MFF UK
Prague

Surface Reflectance Models

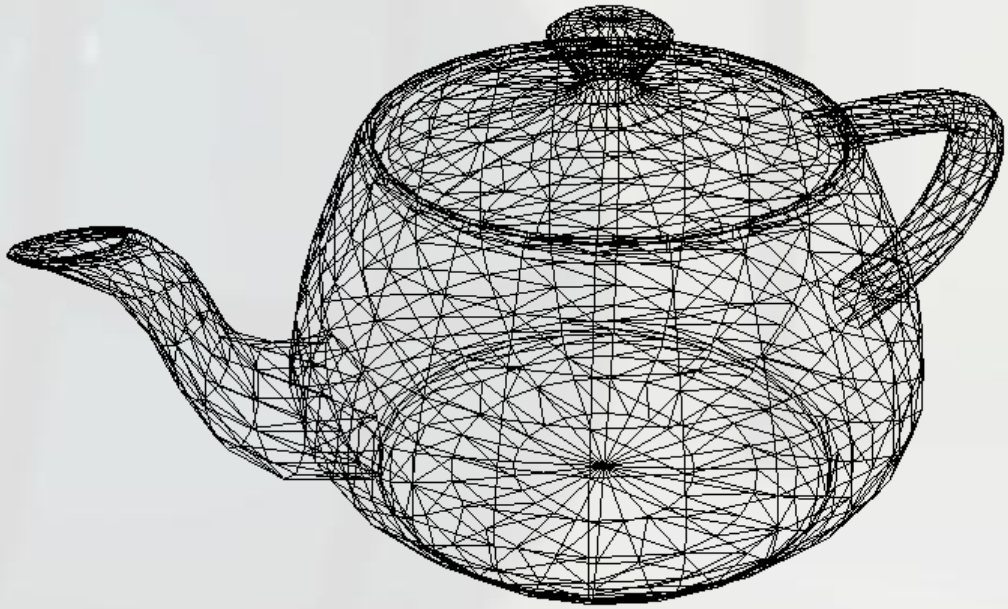
Oskar Elek, MFF UK

Motivation

- Object appearance modeling...

Motivation

- Object appearance:
  - Object geometry



Motivation

- Object appearance:
  - Object material (‘shading’)

Motivation

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- Object appearance:
  - Global illumination

Motivation

- Object appearance:
  - **Object material ('shading')**

Outline

- Introduction
- BRDF
  - Types
  - Properties
  - Sampling
  - Perspectives
- Sample BRDF
- Layered microfacet model
  - Introduction
  - Assumptions
  - Description
  - Details
  - Examples

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Introduction

- Object material modeling...

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  - Colour

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  - Colour
  - Environment reflection (present?, sharp/blurry?, ...)

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  - Specular highlight (present?, small/large?, colour?, ...)

Introduction

- Object material modeling
  - Colour
  - Environment reflection (present?, sharp/blurry?, ...)
  - Specular highlight (present?, small/large?, colour?, ...)
  - Visible surface features

