Monte Carlo Methods for Physically Based Volume Rendering

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Figure 1: Various media rendered with Monte Carlo methods for physically based simulation of light transport in volumes. Three images on the left courtesy of Lee Griggs.

ABSTRACT

We survey methods that utilize Monte Carlo (MC) integration to simulate light transport in scenes with participating media. The goal of this course is to complement a recent EUROGRAPHICS 2018 state-of-the-art report providing a broad overview of most techniques developed to date, including a few methods from neutron transport, with a focus on concepts that are most relevant to CG practitioners.

The wide adoption of path-tracing algorithms in high-end realistic rendering has stimulated many diverse research initiatives aimed at efficiently rendering scenes with participating media. More computational power has enabled holistic approaches that tie volumetric effects and surface scattering together and simplify authoring workflows. Methods that were previously assumed to be incompatible have been unified to allow renderers to benefit from each method's respective strengths. Generally, investigations have shifted away from specialized solutions, e.g. for single- or multiple-scattering approximations or analytical methods, towards the more versatile Monte Carlo algorithms that are currently enjoying a widespread success in many production settings.

The goal of this course is to provide the audience with a deep, up-to-date understanding of key techniques for free-path sampling, transmittance estimation, and light-path construction in participating media, including those that are presently utilized in production rendering systems. We present a coherent overview of the fundamental building blocks and we contrast the various advanced methods that build on them, providing attendees with guidance for implementing existing solutions and developing new ones.

SIGGRAPH '18 Courses, August 12-16, 2018, Vancouver, BC, Canada

ACM ISBN 978-1-4503-5809-5.
https://doi.org/10.1145/3214834.3214880

CCS CONCEPTS

• **Computing methodologies → Computer graphics**; *Rendering*; Ray tracing;

KEYWORDS

Monte Carlo methods, volume rendering, path tracing

ACM Reference Format:
Jan Novák, Iliyan Georgiev, Johannes Hanika, Jaroslav Křivánek, and Wojciech Jarosz. 2018. Monte Carlo Methods for Physically Based Volume Rendering. In *Proceedings of SIGGRAPH '18 Courses.* ACM, New York, NY, USA, 2 pages. https://doi.org/10.1145/3214834.3214880

1 TARGET AUDIENCE

The course should be of interest to a wide spectrum of SIGGRAPH attendees, including students, technical directors, rendering enthusiasts, and researchers interested in physically based rendering of scenes with participating media. Familiarity with basic concepts of scene modeling and rendering is required. A brief overview of the two main background topics—Monte Carlo integration and radiative transport—is provided.

2 CONTENT

We keep the course focused on techniques that form the basis of contemporary physically based rendering engines to provide a coherent overview starting with the basic theory and finishing with a summary of advanced methods.

2.1 Mathematical foundations

In order to open the course to attendees with less expertise, we begin by reviewing the optical properties of matter (i.e. collision coefficients, phase function, etc.) that are key for simulating the propagation of light and clarifying the terminology to remove certain misconceptions, e.g. to point out the difference between anisotropic media and anisotropic scattering profiles.

Next, we discuss the fundamental formalizations of light transport in media, such as the radiative transfer equation (RTE) and the volume rendering equation, and review the concept of Monte Carlo integration, applying it to the aforementioned equations and formalizing their corresponding estimators. We break down these estimators into individual components that we discuss in the follow-up course sessions. We build a light-transport simulator bottom-up, starting with the concepts of free-path sampling and transmittance estimation, gradually working towards the construction of entire light transport paths, and closing the course with an overview of advanced (bidirectional) methods and acceleration data structures.

2.2 Distance sampling

The main building block for constructing a path is the routine for sampling a distance to the next interaction with the medium along a given ray. We discuss analog sampling techniques, which produce free-flight paths in the physical sense, as well as non-analog techniques which allow for deviating from the strict physical propagation process by weighting the samples to yield unbiased results. We introduce these concepts in a homogeneous medium first, where free paths can be sampled analytically, and then generalize to heterogeneous media by discussing approaches such as regular tracking, ray marching, as well as null-collision algorithms which introduce a fictitious collision coefficient and sample distances using a rejection-sampling scheme on top of (semi-)analytic techniques.

We provide a didactic derivation of null-collision methods directly from the RTE by altering its MC estimator to account for fictitious collisions. This enables expressing and contrasting the recently introduced null-collision techniques in a common framework and provides convenient tools for postulating new ones. Our formulation is inspired by the integral formulation of null-collision algorithms of Galtier et al. [2013], but we take the approach of first defining the estimator and then introducing a number of probabilistic arguments (identities) that yield the basic null-collision algorithm. This should feel more familiar to the computer-graphics audience than the initial approach of Galtier et al..

We also discuss the advantages and shortcomings of individual approaches, e.g. the inability of null-collision algorithms to compute a sample's probability density and how this impacts practical applications.

2.3 Transmittance estimation

The third session focuses on transmittance estimation, which is needed when connecting two points with a path segment (e.g. a shadow ray), or when using non-analog distance sampling approaches to construct paths. We discuss how distance sampling techniques can be modified to estimate the fraction of light that travels unobstructed between two points and classify them as either expected-value, collision, or (weighted) track-length estimators. This classification helps understand the strengths and weaknesses of individual approaches and emphasizes the terminology commonly used in fields such as neutron transport and particle physics. This should make it easier for the audience to later familiarize itself with relevant publications in other fields, which we point out and comment on how the adoption of these could further improve the state of the art in rendering volumetrics.

2.4 Building paths

Equipped with the understanding of distance sampling and transmittance estimation, the fourth session utilizes these to build entire light transport paths, first in a purely unidirectional manner and then bidirectionally by considering connections between subpaths sampled from the camera and light. We discuss techniques that aim at reducing estimation variance by importance-sampling distances according to certain terms, e.g. the quadratic light decay with distance, generalizing the importance-sampling concept to joint distributions that allow near-optimal construction of multi-segment shadow connections. A special focus is devoted to two recent methods for handling chromatic media. We compare them closely and emphasize their strengths and weaknesses to allow practitioners to make an informed choice given a particular set of constraints.

2.5 Advanced methods

We discuss numerous approaches developed in the recent years that strive to minimize the variance and (potentially) trading it for bias. We begin with volumetric bidirectional path tracing and describe the specific instance of many-light rendering with a focus on volumetric lighting primitives. We proceed by categorizing the numerous available density-estimation methods, comparing their strengths and weaknesses, and discussing a unified theory that allows for combining bidirectional path tracing and density estimation in a unified framework that yields a robust rendering algorithm. We also touch upon various zero-variance subsurface random-walk schemes developed recently as well as approaches for efficient sampling of emissive media.

2.6 Acceleration data structures

Since data access usually dominates the overall render time, acceleration data structures are key for achieving good performance when rendering heterogeneous media. We therefore briefly discuss the various data structures that have been proposed for accelerating null-collision and regular-tracking algorithms.

2.7 Open problems

The course concludes by repeating the main concepts reviewed and by discussing several outstanding problems to stimulate future work. We describe the challenge of using null-collision methods in conjunction with multiple importance sampling, the desire for self-tuning automatic algorithms, potential generalizations of the RTE, and the future role of machine learning in volume rendering. The course familiarizes its audience with fundamental concepts, an understanding of trade-offs between various approaches, and sufficient confidence for pursuing solutions to presented open problems.

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