CS580: Monte Carlo Ray Tracing:

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Talk Evaluations

- **Do not evaluate based on:**
  - **English**
  - **Relative ranking among presenters**

- **Evaluate based on:**
  - **His/her message**
  - **His/her understanding, and delivery**
  - **Achievement of the team for the project presentation**

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Project Guidelines: Project Topics

- **Any topics related to the course theme are okay**
  - **You can find topics by browsing recent papers**

Expectations

- **Mid-term project presentation**
  - **Introduce problems and explain why it is important**
  - **Give an overall idea on the related work**
  - **Explain what problems those existing techniques have**
  - **(Optional) explain how you can address those problems**
  - **Explain roles of each member**

Expectations

- Final-term project presentation
  - Cover all the materials that you talked for your mid-term project
  - Present your ideas that can address problems of those state-of-the-art techniques
  - Give your qualitatively (or intuitive) reasons how your ideas address them
  - Also, explain expected benefits and drawbacks of your approach
  - (Optional) backup your claims with quantitative results collected by some implementations
  - Explain roles of each members

A few more comments

- **Start to implement a paper, if you don’t have any clear ideas**
  - **While you implement it, you may get ideas about improving it**

- **Utilize any existing materials (codes) with proper ack.**

Project evaluation sheet

You name:
ID:

Score table: higher score is better.

Speaker	Novelty of the project and idea (1 ~ 5)	Practical benefits of the method (1 ~ 5)	Completeness level of the project (1 ~ 5)	Total score (3 ~ 15)	Role of each student is clear and well balanced? (Yes or No)
XXX					
YYY					

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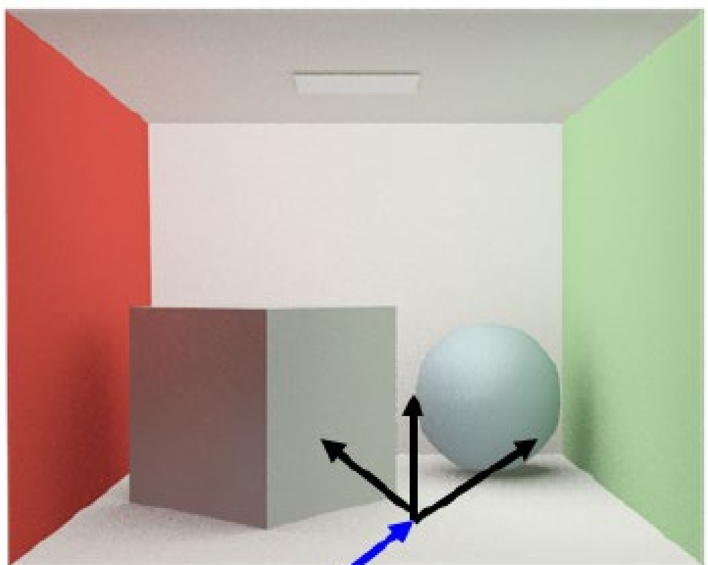
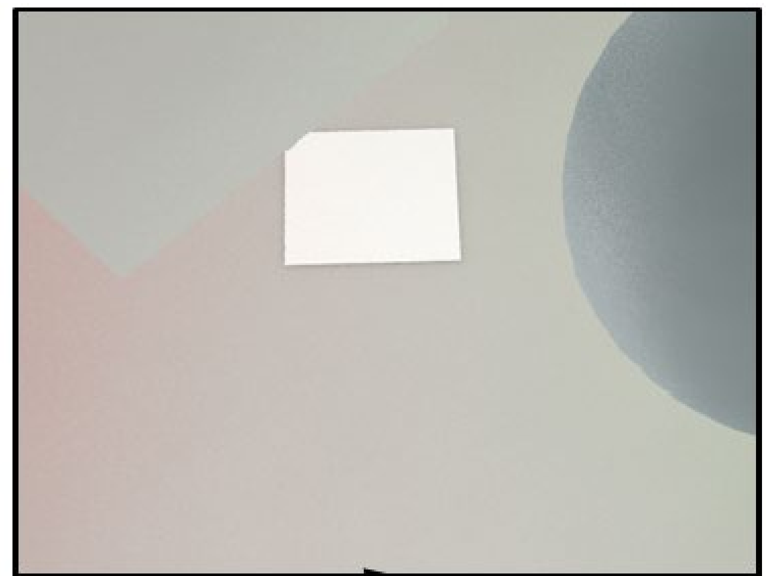
Class Objectives

- **Understand a basic structure of Monte Carlo ray tracing**
  - **Russian roulette for its termination**
  - **Path tracing**
  - **Biased techniques**

Rendering Equation



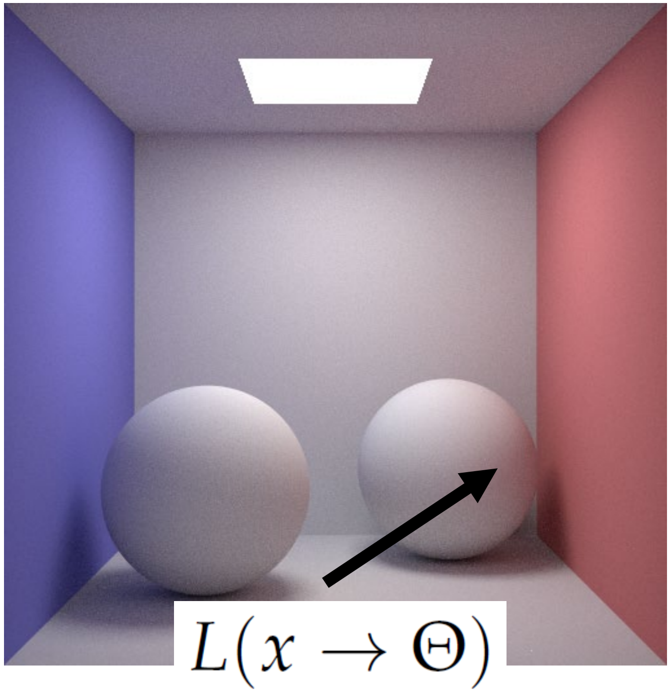


Incoming radiance on the hemisphere

$$L_r(x \rightarrow \Theta) = \int_{\Psi} L(x \leftarrow \Psi) f_r(x, \Psi \rightarrow \Theta) \cos\theta_x dw_{\Psi}$$

Evaluation

- **To compute** $L(x \rightarrow \Theta)$ **:**
  - **Check** $L_e(x \rightarrow \Theta)$
  - **Evaluate** $L_r(x \rightarrow \Theta)$



$$L_r(x \rightarrow \Theta) = \int_{\Psi} L(x \leftarrow \Psi) f_r(x, \Psi \rightarrow \Theta) \cos\theta_x dw_{\Psi}$$

Evaluation

- **Use Monte Carlo**
- **Generate random directions on hemisphere Ψ using pdf p(Ψ)**

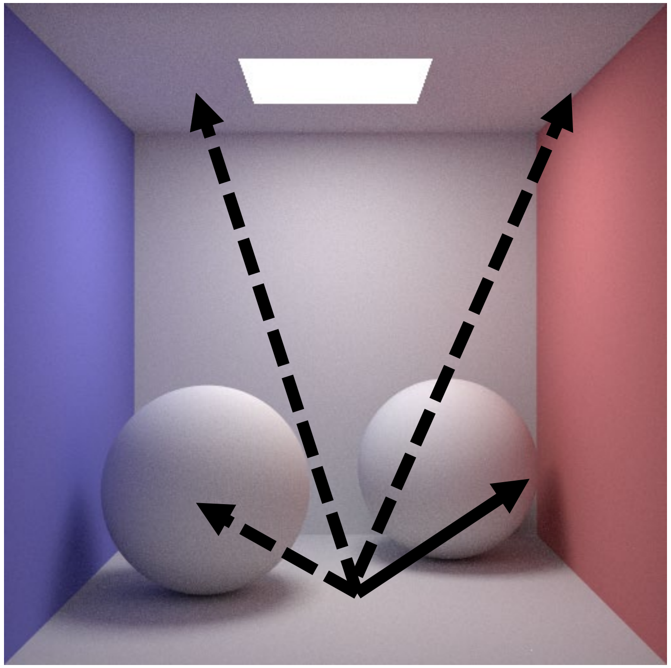
$$L_r(x \rightarrow \Theta) = \int_{\Psi} L(x \leftarrow \Psi) f_r(x, \Psi \rightarrow \Theta) \cos\theta_x dw_{\Psi}$$

$$\hat{L}_r(x \rightarrow \Theta) = \frac{1}{N} \sum_{i=1}^{N} \frac{L(x \leftarrow \Psi_i) f_r(x, \Psi_i \rightarrow \Theta) \cos\theta_x}{p(\Psi_i)}$$

- **How about** $L(x \leftarrow \Psi_i)$ **?**

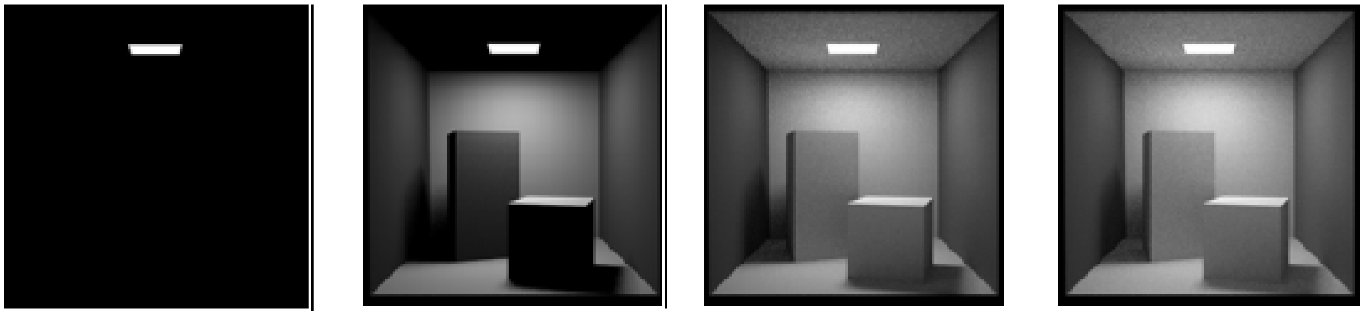
Evaluation

- How about $L(x \leftarrow \Psi_i)$?
- Perform ray casting backward
- Compute radiance from those visible points to x
  - Assume reciprocity



- Recursively perform the process
  - Each additional bounce supports one more indirect illumination

When to end recursion?



