

UNIVERSITY OF CALIFORNIA,
IRVINE

Microscale-based Macroscale Rendering and Its Inverse Rendering
DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY
in Computer Science

by

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Dissertation Committee:
Professor Shuang Zhao, Chair
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DEDICATION

To Myself and My Family

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Chapter 4 is based on an under reviewing paper (“Beyond Mie Theory: Systematic Computation of Bulk Scattering Parameters based on Microphysical Wave Optics”, Yu Guo, Adrian Jarabo and Shuang Zhao). The dissertation author was the primary investigator and author of this paper.

Chapter 5 is based on the material as it appears in ACM Transactions on Graphics, 2020 (“MaterialGAN: Reflectance Capture using a Generative SVBRDF Model”, Yu Guo, Cameron Smith, Miloš Hašan, Kalyan Sunkavalli and Shuang Zhao). The dissertation author was the primary investigator and author of this paper.

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This dissertation is based on a L^AT_EX template for thesis and dissertation documents at UC Irvine [8].

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Position-Free Monte Carlo Simulation for Arbitrary Layered BSDFs ACM Transactions on Graphics	2018
MaterialGAN: Reflectance Capture using a Generative SVBRDF Model ACM Transactions on Graphics	2020
A Bayesian Inference Framework for Procedural Material Parameter Estimation Computer Graphics Forum	2020
Beyond Mie Theory: Systematic Computation of Bulk Scattering Parameters based on Microphysical Wave Optics In submission ...	2021

ABSTRACT OF THE DISSERTATION

Microscale-based Macroscale Rendering and Its Inverse Rendering

By

Yu Guo

Doctor of Philosophy in Computer Science

University of California, Irvine, 2021

Professor Shuang Zhao, Chair

The abstract of your contribution goes here.

Chapter 1

Introduction

In this dissertation, we first address a more general but efficient way to handle complex surface reflectance and volumetric scattering,

Next, we present an optimization based method for SVBRDF reconstruction and then extend it to bayesian inference.

To summarize, we develop a smart technique to render layered material, a framework to compute scatterings in participating media based on wave optics, and given a number of images, how to estimate the material properties. These techniques were presented at multiple conferences [3, 4, 2]. Our specific contributions include:

Position-free Monte Carlo simulation for arbitrary layered BSDFs. Real-world materials are often layered: metallic paints, biological tissues, and many more. Variation in the interface and volumetric scattering properties of the layers leads to a rich diversity of material appearances from anisotropic highlights to complex textures and relief patterns. However, simulating light-layer interactions is a challenging problem. Past analytical or numerical solutions either introduce several approximations and limitations, or rely on ex-

pensive operations on discretized BSDFs, preventing the ability to freely vary the layer properties spatially. In Chapter 3, we introduce a new unbiased layered BSDF model based on Monte Carlo simulation, whose only assumption is the layer assumption itself. Our novel position-free path formulation is fundamentally more powerful at constructing light transport paths than generic light transport algorithms applied to the special case of flat layers, since it is based on a product of solid angle instead of area measures, so does not contain the high-variance geometry terms needed in the standard formulation. We introduce two techniques for sampling the position-free path integral, a forward path tracer with next-event estimation and a full bidirectional estimator. We show a number of examples, featuring multiple layers with surface and volumetric scattering, surface and phase function anisotropy, and spatial variation in all parameters.

Beyond Mie theory: systematic computation of bulk scattering parameters based on microphysical wave optics. Light scattering in participating media and translucent materials is typically modeled using the radiative transfer theory. Under the assumption of independent scattering between particles, it utilizes several bulk scattering parameters to statistically characterize light-matter interactions at the macroscale. To calculate these parameters based on microscale material properties, the Lorenz-Mie theory has been considered the gold standard. In Chapter 4, we present a generalized framework capable of systematically and rigorously computing bulk scattering parameters beyond the far-field assumption of Lorenz-Mie theory. Our technique accounts for microscale wave-optics effects such as diffraction and interference as well as interactions between nearby particles. Our framework is general, can be plugged in any renderer supporting Lorenz-Mie scattering, and allows arbitrary packing rates and particles correlation; we demonstrate this generality by computing bulk scattering parameters for a wide range of materials, including anisotropic and correlated media.

