Real-Time Path Tracing with ReSTIR: A Summary and Abstract

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Real-time rendering of complex scenes with global illumination (GI) remains challenging, especially when considering the computation of indirect lighting. Traditional methods, including path tracing, struggle to maintain real-time frame rates due to the high computational cost associated with tracing rays for indirect illumination. In recent years, *Reservoir-based Spatio-Temporal Importance Resampling* (ReSTIR) algorithms have shown incredible results, with sample reuse speeding direct lighting from millions of dynamic lights [3], diffuse multi-bounce lighting [5](main focus of this paper), and even complex global illumination paths [4].

ReSTIR builds on the math in Talbot et al.'s [7] resampled importance sampling (RIS). By leveraging spatiotemporal resampling to share information about important lighting paths across time and pixels. By resampling multi-bounce indirect lighting paths obtained through path tracing, ReSTIR GI achieves substantial error reduction compared to traditional path tracing methods. This improvement is evident in various test scenes, where ReSTIR GI demonstrates significant improvements. Additionally, when coupled with denoising techniques, ReSTIR GI enables high-quality global illumination rendering at real-time frame rates on modern GPUs.

Additional Key Words and Phrases: Path Tracing, Global Illumination, Importance Sampling

1 INTRODUCTION

Real-time path tracing for cinematic-quality results faces challenges within limited processing time on a single GPU, typically around 16 ms per frame. We propose a method for efficient one-bounce direct lighting sampling from many lights, leveraging resampled importance sampling (RIS). ReSTIR employs a small fixed-size reservoir for stable, real-time performance without complex data structures. It progressively improves each pixel's direct light sampling PDF by reusing statistics from temporal and spatial neighbours. ReSTIR, based on iterative Resampled Importance Sampling, revolutionizes traditional Monte Carlo path tracing by aggregating neighbouring samples for unbiased sample reuse across frames, surpassing traditional post-process denoisers.

2 BACKGROUND

Path tracing simulates light bounces by randomly sampling paths X from the camera to the scene and evaluates the accumulated radiance $f(X)$ along that path. The Monte-Carlo estimate for I_i:

$$L_i = \frac{f(X)}{p(x)} \tag{1}$$

where $p(x)$ is the probability of selecting that path. Averaging these unbiased yet noisy estimates over multiple samples yields less noisy estimates

$$\langle L \rangle = \frac{1}{N} \sum_{i=1}^{N} \frac{f(X_i)}{p_i(X_i)} \tag{2}$$

This method however is very inefficient due to large sample count requirements.

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Importance Sampling. One can greatly reduce the varies in the Monte-Carlo estimator by sampling X from a PDF $p(x) \sim f(x)$. When $p(x)$ is perfectly correlated with $f(x)$, the Monte-Carlo estimator has zero variance. However, since the original function is given by

$$L(x, \omega_o) = \int_H f_r(x, \omega_i \leftrightarrow \omega_o) L(x', \omega_i) G(x, x') V(x, x') d\omega_i \tag{3}$$

is much harder to sample from. Partly due to the visibility term $V(x, x')$. We often draw samples proportional to the individual terms.

Multi-Importance Sampling. There can exist many sampling PDFs to choose from (e.g., the BSDF sampling or the sampling light source L_e). Given M such candidate sampling strategies p_s, MIS draws N_s samples from each strategy and combines them into a single weighted estimator:

$$\langle L \rangle_{\text{MIS}} = \frac{1}{M} \sum_{s=1}^{M} \frac{1}{N_s} \sum_{i=1}^{N_s} w_s(x_i) \frac{f(x_i)}{p_i(x_i)} \tag{4}$$

where weights w_s form a partition of unity $\sum_{s=1}^{M} w_s = 1$. This results in an unbiased estimate. Using the *balance heuristic*, $w_s = \frac{N_s p_s}{\sum_j N_j p_j(x)}$ one can achieve provably good results [8]

Resampled Importance Sampling. The effectiveness of importance sampling depends on the PDF used for generating the samples. RIS provides a solution for these problems. It takes as input a sequence of candidate samples $(x_1, .., x_m)$, gives each candidate a resampling weight w_i, picks one of them $y = x_i$ at random, with probability $p_i = \frac{w_i}{\sum_j w_j}$, and outputs the selected sample.

$$\text{Using weights, } w_i = \frac{\hat{p}(x_i)}{p(x_i)} \quad \text{and} \quad W_y = \frac{1}{\hat{p}(y)} \left(\frac{1}{M} \sum_{i=1}^{M} w_i \right) \tag{5}$$

We get an unbiased estimate $\langle L \rangle_{\text{RIS}} = f(y) W_y$, where as $M \to \infty$, the sample y approach PDF of target function $\hat{p}$

3 PRIOR WORK

Various techniques for real-time simulation of indirect diffuse global illumination have been implemented but most existing methods are heavily biased, whereas the ReSTIR algorithm can achieve either unbiased or very low bias results. Early techniques such as spatial-directional trees and photon maps require prepossessing for data structure construction, leading to high overhead.

Other methods like Virtual Point Lights and a seminal approach by Bekaert et al.[2] have inspired the integration of ReSTIR reservoir resampling and merging algorithms. Recent advancements by Bauszat et al.[1] and West et al.[9] have improved path reuse efficiency, but the described approach offers more general spatiotemporal reuse, unbiased results, and explicit optimization for real-time rendering and GPU acceleration.

