Realistic Image Synthesis

- Progressive Photon Mapping & Vertex Connection and Merging -

Philipp Slusallek

Karol Myszkowski

Gurprit Singh

Corentin Salaun

Overview

- **Today**
  - Progressive Photon Mapping (PPM)
    - Basic Approach
    - Probabilistic Approach
  - Combining Photon Mapping and Bidirectional Path Tracing
    - Vertex connection and merging

- **Next lecture**
  - Radar / Spectral

Reading Materials:

- HACHISUKA, T., OGAKI, S., AND JENSEN, H. W. 2008. Progressive photon mapping. ACM Trans. Graph. 27, 5
- HACHISUKA, T. AND JENSEN, H. W. 2009. Stochastic progressive photon mapping. ACM Trans. Graph. 28, 5.
- HACHISUKA, T., OGAKI, S., AND JENSEN, H. W. 2008. Progressive photon mapping. ACM Trans. Graph. 27, 5
- Knaus, C., and Zwicker, M. 2011. Progressive Photon Mapping: A Probabilistic Approach. *ACM Trans. Graph. 30*.
- Iliyan Georgiev, Jaroslav Křivánek, Tomáš Davidovič, and Philipp Slusallek. 2012. Light transport simulation with vertex connection and merging. ACM Trans. Graph. 31, 6.

Progressive Photon Mapping

Toshiya Hachisuka[*] Shinji Ogaki[†] Henrik Wann Jensen[*]

[*]University of California, San Diego
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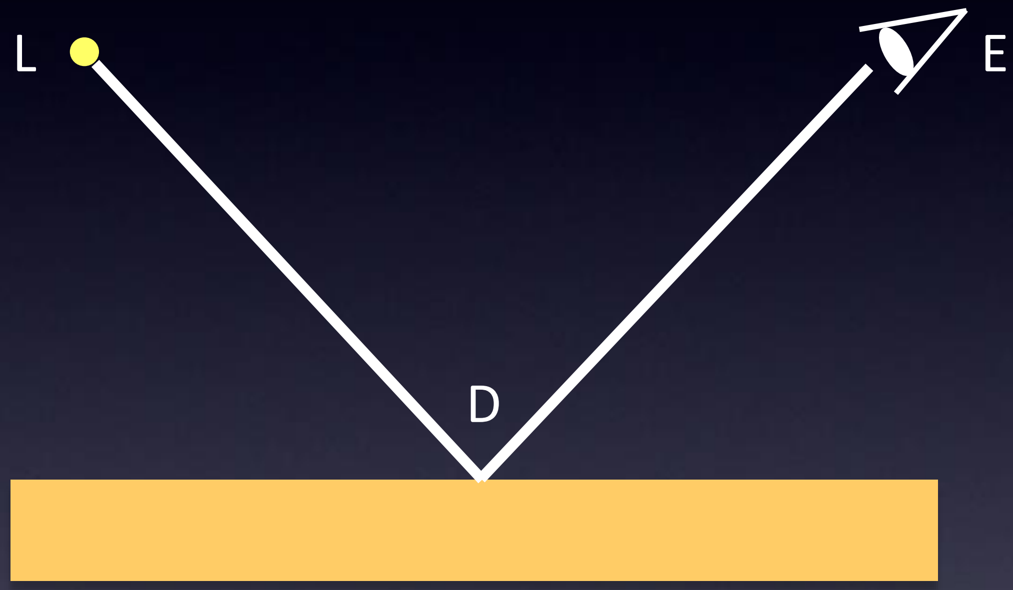
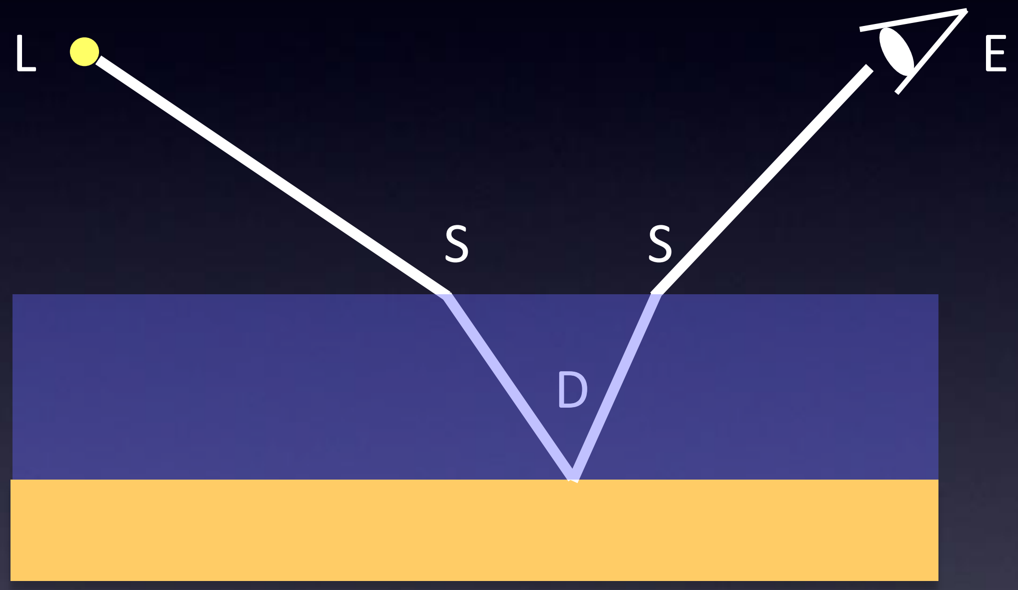
LDE Path

