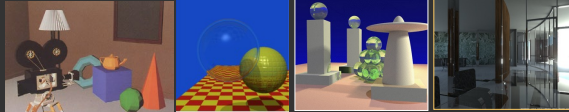


Computer Graphics II: Rendering

CSE 168 [Spr 26], Lecture 12: High Quality Rendering
Ravi Ramamoorthi

<http://viscomp.ucsd.edu/classes/cse168/sp26>



1

To Do

- Homework 4 (importance sampling) due May 18
- These lectures cover more advanced topics
 - May be relevant for your final project
 - Or curiosity in terms of frontiers of modern rendering

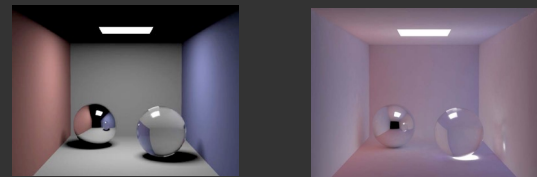
2

Motivation

- Rendering Equation since 86, Path Tracer in HW 3
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- Can it be made more efficient (90s until today)?
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 - Irradiance Caching takes advantage of coherence
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 - Modern adaptive sampling, cut-based integration
- Advanced topics (next time)
- Denoising (next time)

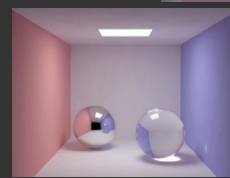
3

Smoothness of Indirect Lighting



Direct

Indirect



Direct + Indirect

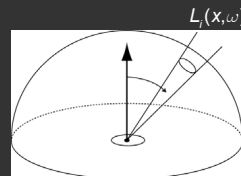
4

Irradiance Caching

- Empirically, (diffuse) interreflections low frequency
- Therefore, should be able to sample sparsely
- Irradiance caching samples irradiance at few points on surfaces, and then interpolates
- Ward, Rubinstein, Clear. SIGGRAPH 88, A ray tracing solution for diffuse interreflection

5

Irradiance Calculation



$$E(x) = \int L_i(x, \omega) \cos \theta d\omega$$

$$E(x) = \frac{\sum_i w(x_i) E_i(x_i)}{\sum_i w(x_i)} \quad w(x) = \frac{1}{\epsilon(x)}$$

$$\epsilon(x) \leq \left| \frac{\partial E}{\partial x}(x - x_0) + \frac{\partial E}{\partial \theta}(\theta - \theta_0) \right|$$

position rotation

$$\leq E_0 \left(\frac{4}{\pi} \frac{\|x - x_0\|}{x_{avg}} + \sqrt{2 - 2\vec{N}(x) \cdot \vec{N}(x_0)} \right)$$

Derivation in Ward paper

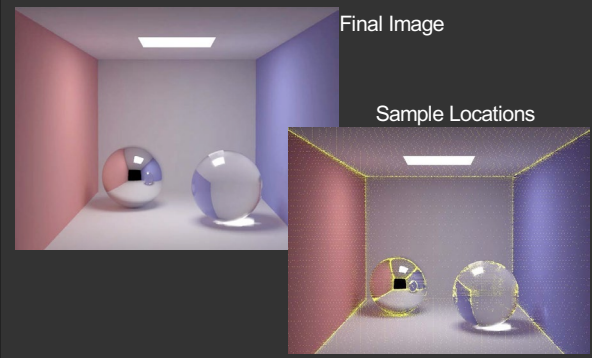
6

Algorithm Outline

- Find all samples with $w(x) > q$
- if (samples found)
 - interpolate
- else
 - compute new irradiance
- N.B. Subsample the image first and then fill in

7

Irradiance Caching Example



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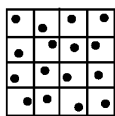
9

Better Sampling

- Smarter ways to Monte Carlo sample
- Long history: Stratified, Importance, Bi-Directional, Multiple Importance, Metropolis
- Good reference is Veach thesis
- We only briefly discuss a couple of strategies