From kavita's slides

- Contributions of further light bounces become less significant
  - Max recursion
  - Some threshold for radiance value

- If we just ignore them, estimators will be biased

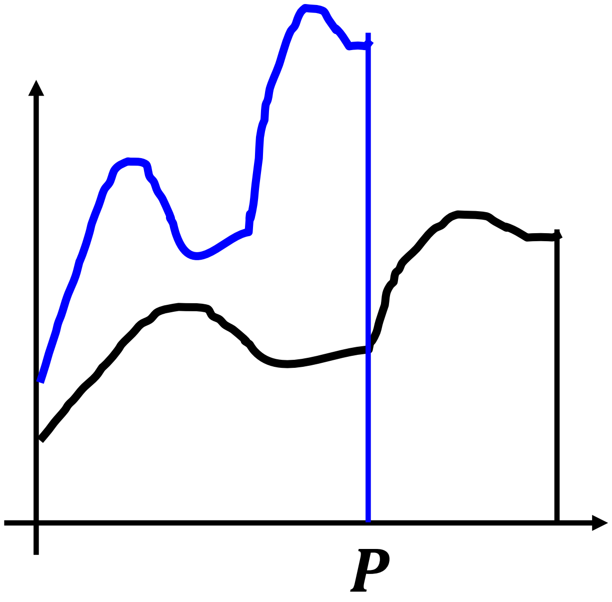
Russian Roulette

- **Integral: Substitute $y = Px$**

$$I = \int_0^1 f(x)dx = \int_0^P \frac{f(y/P)}{P} dy.$$

- **Estimator**

$$\hat{I}_{roulette} = \begin{cases} \frac{f(x_i)}{P} & \text{if } x_i \leq P, \\ 0 & \text{if } x_i > P. \end{cases}$$



- **Variance?**

Russian Roulette

- **Pick absorption probability, α = 1-P**
  - **Recursion is terminated**

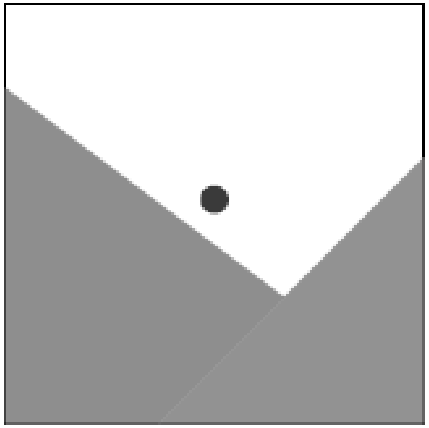
- **P is commonly to be equal to the reflectance of the material of the surface**
  - **Water: 7%**
  - **Snow: 65%**

Algorithm so far

- Shoot primary rays through each pixel
- Shoot indirect rays, sampled over hemisphere
- Terminate recursion using Russian Roulette

Pixel Anti-Aliasing

- **Compute radiance only at the center of pixel**
  - **Produce jaggies**



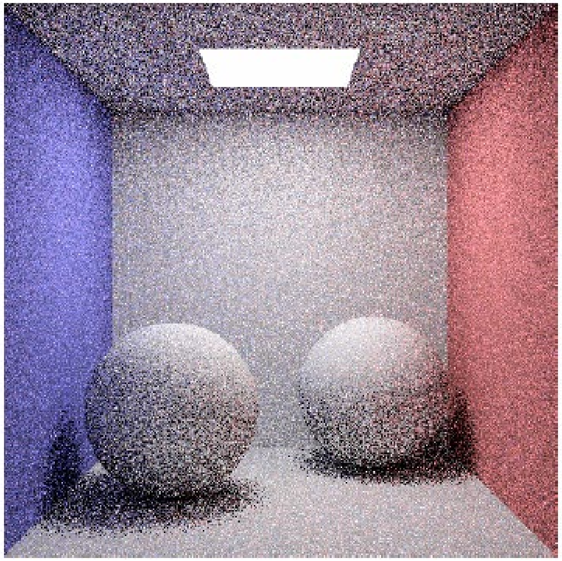
- **We want to evaluate using MC**
- **Simple box filter**
  - **The averaging method**

Stochastic Ray Tracing

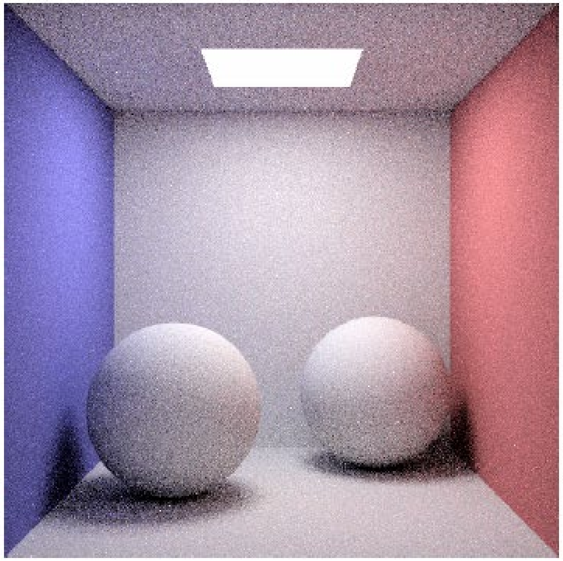
- **Parameters**
  - **Num. of starting ray per pixel**
  - **Num. of random rays for each surface point (branching factor)**

- **Path tracing**
  - **Branching factor = 1**

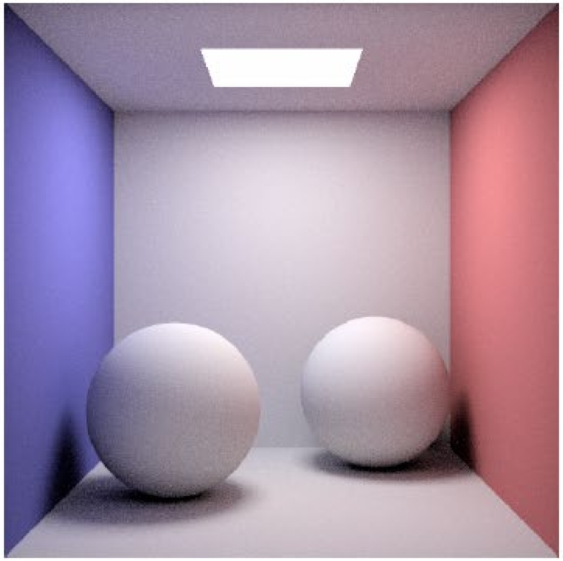
Path Tracing



1 spp
(samples per pixel)



4 spp



16 spp

- **Pixel sampling + light source sampling folded into one method**

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Algorithm so far

- Shoot primary rays through each pixel
- Shoot indirect rays, sampled over hemisphere
  - Path tracing shoots only 1 indirect ray
- Terminate recursion using Russian Roulette

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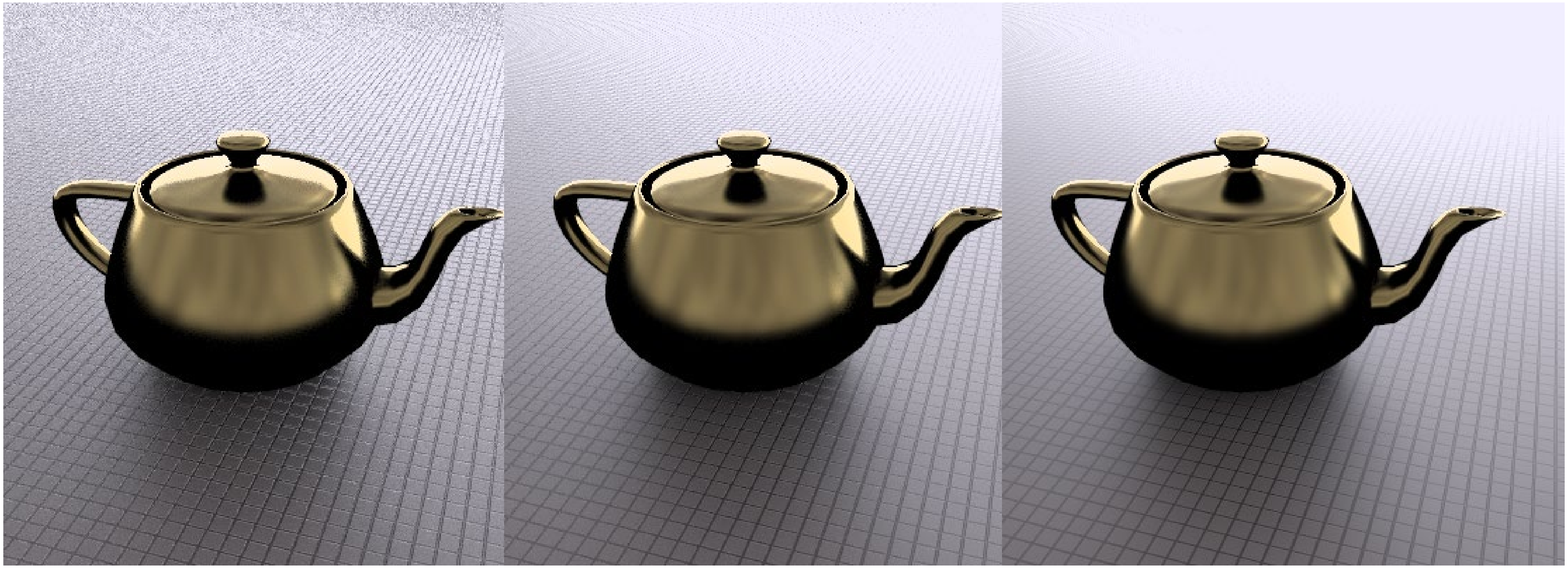
Performance

- **Want better quality with smaller # of samples**
  - **Fewer samples/better performance**
  - **Quasi Monte Carlo: well-distributed samples**
  - **Adaptive sampling**
- **See my book, if you are interested**