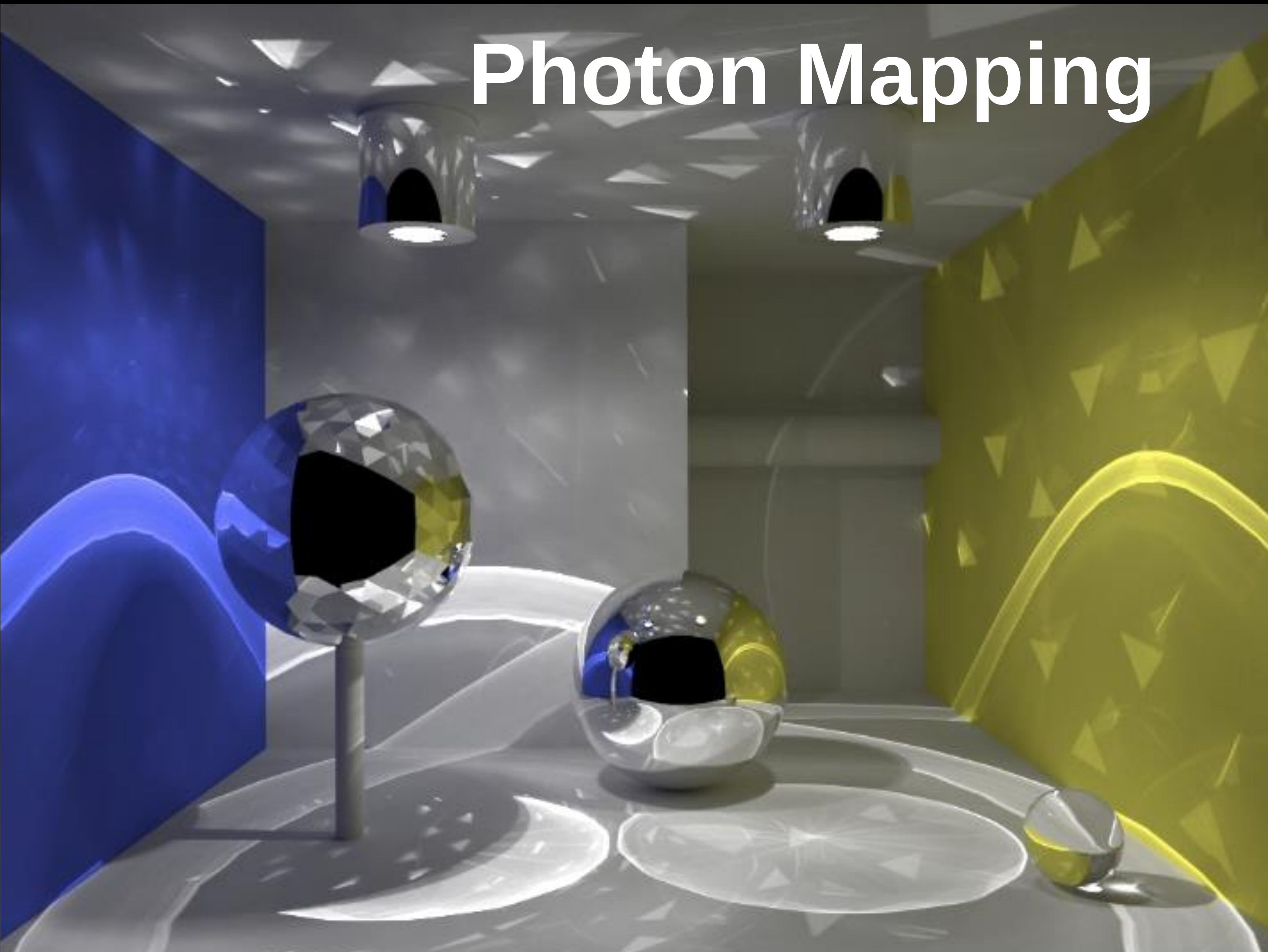


LSDSE Path



Path Tracing

Photon Mapping



Scene courtesy of
Toshiya Hachisuka

Photon Mapping

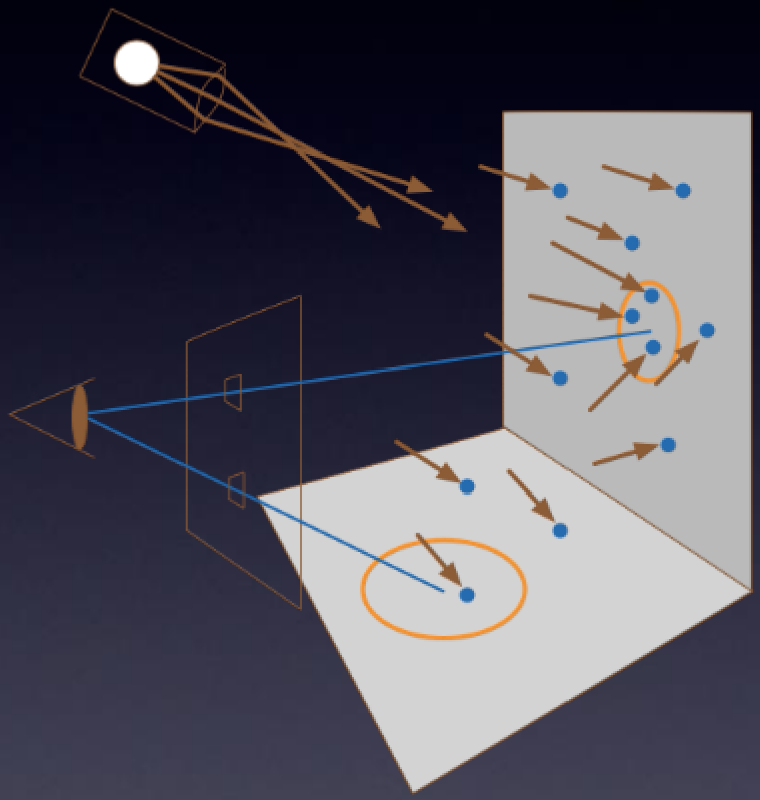
Trace Photons

↓

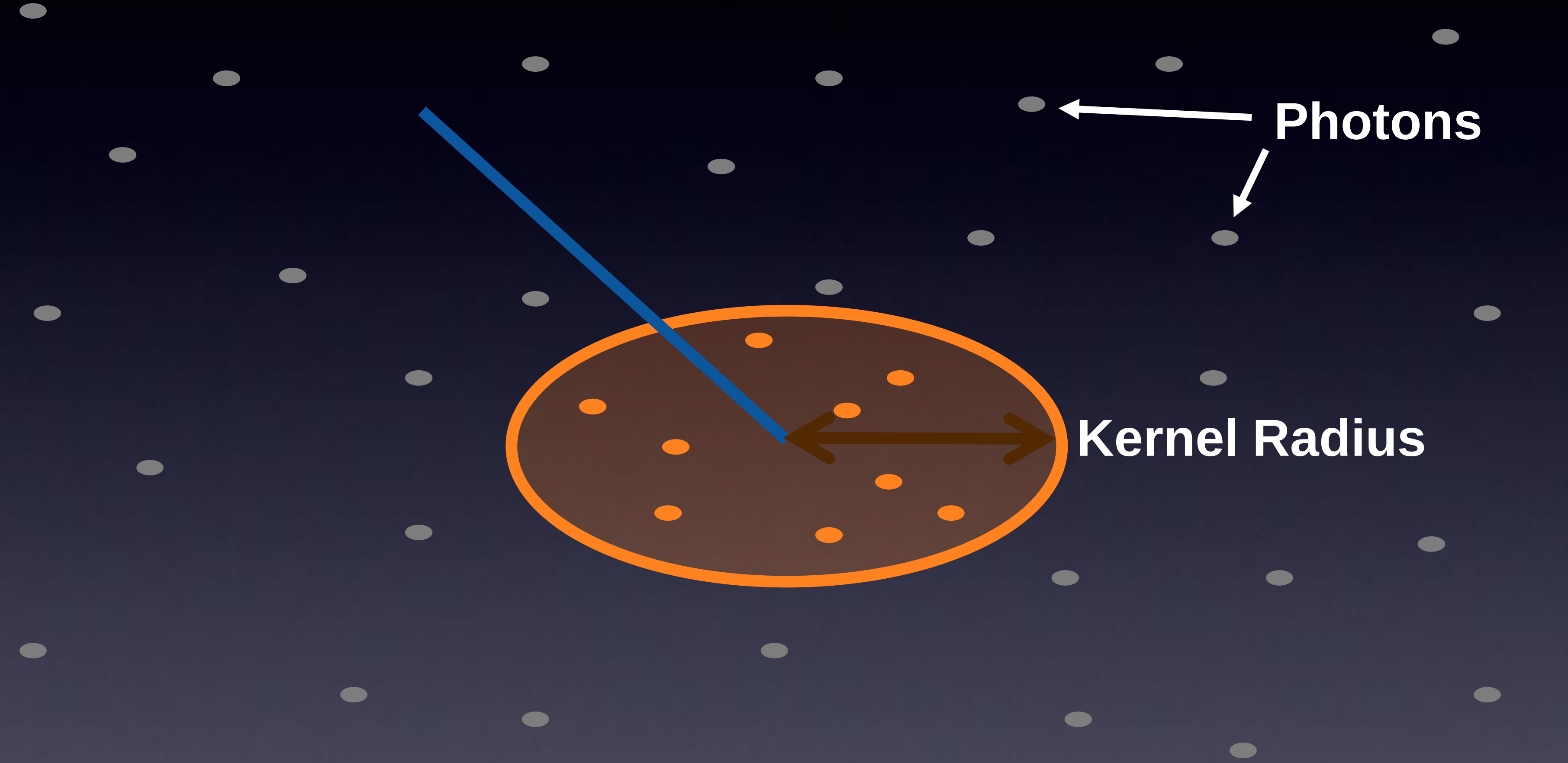
Trace Eye Rays

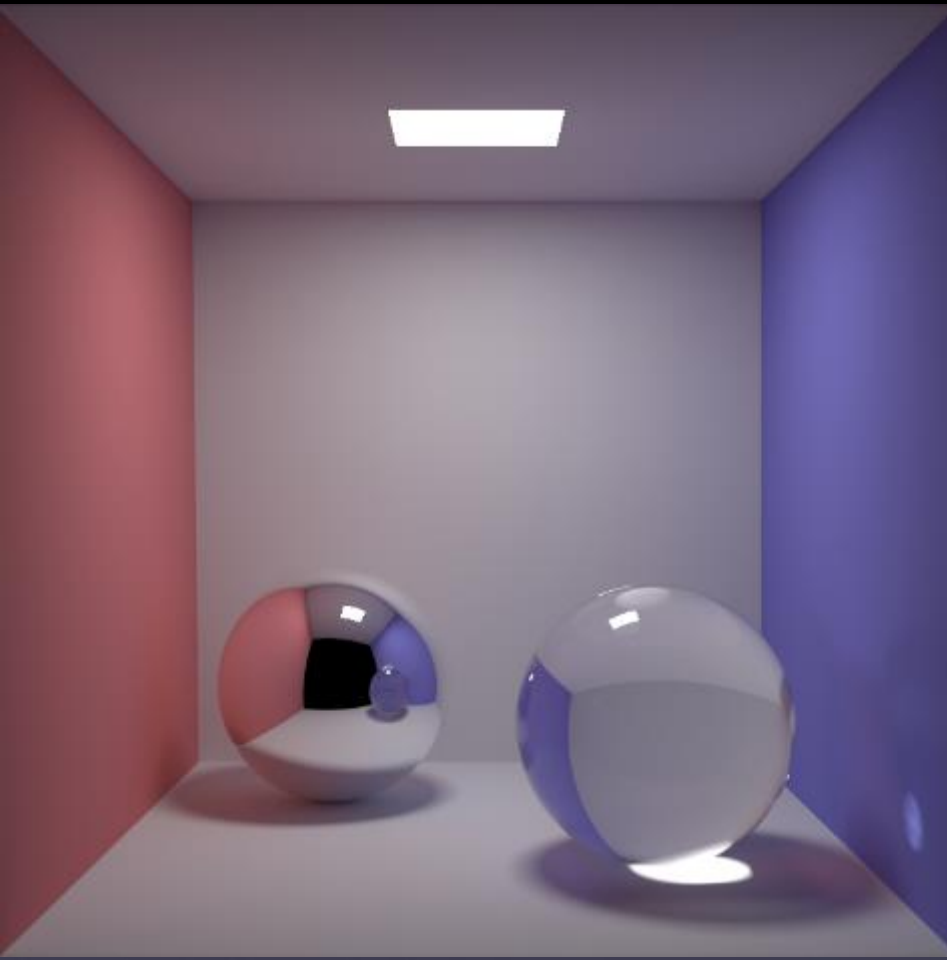
↓

Image

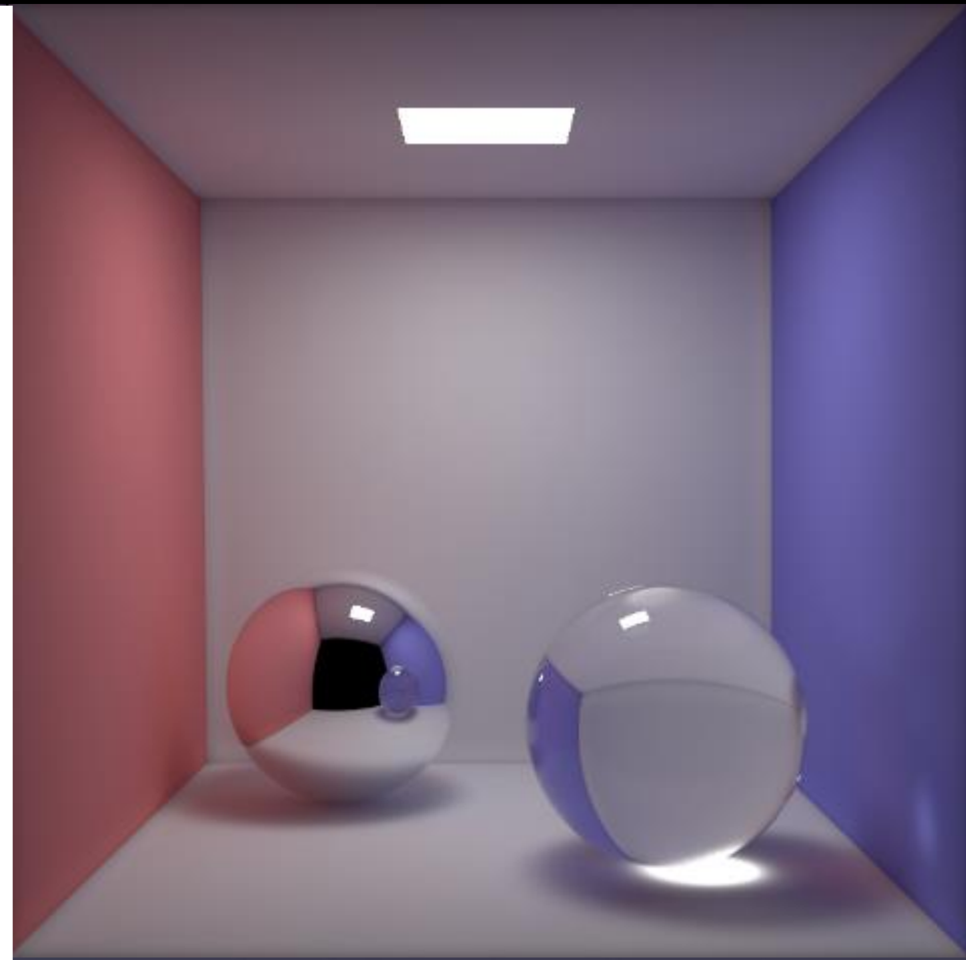


Radiance Estimation

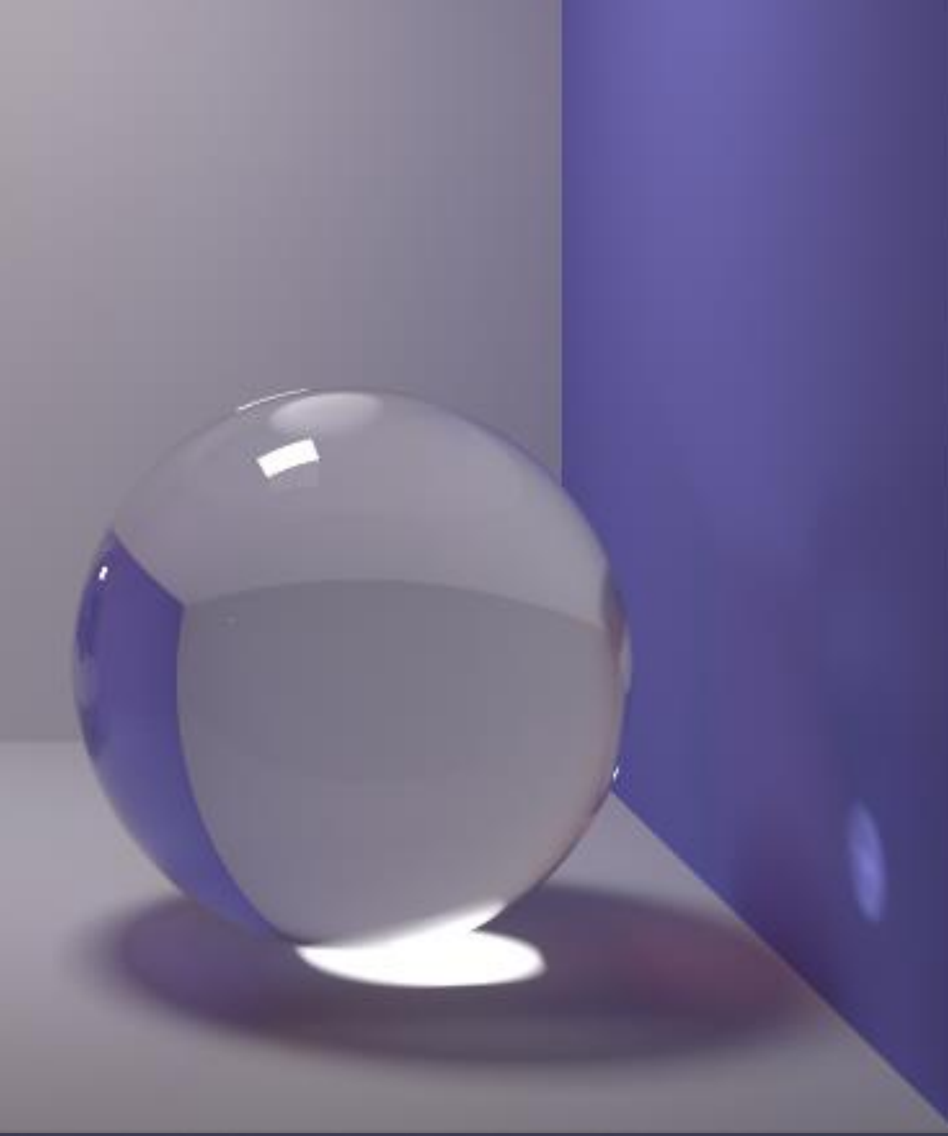




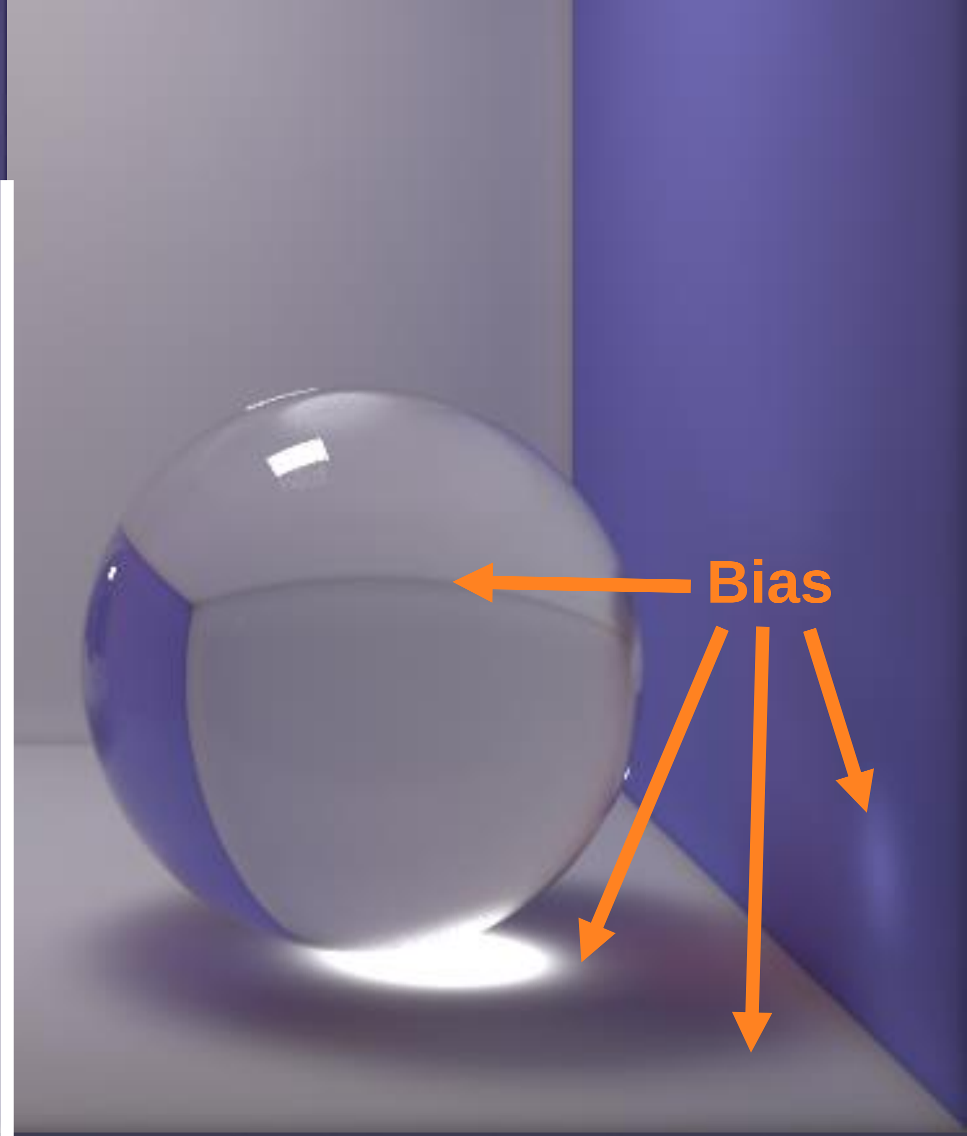
Ground Truth



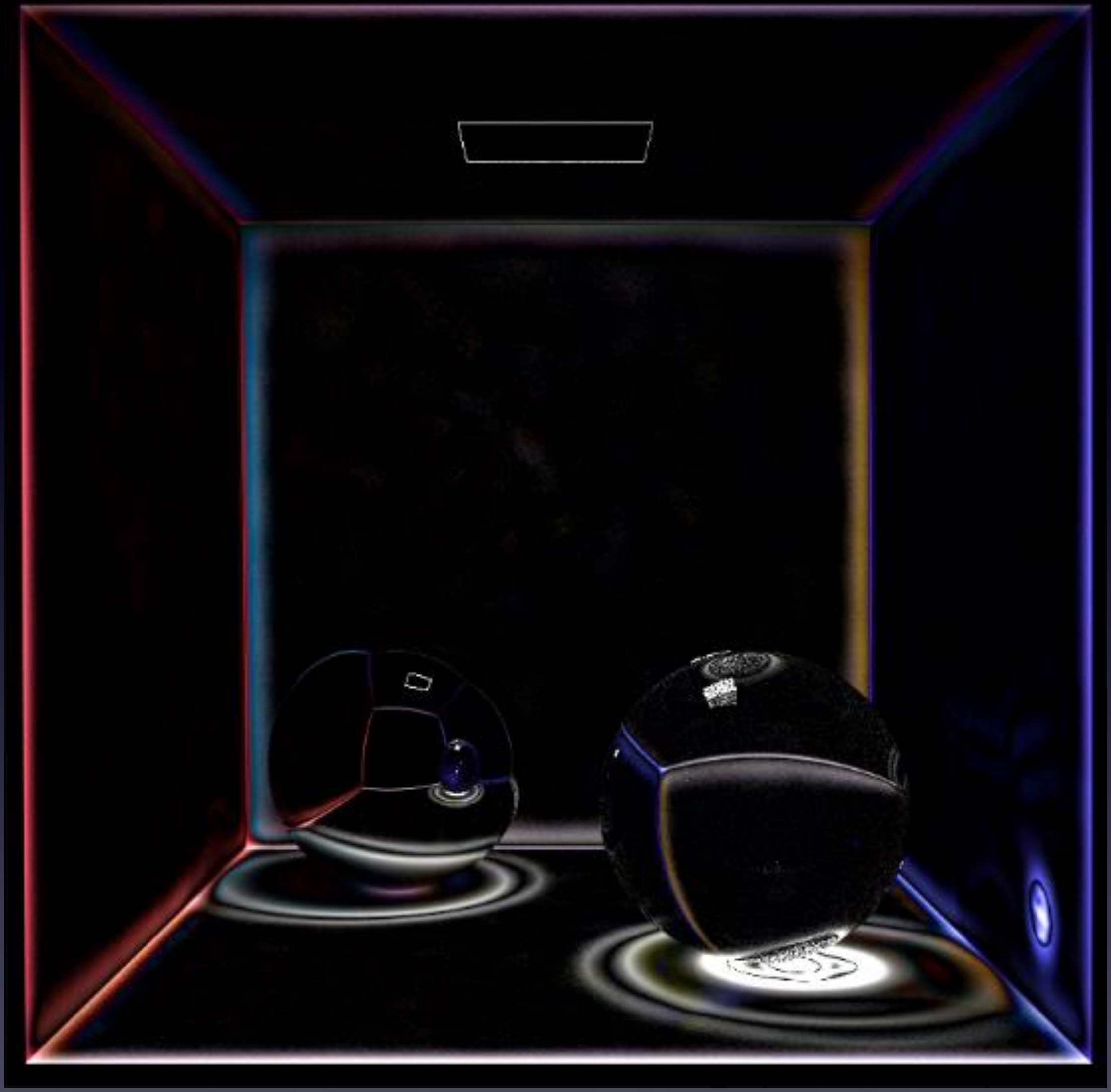
Photon Mapping



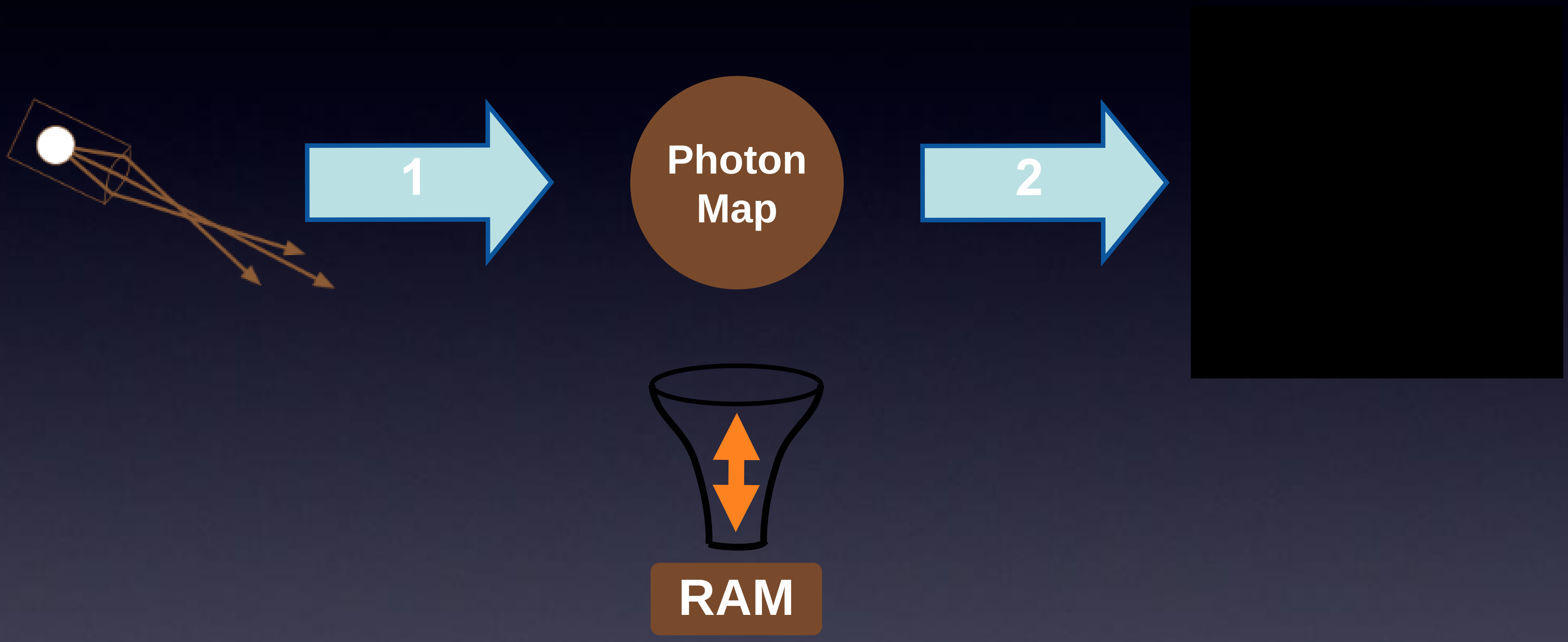
Ground Truth



Photon Mapping

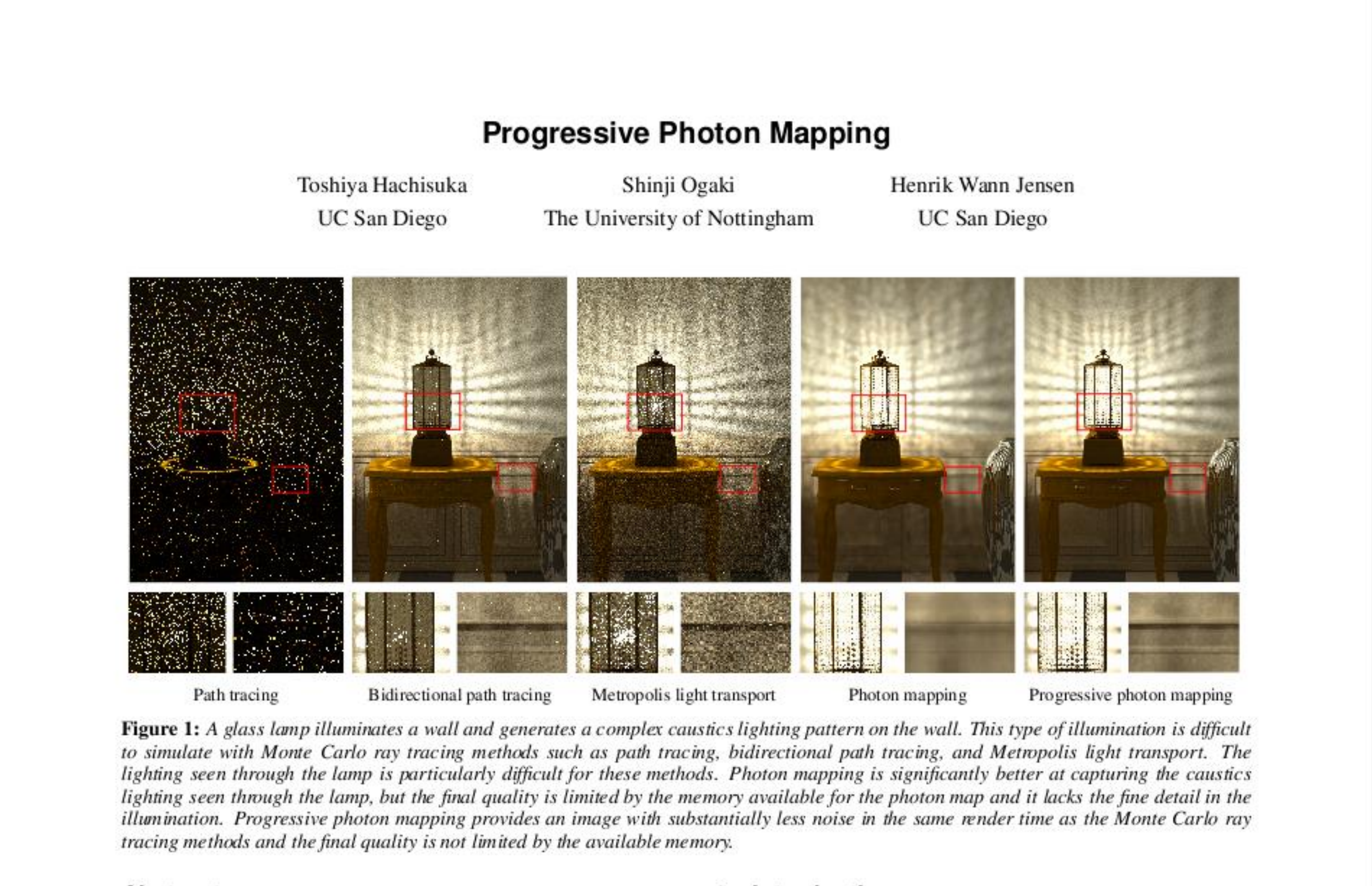


Memory Bottleneck



Progressive Photon Mapping

Hachisuka et al. (2008)



Progressive Photon Mapping

Toshiya Hachisuka	Shinji Ogaki	Henrik Wann Jensen
UC San Diego	The University of Nottingham	UC San Diego

Path tracing | Bidirectional path tracing | Metropolis light transport | Photon mapping | Progressive photon mapping

Figure 1: *A glass lamp illuminates a wall and generates a complex caustics lighting pattern on the wall. This type of illumination is difficult to simulate with Monte Carlo ray tracing methods such as path tracing, bidirectional path tracing, and Metropolis light transport. The lighting seen through the lamp is particularly difficult for these methods. Photon mapping is significantly better at capturing the caustics lighting seen through the lamp, but the final quality is limited by the memory available for the photon map and it lacks the fine detail in the illumination. Progressive photon mapping provides an image with substantially less noise in the same render time as the Monte Carlo ray tracing methods and the final quality is not limited by the available memory.*

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

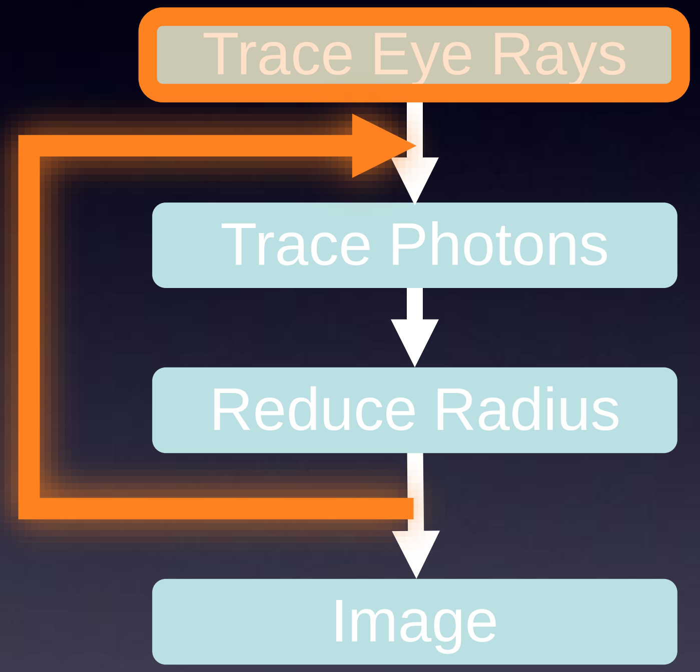
Progressive Photon Mapping

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

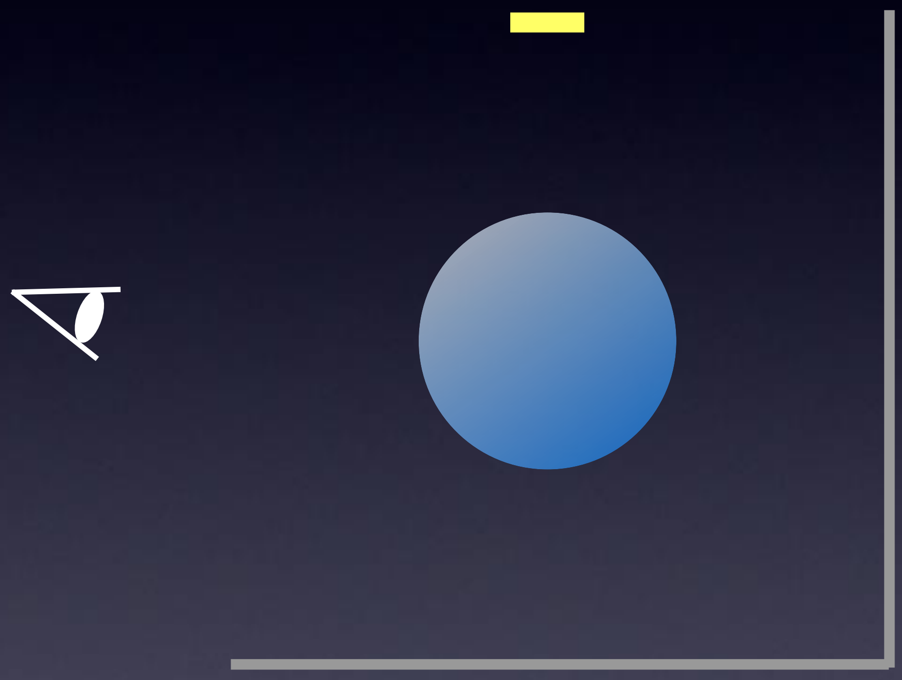
Key Idea

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

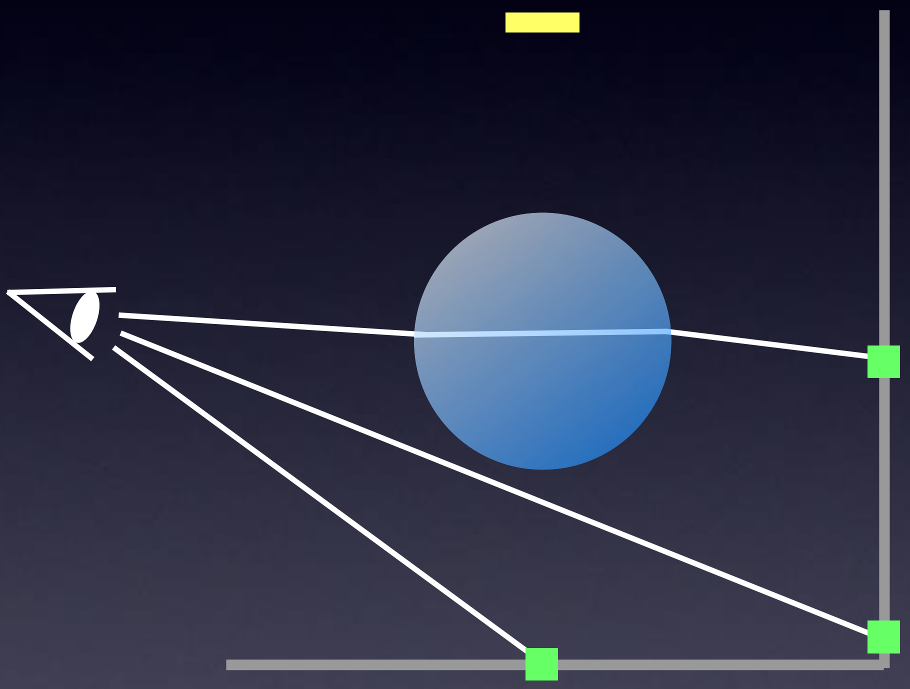
Progressive Photon Mapping



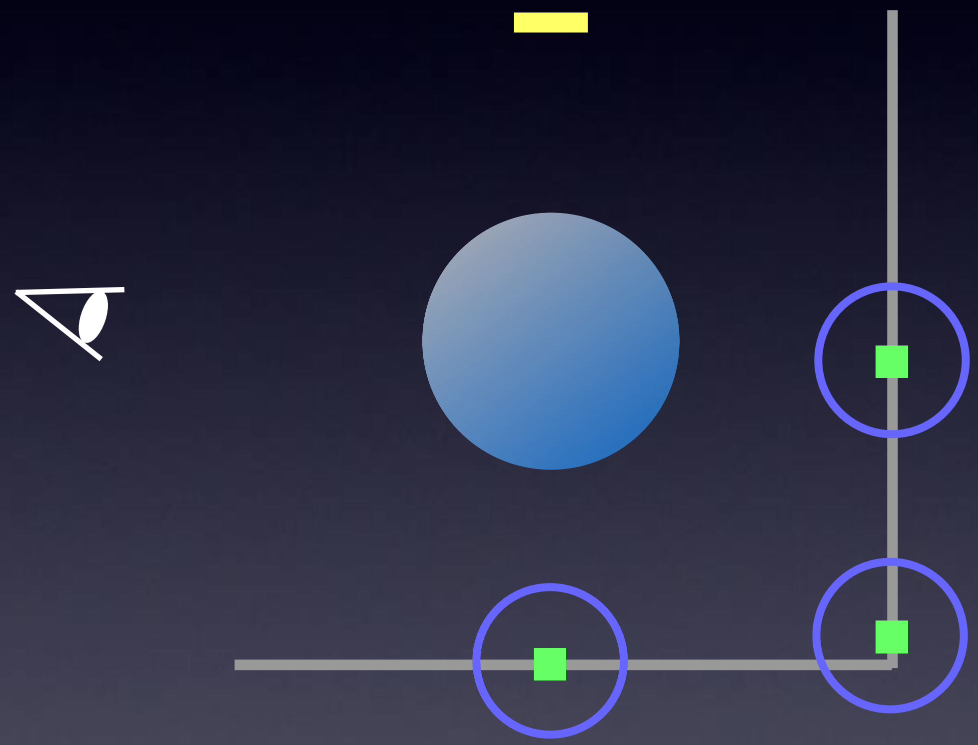
Progressive Photon Mapping - Initial Pass



