Advanced Computer Graphics (Fall 2009)

CS 294, Rendering Lecture 6:

Recent Advances in Monte Carlo Offline Rendering

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http://inst.eecs.berkeley.edu/~cs294-13/fa09

Some slides/ideas courtesy Pat Hanrahan, Henrik Jensen

Discussion

- Problems different over years. Initially, how to make rendering a single picture fast.
- Now, multidimensional effects, multiple images. Include image-based lighting, reflectance.
- Monte Carlo itself is a well known numerical method. But, many recent insights, more to come
- Lecture surveys much work in last decade at high-level. Need to read papers for more depth.

History and Outline

- Is Monte Carlo Rendering solved?
- *Can it be made more efficient (90s):*
  - *Irradiance caching takes advantage of coherence*
  - Correct sampling: Stratified, Multiple Importance, Bidirectional path tracing, Metropolis…
  - Photon Mapping
- Work with Image-Based Appearance (02-06)
  - Importance sampling environment maps, BRDFs
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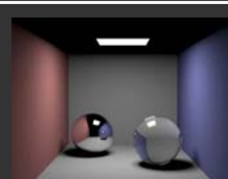
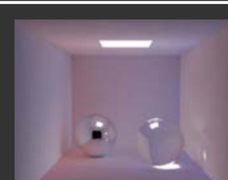
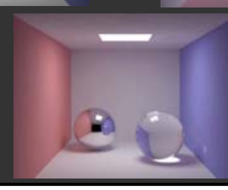
  - Adaptive multidimensional sampling
  - Cut-based hierarchical integration
  - Frequency space analysis

Smoothness of Indirect Lighting


Direct


Indirect

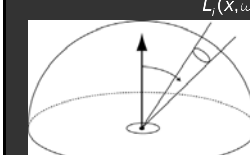

Direct + Indirect

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

Irradiance Calculation



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

$$E(x) = \frac{\sum_i w(x_i) E_i(x_i)}{\sum_i w(x_i)} \qquad w(x) = \frac{1}{\varepsilon(x)}$$

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

position rotation

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

Derivation in Ward paper

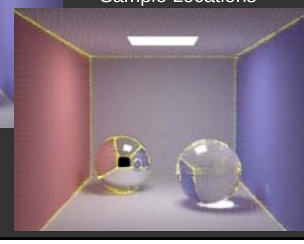
Algorithm Outline

- 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

Irradiance Caching Example

Final Image

Sample Locations



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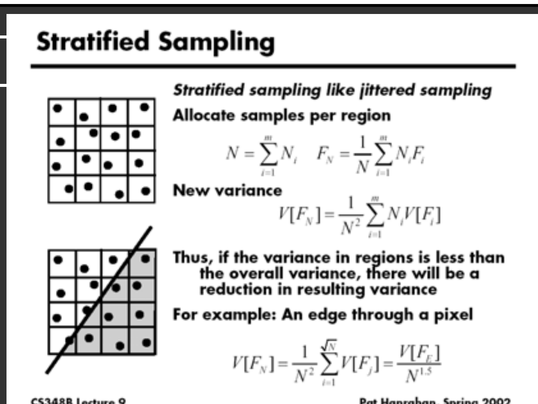
Better Sampling

- 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



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

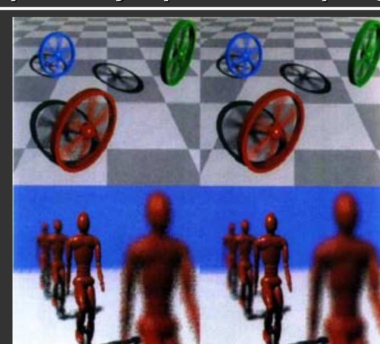
For example: An edge through a pixel

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

CS348B Lecture 9 — Pat Hanrahan, Spring 2002

D. Mitchell 95, Consequences of stratified sampling in graphics

Spectrally Optimal Sampling



Mitchell 91

Space-time Patterns

6	10	2	13
3	14	12	8
15	0	7	11
5	9	4	1

Cook Pattern

Fully populate (x,y) samples
- Recall blue noise good
  - Perceptually pleasing
  - Filtered during resampling
- Jitter to achieve blue noise

15	8	5	2
4	3	14	9
10	13	0	7
1	6	11	12

Pan-diagonal Magic Square

Distribute t samples
- Decorrelate space and time
- Nearby samples in space should differ greatly in time

