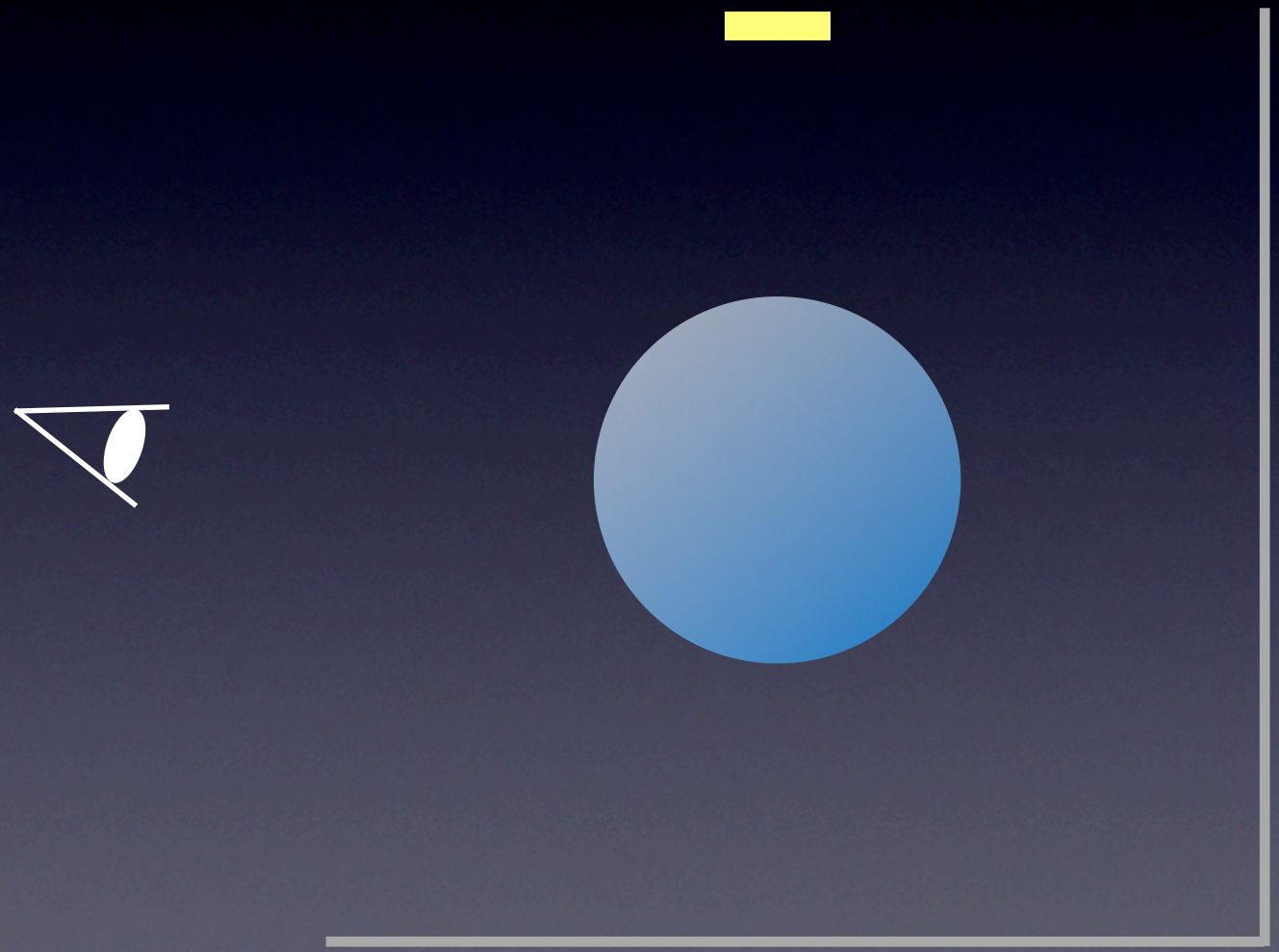
number of photons $N_{i+1} = N_i + \alpha M_i$

radius $R_{i+1} = R_i \sqrt{\frac{N_i + \alpha M_i}{N_i + M_i}}$

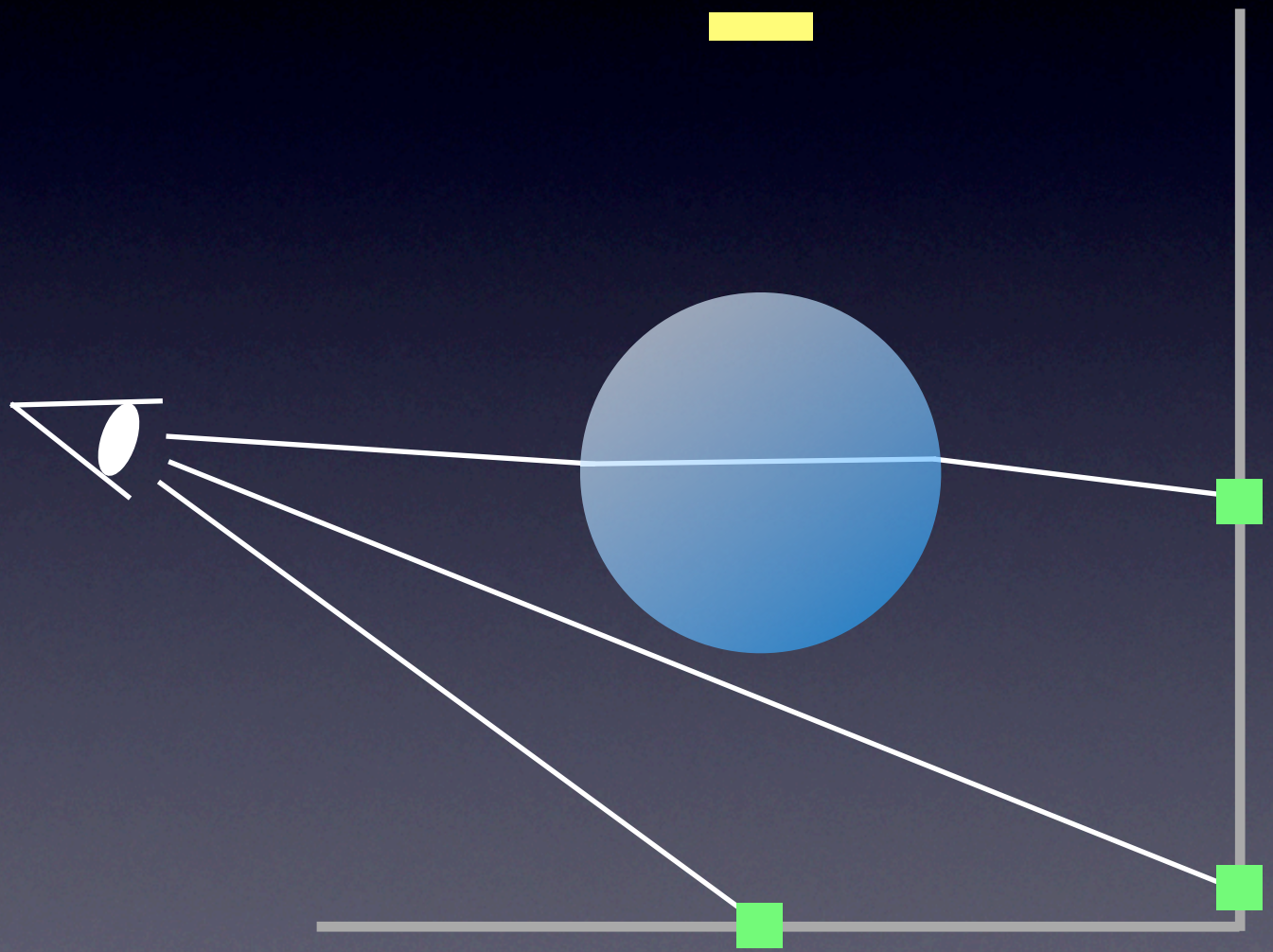
accumulated flux $\tau_{i+1} = \tau_i \frac{N_i + \alpha M_i}{N_i + M_i}$

radiance $L_i = \frac{\tau_i}{\pi {R_i}^2} = \frac{\sum_{p=1}^{N_i} f_r \phi_p}{\pi {R_i}^2}$

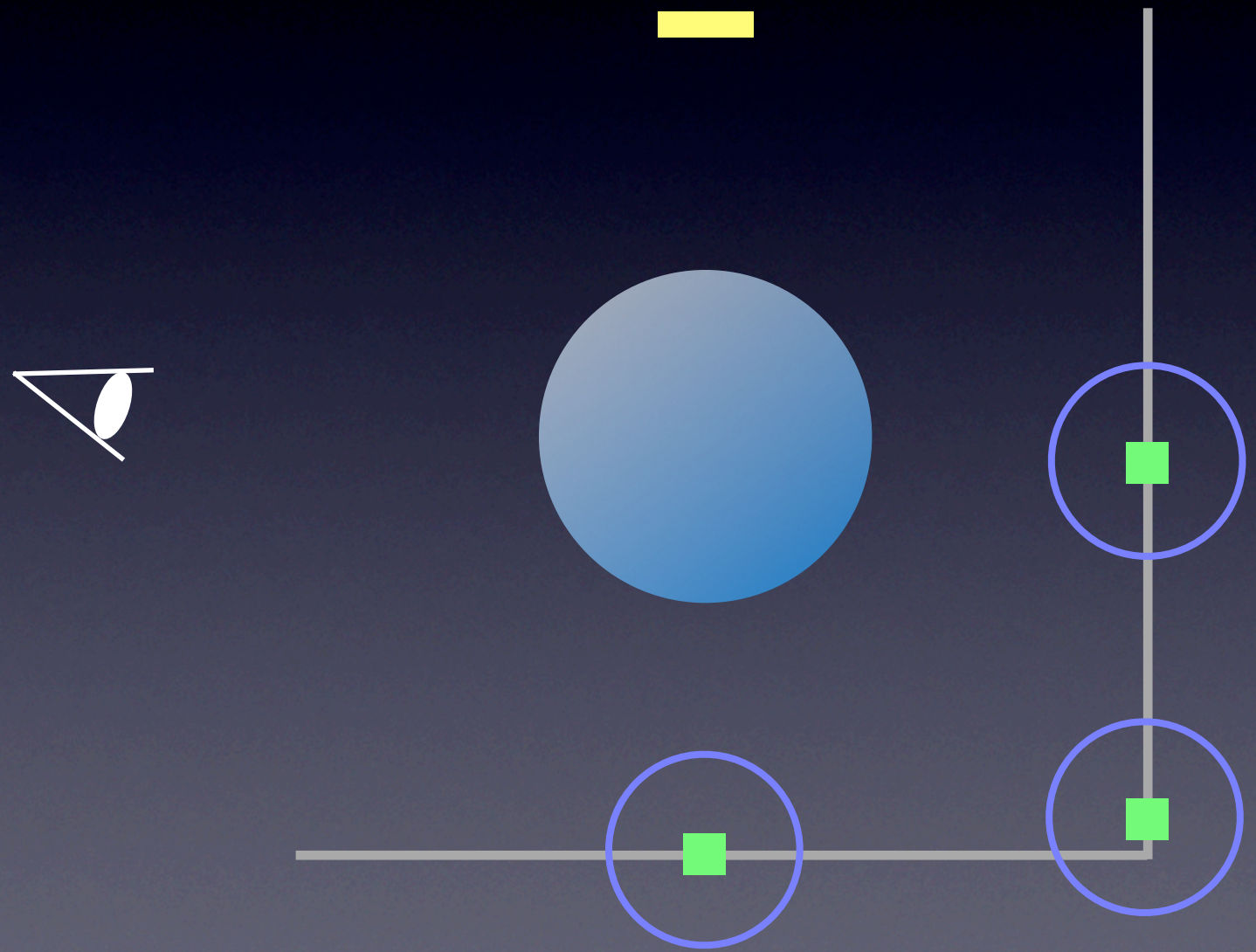
Progressive Photon Mapping - Initial Pass