MaterialGAN: reflectance capture using a generative SVBRDF model. We address the problem of reconstructing spatially-varying BRDFs from a small set of image measurements. This is a fundamentally under-constrained problem, and previous work has relied on using various regularization priors or on capturing many images to produce plausible results. In Chapter 5, we present *MaterialGAN*, a deep generative convolutional network based on StyleGAN2, trained to synthesize realistic SVBRDF parameter maps. We show that MaterialGAN can be used as a powerful material prior in an inverse rendering framework: we optimize in its latent representation to generate material maps that match the appearance of the captured images when rendered. We demonstrate this framework on the task of reconstructing SVBRDFs from images captured under flash illumination using a hand-held mobile phone. Our method succeeds in producing plausible material maps that accurately reproduce the target images, and outperforms previous state-of-the-art material capture methods in evaluations on both synthetic and real data. Furthermore, our GAN-based latent space allows for high-level semantic material editing operations such as generating material variations and material morphing.

A Bayesian Inference Framework for Procedural Material Parameter Estimation. Procedural material models have been gaining traction in many applications thanks to their flexibility, compactness, and easy editability. In Chapter 6, we explore the inverse rendering problem of procedural material parameter estimation from photographs, presenting a unified view of the problem in a Bayesian framework. In addition to computing point estimates of the parameters by optimization, our framework uses a Markov Chain Monte Carlo approach to sample the space of plausible material parameters, providing a collection of plausible matches that a user can choose from, and efficiently handling both discrete and continuous model parameters. To demonstrate the effectiveness of our framework, we fit procedural models of a range of materials—wall plaster, leather, wood, anisotropic brushed metals and layered metallic paints—to both synthetic and real target images.

The dissertation is organized as follows. We first introduce the basic background on light transport and ***** in Chapter 2. From Chapters 3 to 6, we present technical details of our ****, ****, **** and ****, respectively. Finally, we present our conclusion and discuss future research directions in Chapter 7.

Chapter 2

Background

Chapter 3

Microscale Based Surface Rendering

3.1 Introduction

Physically-based shading models have become mature and commonplace in recent years across a number of rendering applications, within entertainment, architecture, and industrial design. However, we are seeing constant progress in the area of material reflection and scattering models, aiming to achieve higher physical realism and to enable more effective material content creation.

Many real world materials are comprised of thin layers with varying compositions. For example, metallic paint is a dielectric coating covering a metallic substrate composed of randomly oriented aluminum flakes; the absorption and scattering properties of the dielectric layer give the material its color and modify its directional scattering properties as well. Many biological materials (e.g. plant leaves) are also layered, and their appearance is a complex combination of the absorption properties, scattering phase function, air-material interface roughness, and thickness variation. Different characteristics of such interfaces and volumetric scattering properties can produce richly diverse material appearances from anisotropic highlights to