Some Example

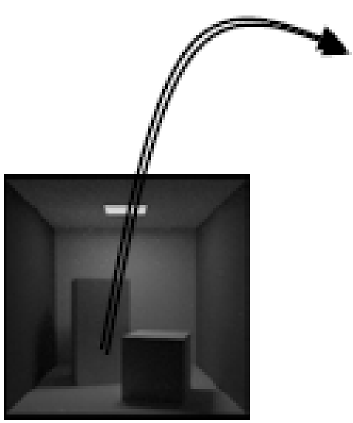


Uniform sampling (64 samples per pixel) | Adaptive sampling | Reference

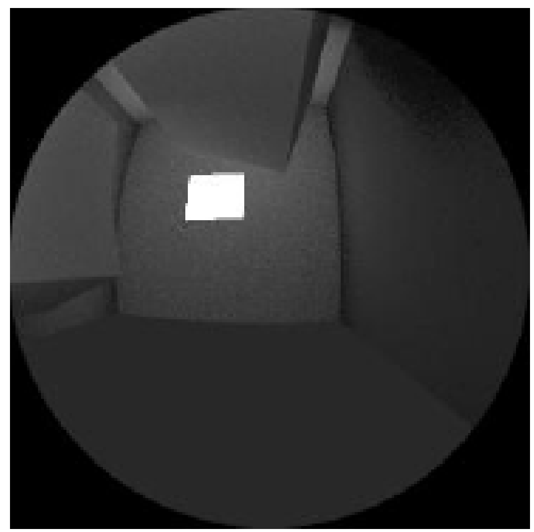
Importance Sampling

$$L(x \to \Theta) = L_e(x \to \Theta) + \int_{\Omega_x} f_r(\Psi \leftrightarrow \Theta) \cdot L(x \leftarrow \Psi) \cdot \cos(\Psi, n_x) \cdot d\omega_\Psi$$

Radiance from light sources + radiance from other surfaces



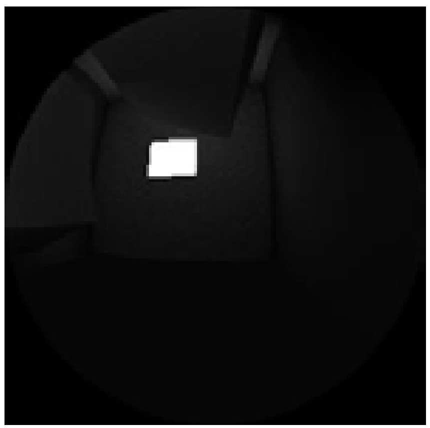
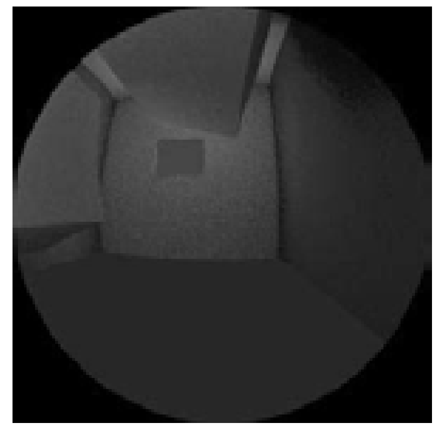
$$= L_e + \int_{\Omega_x}$$



$$\cdot f_r \cdot \cos$$

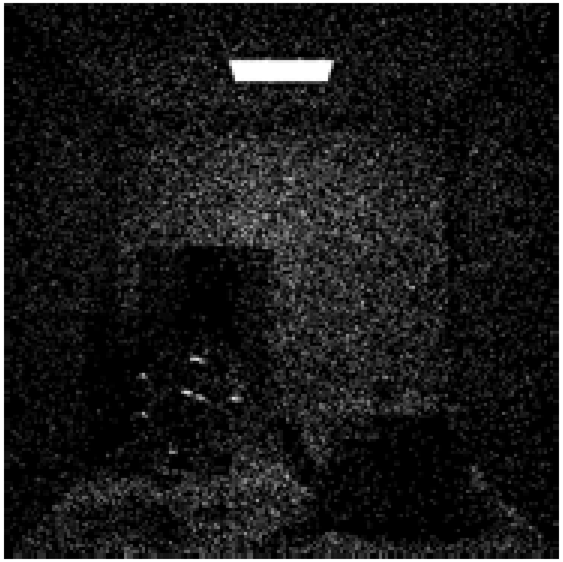
Importance Sampling

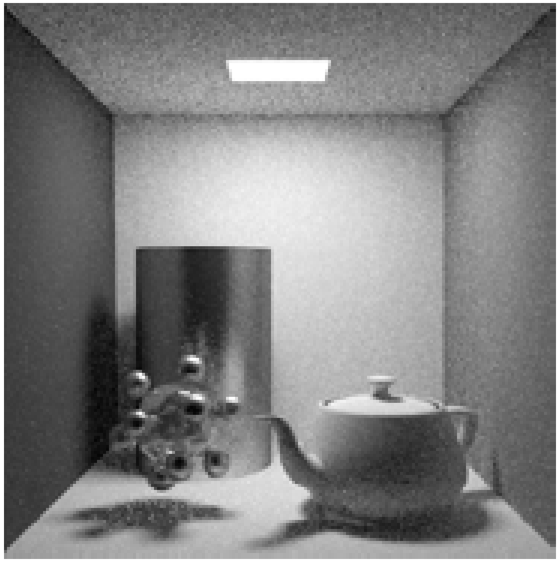
$$L(x \rightarrow \Theta) = L_e + L_{direct} + L_{indirect}$$

$$= L_e + \int_{\Omega_x}$$  $$\cdot f_r \cdot \cos + \int_{\Omega_x}$$  $$\cdot f_r \cdot \cos$$

- So … sample direct and indirect with separate MC integration

Comparison





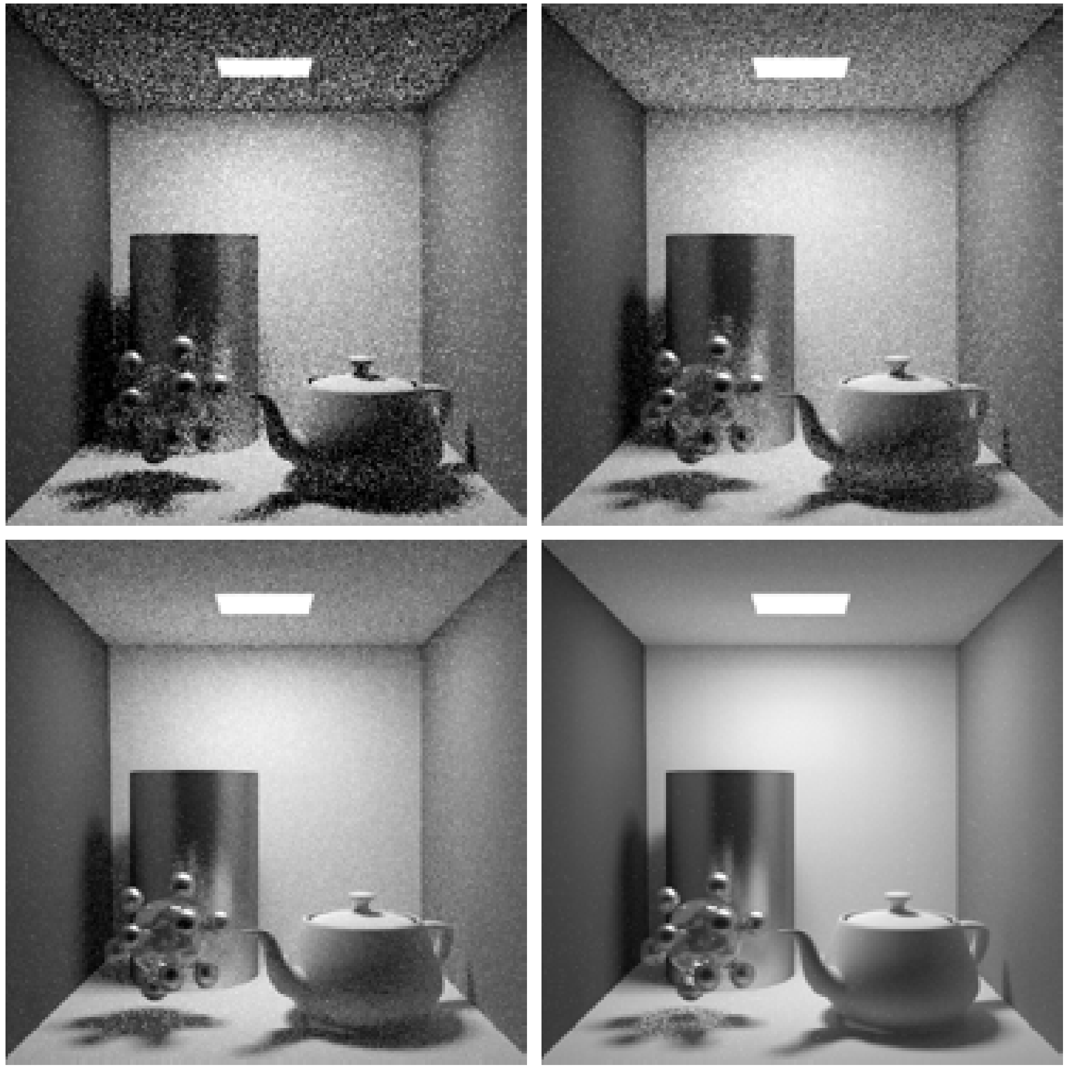
From kavita's slides

- **With and without considering direct illumination**
  - **16 samples / pixel**