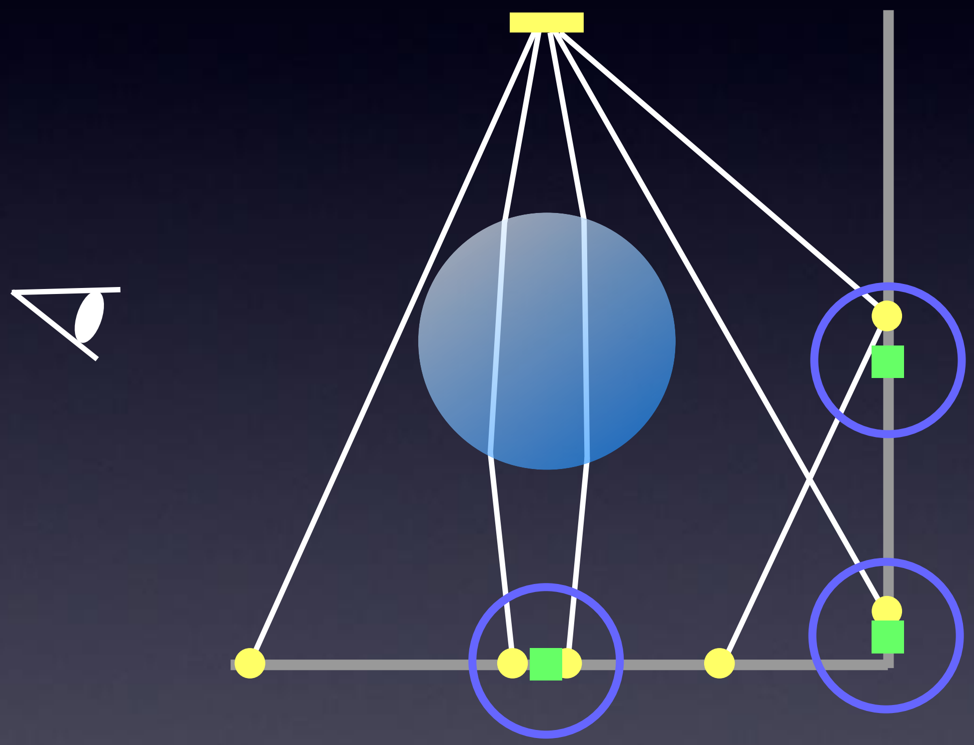
Progressive Photon Mapping - Initial Pass



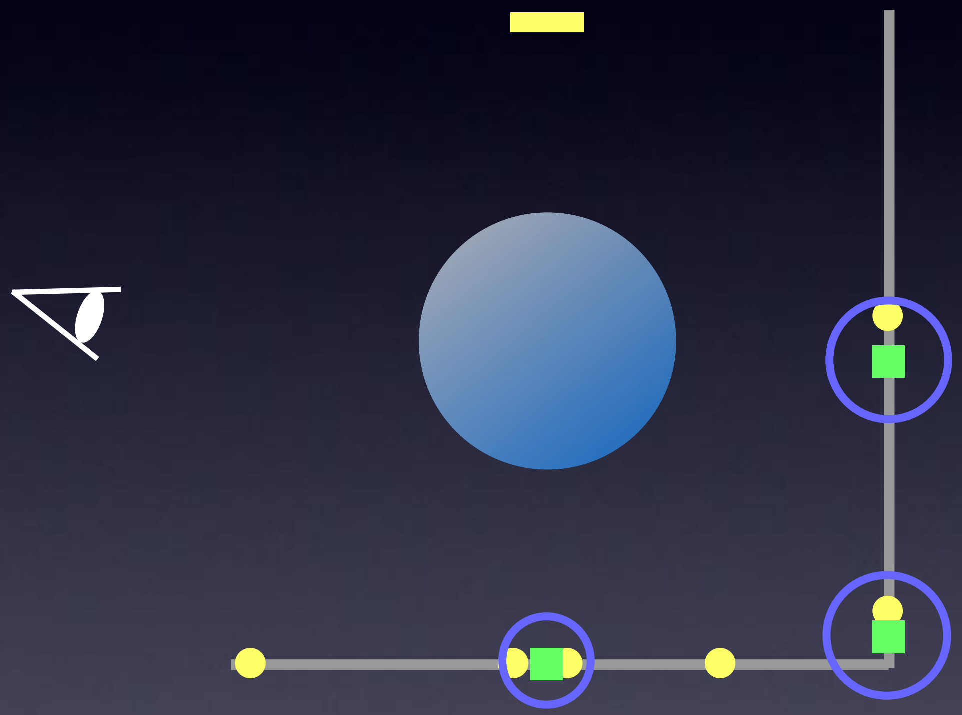
Progressive Photon Mapping - Initial Pass



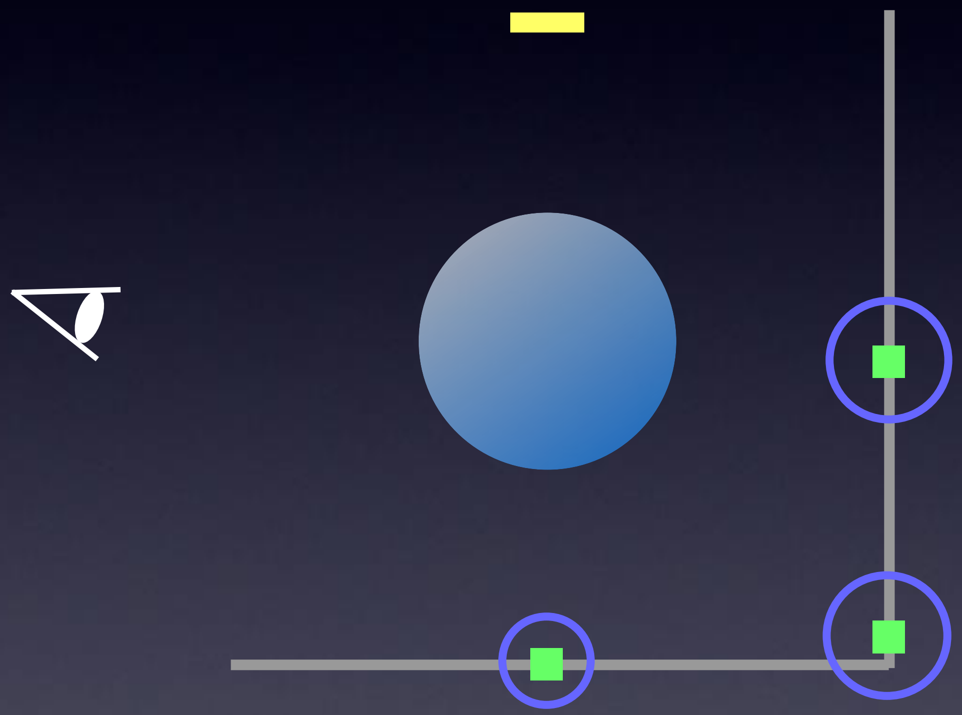
Progressive Photon Mapping - 1st Refinement Pass



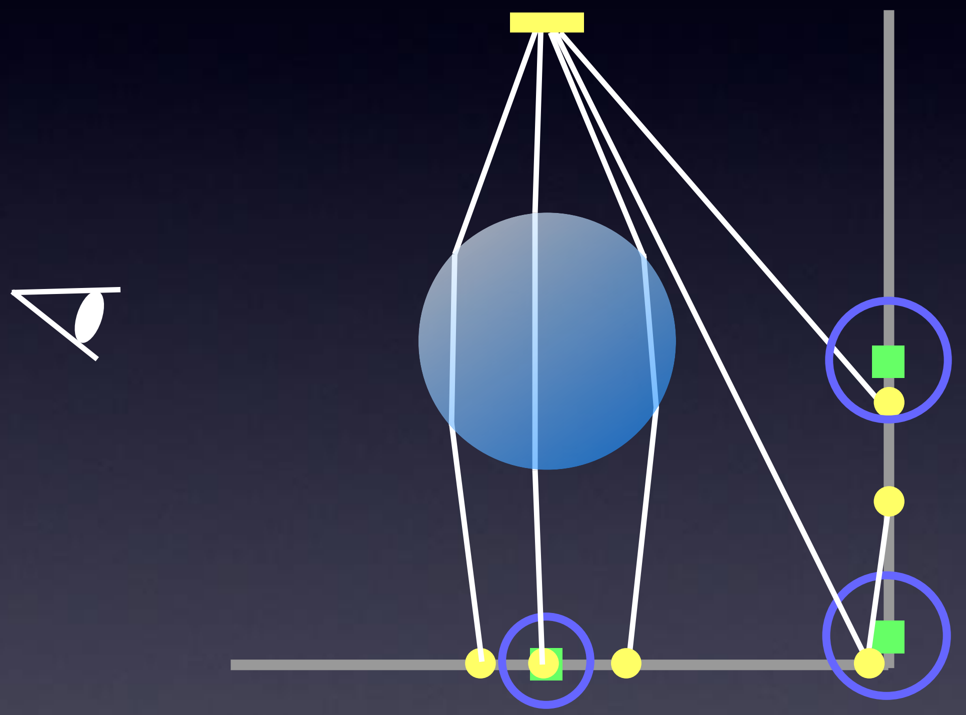
Progressive Photon Mapping - 1st Refinement Pass



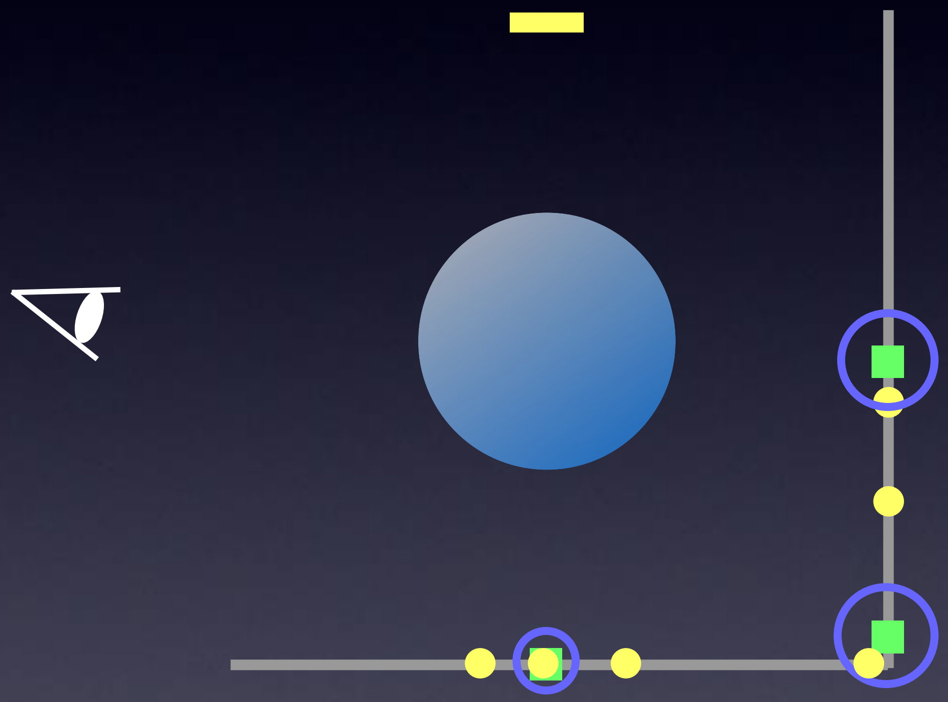
Progressive Photon Mapping - 1st Refinement Pass



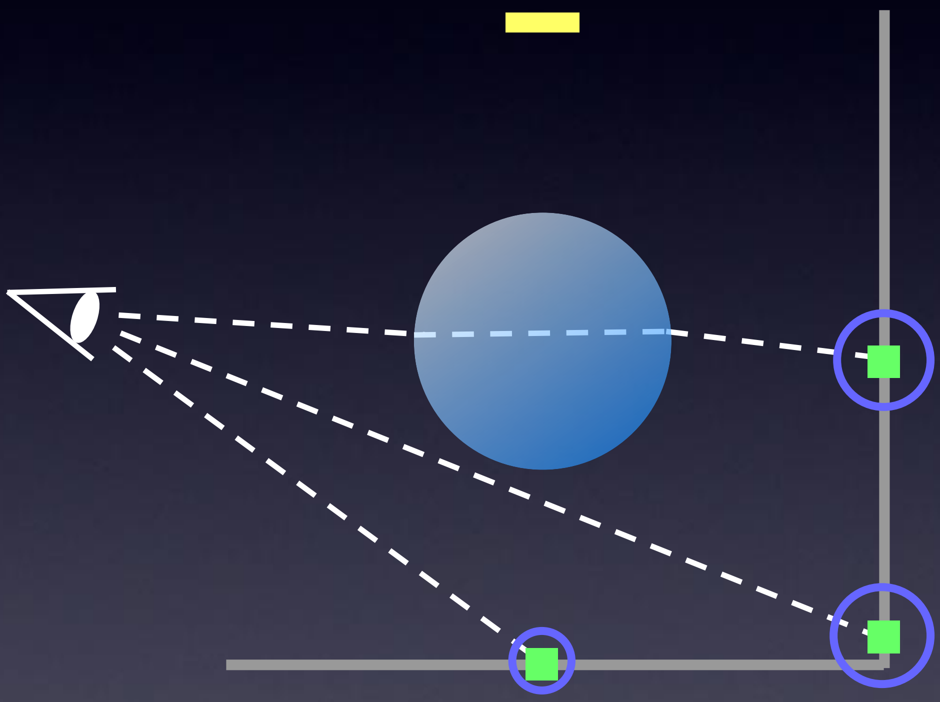
Progressive Photon Mapping - 2nd Refinement Pass



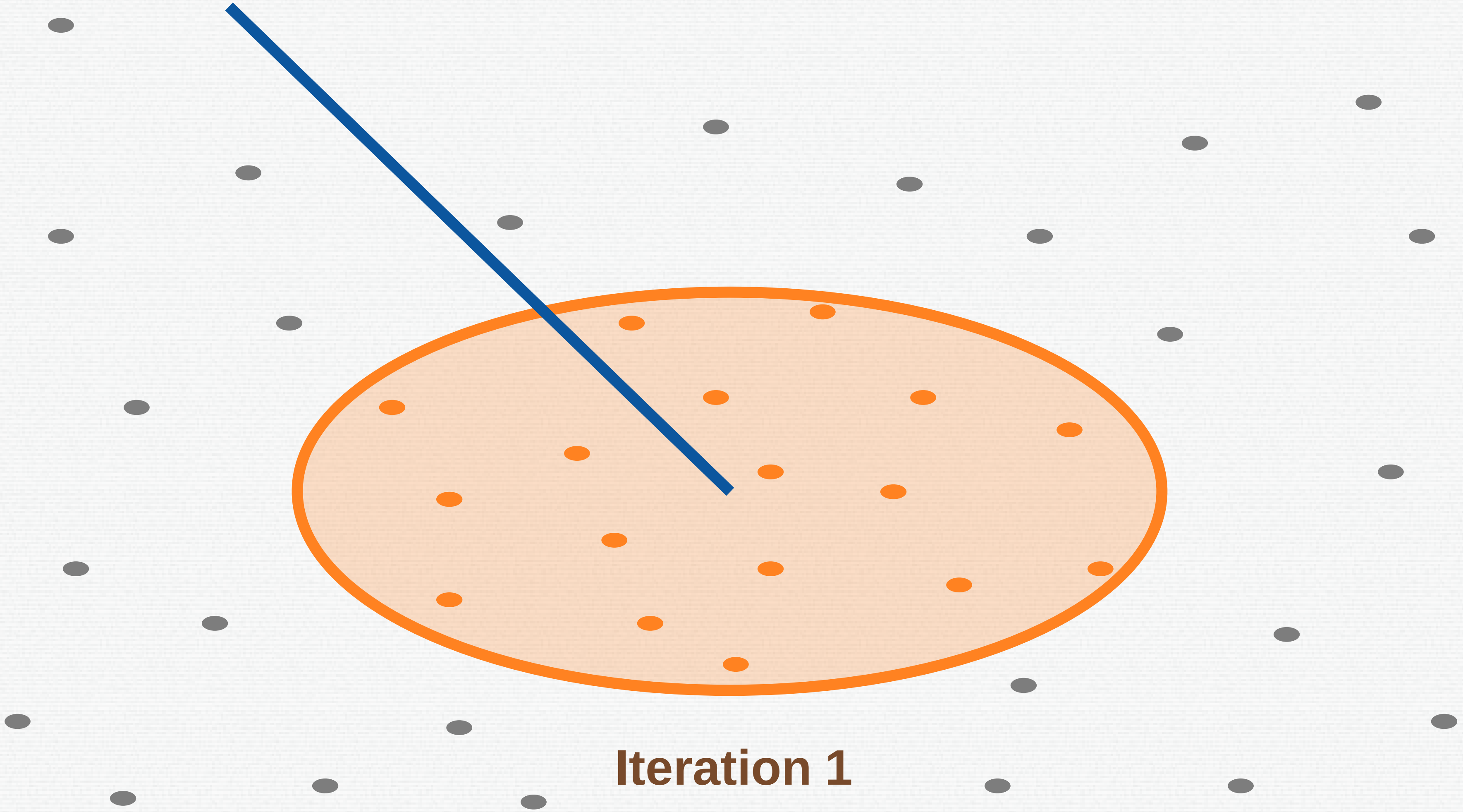
Progressive Photon Mapping - 2nd Refinement Pass



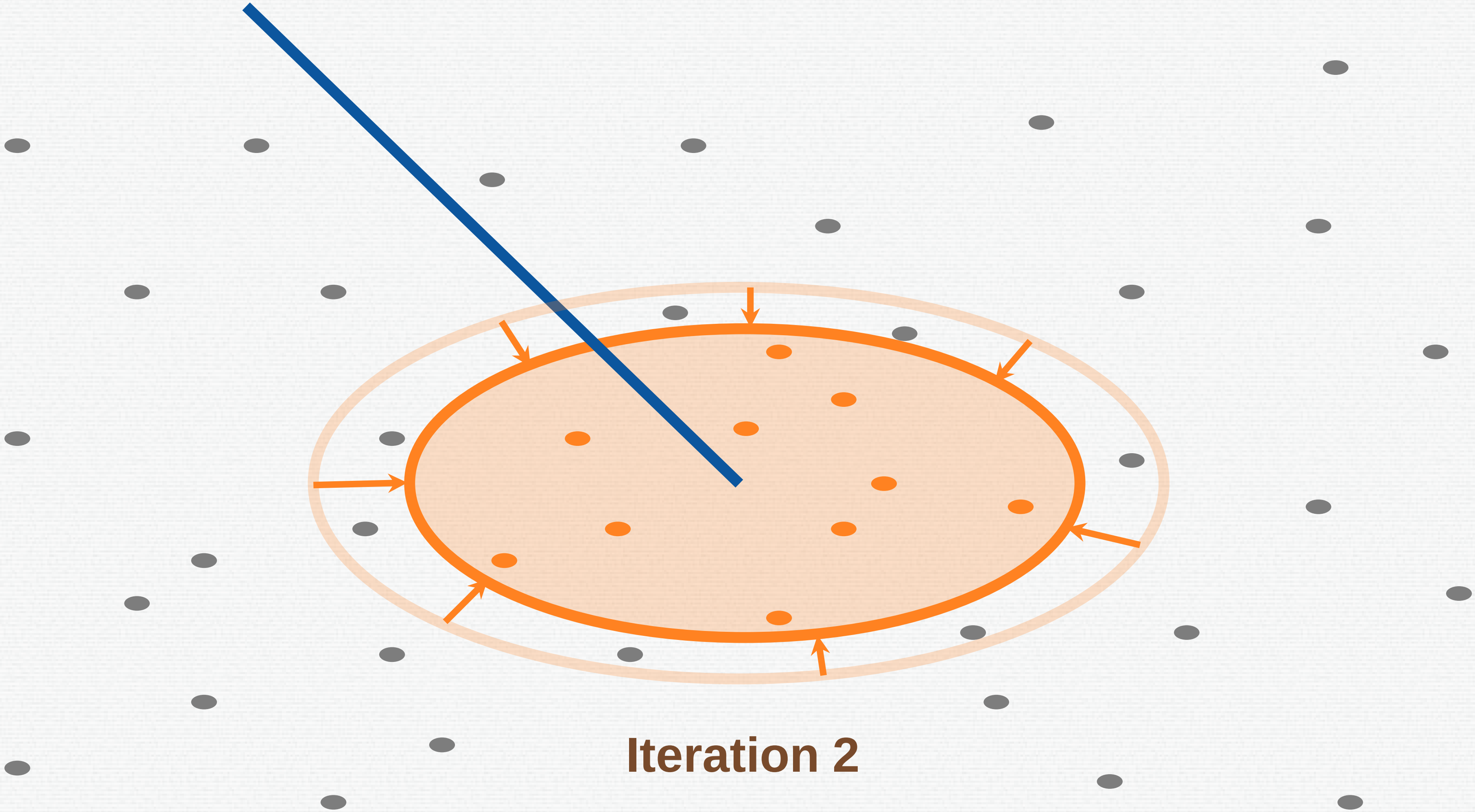
Progressive Photon Mapping - Rendering



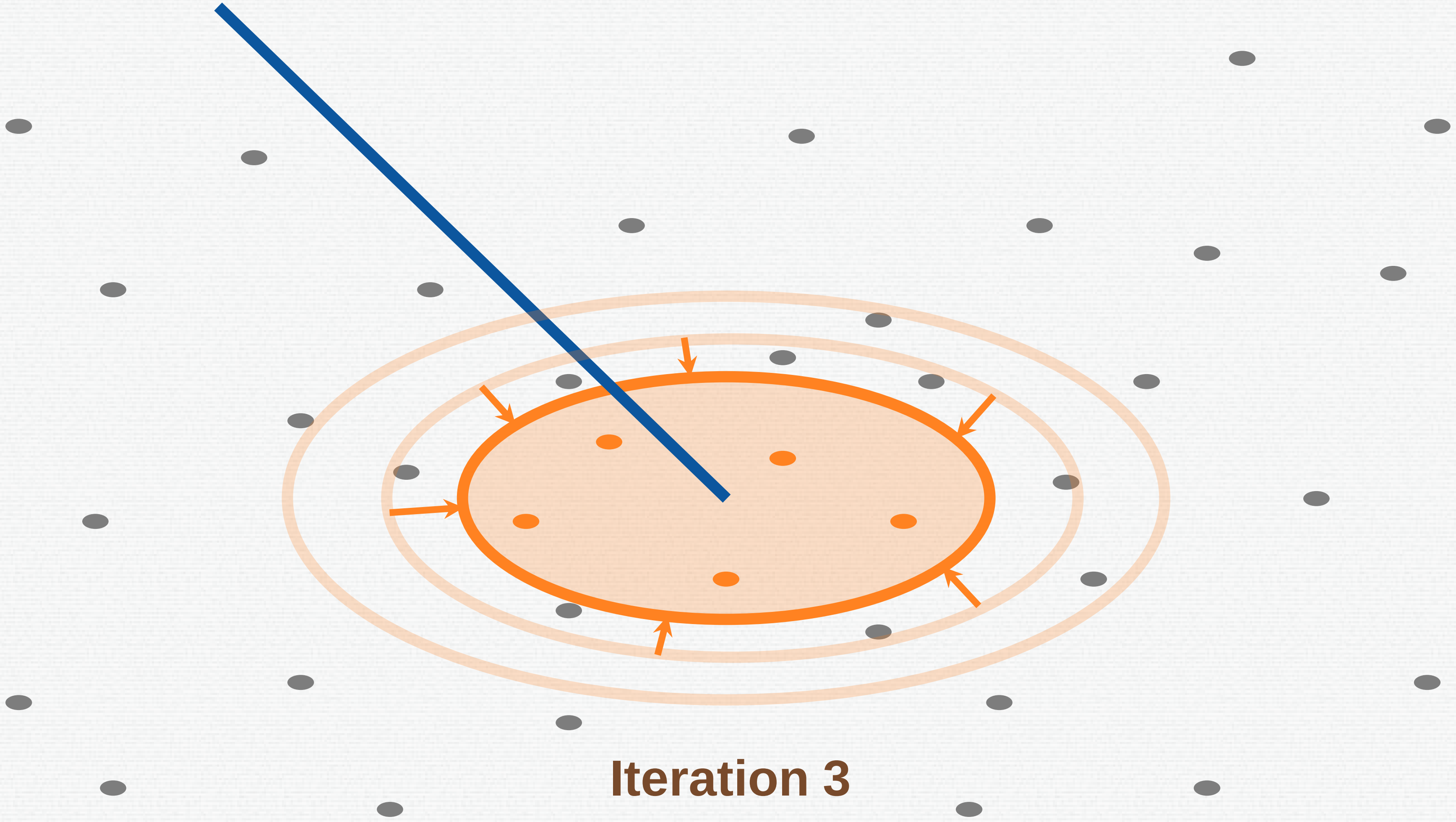
Radius Reduction



Radius Reduction

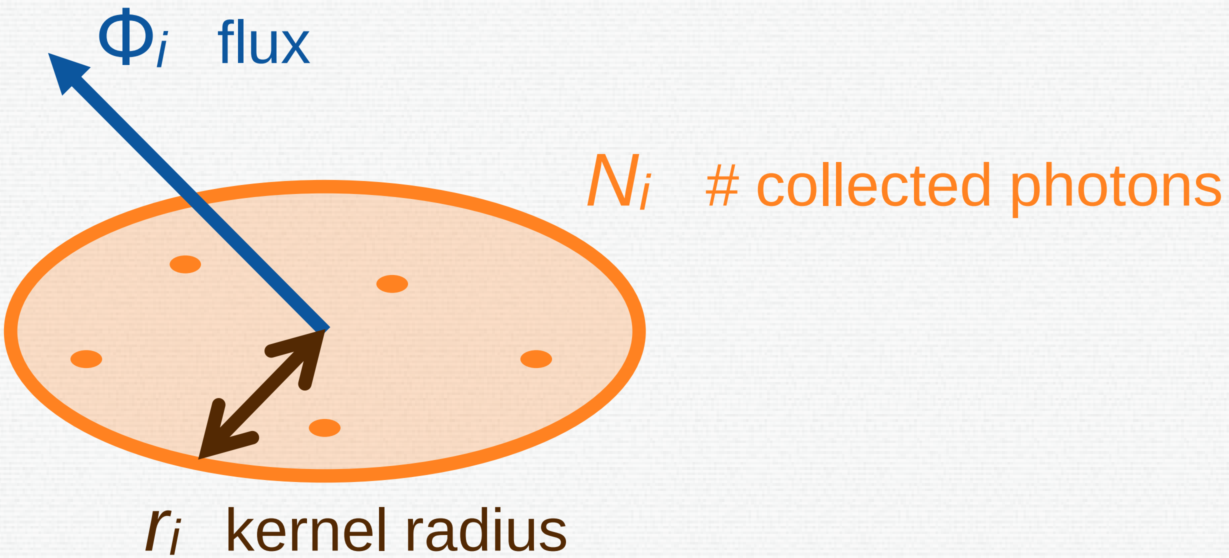


Radius Reduction



Iteration 3

Locations with Statistics



Radius Reduction

$$\frac{r_{i+1}^2}{r_i^2} = \frac{N_i + \alpha M_i}{N_i + M_i}$$

currently collected photons

totally collected photons

Stochastic PPM

Hachisuka & Jensen (2009)


