Multiple-Scattering Microfacet BSDFs with the Smith Model

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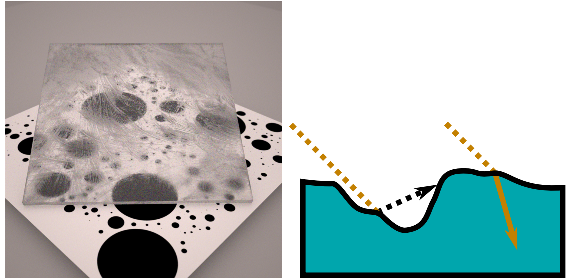

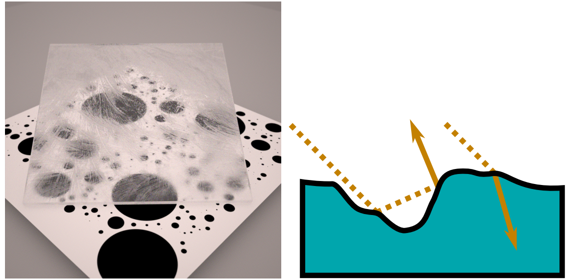

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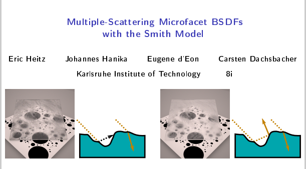
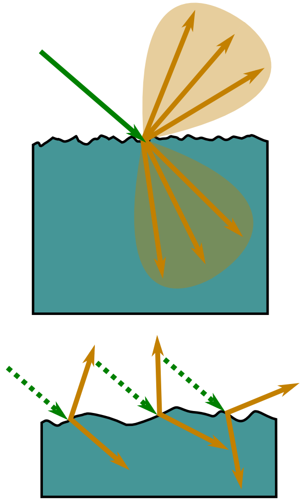
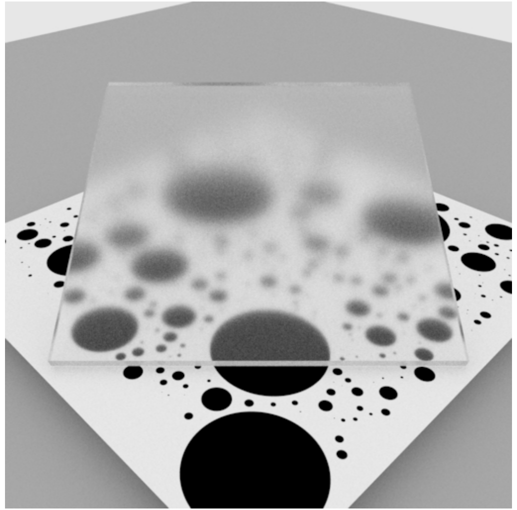
with the Smith Model

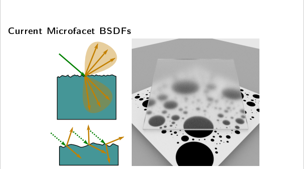


Introduction

Current Microfacet BSDFs

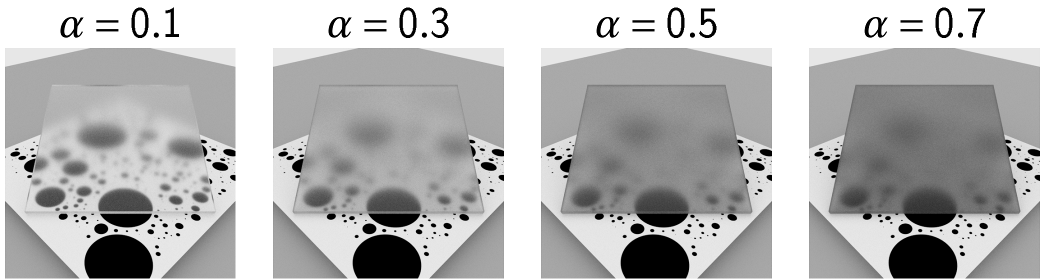




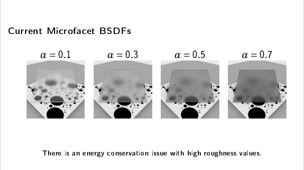


Microfacet theory provides a framework for modeling the appearance of rough surfaces. Roughness is what creates the blurry appearance of surfaces, such as the dielectric plate in this image. In this context, the rough surface is assumed to be made of very small specular microfacets, which are described with a statistical distribution.

Current Microfacet BSDFs



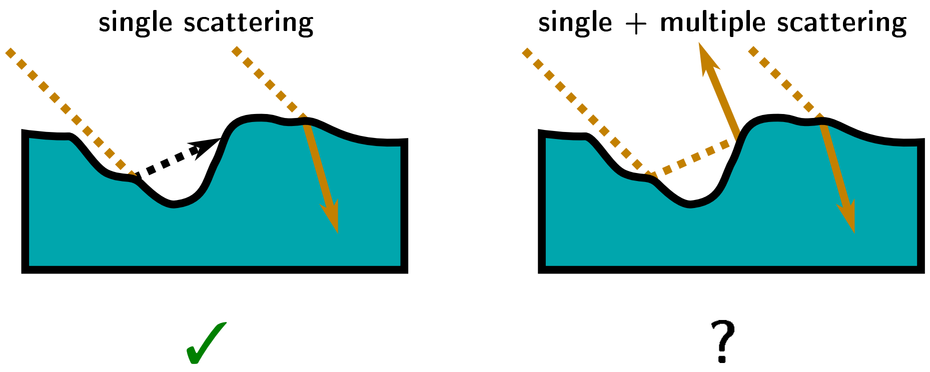
There is an energy conservation issue with high roughness values.



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.

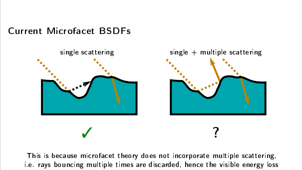
Extending the Disney BRDF to a BSDF with Integrated Subsurface Scattering, Brent Burley
part of Physically Based Shading in Theory and Practice, SIGGRAPH 2015 Course

Current Microfacet BSDFs



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

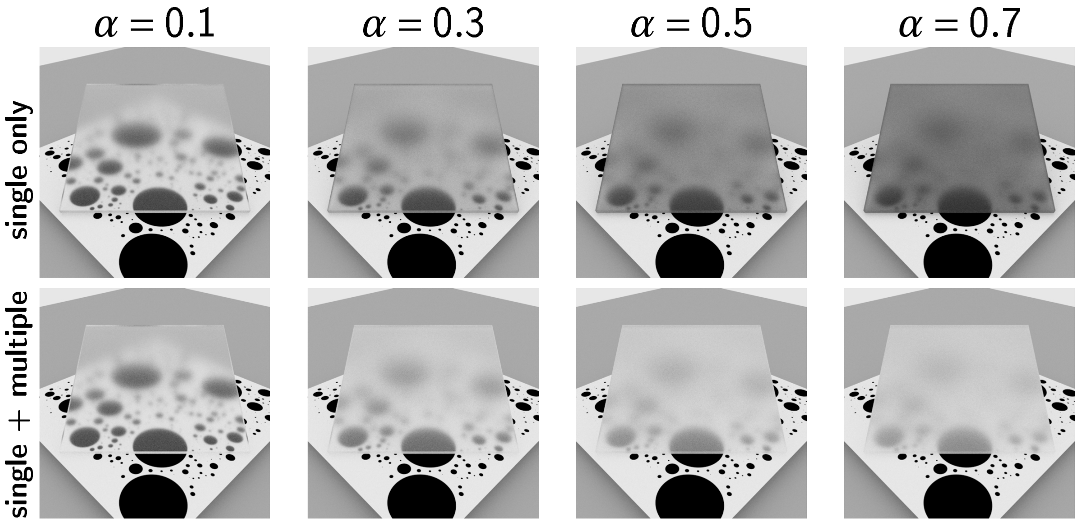
Multiple-Scattering Microfacet BSDFs with the Smith Model



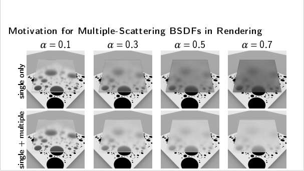
The problem is that current microfacet BSDFs model only single scattering. The multiple-scattering contribution is set to 0, hence the visible energy loss.

Introduction

Motivation for Multiple-Scattering BSDFs in Rendering



Multiple-Scattering Microfacet BSDFs with the Smith Model



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.

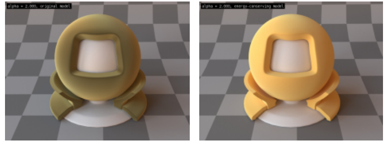
However, we would like to emphasize that fixing energy conservation is not the goal of our paper. Our paper is focused on modeling multiple scattering and designing proper multiple-scattering microfacet BSDFs that are able to predict the actual behavior of multiple scattering on existing microsurfaces.

Introduction

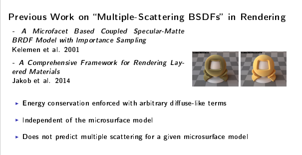
Previous Work on “Multiple-Scattering BSDFs” in Rendering

- *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



Previous works in computer graphics have proposed “multiple-scattering” terms that can fix the energy conservation issue in BSDFs.

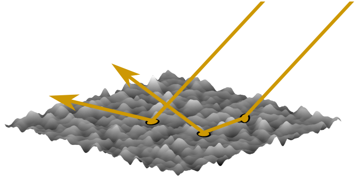
However, they cannot really be regarded as microfacet models, because they are not derived from the assumptions of a microsurface model. They are actually totally independent of the microsurface profile and they could be defined in the same way for non-microfacet BSDFs. So, even though these terms were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

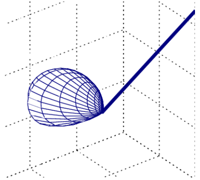
Hence, they are not microfacet multiple-scattering models, they are arbitrary techniques that can be used to fix energy conservation in arbitrary BSDFs.

Introduction

Position of our Work

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

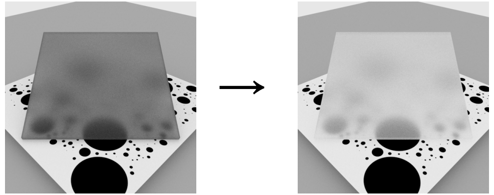


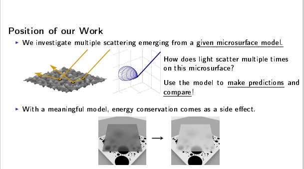


How does light scatter multiple times on this microsurface?

Use the model to make predictions and compare!

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





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?

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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.

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Multiple-Scattering Microfacet BSDFs with the Smith Model

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First, why the Smith model and not something else?

Motivation for the Smith Microsurface Model

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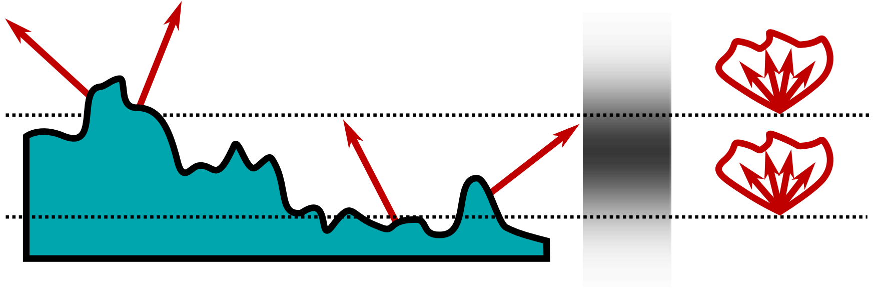
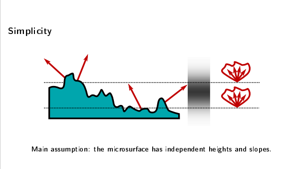
Simplicity



Main assumption: the microsurface has independent heights and slopes.



