Microfacet Model and Material Appearance

19.05.14

Student Presentation

20193163 Hakyeong Kim

Review

- Light Transport for Participating Media (Joowon Lim)
  - Point based light global illumination
  - Higher-Dimensional photon samples for volumetric light transport

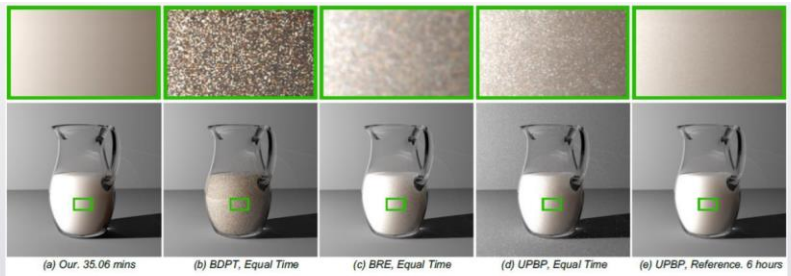
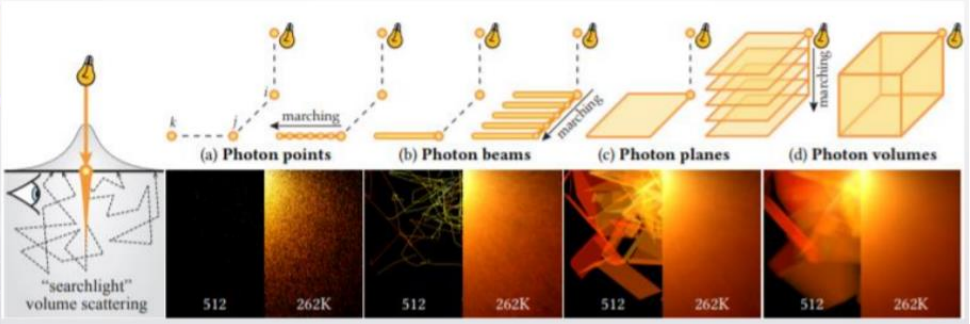


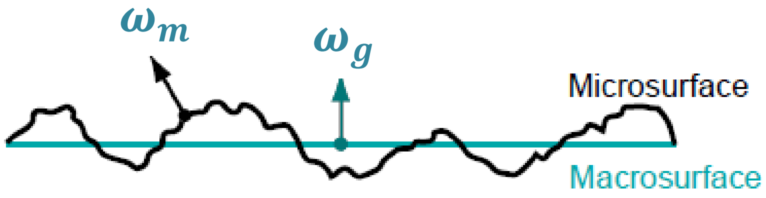
Figure 9: *Material: milk,* $\alpha = \{0.9999, 0.9997, 0.9991\}$, $\ell = \{0.8422, 0.7521, 0.6848\}$. *For this material, with a very large albedo and a small mean free path, multiple scattering effects dominate.*



Microfacet theory

Surface light transport framework

- Assumption: Surface is made up of tiny flat microfacets
- Surface normal $\boldsymbol{\omega_g}$ is average of microfacet normals $\boldsymbol{\omega_m}$



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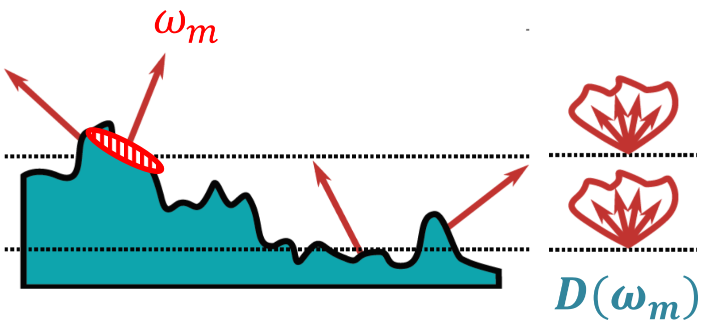
Microfacet theory

Surface light transport framework

- Assumption: Surface is made up of tiny flat microfacets
- Surface normal $\boldsymbol{\omega_g}$ is average of microfacet normals $\boldsymbol{\omega_m}$
- Described by normal distribution function NDF $\boldsymbol{D(\omega_m)}$



Microfacet theory

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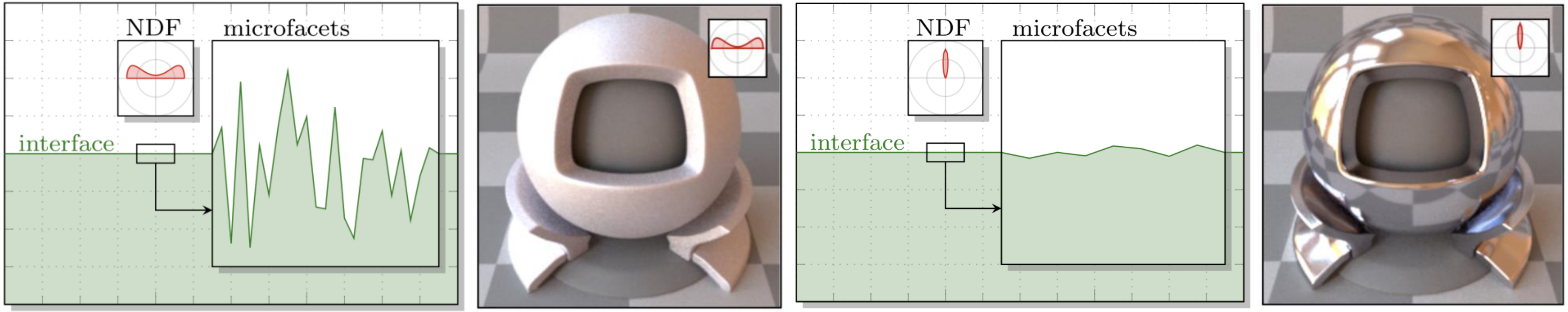
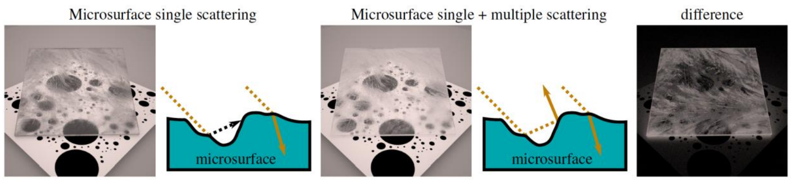


Papers

[1] **Multiple Scattering Microfacet BSDFs with the Smith Model**

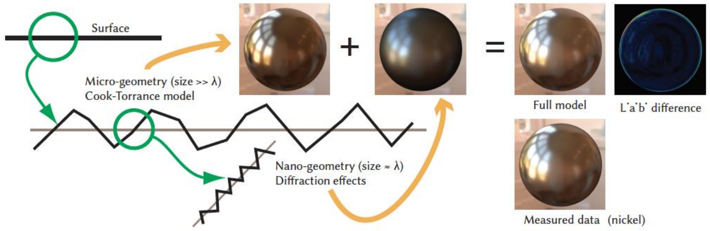
Eric Heitz, Johannes Hanika, Eugene d'Eon

SIGGRAPH 2016



[2] **A Two-Scale Microfacet Reflectance Model Combining Reflection and Diffraction**

Nicolas Holzschuch, Romain Pacanowski, SIGGRAPH 2017



Papers

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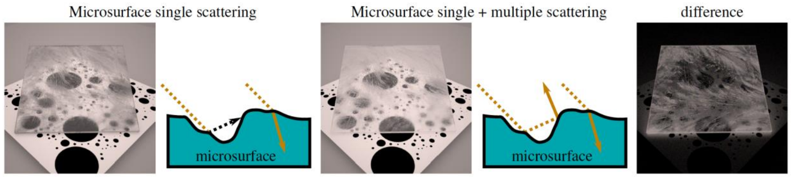

Microfacet model
- **The Smith Model**
- Cook-Torrance Model

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Volumetric Scattering
Microflake theory

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Single-Scattering BSDF/
Unphysical Multiple-Scattering

Multiple-Scattering BSDF

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Papers

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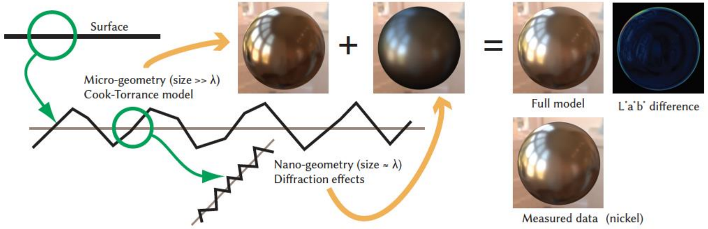
[2] A Two-Scale Microfacet Reflectance Model Combining Reflection and Diffraction