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Stratified Sampling



Stratified sampling like jittered sampling

Allocate samples per region

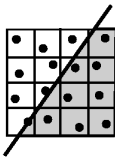
$$N = \sum_{i=1}^m N_i \quad F_N = \frac{1}{N} \sum_{i=1}^m N_i F_i$$

New variance

$$V[F_N] = \frac{1}{N^2} \sum_{i=1}^m N_i V[F_i]$$

Thus, if the variance in regions is less than the overall variance, there will be a reduction in resulting variance

For example: An edge through a pixel



$$V[F_N] = \frac{1}{N^2} \sum_{i=1}^N V[F_i] = \frac{V[F_k]}{N^{1.5}}$$

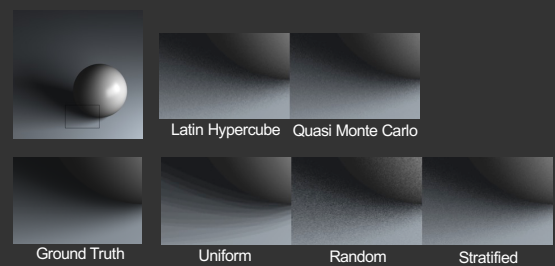
CS348B Lecture 9

Pat Hanrahan, Spring 2002

D. Mitchell 95, Consequences of stratified sampling in graphics

11

Comparison of simple patterns



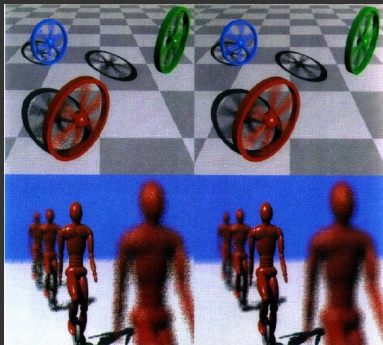
16 samples for area light, 4 samples per pixel, total 64 samples

If interested, see my paper "A Theory of Monte Carlo Visibility Sampling"

Figures courtesy Tianyu Liu

12

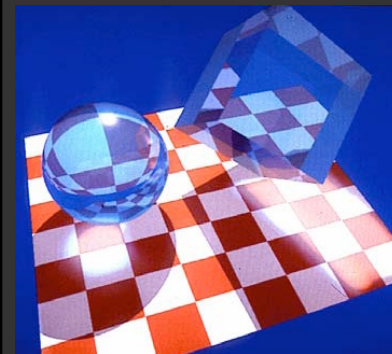
Spectrally Optimal Sampling



Mitchell 91

13

Light Ray Tracing



Backwards Ray Tracing
[Arvo 86]

14

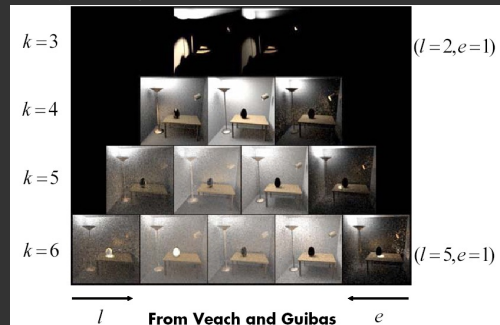
Path Tracing: From Lights

- Step 1. Choose a light ray
- Step 2. Find ray-surface intersection
- Step 3. Reflect or transmit
 - $u = \text{Uniform}()$
 - if $u < \text{reflectance}(x)$
 - Choose new direction $d \sim \text{BRDF}(O||)$
 - goto Step 2
 - else if $u < \text{reflectance}(x) + \text{transmittance}(x)$
 - Choose new direction $d \sim \text{BTDF}(O||)$
 - goto Step 2
 - else // absorption = 1 - reflectance - transmittance
 - terminate on surface; deposit energy

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Bidirectional Path Tracing

Path pyramid ($k = l + e = \text{total number of bounces}$)



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Comparison



Bidirectional path tracing

Path tracing

From Veach and Guibas

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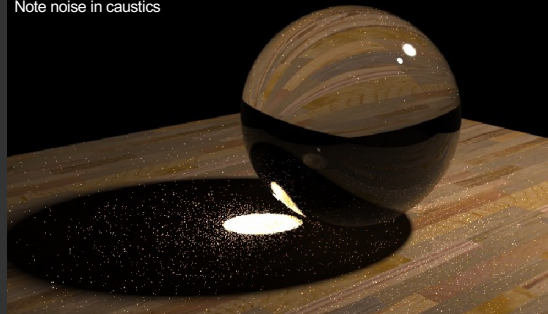
Why Photon Map?