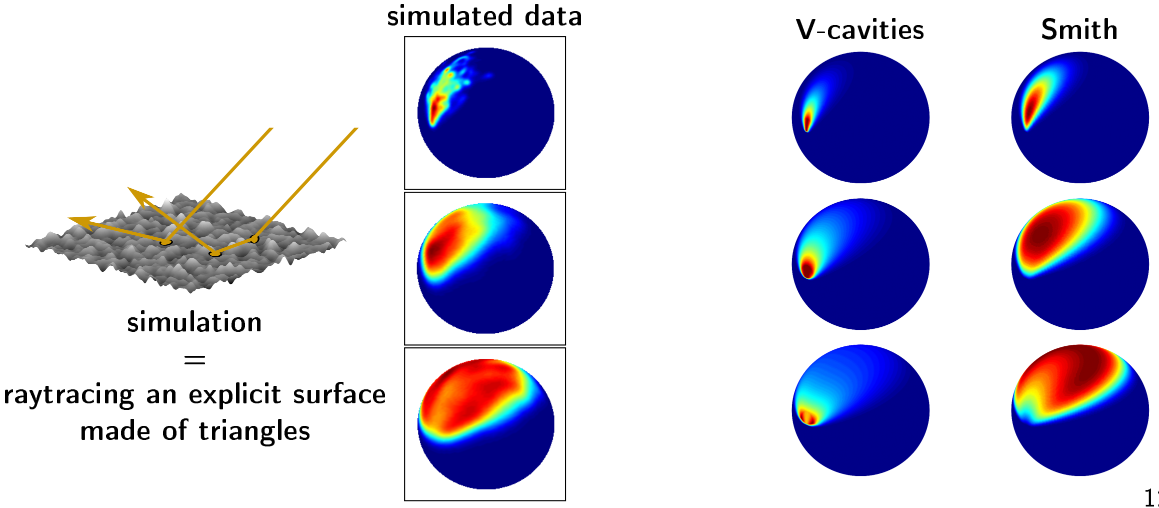
In this paper, we are interested in pushing microfacet theory forward by exploring the predictive power of a mathematically correct model.

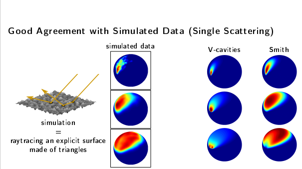
The Smith model is a very good choice for exploring the microfacet equations because it is based on very simple assumptions and comes with closed-form solutions (at least for single scattering).

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.

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?

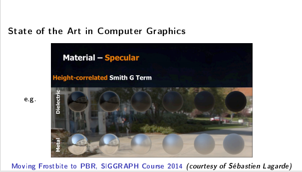
The plots are from *Understanding the Masking-Shadowing Function in Microfacet-Based BRDFs*, Heitz 2014.

Motivation for the Smith Microsurface Model

State of the Art in Computer Graphics

e.g.

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



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.

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

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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!

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Polarized infrared reflectivity of 2D sea surfaces with two surface reflections
Li et al. 2014
- No multiple-scattering BSDFs with the Smith microsurface model!

In the field of physics, we found models for the albedo (or the reflectivity) of surfaces after multiple bounces. But the albedo is only the average value of the BSDF. We did not find models for the BSDF itself. While the albedo is apparently interesting in physics, in a computer graphics context we need to have access to the full BSDF to compute images.

Furthermore, models from the field of physics are often limited to two bounces, or defined in 1D. In contrast, our model handles an arbitrary number of bounces on 2D microsurfaces (Beckmann or GGX).

It is also very interesting to note that physicists validate their models by comparing the models' predictions to simulated data, computed on explicit surfaces represented with triangles. Comparisons to simulated data instead of measured data is the standard validation in physics. We use the same approach to validate the predictions made by our model.

(Christophe Bourlier's webpage: `http://christophebourlier.perso.sfr.fr/topics.htm`)

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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

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Now that we have motivated the choice of the Smith 1967 model, we may wonder why nobody derived its multiple-scattering BSDF in the past 50 years.

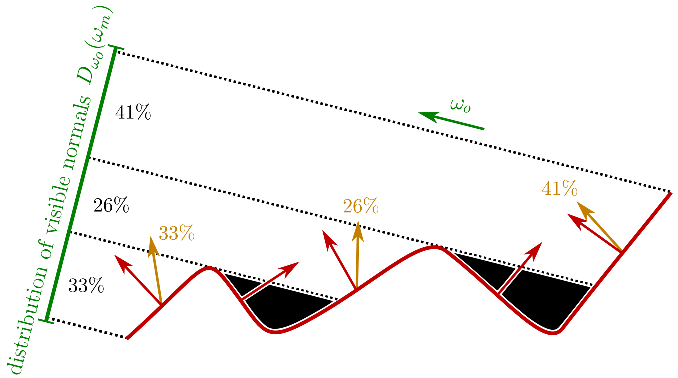
What do we have now that people didn't have before?

Recent Advances with the Smith Model

Multiple-Scattering Microfacet BSDFs with the Smith Model

Recent Advances with the Smith Model

New Insights into Smith Masking-Shadowing (2014)

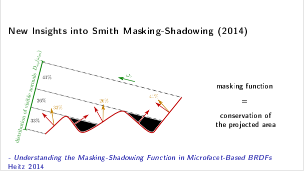


masking function

=

conservation of the projected area

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

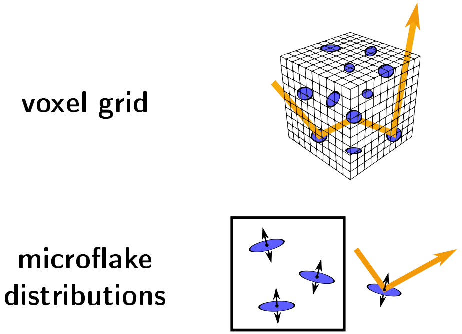


Heitz recently proposed a review of microfacet theory with emphasis on the masking function. One of the main observations provided in this paper is that the masking function should be such that the projected area of the microsurface onto an arbitrary direction is preserved. With this observation, the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

In our paper, we use this idea to show how the Smith Λ 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.

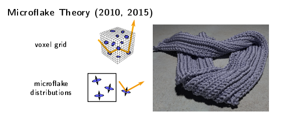
Recent Advances with the Smith Model

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

Multiple-Scattering Microfacet BSDFs with the Smith Model

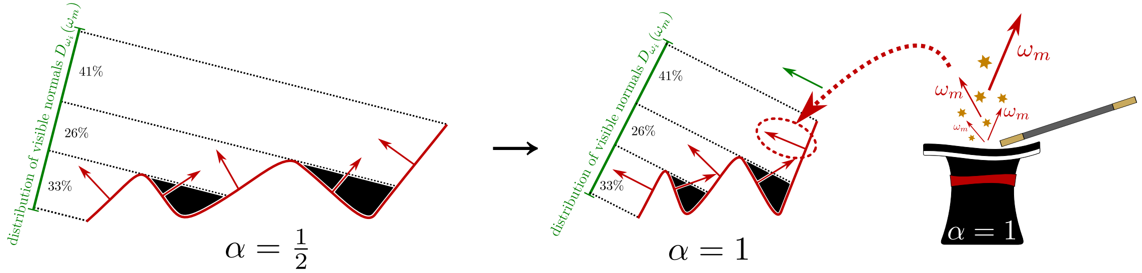


Microflake theory was introduced by Jakob et al. in 2010 to model anisotropic volumes. We propose to derive the equations of a Smith microsurface starting from such a volumetric microflake model. We will derive the Smith microsurface free-path and phase function and they obey the non-classical reciprocity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

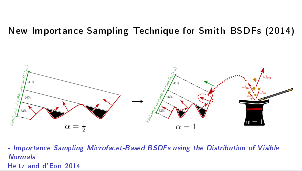
Starting from these observations, we make the connection and we show how a Smith microsurface can be defined as a microflake volume with some additional constraints.

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 $\theta \in [\pi/2, \pi]$, 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.

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- Simple assumptions, good predictions, computer graphics state of the art
- Smith multiple-scattering BSDFs not available yet, even in physics

Why now (2015)?

- New insights(2014), microflake theory(2010,2015), new importance sampling(2014)

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

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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.

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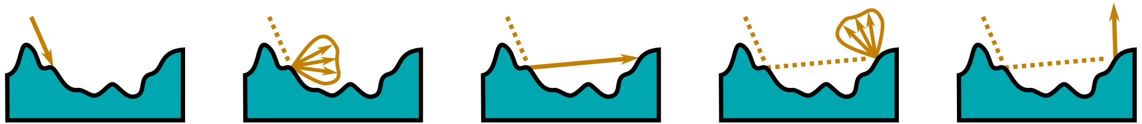
So, what kind of interesting insights did we gain from those previous works?

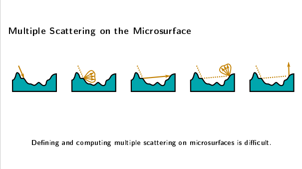
Insights

Insights

Multiple Scattering on the Microsurface



Defining and computing multiple scattering on microsurfaces is difficult.

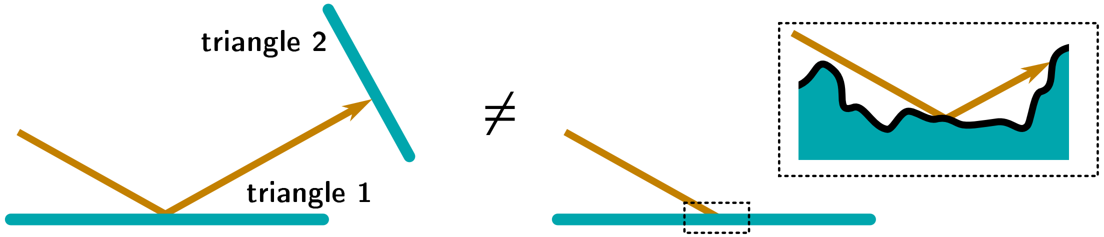


Multiple scattering is what we get if we trace paths on the microsurface.

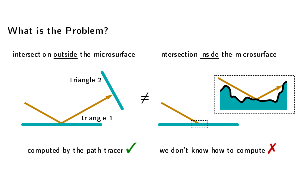
But this is complicated to do. Why is that?

What is the Problem?

intersection outside the microsurface | intersection inside the microsurface



computed by the path tracer ✓ | we don't know how to compute ✗



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.

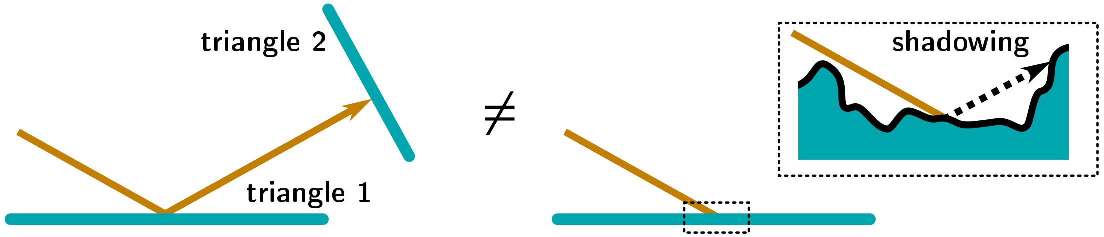
However, the microsurface is not represented explicitly with triangles, and the path tracer does not know how to intersect it explicitly. We can say that microintersections are difficult to compute.

Insights

What is the Problem?

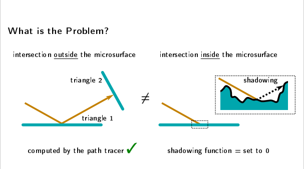
intersection outside the microsurface

intersection inside the microsurface



computed by the path tracer ✓

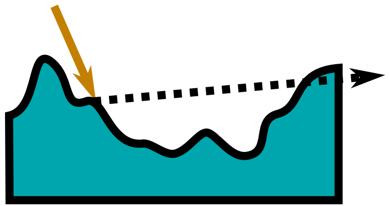
shadowing function = set to 0



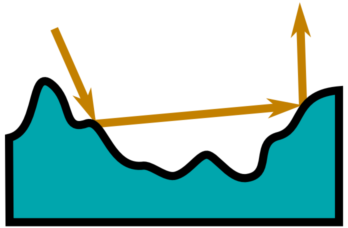
Since microintersections cannot be computed explicitly, the single-scattering BSDF incorporates a shadowing function that statistically accounts for those intersections and sets their contribution to 0.

What is the Problem?

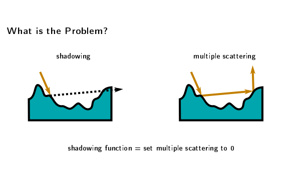
shadowing



multiple scattering



shadowing function = set multiple scattering to 0

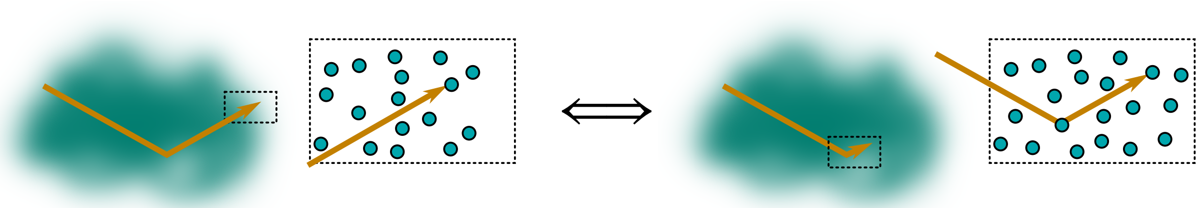


Intuitively, the shadowing function in microfacet BSDF is a replacement for multiple scattering. Since we don't know how to compute the multiple scattering, we set it to 0 with the shadowing function.