Nicolas Holzschuch, Romain Pacanowski, SIGGRAPH 2017



Microfacet model
- The Smith Model
- **Cook-Torrance Model**

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Diffraction model
Harvey-Shack Theory

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New Reflectance model that both considers Reflection and Diffraction

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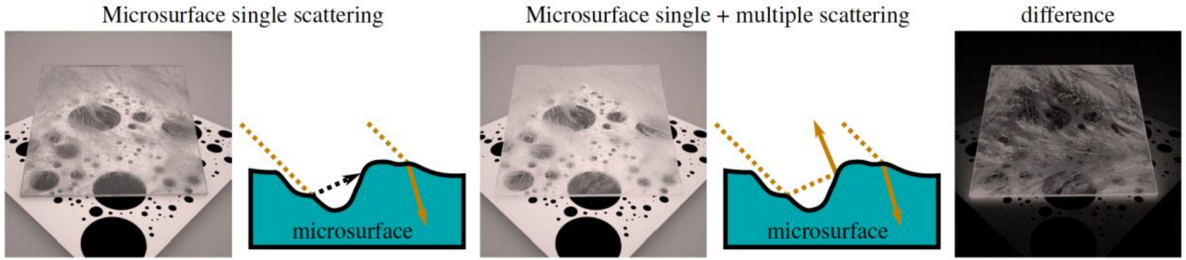

SIGGRAPH 2016

MULTIPLE SCATTERING MICROFACET BSDFS WITH THE SMITH MODEL

ERIC HEITZ, JOHANNES HANIKA, EUGENE D'EON

Overview

1. Background

- Smith Model
- Microflake Theory

2. Model

- Define medium
- Track intersection (Extinction coefficient & free-path distribution)
- Track light scatter (Phase function)
- Simulate random walk
- Define multiple-scattering BSDF (Expectation of random walk)

3. Evaluation

Smith Model

Statistical model of random microsurface described by

Distributions of Heights and Distributions of Normals

1

Main Assumption : $P^1(h)$ and $D(\omega_m)$ is independent

$\Longrightarrow$ Final reflectance is independent of height distribution

$\boldsymbol{P^1(h)}$: Uniform, Gaussain

$\boldsymbol{D(\omega_m)}$: Anisotropic Beckmann distribution, GGX distribution

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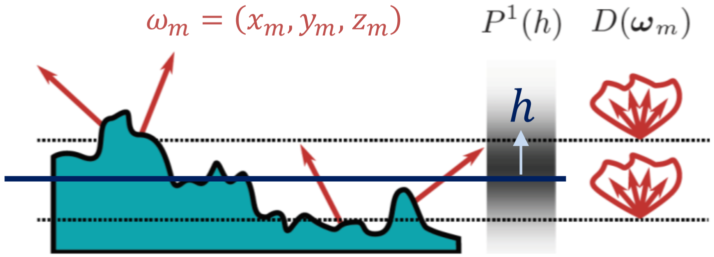

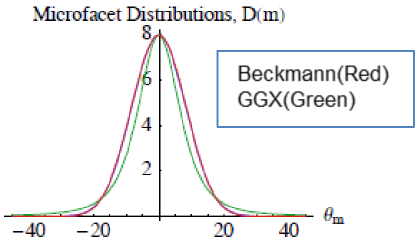

Smith Model

Classic Single-Scattering BSDF

(Bidirectional Scattering Distribution Function)

$$f(\omega_i,\omega_o)=\int_\Omega f_m(\omega_i,\omega_m,\omega_o)\langle\omega_o,\omega_m\rangle\frac{G_2(\omega_i,\omega_m,\omega_o)}{G_1(\omega_i,\omega_m)}D_{\omega_i}(\omega_m)d\omega_m$$

Smith Model

Classic Single-Scattering BSDF

(Bidirectional Scattering Distribution Function)

1 •

$$f(\omega_i,\omega_o)=\int_\Omega \boxed{f_m(\omega_i,\omega_m,\omega_o)}\langle\omega_o,\omega_m\rangle \frac{G_2(\omega_i,\omega_m,\omega_o)}{G_1(\omega_i,\omega_m)} D_{\omega_i}(\omega_m)d\omega_m$$

Micro-BRDF

2

f_m **of each materials :**

	BRDF(Reflection)		BTDF(Transmission)
• Rough dielectric	$\frac{F(\omega_i,\omega_{h_r})\,\delta_{\omega_{h_r}}(\omega_m)}{4\,\lvert\omega_i\cdot\omega_{h_r}\rvert}$	+	$\frac{\eta_o^2\,(1-F(\omega_i,\omega_{h_t}))\,\delta_{\omega_{h_r}}(\omega_m)}{(\eta_i(\omega_i\cdot\omega_{h_t})+\eta_o(\omega_o\cdot\omega_{h_t}))^2}$
• Rough conductor	f_r^{diel}	+	0
• Rough diffuse	$\frac{a}{\pi}\langle\omega_o,\omega_m\rangle$		

3

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Smith Model

Classic Single-Scattering BSDF

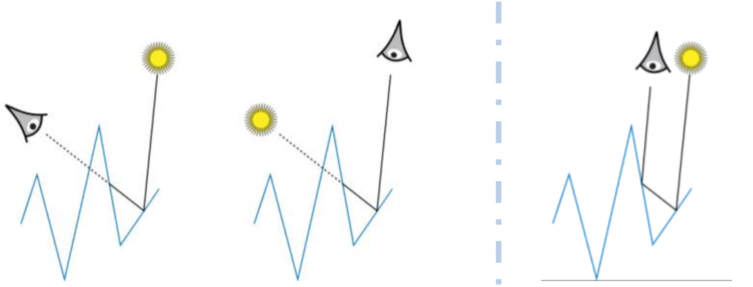
(Bidirectional Scattering Distribution Function)

Visible Normal Distribution

$$f(\omega_i,\omega_o)=\int_\Omega f_m(\omega_i,\omega_m,\omega_o)\langle\omega_o,\omega_m\rangle \boxed{\frac{G_2(\omega_i,\omega_m,\omega_o)}{G_1(\omega_i,\omega_m)}}\boxed{D_{\omega_i}(\omega_m)}\,d\omega_m$$

Masking-shadowing function

Masking-shadowing function



Masking function Visibility to viewer

Shadowing function Visibility to light

Multiple Scattering

Only allows single scattering

Visible Normal Distribution

$$D_{\omega_i}(\omega_m)=\frac{G_1^{dist}(\omega_i)\langle\omega_i,\omega_m\rangle D(\omega_m)}{\cos\theta_i}$$

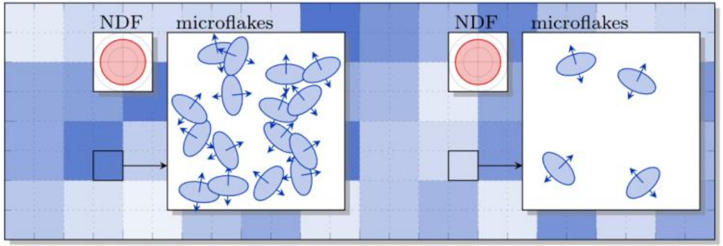
$$\boxed{\cos\theta_i=\int_\Omega G_1(\omega_i,\omega_m)\langle\omega_i,\omega_m\rangle D(\omega_m)\,d\omega_m}$$

Smith-like masking function ➔ Microflake theory

Microflake theory

[Jakob et al. 2010]

- Framework that describes volumetric scattering
- Use oriented non-spherical particals defined by **distribution of normals**



Microflake theory

Light Transport in Volume : Anisotropic Radiative Transfer Equation

1

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Directional derivative of radiance

$$\boxed{(\omega_i \cdot \nabla) L(\omega_i)} = -\sigma_t(\omega_i) L(\omega_i) + \sigma_s(\omega_i) \int_\Omega f_p(\omega_i \to \omega_o) L(\omega_o) d\omega_o + Q(\omega_i)$$

2

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Microflake theory

Light Transport in Volume : Anisotropic Radiative Transfer Equation

1
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Directional derivative of radiance

$$\boxed{(\omega_i \cdot \nabla) L(\omega_i)} = \boxed{-\sigma_t(\omega_i)} L(\omega_i) + \boxed{\sigma_s(\omega_i)} \int_\Omega f_p(\omega_i \to \omega_o) L(\omega_o) d\omega_o + Q(\omega_i)$$

