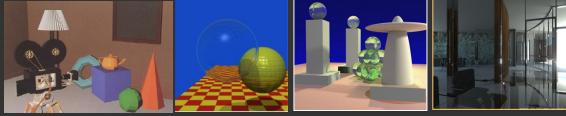


## Computer Graphics II: Rendering

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

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



1

## Motivation

- Rendering Equation since 86, Path Tracer in HW 3
- So, is Monte Carlo rendering solved?
- *Can it be made more efficient (90s until today)?*
  - Multiple Importance Sampling (Homework 4)
  - *Irradiance Caching takes advantage of coherence*
  - Correct sampling: Stratified, Multiple Importance, Bidirectional Path Tracing, Metropolis, VCM/UPS, ...
  - Photon Mapping
  - Modern adaptive sampling, cut-based integration
- Advanced topics (next time)
- Denoising (next time)

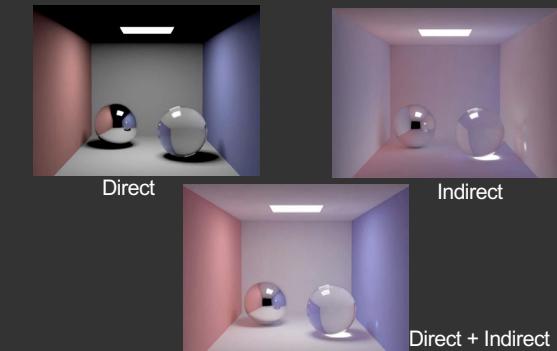
3

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

## Smoothness of Indirect Lighting



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## 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*

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## Irradiance Calculation

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

### Derivation in Ward paper

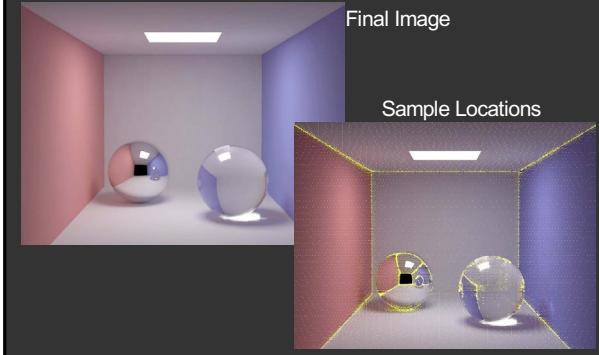
6

## 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

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## Irradiance Caching Example



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## 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

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

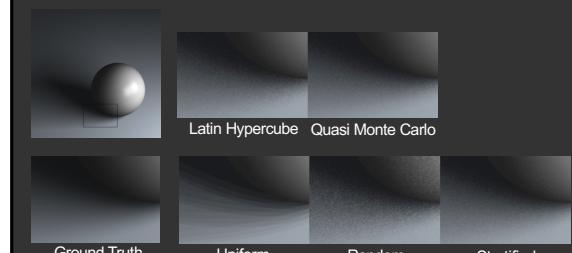
CS348B Lecture 9

Pat Hanrahan, Spring 2002

D. Mitchell 95, Consequences of stratified sampling in graphics

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## Comparison of simple patterns



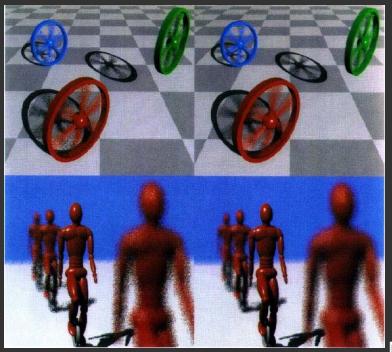
16 samples for area light, 4 samples per pixel, total 64 samples

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

Figures courtesy Tianyu Liu

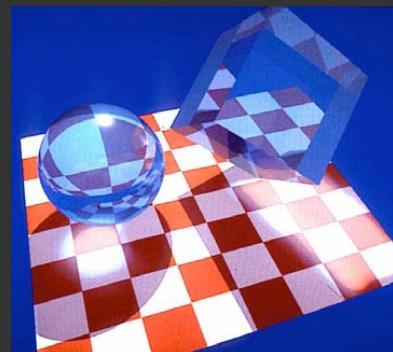
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## Spectrally Optimal Sampling