Stochastic Progressive Photon Mapping

Toshiya Hachisuka   Henrik Wann Jensen

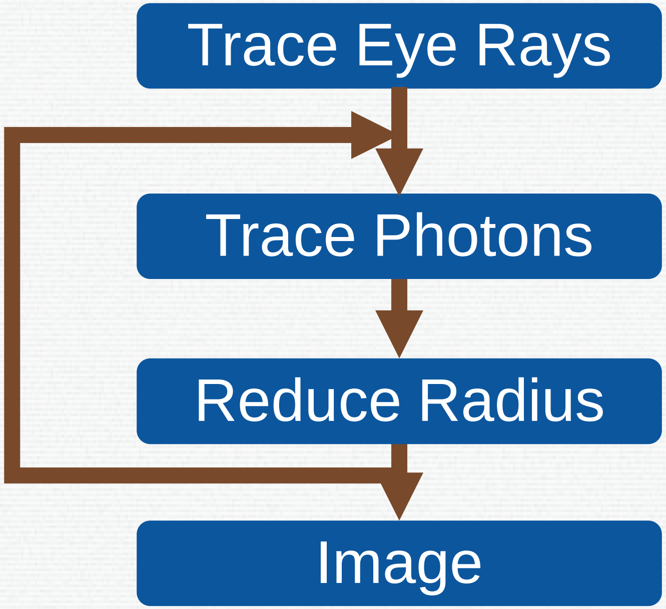
UC San Diego

Abstract

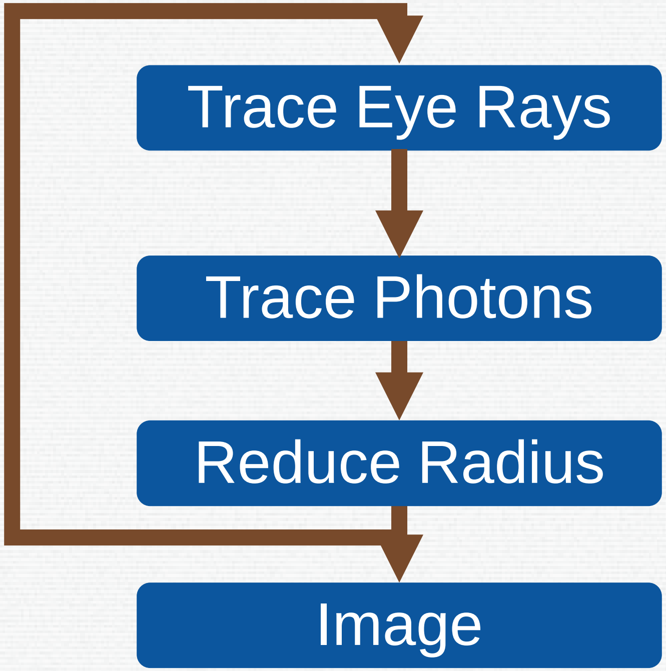
1 Introduction

- ★ Glossy reflections
- ★ Depth of field
- ★ Motion blur

Stochastic PPM



Stochastic PPM



SIGGRAPH2011

Progressive Photon Mapping: A Probabilistic Approach

Claude Knaus and Matthias Zwicker

University of Bern

cgg
computer graphics group

b
UNIVERSIT
BERN

Our Probabilistic Approach

- New derivation using probabilistic perspective
- No local statistics
- Parallelization
- Convergence analysis
- Arbitrary radiance estimation kernels
- Easy to generalize

Radiance Estimation

$$L(x) \approx \frac{1}{N_e} \sum_{i=1}^{N_s} k_r(x_i - x)\gamma_i$$

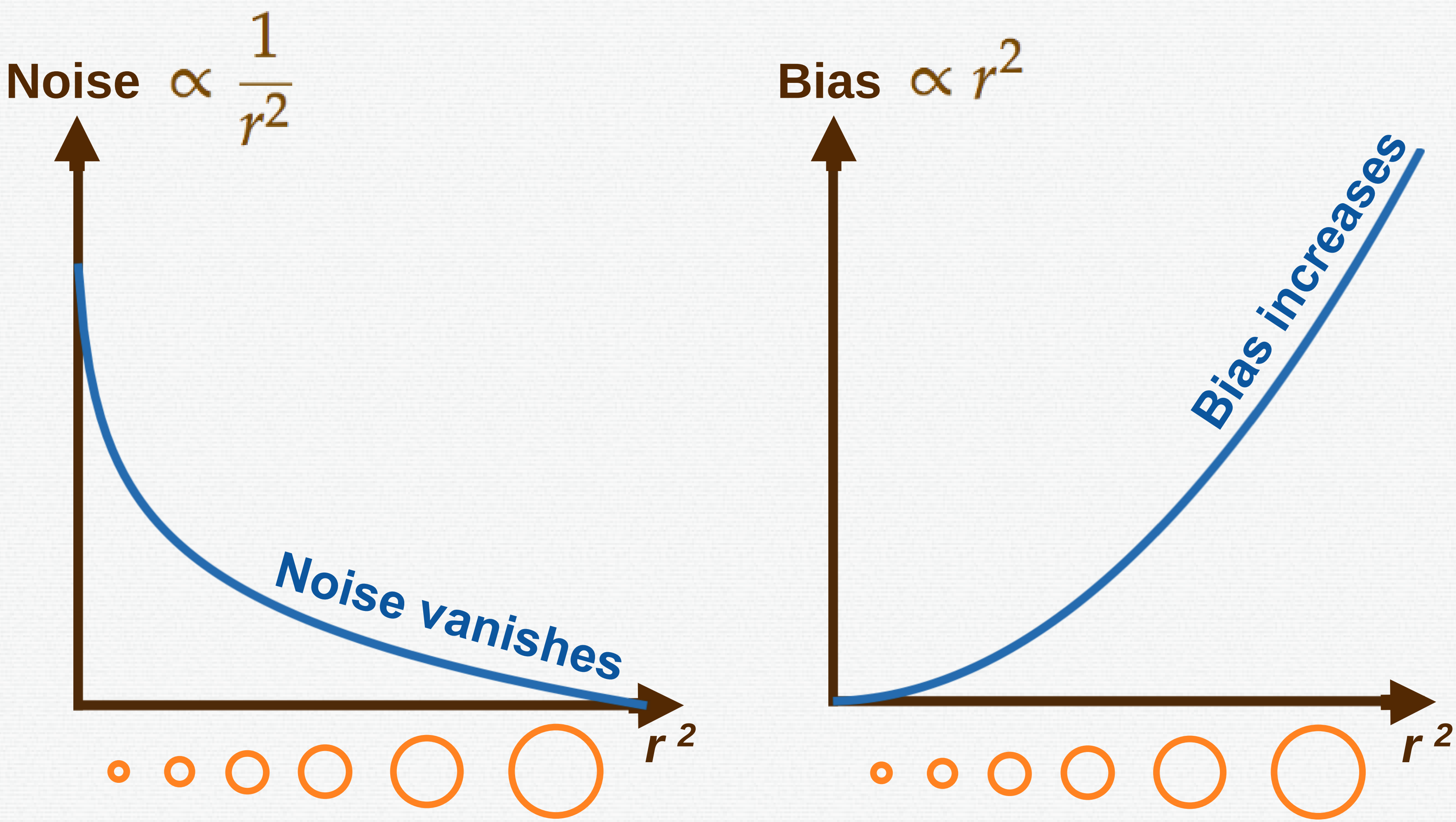
Stored Photons

Emitted Photons

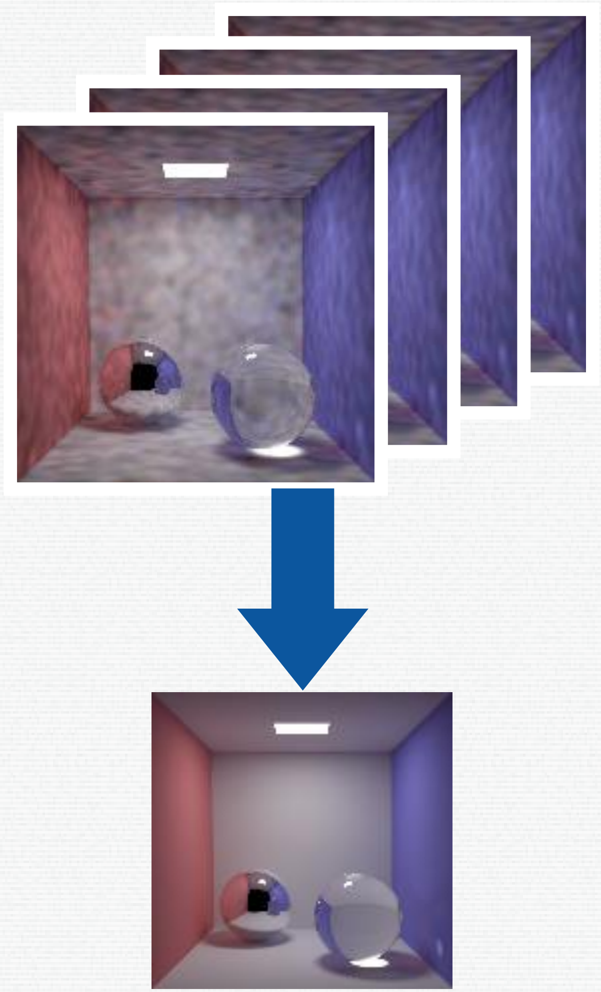
Kernel with Radius *r*

Photon Position

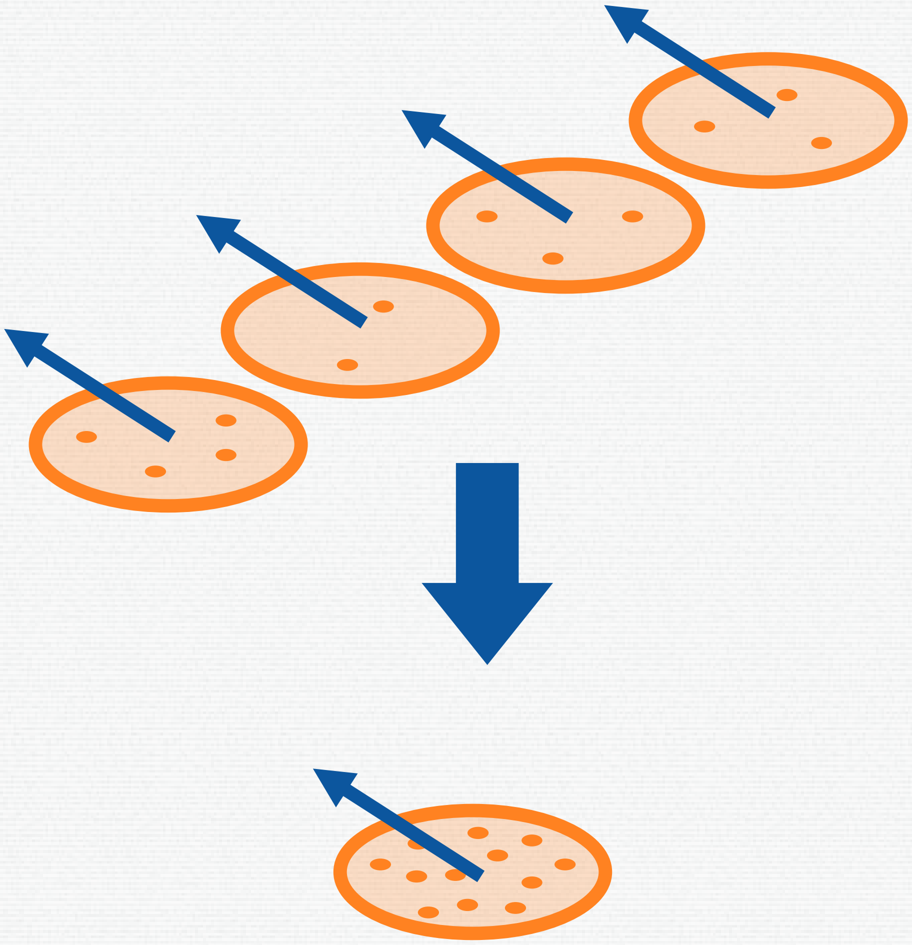
Photon Power



Noise $\propto \frac{1}{r^2}$
Noise vanishes
r^2
Bias $\propto r^2$
Bias increases
r^2