Mitchell (1991) designs

CS348B Lecture 9 Pat Hanrahan, Spring 2002

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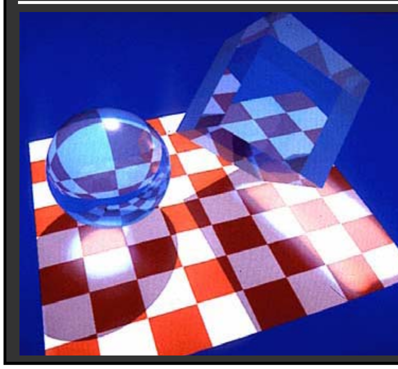
Light Ray Tracing



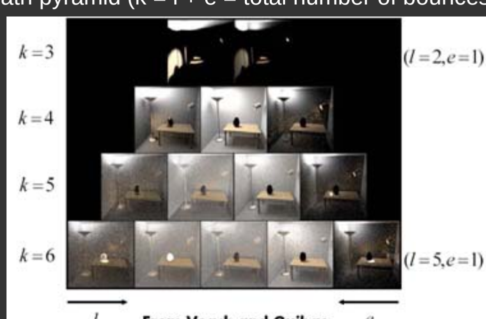
Backwards Ray Tracing [Arvo 86]

Path Tracing: From Lights

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

Bidirectional Path Tracing

Path pyramid (k = l + e = total number of bounces)



From Veach and Guibas

Comparison

Bidirectional path tracing

Path tracing

From Veach and Guibas

Why Photon Map?

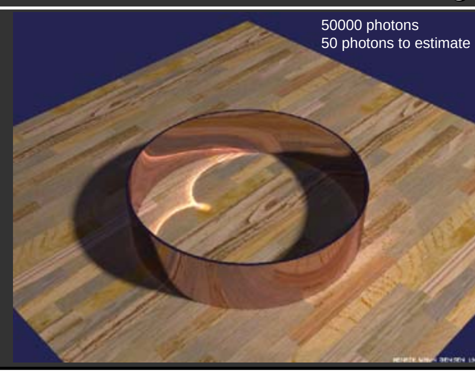
- Some visual effects like caustics hard with standard path tracing from eye
- May usually miss light source altogether
- Instead, store “photons” from light in kd-tree
- Look-up into this as needed
- Combines tracing from light source, and eye
- Similar to bidirectional path tracing, but compute photon 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*)

