Multiple-Scattering Microfacet BSDFs
with the Smith Model

Eric Heitz  Johannes Hanik  Eugene d'Eon  Carsten Dachsbacher
Karlsruhe Institute of Technology  8i
Introduction
Microfacet theory provides a framework for modeling the appearance of rough surfaces. Roughness is what creates the blurry appearance of surfaces, such as the dielectric plate in this image. In this context, the rough surface is assumed to be made of very small specular microfacets, which are described with a statistical distribution.
Introduction

Current Microfacet BSDFs

$\alpha = 0.1$  $\alpha = 0.3$  $\alpha = 0.5$  $\alpha = 0.7$

There is an energy conservation issue with high roughness values.

Multiple-Scattering Microfacet BSDFs with the Smith Model

An important issue with microfacet BSDFs is the lack of energy conservation, especially for large roughness values. This issue is considered an important problem in practice, and has been motivated again this year in the SIGGRAPH Course on physically based shading.

*Extending the Disney BRDF to a BSDF with Integrated Subsurface Scattering, Brent Burley*  
part of Physically Based Shading in Theory and Practice,  
SIGGRAPH 2015 Course
Introduction

Current Microfacet BSDFs

single scattering

single + multiple scattering

This is because microfacet theory does not incorporate multiple scattering, i.e. rays bouncing multiple times are discarded, hence the visible energy loss.

Multiple-Scattering Microfacet BSDFs with the Smith Model

The problem is that current microfacet BSDFs model only single scattering. The multiple-scattering contribution is set to 0, hence the visible energy loss.
Motivation for Multiple-Scattering BSDFs in Rendering

\[ \alpha = 0.1 \quad \alpha = 0.3 \quad \alpha = 0.5 \quad \alpha = 0.7 \]

In this paper, we propose a microfacet BSDF model that incorporates the multiple-scattering component.

We can see that using a multiple-scattering BSDF fixes the energy conservation issue.

However, we would like to emphasize that fixing energy conservation is not the goal of our paper. Our paper is focused on modeling multiple scattering and designing proper multiple-scattering microfacet BSDFs that are able to predict the actual behavior of multiple scattering on existing microsurfaces.
Introduction

Previous Work on “Multiple-Scattering BSDFs” in Rendering

- A Microfacet Based Coupled Specular-Matte BRDF Model with Importance Sampling
  Kelemen et al. 2001

- A Comprehensive Framework for Rendering Layered Materials
  Jakob et al. 2014

  - Energy conservation enforced with arbitrary diffuse-like terms
  - Independent of the microsurface model
  - Does not predict multiple scattering for a given microsurface model

Multiple-Scattering Microfacet BSDFs with the Smith Model

Previous works in computer graphics have proposed “multiple-scattering” terms that can fix the energy conservation issue in BSDFs. However, they cannot really be regarded as microfacet models, because they are not derived from the assumptions of a microsurface model. They are actually totally independent of the microsurface profile and they could be defined in the same way for non-microfacet BSDFs. So, even though these terms were called ‘multiple scattering’, they do not make any prediction regarding the actual multiple scattering occurring on microsurfaces.

Hence, they are not microfacet multiple-scattering models, they are arbitrary techniques that can be used to fix energy conservation in arbitrary BSDFs.
Introduction

Position of our Work

- We investigate multiple scattering emerging from a given microsurface model.

  How does light scatter multiple times on this microsurface? Use the model to make predictions and compare!

- With a meaningful model, energy conservation comes as a side effect.

Multiple-Scattering Microfacet BSDFs with the Smith Model

In contrast, we are interested in deriving the multiple-scattering BSDF predicted by a given microsurface model, namely the Smith model. We want to answer the question: “If I have a Smith microsurface, what is its multiple-scattering BSDF?”

We want to test the predictive power of this model, compared to a simulation of multiple scattering on an actual microsurface. This question is interesting, because if we can answer it, we will find out whether this microsurface model is worth investigating further or not.

Furthermore, if we manage to derive this BSDF, then energy conservation comes naturally as a side effect of having the correct multiple scattering, and does not need to be hacked in with arbitrary techniques.
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?

Why now (2015)?

What are the main ideas of our multiple-scattering model?