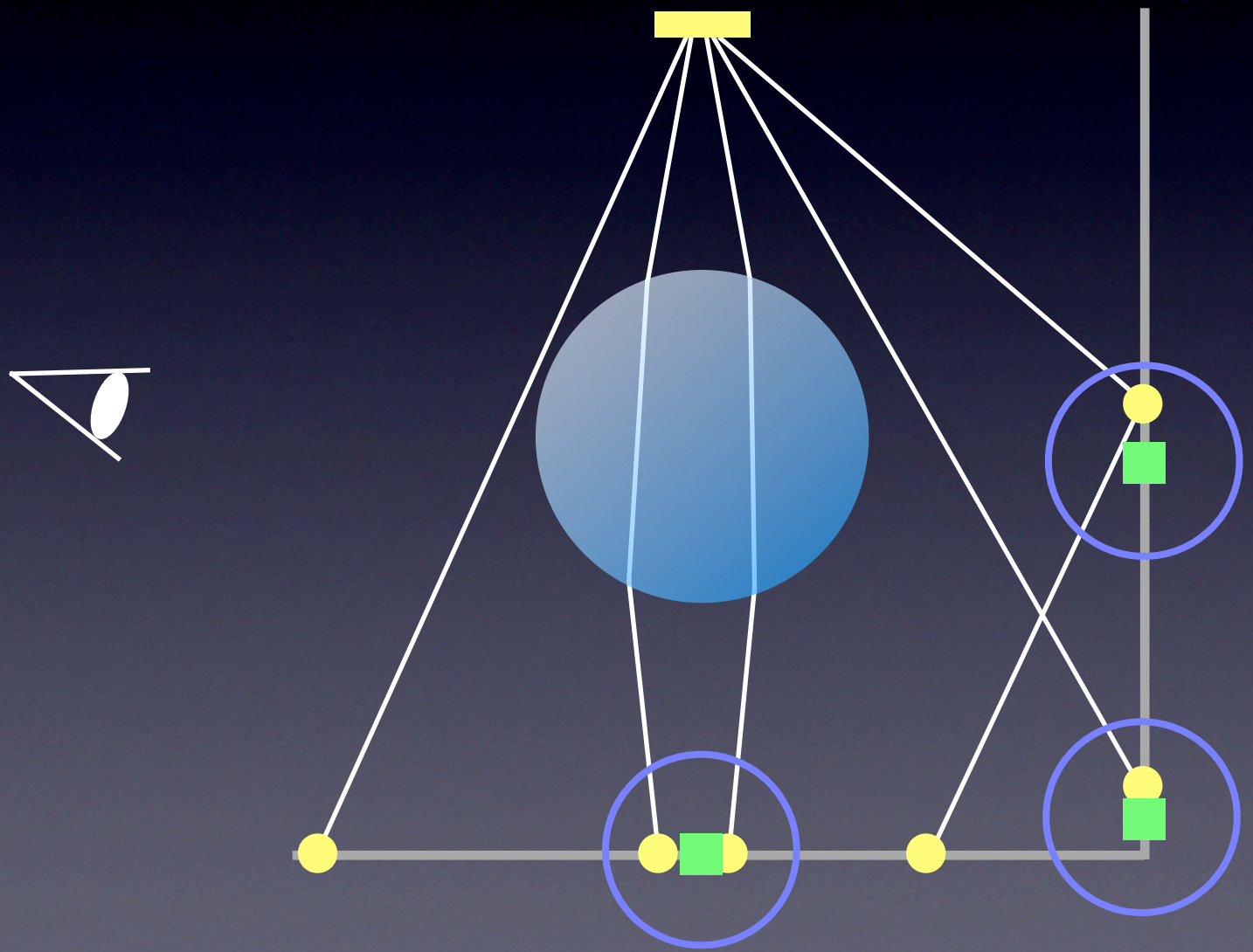
Progressive Photon Mapping - Initial Pass



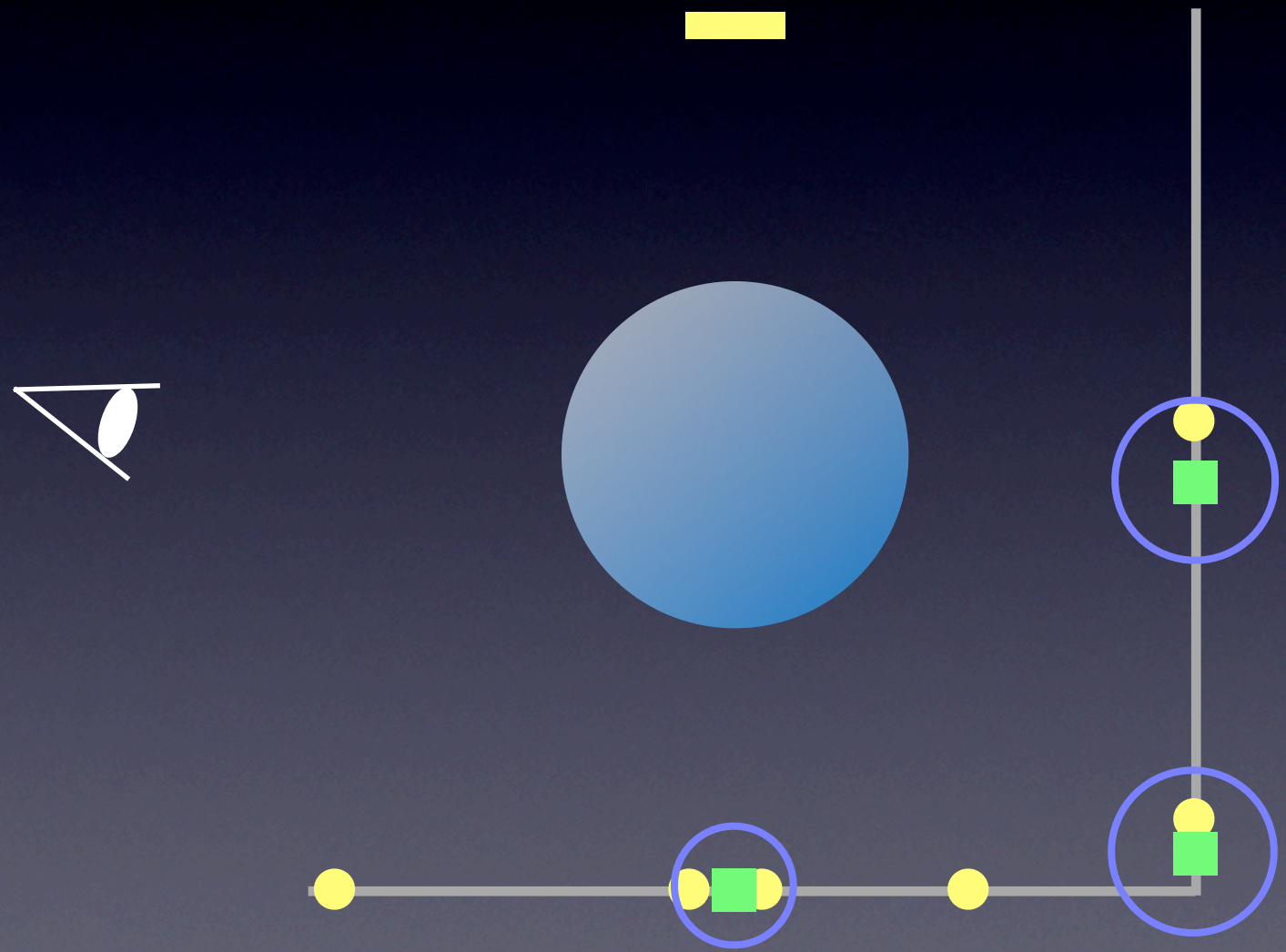
Progressive Photon Mapping - Initial Pass



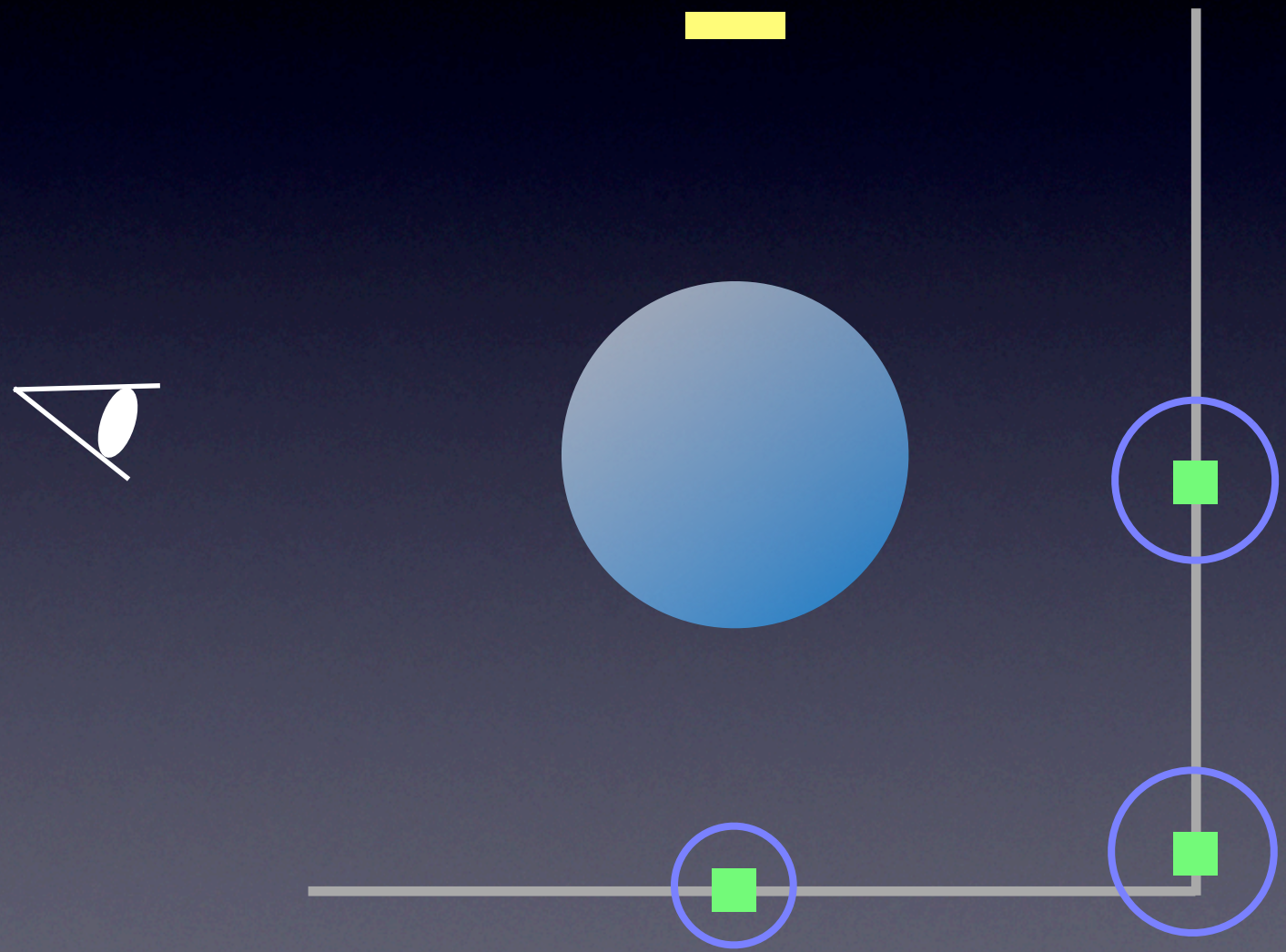
Progressive Photon Mapping - 1st Refinement Pass