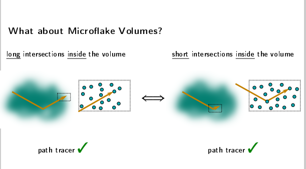
Insights

What about Microflake Volumes?

long intersections inside the volume | short intersections inside the volume



path tracer ✓ | path tracer ✓



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)?

- New insights(2014), microflake theory(2010,2015), new importance sampling(2014)

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?

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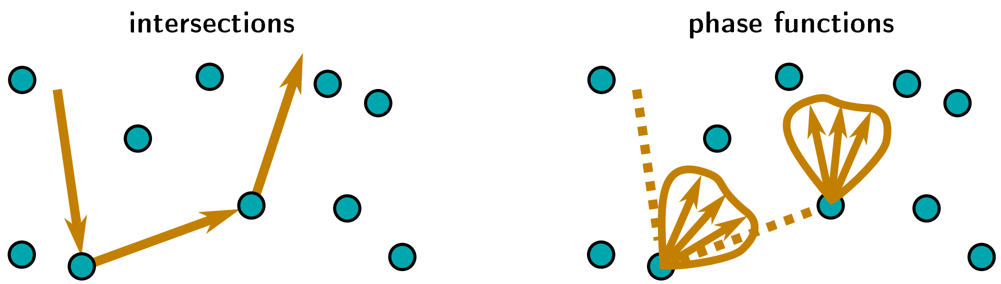
Overview of our Model

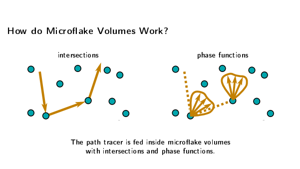
Overview of our Model

Overview of our Model

How do Microflake Volumes Work?



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



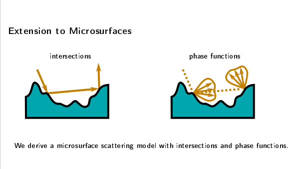
A volumetric path tracer that is able to compute multiple scattering between microflakes is fed with two primitives: intersections and phase functions.

Overview of our Model

Extension to Microsurfaces

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

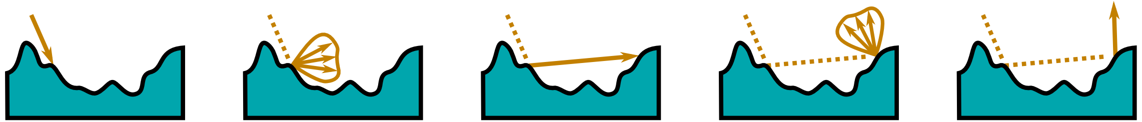
Multiple-Scattering Microfacet BSDFs with the Smith Model



To define multiple scattering on the microsurface, we define equivalent primitives for the Smith microsuface model.

Overview of our Model

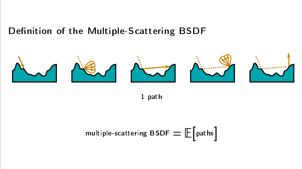
Definition of the Multiple-Scattering BSDF



1 path

multiple-scattering BSDF $= \mathbb{E}\left[\text{paths}\right]$

Multiple-Scattering Microfacet BSDFs with the Smith Model



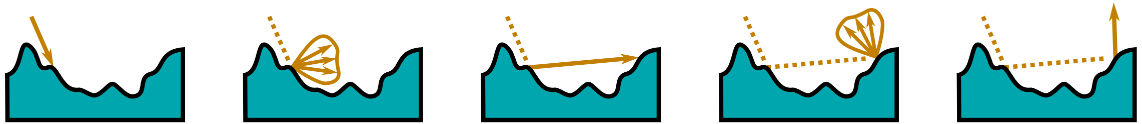
With these primitives, we can define a scattering process occurring on the microsurface. Intuitively we can say that we can do some statistical path tracing on the microsurface.

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

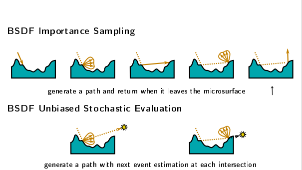
BSDF Importance Sampling



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?

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How do we validate our model?

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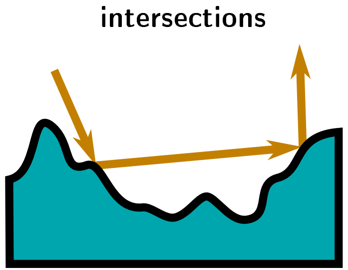
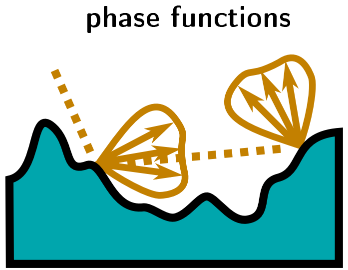
That was an overview of the main ideas.

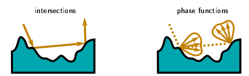
Now, more concretely, what are the ingredients of our model?

Our Smith Microsurface Model



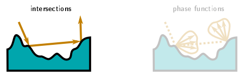


Multiple-Scattering Microfacet BSDFs with the Smith Model



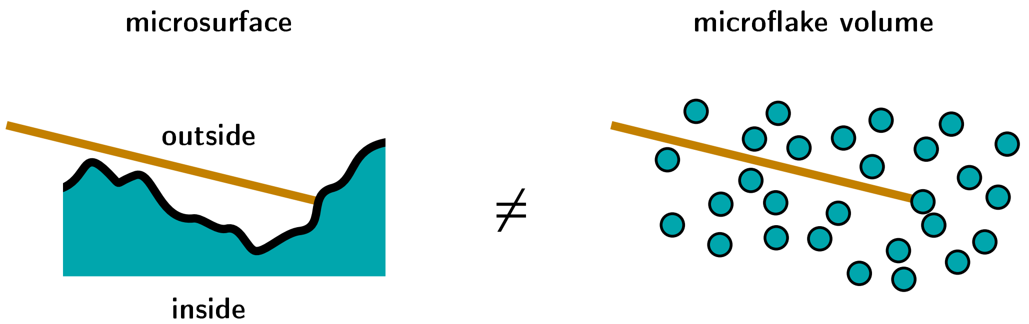
We have seen that path tracing on the microsurface can be achieved if we have a model for intersections and a model for the phase functions associated with the microsurface.

Microsurface Intersections with the Smith Model

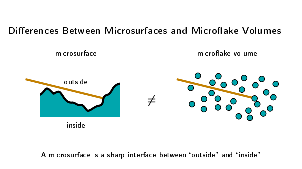


Let's talk about the intersection model.

Differences Between Microsurfaces and Microflake Volumes



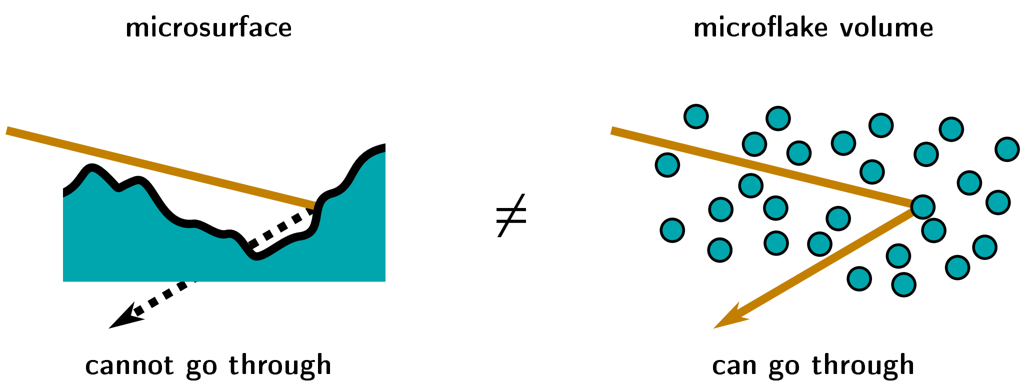
A microsurface is a sharp interface between “outside” and “inside”.



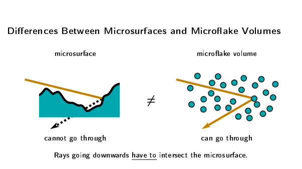
Our multiple-scattering model is inspired by how multiple scattering is computed in microflake volumes.

However, the intersection model for volumes cannot be directly applied to surfaces. This is because a surface is a sharp interface between inside and outside regions, while a volume is not a sharp interface.

Differences Between Microsurfaces and Microflake Volumes



Rays going downwards have to intersect the microsurface.

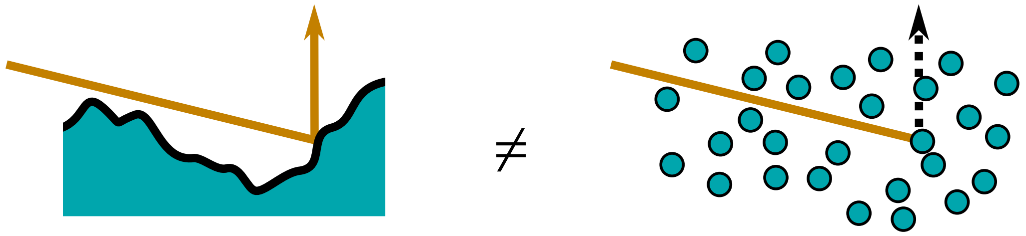


Because of this fundamental difference, intersection models for volumes and surfaces have different properties.

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.

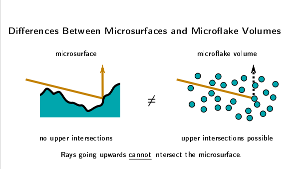
Differences Between Microsurfaces and Microflake Volumes

microsurface | microflake volume



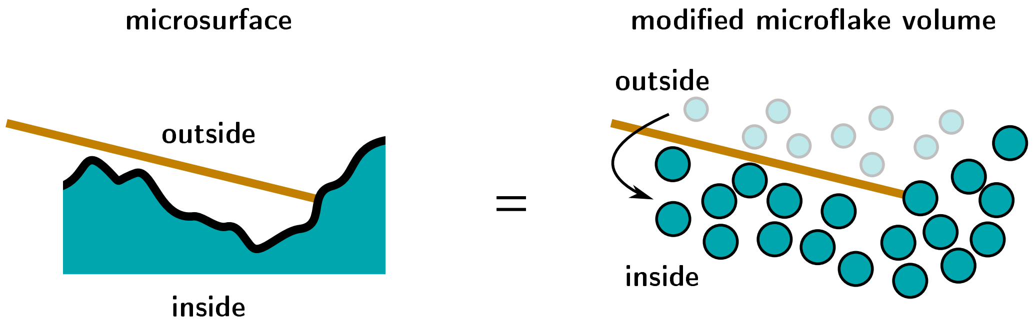
no upper intersections | upper intersections possible

Rays going upwards cannot intersect the microsurface.

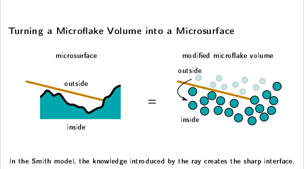


Another difference is that a ray going upwards will never intersect the surface (the Smith model assumes a heightfield), while a ray going upwards can always intersect a particle above its starting point within a volume.

Turning a Microflake Volume into a Microsurface



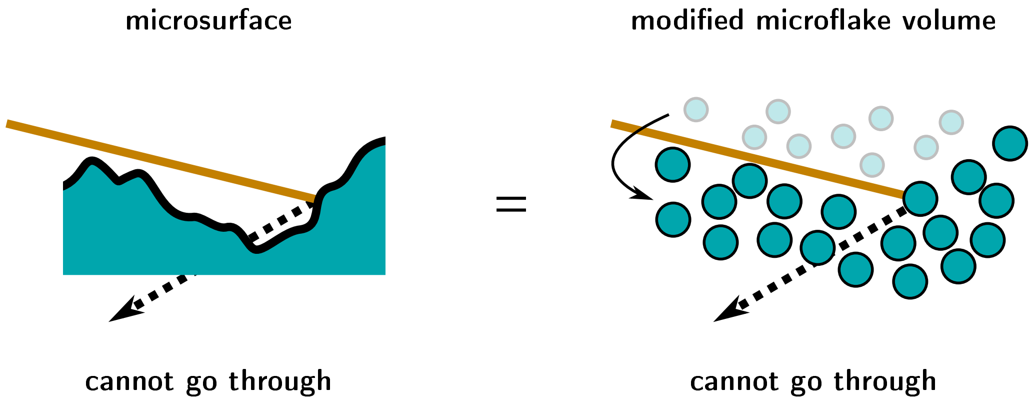
In the Smith model, the knowledge introduced by the ray creates the sharp interface.



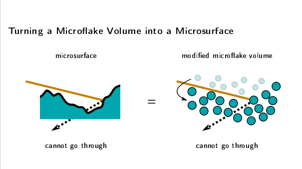
The Smith model can be seen as a volumetric model that has been modified to obtain the properties of a surface. The idea of the Smith model is to use the knowledge provided by the ray to introduce the concept of a sharp surface interface that separates inside and outside.