How do we model the microsurface?

How do we validate our model?

In contrast to the paper, which is math heavy and systematic, this talk is focused on the storytelling and the motivation of our work.

In this talk, we answer the following questions.
Why investigate multiple scattering with the Smith 1967 microsurface model?

Why now (2015)?

What are the main ideas of our multiple-scattering model?

How do we model the microsurface?

How do we validate our model?

First, why the Smith model and not something else?
Motivation for the Smith Microsurface Model
Motivation for the Smith Microsurface Model

Simplicity

Main assumption: the microsurface has independent heights and slopes.

In this paper, we are interested in pushing microfacet theory forward by exploring the predictive power of a mathematically correct model.

The Smith model is a very good choice for exploring the microfacet equations because it is based on very simple assumptions and comes with closed-form solutions (at least for single scattering).

Even though its assumptions are very simple, the equations of the Smith model are mathematically correct, in contrast to other common models. The Smith model offers a strong basis for solid mathematical investigations.

See Understanding the Masking-Shadowing Function in Microfacet-Based BRDFs, Heitz 2014.
Motivation for the Smith Microsurface Model

Good Agreement with Simulated Data (Single Scattering)

In fact, even though the assumptions of the Smith model seem oversimplistic, the predictions show good agreement with simulated data in the case of single scattering. Alternatives, such as the V-cavity model, are also simple and mathematically correct, but their predictions are not as good.

One could say that the simplicity, the convenience and the accuracy of the Smith model make it somehow “canonical”. This is why it is so interesting to push it and examine the multiple scattering that is predicted by this model.

Will the Smith model remain accurate or is it going to break down with multiple scattering?

The plots are from *Understanding the Masking-Shadowing Function in Microfacet-Based BRDFs*, Heitz 2014.
Motivation for the Smith Microsurface Model

State of the Art in Computer Graphics

*Material – Specular*

Height-correlated Smith G Term

Furthermore, nowadays (2015), microfacet BRDFs used in the videogame industry and the movie industry are mainly based on the Smith model. We refer the reader to the

SIGGRAPH courses on physically based shading, from 2012 to 2015

to see how microfacet BRDFs based on the Smith model have become standard in the industry.

This is also a good reason to explore this model further: a direct extension of the Smith model might be usable with existing assets and techniques.

*Moving Frostbite to PBR, SIGGRAPH Course 2014 (courtesy of Sébastien Lagarde)*
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art

Why now (2015)?

What are the main ideas of our multiple-scattering model?

How do we model the microsurface?

How do we validate our model?
Motivation for the Smith Microsurface Model

Previous Work in Physics (see Christophe Bourlier’s website)

- Simulations with explicit surfaces (triangles) instead of microfacet models, e.g.
  *The polarized emissivity of a wind-roughened sea surface: A Monte Carlo model*
  Henderson et al. 2003

- Models for the microsurface albedo/reflectivity, limited to 2 bounces, e.g.
  *Multiple scattering in the high-frequency limit with second-order shadowing function from 2D anisotropic rough dielectric surfaces: I. Theoretical study*
  Bourlier et al. 2004

  *Polarized infrared reflectivity of 2D sea surfaces with two surface reflections*
  Li et al. 2014

- No multiple-scattering BSDFs with the Smith microsurface model!
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?

How do we model the microsurface?

How do we validate our model?
Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?

How do we model the microsurface?

How do we validate our model?
Recent Advances with the Smith Model
Recent Advances with the Smith Model

New Insights into Smith Masking-Shadowing (2014)

masking function = conservation of the projected area

- Understanding the Masking-Shadowing Function in Microfacet-Based BRDFs
  Heitz 2014

Multiple-Scattering Microfacet BSDFs with the Smith Model

Heitz recently proposed a review of microfacet theory with emphasis on the masking function. One of the main observations provided in this paper is that the masking function should be such that the projected area of the microsurface onto an arbitrary direction is preserved. With this observation, the derivation of the Smith masking function is straightforward.