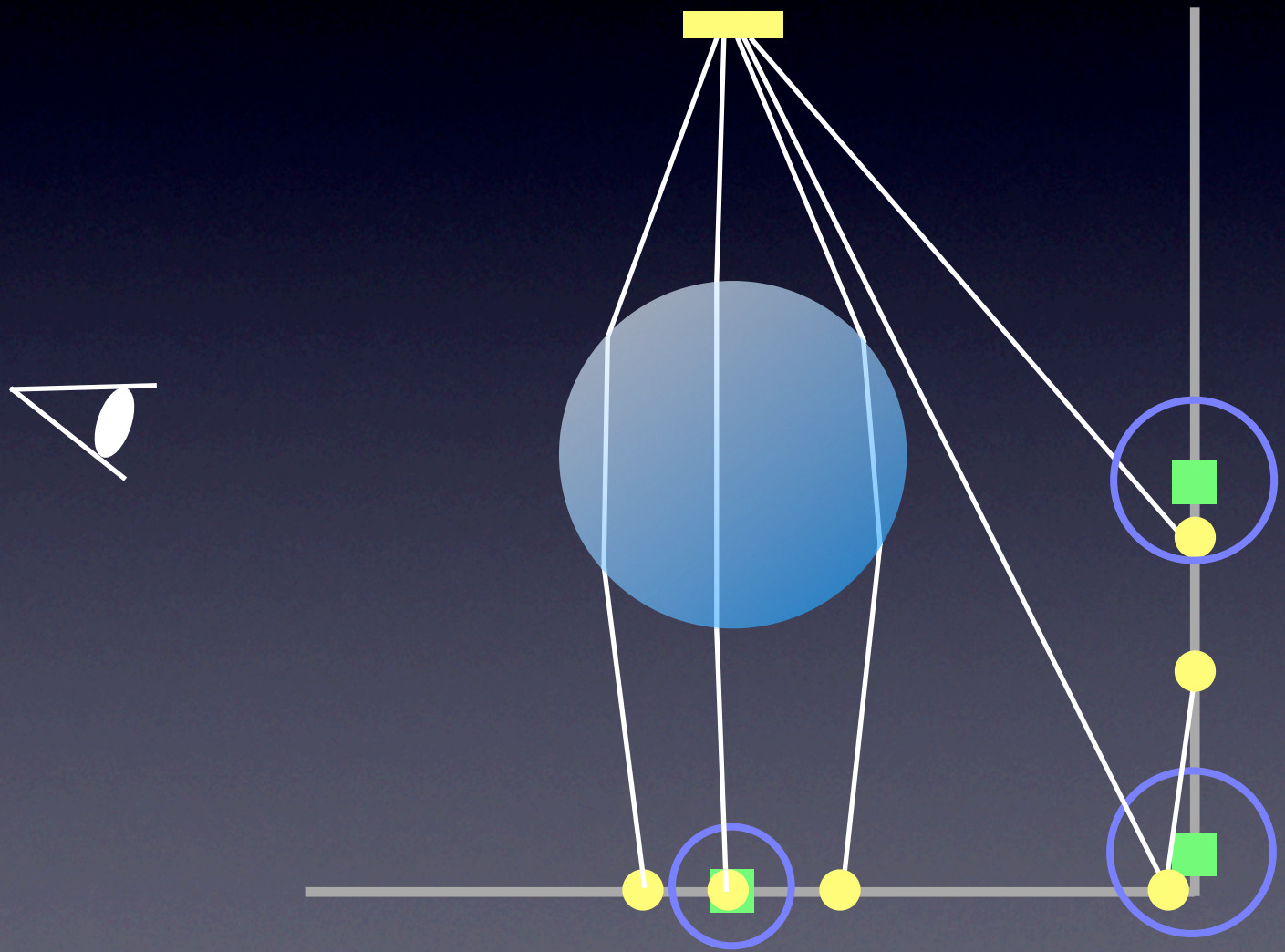
Progressive Photon Mapping - 1st Refinement Pass



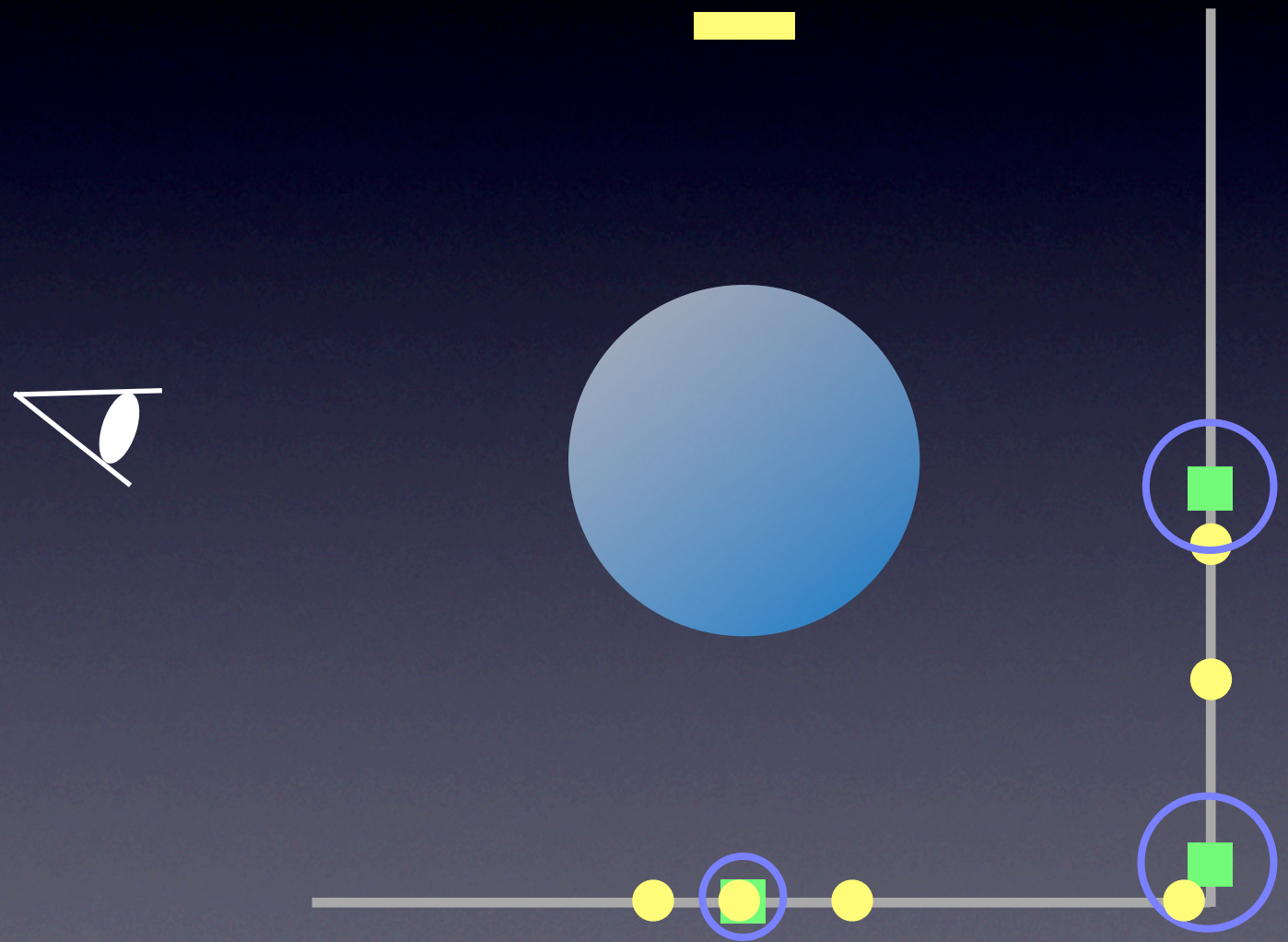
Progressive Photon Mapping - 1st Refinement Pass



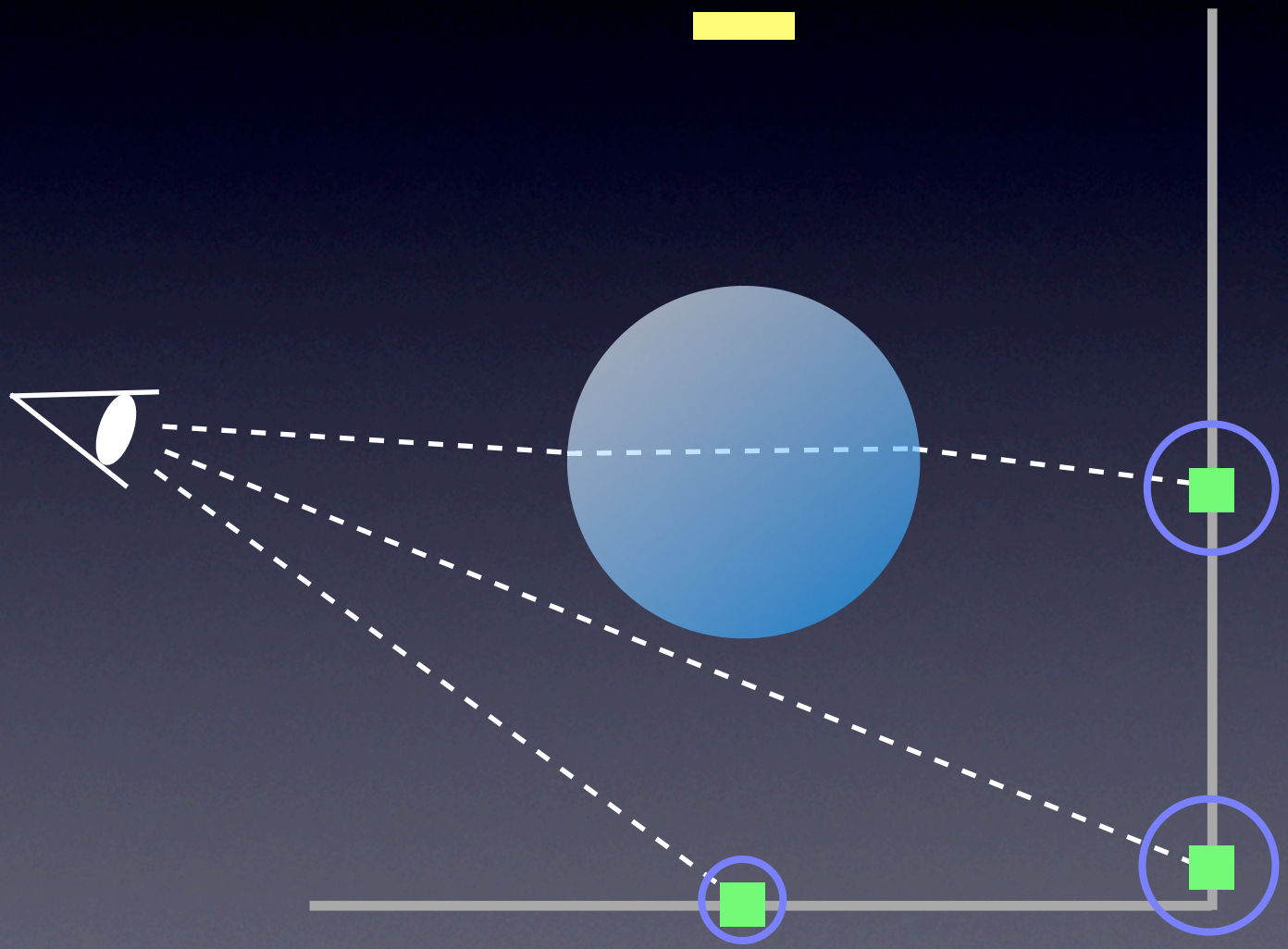
Progressive Photon Mapping - 2nd Refinement Pass