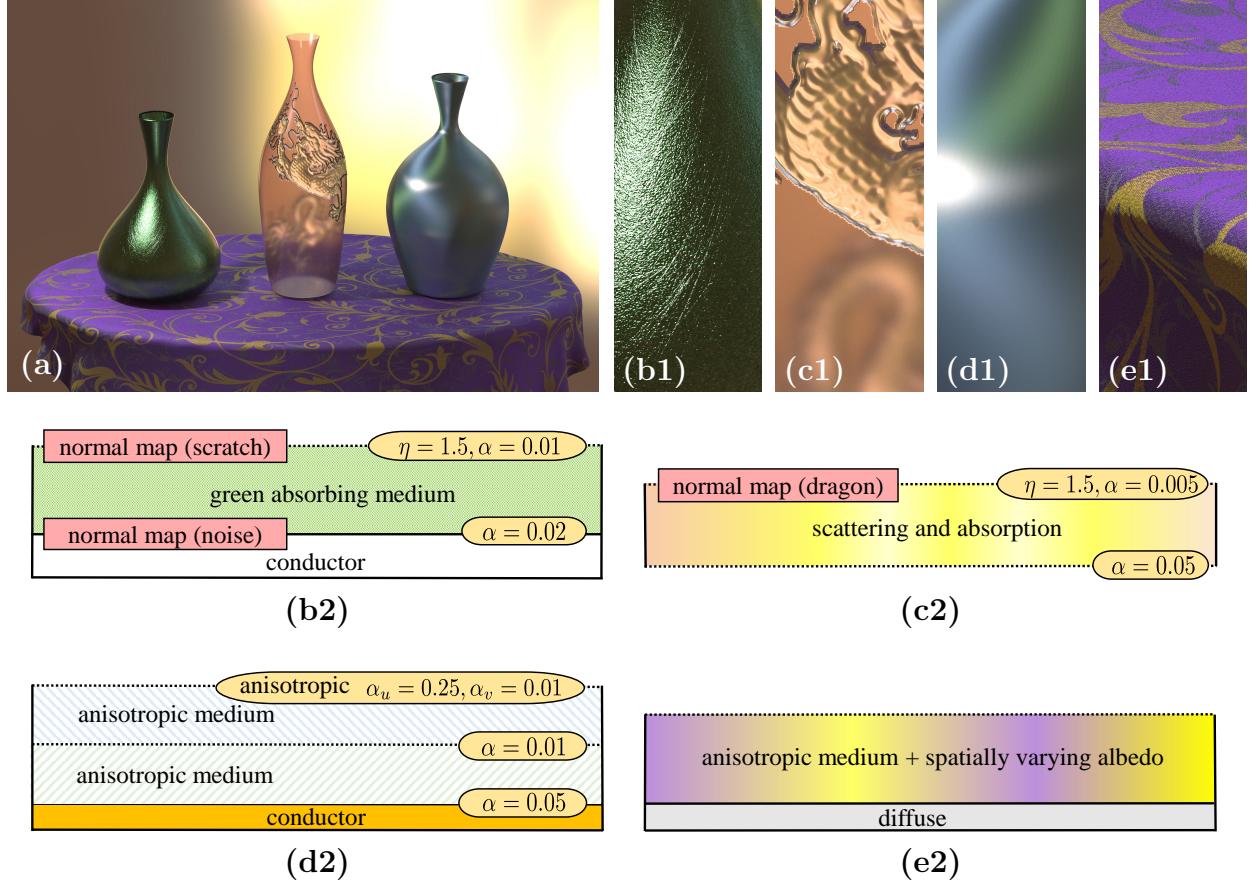


Figure 3.1: We introduce a new BSDF model leveraging an efficient Monte Carlo simulation algorithm applied locally to layered geometries. Our model enjoys the flexibility of using arbitrary layer interfaces and internal media and is capable of reproducing a wide variety of appearances. This example contains three vases on a tablecloth, all described using our BSDF model (see the insets for layer configurations).

complex textures. Furthermore, detailed layer thickness variations, scratches and bumps on the layer interfaces give these materials additional richness. Accurately understanding and simulating these interactions is therefore key to further progress in the rendering of materials.

However, explicitly simulating light-layer interactions by modeling the full geometry of these layers would be very expensive and cumbersome. The complex and spatially varying interface and internal microgeometries are much too costly to describe and simulate using standard 3D scene modeling tools such as triangle meshes and volumetric grids. Furthermore, due to the presence of multiple refractive interfaces, it can be very challenging to correctly construct

light transport paths that connect light scattering locations to light sources, a key operation in most practical Monte Carlo rendering systems. Cheap approximations to these light transport problems (e.g. ignoring refraction, or composing layers using simple blending) are not sufficient to achieve true realism.

A few techniques have been developed to address this problem. Weidlich and Wilkie [9] construct a simple and flexible analytical model. However, significant approximations are necessary; interface roughness is not fully handled for transmission, and no volumetric scattering is supported. The work of Belcour [1] recently introduced a more advanced approach based on tracking low-order moments of the BSDF lobes; however, it still introduces some approximations and limitations. On the other hand, Jakob et al. [7] (with a recent follow-up [10]) introduce a solution that is very accurate, but expensive: it represents BSDFs as discretized datasets and relies on expensive Fourier-domain operations on these to implement layer composition and thickness adjustment. This makes free spatial variation of the layer properties prohibitively expensive: a significant limitation in practice.

In this paper, we introduce a new layered BSDF model without the above limitations. Our model provides an accurate, unbiased solution; to our knowledge, it is the only such model. Unlike previous work, we do not attempt to derive an analytic model for the BSDF lobe shapes. Instead, inside the evaluation and sampling routines of the layered BSDF, we run a Monte Carlo simulation of light transport within flat slabs. This is substantially faster than explicitly constructing the layer geometry, because no expensive scene ray tracing is required. Our model computes an accurate solution of the layered light transport problem. It is based on physical interface and volume scattering models, conserves energy and is reciprocal when possible. It can also be easily integrated into standard Monte Carlo rendering systems. This requires no precomputation and thus can efficiently handle spatially varying appearances. It also supports the full range of editability of the layer properties, both interface and volumetric, and allows anisotropy in both interface BSDFs and phase functions.

In fact, the only limiting assumption of our model is the layer assumption itself.

Our solution is fundamentally more powerful at constructing light transport paths than generic transport algorithms (e.g standard path tracing, bidirectional or Metropolis transport); see Figure 3.2. We introduce a modified path integral framework for light transport in flat slabs, superior to the standard path formulation in this setting. Because it is based on a product of solid angle instead of area measures, it does not contain the high-variance geometry terms needed in standard algorithms. We introduce two simulation techniques within this formulation: the first is analogous to a forward path tracer with next event estimation through layer boundaries and multiple importance sampling; the second is a fully bidirectional estimator. We show the capabilities of this solution on a number of examples, featuring multiple layers with surface and volumetric scattering. Our examples show spatial variation in all parameters: surface BSDF, volume and phase function parameters, layer thickness and surface normal. See Figure 3.1.