Attenuation coefficient

Scattering coefficient

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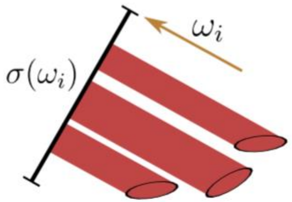
projected area $\sigma(\boldsymbol{\omega}_i)$



$$\sigma_t(\omega_i) = \boxed{\rho\sigma}(\omega_i)$$

$$\sigma_s(\omega_i) = \alpha\boxed{\rho\sigma}(\omega_i)$$

ρ : volume density

α : direction independent albedo

σ : microflake projected area

$$\sigma(\omega_i) = \int_\Omega \langle \omega_i, \omega_m \rangle D(\omega_m) d\omega_m$$

VISUAL COMPUTING Lab

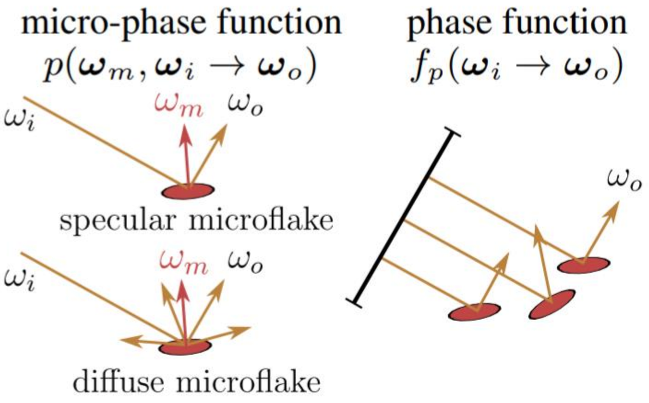
Microflake theory

Light Transport in Volume : Anisotropic Radiative Transfer Equation

Directional derivative of radiance

$$\boxed{(\omega_i \cdot \nabla) L(\omega_i)} = -\sigma_t(\omega_i) L(\omega_i) + \sigma_s(\omega_i) \int_\Omega \boxed{f_p(\omega_i \to \omega_o)} L(\omega_o) d\omega_o + Q(\omega_i)$$

Phase Function



$$f_p(\omega_i \to \omega_o)$$

$$= \frac{1}{\sigma(\omega_i)} \int_\Omega p(\omega_m, \omega_i \to \omega_o) \langle \omega_i, \omega_m \rangle D(\omega_m) d\omega_m$$

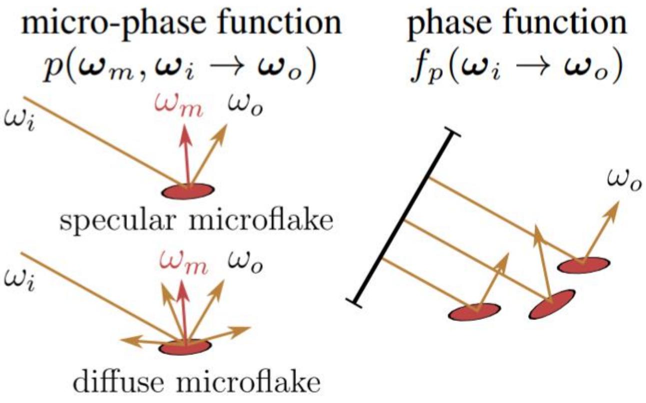
Microflake theory

Light Transport in Volume : Anisotropic Radiative Transfer Equation

Directional derivative of radiance

$$\boxed{(\omega_i \cdot \nabla) L(\omega_i)} = -\sigma_t(\omega_i) L(\omega_i) + \sigma_s(\omega_i) \int_\Omega \boxed{f_p(\omega_i \rightarrow \omega_o)} L(\omega_o) d\omega_o + Q(\omega_i)$$

Phase Function



$$f_p(\omega_i \rightarrow \omega_o) = \frac{1}{\sigma(\omega_i)} \int_\Omega p(\omega_m, \omega_i \rightarrow \omega_o) \boxed{\langle \omega_i, \omega_m \rangle D(\omega_m)} d\omega_m$$

“Smith-like” masking function

Recall Smith model

$$\boxed{\cos\theta_i = \int_\Omega G_1(\omega_i, \omega_m) \langle \omega_i, \omega_m \rangle D(\omega_m) d\omega_m}$$

Without shadowing function → Multiple Scattering

Multiple Scattering BSDF Model

1) Build medium

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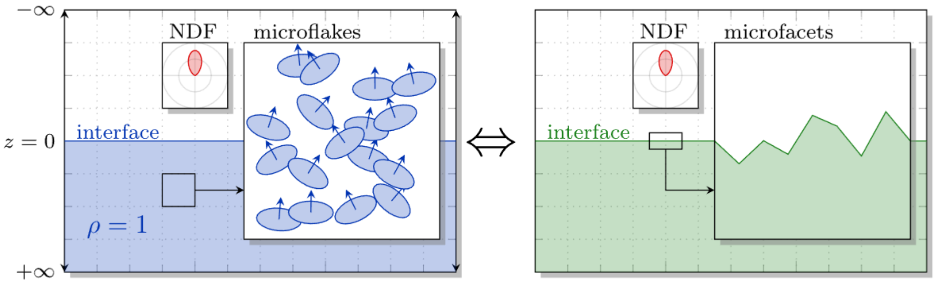
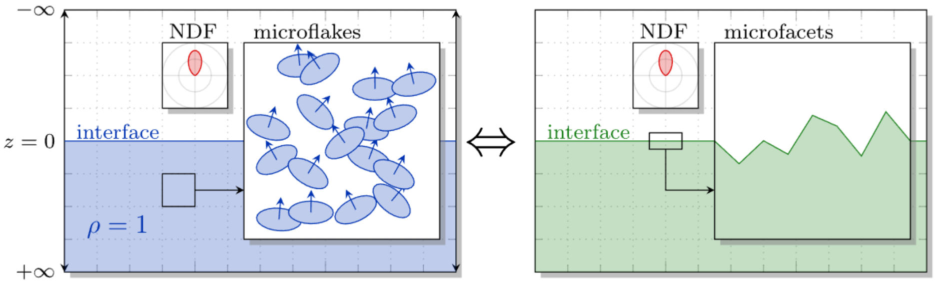


Multiple Scattering BSDF Model

1) Build medium



Volume density

$$\rho^{Smith}(h') = P^1(h' \mid h' \le h) = \frac{\chi^+(h' \le h)\, P^1(h')}{C^1(h)} \quad \Rightarrow \quad \rho^{Smith}(h) = \frac{P^1(h)}{C^1(h)}$$

Projected area

$$\sigma^{microflake}(\omega_r) = \int_\Omega \langle -\omega_r, \omega_m \rangle D(\omega_m)\, d\omega_m \quad \Rightarrow \quad \sigma^{Smith}(\omega_r) = \int_\Omega \langle -\omega_r, \omega_m \rangle D(\omega_m)\, d\omega_m = \Lambda(\omega_r) \cos\theta_r$$

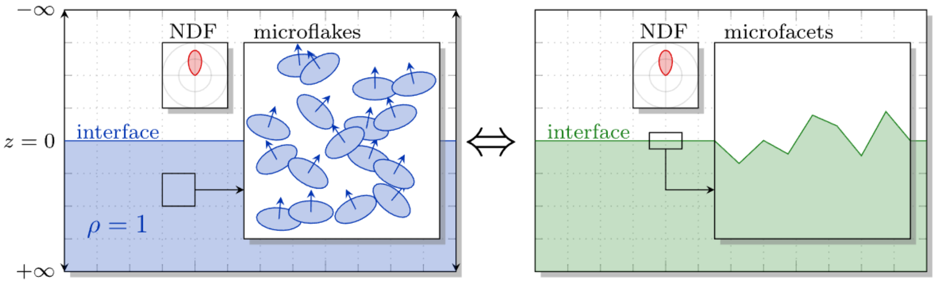
Extinction coefficient

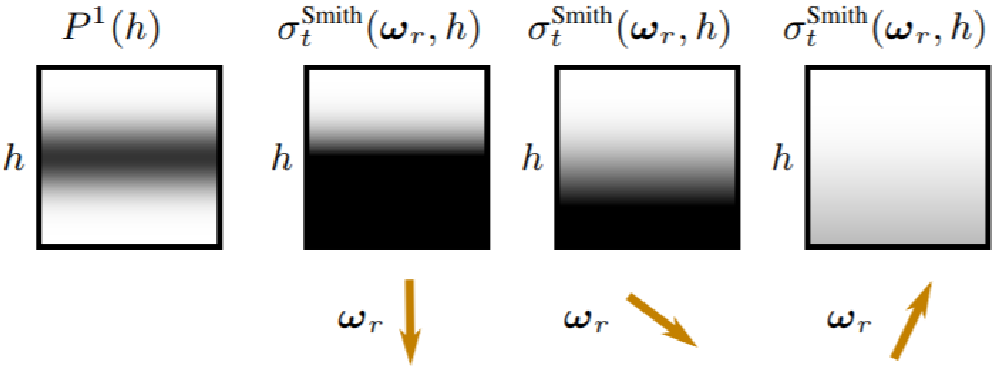
$$\sigma_t^{microflake}(\omega_r) = \rho^{microflake} \sigma^{microflake}(\omega_r) \quad \Rightarrow \quad \sigma_t^{Smith}(\omega_r) = \rho^{Smith} \sigma^{Smith}(\omega_r)$$