Progressive Photon Mapping - 2nd Refinement Pass

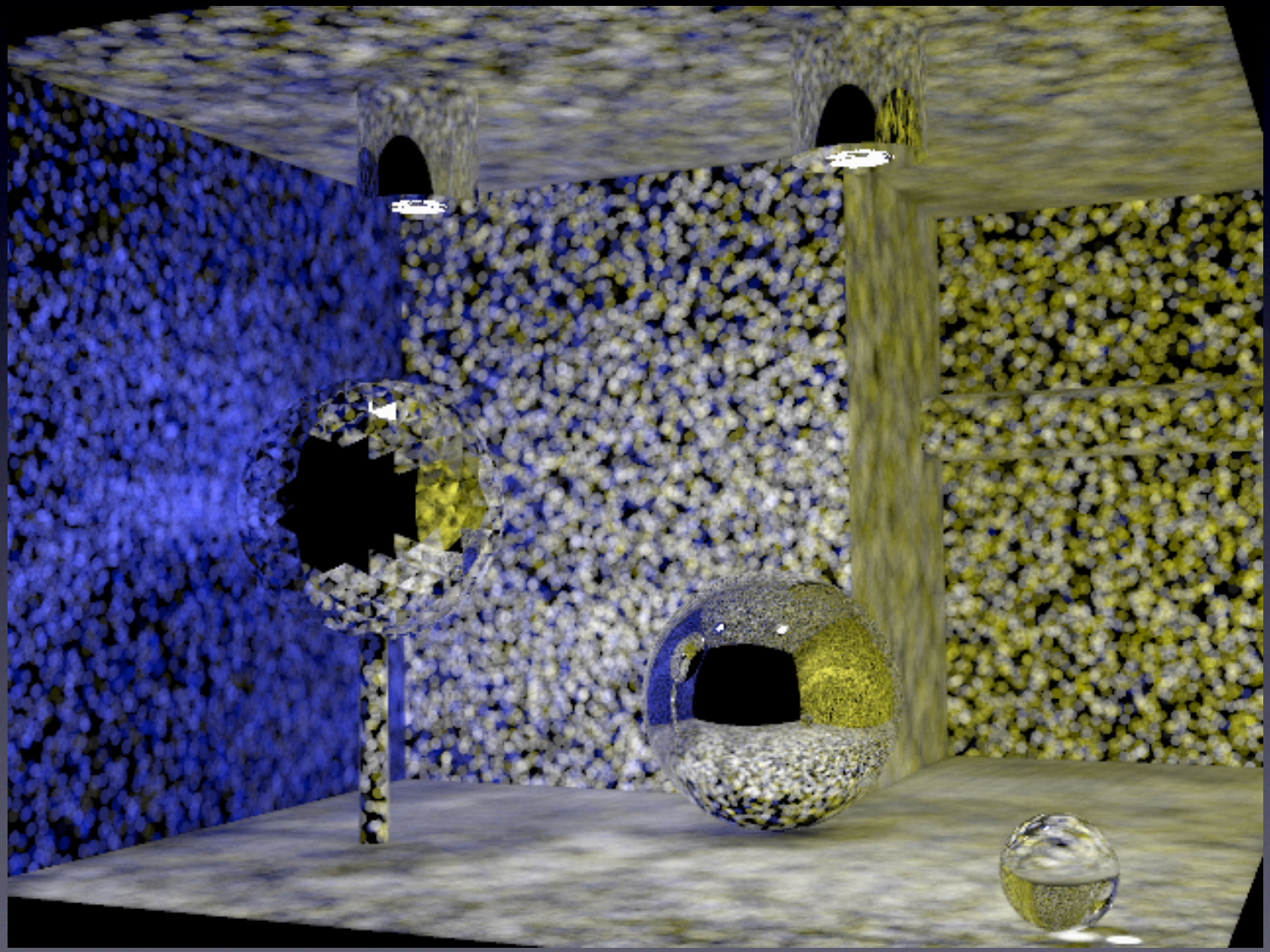


Progressive Photon Mapping - Rendering

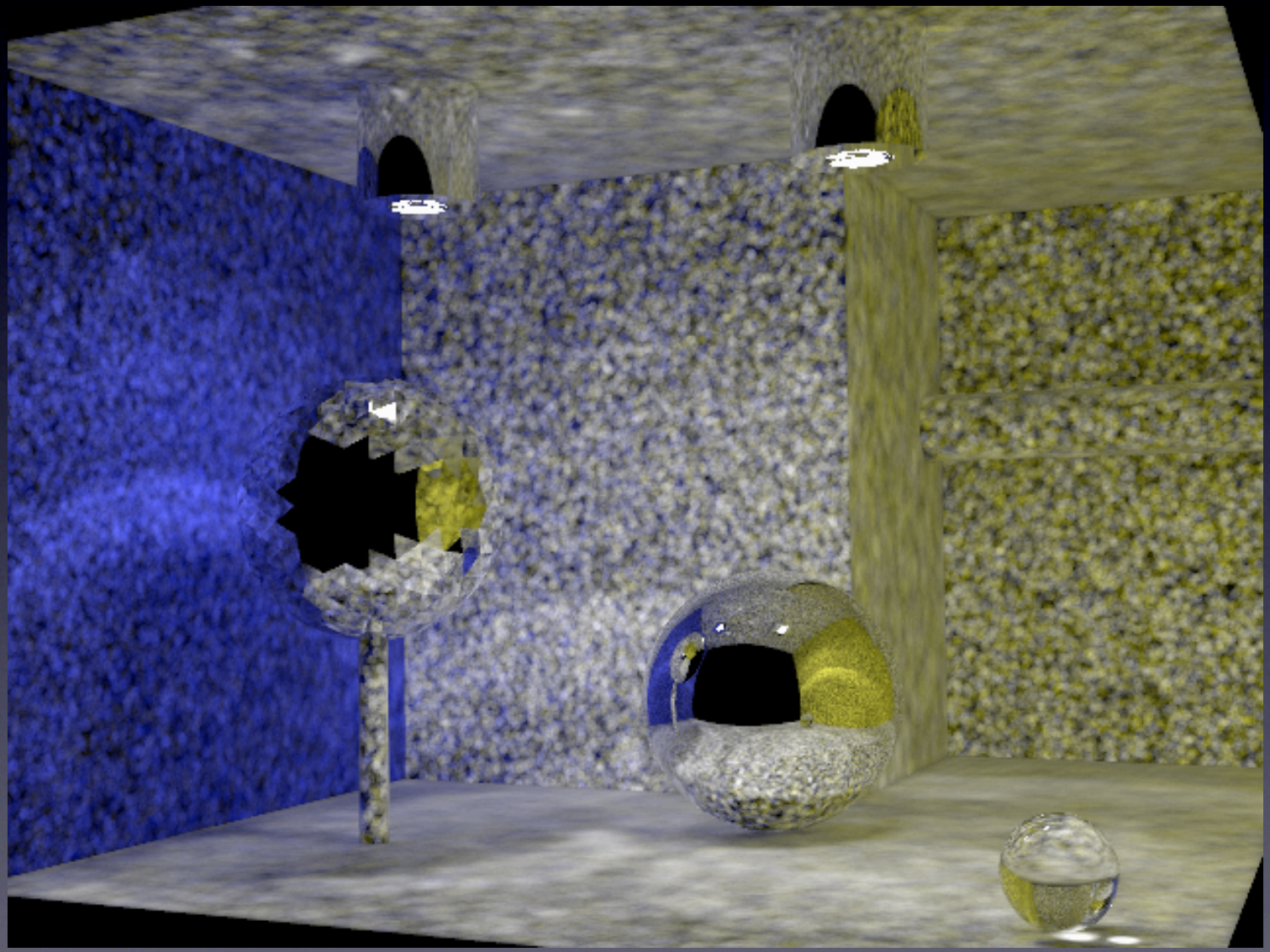


Results

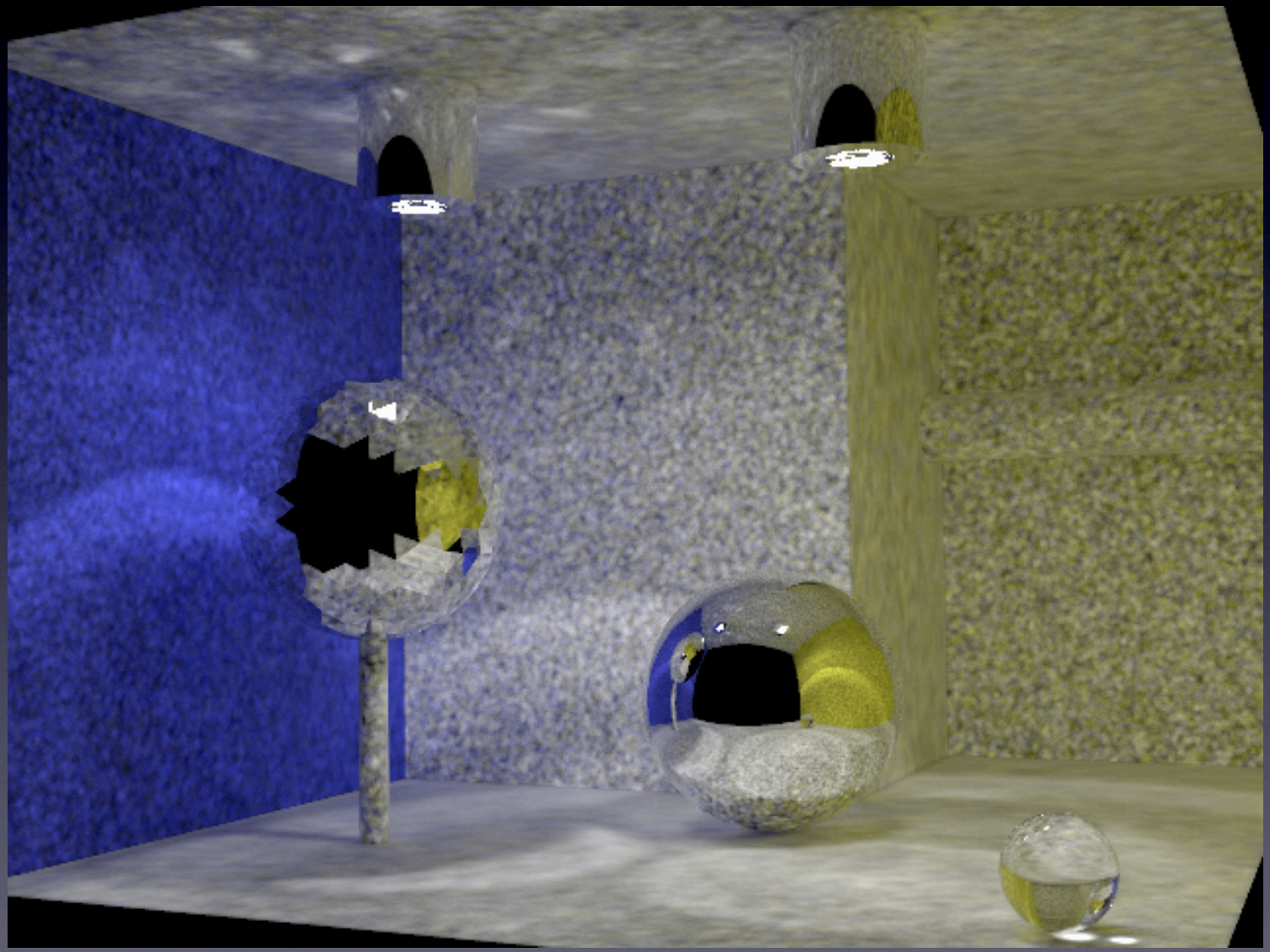
Convergence (100k photons)



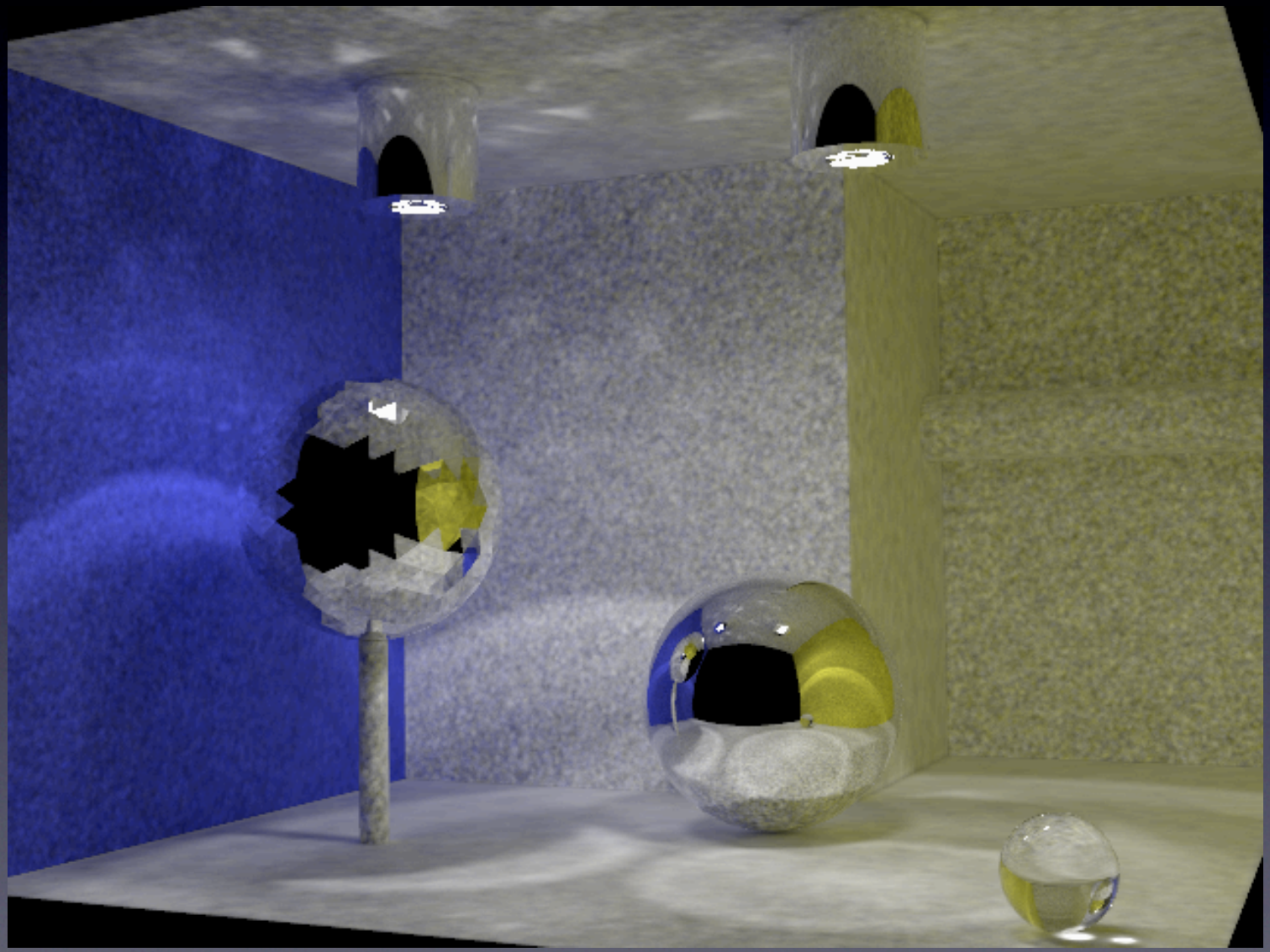
Convergence (400k photons)