Rays per pixel

1 sample/ pixel

4 samples/ pixel



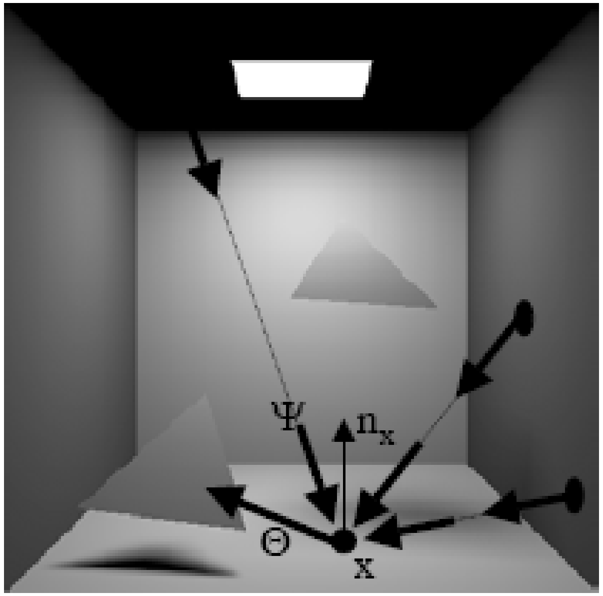
16 samples/ pixel

256 samples/ pixel

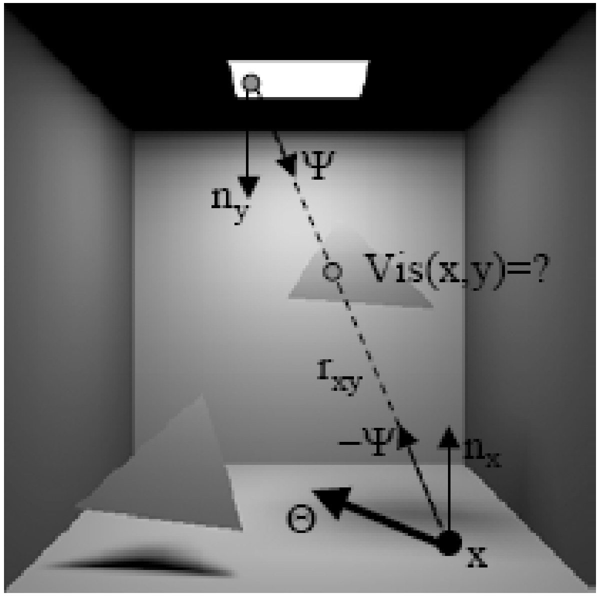
Direct Illumination

$$L(x \to \Theta) = \int_{A_{source}} f_r(x, -\Psi \leftrightarrow \Theta) \cdot L(y \to \Psi) \cdot G(x,y) \cdot dA_y$$

$$G(x,y) = \frac{\cos(n_x, \Theta)\cos(n_y, \Psi) Vis(x,y)}{r_{xy}^2}$$



hemisphere integration



area integration

Estimator for direct lighting

- Pick a point on the light's surface with pdf

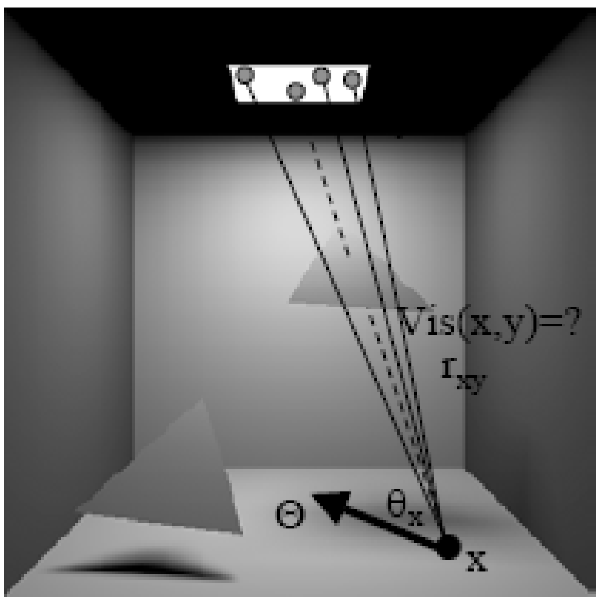
$$p(y)$$

- For N samples, direct light at point x is:

$$E(x) = \frac{1}{N} \sum_{i=1}^{N} \frac{f_r L_{source} \frac{\cos\theta_x \cos\theta_{\bar{y}_i}}{r_{x\bar{y}_i}^2} Vis(x, \bar{y}_i)}{p(\bar{y}_i)}$$

Generating direct paths

- Pick surface points y_i on light source
- Evaluate direct illumination integral



$$\langle L(x \to \Theta) \rangle = \frac{1}{N} \sum_{i=1}^{N} \frac{f_r(\ldots)L(\ldots)G(x, y_i)}{p(y_i)}$$

PDF for sampling light

- Uniform

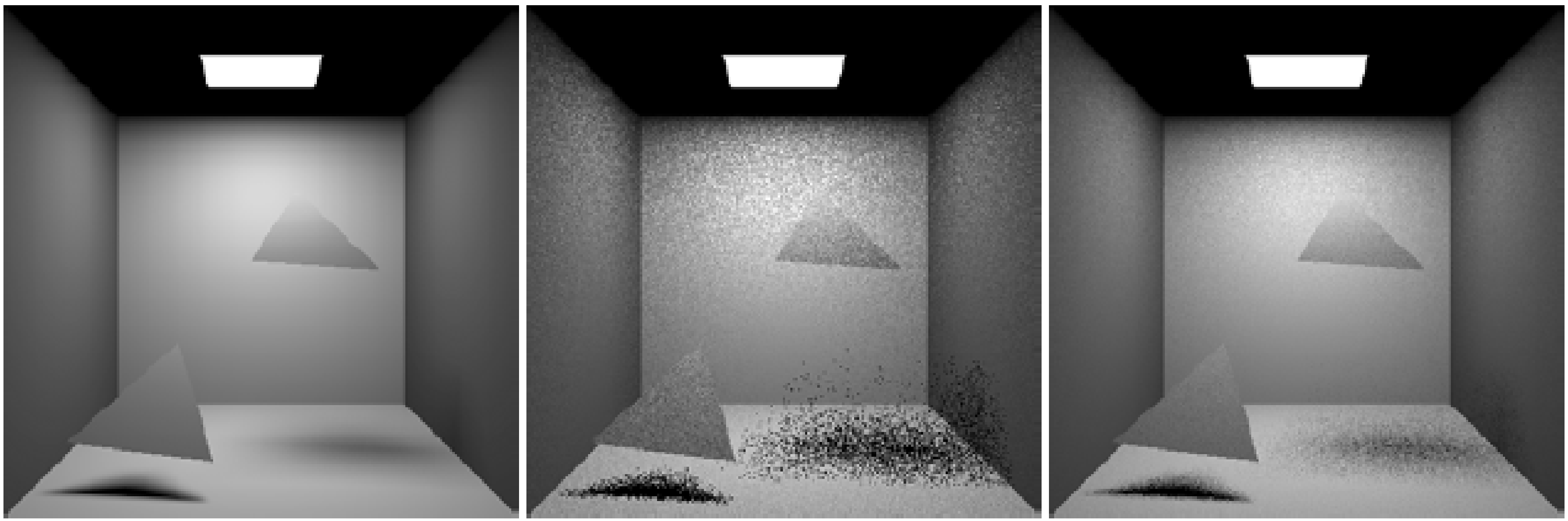
$$p(y) = \frac{1}{Area_{source}}$$

- Pick a point uniformly over light's area
  - Can stratify samples

- Estimator:

$$E(x) = \frac{Area_{source}}{N} \sum_{i=1}^{N} f_r L_{source} \frac{\cos\theta_x \cos\theta_{\bar{y}_i}}{r^2_{x\bar{y}_i}} Vis(x, \bar{y}_i)$$

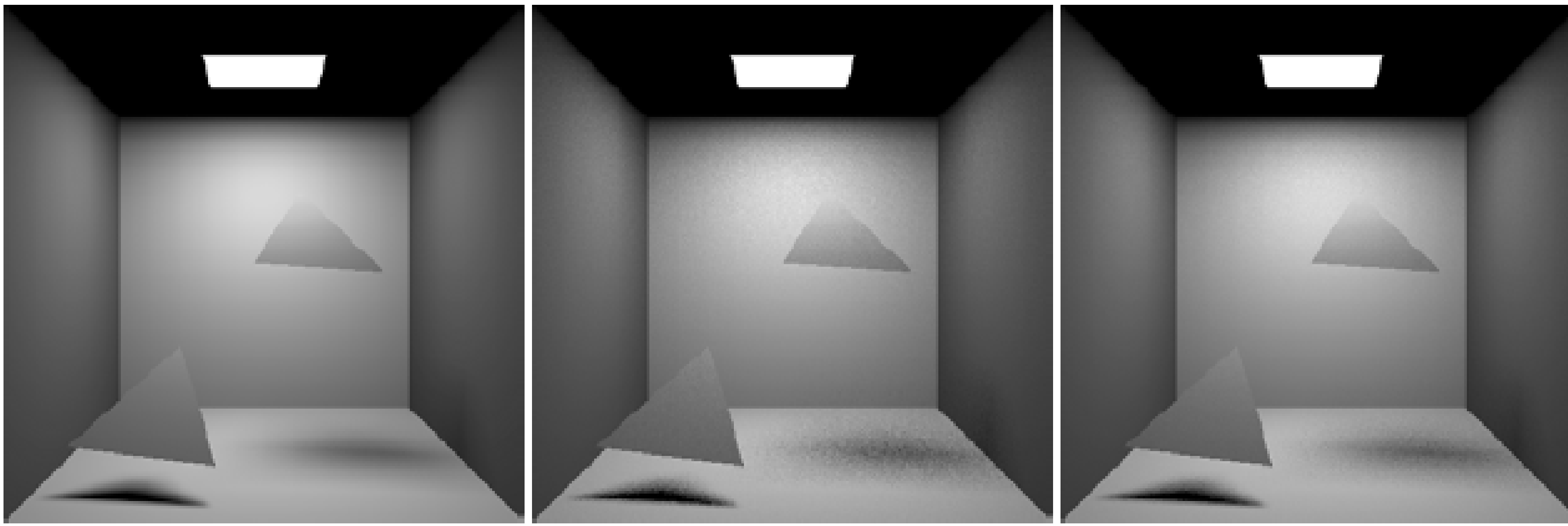
More points ...



1 shadow ray   9 shadow rays

$$E(x) = \frac{Area_{source}}{N} \sum_{i=1}^{N} f_r L_{source} \frac{\cos\theta_x \cos\theta_{\bar{y}_i}}{r^2_{x\bar{y}_i}} Vis(x, \bar{y}_i)$$

Even more points ...