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.

Turning a Microflake Volume into a Microsurface



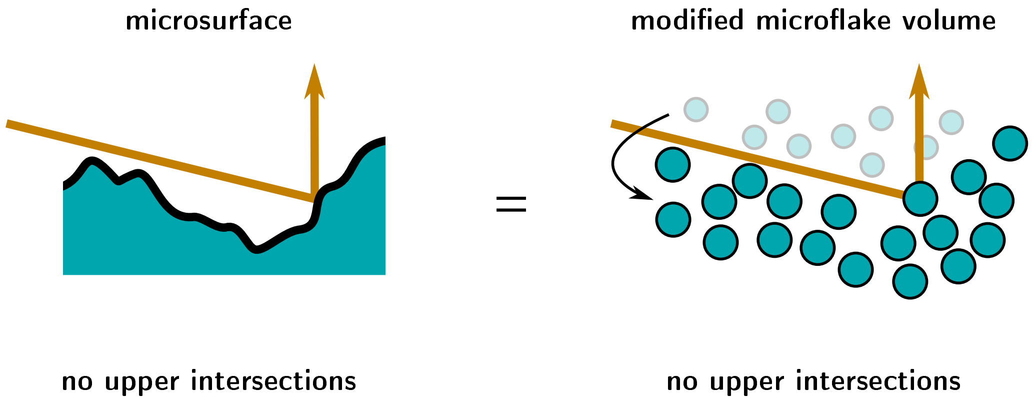
Multiple-Scattering Microfacet BSDFs with the Smith Model

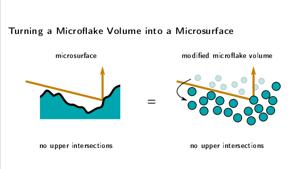


In the Smith model, the more the ray goes down, the more the probability of the inside being below increases, i.e. the ray is getting closer to the interface of the surface and it will eventually intersect the interface.

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

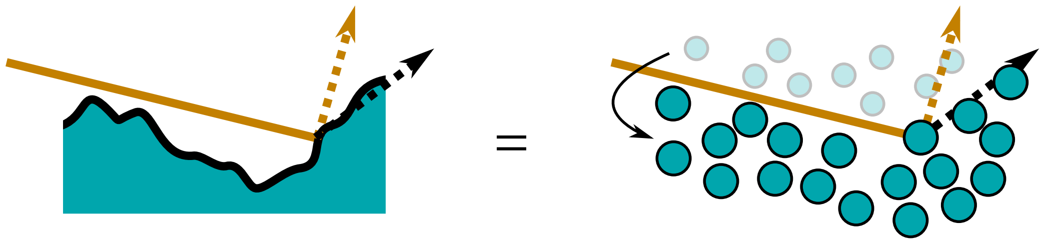
Turning a Microflake Volume into a Microsurface

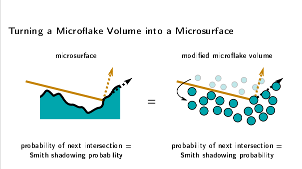




Another property is that, thanks to the projected area of the microfacets, rays going up will not intersect the volume, i.e. they go through the outside part of the volume.

Turning a Microflake Volume into a Microsurface



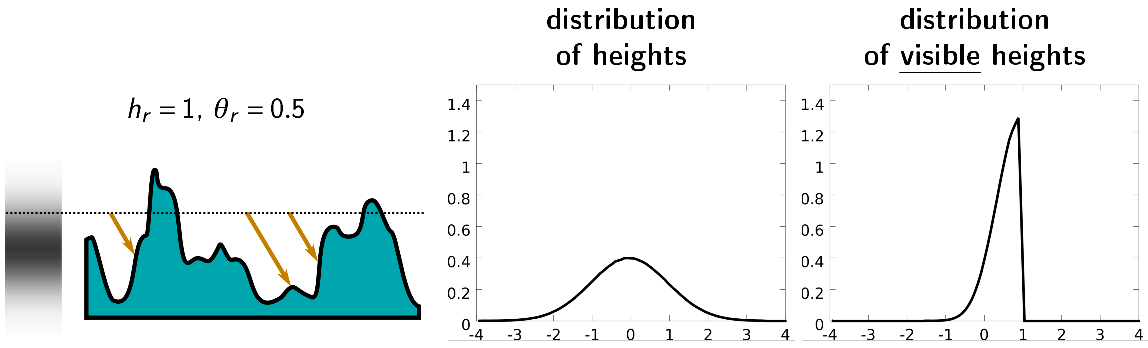


Furthermore, the average probability of further intersections in this modified volume yields exactly the Smith shadowing probability used in the classic single scattering model.

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!

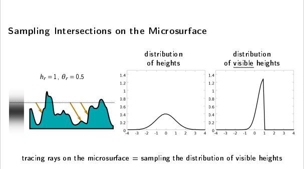
Microsurface Intersections with the Smith Model

Sampling Intersections on the Microsurface



tracing rays on the microsurface = sampling the distribution of visible heights

Multiple-Scattering Microfacet BSDFs with the Smith 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 raytracing 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.

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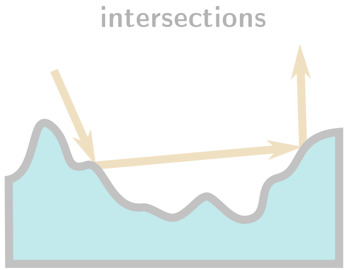
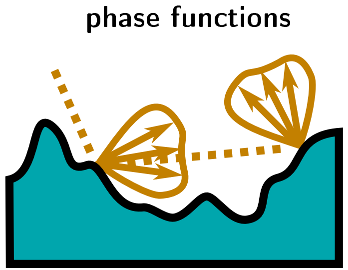
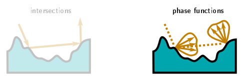
Microsurface Phase Functions with the Smith Model



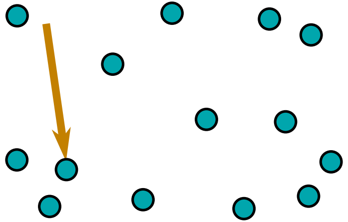




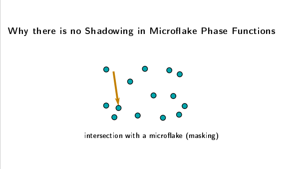
After an intersection is found, we have to deal with the phase function of the microsurface for the next scattering direction to be computed.

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.

Why there is no Shadowing in Microflake Phase Functions



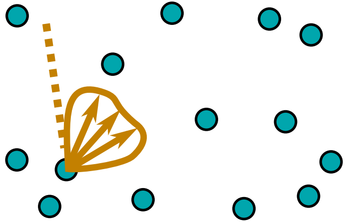
intersection with a microflake (masking)



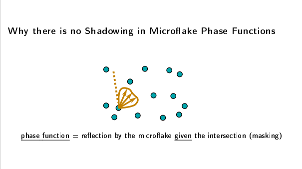
An interesting observation is that microflake phase functions incorporate a “Smith-like” masking function, but do not incorporate shadowing. We will find out why.

When an intersection is found, it means that the intersection point is visible for the incident direction. Hence it is not masked.

Why there is no Shadowing in Microflake Phase Functions



phase function = reflection by the microflake given the intersection (masking)

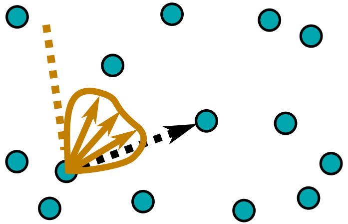


The phase function is the distribution of reflected directions given that there was an intersection. If the material is non-absorptive, then all of the energy is reflected after the intersection.

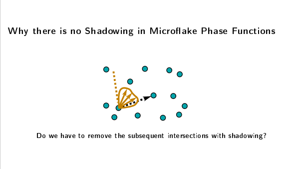
Intuitively, what we are modeling can be explained as: "*If 100 rays intersect a microflake (masking), then 100 rays will be reflected somewhere (phase function).*"
We model rays intersecting microflakes with the introduction of the masking function in the phase function. Hence, the masking function can be see as the normalization factor of the phase function (100 rays before and after).

More details can be found in
- *Understanding the Masking-Shadowing Function in Microfacet-Based BRDFs*, Heitz 2014
- *The SGGX Microflake Distribution*, Heitz et al. 2015

Why there is no Shadowing in Microflake Phase Functions



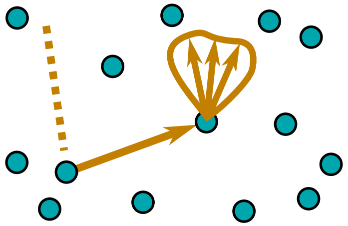
Do we have to remove the subsequent intersections with shadowing?



If were we to follow the single-scattering BSDF derivation in microfacet theory, at this point of the derivation, we would introduce a shadowing function to account for (set to 0) the next intersection.

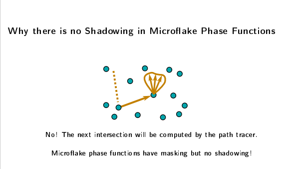
Is this required for a microflake volume?

Why there is no Shadowing in Microflake Phase Functions



No! The next intersection will be computed by the path tracer.

Microflake phase functions have masking but no shadowing!

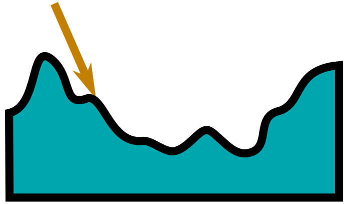


No, shadowing is not required!

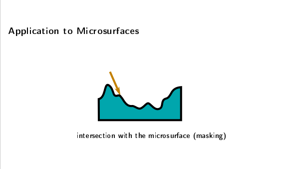
Remember that the purpose of shadowing is to remove the contribution of the subsequent intersections if we are not able to compute them. But in a microflake volume they are computed. Indeed, the next intersection (if there is one) will be sampled by the path tracer and the next phase function will be evaluated, etc.

This is why microflake phase functions have masking (account for the current intersection), but do not have shadowing (do not account for the next intersection, but leave it to the path tracer).

Application to Microsurfaces



intersection with the microsurface (masking)

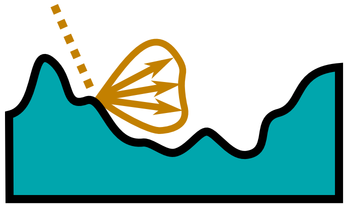


Now let's see what happens if we apply the same concept to a microsurface.

Here we have an intersection, so again it means that the intersection point is not masked for the incident direction.

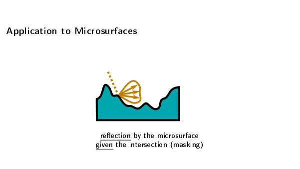
Microsurface Phase Functions with the Smith Model

Application to Microsurfaces



reflection by the microsurface
given the intersection (masking)

Multiple-Scattering Microfacet BSDFs with the Smith Model



In exactly the same way, the microsurface phase function is the distribution of reflected directions given that there was an intersection. If the material is non-absorptive, then all of the energy is reflected after the intersection.

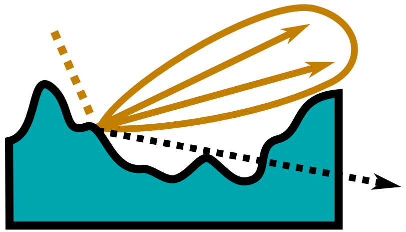
Heitz calls the energy conservation of this function (with masking and no shadowing) the *Weak White Furnace Test*:

$$\int_{\Omega} \frac{G_1(\omega_h, \omega_i)\, D(\omega_h)}{4\,|\omega_g \cdot \omega_i|} = 1 \quad (1)$$

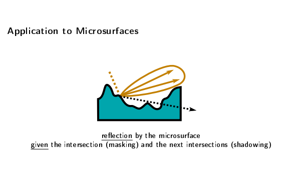
See *Understanding the Masking-Shadowing Function in Microfacet-Based BRDFs*, Heitz 2014

Microsurface Phase Functions with the Smith Model

Application to Microsurfaces



reflection by the microsurface
given the intersection (masking) and the next intersections (shadowing)



At this point in the derivation of classic single-scattering microfacet BSDFs, we need to remove the contribution of the rays intersecting the microsurface again with the introduction of the shadowing function. Contrary to the phase function (masking only) the single-scattering BSDF (masking and shadowing) is responsible for some energy loss:

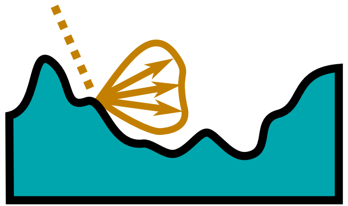
$$\int_\Omega \frac{G_2(\omega_h,\omega_i,\omega_o)\, D(\omega_h)}{4\,|\omega_g \cdot \omega_i|} \leq 1 \qquad (2)$$

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

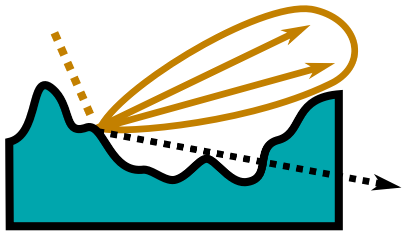
Microsurface Phase Functions with the Smith Model

Application to Microsurfaces

phase function



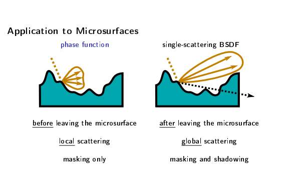
single-scattering BSDF



before leaving the microsurface — after leaving the microsurface

local scattering — global scattering

masking only — masking and shadowing



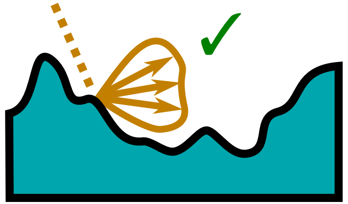
Here is the main difference between the microsurface phase function and the microsurface BSDF.