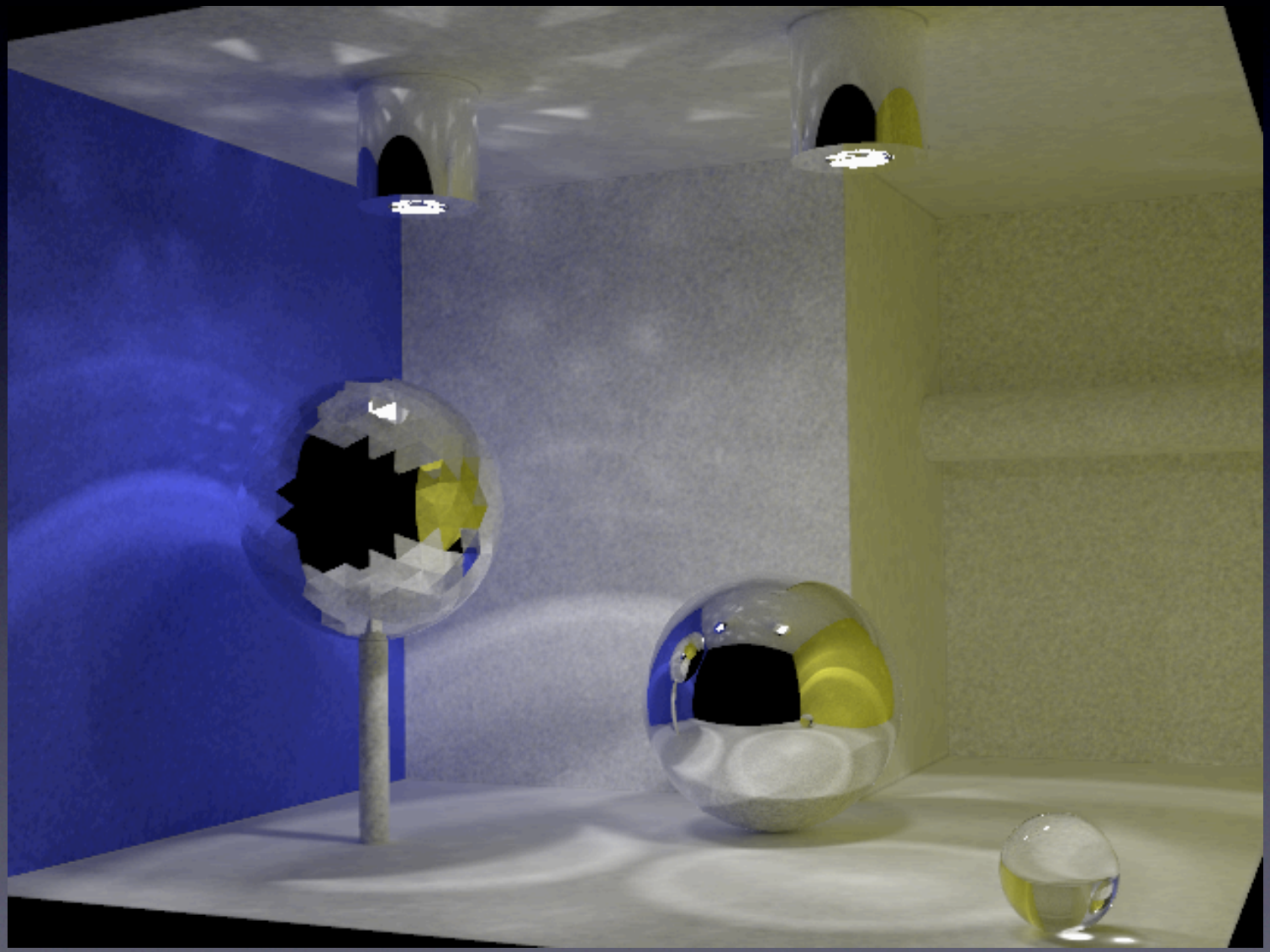
Convergence (1.6M photons)



Convergence (6.4M photons)



Convergence (25.6M photons)



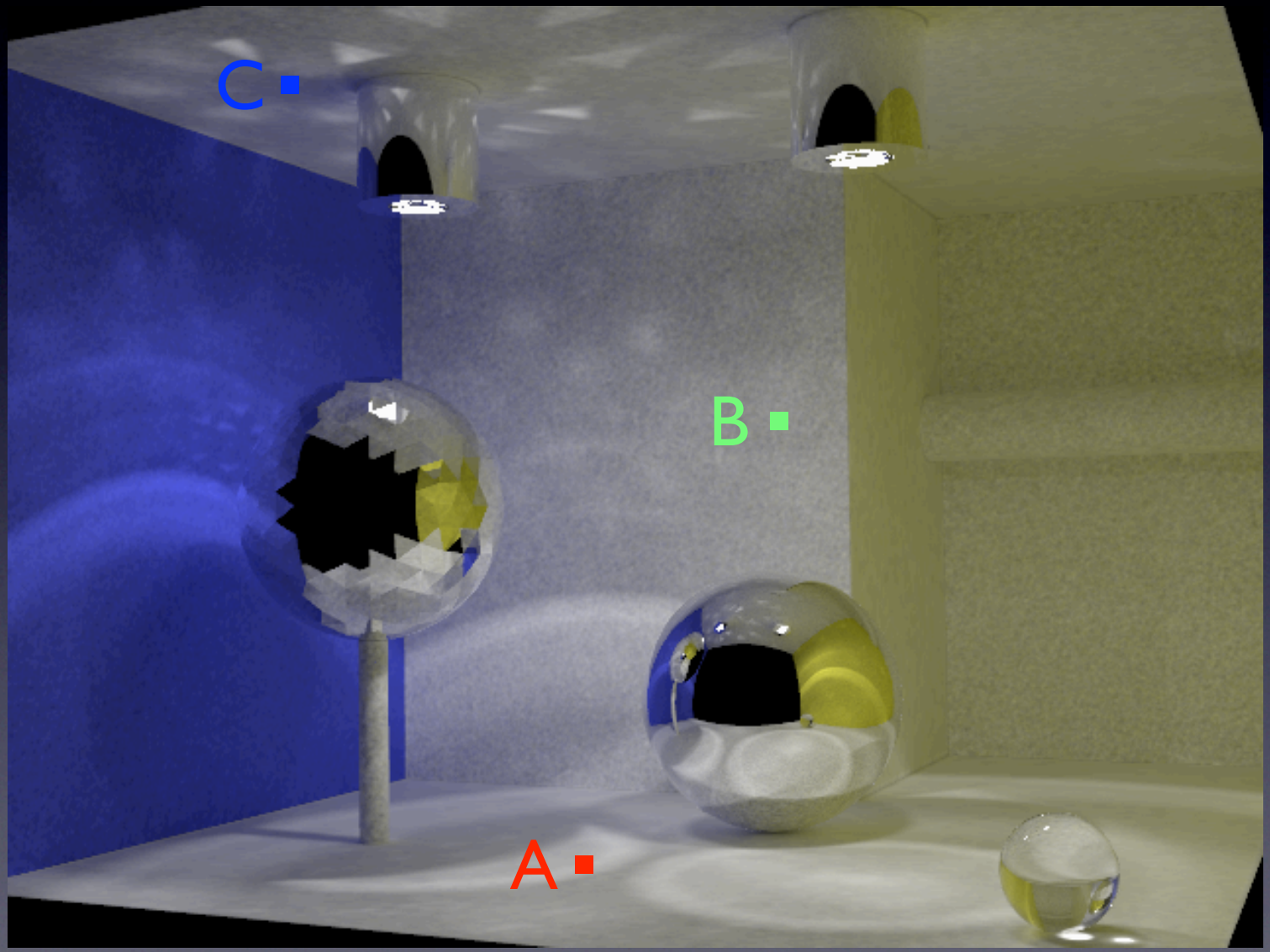
Robustness

$$L(x,\vec{\omega}) = L_e(x,\vec{\omega}) + \int_A L(z \to x)\, f_r(x,\vec{\omega}, z \to x) \boxed{G(x,z)} dA_z$$

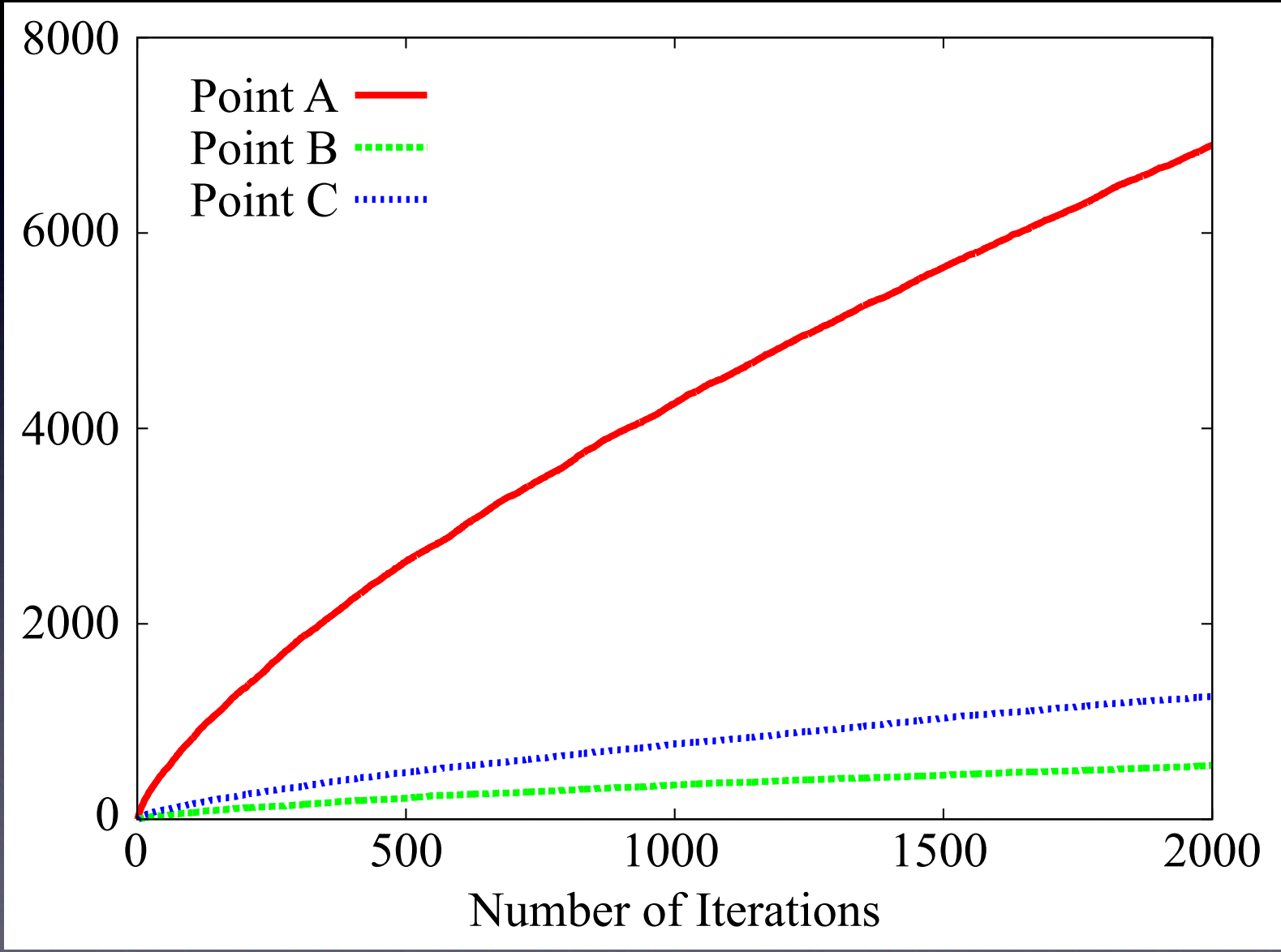
$$G(x,z) = \frac{\cos(n_x,\vec{\omega})\cos(n_z,-\vec{\omega})\, V(x,z)}{\boxed{||x-z||^2}}$$