In our paper, we use this idea to show how the Smith $\Lambda$ function relates to the projected area of the microfacets and how it can be extended to incident directions coming from the lower hemisphere $\theta \in [\pi/2, \pi]$, which never happens with single scattering, but occurs with multiple scattering. Hence, we generalize the Smith masking function to the entire sphere instead of only the upper part.
Microflake Theory (2010, 2015)

- A radiative transfer framework for rendering materials with anisotropic structure
  Jakob et al. 2010
- The SGGX Microflake Distribution
  Heitz et al. 2015

Microflake theory was introduced by Jakob et al. in 2010 to model anisotropic volumes. We propose to derive the equations of a Smith microsurface starting from such a volumetric microflake model. We will derive the Smith microsurface free-path and phase function and they obey the non-classical reciprocity conditions derived by Jakob et al.

The relation of this volumetric framework and Smith’s assumptions is discussed by Heitz et al. in their SGGX paper (2015). They show that the assumptions of the microflake volumes (visibility and orientation of the microflakes are independent) are equivalent to the assumptions of the Smith model. Furthermore, they show that the normalization coefficient of microflake phase functions is equivalent to the Smith masking function.

Starting from these observations, we make the connection and we show how a Smith microsurface can be defined as a microflake volume with some additional constraints.
Recent Advances with the Smith Model

New Importance Sampling Technique for Smith BSDFs (2014)

- Importance Sampling Microfacet-Based BSDFs using the Distribution of Visible Normals
  Heitz and d'Eon 2014

Multiple-Scattering Microfacet BSDFs with the Smith Model

For the multiple-scattering model to be practical, we need a way to compute it. In practice, we compute it by simulating a random walk on the microsurface. This makes heavy use of importance sampling.

We use the VNDF importance sampling proposed in 2014 by Heitz and d'Eon. With the previous importance sampling technique, the images would have been full of ‘firefly’ artifacts due to high sampling weights accumulated during the walks. Thanks to this recent technique, random walks can be computed and converge in a reasonable amount of time. This technique is mandatory for the model to be practical.

One of our contributions is to extend this VNDF sampling technique for incident directions coming from the lower hemisphere $\theta \in \left[\pi/2, \pi\right]$, which never happens with single scattering, but occurs with multiple scattering. We provide these extensions (with C++ code) for Beckmann and GGX in our supplemental material.
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?

How do we model the microsurface?

How do we validate our model?

Multiple-Scattering Microfacet BSDFs with the Smith Model

Even though the Smith model is an oldie (1967), we were able to derive its multiple-scattering BSDF only now (2015), because we built it on top of very recent advances (2010, 2014 and 2015) related to this model.

Without the formalism introduced by microflake theory and the connection with Smith’s assumptions, our work would not have been possible.

Without the importance sampling technique based on the VNDF, our work would not have been practical.

This also explains why there is no equivalent work in the physics community today.
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?

How do we model the microsurface?

How do we validate our model?

So, what kind of interesting insights did we gain from those previous works?
Multiple-Scattering Microfacet BSDFs with the Smith Model
Multiple Scattering on the Microsurface

Defining and computing multiple scattering on microsurfaces is difficult.

Multiple scattering is what we get if we trace paths on the microsurface.

But this is complicated to do. Why is that?
What is the Problem?

The problem is that a path tracer is very good at computing intersections between triangles. We can say that the path tracer is able to compute macrointersections.

However, the microsurface is not represented explicitly with triangles, and the path tracer does not know how to intersect it explicitly. We can say that microintersections are difficult to compute.
What is the Problem?

intersection outside the microsurface

triangle 2

triangle 1

≠

intersection inside the microsurface

shadowing

computed by the path tracer ✓

shadowing function = set to 0

Since microintersections cannot be computed explicitly, the single-scattering BSDF incorporates a shadowing function that statistically accounts for those intersections and sets their contribution to 0.
Intuitively, the shadowing function in microfacet BSDF is a replacement for multiple scattering. Since we don’t know how to compute the multiple scattering, we set it to 0 with the shadowing function.
What about Microflake Volumes?

The way microflake theory deals with this problem is very interesting.

We have seen that with surface scattering, there is a difference between macrointersections (triangles) and microintersections on the microsurface. In contrast, in a microflake volume, all of the intersections are microintersections. There is no concept of being inside or outside the volume: everything is inside and only the density changes. As a result, all of the intersections can be considered to be microintersections, but with varying distances, depending on the volumetric density.