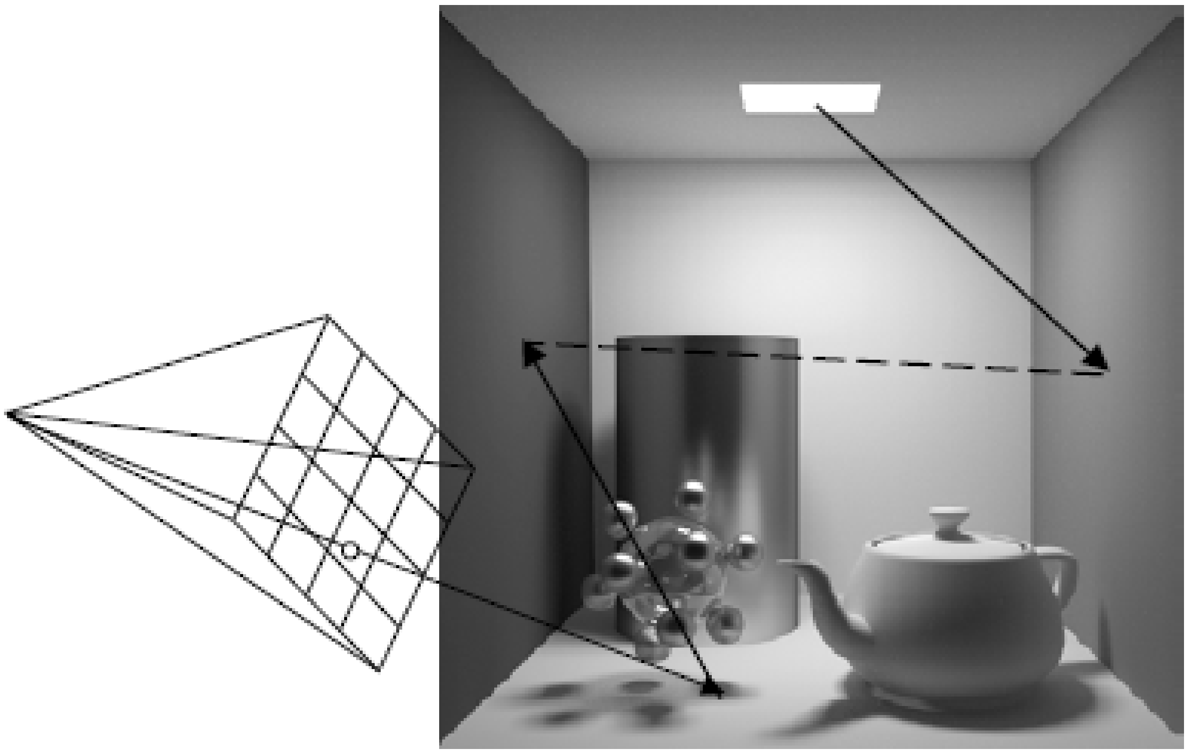


36 shadow rays 100 shadow rays

$$E(x) = \frac{Area_{source}}{N} \sum_{i=1}^{N} f_r L_{source} \frac{\cos\theta_x \cos\theta_{\bar{y}_i}}{r_{x\bar{y}_i}^2} Vis(x, \bar{y}_i)$$

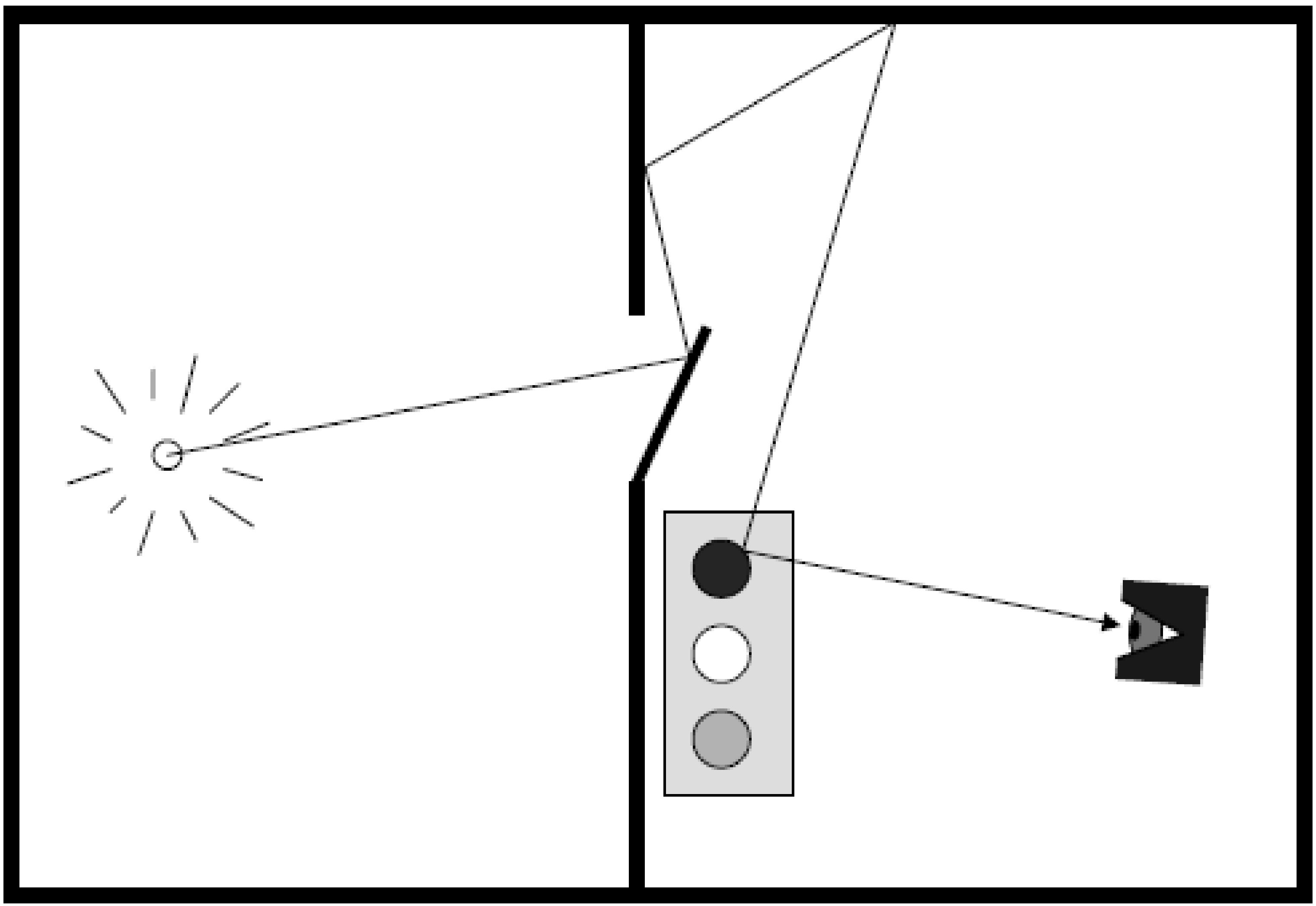
Bidirectional Path Tracing

- Or paths generated from both camera and source at the same time ...!