- Progressive photon mapping avoids the singularity since no lighting is sampled explicitly

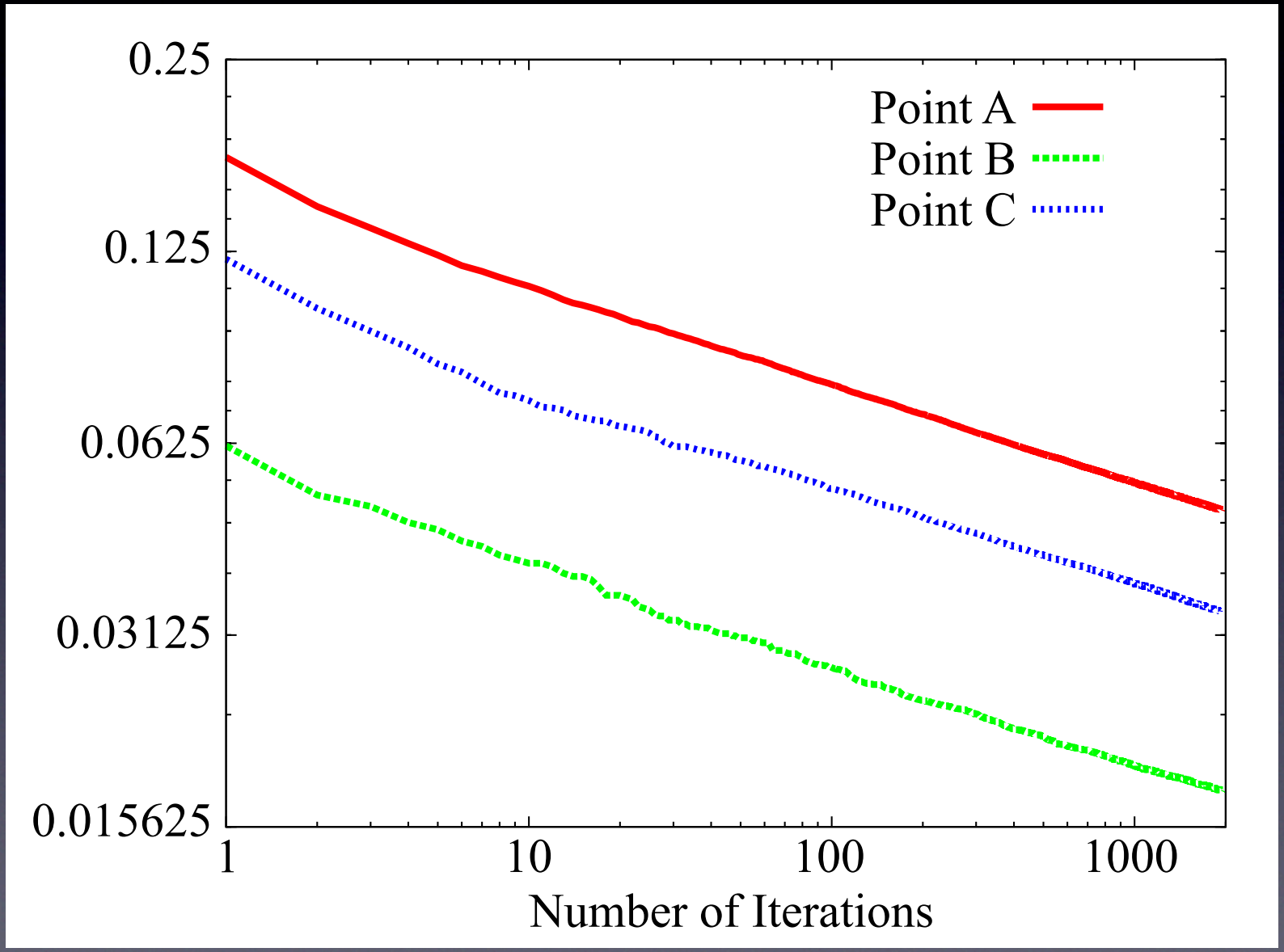
Statistics on Points



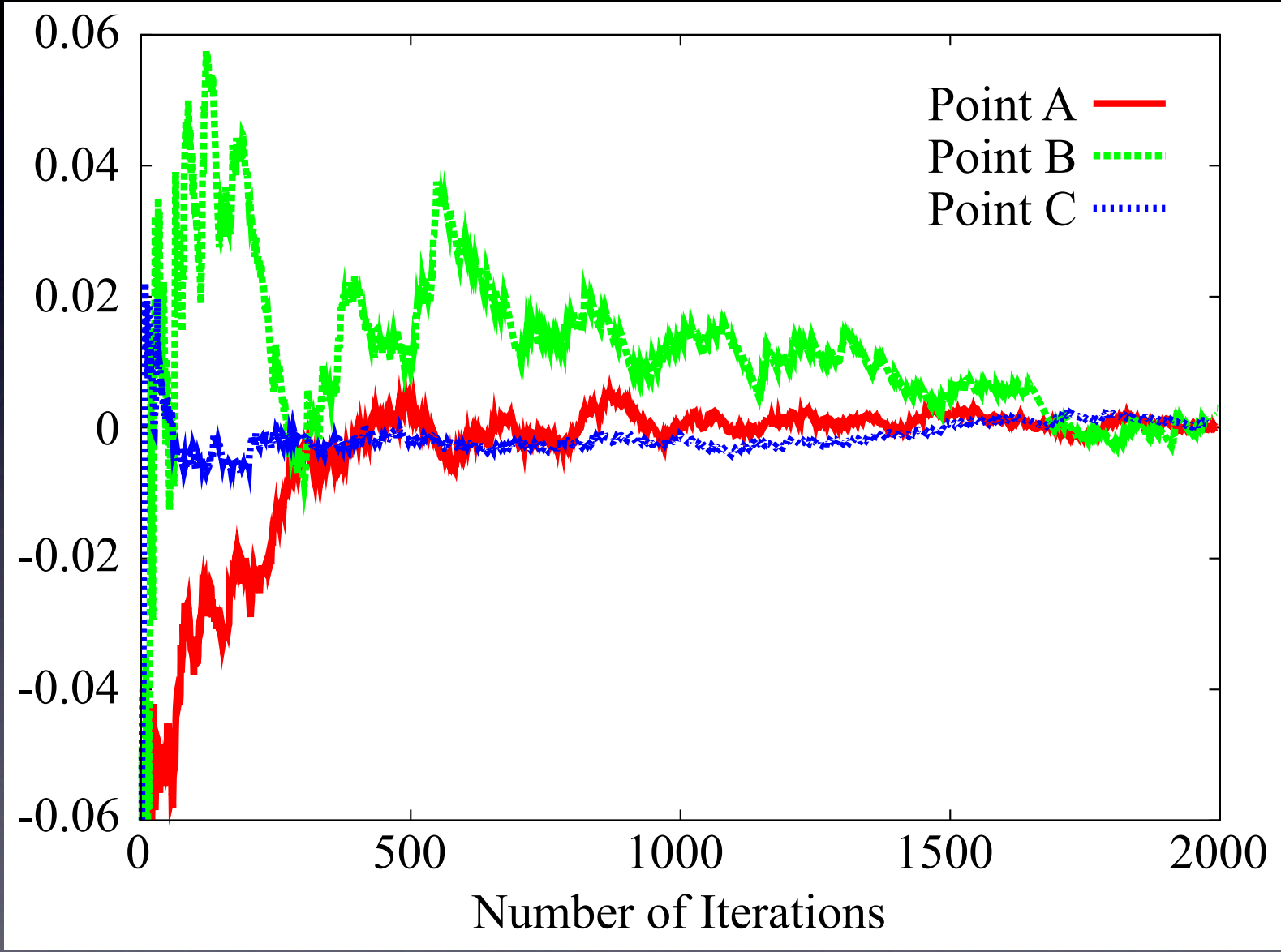
Number of Local Photons



Radius


0.25
0.125
0.0625
0.03125
0.015625
1
10
100
1000
Number of Iterations
Point A
Point B
Point C