And all of the intersections are computed by the path tracer (for instance with Woodcock tracking). Hence, there is no need to model multiple scattering in microflake phase functions: multiple scattering between microflakes is already computed by the path tracer.
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?
- Insight: multiple scattering in microflake volumes is computed by the path tracer

How do we model the microsurface?

How do we validate our model?
Overview of our Model
Overview of our Model

How do Microflake Volumes Work?

intersections

phase functions

The path tracer is fed inside microflake volumes with intersections and phase functions.

A volumetric path tracer that is able to compute multiple scattering between microflakes is fed with two primitives: intersections and phase functions.
Overview of our Model

Extension to Microsurfaces

We derive a microsurface scattering model with intersections and phase functions.

Multiple-Scattering Microfacet BSDFs with the Smith Model

To define multiple scattering on the microsurface, we define equivalent primitives for the Smith microsurface model.
Overview of our Model

Definition of the Multiple-Scattering BSDF

With these primitives, we can define a scattering process occurring on the microsurface. Intuitively we can say that we can do some statistical path tracing on the microsurface.

The multiple-scattering BSDF models the light transport emerging from this statistical path tracing, i.e. it is defined as the expectation of all of the paths that can be statistically traced on the microsurface.

We will see that the BSDF defined in this way has all of the expected properties of a classic BSDF (energy conservation, reciprocity, etc.).
Overview of our Model

BSDF Importance Sampling

generate a path and return when it leaves the microsurface

↑

BSDF Unbiased Stochastic Evaluation

generate a path with next event estimation at each intersection

With this definition, it is hard to derive a closed-form for the BSDF (maybe there is one, but we did not find it). Nevertheless, we can use the definition to make it practical.

Since the BSDF is the expectation of all of the paths that can be traced on the microsurface, importance sampling can be done straightforwardly by generating one path.

We can construct an unbiased stochastic estimate by tracing one path and evaluating the phase function at each intersection, i.e. using next event estimation, as in classic path tracing.

With importance sampling and unbiased stochastic evaluation, we have everything required to implement a classic BSDF plugin. We provide more details regarding the implementation of a BSDF plugin in the paper.
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?
- Insight: multiple scattering in microflake volumes is computed by the path tracer
- Multiple-scattering BSDF = expectation of paths traced on the microsurface

How do we model the microsurface?

How do we validate our model?
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?
- Insight: multiple scattering in microflake volumes is computed by the path tracer
- Multiple-scattering BSDF = expectation of paths traced on the microsurface

How do we model the microsurface?

How do we validate our model?

Multiple-Scattering Microfacet BSDFs with the Smith Model

That was an overview of the main ideas.

Now, more concretely, what are the ingredients of our model?
We have seen that path tracing on the microsurface can be achieved if we have a model for intersections and a model for the phase functions associated with the microsurface.
Microsurface Intersections with the Smith Model

Let's talk about the intersection model.
A microsurface is a sharp interface between “outside” and “inside.”
Microsurface Intersections with the Smith Model

Differences Between Microsurfaces and Microflake Volumes

Microsurface cannot go through
Microflake volume can go through

\( \neq \)

Rays going downwards have to intersect the microsurface.

Multiple-Scattering Microfacet BSDFs with the Smith Model

Because of this fundamental difference, intersection models for volumes and surfaces have different properties.

For instance, a ray can never go through a surface without intersecting it. In contrast, a ray can possibly go through a volume, even if it has a very high density. The higher the density, the lower the probability of going through the volume, but there is always a non-zero probability that this happens.
Microsurface Intersections with the Smith Model

Differences Between Microsurfaces and Microflake Volumes

- Microsurface: no upper intersections
- Microflake Volume: upper intersections possible

Rays going upwards cannot intersect the microsurface.

Another difference is that a ray going upwards will never intersect the surface (the Smith model assumes a heightfield), while a ray going upwards can always intersect a particle above its starting point within a volume.
Turning a Microflake Volume into a Microsurface

In the Smith model, the knowledge introduced by the ray creates the sharp interface.