- Some visual effects like caustics hard with standard path tracing from eye
- May usually miss light source altogether
- Instead, store "photons" from light in kd-tree
- Look-up into this as needed
- Combines tracing from light source, and eye
- Similar to bidirectional path tracing, but compute photon map only once for all eye rays
- Global Illumination using Photon Maps* H. Jensen. *Rendering Techniques (EGSR 1996)*, pp 21-30. (Also book: *Realistic Image Synthesis using Photon Mapping*)

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Caustics

Path Tracing: 1000 paths/pixel
Note noise in caustics



Slides courtesy Henrik Wann Jensen

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Caustics

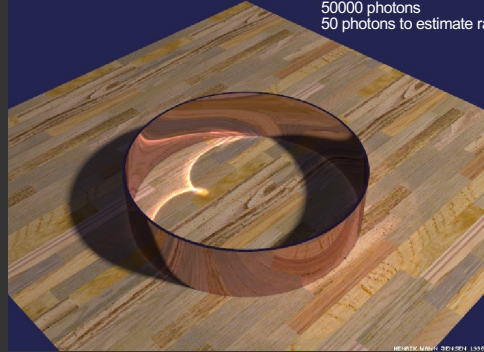
Photon Mapping: 10000 photons
50 photons in radiance estimate



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Reflections Inside a Metal Ring

50000 photons
50 photons to estimate radiance



22

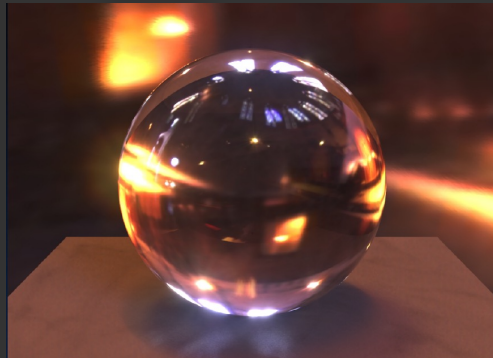
Caustics on Glossy Surfaces



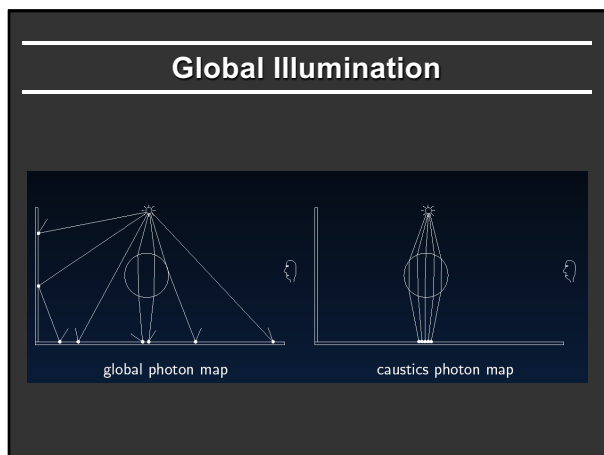
340000 photons, 100 photons in radiance estimate