Error of Estimate

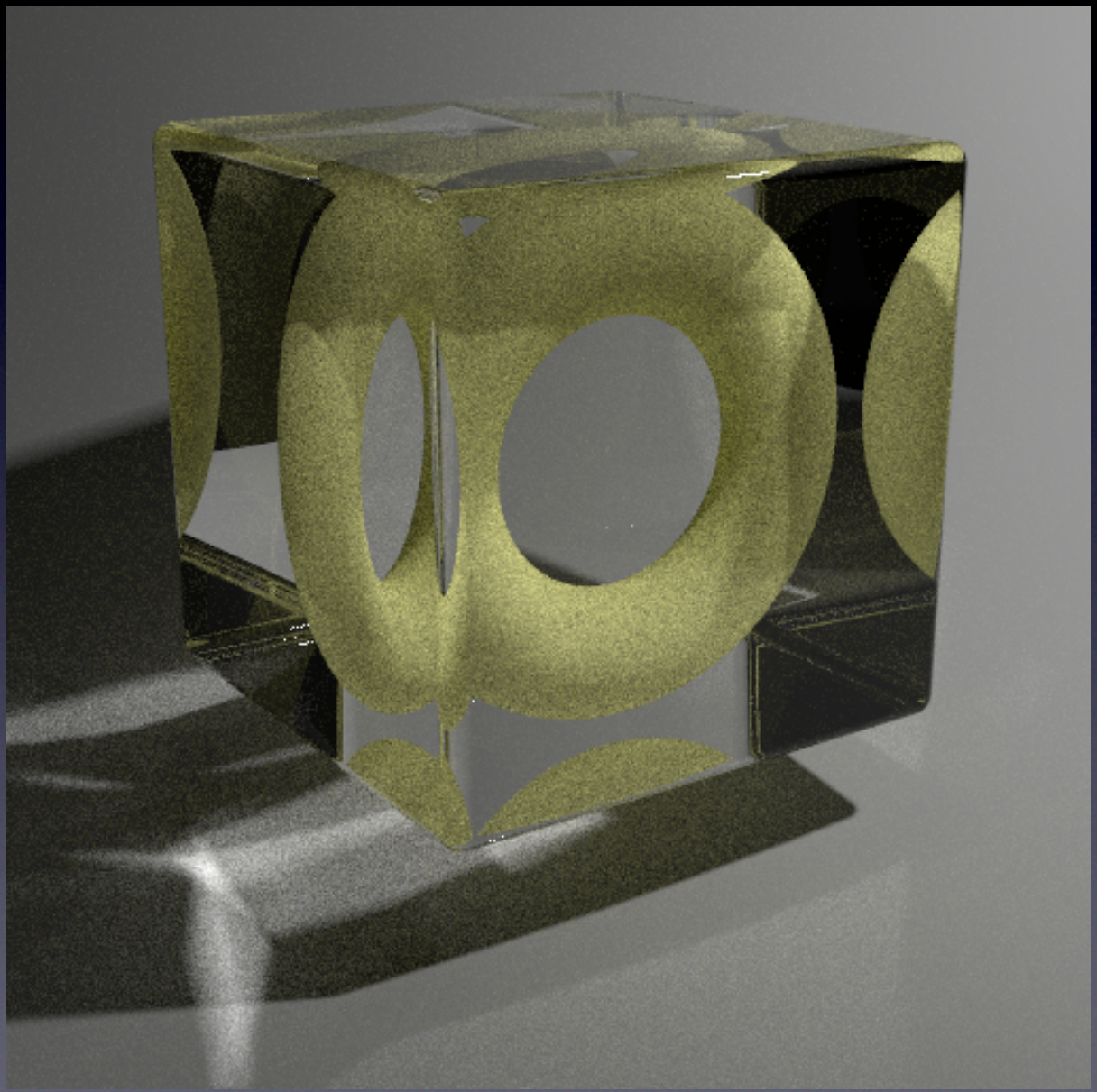


Implementation

- Use the same ray tracing core

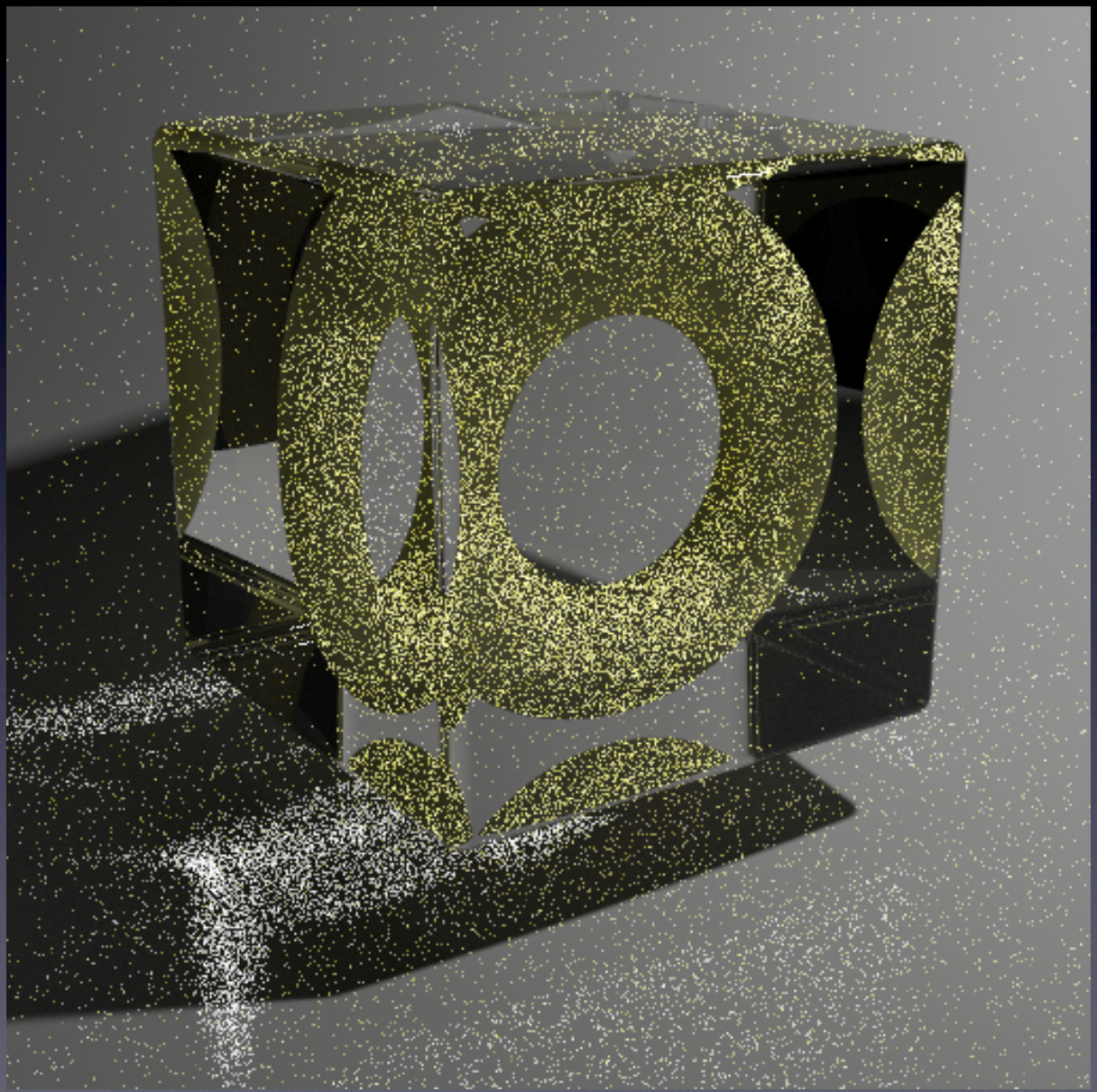
- Path Tracing with shadow rays [Kajiya 86] (PT)
- Bidirectional Path Tracing [Veach 95] (BDPT)
- Metropolis Light Transport [Veach 97][Kelemen 02] (MLT)
- Photon Mapping [Jensen 95] (PM)

Torus in Cube - Reference (Path Tracing)