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## Light Ray Tracing



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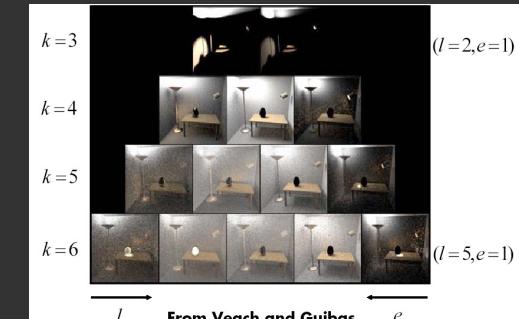
## Path Tracing: From Lights

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



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  - *Photon Mapping*
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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



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## Caustics on Glossy Surfaces



340000 photons, 100 photons in radiance estimate

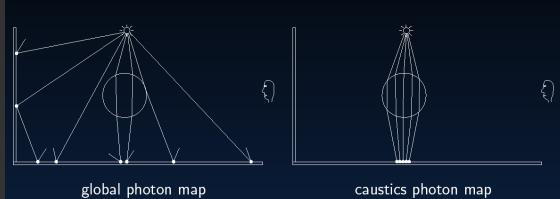
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## HDR Environment Illumination



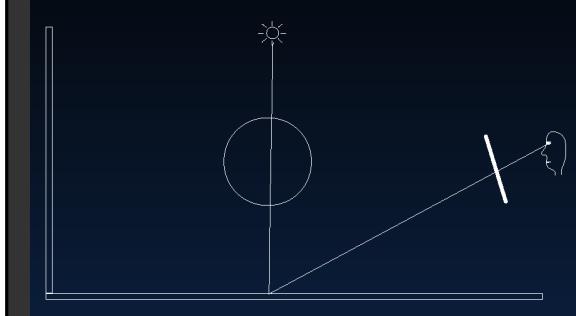
24

### Global Illumination



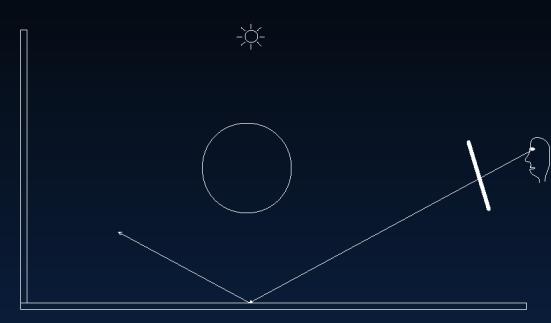
25

### Direct Illumination



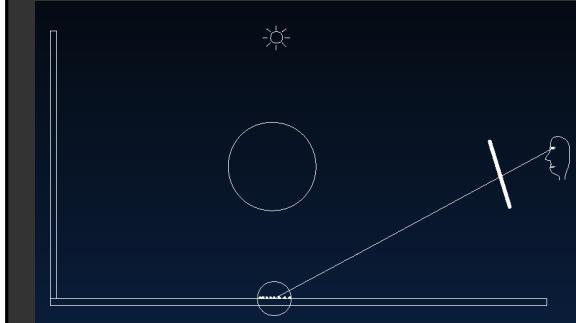
26

### Specular Reflection



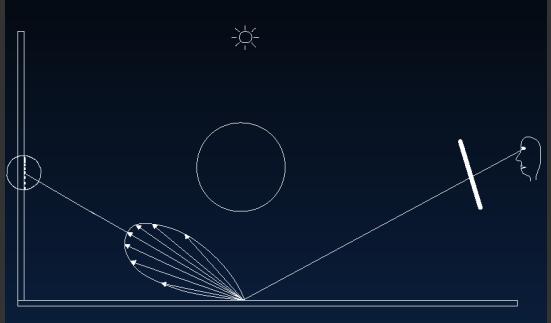
27

### Caustics



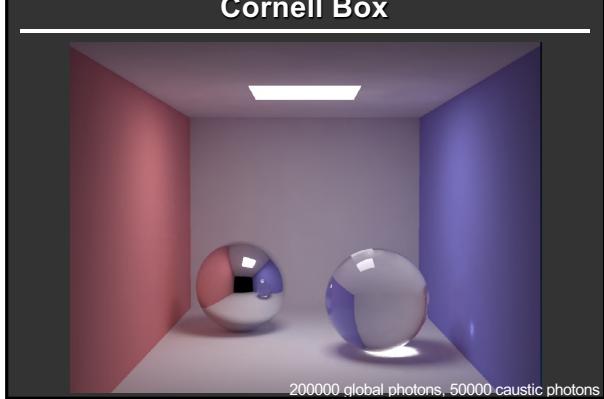
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### Indirect Illumination