23

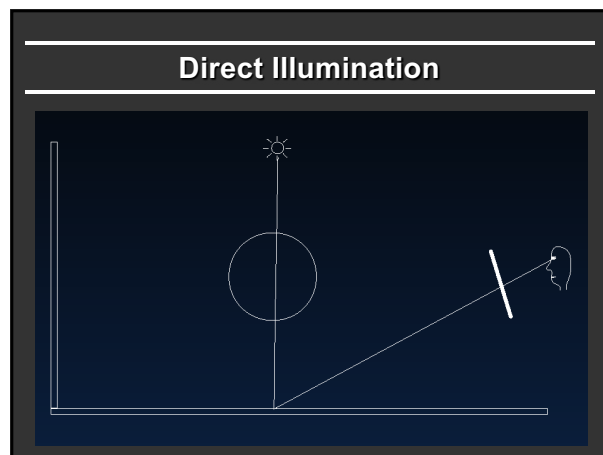
HDR Environment Illumination



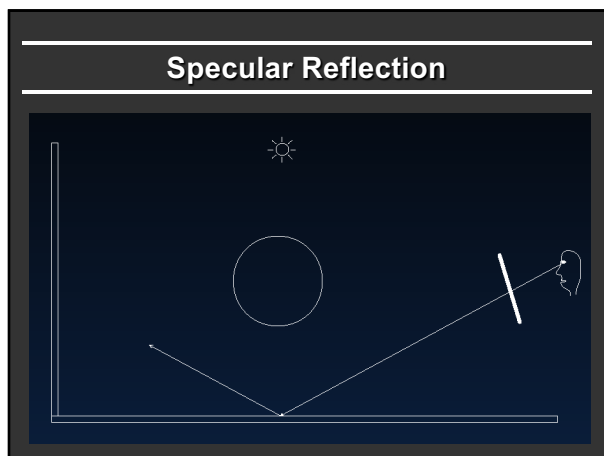
24



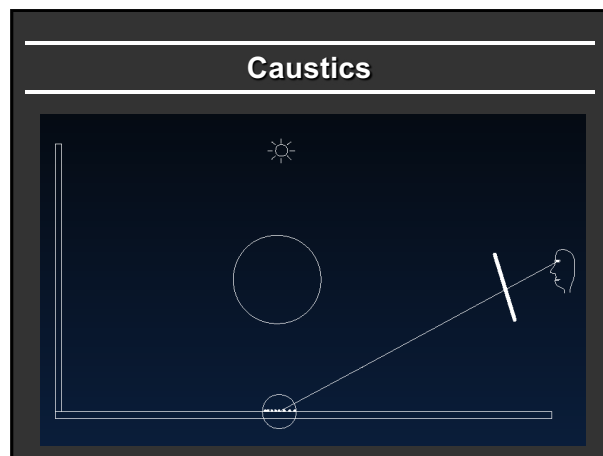
25



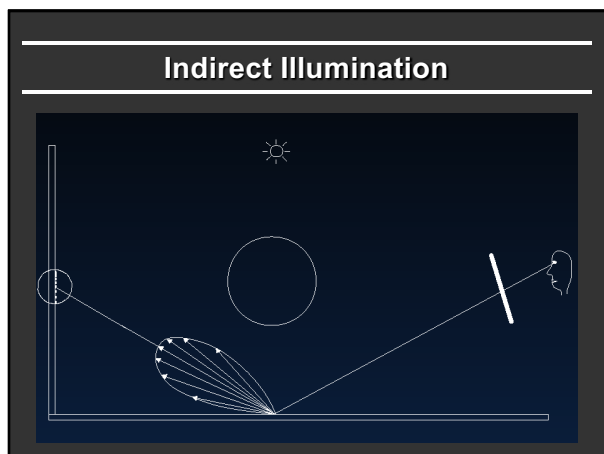
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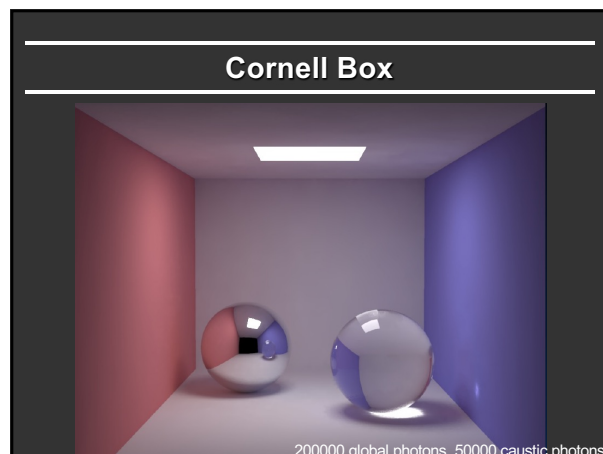
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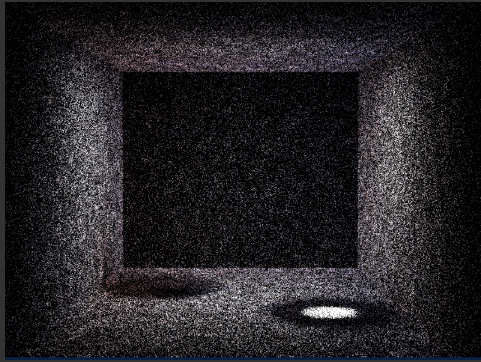