1) Build medium

1

2





3

Multiple Scattering BSDF

2) Track intersection

1

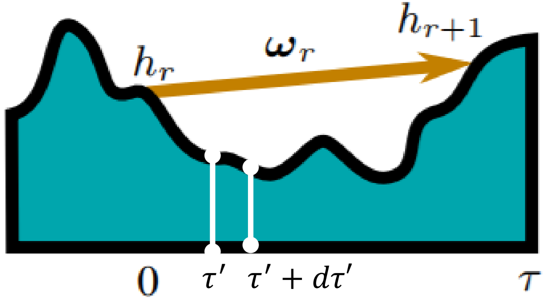
- **Microsurface intersection Probability**

$G_1^{dist}(\omega_r, h_r, \tau)$ Probability that there is no intersection in $[0, \tau]$

2

$$= \exp\left(-\int_0^{\tau} \sigma_t^{Smith}(\omega_r, h_r + \tau' \cot\theta_r) \left\| \frac{\partial d}{\partial \tau} \right\| d\tau' \right)$$

$$= \left(\frac{C^1(h)}{C^1(h_r + \tau' \cot\theta_r)} \right)^{\Lambda(\omega_r)} = \left(\frac{C^1(h)}{C^1(h_{r+1})} \right)^{\Lambda(\omega_r)}$$



- **Free-Path Distribution**

3

$$C^1_{h_r,\omega_r}(h_{r+1}) = \begin{cases} 0 & \text{if } \tau < 0 \\ 1 - G_1^{dist}(\omega_r, h_r, \tau) & \text{if } 0 \le \tau < \infty \\ 1 & \text{if } \tau = \infty \end{cases}$$

Multiple Scattering BSDF

2) Track intersection

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- **Free Path Sampling**

Algorithm 1 Sample height $h_{r+1}(\boldsymbol{\omega}_r, h_r, \mathcal{U})$

if $\mathcal{U} \geq 1 - G_1^{\text{dist}}(\boldsymbol{\omega}_r, h_r, \infty)$ **then** ▷ Leave the microsurface
    $h_{r+1} = \infty$
else ▷ Intersect the microsurface
    $h_{r+1} = C^{-1}\left(\frac{C^1(h_r)}{(1-\mathcal{U})^{1/\Lambda(\boldsymbol{\omega}_r)}}\right)$
end if
return h_{r+1}

Multiple Scattering BSDF

3) Track light scatter

1

- **Phase Function** $p(\omega_i,\omega_o)=\int_\Omega f_m(\omega_m,\omega_i,\omega_o)\langle\omega_i,\omega_m\rangle D_{\omega_i}(\omega_m)\,d\omega_m$

2

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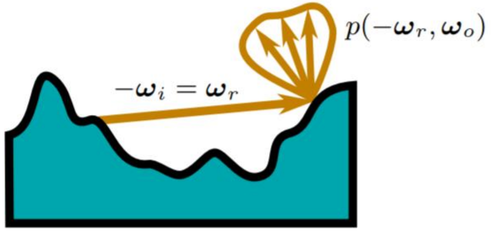
$$D_{\omega_i}(\omega_m)=\frac{\langle\omega_i,\omega_m\rangle D(\omega_m)}{\int_\Omega\langle\omega_i,\omega_m\rangle D(\omega_m)d\omega_m}=\frac{\langle\omega_i,\omega_m\rangle D(\omega_m)}{\sigma^{Smith}(-\omega_i)}$$

Algorithm 2 Sample generic phase function

$\boldsymbol{\omega}_m \leftarrow$ sample $D_{\boldsymbol{\omega}_i}$
$(w,\boldsymbol{\omega}_o) \leftarrow$ sample $f_m(\boldsymbol{\omega}_i,\boldsymbol{\omega}_o,\boldsymbol{\omega}_m)\cos\theta_o$



Multiple Scattering BSDF

4) Simulate random walk

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Algorithm 7 Random Walk

$h_0 \leftarrow \infty$ ▷ initial height
$e_1 \leftarrow 1$ ▷ initial energy
$\boldsymbol{\omega}_1 \leftarrow -\boldsymbol{\omega}_i$ ▷ initial direction
$r \leftarrow 1$ ▷ initial index

while true do
  $h_r \leftarrow$ sample $(h_{r-1}, \boldsymbol{\omega}_r)$ ▷ next height
  if $h_r = \infty$ **then** ▷ leave microsurface?
    break
  end if
  $(\boldsymbol{\omega}_{r+1}, w_{r+1}) \leftarrow$ sample $p(-\boldsymbol{\omega}_r, .)$ ▷ next direction
  $e_{r+1} \leftarrow w_{r+1}\, e_r$ ▷ next energy
  $r \leftarrow r+1$
end while

Track intersection

Algorithm 1 Sample height $h_{r+1}(\boldsymbol{\omega}_r, h_r, \mathcal{U})$

if $\mathcal{U} \geq 1 - G_1^{\text{dist}}(\boldsymbol{\omega}_r, h_r, \infty)$ **then** ▷ Leave the microsurface
  $h_{r+1} = \infty$
else ▷ Intersect the microsurface
  $h_{r+1} = C^{-1}\left(\frac{C^1(h_r)}{(1-\mathcal{U})^{1/\Lambda(\boldsymbol{\omega}_r)}}\right)$
end if
return h_{r+1}

Algorithm 2 Sample generic phase function

$\boldsymbol{\omega}_m \leftarrow$ sample $D_{\boldsymbol{\omega}_i}$
$(w, \boldsymbol{\omega}_o) \leftarrow$ sample $f_m(\boldsymbol{\omega}_i, \boldsymbol{\omega}_o, \boldsymbol{\omega}_m)\ \cos\theta_o$

Track light scatter

sample height h_1

starting from
- height $h_0 = +\infty$
- direction $\boldsymbol{\omega}_1 = -\boldsymbol{\omega}_i$
- energy $e_1 = 1$

sample direction $\boldsymbol{\omega}_2$
and **weight** w_2
with phase function
$p(-\boldsymbol{\omega}_1, .)$

sample height h_2

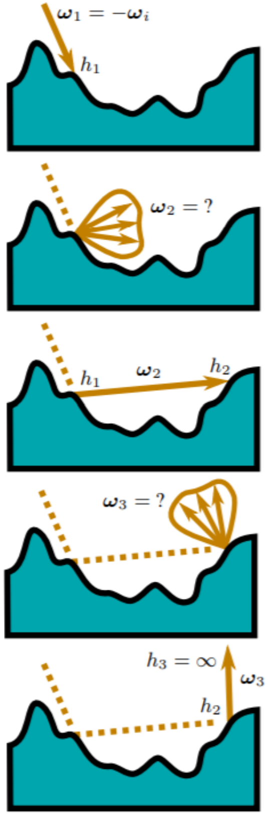
starting from
- height h_1
- direction $\boldsymbol{\omega}_2$
- energy $e_2 = w_2\, e_1$

sample direction $\boldsymbol{\omega}_3$
and **weight** w_3
with phase function
$p(-\boldsymbol{\omega}_2, .)$

sample height h_3

starting from
- height h_2
- direction $\boldsymbol{\omega}_3$
- energy $e_3 = w_3\, e_2$

$h_3 = \infty$, **stop**



Multiple Scattering BSDF

5) Define multiple scattering BSDF

1 ## : Expectation of random walk

Random walk

Sequence of N heights, directions and energy throughput $[(\omega_1, h_1, e_1), \ldots, (\omega_N, h_N, e_N),]$

2 ### Distribution

- Contribution of r^{th} bounce in direction ω_O $$E_r(\omega_o) = e_r\, p\left(-\omega_r, \omega_o\right) G_1^{dist}(\omega_o, h_r)$$
- Total scattered energy by random walk $$E_{1,\ldots,N}(\omega_o) = \sum_{r=1}^{N} E_r(\omega_o)$$
- Mutiple Scattering BRDF $$f(\omega_i, \omega_o)\cos\theta_o = \mathrm{E}\left[E_{1,\ldots,N}(\omega_o)\right]$$