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### Cornell Box



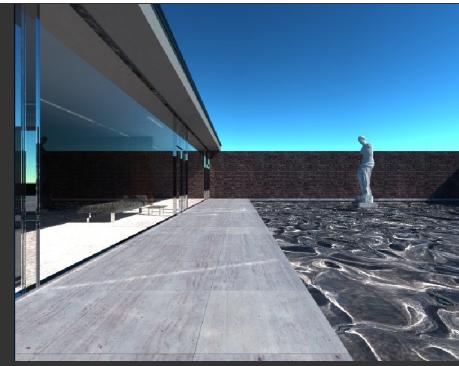
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### Box: Global Photons



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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

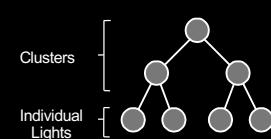


Area lights + Sun/sky + Indirect

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### Key Concepts

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



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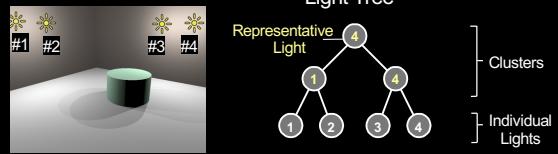
## Key Concepts

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



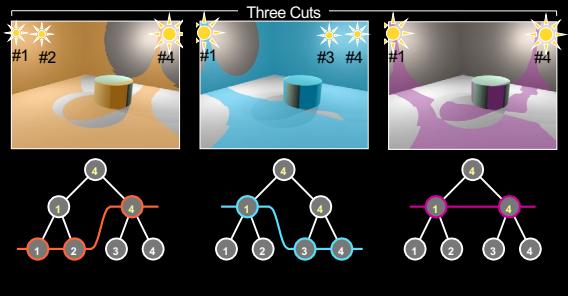
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## Simple Example



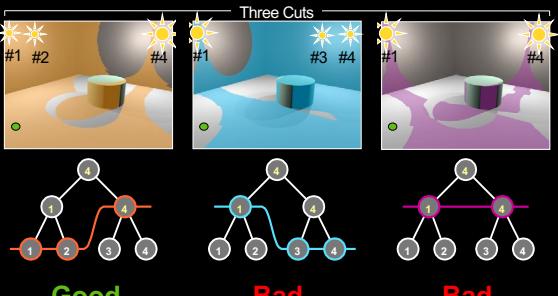
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## Three Example Cuts