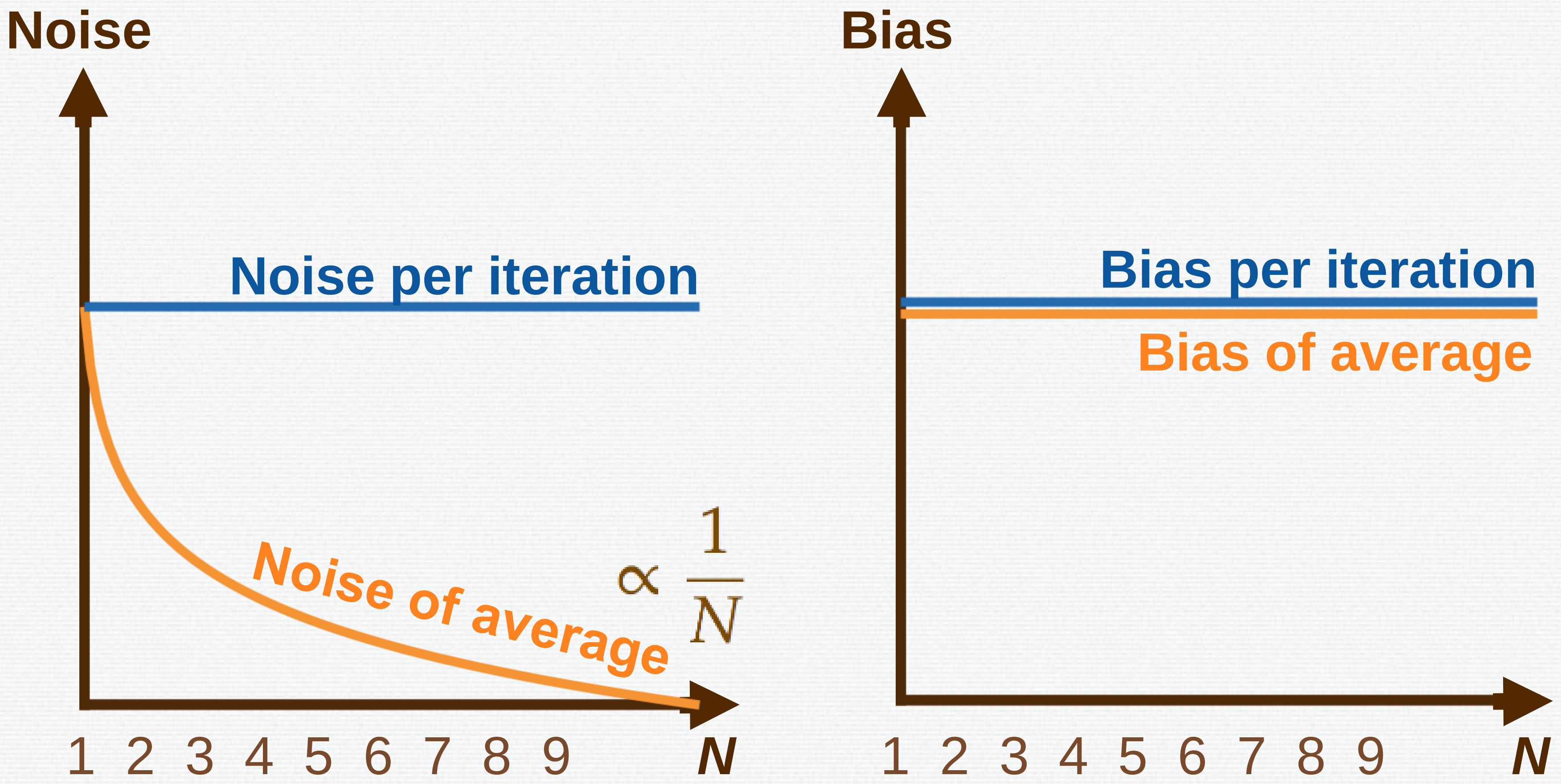


Averaged Image

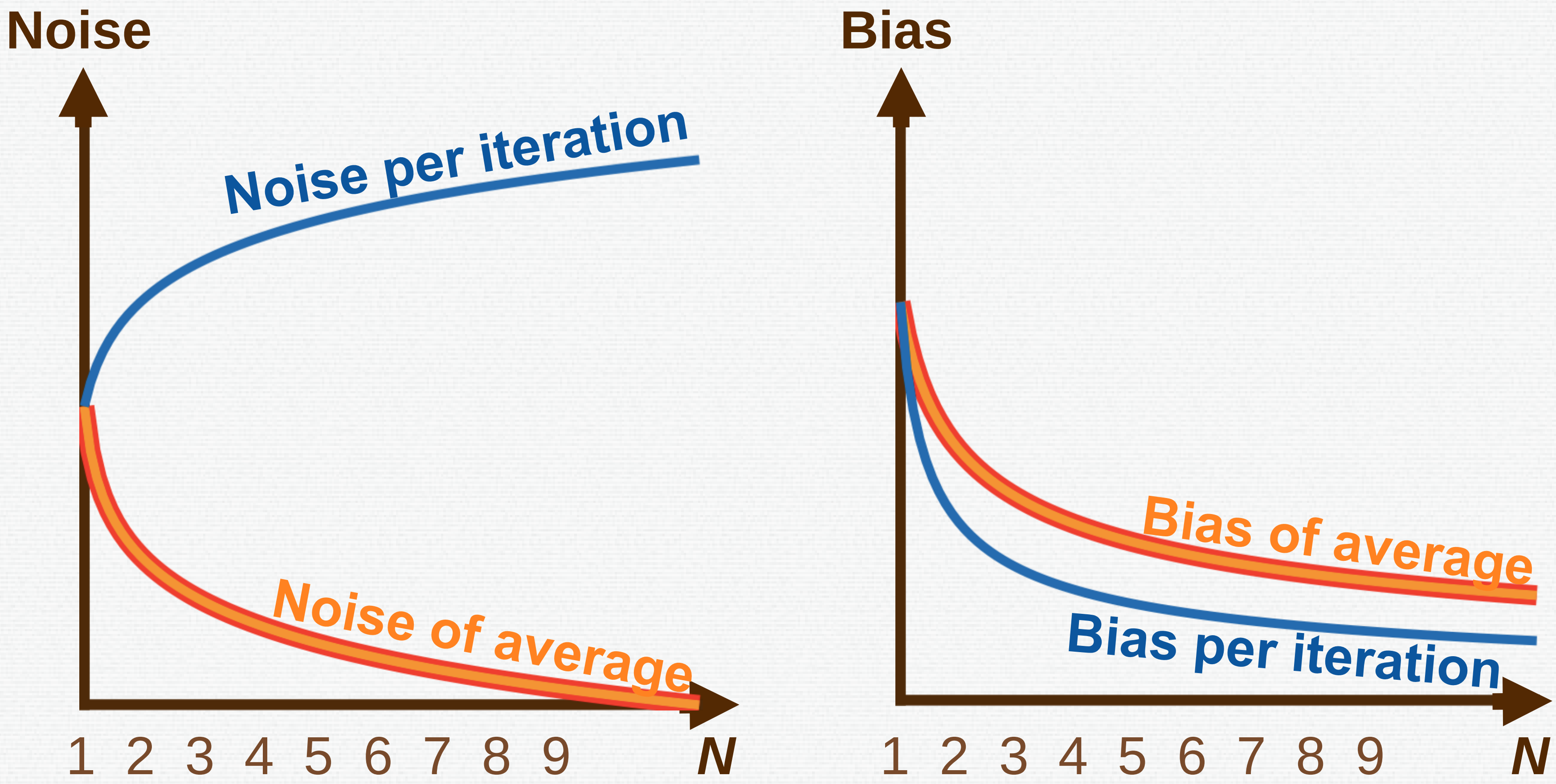


Averaged Radiance Estimate

Averaged Radiance Estimates

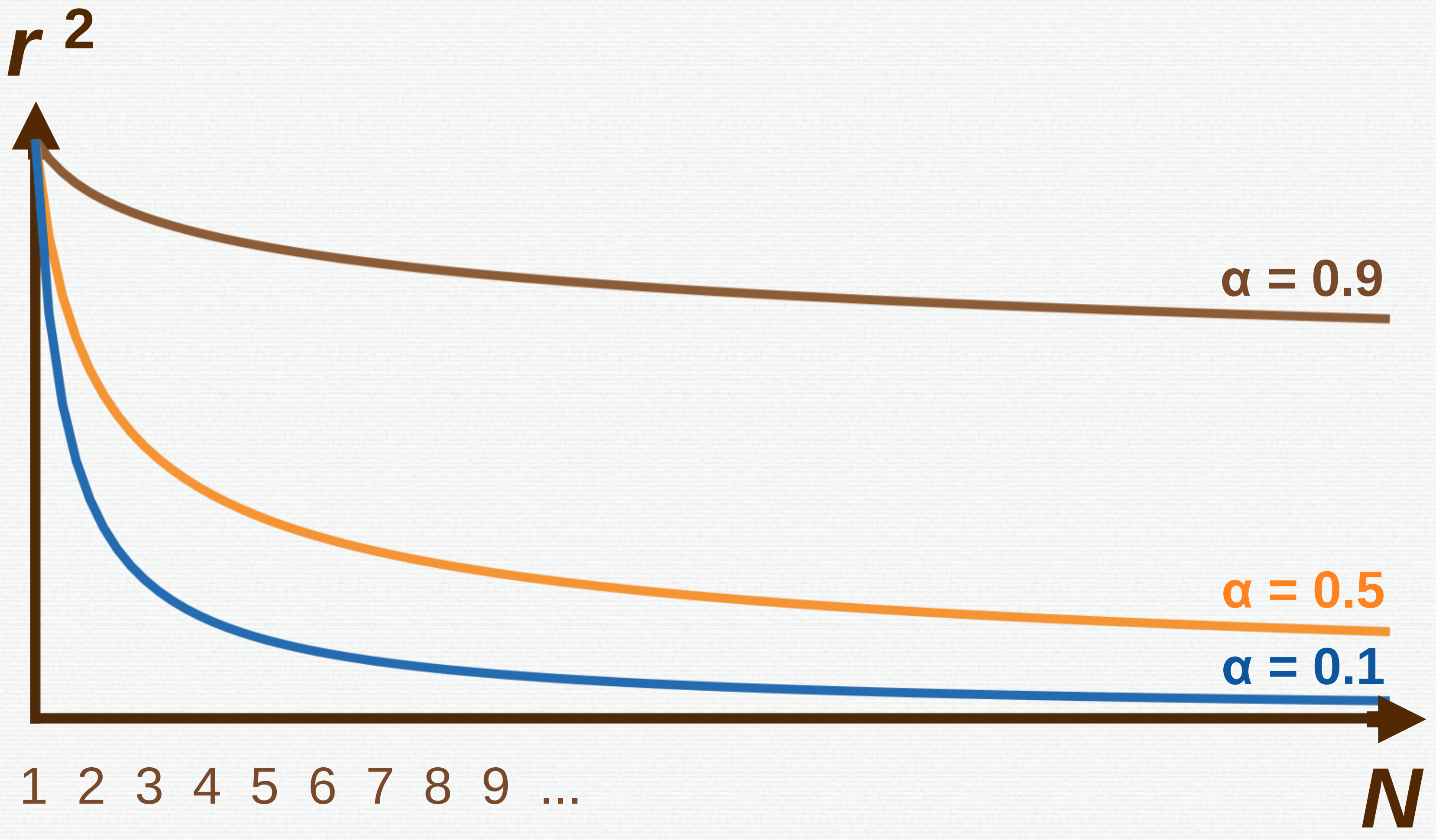


Averaging + Radius Reduction



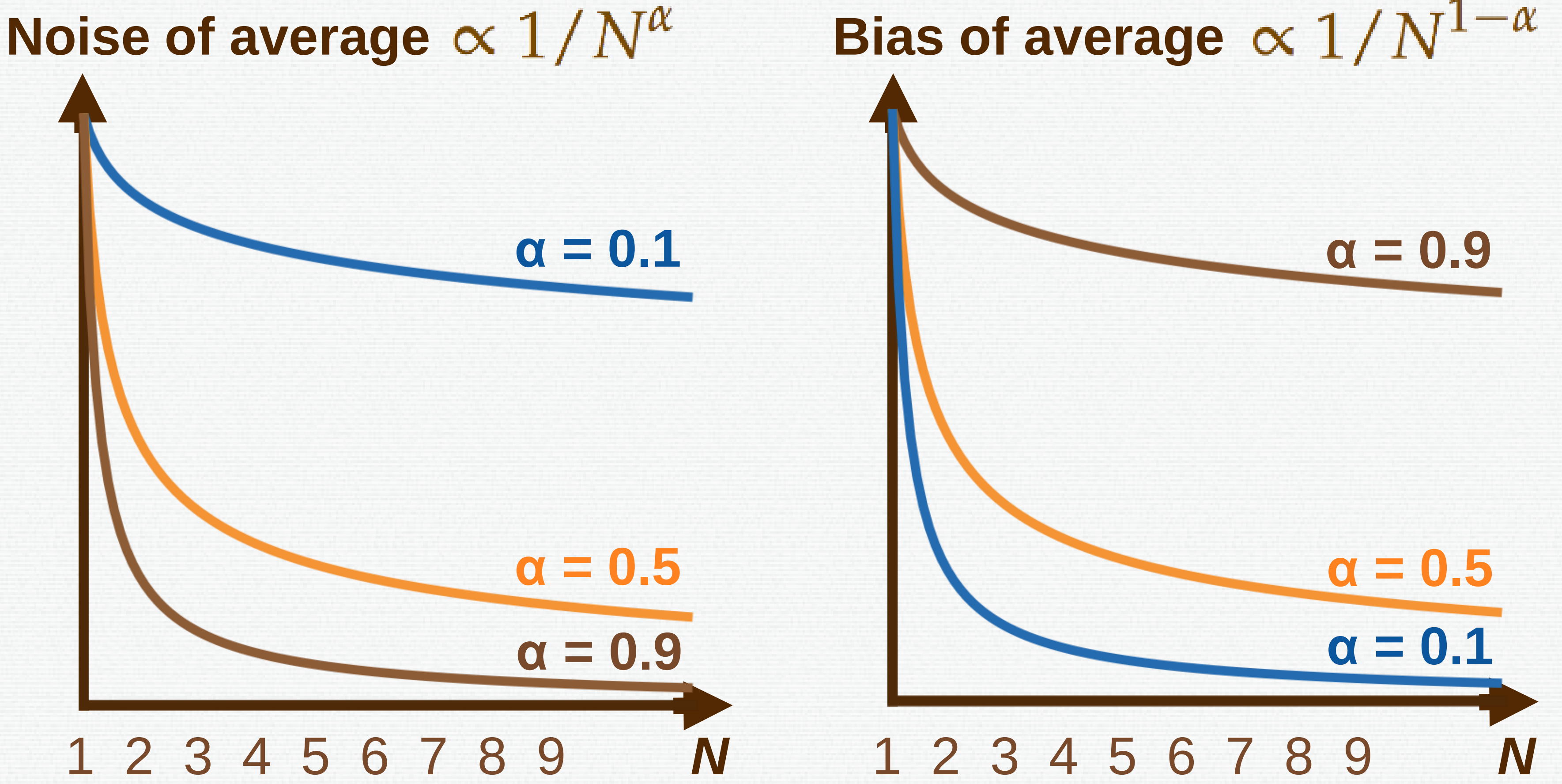
Radius Sequence

$$\frac{r_{i+1}^2}{r_i^2} = \frac{i+\alpha}{i+1}$$



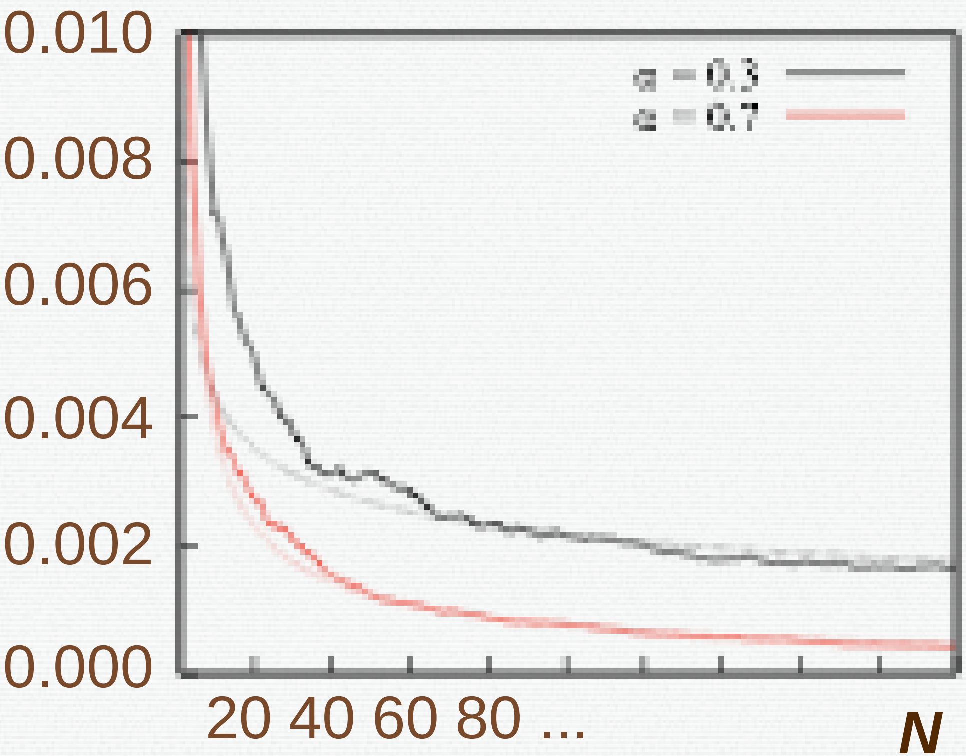
r 2
α = 0.9
α = 0.5
α = 0.1
1 2 3 4 5 6 7 8 9 ...
N

Asymptotic Convergence

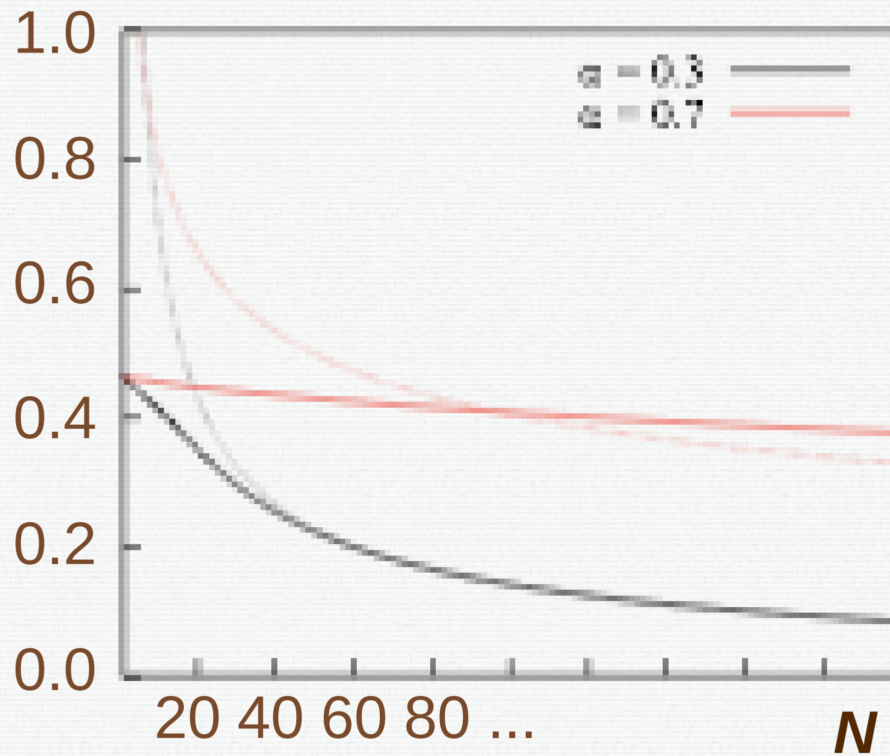


Empirical Validation

Noise of average



Bias of average



No Statistics Needed

PPM Radius Update Rule

$$\frac{r_{i+1}^2}{r_i^2} = \frac{N_i + \alpha M_i}{N_i + M_i}$$

Local Statistics

Our Radius Sequence

$$\frac{r_{i+1}^2}{r_i^2} = \frac{i + \alpha}{i + 1}$$

No Local Statistics!

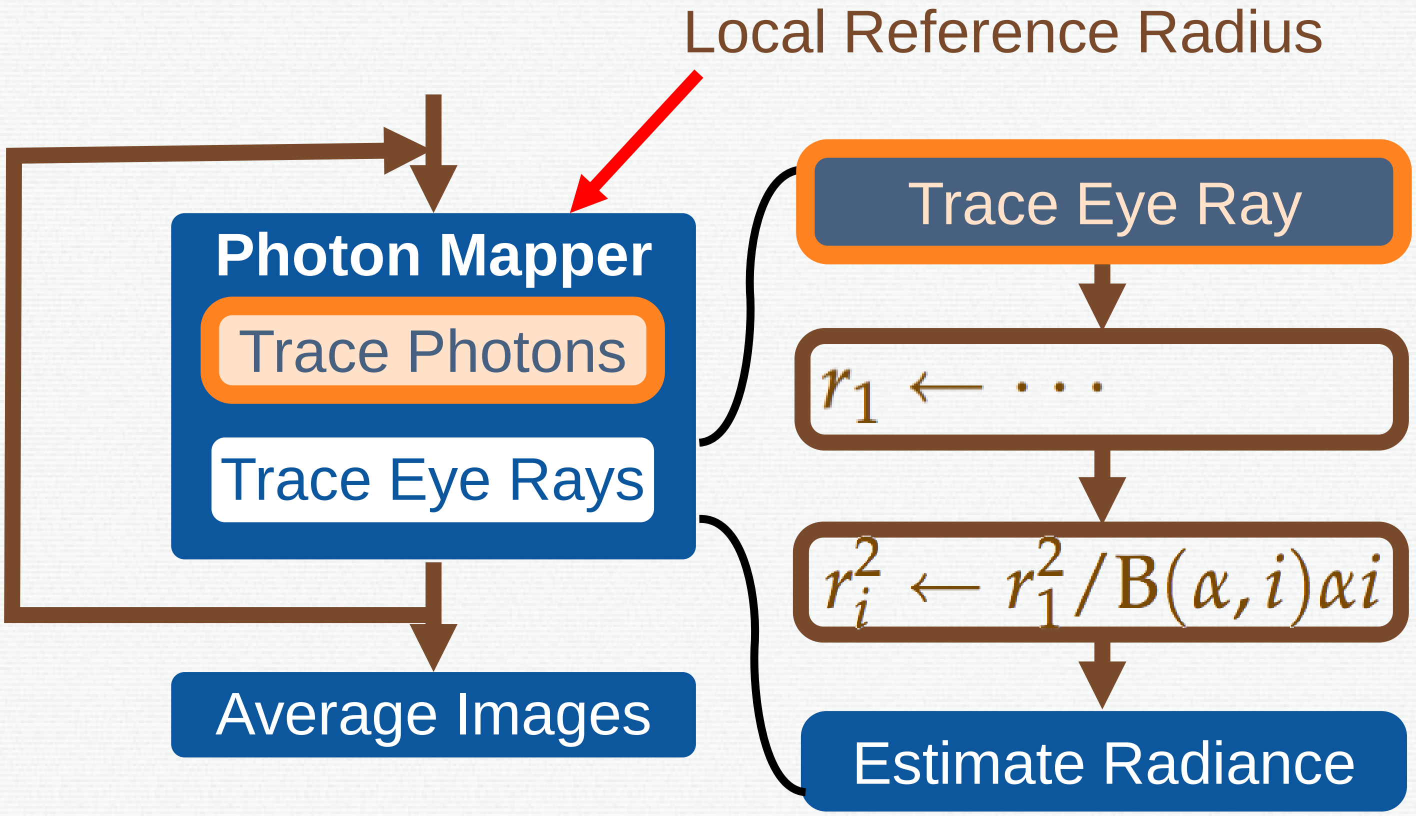
Radius Sequence (Explicit)

Reference Radius

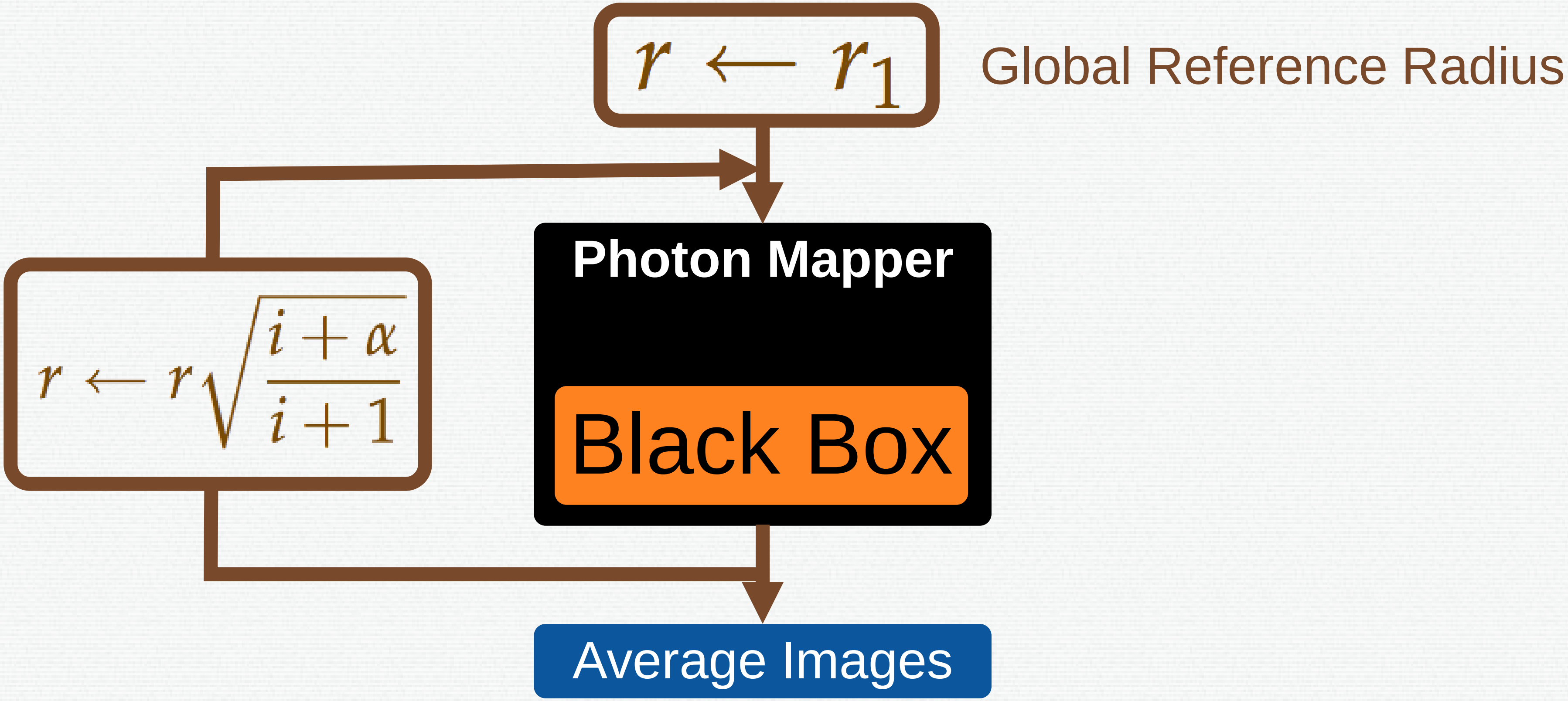
$$r_i^2 = \frac{r_1^2}{\mathrm{B}(\alpha, i)\alpha i}$$

Beta Function

Our Algorithm



Script



$r \leftarrow r_1$
Global Reference Radius
$r \leftarrow r\sqrt{\frac{i+\alpha}{i+1}}$
Photon Mapper
Black Box
Average Images