3 $$= \mathrm{E}\left[\sum_{r=1}^{N} e_r\, p\left(-\omega_r, \omega_o\right) G_1^{dist}(\omega_o, h_r)\right]$$

Multiple Scattering BSDF

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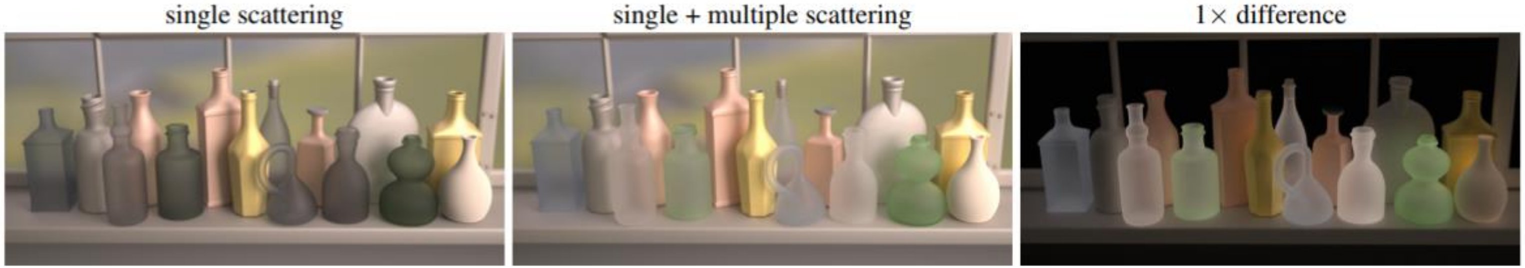
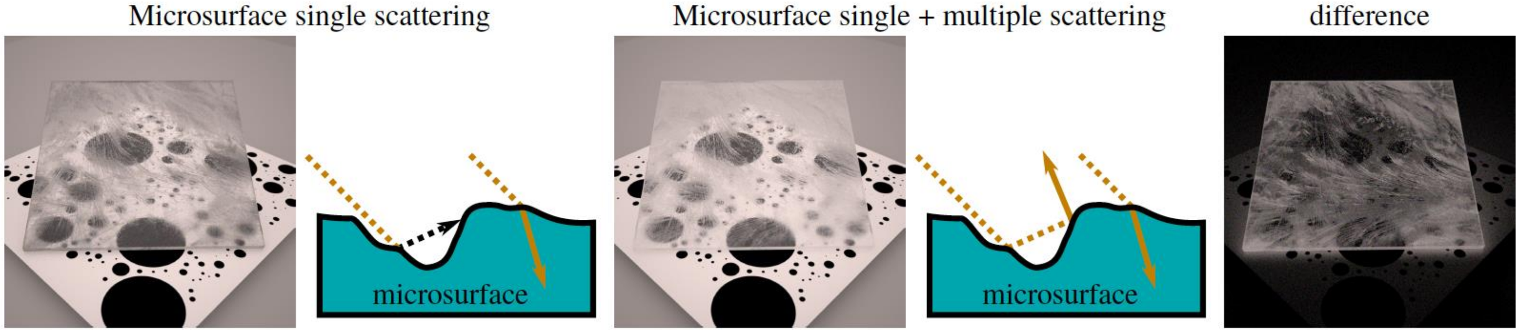
Result

- Practical rendering





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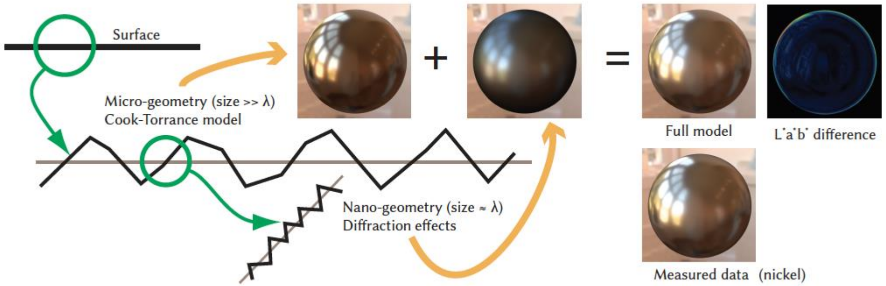


SIGGRAPH 2017

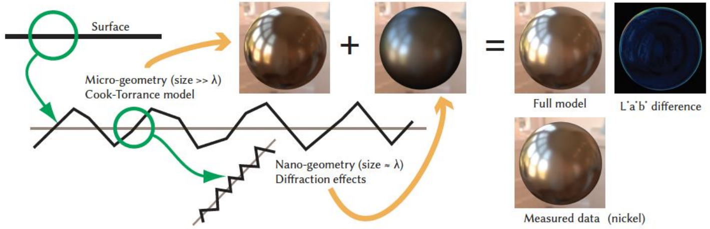
A TWO-SCALE MICROFACET REFLECTANCE MODEL COMBINING REFLECTION AND DIFFRACTION

NICOLAS HOLZSCHUCH, ROMAIN PACANOWSKI

Papers

[2] A Two-Scale Microfacet Reflectance Model Combining Reflection and Diffraction

Nicolas Holzschuch, Romain Pacanowski, SIGGRAPH 2017



Microfacet model
- The Smith Model
- **Cook-Torrance Model**

+

Diffraction model
Harvey-Shack Theory

=

New Reflectance model that both considers Reflection and Diffraction

Overview

1. Background

- Cook-Torrance Model
- Modified Harvey-Shack Theory

2. Model

- Two-scale BRDF model
- NDF

3. Evaluation

Cook-Torrance Model

Main Assumption:

1. Microfacet is larger than light wavelength → Geometric optic applies
2. Each microfacet act as specular mirror

1

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$$\rho_{\mu F}(i,o) = F(i,o)\frac{\delta(refl(i),o)}{\cos\theta_o}$$

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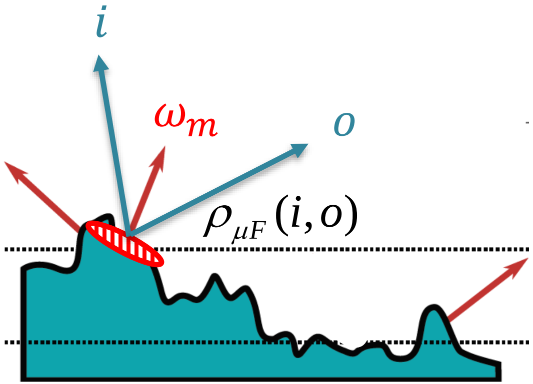

Cook-Torrance Model

Main Assumption:

1. Microfacet is larger than light wavelength → Geometric optic applies
2. Each microfacet act as specular mirror

1

$$\rho_{\mu F}(i,o) = F(i,o)\frac{\delta(refl(i),o)}{\cos\theta_o} \quad \Rightarrow \quad \rho_{Cook-Torrance}(\omega_i,\omega_o) = \frac{DFG}{4\cos\theta_i\cos\theta_o}$$

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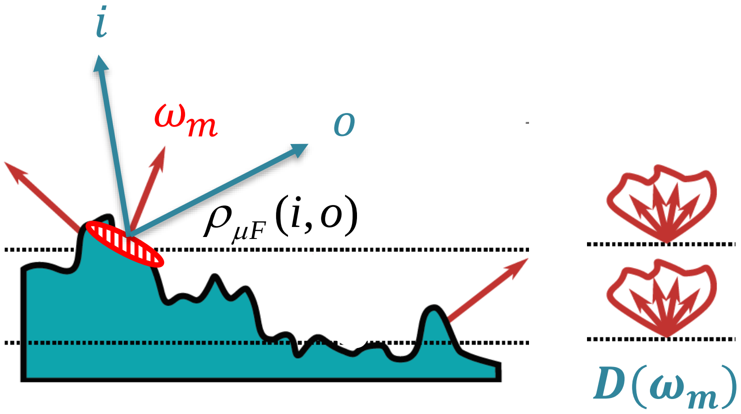

Cook-Torrance Model

Main Assumption:

1. Microfacet is larger than light wavelength → Geometric optic applies
2. Each microfacet act as specular mirror

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$$\rho_{\mu F}(i,o) = F(i,o)\frac{\delta(refl(i),o)}{\cos\theta_o} \quad \Rightarrow \quad \rho_{Cook-Torrance}(\omega_i,\omega_o) = \frac{DFG}{4\cos\theta_i\cos\theta_o}$$

