Exploring GPU-Based Monte-Carlo Methods for Global Illumination and Dynamic Irradiance Field Probes: Theory to Implementation

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Global illumination (GI) is essential for achieving photorealistic rendering by simulating the indirect interactions of light within a scene. While Monte Carlo ray tracing offers high-fidelity results, its computational cost makes it impractical for real-time applications. This report explores how Monte Carlo-based GI can be adapted for real-time rendering through the use of irradiance field probes. I begin by covering the fundamentals of Monte Carlo ray tracing and the challenges of real-time GI, then introduce irradiance probes as a practical solution to bridge the gap between quality and performance. The implementation is done in a 2D discretized space, using a Signed Distance Field (SDF) representation. While most GI research focuses on 3D scenes, this work explores how similar concepts can be applied in 2D offering potential value for 2D engines aiming for more realistic lighting.

CCS Concepts: • **Computing methodologies** → **Rendering**.

Additional Key Words and Phrases: Global illumination, raytracing, offline rendering, real-time rendering

1 INTRODUCTION

Global illumination (GI) is essential for realistic lighting, as it simulates both direct and indirect light interactions within a scene. Unlike direct illumination, GI captures how light reflects, refracts, and diffuses across surfaces, resulting in more cohesive visuals.

This report explores GI algorithms with an emphasis on GPU-based implementations using compute shaders. It begins with Monte Carlo ray tracing, a probabilistic technique foundational to many physically based rendering methods. The goal is to adapt this approach to 2D, using a discretized Signed Distance Field (SDF) instead of traditional 3D geometry.

To support real-time applications, the report then investigates irradiance field probes—an efficient approximation technique that decouples light sampling from scene geometry. This makes it well-suited for dynamic or large environments where full ray tracing is computationally expensive.

I compare the performance and visual quality of irradiance probes with Monte Carlo ray tracing, and conclude by briefly discussing extensions other works that improve the probe system's dynamism and memory efficiency, which is something I can maybe explore in the future.

1.1 Report Structure

Introduction: Overview of Global Illumination and its significance in realistic rendering (this section).

Related Work:

- **Monte Carlo Ray Tracing**: Explanation of the ray tracing method and its role in simulating light transport.
- **Challenges of Real-Time GI**: A discussion on the computational challenges that make GI difficult to perform in real-time.
- **Real-Time GI with Irradiance Probes**: Introduction to irradiance field probes and how they enable real-time indirect lighting.
- **Supercharging Irradiance Fields**: A brief look at extensions to make probes dynamic and space-efficient.

Approach:

- **SDF-Based Render Pipeline**: Description of the custom 2D rendering pipeline and use of Signed Distance Fields to represent geometry.
- **Monte Carlo GI in 2D**: Adaptation and implementation of Monte Carlo ray tracing in a 2D SDF environment.
- **Real-Time Irradiance Probes**: Details on implementing irradiance probes on the GPU for fast and scalable GI.

Performance Evaluation:

- **Benchmarks**: Performance measurements of the irradiance probe system vs. traditional Monte Carlo ray tracing.
- **Image Comparisons**: Visual comparisons to evaluate the trade-offs between quality and speed.

Conclusion:

- Summary of findings, limitations, and suggestions for future work.

Through this project, I aim to investigate how core GI algorithms work and written for the GPU and how they can be translated into real-time rendering a simplified 2D context.

2 RELATED WORK

2.1 Monte Carlo Ray Tracing

2.2 Challenges of Real-Time GI

2.3 Real-Time GI with Irradiance Probes

2.4 Supercharging Irradiance Fields

3 APPROACH

3.1 SDF-Based Render Pipeline

3.2 Monte Carlo GI in 2D

3.3 Real-Time Irradiance Probes

4 PERFORMANCE EVALUATION

4.1 Benchmarks

4.2 Image Comparisons

5 CONCLUSION

ACKNOWLEDGMENTS

All my friends and peers <3.

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REFERENCES

Last modified Sunday 6th April, 2025