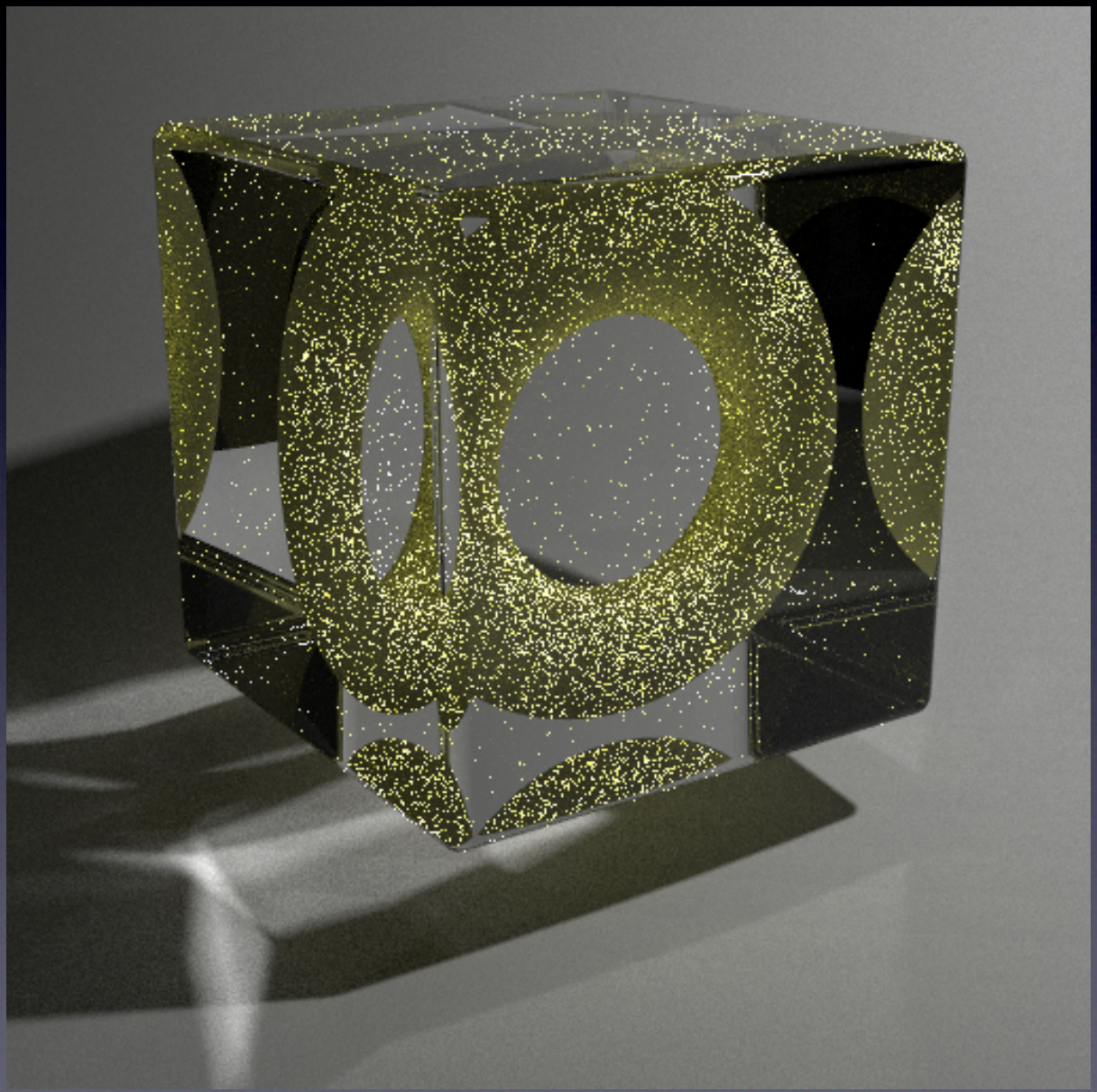
51500 samples
91 hours

Torus in Cube - Path Tracing



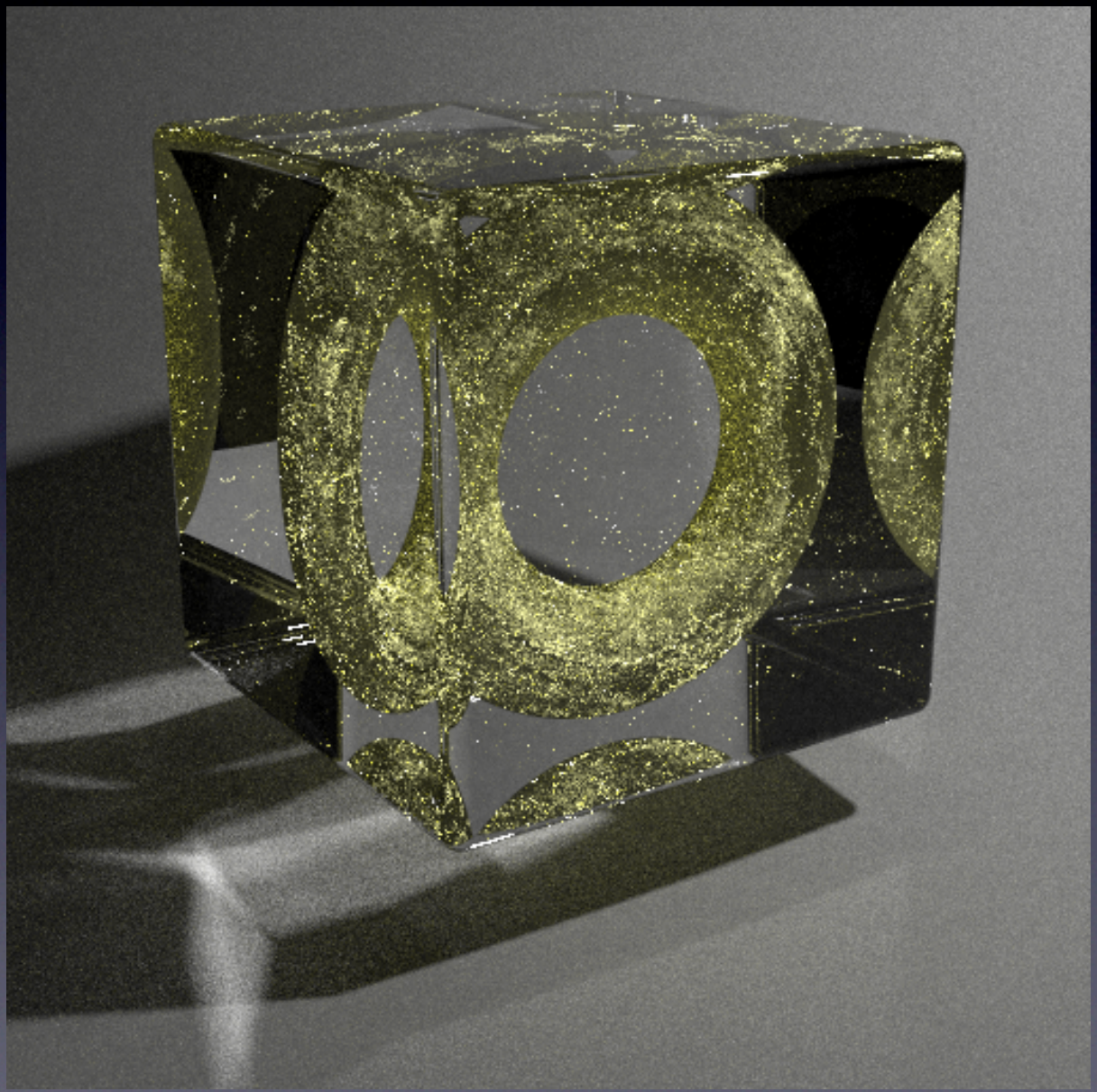
1050 samples
2 hours

Torus in Cube - Bidirectional Path Tracing



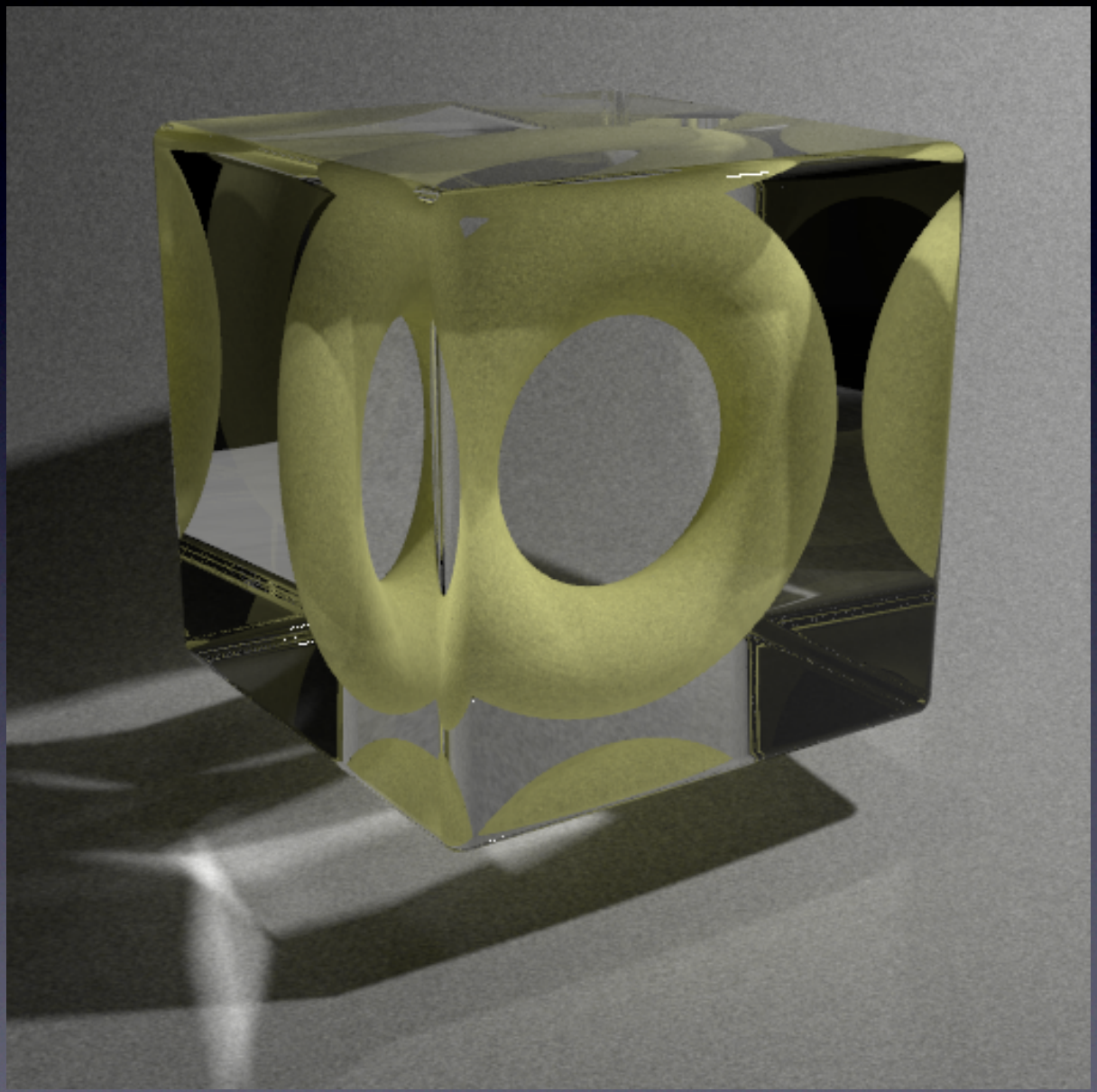
550 samples
2 hours

Torus in Cube - Metropolis Light Transport



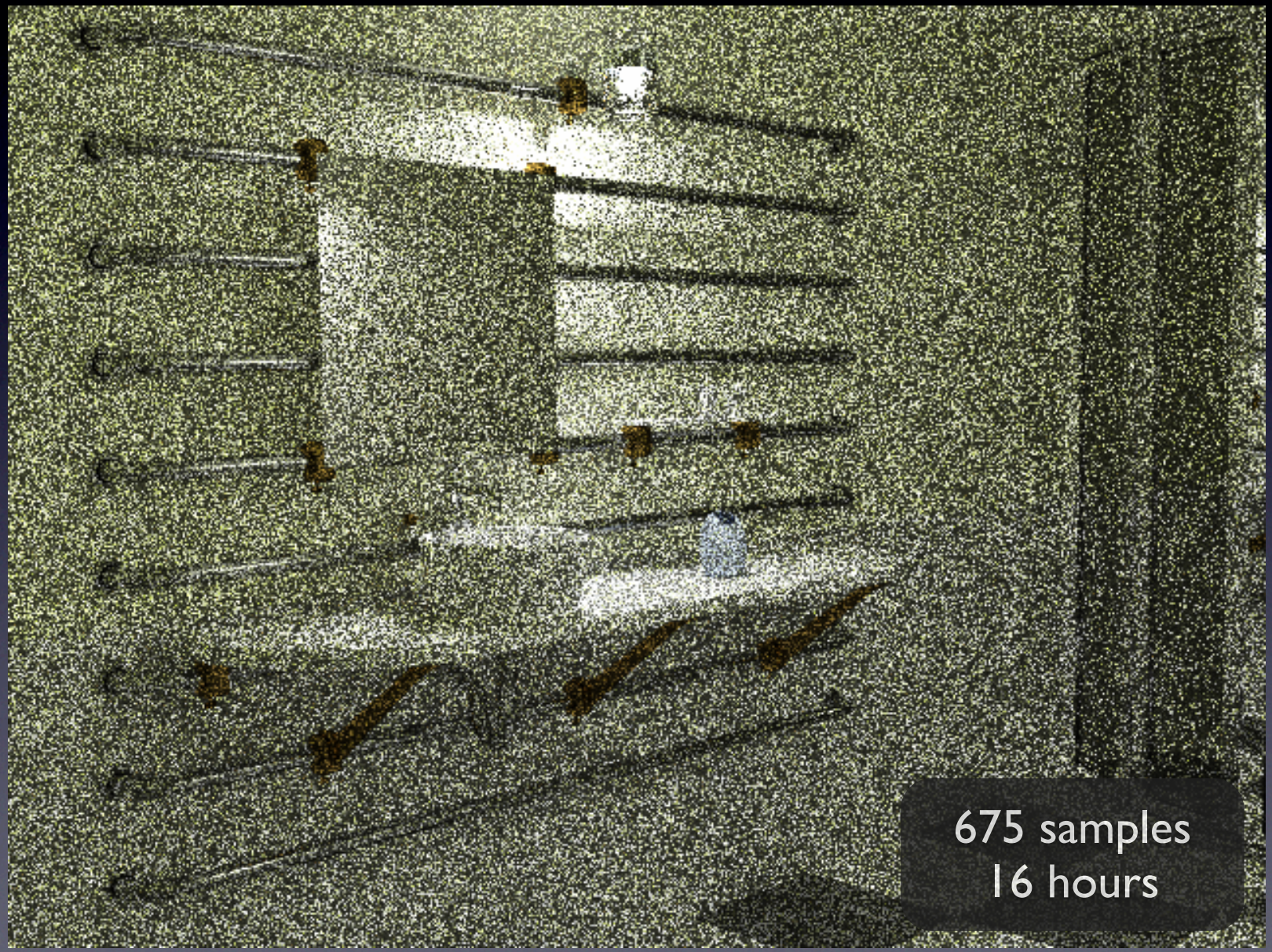
359 mutations
2 hours

Torus in Cube - Progressive Photon Mapping



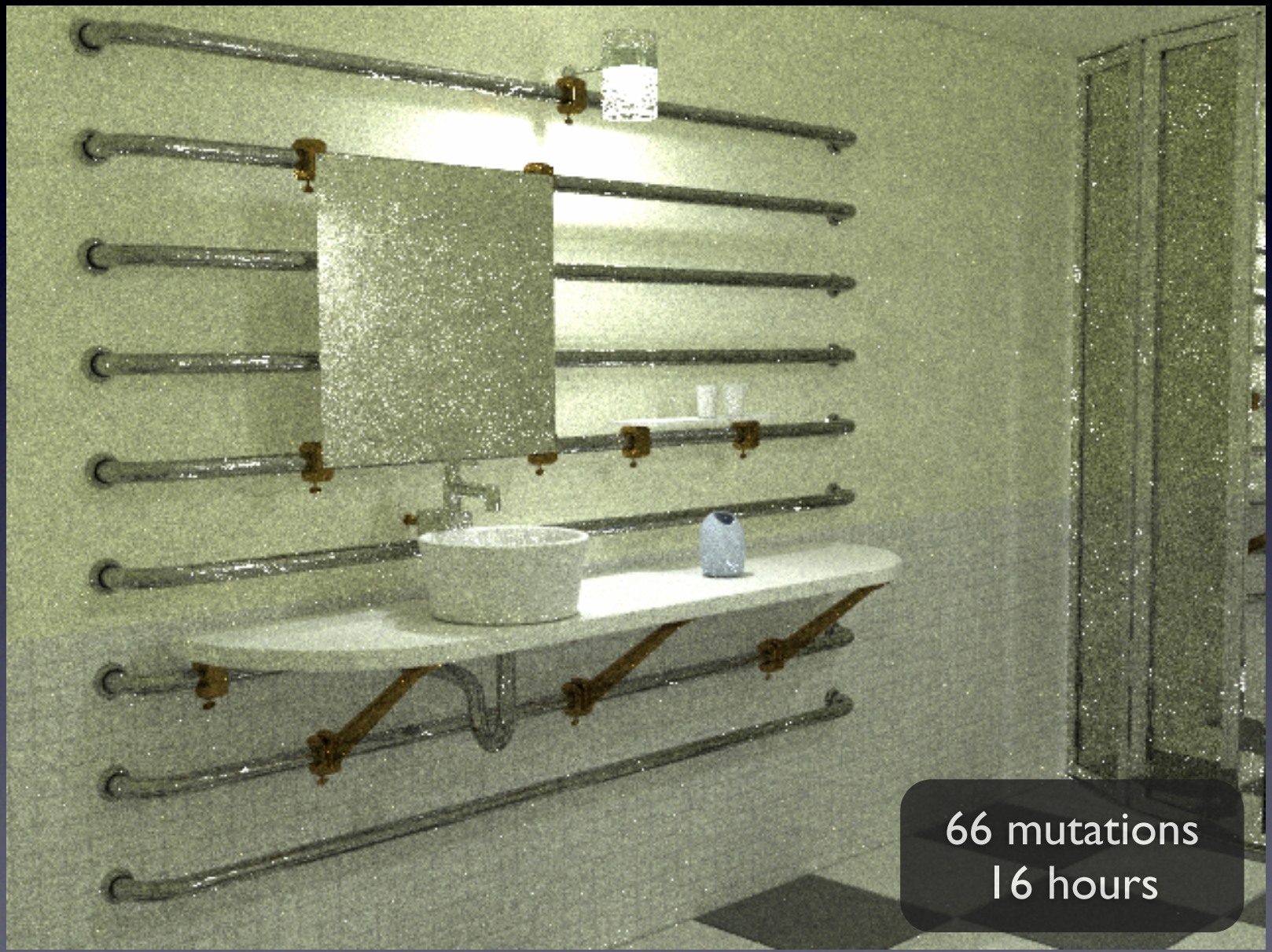
52M photons
2 hours

Bathroom - Path Tracing



Bathroom - Bidirectional Path Tracing

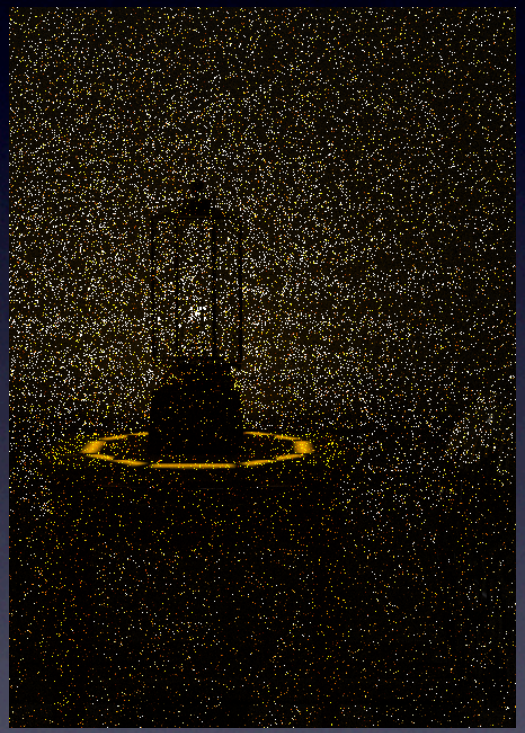
Bathroom - Metropolis Light Transport



Bathroom - Photon Mapping

Bathroom - Progressive Photon Mapping

Glass Desk Lamp

PT	BDPT	MLT	PPM
			
840 samples 22 hours	80 samples 22 hours	82 mutations 22 hours	165M photons 22 hours

Conclusion

- New formulation of photon mapping
  - Robust for *any* light path including SDS path
  - Arbitrary accuracy using finite memory
  - New progressive density estimation algorithm
  - Easy to implement

Future Work

How many photons are enough?

Acknowledgements

- NSF grant CPA 0701992
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- UC San Diego
  graphics lab members