1
2
3
4
5
6
1000

1

2

3

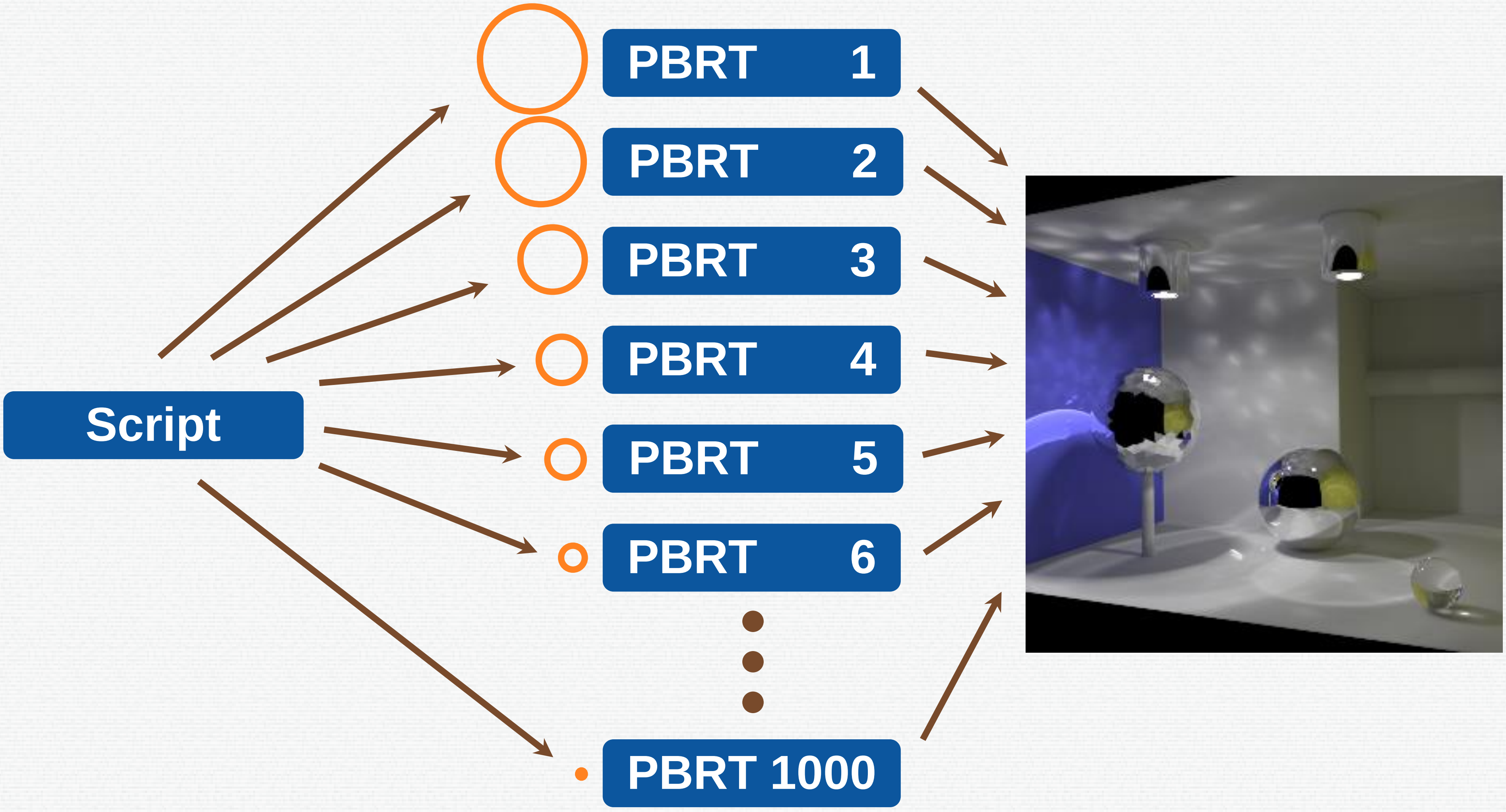
4

5

6

⋮

1000


Script
PBRT 1
PBRT 2
PBRT 3
PBRT 4
PBRT 5
PBRT 6
PBRT 1000

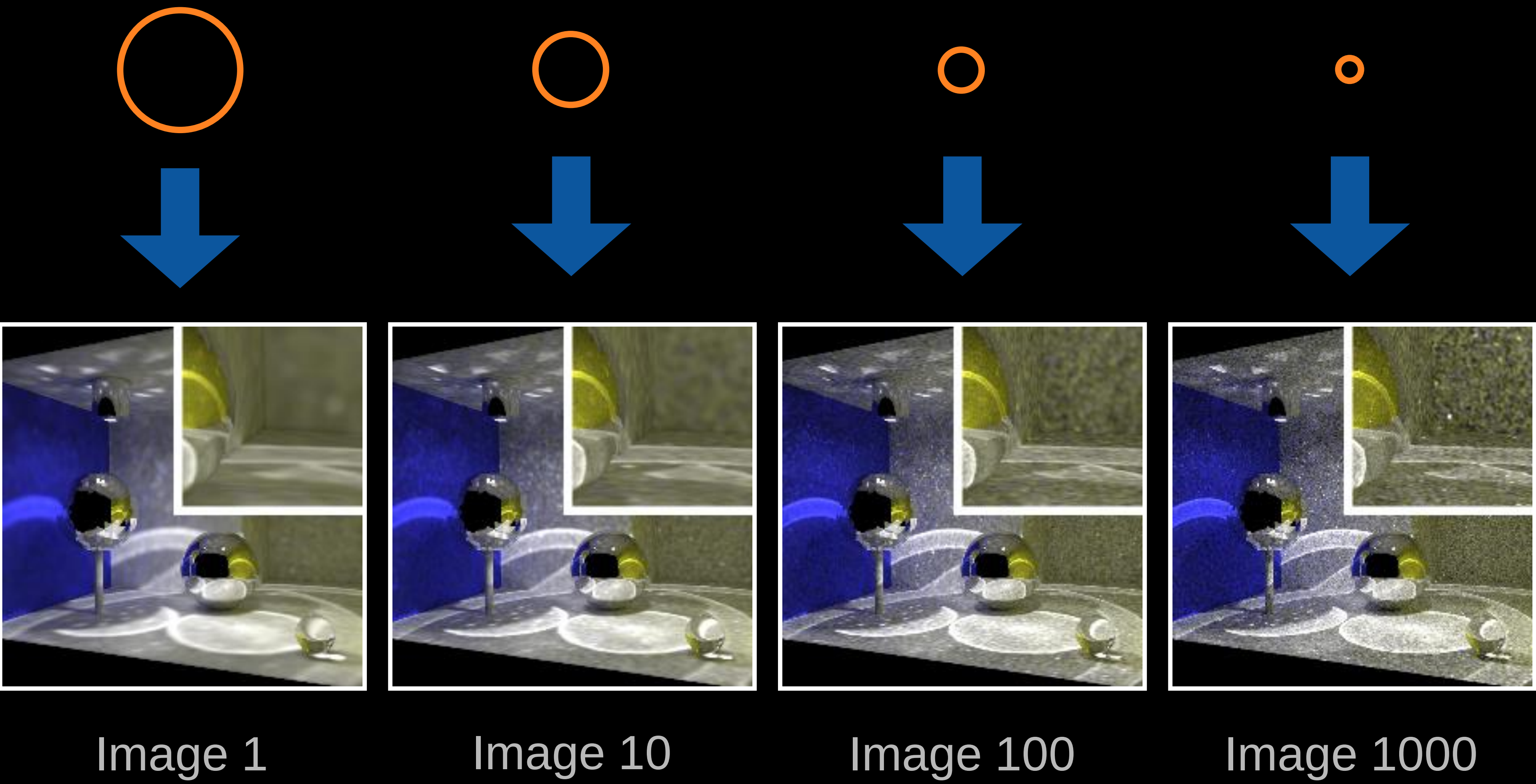
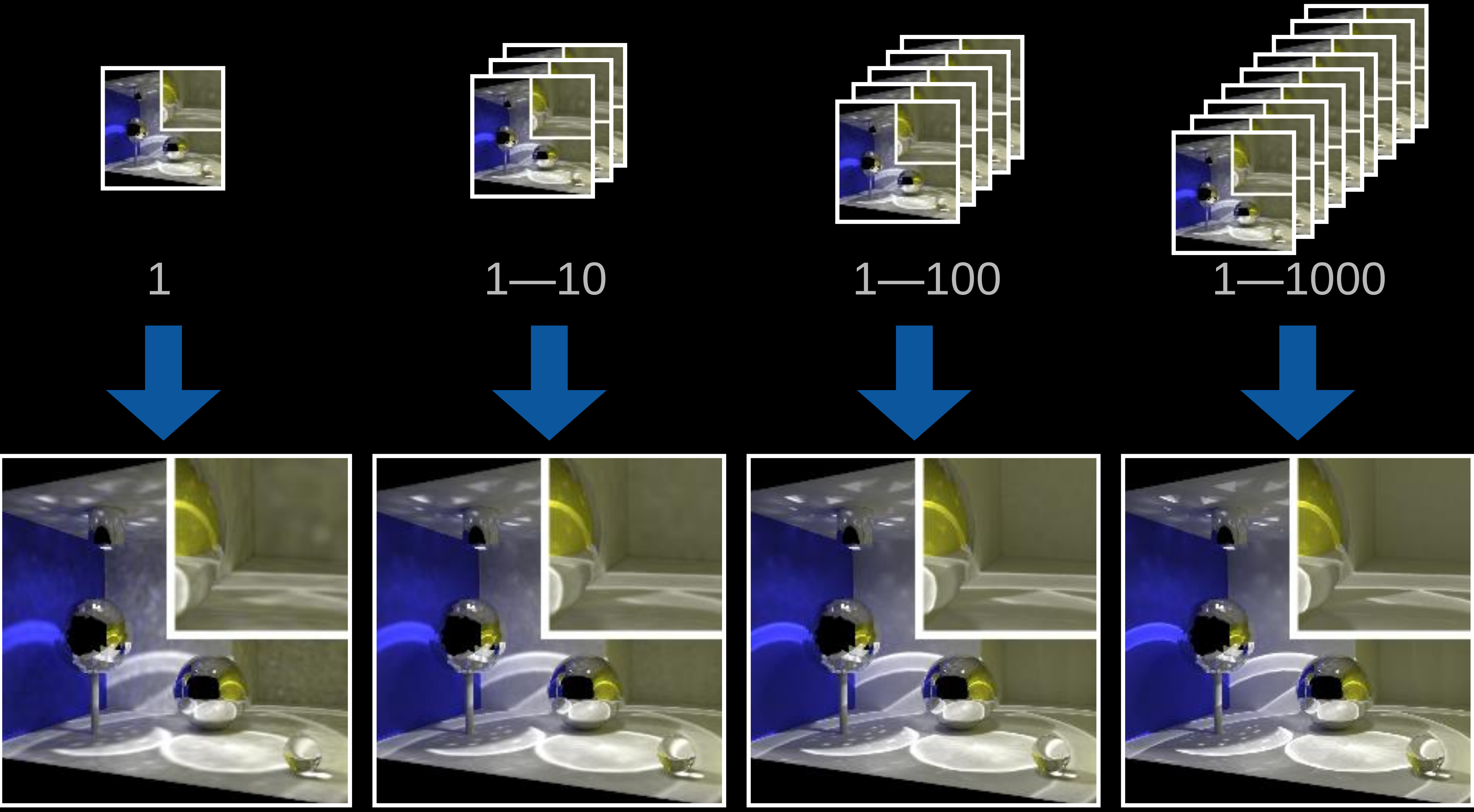
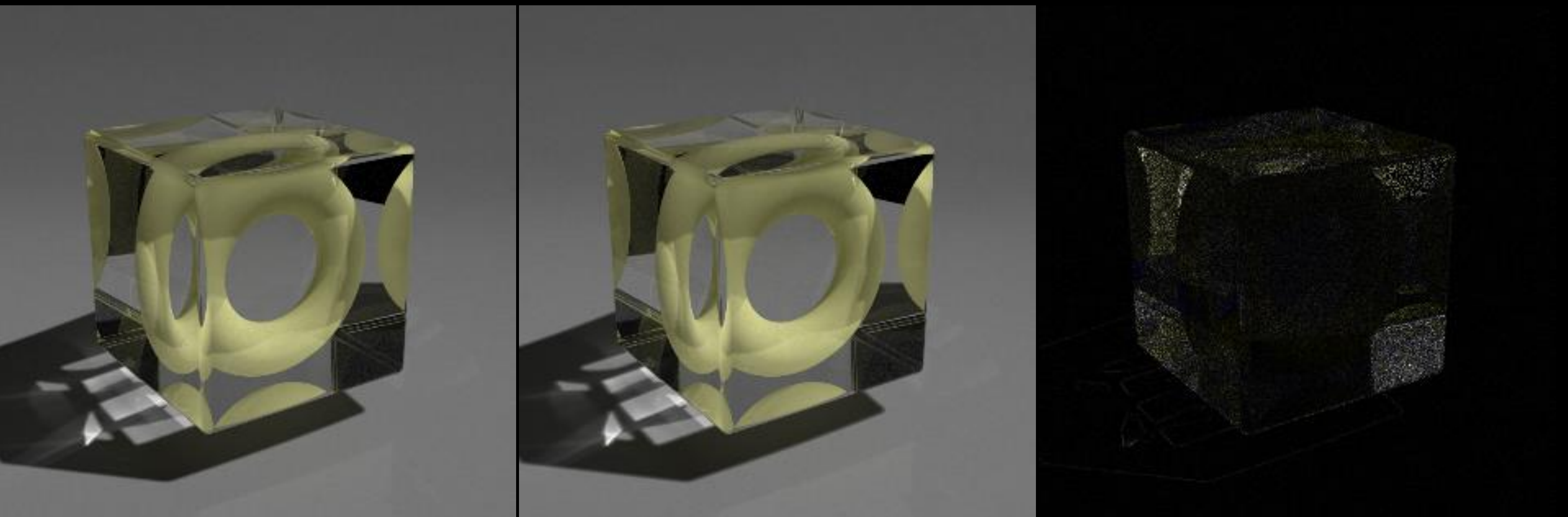