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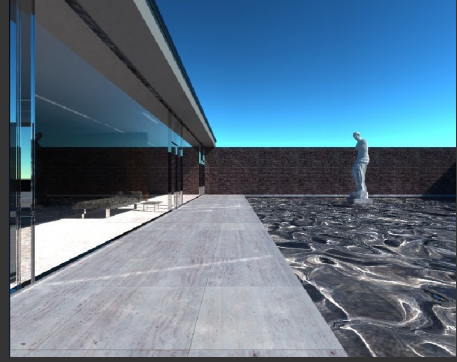
30

Box: Global Photons



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Mies House: Swimming Pool



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Lightcuts

- Efficient, accurate complex illumination



Environment map lighting & indirect
Time 111s

Textured area lights & indirect
Time 98s

(640x480, Anti-aliased, Glossy materials)
From Walter et al. SIGGRAPH 05

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Complex Lighting

- Simulate complex illumination using point lights
 - Area lights
 - HDR environment maps
 - Sun & sky light
 - Indirect illumination
- Unifies illumination
 - Enables tradeoffs between components

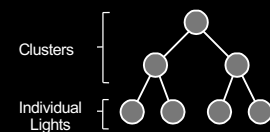


Area lights + Sun/sky + Indirect

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Key Concepts

- Light Cluster
- Light Tree
 - Binary tree of lights and clusters



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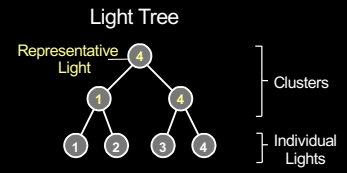
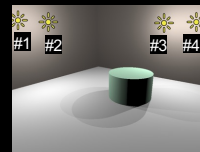
Key Concepts

- Light Cluster
- Light Tree
- A Cut
 - A set of nodes that partitions the lights into clusters



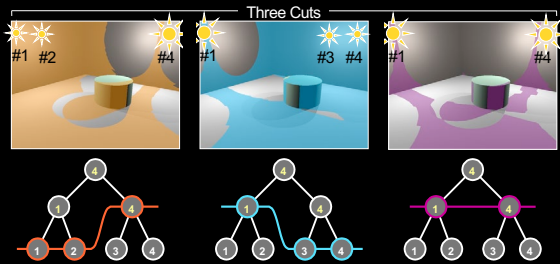
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Simple Example



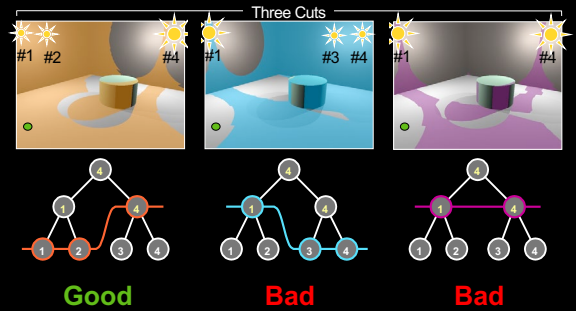
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Three Example Cuts