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

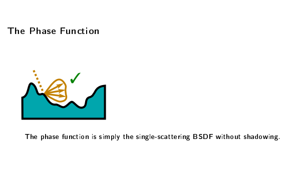
BSDFs model how rays are reflected by the microsurface after they have left it. They describe the global scattering occurring on the microsurface. The BSDFs have to incorporate multiple scattering or set it to 0 with a shadowing function.

Microsurface Phase Functions with the Smith Model

The Phase Function

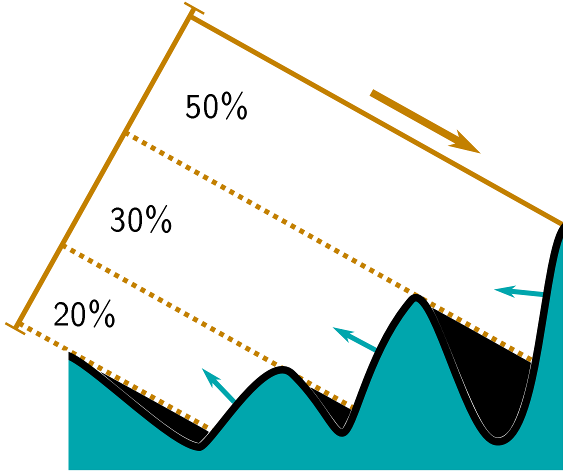


The phase function is simply the single-scattering BSDF without shadowing.

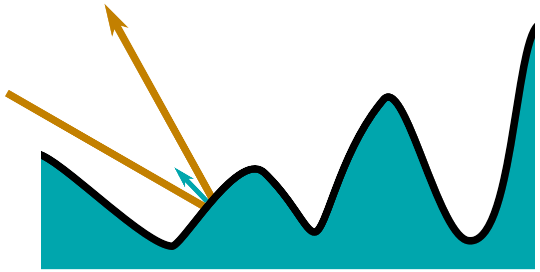


With this intuition, we can see that the phase function of a microsurface is simply the single-scattering BSDF without the shadowing function. And we know how to compute it...

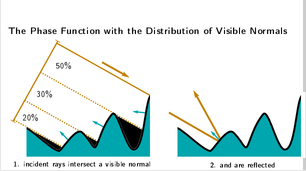
The Phase Function with the Distribution of Visible Normals



1. incident rays intersect a visible normal



2. and are reflected



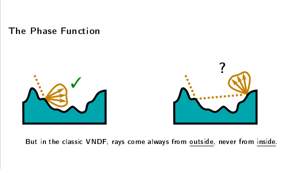
...but we still have some work to do, because the definition of the single-scattering BSDF is not yet general enough.

The phase function (or the single-scattering BSDF) is built on top of the distribution of visible normals (VNDF). What this models is the probability for each microfacet to be intersected given its cosine projection factor, as well as how the microfacets would reflect the incident direction.

However, the VNDF is usually only defined for incident directions coming from above the surface ($\theta_i \in [0, \frac{\pi}{2}]$).

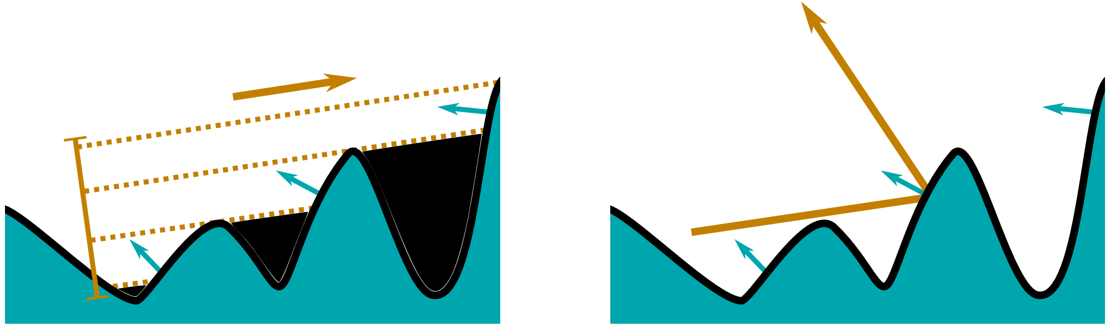
The Phase Function

But in the classic VNDF, rays come always from outside, never from inside.

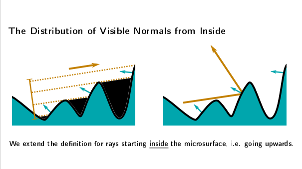


However, if we want to compute the phase function after a previous intersection with the microsurface, the incident direction might come from inside the microsurface ($\theta_i \in [\frac{\pi}{2}, \pi)$).

The Distribution of Visible Normals from Inside



We extend the definition for rays starting inside the microsurface, i.e. going upwards.

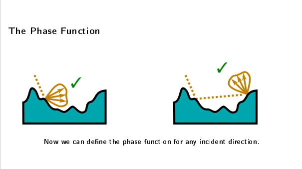


We generalize the definition of the VNDF for directions coming from the lower hemisphere (details for Beckmann and GGX are given in the supplemental material).

Microsurface Phase Functions with the Smith Model

The Phase Function

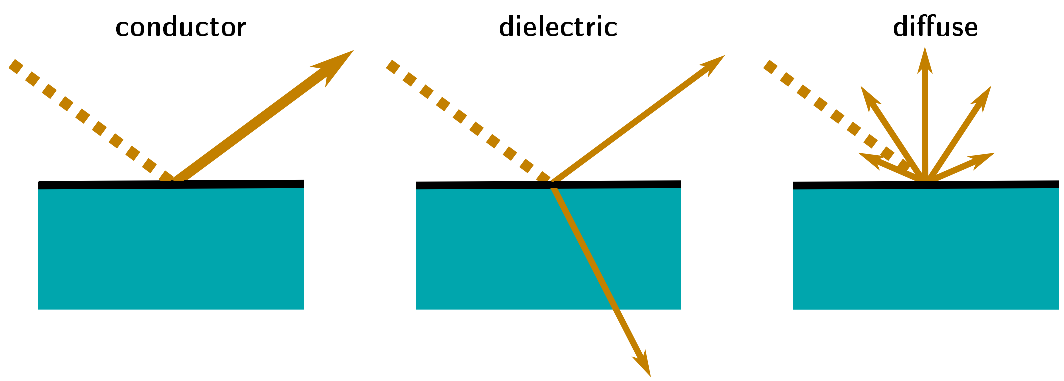
Now we can define the phase function for any incident direction.



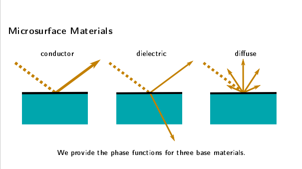
And now we can define the phase function for any incident direction.

Microsurface Phase Functions with the Smith Model

Microsurface Materials



We provide the phase functions for three base materials.



In the previous figures, we only illustrated reflections produced by perfect mirror-like microfacets. In the paper, we derive the phase functions of three base microsurface materials: conductor, dielectric and diffuse.

Note that in the case of dielectrics, the rays can be transmitted through the material, then scattered on the microsurface of the other side of the interface. In this case the computations of the intersection model can be updated by swapping the inside and the outside. Details are provided in the paper and the 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)?

- New insights(2014), microflake theory(2010,2015), new importance sampling(2014)

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?

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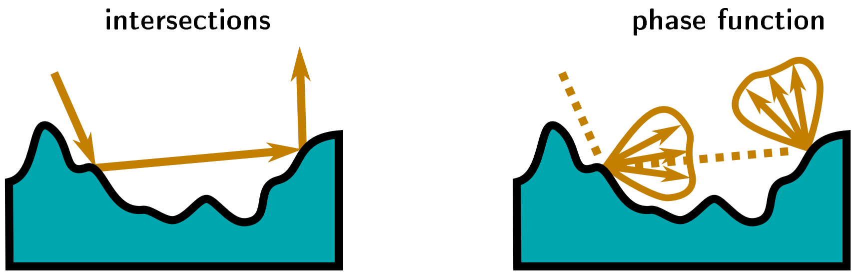
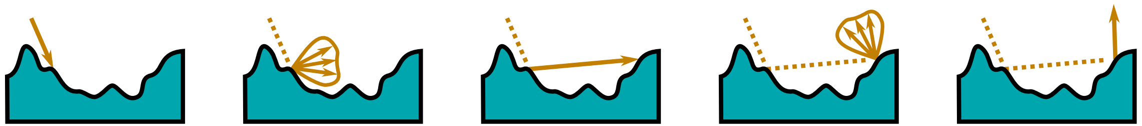
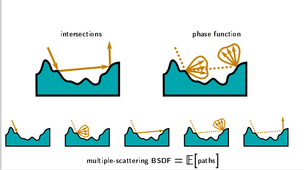
Our Smith Microsurface Model





multiple-scattering BSDF $= \mathbb{E}\left[\text{paths}\right]$

Multiple-Scattering Microfacet BSDFs with the Smith Model



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

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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?

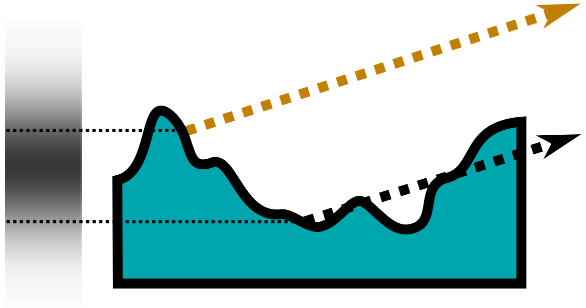
How can we be sure that it is really the BSDF associated with the Smith model?

Validating the Math

We validated the math by verifying the properties of the model numerically with our implementation.

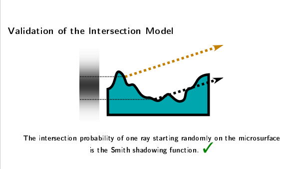
Our C++ implementation and the tests we made are provided and detailed in our supplemental material.