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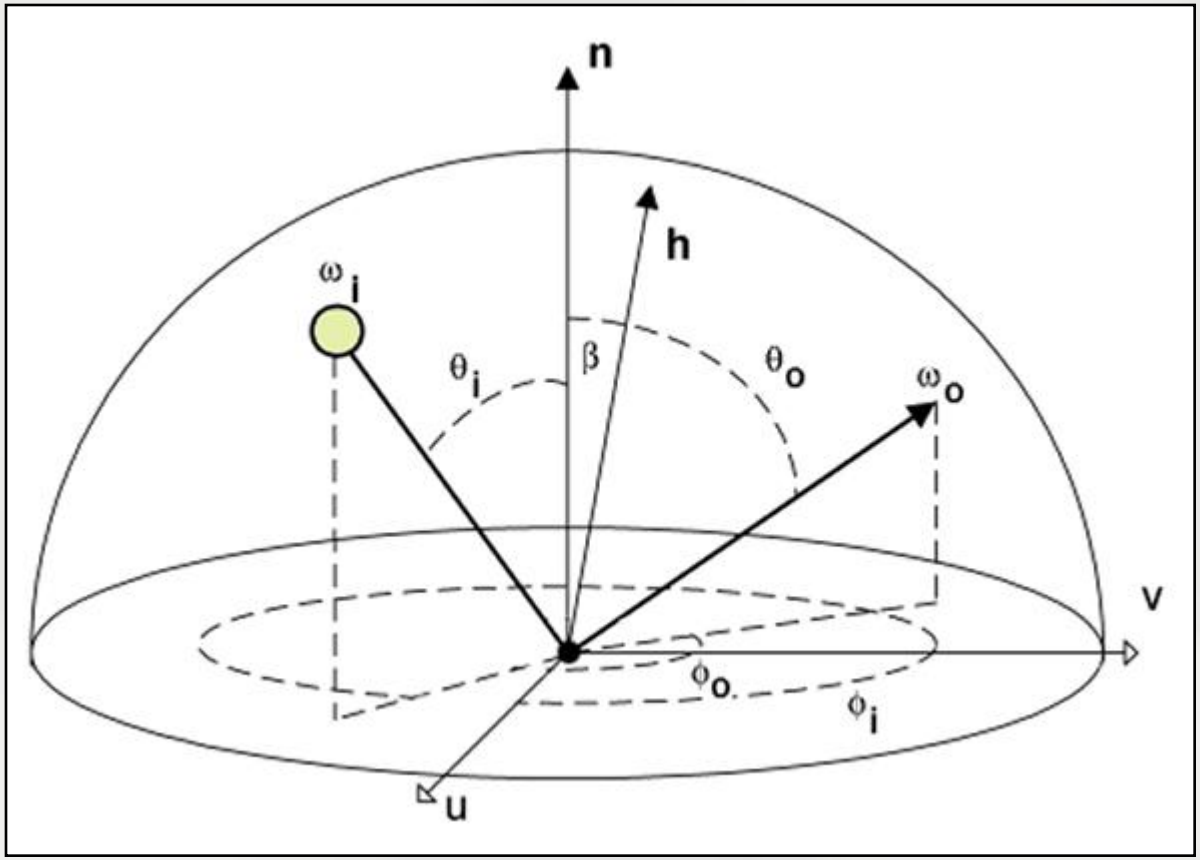
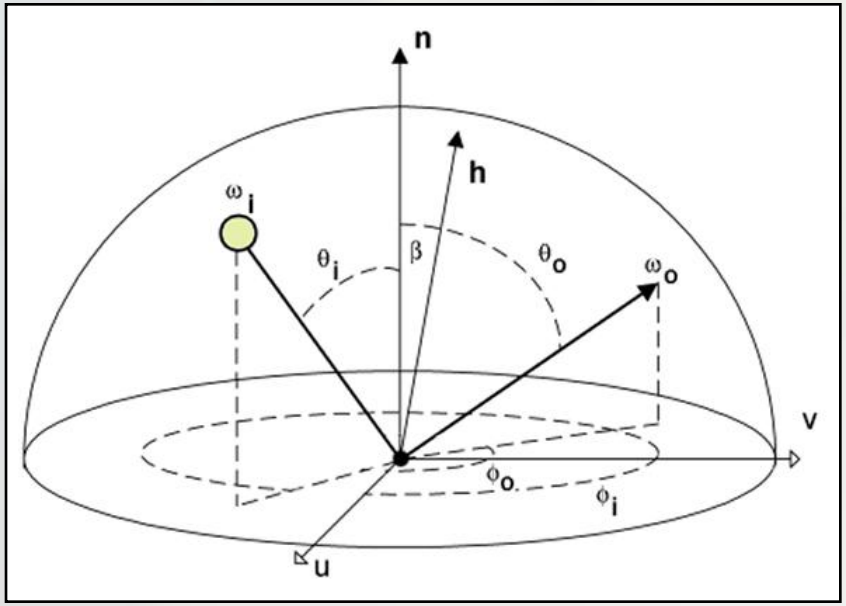
- Bidirectional Reflectance Distribution Function



BRDF

$$f_r(\Theta_i, \Theta_r, x, y, \lambda) = \frac{d^2 L_r(\Theta_r, x, y, \lambda)}{L_i(\Theta_i, x, y, \lambda)\cos\theta_i dA d\omega_i}$$

- Incident/reflected vectors
- Surface position
- Wavelength
- Incident radiance
- Reflected radiance