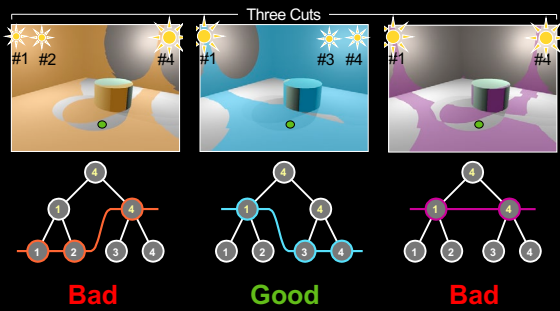
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Three Example Cuts



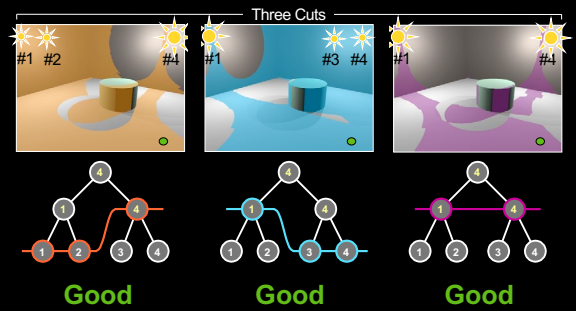
40

Three Example Cuts



41

Three Example Cuts



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What is ReSTIR?

(Aka Reservoir-based Spatiotemporal Importance Resampling)

- Simply: A way to reuse samples by sharing among pixels
 - Ray tracing is expensive
 - By amortizing costs, we increase the **effective** sample count
 - ReSTIR gives a 100x to 10,000x sample count multiplier
 - Exact multiplier is hard to measure; handwavy
- Think: A post-process denoiser, but **inside** the renderer
 - Denoiser says: "neighbors are similar, so blur colors across pixels"
 - ReSTIR says: "neighbors are similar, so reuse samples (or PDFs) across pixels"
- Unlike denoising, ReSTIR can be unbiased
 - Why? In the renderer, we can reuse data **before** throwing important stuff away

2.1 ms

Path tracing with 1 path per pixel

10.0 ms

ReSTIR with 1 sample per pixel

45

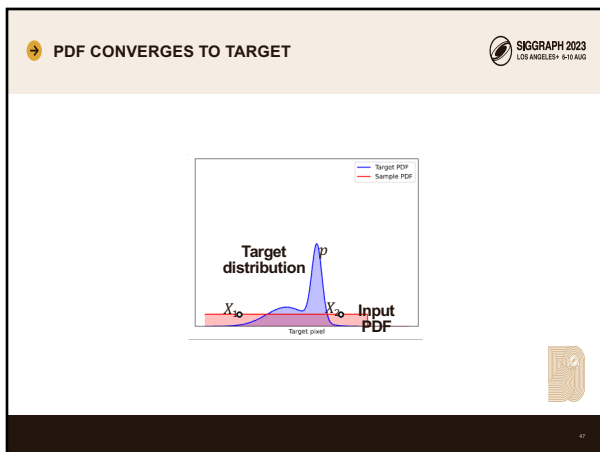
RESAMPLED IMPORTANCE SAMPLING

RIS: a machine that produces samples approximately proportionally to a target distribution