Validation of the Intersection Model



The intersection probability of one ray starting randomly on the microsurface is the Smith shadowing function. ✓

Multiple-Scattering Microfacet BSDFs with the Smith Model

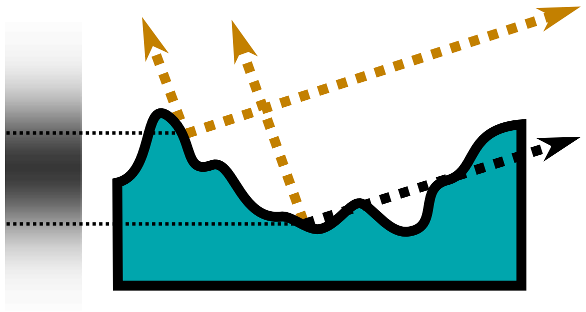


We verified that if we generate random points according to the microsurface height PDF and if we average the number of intersections found by our intersection model, we get exactly the Smith shadowing function:

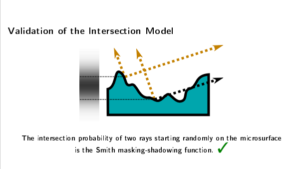
$$\mathbb{E}[\text{intersection in } \omega_i] = G_1(\omega_i) = \frac{1}{1+\Lambda(\omega_i)}. \tag{3}$$

Validating the Math

Validation of the Intersection Model



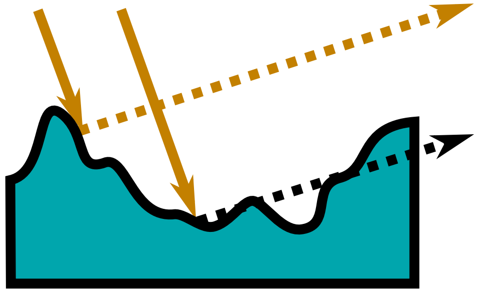
The intersection probability of two rays starting randomly on the microsurface is the Smith masking-shadowing function. ✓



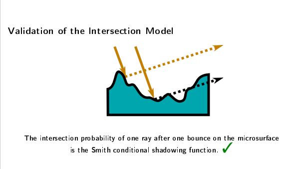
We verified that if we generate random points according to the microsurface height PDF and average the number of intersections found by our intersection model in two different directions, we get exactly the Smith masking-shadowing function:

$$\mathbb{E}[\text{intersection in } \omega_i \text{ and } \omega_o] = G_2(\omega_i, \omega_o) = \frac{1}{1 + \Lambda(\omega_i) + \Lambda(\omega_o)}. \quad (4)$$

Validation of the Intersection Model



The intersection probability of one ray after one bounce on the microsurface is the Smith conditional shadowing function. ✓

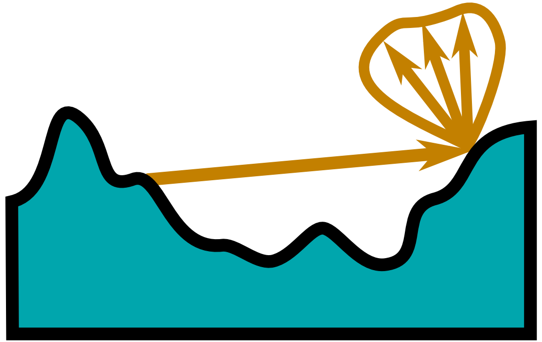


We verified that if we use our model to compute intersections points from a given direction and then average the number of intersections found in another direction, we get exactly the conditional shadowing function. The conditional shadowing function tells us: "*What is the probability that the point is shadowed in direction ω_o given that it is not in direction ω_i?*"

$$\mathbb{E}[\text{intersection in } \omega_o \text{ given } \omega_i] = \frac{G_2(\omega_i, \omega_o)}{G_1(\omega_i)} = \frac{1 + \Lambda(\omega_i)}{1 + \Lambda(\omega_i) + \Lambda(\omega_o)}. \qquad (5)$$

By testing these different properties, we have verified that our intersection model is consistent with the classic Smith masking and shadowing function.

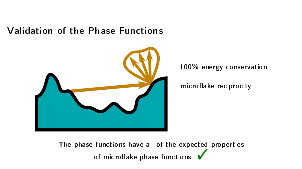
Validation of the Phase Functions



100% energy conservation

microflake reciprocity

The phase functions have all of the expected properties of microflake phase functions. ✓



We validated numerically that our phase functions have all of the expected properties of phase functions, i.e. that they are correctly normalized (energy conserving) in any configuration:

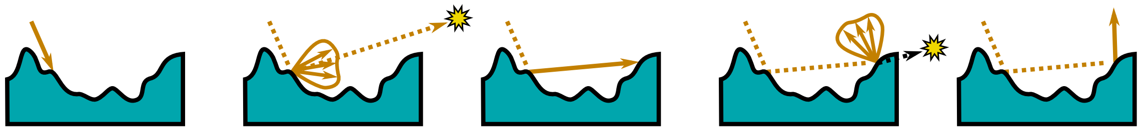
$$\int_{\Omega} p(\omega_i, \omega_o)\, d\omega_o = 1 \tag{6}$$

and that they satisfy the unusual reciprocity condition of microflake phase functions:

$$\sigma(-\omega_i)\, p(\omega_i, \omega_o) = \sigma(-\omega_o)\, p(\omega_o, \omega_i) \tag{7}$$

Validating the Math

Validation of the Multiple-Scattering BSDF



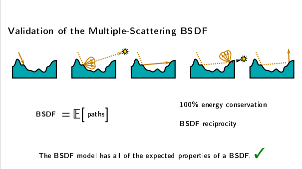
BSDF $= \mathbb{E}\left[\text{ paths }\right]$

100% energy conservation

BSDF reciprocity

The BSDF model has all of the expected properties of a BSDF. ✓

Multiple-Scattering Microfacet BSDFs with the Smith Model



We validated numerically that the BSDF models defined as the expectation of random walks occurring on the microsurface have all of the expected properties of a BSDF, i.e. that they are energy conserving (for a non-absorptive material):

$$\int_{\Omega} f(\omega_i, \omega_o) \cos\theta_o \, d\omega_o = 1 \tag{8}$$

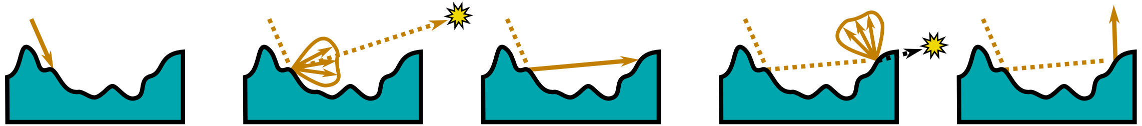
and that they satisfy the classic reciprocity condition of BSDFs:

$$f(\omega_i, \omega_o) = f(\omega_o, \omega_i). \tag{9}$$

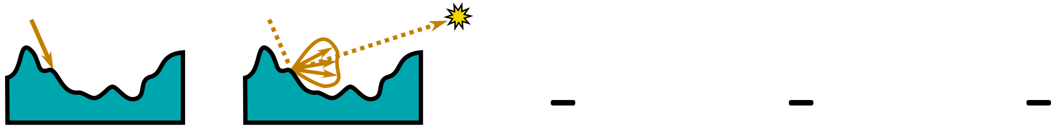
Even though we did not find a closed-form expression for the model, the mathematical function defined by this expectation $\mathbb{E}$[paths] is indeed a BSDF!

Validating the Math

Validation of the Multiple-Scattering BSDF

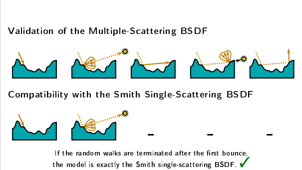


Compatibility with the Smith Single-Scattering BSDF



If the random walks are terminated after the first bounce,
the model is exactly the Smith single-scattering BSDF. ✓

Multiple-Scattering Microfacet BSDFs with the Smith Model



Furthermore, we verified that if the paths are cut after the first bounce, the BSDF is exactly the classic Smith single-scattering BSDF which has a closed-form expression:

$$\mathbb{E}[\text{paths of length } 1] = \text{classic closed-form single-scattering BSDF} \quad (10)$$

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- 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

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- We verified all the mathematical properties of the model

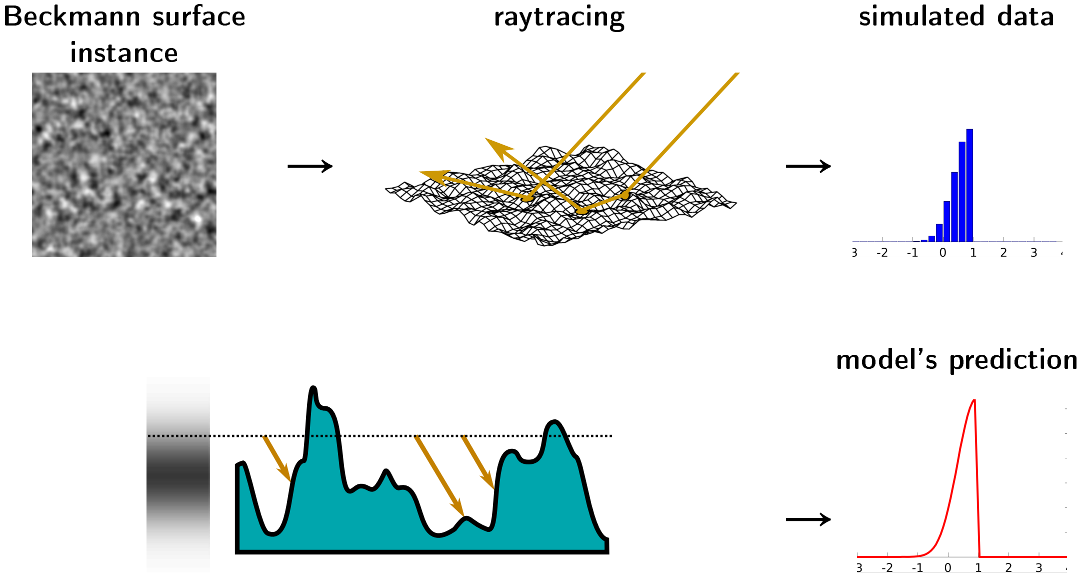
These unit tests show that our model is indeed a BSDF and is totally consistent with the classic properties of a Smith microsurface.

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?

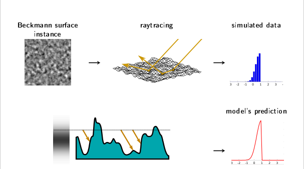
Validation: Comparison against Simulated Data

Validation: Comparison against Simulated Data

Validation: Comparison against Simulated Data



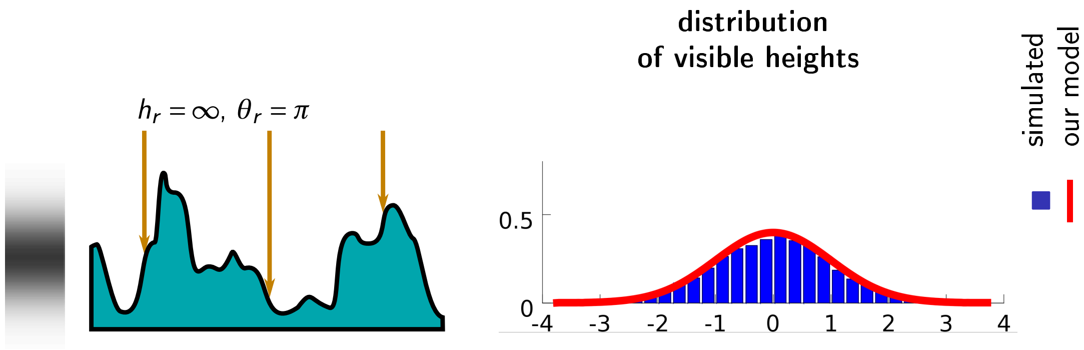
Multiple-Scattering Microfacet BSDFs with the Smith Model

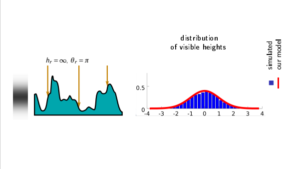


To compute simulated data, we create an instance of a Beckmann surface—using a Gaussian-like noise primitive with controllable roughness parameters—and we parameterize our Smith model with the same statistics.

In this first comparison test, we compute the set of the intersection heights computed with the raytracing simulation and we compare them to the distribution of visible heights predicted by the model.

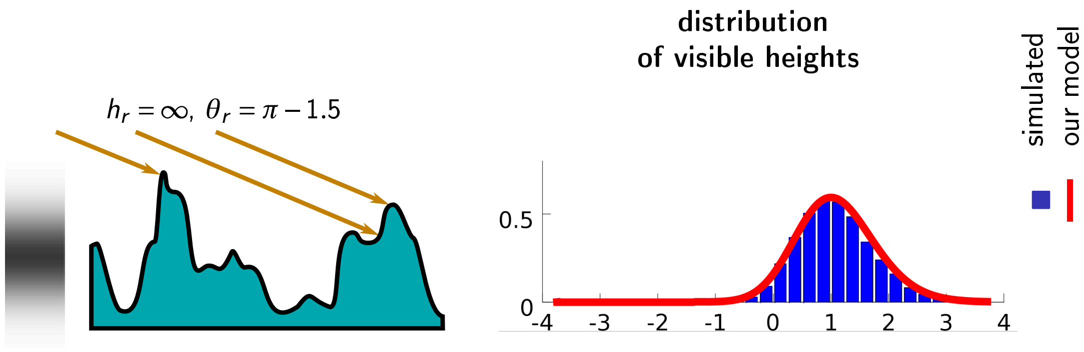
Validation: Comparison against Simulated Data



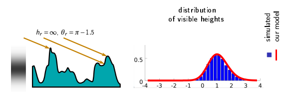


A first observation is that, at normal incidence ($\theta_r = \pi$), when the ray starts outside of the microsurface ($h_r = \infty$), the distribution of visible heights is exactly the Gaussian distribution of heights of the microsurface. Indeed, in this case there are no visibility effects such as masking.