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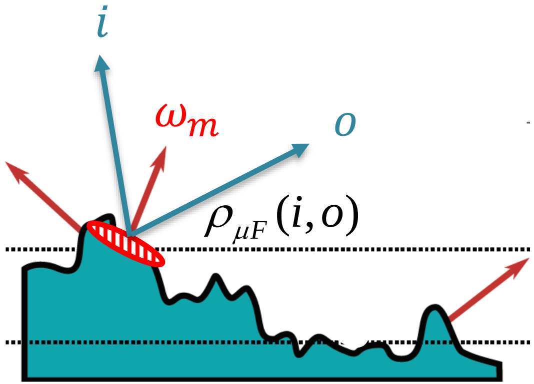
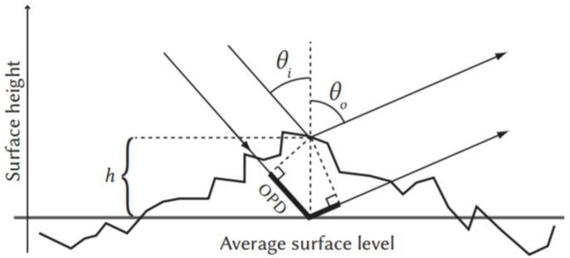


$F(\eta,\theta_d)$: Fresnel term

- Defines material color
- Only wavelength determinant

Harvey-Shack theory

- Based on **optical path length (OPD) difference**
  $OPD = (\cos\theta_i + \cos\theta_o)h(x, y)$
- **Phase difference**: $(2\pi / \lambda)(\cos\theta_i + \cos\theta_o)h(x, y)$



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VISUAL COMPUTING Lab

Harvey-Shack theory

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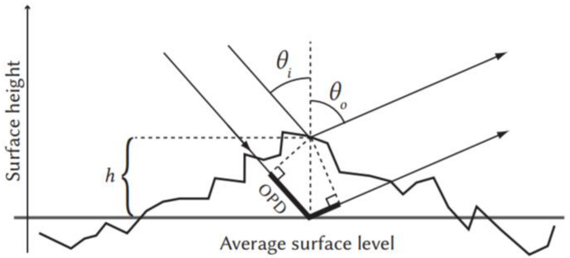
- Based on **optical path length (OPD) difference**
  $OPD = (\cos\theta_i + \cos\theta_o)h(x,y)$
- **Phase difference**: $(2\pi/\lambda)(\cos\theta_i + \cos\theta_o)h(x,y)$



Average

$$\rho_{diff}(\omega_i,\omega_o) = AF(\omega_i,\omega_o)\frac{\delta(refl(\omega_i),\omega_o)}{\cos\theta_o} + (1-A)Q(\omega_i,\omega_o)S_{HS}(f)$$

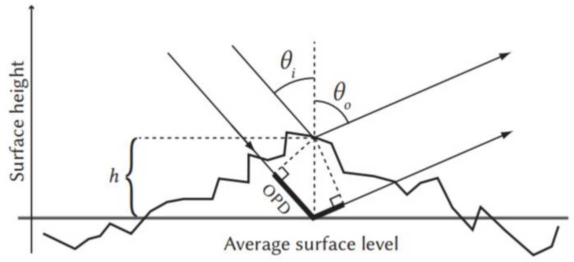
Specular lobe **Scattered lobe**

Harvey-Shack theory

- Based on **optical path length (OPD) difference**

  $OPD = (\cos\theta_i + \cos\theta_o)h(x,y)$

- **Phase difference**: $(2\pi/\lambda)(\cos\theta_i + \cos\theta_o)h(x,y)$



Average

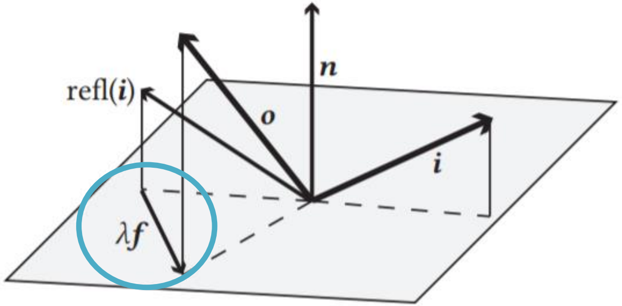
Mirror reflection direction

$$\rho_{diff}(\omega_i,\omega_o) = AF(\omega_i,\omega_o)\frac{\delta(refl(\omega_i),\omega_o)}{\cos\theta_o} + (1-A)Q(\omega_i,\omega_o)S_{HS}(f)$$

$$A = e^{-\left(2\pi\frac{\sigma_s}{\lambda}(\cos\theta_i+\cos\theta_0)\right)^2}$$

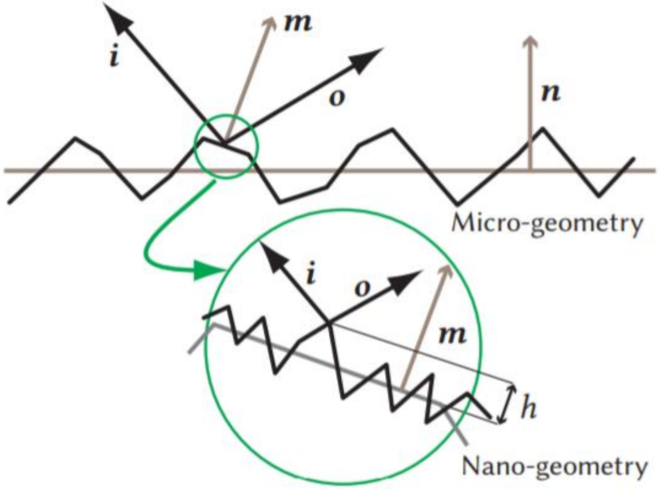
σ_s: Surface roughness

= Variance of height distribution



Two-Scale BRDF model

- **Surface detail**
  - Micro-geometry : larger than light wavelength
  - Nano-geometry : similar to light wavelength



Two-Scale BRDF model

- **Generic BRDF in original microfacet framework**

$$\rho(\omega_i,\omega_o)=\int_\Omega \left|\frac{\omega_i\cdot\omega_m}{\omega_i\cdot\omega_n}\right| f_s(\omega_i,\omega_m,\omega_o)\langle\omega_o,\omega_m\rangle\left|\frac{\omega_o\cdot\omega_m}{\omega_o\cdot\omega_n}\right| G(\omega_i,\omega_o)D(\omega_m)d\omega_m$$

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Two-Scale BRDF model

- **Generic BRDF in original microfacet framework**

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$$\rho(\omega_i,\omega_o)=\int_\Omega \left|\frac{\omega_i\cdot\omega_m}{\omega_i\cdot\omega_n}\right| \boxed{f_s(\omega_i,\omega_m,\omega_o)} \langle\omega_o,\omega_m\rangle \left|\frac{\omega_o\cdot\omega_m}{\omega_o\cdot\omega_n}\right| G(\omega_i,\omega_o)D(\omega_m)d\omega_m$$

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Recall) Cook- Torrance model if **microfacet reflectance** is Dirac,

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$$\rho_{\mu F}(i,o)=F(i,o)\delta(refl(i),o)$$

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Two-Scale BRDF model

- **Generic BRDF in original microfacet framework**

1

$$\rho(\omega_i,\omega_o)=\int_\Omega \left|\frac{\omega_i\cdot\omega_m}{\omega_i\cdot\omega_n}\right| \boxed{f_s(\omega_i,\omega_m,\omega_o)} \langle\omega_o,\omega_m\rangle \left|\frac{\omega_o\cdot\omega_m}{\omega_o\cdot\omega_n}\right| G(\omega_i,\omega_o)D(\omega_m)d\omega_m$$

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Diffraction model

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$$f_s(\omega_i,\omega_o,\omega_m)=AF(\omega_i,\omega_o)\delta(refl(\omega_i),\omega_o)+(1-A)Q(\omega_i,\omega_o)S_{HS}(f)$$

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Two-Scale BRDF model

- **Generic BRDF in original microfacet framework**

1

$$\rho(\omega_i,\omega_o)=\int_\Omega \left|\frac{\omega_i\cdot\omega_m}{\omega_i\cdot\omega_n}\right| \boxed{f_s(\omega_i,\omega_m,\omega_o)} \langle\omega_o,\omega_m\rangle \left|\frac{\omega_o\cdot\omega_m}{\omega_o\cdot\omega_n}\right| G(\omega_i,\omega_o)D(\omega_m)d\omega_m$$

Diffraction model

2

$$f_s(\omega_i,\omega_o,\omega_m)=AF(\omega_i,\omega_o)\delta(refl(\omega_i),\omega_o)+(1-A)Q(\omega_i,\omega_o)S_{HS}(f)$$