Image 1
Image 10
Image 100
Image 1000



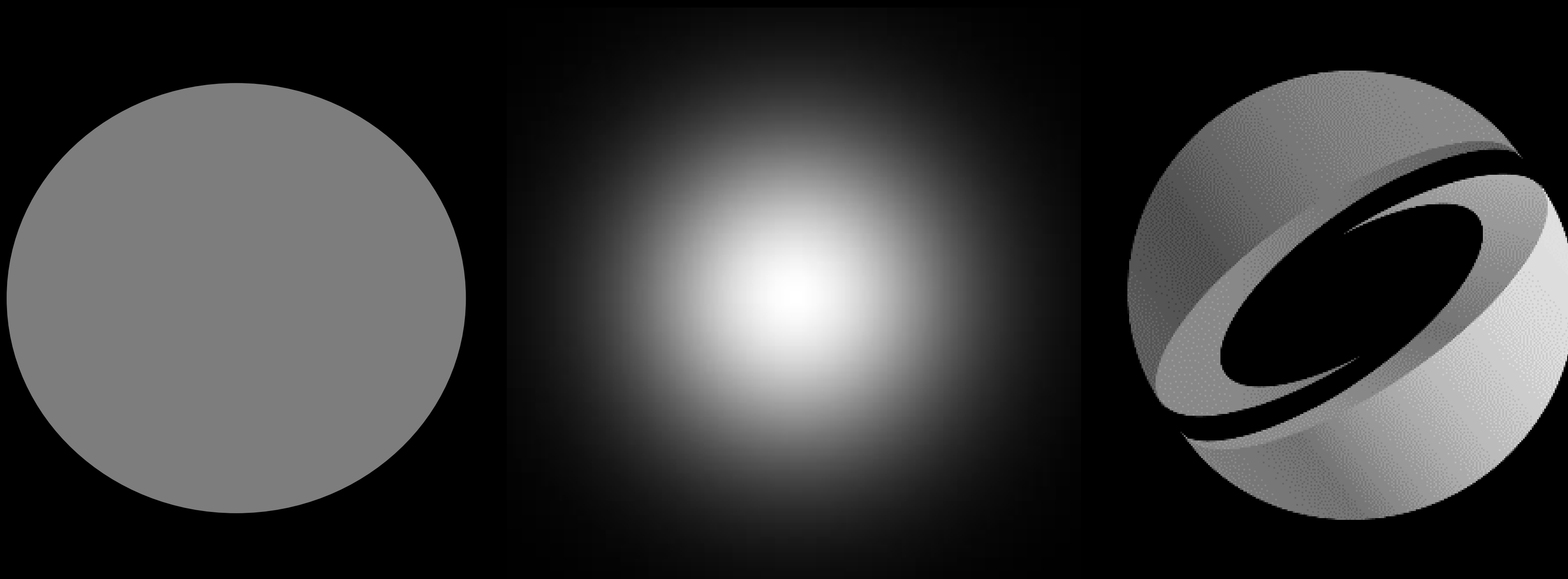
1
1—10
1—100
1—1000

Stochastic PPM | Our method | 20x Difference

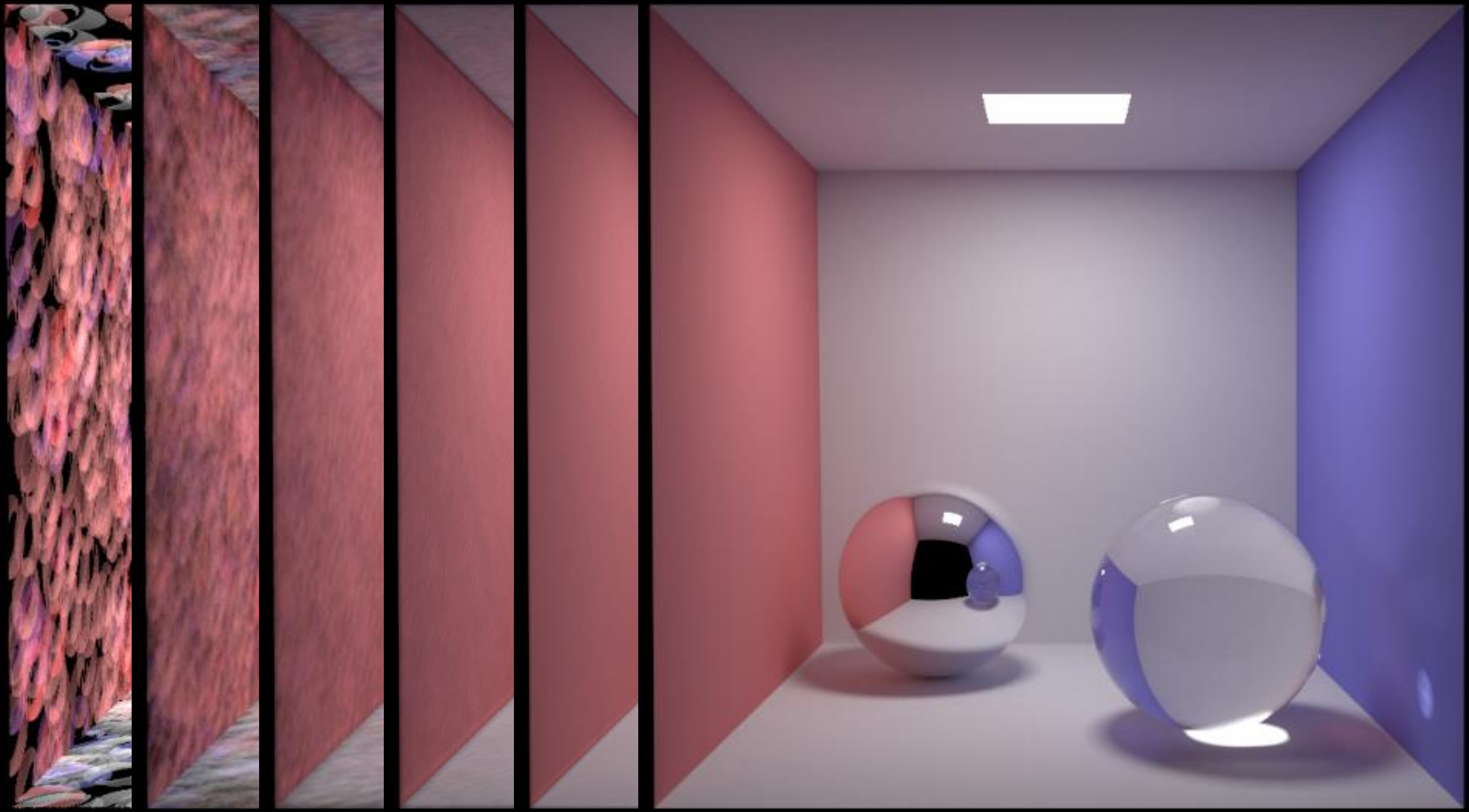


Scene courtesy of Toshiya Hachisuka

Arbitrary Kernels



Box | Gaussian | **SIGGRAPH**



Stochastic Effects

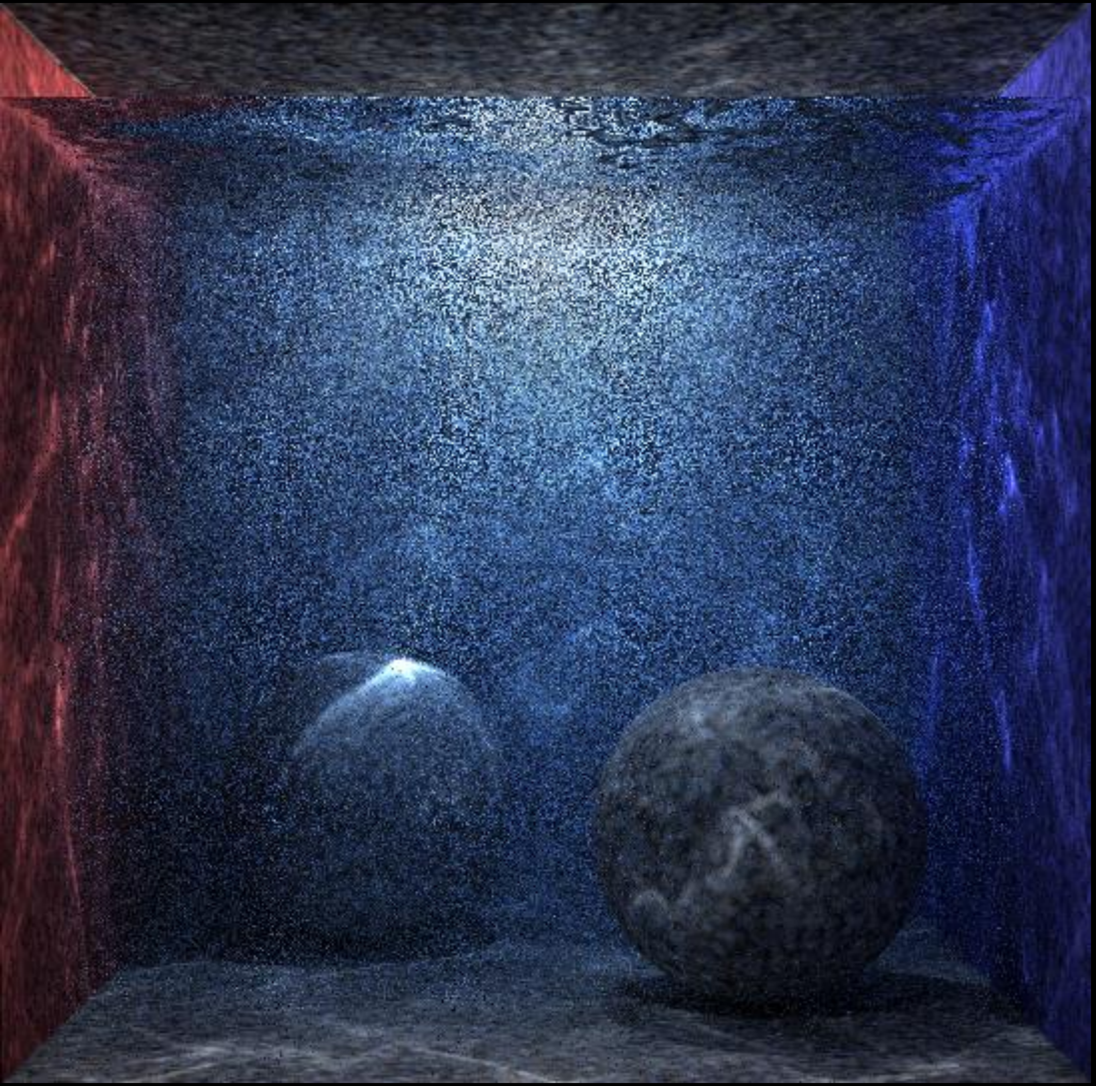
Scene courtesy of Toshiya Hachisuka

Participating Media

$$\frac{r_{i+1}^{2}}{r_{i}^{2}} = \frac{i+\alpha}{i+1}$$

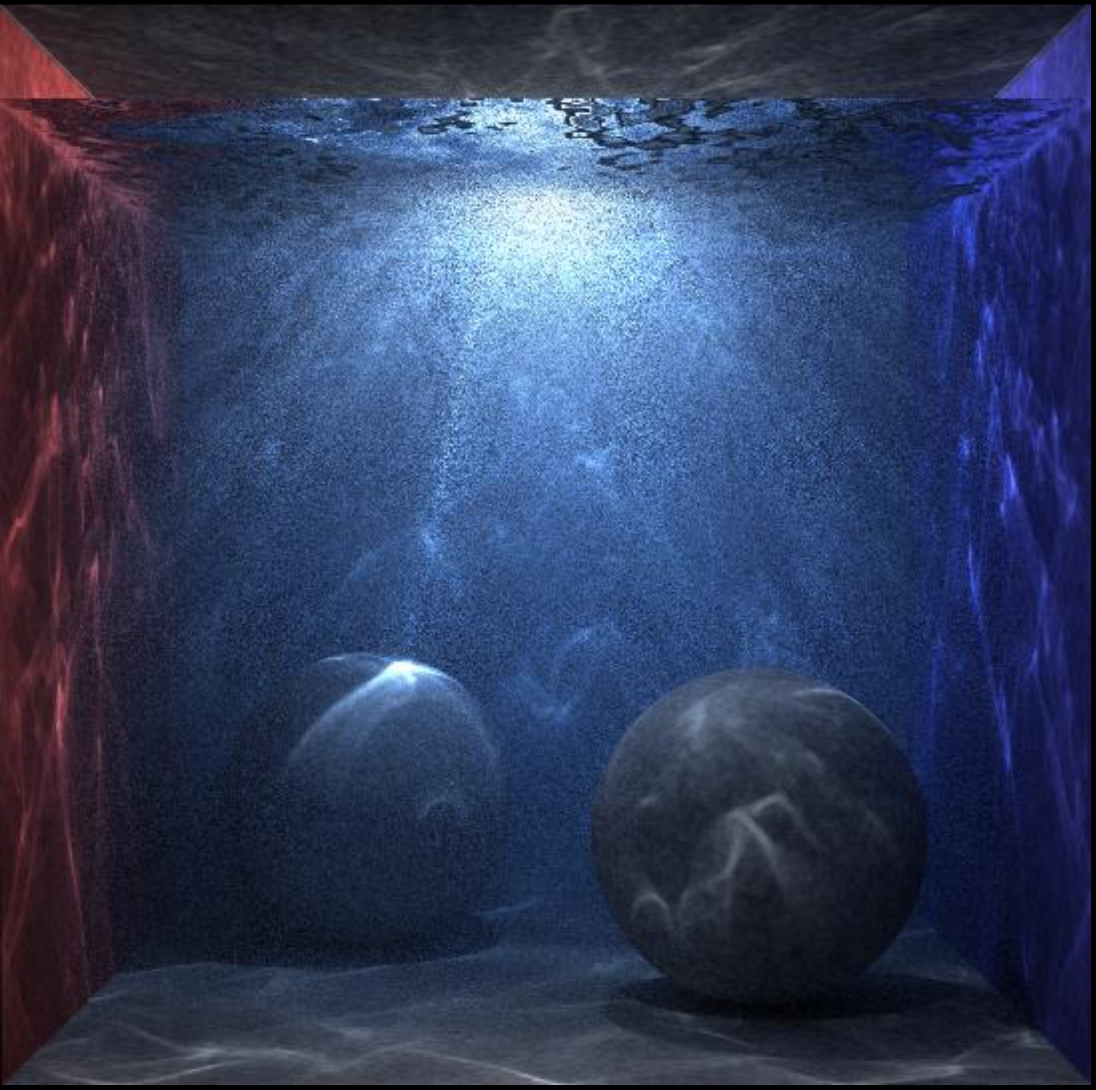
Participating Media

$$\frac{r_{i+1}^3}{r_i^3} = \frac{i+\alpha}{i+1}$$



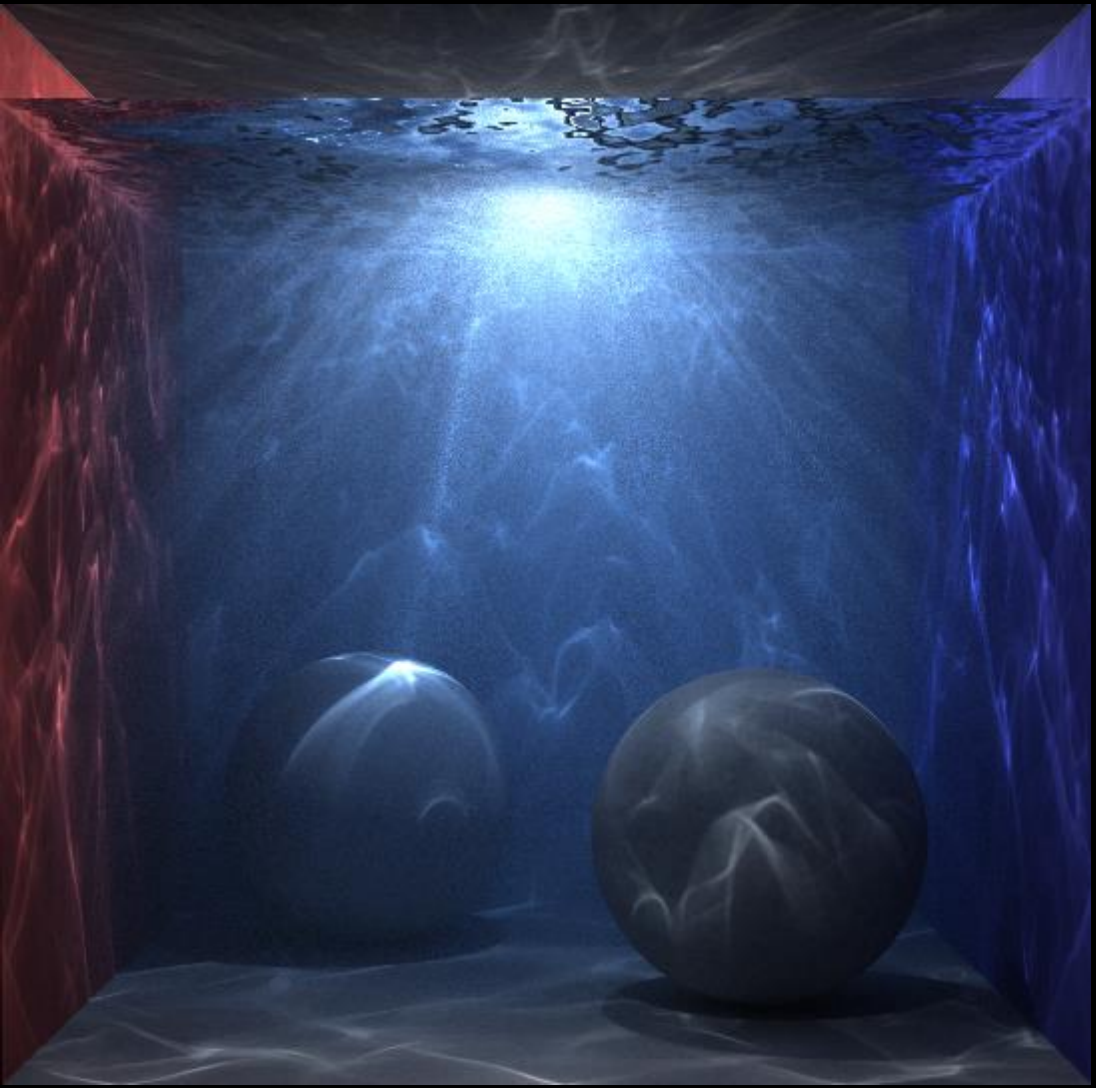
1 iteration

2 million photons



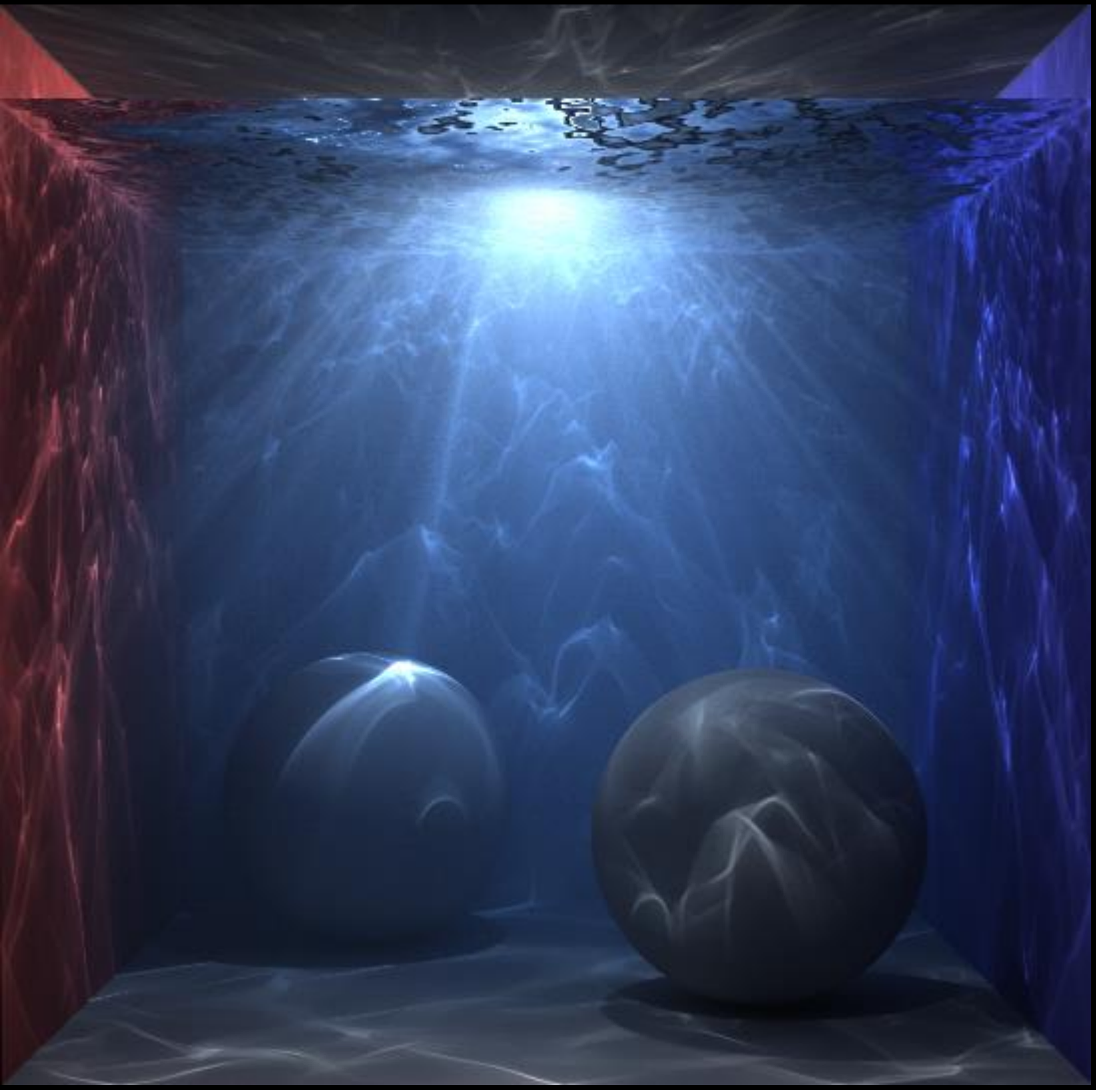
10 iterations

20 million photons



100 iterations

200 million photons



1000 iterations

2 billion photons

Conclusions

- Probabilistic analysis
- Asymptotic convergence
- No local statistics
- Parallelization
- Arbitrary kernels
- Participating media

SIGGRAPH ASIA 2013

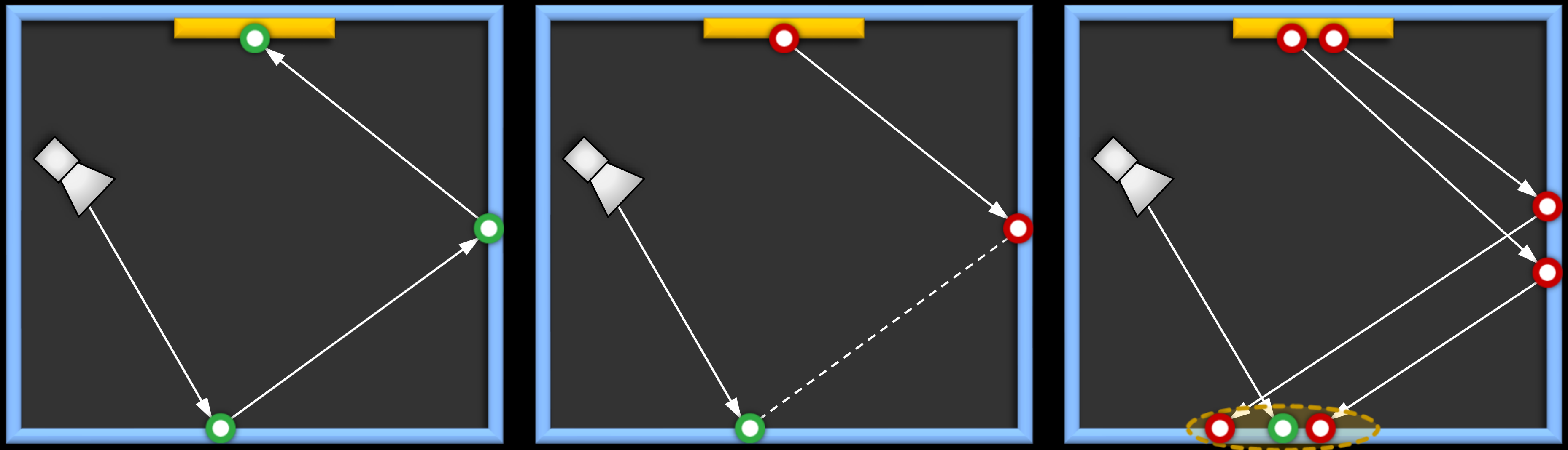
Combining Photon Mapping and Bidirectional Path Tracing


Bidirectional path tracing (30 min)


Stochastic progressive photon mapping (30 min)

Combined algorithm (30 min)

BPT vs PM



Unidirectional sampling	Vertex connection	Density estimation
Bidirectional path tracing		Photon mapping

Problem statement

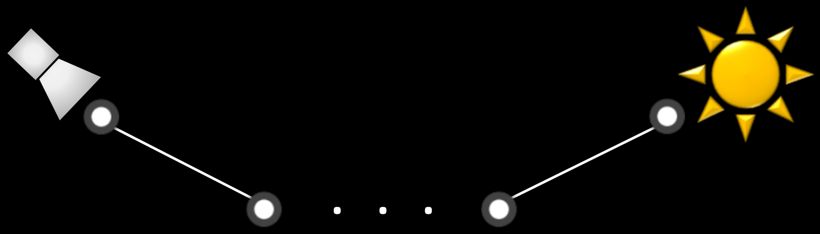
- **BPT** & **PM**: different solutions to the same problem
  - If we ignore bias in PM
- Want to combine
  - Best of both
  - Automatically
- ☹ Problem: Different mathematical frameworks
  - **BPT**: Monte Carlo integration
  - **PM**: Density estimation

Overview

- ☹ Problem: Different mathematical frameworks
- ☺ Solution: Cast both in the same framework
  - Path integral framework *[Veach 1997]*
  - Multiple importance sampling
  - New insight

$$I_j = \int_\Omega f_j(\overline{\mathbf{x}})\, d\mu(\overline{\mathbf{x}})$$

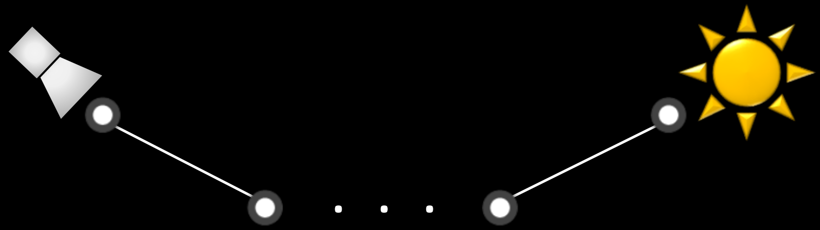
$$\langle I_j \rangle = \frac{f_j(\overline{\mathbf{x}})}{p(\overline{\mathbf{x}})}$$



Combination

- Multiple importance sampling *[Veach and Guibas 1995]*
  - Balance heuristic for n techniques

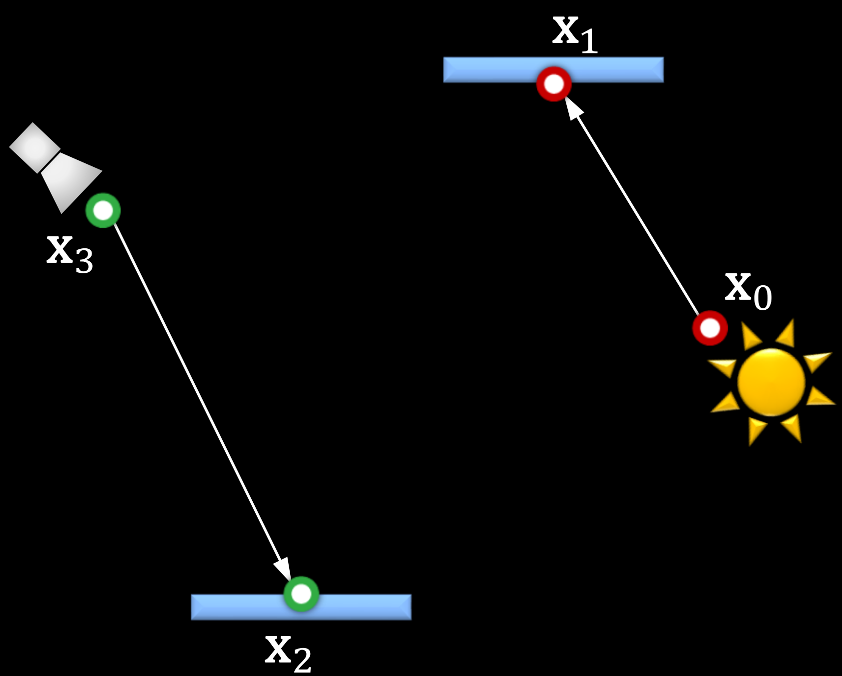
$$w_j(\bar{\mathbf{x}}) = \frac{p_j(\bar{\mathbf{x}})}{\sum_{k=1}^{n} p_k(\bar{\mathbf{x}})}$$



- Need to:
  1) Find a common definition of a path
     - In a common space
  2) Derive path probability density function (pdf)
     - With common units