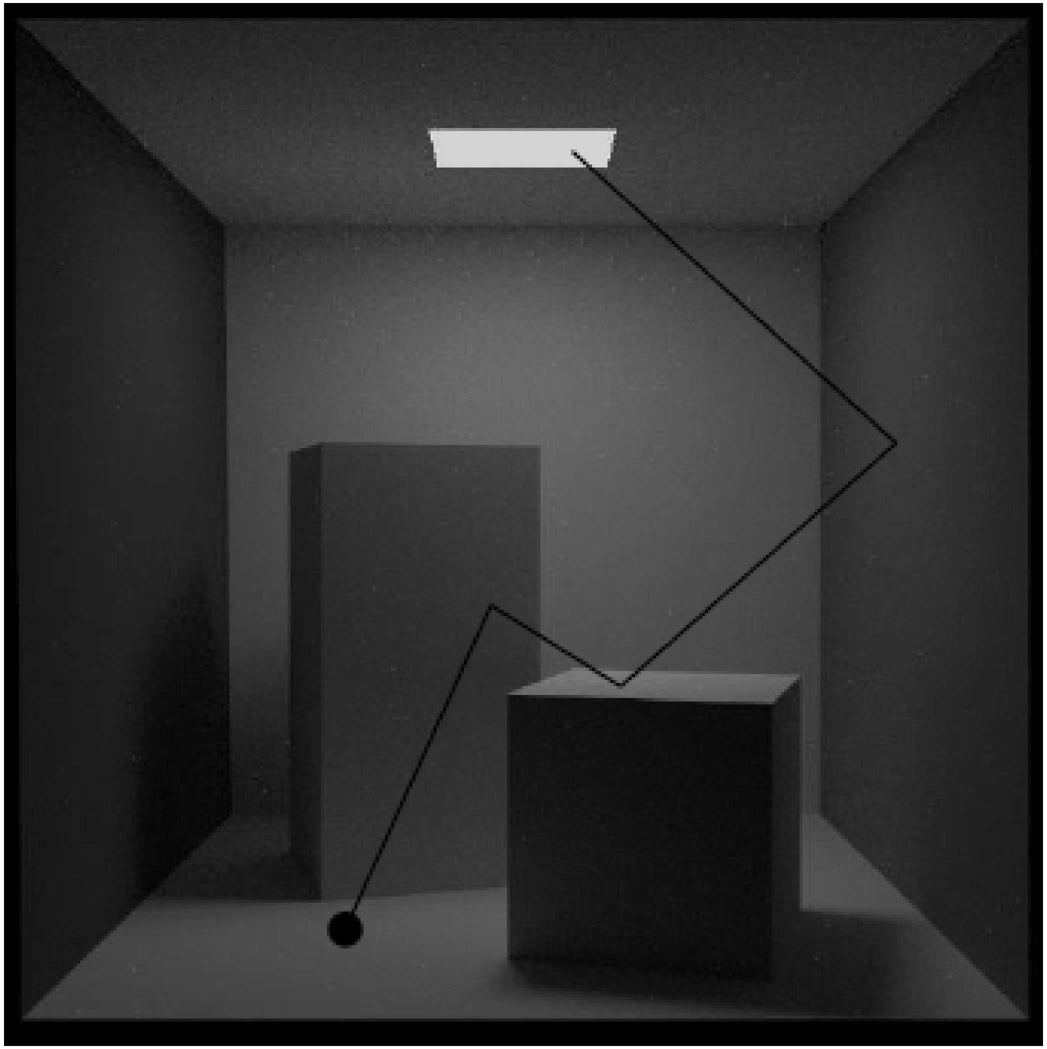


- Connect endpoints to compute final contribution

Metropolis



Metropolis



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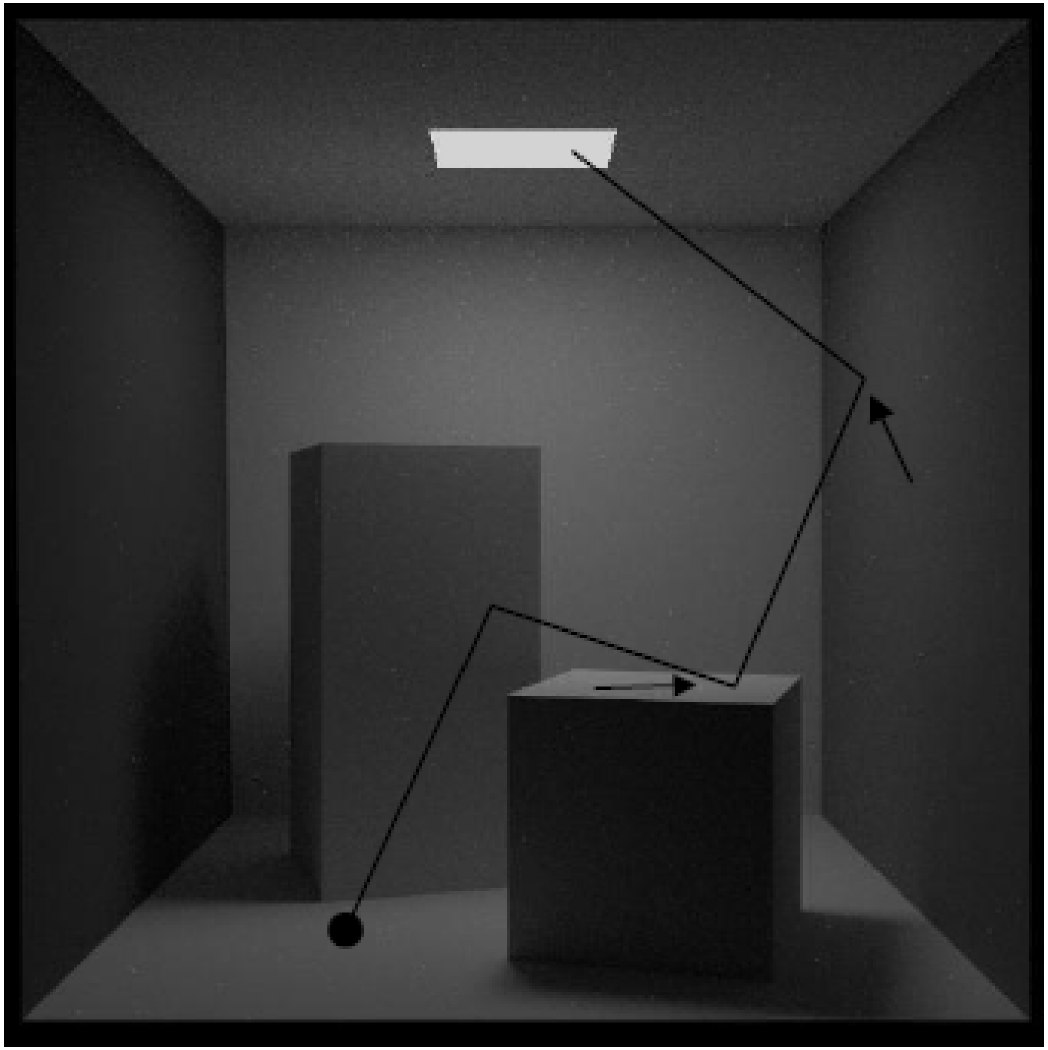
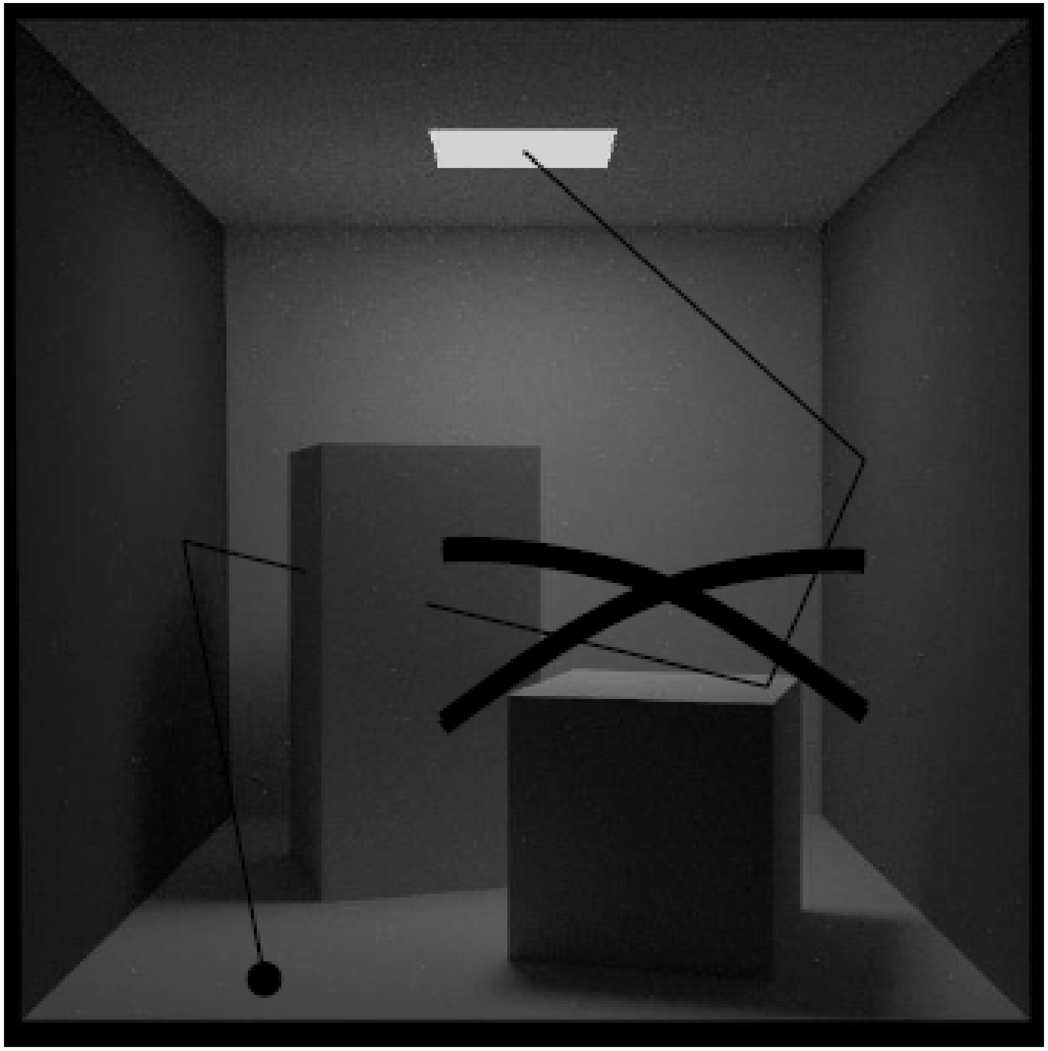
valid path

Metropolis



small perturbations

Metropolis



Accept mutations based on energy transport

Unbiased vs. Consistent

- **Unbiased**
  - **No systematic error**
  - **$E[I_{estimator}] = I$**
  - **Better results with larger N**

- **Consistent**
  - **Converges to correct results with more samples**
  - **$E[I_{estimator}] = I + \varepsilon$, where $\lim_{n \to \infty} \varepsilon = 0$**

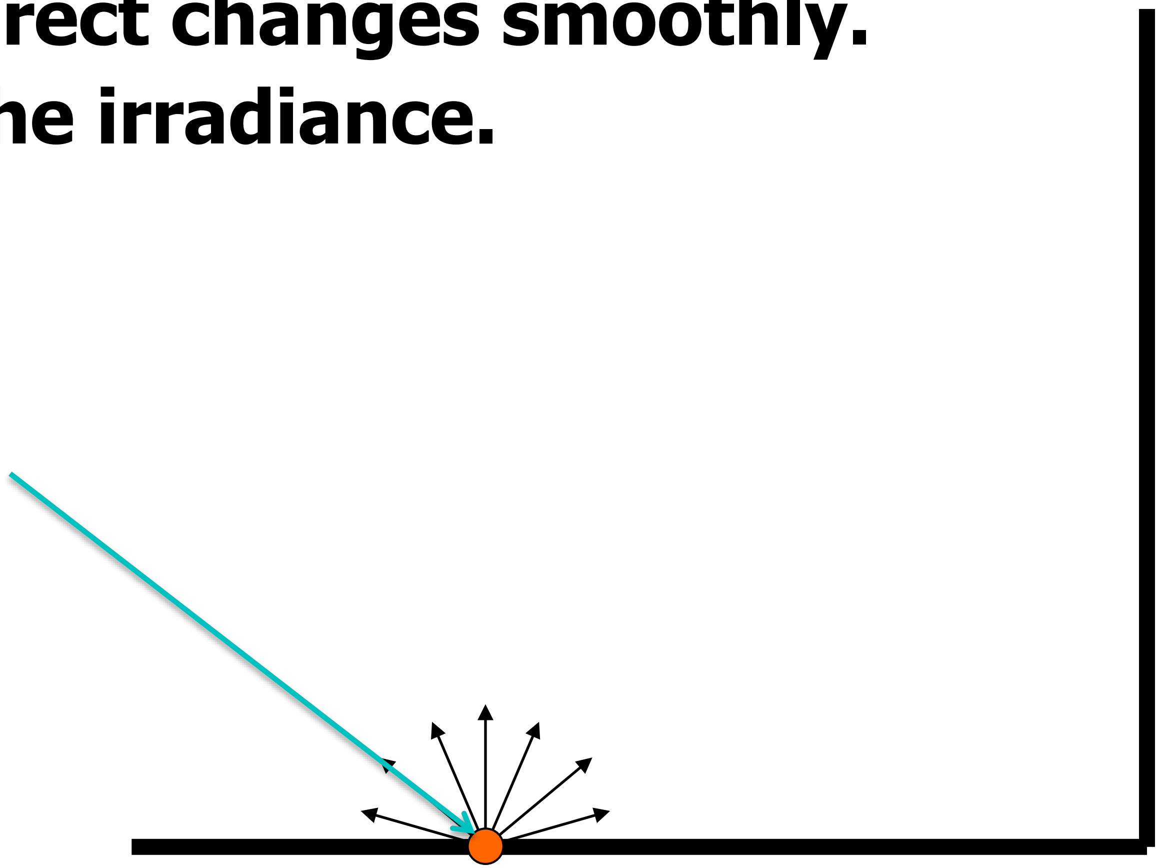
Biased Methods

- MC methods
  - Too noisy and slow
  - Nose is objectionable

- Biased methods: store information (caching)
  - Irradiance caching
  - Photon mapping

Biased Methods: Irradiance Caching

- Indirect changes smoothly.
- Cache irradiance.