The Smith model can be seen as a volumetric model that has been modified to obtain the properties of a surface. The idea of the Smith model is to use the knowledge provided by the ray to introduce the concept of a sharp surface interface that separates inside and outside.

The ray only travels outside of the microsurface. Hence, if the ray can travel freely along a line segment outside the microsurface, we know that all of the points above this segment cannot be inside (because the Smith model is a heightfield). The Smith model uses this knowledge to discard the density of the volume that is above the ray. Since this density cannot just disappear, it is reintroduced below the ray. Hence, the probability of the space below the ray being inside increases.
Microsurface Intersections with the Smith Model

Turning a Microflake Volume into a Microsurface

In the Smith model, the more the ray goes down, the more the probability of the inside being below increases, i.e. the ray is getting closer to the interface of the surface and it will eventually intersect the interface.

As a result, the ray can never go through the Smith volume; the model creates an opaque surface-like interface.
Microsurface Intersections with the Smith Model

Turning a Microflake Volume into a Microsurface

Another property is that, thanks to the projected area of the microfacets, rays going up will not intersect the volume, i.e. they go through the outside part of the volume.
Microsurface Intersections with the Smith Model

Turning a Microflake Volume into a Microsurface

- Probability of next intersection = Smith shadowing probability

Multiple-Scattering Microfacet BSDFs with the Smith Model

Furthermore, the average probability of further intersections in this modified volume yields exactly the Smith shadowing probability used in the classic single scattering model.

For these reasons, the intersection model of the modified volume effectively behaves like a heightfield, with all of the statistics expected of a Smith microsurface. This is the Smith microsurface model!
From the definition of this non-classical volumetric model, we derive a free-path PDF, in the same way that is done for classic volumetric media. This PDF represents how much distance can be traveled by the ray before finding an intersection with the microsurface.

We convert the free-path distances into microsurface heights by multiplying them with the slope of the ray direction. This tells us how the heights of the potential intersection points are distributed and we call it "the distribution of visible heights". Indeed, like the distribution of visible normals, it is simply the microsurface height distribution modulated by the visibility of the ray.

This is the first milestone towards ray tracing a statistical microsurface: we compute intersections between a ray and the microsurface by generating random samples from the distribution of visible heights for this ray.
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?
- Insight: multiple scattering in microflake volumes is computed by the path tracer
- Multiple-scattering BSDF = expectation of paths traced on the microsurface

How do we model the microsurface?
- Intersection model = modified microflake volume

How do we validate our model?
After an intersection is found, we have to deal with the phase function of the microsurface for the next scattering direction to be computed.

What does it mean to talk about a phase function of a microsurface? To understand what it means, we need to gather some concepts related to masking and shadowing.
Microsurface Phase Functions with the Smith Model

Application to Microsurfaces

Phase functions model how rays are reflected by the microsurface before leaving the microsurface. They describe a local scattering event at an intersection point (masking). They do not have to incorporate multiple scattering.

BSDFs model how rays are reflected by the microsurface after they have left it. They describe the global scattering occurring on the microsurface. The BSDFs have to incorporate multiple scattering or set it to 0 with a shadowing function.
Now we can define the phase function for any incident direction.
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?
- Insight: multiple scattering in microflake volumes is computed by the path tracer
- Multiple-scattering BSDF = expectation of paths traced on the microsurface

How do we model the microsurface?
- Intersection model = modified microflake volume
- Phase function = BSDF without shadowing extended to $[0, \pi)$

How do we validate our model?
Our Smith Microsurface Model

Now we have all of the ingredients that we needed to define our multiple-scattering BSDF!
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?
- Insight: multiple scattering in microflake volumes is computed by the path tracer
- Multiple-scattering BSDF = expectation of paths traced on the microsurface

How do we model the microsurface?
- Intersection model = modified microflake volume
- Phase function = BSDF without shadowing extended to $[0, \pi)$

How do we validate our model?
- We verified all the mathematical properties of the model
- The predictions of the model match simulated data

A very important question is the validation of the model.

Our goal was to design a model that is mathematically correct. Our model is built on top of different intermediate milestones (intersections and phase functions) and is defined as a statistical expectation. It is not obvious that we did not introduce mistakes in the model or in the derivations!