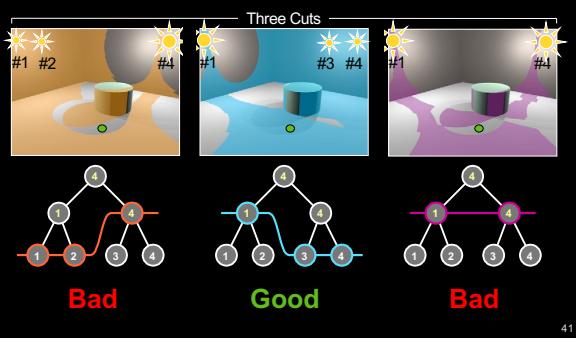
39

## Three Example Cuts



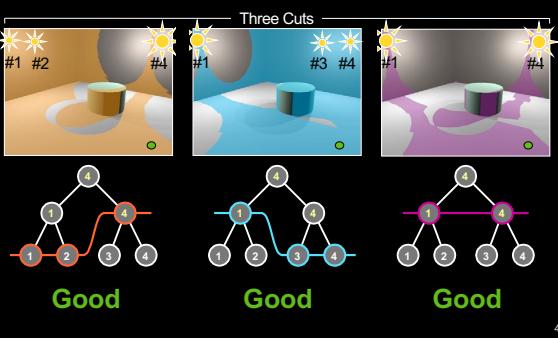
40

## Three Example Cuts



41

## Three Example Cuts



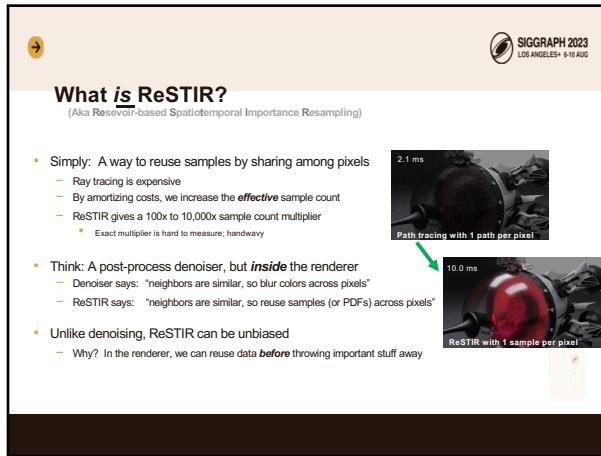
42



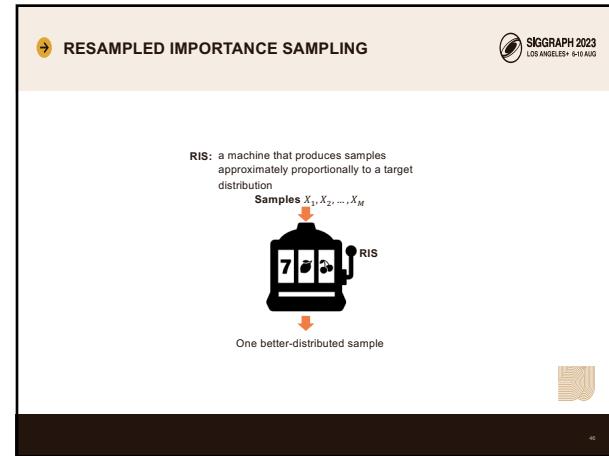
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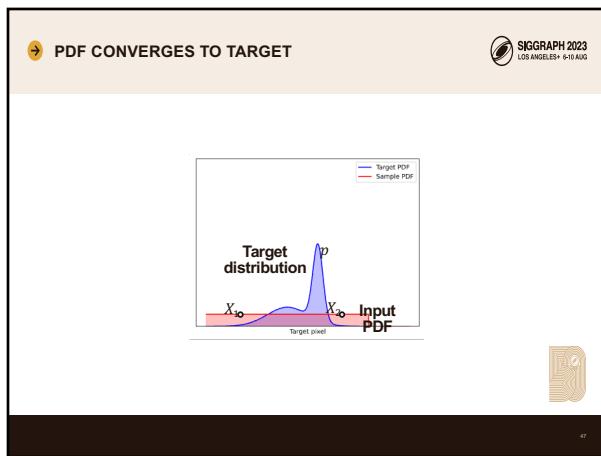
44



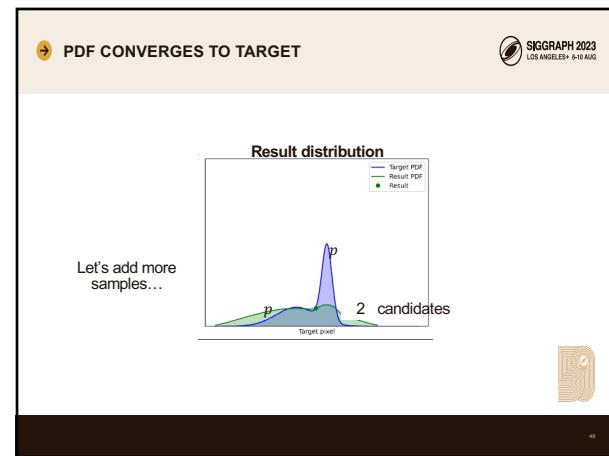
45



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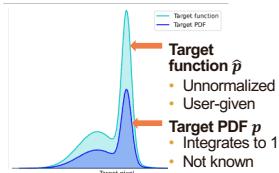
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## RIS: CONCEPTS