3.2 Related Work

3.2.1 Discretized layered BSDFs

Previously, a number of BSDF models have been proposed to describe layers with various assumptions on the interface and subsurface scattering.

An early analytical model by Hanrahan and Krueger [5] already supported multiple layers, but only single scattering, and without supporting arbitrary BSDFs at interfaces. They also proposed to add multiple scattering by Monte Carlo simulation, but their simulation approach only considers volume scattering events (as opposed to a combination of volume and rough interface events). Furthermore, it uses binning on the outgoing direction, as

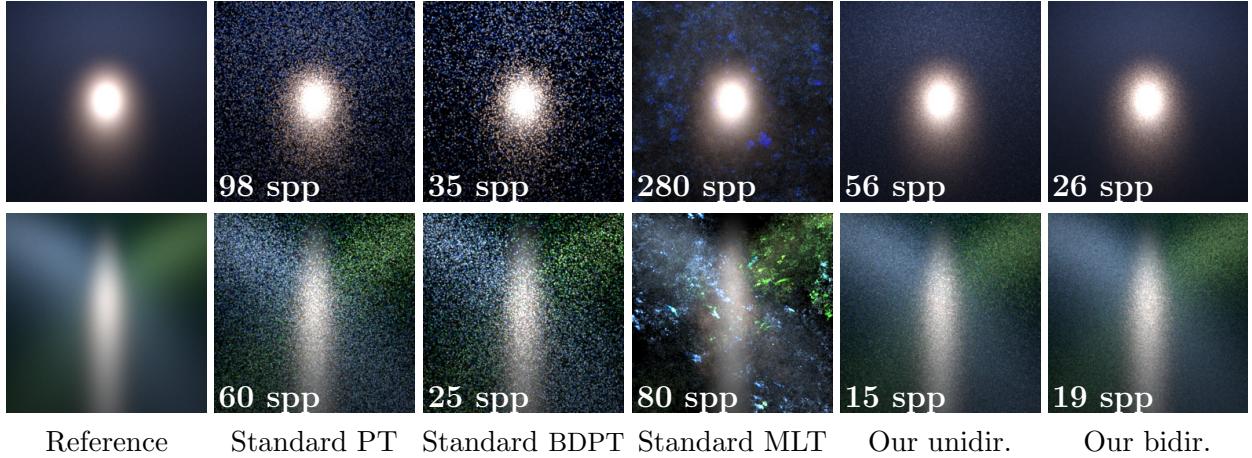


Figure 3.2: **Equal-time comparisons** of our unidirectional and bidirectional approach to standard transport algorithms, on a simple flat layered configuration lit by a small area light. For standard PT, BDPT and MLT, results are all generated using 3D tracing by applying these algorithms in a simple 3D scene containing a very large slab with flat interfaces. **Top:** A single slab with Henyey-Greenstein scattering between two interfaces, where our estimators perform similarly, but both significantly outperform path tracing, bidirectional and Metropolis transport. **Bottom:** A more complex configuration with two slabs and three interfaces; both media are using an anisotropic microflake phase function [6]. Our bidirectional estimator is a clear winner in this case. The references are generated using standard PT with 100K spp, and all the other images are rendered in 10 seconds.

opposed to an efficient BSDF evaluation method for a given outgoing direction, which is provided by our approach.

Chapter 4

Microscale Based Volumetric Rendering

Chapter 5

Inverse Rendering for Macroscale Material Parameters

Chapter 6

Inverse Rendering for Microscale Material Parameters

Chapter 7

Conclusion and Future work

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Appendix A

Appendix for Chapter 3

A.1 Detailed Derivations

We now provide detailed derivations for the key equations in §??.

Position-free radiative transfer equation. Traditionally, the radiative transfer equation (RTE) involves an integral over free-flight distance t :

A.2 Efficient Weight Computation

Weights of Light Transport Paths.

Efficient Weight Computation.

A.3 MIS with stochastic function and weight evaluation

Introduction. While Monte Carlo integration and multiple importance sampling (MIS) are widely used in practice, we use extended versions of these techniques: our MIS weighting is based on approximate (not exact) pdfs, and our weight and function evaluation are both stochastic (i.e. they consume additional random numbers, and are equal to the true weight and function value only in expectation). For this reason, we review standard Monte Carlo and MIS estimators, and show that our extensions still lead to unbiased results.

Monte Carlo estimator.

Combining estimators through MIS.

Stochastic function evaluation.

Stochastic weight and function evaluation