3

$$\rho(\omega_i,\omega_o)=A_{spec}(\theta_d)\rho_{Cook-Torrance}+\rho_{Cook-TorranceDiffraction}$$

Standard Cook-Torrance Lobe **Cook Torrance Diffraction Lobe**

Two-Scale BRDF model

- **Generic BRDF in original microfacet framework**

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$$\rho(\omega_i,\omega_o) = \int_\Omega \left|\frac{\omega_i\cdot\omega_m}{\omega_i\cdot\omega_n}\right| \boxed{f_s(\omega_i,\omega_m,\omega_o)} \langle\omega_o,\omega_m\rangle \left|\frac{\omega_o\cdot\omega_m}{\omega_o\cdot\omega_n}\right| G(\omega_i,\omega_o)D(\omega_m)d\omega_m$$

Diffraction model

$$f_s(\omega_i,\omega_o,\omega_m) = AF(\omega_i,\omega_o)\delta(refl(\omega_i),\omega_o) + (1-A)Q(\omega_i,\omega_o)S_{HS}(f)$$

$$\rho(\omega_i,\omega_o) = A_{spec}(\theta_d)\rho_{Cook-Torrance} + \rho_{Cook-TorranceDiffraction}$$

$$= e^{-\left(2\pi\frac{\sigma_{rel}}{\lambda}(\omega_i\cdot\omega_m+\omega_o\cdot\omega_m)\right)^2} \qquad = \frac{DFG}{4\cos\theta_i\cos\theta_o}$$

Approximation

Spherical convolution between $\boldsymbol{D}$ and $\boldsymbol{S_{HS}}$

Two-Scale BRDF model

- **Generic BRDF in original microfacet framework**

$$\rho(\omega_i,\omega_o)=\int_\Omega \left|\frac{\omega_i\cdot\omega_m}{\omega_i\cdot\omega_n}\right| f_s(\omega_i,\omega_m,\omega_o)\langle\omega_o,\omega_m\rangle \left|\frac{\omega_o\cdot\omega_m}{\omega_o\cdot\omega_n}\right| \boxed{G(\omega_i,\omega_o)D(\omega_m)}\, d\omega_m$$

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  - **NDF $D(\omega_m)$: Exponential power distribution**
  - **Shadow function $G(\theta_h)$: $\frac{1}{1+\Lambda(\beta+tan\theta)}$, computed by Smith's method**

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Two-Scale BRDF model

- **Result**
  - **Validation with measured materials(MERL database)**

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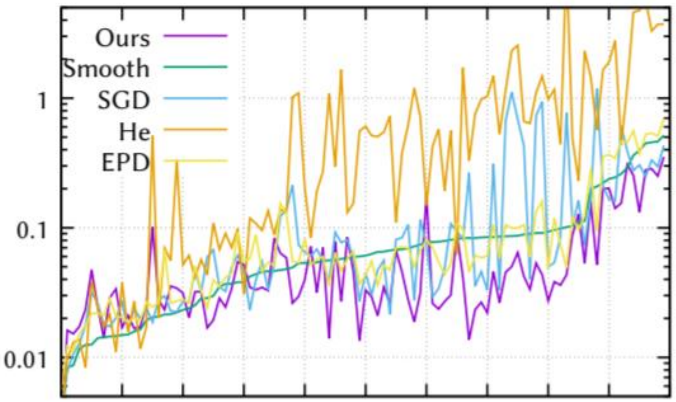

Fig. 11. RMSE on the BRDF for all materials in the MERL database.

Two-Scale BRDF model

- **Result**
  - Validation with measured materials(Good performance)

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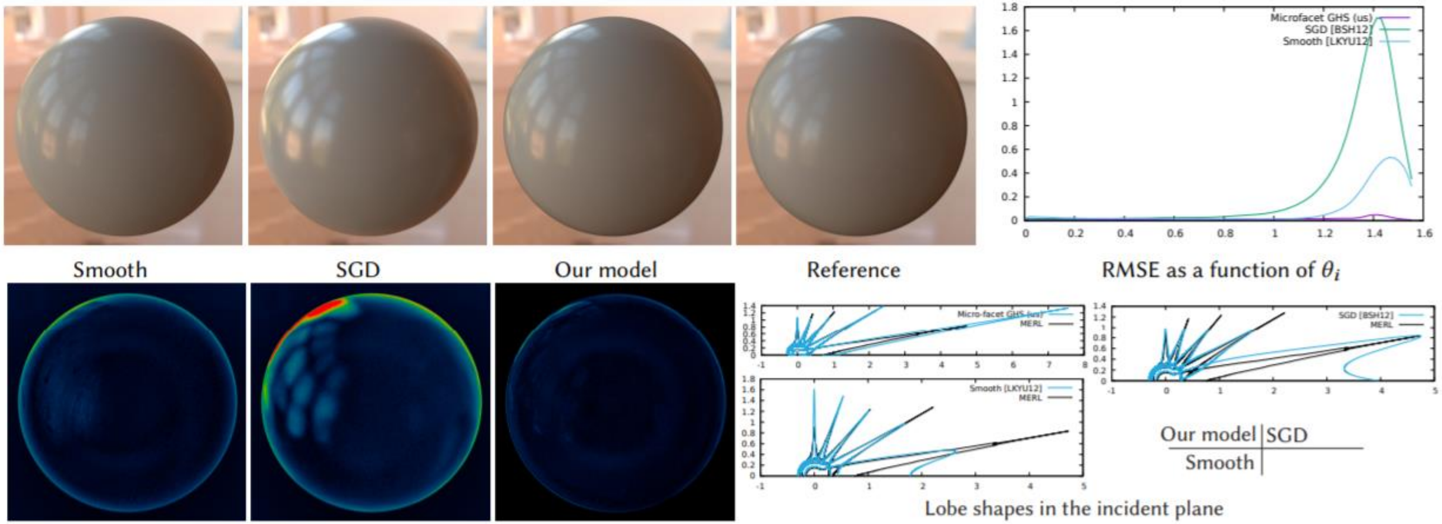

Fig. 12. A material where our model performs well: gray-plastic. Material behaviour predicted by our model is extremely close to measured data. Difference images use the Lab color space.

Two-Scale BRDF model

- **Result**
  - Validation with measured materials (materials with larger RMSE)

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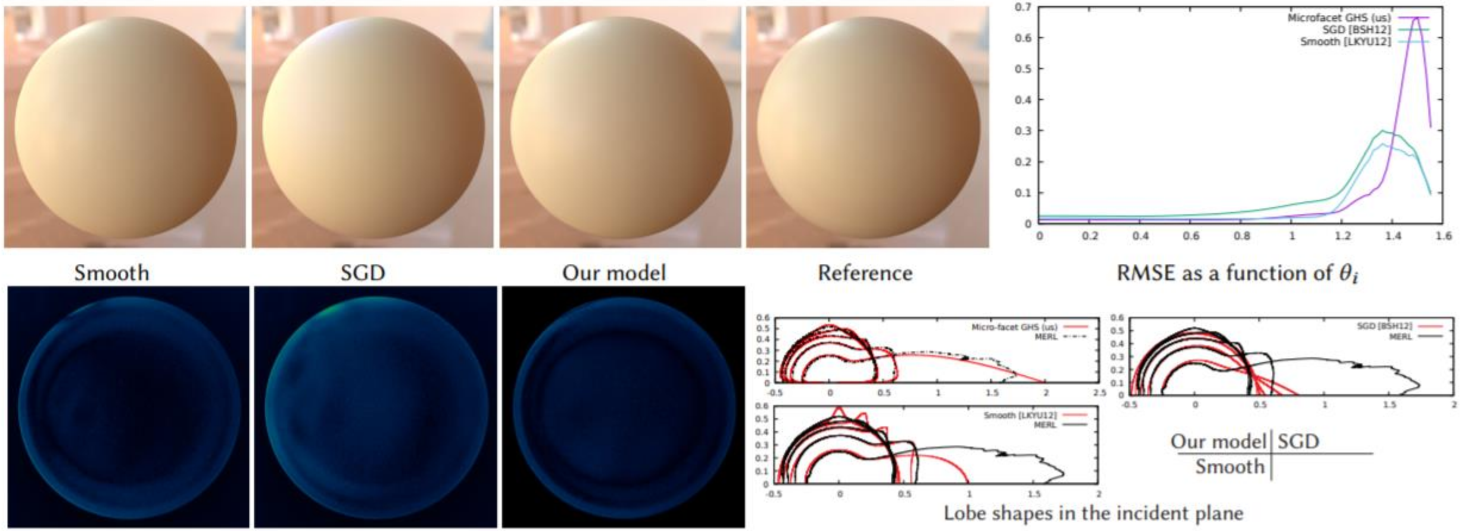


Fig. 13. A material where RMSE for our model is larger than for others: `white-diffuse-bball`. Images and lobe shapes generated by our model are actually closer to the reference, except at grazing angles. Difference images use the Lab color space.