How can we be sure that what we modeled is actually a mathematically correct BSDF?
How can we be sure that it is really the BSDF associated with the Smith model?
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?
- Insight: multiple scattering in microflake volumes is computed by the path tracer
- Multiple-scattering BSDF = expectation of paths traced on the microsurface

How do we model the microsurface?
- Intersection model = modified microflake volume
- Phase function = BSDF without shadowing extended to $[0, \pi)$

How do we validate our model?
- We verified all the mathematical properties of the model

Multiple-Scattering Microfacet BSDFs with the Smith Model

These unit tests show that our model is indeed a BSDF and is totally consistent with the classic properties of a Smith microsurface.

Now that we now that we got it right, we can compare it to numerical simulations. What is the predictive power of the Smith model compared to simulated data?
Validation: Comparison against Simulated Data
Validation: Comparison against Simulated Data

In this second comparison test, we raytrace the Beckmann surface instance and record the set of outgoing directions. We compare it to the prediction of our Smith multiple-scattering BSDF model.
Validation: Comparison against Simulated Data

Dielectric

1st bounce
$E_r = 0.403$
$E_t = 0.434$

2nd bounce
$E_r = 0.088$
$E_t = 0.057$

3rd bounce
$E_r = 0.010$
$E_t = 0.005$

Simulated
$E_r = 0.395$
$E_t = 0.426$

Our model
$E_r = 0.098$
$E_t = 0.065$

$E_r = 0.008$
$E_t = 0.006$

Multiple-Scattering Microfacet BSDFs with the Smith Model

These are the reflected (blue) and transmitted (red) lobes of a dielectric surface. We can see that the model’s prediction matches the energy distribution in the different scattering orders and the lobe’s shape.

More comparisons are available in our supplemental material.
Validation: Comparison against Simulated Data

Conductor

1st bounce
$E_r = 0.561$

2nd bounce
$E_r = 0.389$

3rd bounce
$E_r = 0.049$

simulated

$E_r = 0.542$
$E_r = 0.398$
$E_r = 0.059$

our model

Multiple-Scattering Microfacet BSDFs with the Smith Model
Validation: Comparison against Simulated Data

Diffuse

\[ E_r = 0.774 \]
\[ E_r = 0.174 \]
\[ E_r = 0.051 \]

\[ E_r = 0.762 \]
\[ E_r = 0.181 \]
\[ E_r = 0.056 \]
Talk Outline

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?
- Insight: multiple scattering in microflake volumes is computed by the path tracer
- Multiple-scattering BSDF = expectation of paths traced on the microsurface

How do we model the microsurface?
- Intersection model = modified microflake volume
- Phase function = BSDF without shadowing extended to \([0, \pi]\)

How do we validate our model?
- We verified all the mathematical properties of the model
- The predictions of the model match simulated data
**Talk Outline**

Why investigate multiple scattering with the Smith 1967 microsurface model?
- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

What are the main ideas of our multiple-scattering model?
- Insight: multiple scattering in microflake volumes is computed by the path tracer
- Multiple-scattering BSDF = expectation of paths traced on the microsurface

How do we model the microsurface?
- Intersection model = modified microflake volume
- Phase function = BSDF without shadowing extended to $[0, \pi)$

How do we validate our model?
- We verified all the mathematical properties of the model
- The predictions of the model match simulated data

---

Multiple-Scattering Microfacet BSDFs with the Smith Model

That's it for the model.

Now that we know that it is mathematically correct and that it makes good predictions, we can have a look at some renderings!
Results

Multiple-Scattering Microfacet BSDFs with the Smith Model
Results

\[ \alpha = 0.1 \]
\[ \alpha = 0.5 \]
\[ \alpha = 1.0 \]

Multiple-Scattering Microfacet BSDFs with the Smith Model

\text{diffuse single}

\text{diffuse single + multiple}
Results

\[ \alpha = 0.05 \]
\[ \alpha = 0.4 \]
\[ \alpha = 1.0 \]

Multiple-Scattering Microfacet BSDFs with the Smith Model
Results

- Single scattering: 87% overhead
- Single + multiple scattering: 94% overhead

Multiple-Scattering Microfacet BSDFs with the Smith Model
Thank you for your attention :-)