From Wang's slides

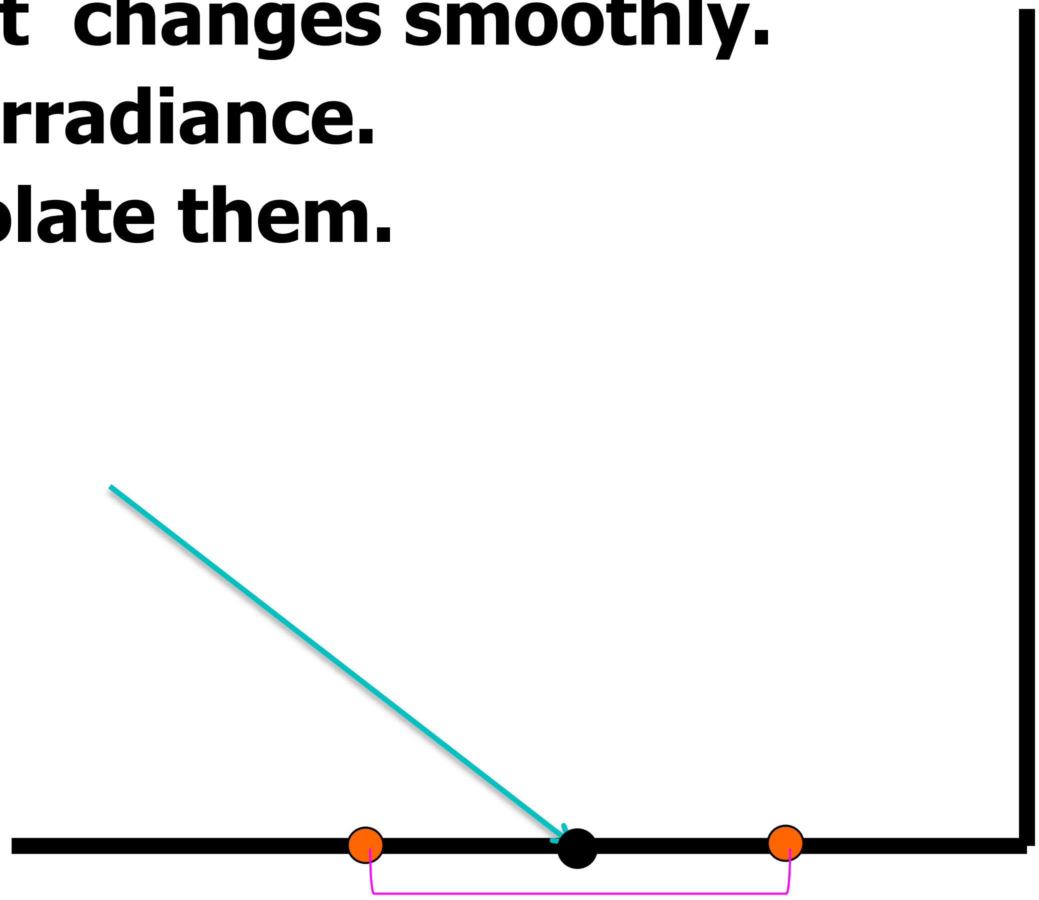
Irradiance Caching

- Indirect changes smoothly.
- Cache irradiance.

From Wang's slides

Irradiance Caching

- Indirect changes smoothly.
- Cache irradiance.
- Interpolate them.

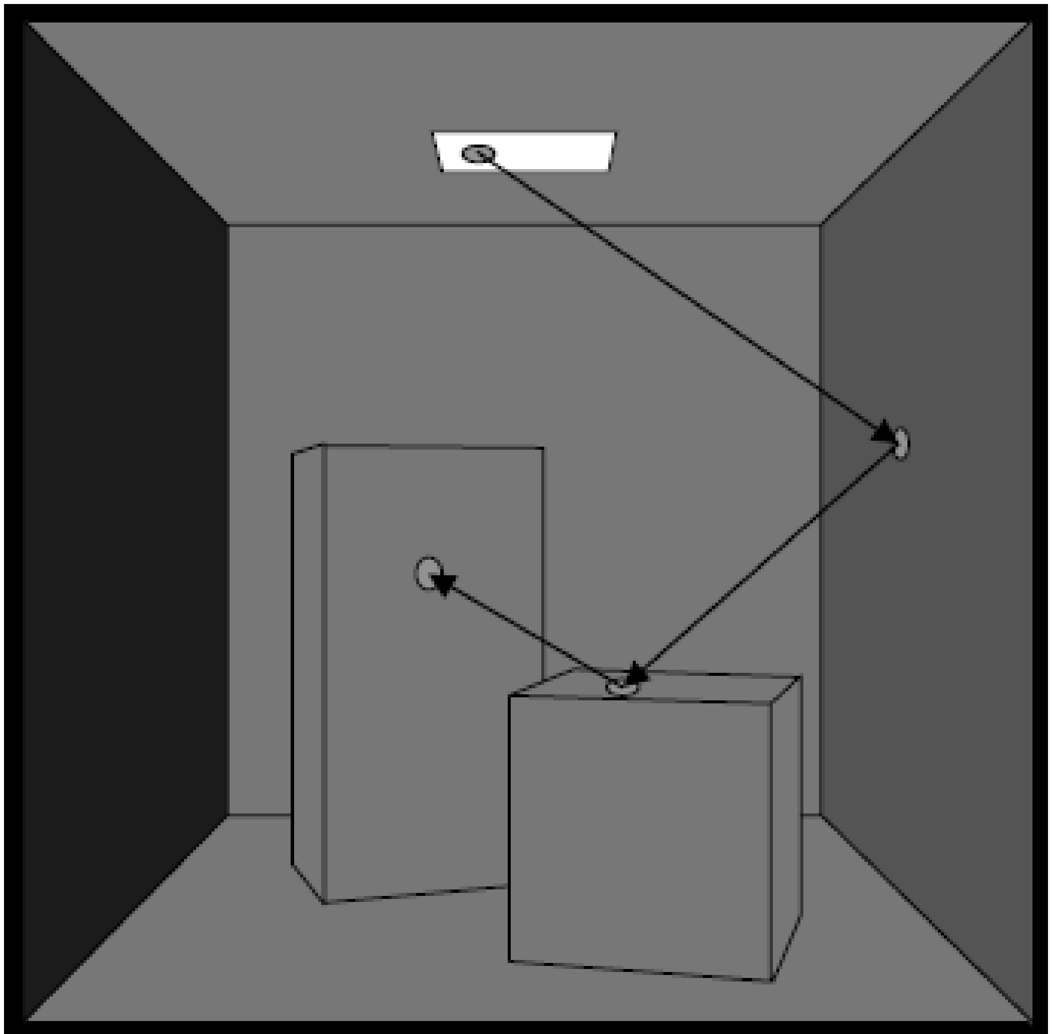


From Wang's slides

Biased Method: Photon Mapping

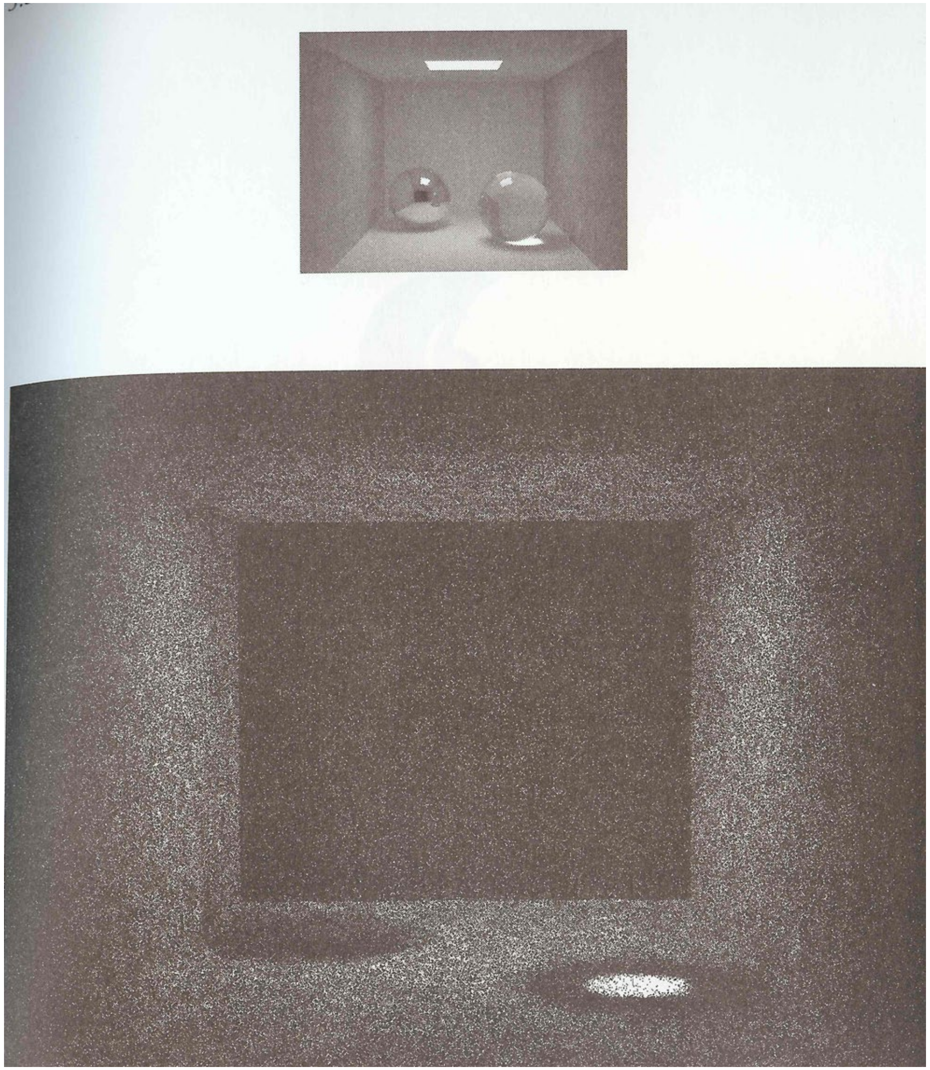
- 2 passes:
  - Shoot “photons” (light-rays) and record any hit-points
  - Shoot viewing rays and collect information from stored photons