Validation: Comparison against Simulated Data



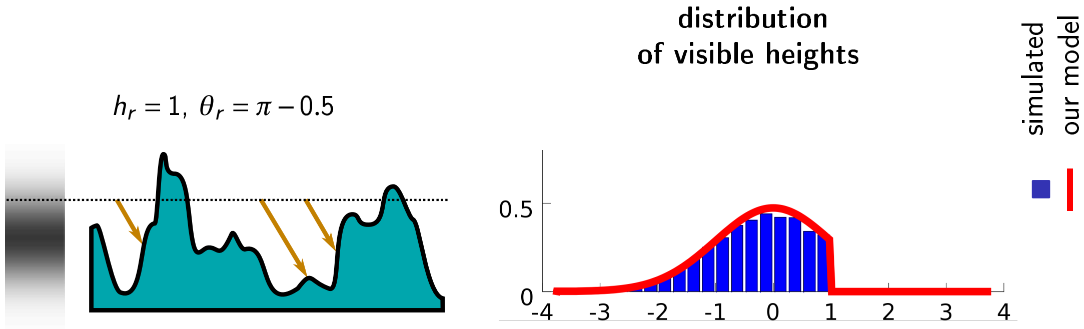
Multiple-Scattering Microfacet BSDFs with the Smith Model



In this new example we can see that the more the incident direction is tilted, the more the distribution of visible heights is shifted towards the top of the microsurface because of masking effects.

We observe this effect in both the raytraced data and our model.

Validation: Comparison against Simulated Data



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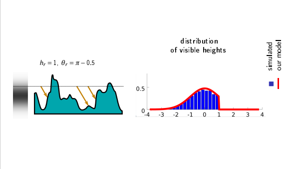
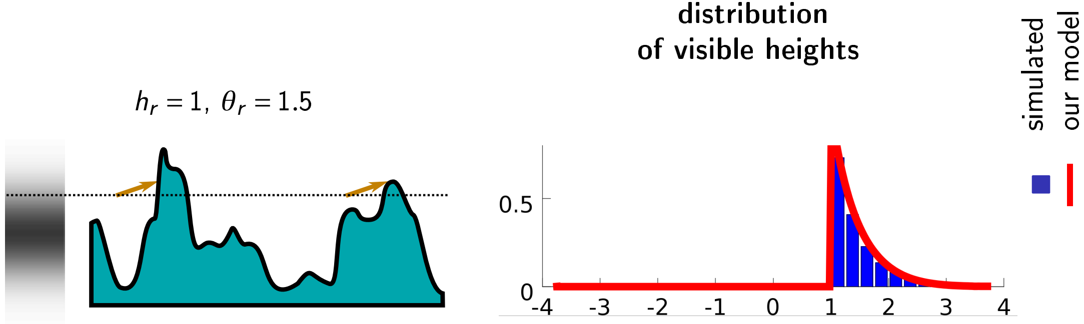
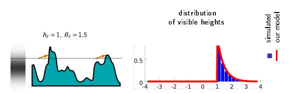


This example shows how the distribution of visible heights is cut when the ray does not start outside of the microsurface. Indeed, if the ray is going down, the heights above the ray cannot be intersected.

Validation: Comparison against Simulated Data





This last example shows what happens for rays going upwards. In this case, the distribution is truncated on the other side.

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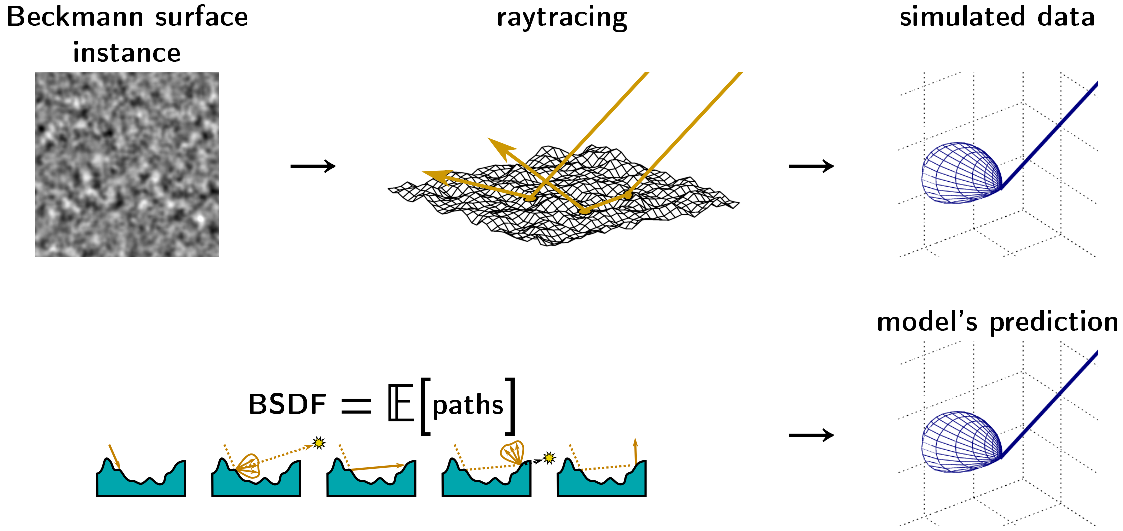

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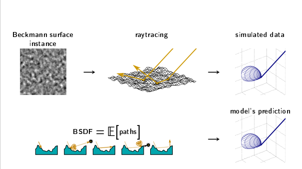
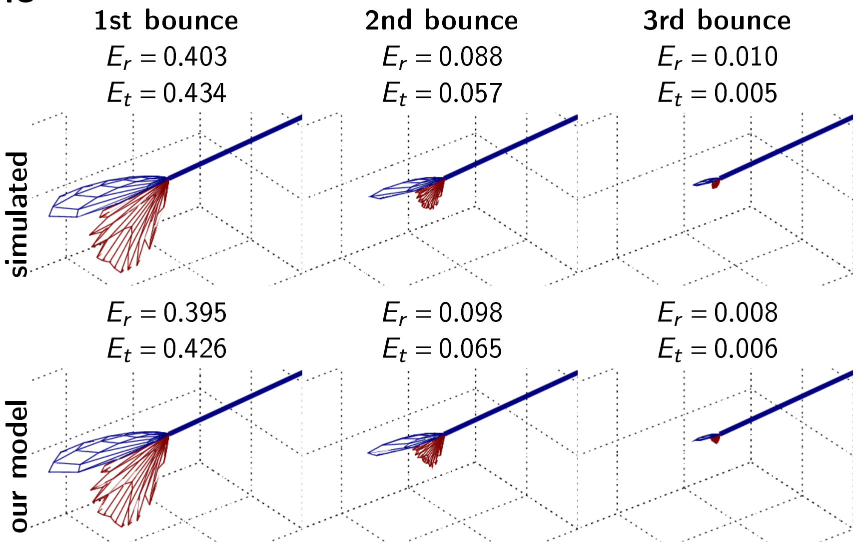


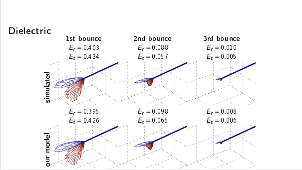
In this second comparison test, we raytrace the Beckmann surface instance and record the set of outgoing directions. We compare it to the prediction of our Smith multiple-scattering BSDF model.

Validation: Comparison against Simulated Data

Dielectric



Multiple-Scattering Microfacet BSDFs with the Smith Model

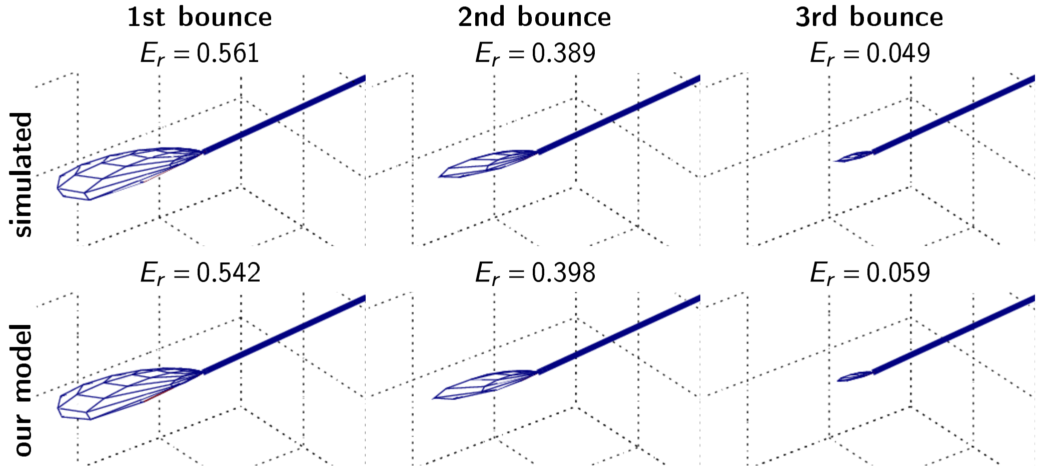


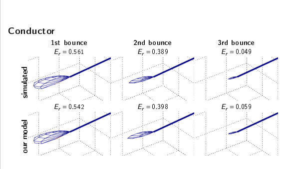
These are the reflected (blue) and transmitted (red) lobes of a dielectric surface. We can see that the model's prediction matches the energy distribution in the different scattering orders and the lobe's shape.

More comparisons are available in our supplemental material.

Validation: Comparison against Simulated Data

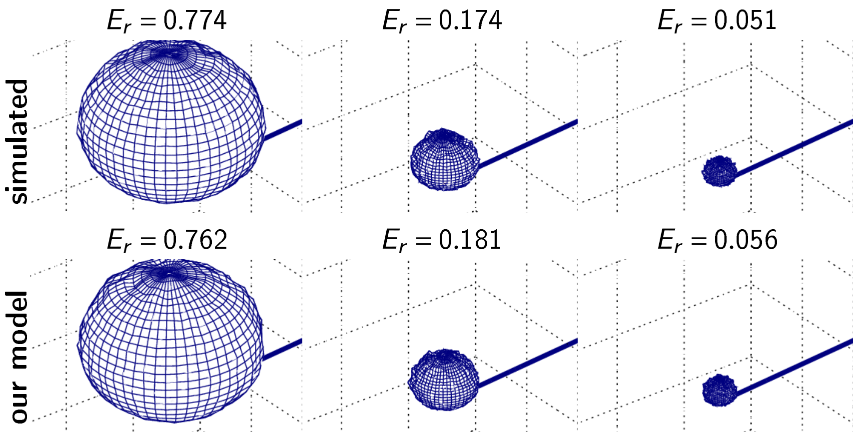
Conductor

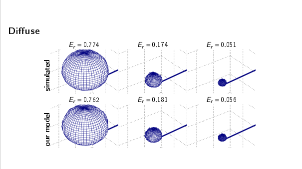




Validation: Comparison against Simulated Data

Diffuse





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)?
- New insights(2014), microflake theory(2010,2015), new importance sampling(2014)

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**

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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

Implementation of our Model

- Conductor, dielectric, and diffuse base materials
- Beckmann and GGX distributions
- Supports anisotropy
- Supports textured roughness/anisotropy/albedo
- Stochastic unbiased evaluation and importance sampling
- No precomputed data

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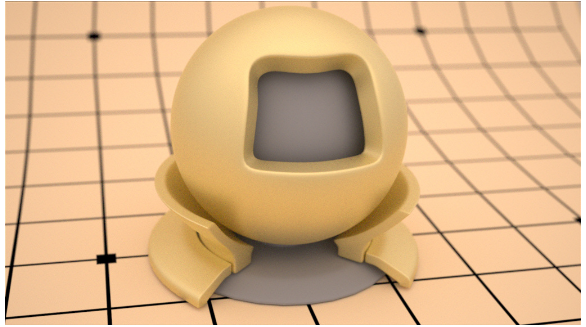
In our supplemental material, we provide a tutorial implementation of the multiple-scattering BSDFs associated with various materials.

Our implementation is 100% analytical, it does not require precomputed data and it supports varying roughness and anisotropy (Beckmann and GGX).