Caustics

Slides courtesy Henrik Wann Jensen

Caustics

Reflections Inside a Metal Ring



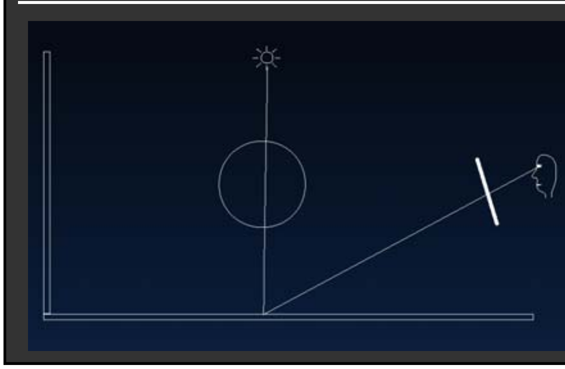
Caustics on Glossy Surfaces

340000 photons, 100 photons in radiance estimate

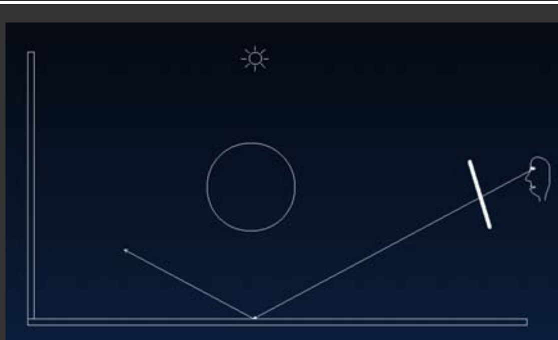
HDR Environment Illumination

Global Illumination

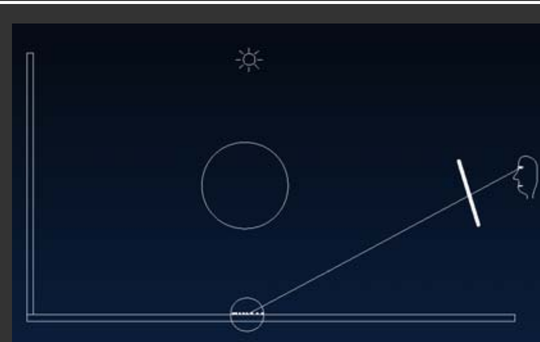
Direct Illumination



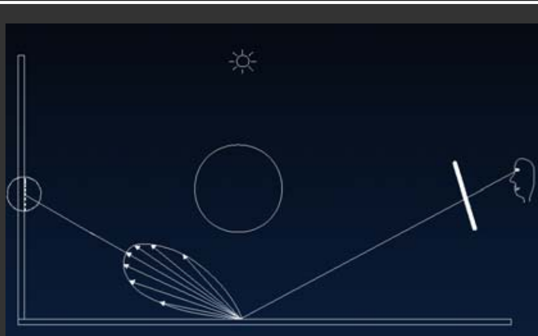
Specular Reflection



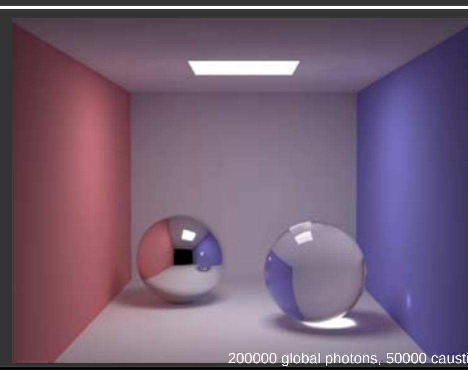
Caustics



Indirect Illumination



Cornell Box



200000 global photons, 50000 caustic photons

Box: Global Photons

Mies House: Swimming Pool

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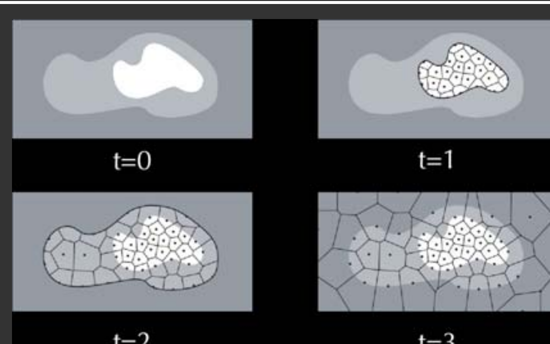
Image-Based Appearance

- Standard global illumination is difficult, but the emitters and reflective properties are simple
- In mid-1990s, interest in appearance acquired from real world, such as image-based lighting
- Environment Maps, measured BRDFs. These are functions. E.g. any of million pixels emitter
- How to (importance) sample lighting, BRDFs?
  - Agarwal et al. SIGGRAPH 03, Lawrence et al. SIGGRAPH 04, Clarberg et al. SIGGRAPH 05

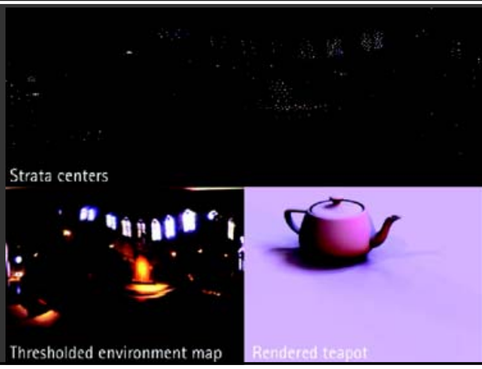
Structured Importance Sampling

- Goal: Reduce environment to point lights

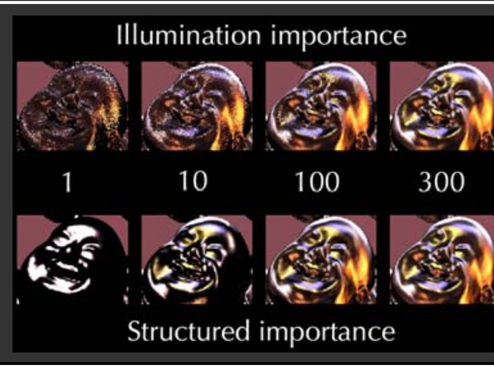
Hierarchical Stratification



Structured Importance Sampling



Glossy BRDF



BRDF Sampling

- Lighting is only one component. Must be able to importance sample the BRDF in glob. Illum.
- In 2004, no good importance sampling schemes for most BRDFs, including common Torrance-Sparrow
- From Lawrence et al. 04, factor BRDF into data-driven terms that can each be importance sampled

Complex BRDF Models

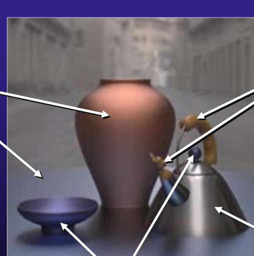
Analytic

[Cook & Torrance 1982]

Measured

[Matusik et. al. 2003]

Motivation



Key Idea

- Project 4D BRDF into sum of products of 2D function dependent on ω_o and 2D function dependent on ω_i :

$$f_r(\omega_o,\omega_i)(n\cdot\omega_i) = \sum_{j=1}^{J} F_j(\omega_o)\, G_j(\omega_p)$$

ω_p depends **only** on the incoming direction and some re-parameterization of the hemisphere.