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LOS ANGELES+ 6-10 AUG



Used in selection probabilities

Result PDF approximately p



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## RIS: ALGORITHM

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```

* function ResampledImportanceSampling(M)
  // Generate candidates  $(X_1, \dots, X_M)$ 
  for  $i \leftarrow 1$  to  $M$  do
    generate  $X_i$ 
     $w_i \leftarrow m_i(X_i) \hat{p}(X_i) W_{X_i}$ 
  // Select  $Y$  from the candidates
   $Y, W_Y \leftarrow \emptyset, 0$ 
   $s = \text{randomIndex}(w_1, \dots, w_M)$ 
  if  $s \neq \emptyset$  then
     $Y \leftarrow X_s$ 
     $W_Y \leftarrow \frac{1}{p(Y)} \sum_i w_i$ 
  else
    4. Choose  $Y$  randomly from the  $X_i$  proportionally to  $w_i$  [see course notes]
  5. Evaluate the UCW:  $W_Y = \frac{1}{p(Y)} \sum_{j=1}^M w_j$ 
  return  $Y, W_Y$ 

```

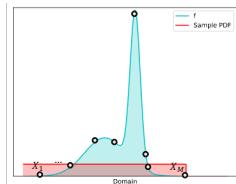


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## EXAMPLE: SIMPLE INTEGRATION (RIS IS SAMPLE AGGREGATION)

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LOS ANGELES+ 6-10 AUG

1. Take the  $M$  samples
2. Evaluate resampling weights  $w_i = m_i(X_i) \hat{p}(X_i) W_{X_i}$   
All samples identically distributed:  $\frac{1}{M}$   
Best if we can afford it:  $\hat{p}(x) = f(x)$   
We know  $p: W_{X_i} = \frac{1}{M p(X_i)}$
3. Choose  $Y$  proportionally to  $w_i = \frac{1}{M p(X_i)}$

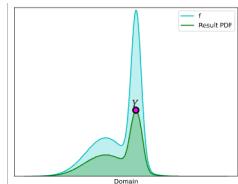


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## EXAMPLE: SIMPLE INTEGRATION (RIS IS SAMPLE AGGREGATION)

SIGGRAPH 2023  
LOS ANGELES+ 6-10 AUG

1. Take candidates  $(X_1, X_2, \dots, X_M)$
2. Evaluate resampling MIS weights:  $m_i(X_i)$  e.g.  $\frac{1}{M}$
3. Evaluate resampling weights  $w_i$  e.g.  $W_{X_i} = \frac{1}{p(X_i)}$
4. Evaluate contribution weight  $W_Y = \frac{1}{p(Y)} \sum_{i=1}^M w_i$   
We chose:  $f(Y) = \frac{1}{M p(X_i)}$
5. Integrate:  $\langle f \rangle = f(Y) W_Y = \dots = \frac{1}{M} \sum_{i=1}^M \frac{f(X_i)}{p(X_i)}$



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## RIS IS AN AGGREGATION MACHINE

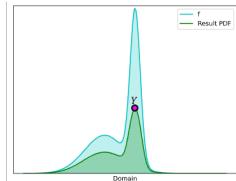
SIGGRAPH 2023  
LOS ANGELES+ 6-10 AUG

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

How? Improved PDF! (By weighted selection)

RIS is an aggregation machine

With  $\hat{p} \neq f$ , the result is somewhat worse due to  $\text{Var}(\hat{f})$



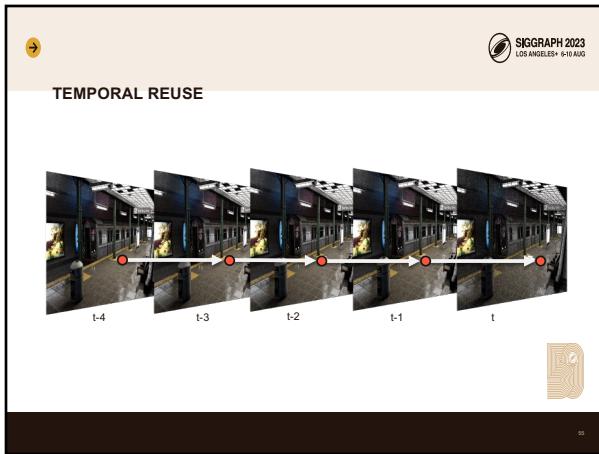
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## TEMPORAL REUSE

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**TEMPORAL REUSE**

```

1 void reuseTemporally()
2   Reservoir r
3   Sample cur = pixelSample[q]
4   w = mTime(cur.x) · p(cur.x) · cur.W
5   r.addSample(cur, w)
6   Sample prev = lastFramePixelSample[q]
7   w = mTime(prev.x) · p(prev.x) · prev.W
8   r.addSample(prev, w)
9   y = r.sampleOut
10  W = 1/p(y) · r.wSum
11  pixelSample[q] = Sample {y, W}

```

**Render passes:**

- generateSamples()
- reuseTemporally()
- reuseSpatially()
- ...
- shadePixel()

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