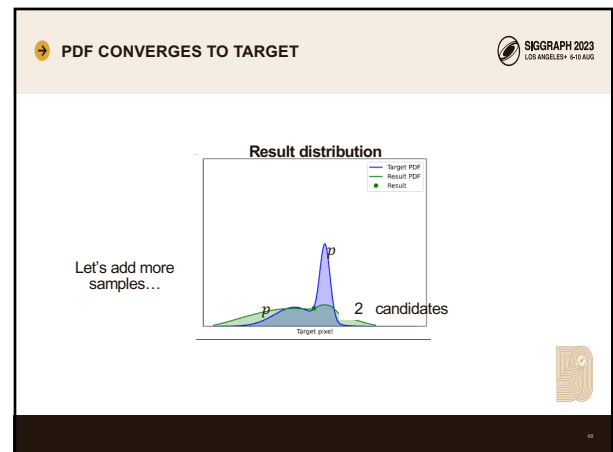
Samples X_1, X_2, \dots, X_M

One better-distributed sample

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RIS: CONCEPTS

Target function \tilde{p}

- Unnormalized
- User-given

Target PDF p

- Integrates to 1
- Not known

Used in selection probabilities

Result PDF approximately p

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RIS: ALGORITHM

```

9 function ResampledImportanceSampling(M)
10 // Generate candidates  $(X_1, \dots, X_M)$ 
11 for  $i \leftarrow 1$  to  $M$  do
12   generate  $X_i$ 
13    $w_i \leftarrow m_i(X_i) \tilde{p}(X_i) W_{X_i}$ 
14 // Select  $Y$  from the candidates
15  $Y, W_Y \leftarrow 0, 0$ 
16  $s = \text{randomIndex}(w_1, \dots, w_M)$ 
17 if  $s \neq 0$  then
18    $Y \leftarrow X_s$ 
19    $W_Y \leftarrow \frac{1}{\tilde{p}(Y)} \sum_i w_i$ 
20 return  $Y, W_Y$ 
  
```

- Take candidates (X_1, X_2, \dots, X_M)
- Evaluate resampling MIS weights: $m_i(X_i)$ e.g. $\frac{1}{\tilde{p}(X_i)}$
- Evaluate resampling weights w_i e.g. $W_{X_i} = \frac{1}{\tilde{p}(X_i)}$
- Choose Y randomly from the X_i proportionally to w_i [see course notes]
- Evaluate the UCW: $W_Y = \frac{1}{\tilde{p}(Y)} \sum_{i=1}^M w_i$

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EXAMPLE: SIMPLE INTEGRATION (RIS IS SAMPLE AGGREGATION)

- Take the M samples
- Evaluate resampling weights $w_i = m_i(X_i) \tilde{p}(X_i) W_{X_i}$

All samples identically distributed: $\frac{1}{M}$

Best if we can afford it: $\tilde{p}(x) = f(x)$

We know p : $W_{X_i} = \frac{1}{\tilde{p}(X_i)}$

- Choose Y proportionally to $w_i = \frac{1}{\tilde{p}(X_i)}$

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EXAMPLE: SIMPLE INTEGRATION (RIS IS SAMPLE AGGREGATION)

- Evaluate contribution weight $W_Y = \frac{1}{\tilde{p}(Y)} \sum_{i=1}^M w_i$

We chose: $f(Y)$

$\frac{1}{M} \frac{f(X_i)}{\tilde{p}(X_i)}$

- Integrate: $I(f) = f(Y) W_Y = \dots = \frac{1}{M} \sum_{i=1}^M \frac{f(X_i)}{\tilde{p}(X_i)}$

One-sample RIS estimator = traditional Monte Carlo estimator with M samples!

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RIS IS AN AGGREGATION MACHINE

We got single sample that's as good as the inputs combined!

How? Improved PDF! (By weighted selection)

RIS is an aggregation machine

With $\tilde{p} = f$, the result is somewhat worse due to $\text{Var}(\frac{1}{M})$

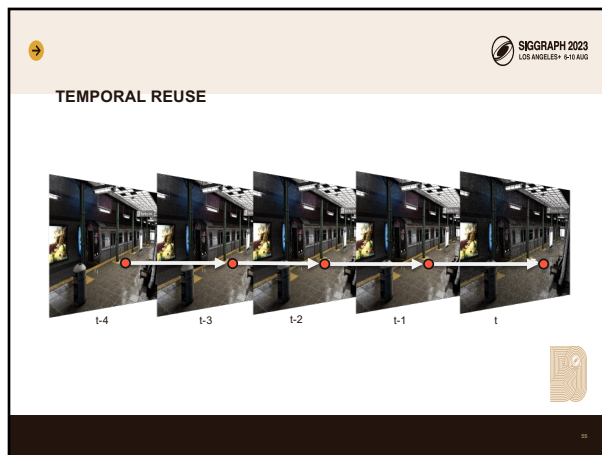
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TEMPORAL REUSE

Previous Frame

Current Frame

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