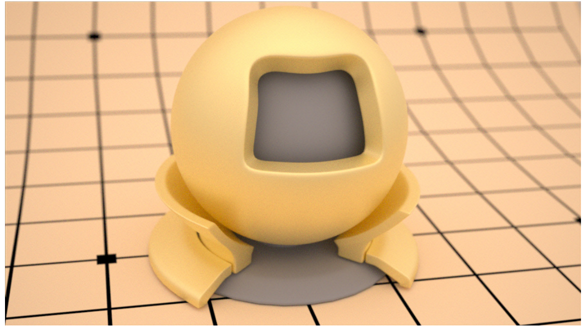
Results

Gold Conductor with GGX distribution

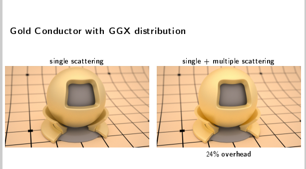
single scattering



single + multiple scattering

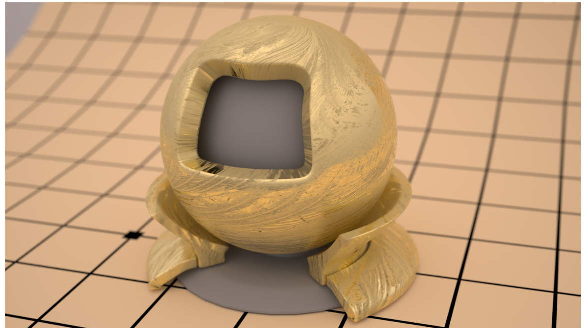


24% overhead

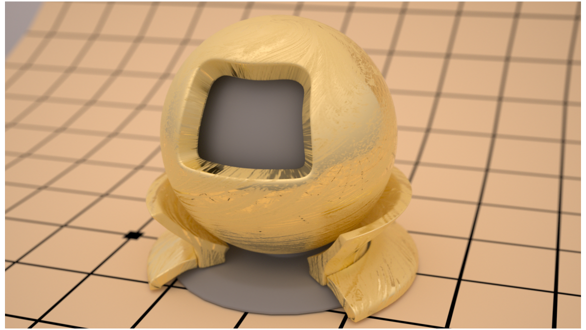


Textured Roughness

single scattering



single + multiple scattering



27% overhead

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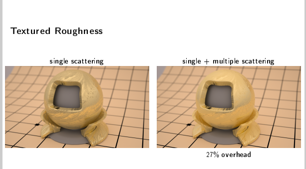
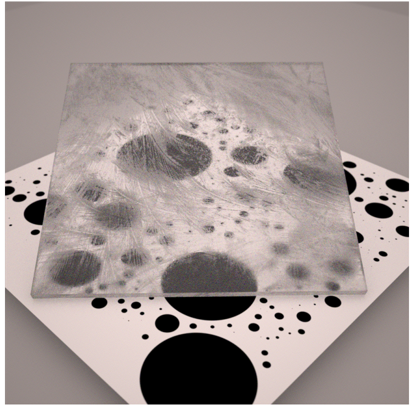
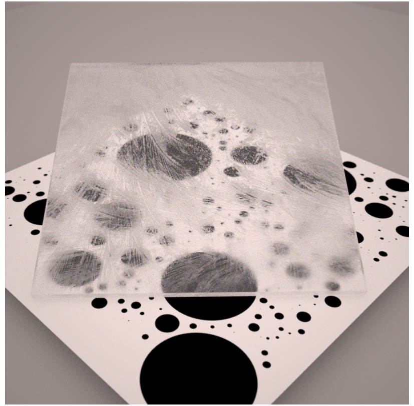


Dielectric with Textured Roughness

single scattering

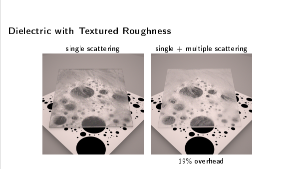


single + multiple scattering

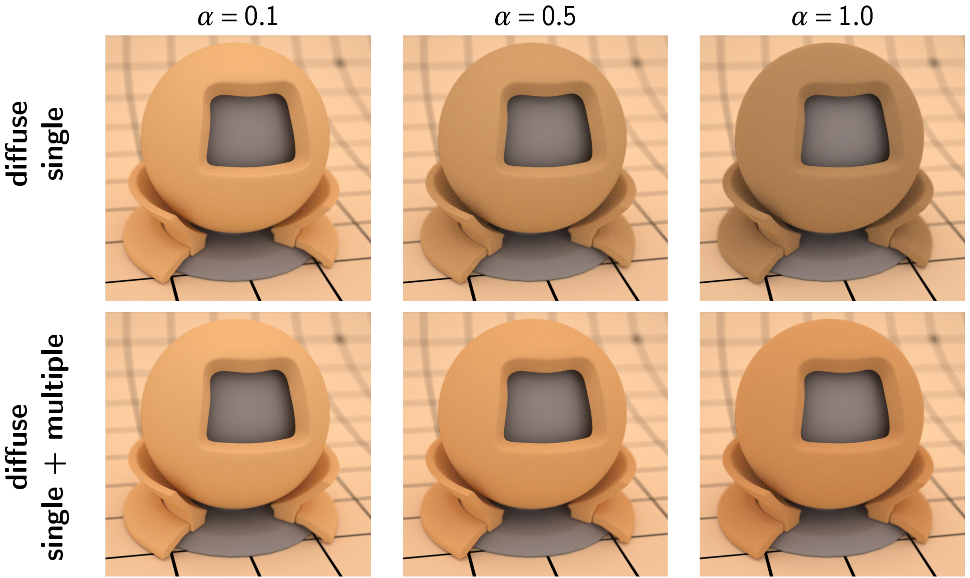


19% overhead

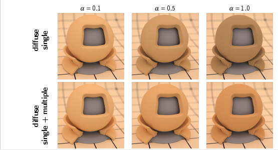
Multiple-Scattering Microfacet BSDFs with the Smith Model



Results



$\alpha = 0.1$
$\alpha = 0.5$
$\alpha = 1.0$
diffuse
single
diffuse
single + multiple



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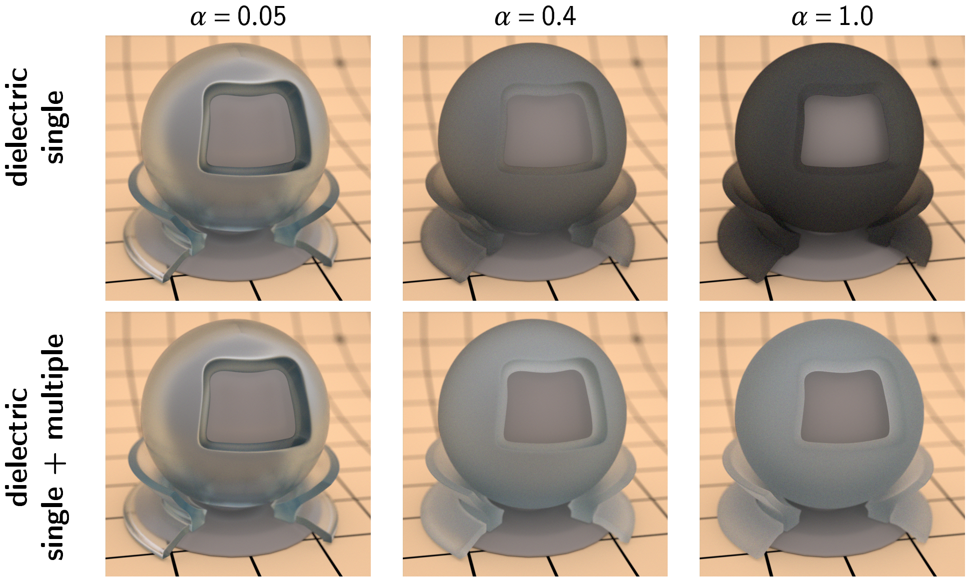
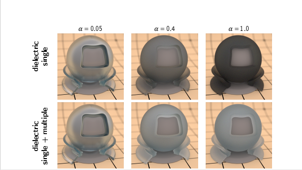


Multiple-Scattering Microfacet BSDFs with the Smith Model

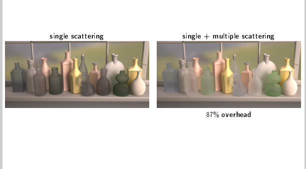


Results

single scattering

single + multiple scattering

87% overhead



Frequently Asked Questions

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Lack of closed-form evaluation

Q: If there is no closed-form evaluation, can we really call it a BSDF?

A1: It is not because <u>we</u> were not able to derive a closed-form expression that it does not exist.

A2: BSDF means Bidirectional Scattering Distribution Function, i.e. a BSDF is a mathematical function with some physical properties. Our multiple-scattering BSDF defined as the expectation

$$\text{BSDF} = \mathbb{E}\Big[\text{paths}\Big]$$

is a well-defined mathematical function and it has all of the required physical properties of a BSDF. Whether it has a closed-form expression is independent of it being a BSDF or not.

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We should not confuse mathematical functions and the ability to evaluate them. The last is engineering, not math.

With our definition of the BSDF as an expected value, we can evaluate it at arbitrary precision (by averaging a lot of paths). We can do that on the fly (this is what we do), but we can also precompute the BSDF and store it in a look-up table.

Similarly, many common functions do not have closed-form expressions. For instance, this is the case for the error function *erf*(): it has to be approximated to be computed `http://www.johndcook.com/blog/cpp_erf/`.
But this does not mean that *erf*() is not a function.

Frequently Asked Questions

Comparison to Jakob et al.'s Layered Materials Framework (1)

Q: How does your model compare to Jakob's layered materials? They also have a multiple-scattering term.

A: As explained, they don't have a multiple-scattering <u>model</u>. They have <u>something</u> that fixes energy conservation in BSDFs that they call "multiple scattering", but it is not the result of modeling multiple scattering on a given microsurface.

For instance, they assume that what they call "multiple scattering" is diffuse-like. But we have seen in the simulated data that actual multiple scattering is not diffuse-like. It is, on the contrary, very directional.

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

Frequently Asked Questions

Comparison to Jakob et al.'s Layered Materials Framework (2)

Q: OK, but they don't use stochastic evaluation, so their technique is more practical.

A1: They don't use stochastic evaluation because they precompute and store the BSDF (their "multiple scattering" term has no closed-form expression either). Obviously, we can also precompute and store our BSDF (possibly with their Fourier series representation) and get rid of the stochastic evaluation.

A2: However, in practice, their representation prevents the use of spatially varying material properties like textured albedos, Fresnel, roughness and anisotropy. Especially, precomputing and storing every configuration with anisotropic materials requires high-dimensional tables and is not practical. In contrast, our technique does not use any precomputed data at all, whatever the material properties are. Choosing the stochastic evaluation or the precomputed data is a matter of trade-off.

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

Comparison to Jakob et al.'s Layered Materials Framework (3)

Q: But they also have multiple-scattering between different layers and you don't.

A1: Jakob's multi-layer framework is not really a concurrent work. They solve different problems: compact representation and scattering between different layers. In contrast, we propose a deep study of scattering inside one layer.

A2: We can actually use our model to improve Jakob et al.'s framework: we can replace their precomputed diffuse-like "multiple scattering" with our Smith multiple scattering, which we can also precompute and store with their Fourier series representation.
If we do that, we get the best of both works: accurate scattering in one layer (ours) and scattering between different layers (theirs).

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

Frequently Asked Questions

Comparison to real-world Measured BSDFs

Q: Why did you not compare your model to real-world measured BSDFs?

A1: We do not have access to such data, especially with separated scattering orders.

A2: Comparing to simulated data is a safer way to validate the model. The Beckmann surface instances that we generate have known roughness values and base material. We use them to parameterize our model and there is no degree of freedom left. Furthermore, we avoid all of the inconvenience of measured data (noise, lack of grazing angles, etc.). This is an established and robust way to validate a theoretical model and most physics papers do that.
For example: `http://christophebourlier.perso.sfr.fr/topics.htm`

A3: It only makes sense to compare to real-world data once the model is validated against the simulations, not before. This is out of the scope of this paper.

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In computer graphics, people tend to validate their models only against real-world materials for which the material properties (roughness, base material) are generally unknown. Hence, they explore the parameter space of the model and keep the best fit to validate the model.

So, the more parameters a model has, the more degrees of freedom can be adjusted and the better the model will fit measured data. But it does not mean that the model provides a good explanation regarding the actual physics of the material. What are we really testing in this case? The model or the fit? The more degrees of freedom, the more the validation and the predictive power of the model weaken.

Hence, it is very important to test models with as few degrees of freedom as possible. Comparison to simulated data—where the roughness and the base material are known (i.e. 0 degree of freedom left)—is a very robust way to test and validate a model.

Frequently Asked Questions

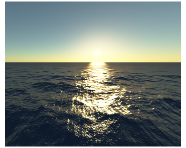
Usage with Artificial Data

Q: Does it mean that the model might be accurate with artificial data, like noise?

A1: Indeed, many noise primitives create Gaussian heightfields that are equivalent to the surface instances we used to validate the model. Our model can thus be used in multi-scale procedural frameworks with transitions from geometry to BSDF where multiple-scattering is incorporated consistently across the scales.

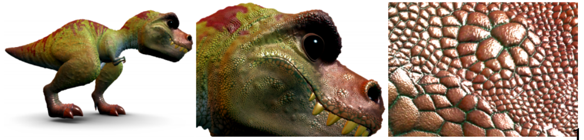
A2: Since our model is parametric and supports anisotropy, it is also 100% compatible with explicit multi-scale representations such as LEAN/LEADR mapping.

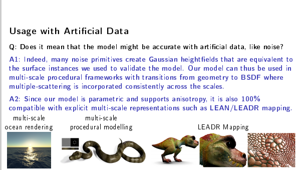
multi-scale
ocean rendering



multi-scale
procedural modelling

LEADR Mapping





The images ae respectively from

Real-time Realistic Ocean Lighting, Bruneton et al. 2010

Local random-phase noise for procedural texturing , Gilet et al. 2014

Linear Efficient Antialiased Displacement and Reflectance Mapping, Dupuy et al. 2013

Thank you for your attention :-)

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