Pass 1: shoot photons



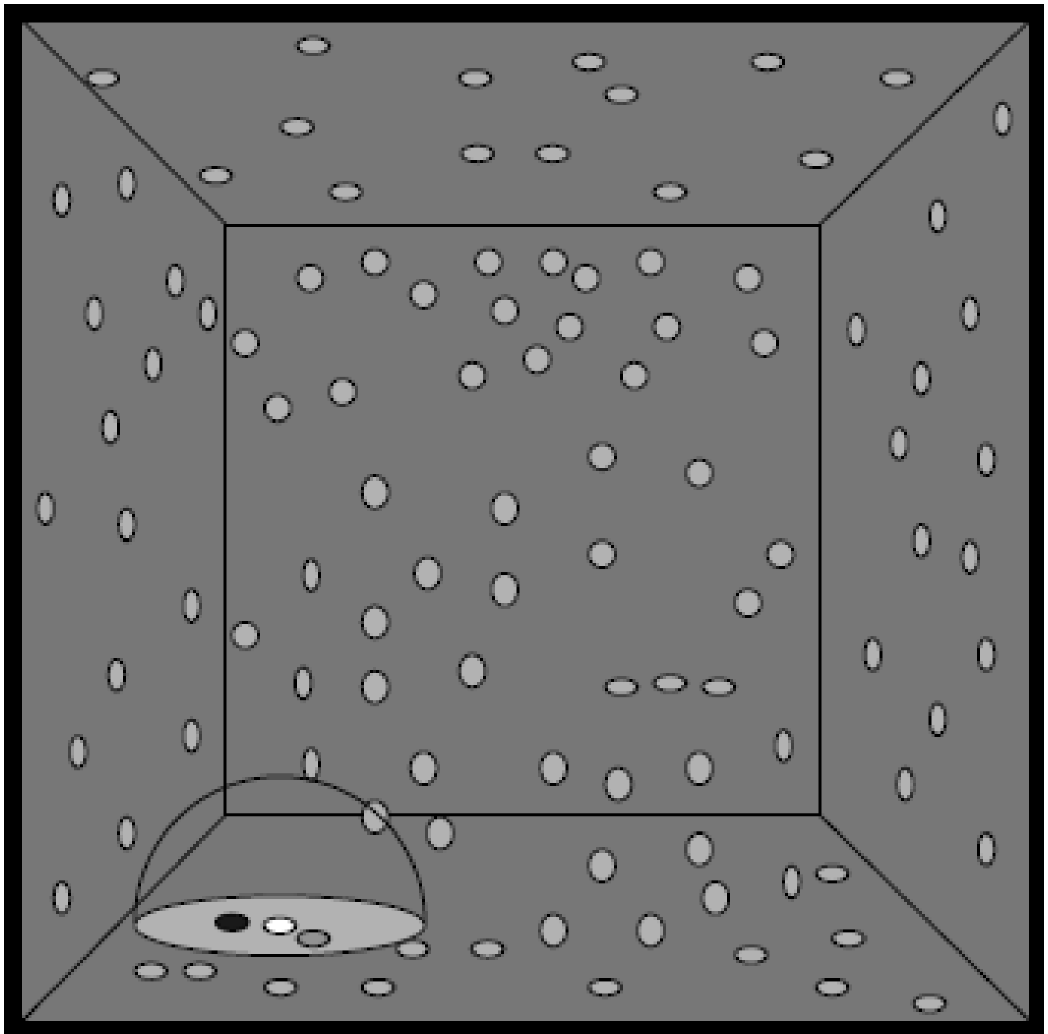
- Light path generated using MC techniques and Russian Roulette
- Store:
  - position
  - incoming direction
  - color
  - ...

Stored Photons



Generate a few hundreds of thousands of photons

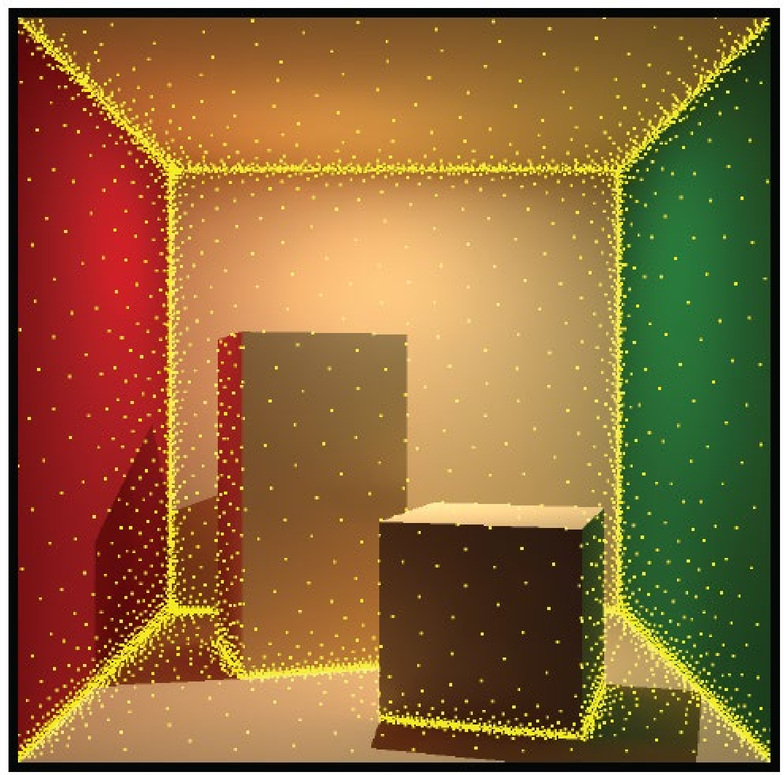
Pass 2: viewing ray



- Search for N closest photons (+check normal)
- Assume these photons hit the point we're interested in
- Compute average radiance

Direct **Indirect**

Indirect ≈



From thesis of Jarosz

Result

350K photons for the caustic map

Result

350K photons for the caustic map

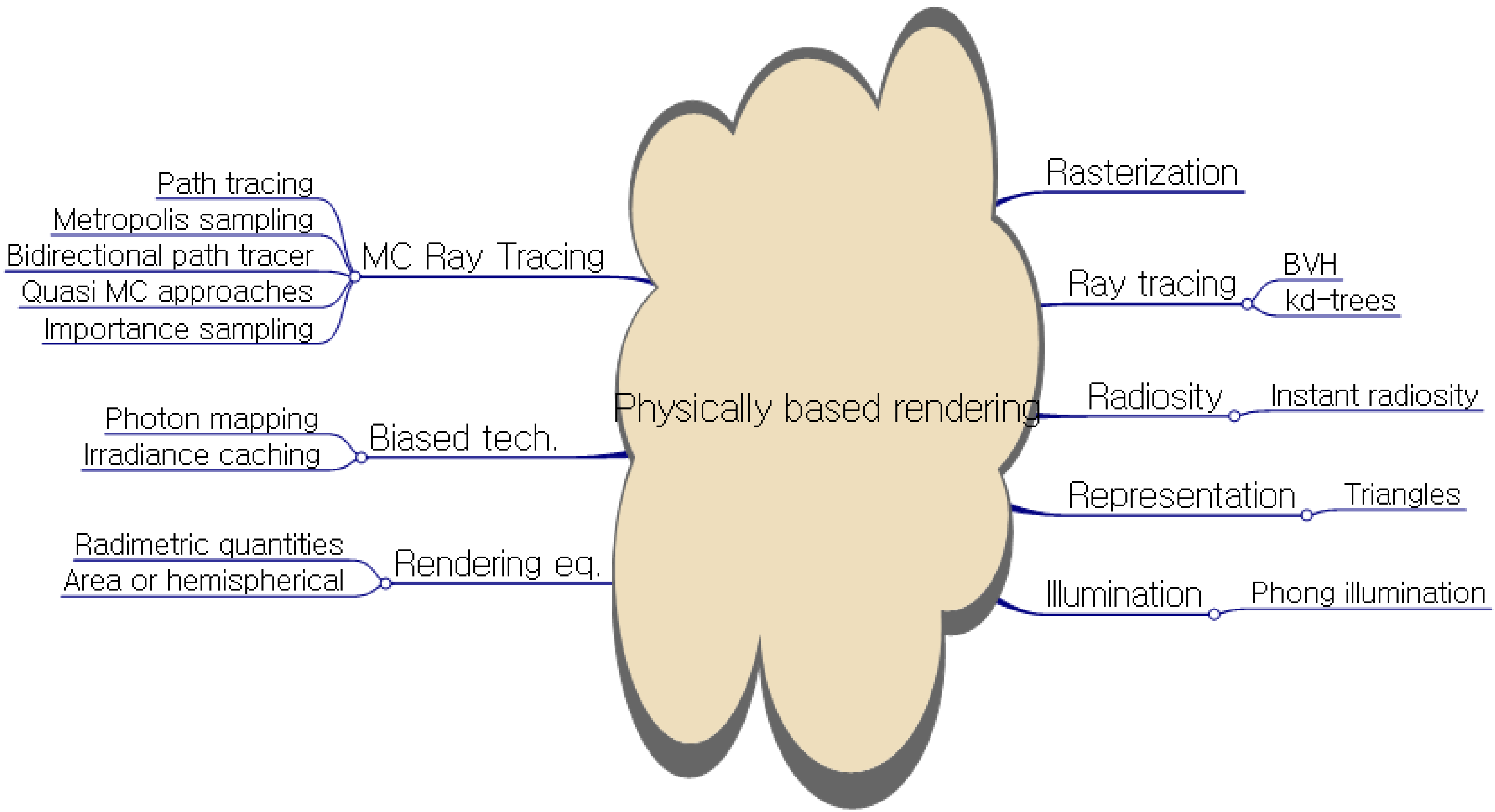
Class Objectives were:

- **Understand a basic structure of Monte Carlo ray tracing**
  - **Russian roulette for its termination**
  - **Path tracing**

Summary

- Two basic building blocks
- Radiometry
- Rendering equation
- MC integration
- MC ray tracing
  - Unbiased methods
  - Biased methods

Summary


Physically based rendering
MC Ray Tracing
Path tracing
Metropolis sampling
Bidirectional path tracer
Quasi MC approaches
Importance sampling
Biased tech.
Photon mapping
Irradiance caching
Rendering eq.
Radimetric quantities
Area or hemispherical
Rasterization
Ray tracing
BVH
kd-trees
Radiosity
Instant radiosity
Representation
Triangles
Illumination
Phong illumination

Next Time…

- **Denoising techniques**

Homework

- **Go over the next lecture slides before the class**
- **Watch 2 SIG/CVPR/ISMAR videos and submit your summaries every Mon. class**
  - **Just one paragraph for each summary**
  - **Any top-tier conf (e.g., ICRA) is okay**

Example:

Title: XXX XXXX XXXX

Abstract: this video is about accelerating the performance of ray tracing. To achieve its goal, they design a new technique for reordering rays, since by doing so, they can improve the ray coherence and thus improve the overall performance.

Any Questions?

- **Submit three times before the mid-term exam**
- **Come up with one question on what we have discussed in the class and submit:**
  - **1 for typical or already answered questions**
  - **2 for questions that have some thoughts or surprise me**