ROBUST MONTE CARLO METHODS FOR LIGHT TRANSPORT SIMULATION

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by
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I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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Abstract

Light transport algorithms generate realistic images by simulating the emission and scattering of light in an artificial environment. Applications include lighting design, architecture, and computer animation, while related engineering disciplines include neutron transport and radiative heat transfer. The main challenge with these algorithms is the high complexity of the geometric, scattering, and illumination models that are typically used. In this dissertation, we develop new Monte Carlo techniques that greatly extend the range of input models for which light transport simulations are practical. Our contributions include new theoretical models, statistical methods, and rendering algorithms.

We start by developing a rigorous theoretical basis for *bidirectional light transport algorithms* (those that combine direct and adjoint techniques). First, we propose a linear operator formulation that does not depend on any assumptions about the physical validity of the input scene. We show how to obtain mathematically correct results using a variety of bidirectional techniques. Next we derive a different formulation, such that for any physically valid input scene, the transport operators are symmetric. This symmetry is important for both theory and implementations, and is based on a new reciprocity condition that we derive for transmissive materials. Finally, we show how light transport can be formulated as an integral over a space of paths. This framework allows new sampling and integration techniques to be applied, such as the Metropolis sampling algorithm. We also use this model to investigate the limitations of unbiased Monte Carlo methods, and to show that certain kinds of paths cannot be sampled.

Our statistical contributions include a new technique called *multiple importance sampling*, which can greatly increase the robustness of Monte Carlo integration. It uses more than one sampling technique to evaluate an integral, and then combines these samples in a

way that is provably close to optimal. This leads to estimators that have low variance for a broad class of integrands. We also describe a new variance reduction technique called *efficiency-optimized Russian roulette*.

Finally, we link these ideas together to obtain new Monte Carlo light transport algorithms. *Bidirectional path tracing* uses a family of different path sampling techniques that generate some path vertices starting from a light source, and some starting from a sensor. We show that when these techniques are combined using multiple importance sampling, a large range of difficult lighting effects can be handled efficiently. The algorithm is unbiased, handles arbitrary geometry and materials, and is relatively simple to implement.

The second algorithm we describe is *Metropolis light transport*, inspired by the Metropolis sampling method from computational physics. Paths are generated by following a random walk through path space, such that the probability density of visiting each path is proportional to the contribution it makes to the ideal image. The resulting algorithm is unbiased, uses little storage, handles arbitrary geometry and materials, and can be orders of magnitude more efficient than previous unbiased approaches. It performs especially well on problems that are usually considered difficult, e.g. those involving bright indirect light, small geometric holes, or glossy surfaces. To our knowledge, this is the first application of the Metropolis method to transport problems of any kind.

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To Luanne

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