THANK YOU

Quiz

1. What is responsible for material appearance both in classical microfacet and microflake theory?
   ① Height distribution function
   ② Normal distribution function
   ③ Extinction coefficient
   ④ Phase function

2. Which one is not microfacet model?
   ① Smith Model
   ② Cook-Torrance model
   ③ Harvey-Shack model

ADDITIONAL SLIDES

The Smith Model → Single Scattering BSDF

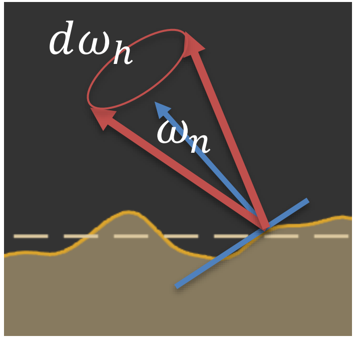
Distribution of heights

Distribution of normals

Smith masking function

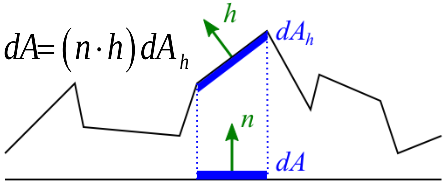
Masking-shadowing function

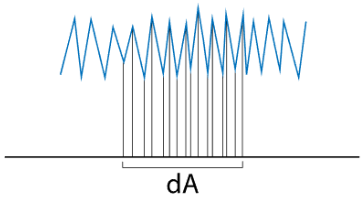
Distribution of visible normals



- Probability that ω_n is in ω_h - X
- $\int_\Omega D(h)(n\cdot h)d\omega_h = 1 \quad dA_h = D(h)d\omega_h A$
- Projected surface area of the microfacets above area is equal to *dA*

$$\frac{1}{A}\int_\Omega (n\cdot h)dA_h = \int_\Omega D(h)(n\cdot h)d\omega_h = 1$$





Microfacet Theory

The Smith Model → Single Scattering BSDF

Distribution of heights

Distribution of normals

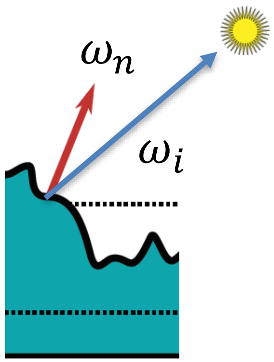
Smith masking function

Masking-shadowing function

Distribution of visible normals

Visibility of a point on microsurface

$$G_1(\omega_i, \omega_m, h) = G_1^{local}(\omega_i, \omega_m) G_1^{dist}(\omega_i, h)$$



VISUAL COMPUTING Lab

The Smith Model → Single Scattering BSDF

Distribution of heights

Distribution of normals

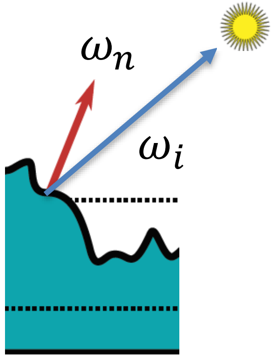
Smith masking function

Masking-shadowing function

Distribution of visible normals

Visibility of a point on microsurface

$$G_1(\omega_i,\omega_m,h) = \underbrace{G_1^{local}(\omega_i,\omega_m)}_{\text{Non-backfacing}} G_1^{dist}(\omega_i,h)$$



$$G_1^{local}(\omega_i,\omega_m) = \chi^+(\omega_i\cdot\omega_m)$$

The Smith Model → Single Scattering BSDF

Distribution of heights

Distribution of normals

Smith masking function

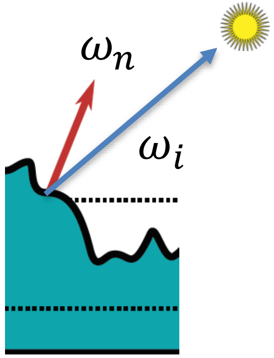
Masking-shadowing function

Distribution of visible normals

Visibility of a point on microsurface

$$G_1(\omega_i, \omega_m, h) = G_1^{local}(\omega_i, \omega_m) \underline{G_1^{dist}(\omega_i, h)}$$

Probability that ray does not intersect microsurface



Smith lambda function

$$G_1^{dist}(\omega_i, h) = C^1(h)^{\Lambda(\omega_i)}$$

CDF of heights

Microfacet Theory

The Smith Model → Single Scattering BSDF

Distribution of heights

Distribution of normals

Smith masking function

Masking-shadowing function

Distribution of visible normals

Masking function averaged over all **heights**

$$\underline{G_1^{dist}(\omega_i)} = \int_{-\infty}^{\infty} G_1^{dist}(\omega_i, h) P^1(h) dh = \frac{1}{1+\Lambda(\omega_i)}$$

$$G_1(\omega_i, \omega_m) = G_1^{local}(\omega_i, \omega_m) \underline{G_1^{dist}(\omega_i)}$$

Microfacet Theory

The Smith Model → Single Scattering BSDF

Distribution of heights

Distribution of normals

Smith masking function

Masking-shadowing function

Distribution of visible normals

$$G_2(\omega_i,\omega_m,\omega_o) = \underbrace{G_1^{local}(\omega_i,\omega_m)G_1^{local}(\omega_o,h)}_{\text{Visible to both ingoing and outgoing direction}}\underbrace{G_2^{dist}(\omega_i,\omega_o)}_{\text{Height-correlated distant masking-shadowing function}}$$

$$G_2^{dist}(\omega_i,\omega_o) = \int_{-\infty}^{\infty} \underline{G_1^{dist}(\omega_i,h)G_1^{dist}(\omega_o,h)}P^1(h)dh$$

$$= \begin{cases} \dfrac{1}{1+\Lambda(\omega_i)+\Lambda(\omega_o)} \\ B(1+\Lambda(\omega_i),1+\Lambda(\omega_o)) \end{cases}$$

The Smith Model → Single Scattering BSDF

Distribution of heights

Distribution of normals

Smith masking function

Masking-shadowing function

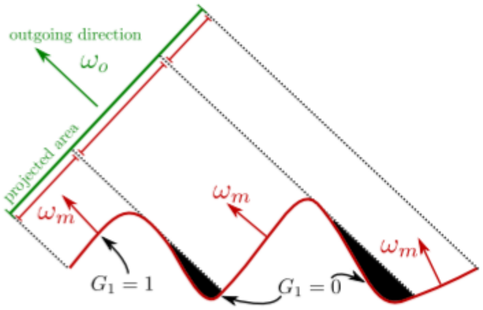
Distribution of visible normals

DVNF of Smith model

$$D_{\omega_i}(\omega_m) = \frac{G_1^{dist}(\omega_i)\langle\omega_i,\omega_m\rangle D(\omega_m)}{\cos\theta_i} = \frac{\langle\omega_i,\omega_m\rangle D(\omega_m)}{\cos\theta_i(1+\Lambda(\omega_i))}$$

Normalization [1]
Visible microsurface
= Projected area of geometric surface

$$\cos\theta_i = \int_\Omega G_1(\omega_i,\omega_m)\langle\omega_i,\omega_m\rangle D(\omega_m)\,d\omega_m$$



[1] Understanding the Masking-Shadowing Function in Microfacet-Based BRDFs, Eric Heitz, 2014

The Smith Model → Single Scattering BSDF

Distribution of heights $P^1(h)$

Distribution of normal $D(\omega_m)$

Smith masking function $G_1(\omega_i, \omega_o)$

Masking-shadowing function $G_2(\omega_i, \omega_o, \omega_m)$

Distribution of visible normals $D_{\omega_i}(\omega_m)$

Single-Scattering BSDF of Generic Rough Materials

$$f(\omega_i, \omega_o) = \int_\Omega \underbrace{f_m(\omega_i, \omega_m, \omega_o)}_{\text{Micro-BRDF}} \langle \omega_o, \omega_m \rangle \frac{G_2(\omega_i, \omega_m, \omega_o)}{G_1(\omega_i, \omega_m)} D_{\omega_i}(\omega_m) d\omega_m$$

Given visible for ω_i, visible for ω_o

Derivable: Rough dielectric, rough conductor, rough diffuse