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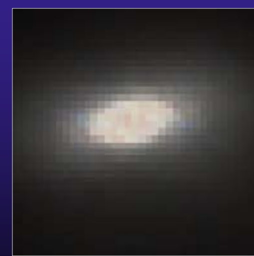
Measured Nickel BRDF

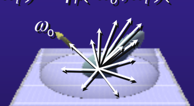


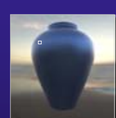
Original

Reconstruction of 2-Term Factored Representation (18KB)

Sampling Factored BRDF

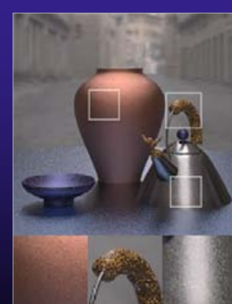
$$P(\omega_i)\propto f_r(\omega_o,\omega_i)(n\cdot\omega_i)$$



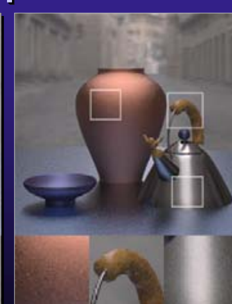


	$F_1(\omega_o)$	$F_2(\omega_o)$	...	$F_J(\omega_o)$
EVALUATE	0.1	0.75		0.1
SELECT TERM		$G_2(\omega_i)$		
SAMPLE		ω_i		

300 Samples/Pixel



Sampling Lafortune Fit



Our Method

Subsequent Work

- Multiple Importance Sampling [Veach 95] of BRDF and Environment Map [Lawrence 05]
- Fast Wavelet Products [Ng et al. 04]
- Wavelet Importance Sampling of product of lighting and BRDF [Clarberg et al. 05]
- Some efforts to also consider visibility

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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

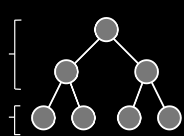
Complex Lighting

- 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

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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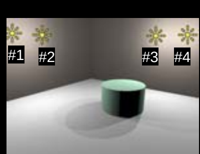
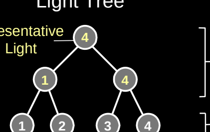
Simple Example





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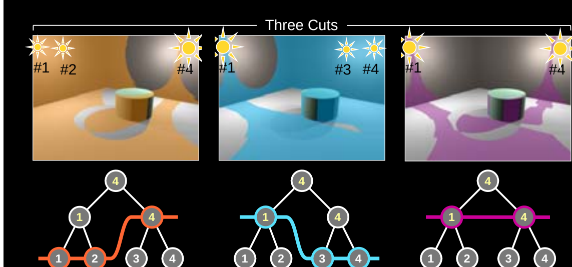
Three Example Cuts



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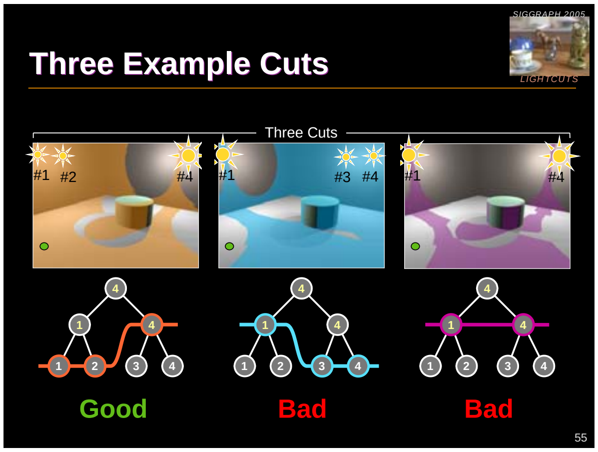
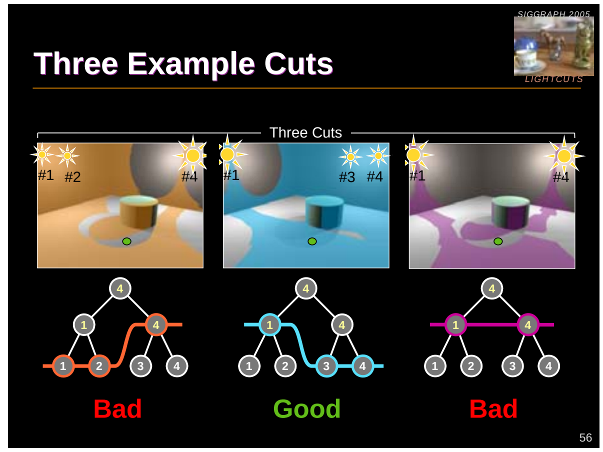