4 IMPLEMENTATION

The ReSTIR GI algorithm distributes samples in the directions that capture the indirect illumination by associating points on surfaces with the radiance they scatter back along an incident ray for spatial and temporal reuse.

The algorithm maintains three image-sized buffers that store the following values at each pixel:

- Initial sample buffer: a buffer of initial samples of type SAMPLE
- Temporal reservoir buffer: a buffer of RESERVOIRs that accept samples from applying WRS to the previous samples generated in the pixel.
- Spatial reservoir buffer: a buffer of RESERVOIRs that accept samples from applying WRS to samples from nearby pixels.

Each SAMPLE stores both the local geometry and outgoing radiance at the sample computed using Monte Carlo path tracing techniques, including next event estimation and multiple importance sampling as well as the local geometry at the original visible point that generated the sample. The visible points are the positions on surfaces in the scene that are visible from the camera at each pixel and its geometry and the random numbers used for path tracing are used for sample validation.

After initial samples are generated, temporal resampling is applied. In this stage, for each pixel, we read the sample from the initial sample buffer and use it to update the temporal reservoir randomly, computing the RIS weight with the source PDF as the PDF for the sampled direction $p_q(\omega_i)$ and $\hat{p}$ as defined as $\hat{p} = L_o(x_s, -\omega_i)$.In practice, sampling long paths in every pixel of every frame may cause a significant performance impact so only a small fraction of pixels are used and then are reweighed based on direct illumination paths.

After temporal use, spatial reuse is applied. Samples are taken from the temporal reservoirs at nearby pixels and resampled into a separate spatial reservoir accounting for differences in the source PDF between pixels that are due to the fact that the sampling scheme is based on the visible point's position and surface normal.

In each frame, each pixel's temporal reservoir accepts newly generated samples. Instead of always reusing other spatial reservoirs, each spatial reservoir only reuses temporal reservoirs from neighbouring pixels to suppress bias. When the sample count is low, each spatial reservoir reuses other spatial reservoirs to boost convergence. In the sample validation frame, the initial sampling pass reads sample information and traces the same rays to validate radiance values.

5 RESULTS

Figure 1 shows a challenging scene for path tracing, as direct lighting is concentrated in small regions, making it difficult to find indirect lighting paths. ReSTIR GI is much more effective thanks to sample reuse in both space and time.

For ReSTIR GI, the image shown is captured after 32 frames of temporal resampling. ReSTIR GI provides a reduction in MSE ranging from 14.6× to 141× for the biased variant, and 9.3× to 166× for the unbiased version of it.

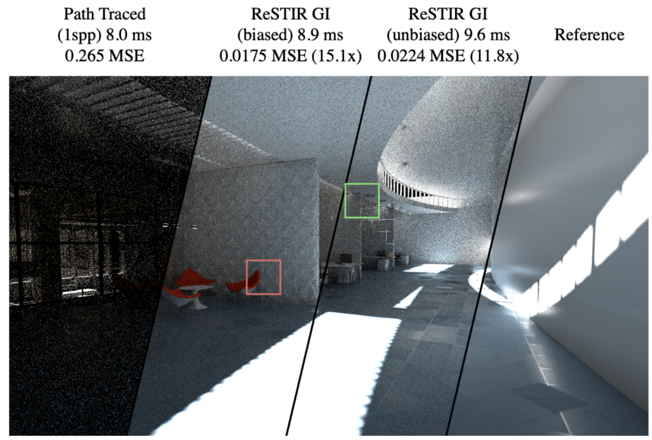

Fig. 1. Equal time comparison of two-bounce path tracing with ReSTIR rendered using NVIDIA 3090 RTX GPU and no post-process effects except tone mapping. Figure adapted from [6]

6 LIMITATIONS

Sample validation can effectively suppress temporal bias in scenes with dynamic lighting demonstrating the improvements for sequences showing dynamic lights and moving cameras. With sample validation, all stale samples are discarded and the algorithm adapts to new lighting quickly. However, bias still exists due to overestimated lighting using new samples.

The bias of the ReSTIR GI algorithm is mainly caused by visibility changes in neighbourhood pixels. The spatial reuse result shows bias in shadow areas, which is caused by reusing reservoirs outside the shadow area. Comparing geometric similarity cannot discard these reservoirs. Besides, the glossy reflection component also worsens bias on the floor. The choice of initial sampling method and target PDF also affects the result. Uniform hemisphere sampling for initial samples causes lower variance than cosine-weighted sampling, especially for light from grazing angles. The cost of ReSTIR GI may still be too high for some real-time applications, especially with lower-end GPUs. The resolution of the reservoir buffers can be decreased to reduce computation. However, in this case, spatial reuse may be unstable when there are detailed normal maps.

Using screen space buffers for sample reservoirs is convenient but has drawbacks. Fast camera movements can lead to insufficient sampling and noise. Perfectly specular objects pose challenges, requiring accurate representation of the first non-specular object along the ray path. Multi-bounce global illumination with glossy surfaces undermines the assumption of Lambertian scattering and reduces spatial sample reuse effectiveness. Concentrated indirect lighting complicates effective sampling even with spatial and temporal reuse.

7 IMPROVEMENTS

Future research could explore alternative methods for generating sample points, such as tracing paths from light sources. Combining techniques like virtual point lights with resampling approaches may offer additional ways to sample indirect lighting effectively.

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