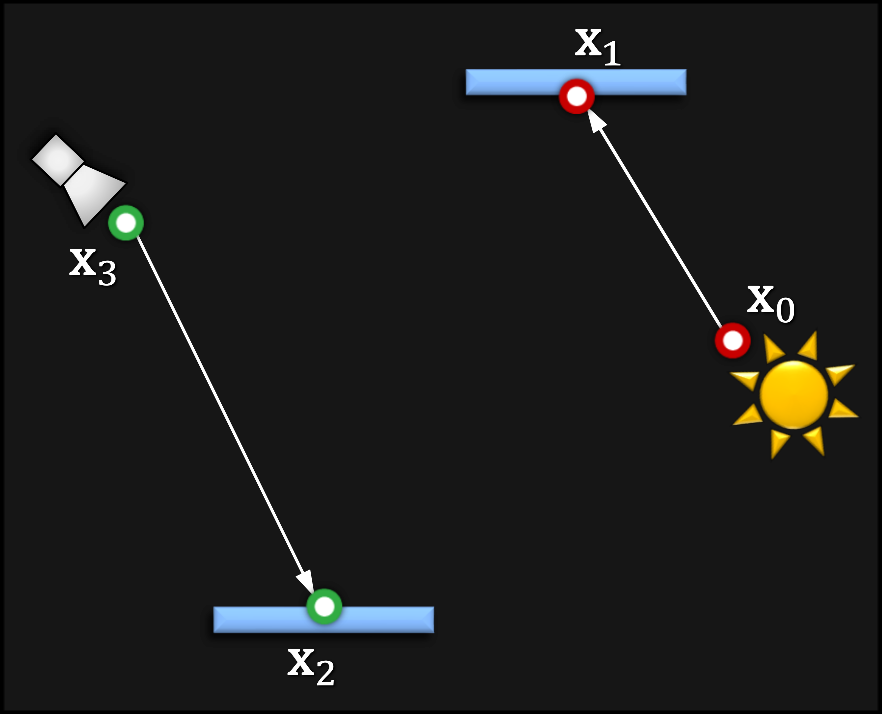
Bidirectional path sampling

- Light vertex
- Camera vertex



Bidirectional path sampling

- Light vertex
- Camera vertex



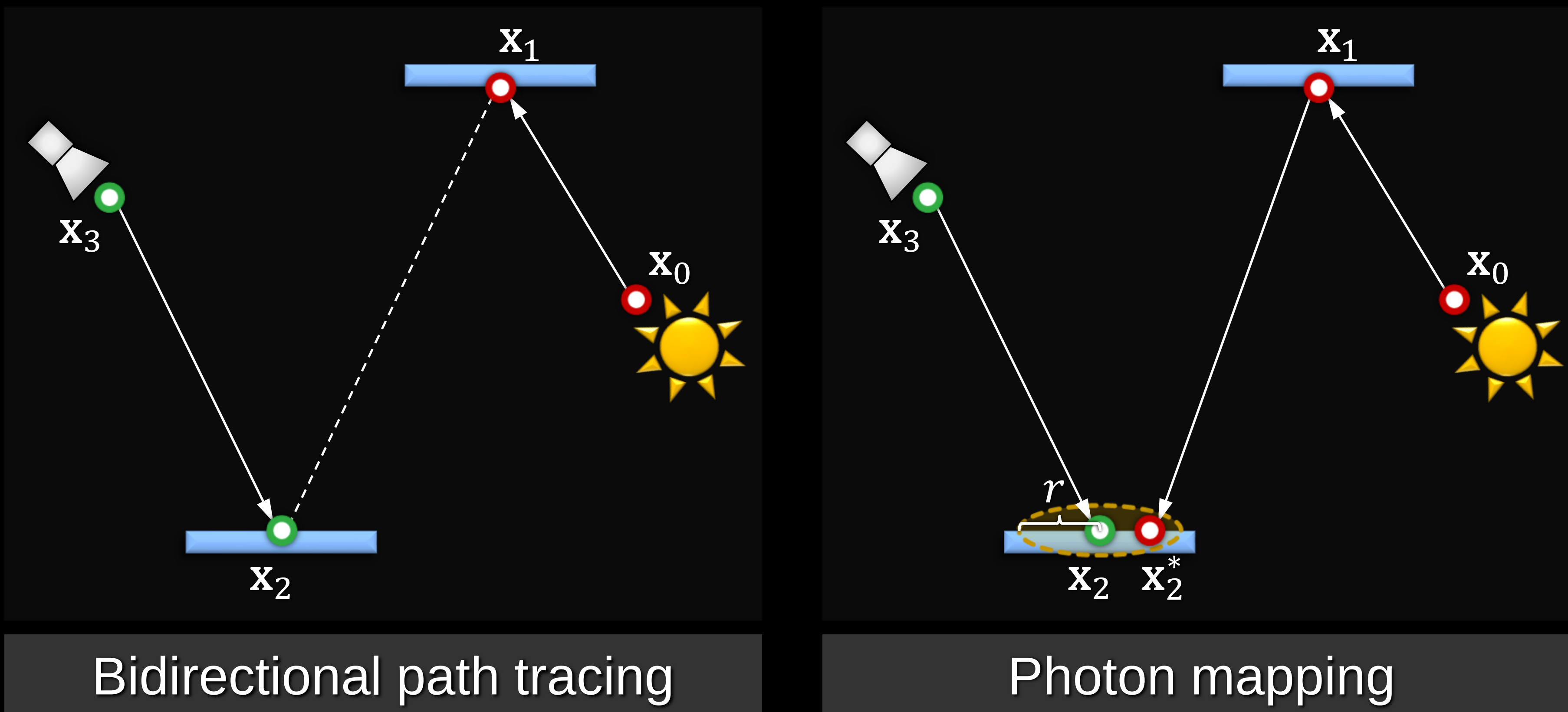
Bidirectional path tracing

Photon mapping

Bidirectional path sampling

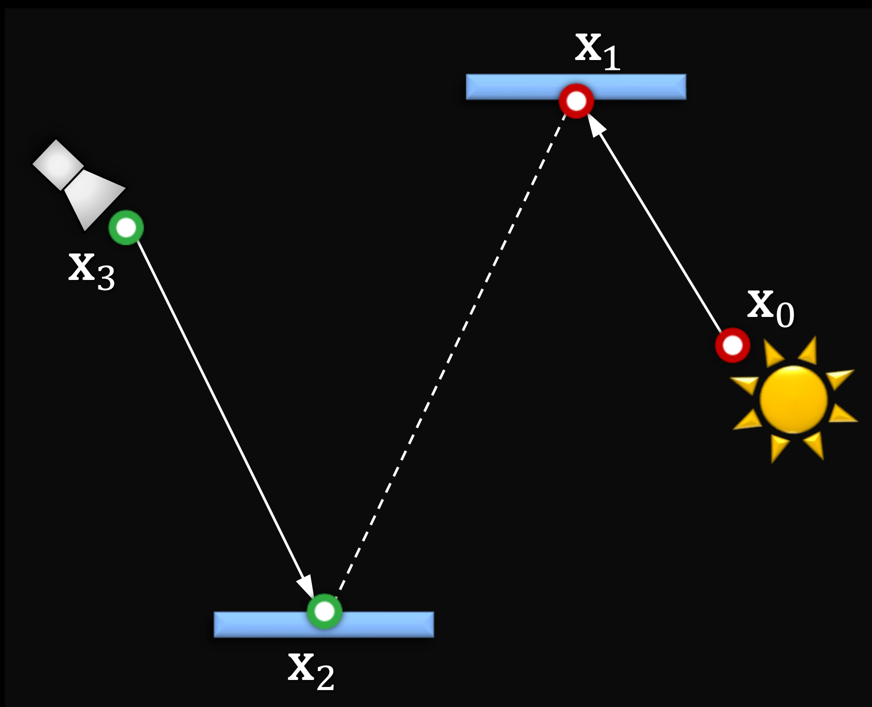
Light vertex

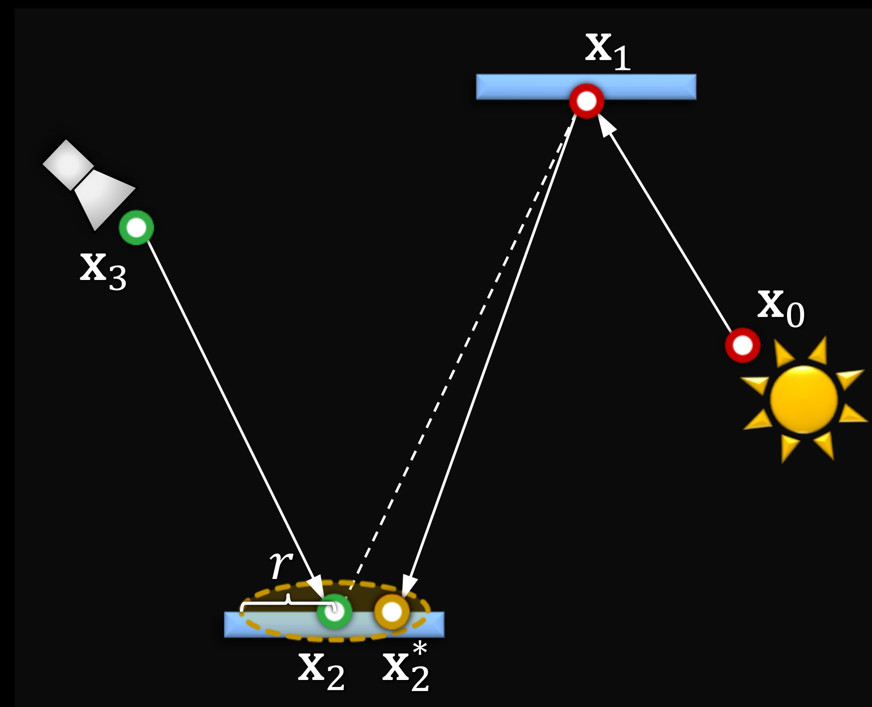
Camera vertex



Vertex merging *[Georgiev et al. 2012]*

- Light vertex
- Camera vertex





Vertex connection

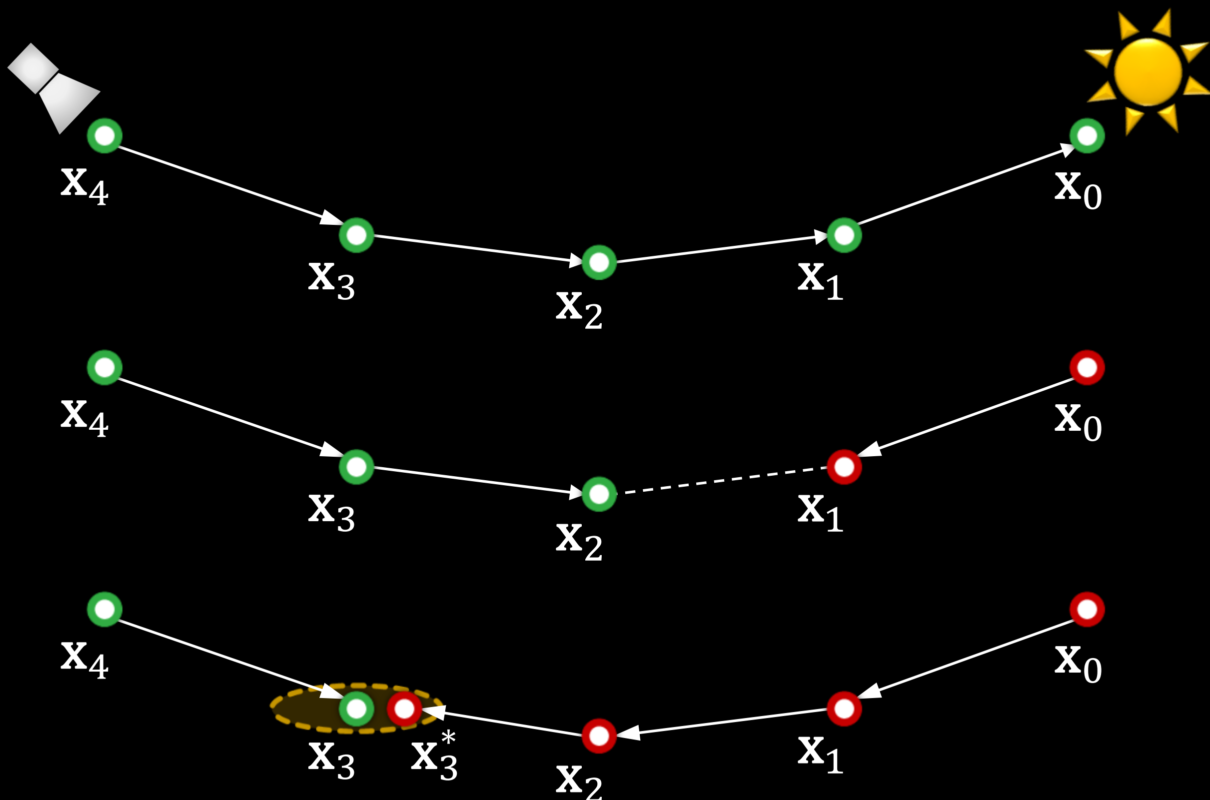
$$p_{VC}(\bar{\mathbf{x}}) = p(\mathbf{x}_0)p(\mathbf{x}_0 \to \mathbf{x}_1)\, p(\mathbf{x}_3)p(\mathbf{x}_3 \to \mathbf{x}_2)$$

Photon mapping

$$p_{VM}(\bar{\mathbf{x}}) \approx p(\mathbf{x}_0)p(\mathbf{x}_0 \to \mathbf{x}_1)\, P(\|\mathbf{x}_2 - \mathbf{x}_2^*\| < r)\, p(\mathbf{x}_3)p(\mathbf{x}_3 \to \mathbf{x}_2)$$

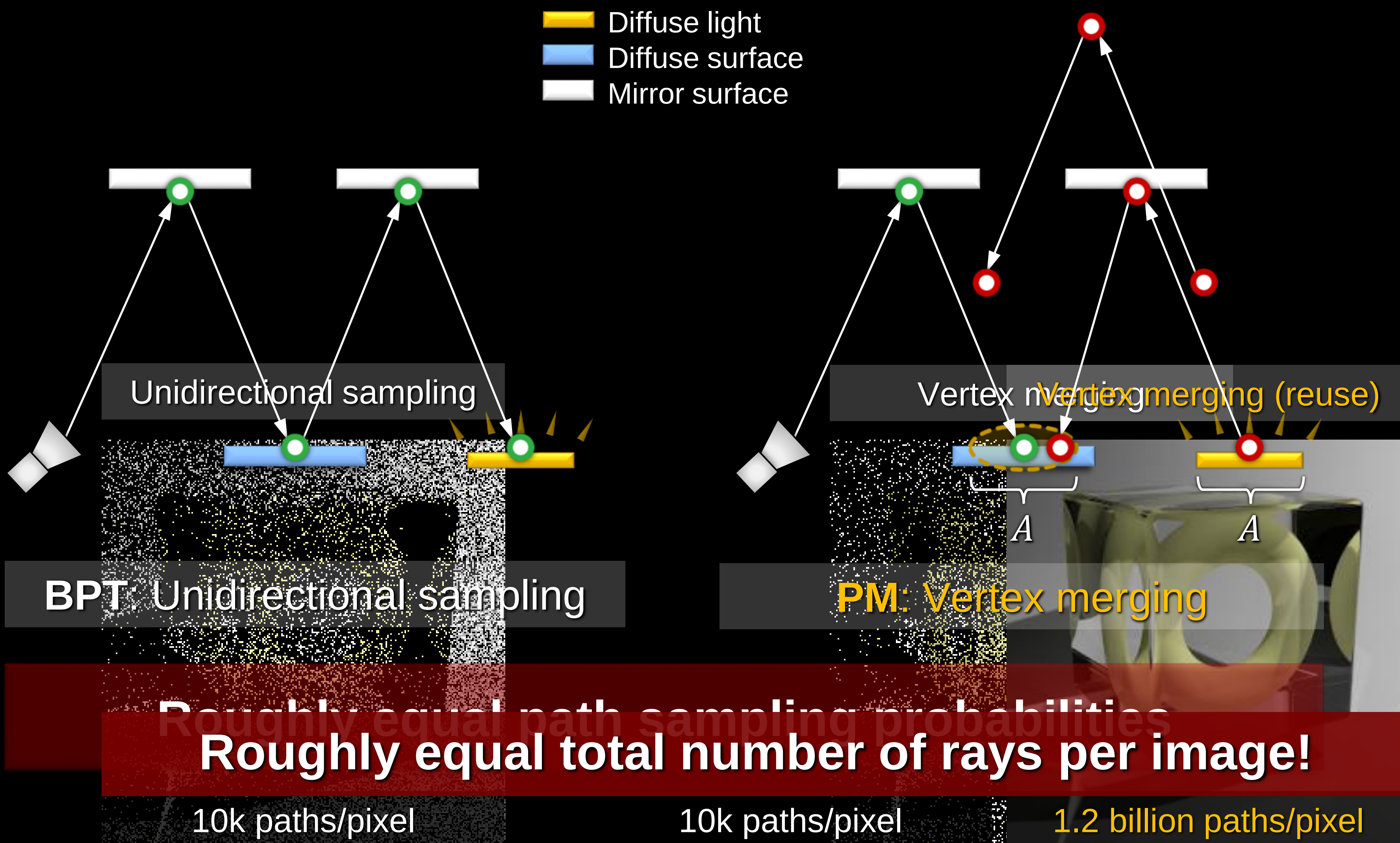
Sampling technique summary

Light vertex
Camera vertex



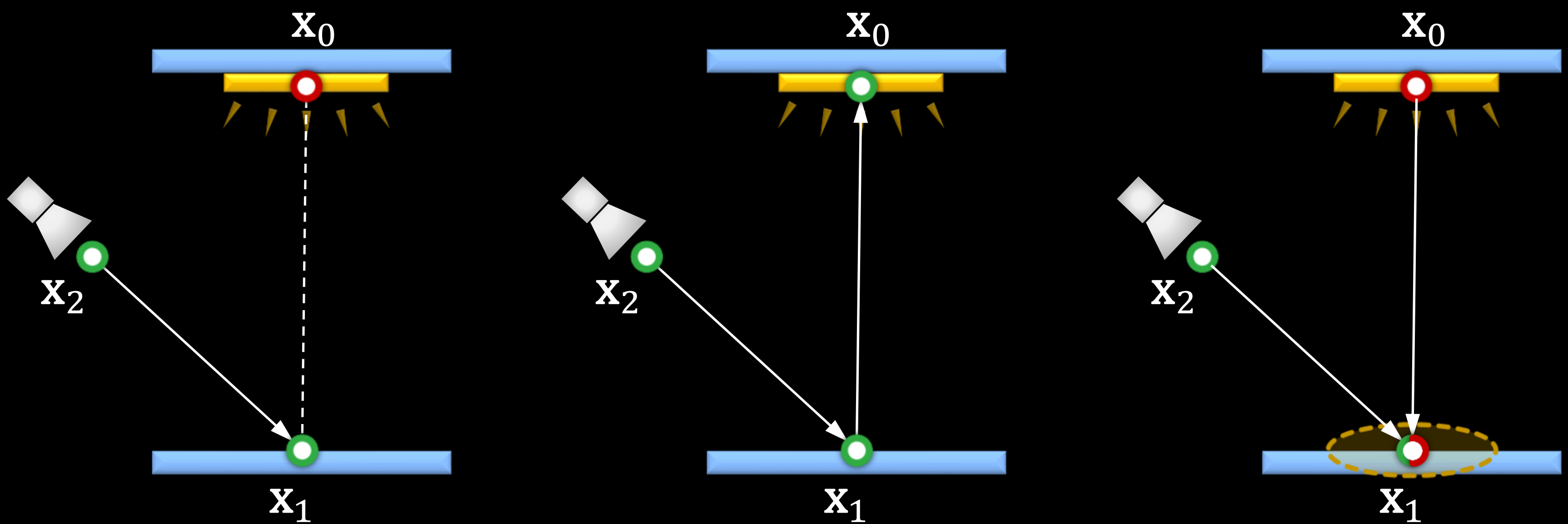
Unidirectional	2 ways
Vertex connection	4 ways
Photon mapping	5 ways
Total	**11 ways**

Technique comparison



Technique comparison

Diffuse light
Diffuse surface



Vertex connection (**VC**)

Unidirectional sampling (**US**)

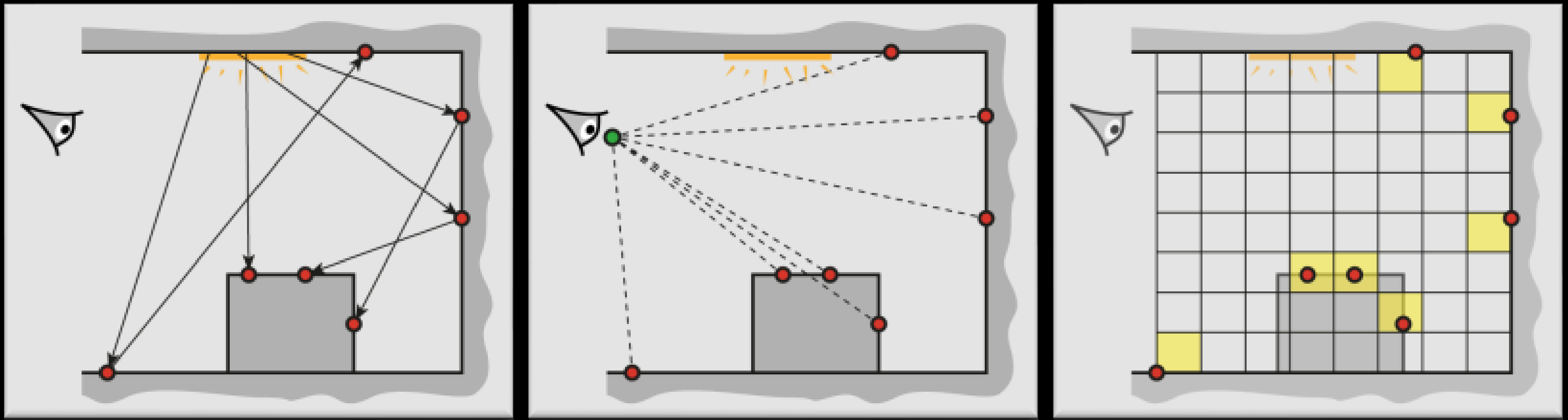
Vertex merging (**VM**)

Roughly equal sampling densities

$$p_{US} \approx p_{VM} \approx \frac{p_{VC}}{100{,}000}$$

Combined algorithm

Stage 1: Light sub-path sampling

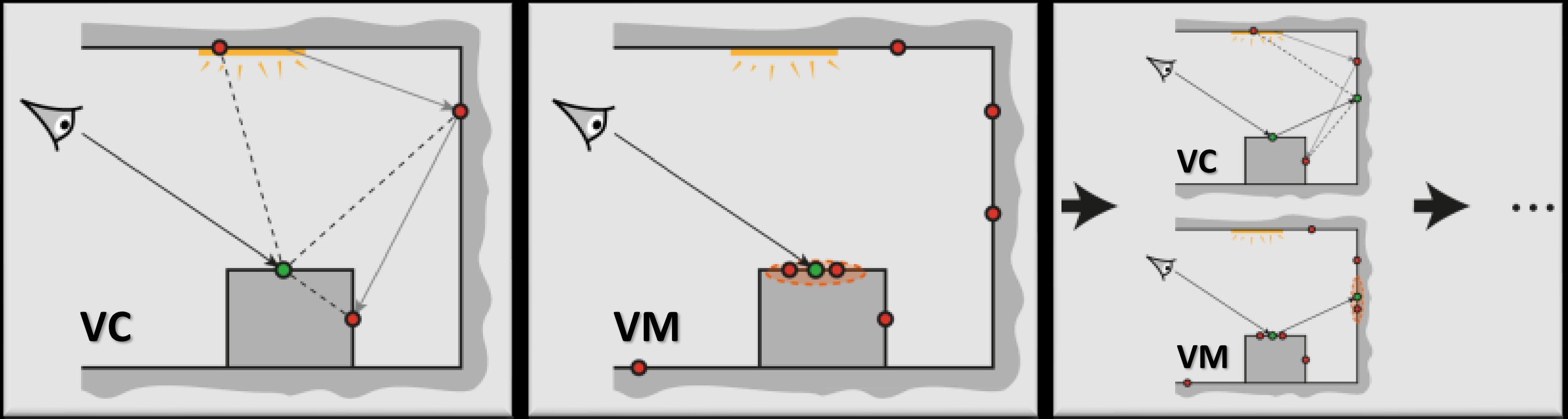


a) Trace sub-paths

b) Connect to eye

c) Build search structure

Stage 2: Eye sub-path sampling



a) Vertex connection

b) Vertex merging

c) Continue sub-path

Bidirectional path tracing (30 min)

Stochastic progressive photon mapping (30 min)


Combined algorithm (30 min)

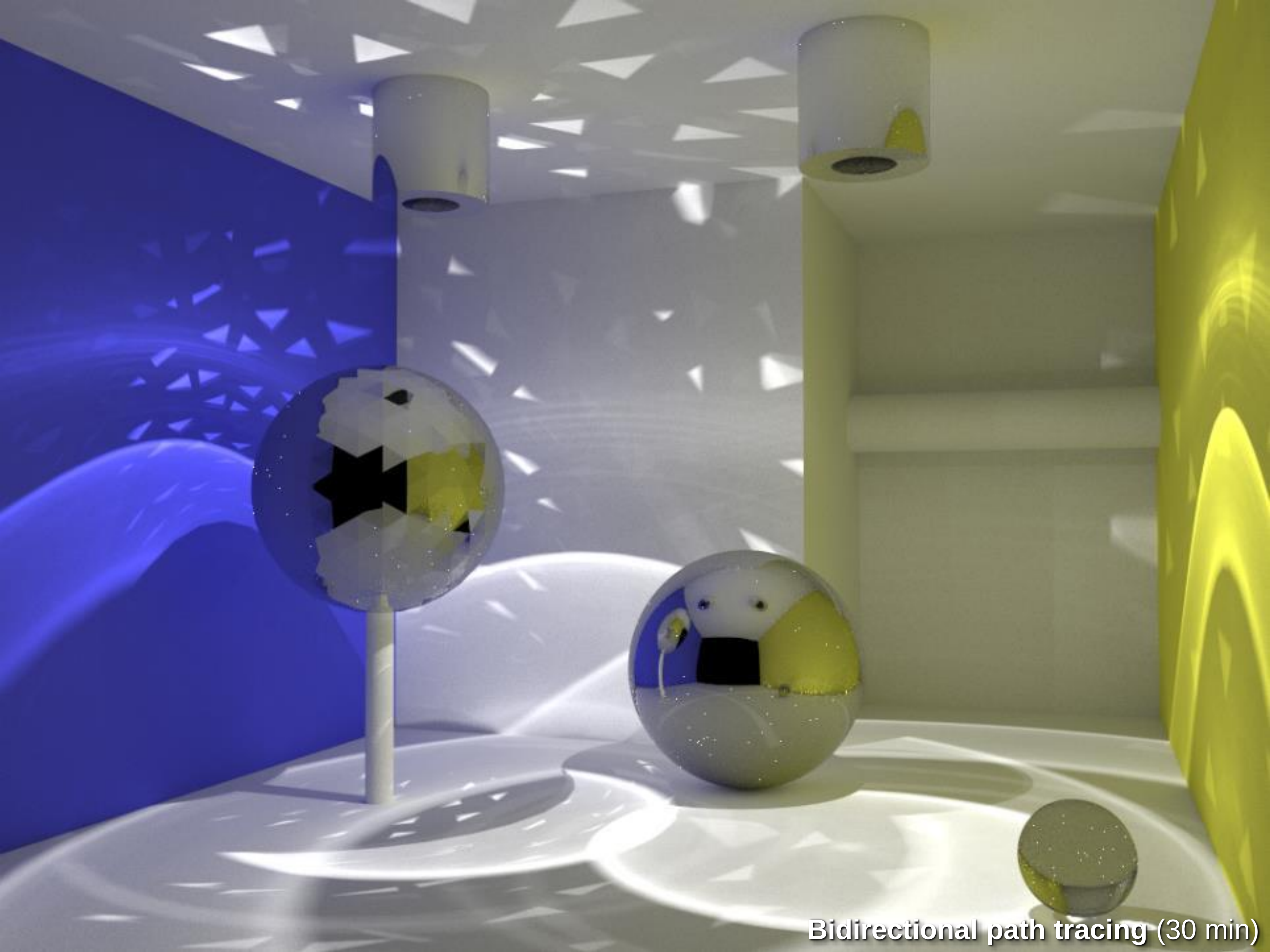

PM
BPT
Relative technique contributions


AA-340
Bidirectional path tracing (30 min)

Stochastic progressive photon mapping (30 min)

Combined algorithm (30 min)

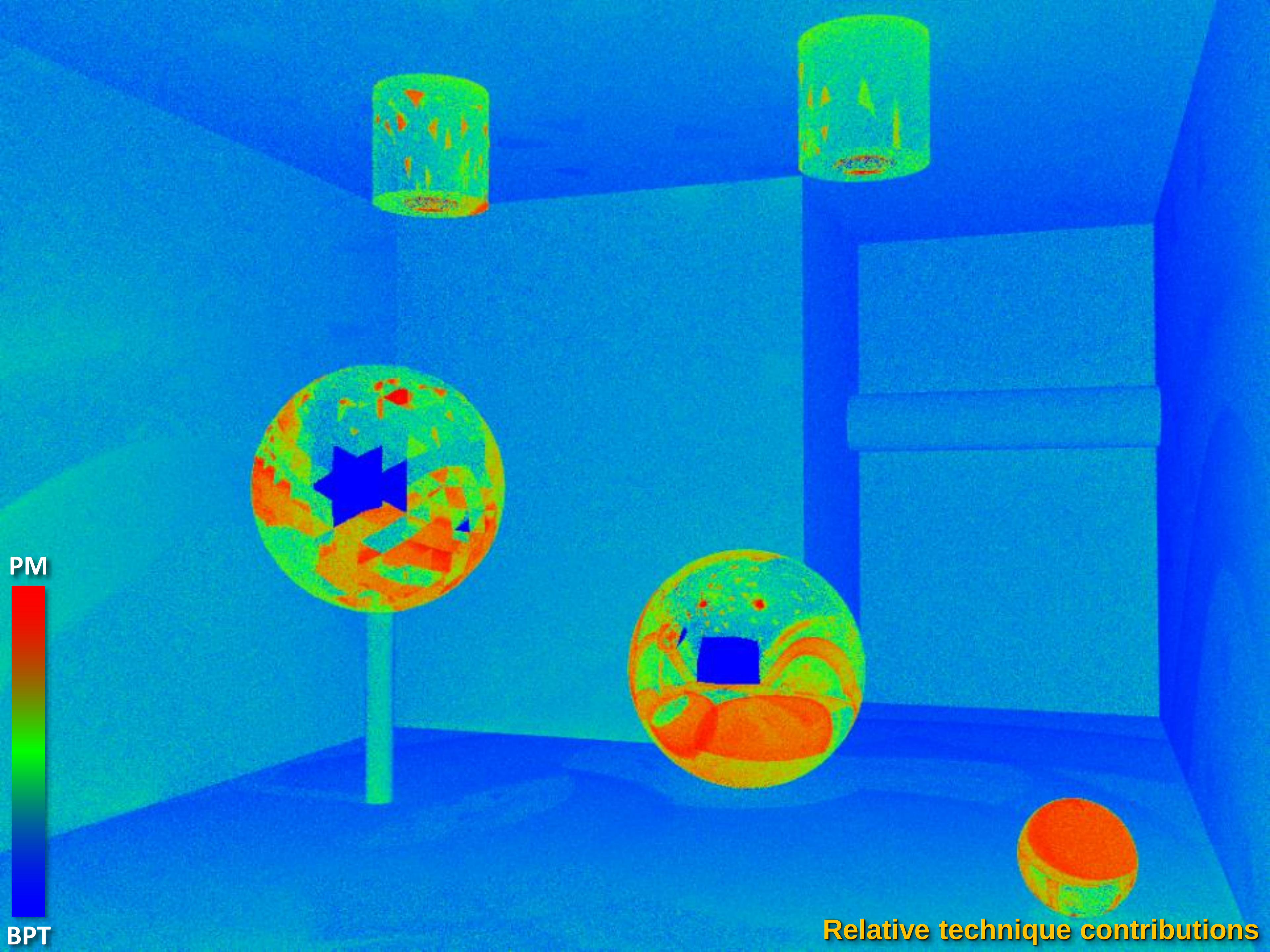

PM
BPT
AA-340
Relative technique contributions



Bidirectional path tracing (30 min)


Stochastic progressive photon mapping (30 min)

Combined algorithm (30 min)


PM
BPT
Relative technique contributions

Additional material

- **A path space extension for robust light transport simulation** *[Hachisuka et al. 2012]*
  - Paper, supplemental analysis *[http://cs.au.dk/~toshiya/]*

- **Light transport simulation with vertex connection & merging** *[Georgiev et al. 2012]*
  - Paper, tech. report, image comparisons *[http://www.iliyan.com]*

Wrap up

- Two approaches
  - Same result
- Error convergence
  - BPT: $O(N^{-0.5})$
  - PPM: $O(N^{-0.33})$
  - Combined: $O(N^{-0.5})$
- Remaining challenges