SIGGRAPH 2005
Three Example Cuts
LIGHTCUTS
Three Cuts
#1 #2 #4
#1 #3 #4
#1 #4
Good
Bad
Bad
55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Three Example Cuts
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#1 #3 #4
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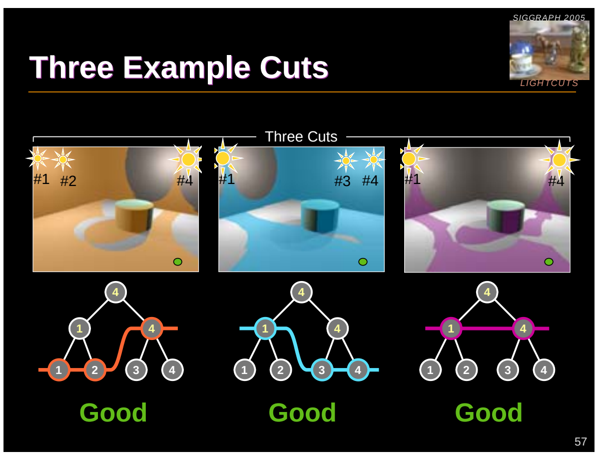
Bad
Good
Bad
56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#1 #2 #4
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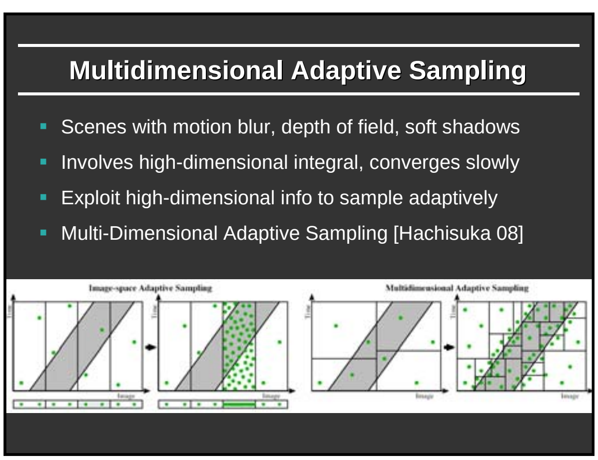
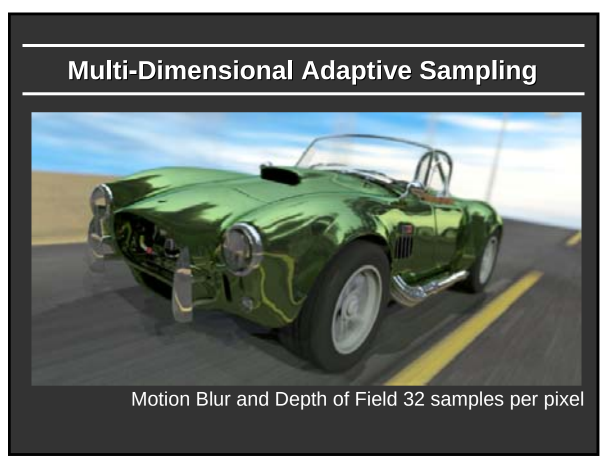
#1 #4
Good
Good
Good
57


Tableau, 630K polygons, 13000 lights, (EnvMap+Indirect)
Avg. shadow rays per eye ray 17 (0.13%)
58


Multidimensional Adaptive Sampling
Scenes with motion blur, depth of field, soft shadows
Involves high-dimensional integral, converges slowly
Exploit high-dimensional info to sample adaptively
Multi-Dimensional Adaptive Sampling [Hachisuka 08]
Image-space Adaptive Sampling
Multidimensional Adaptive Sampling


Multi-Dimensional Adaptive Sampling
Motion Blur and Depth of Field 32 samples per pixel

Recent Results

- Frequency Analysis and Sheared Reconstruction for Rendering Motion Blur Egan et al. 09
- Fourier Depth of Field Subr et al. 09
- These papers consider frequency analysis of particular phenomena – sparse sampling, reconstruction.

- Adaptive Wavelet Rendering Overbeck et al. 09 renders directly into wavelet domain for general high-D effects. Minimal overhead: simple and fast

Adaptive Wavelet Rendering