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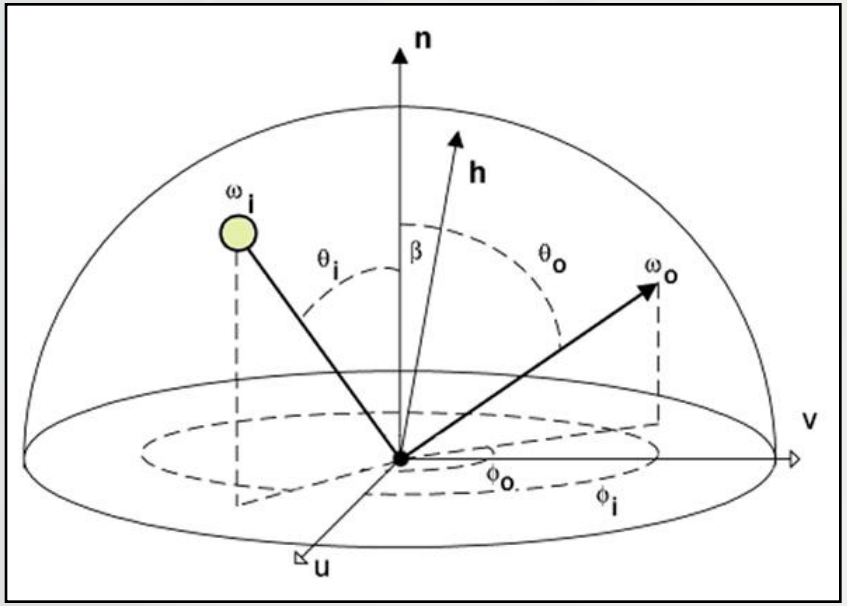

BRDF

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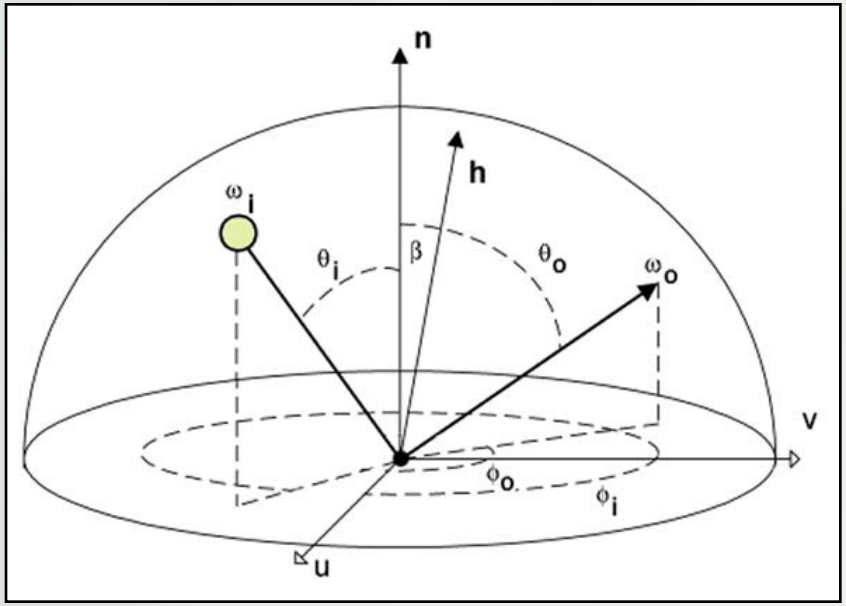
- Incident/reflected vectors
- **Surface position** (correctly not part of BRDF)
- Wavelength
- Incident radiance
- Reflected radiance



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- Surface position
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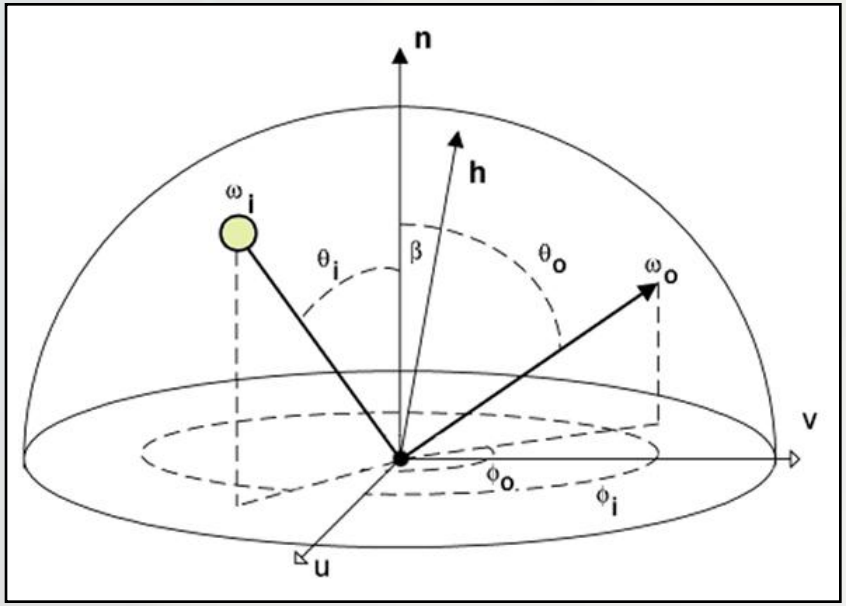

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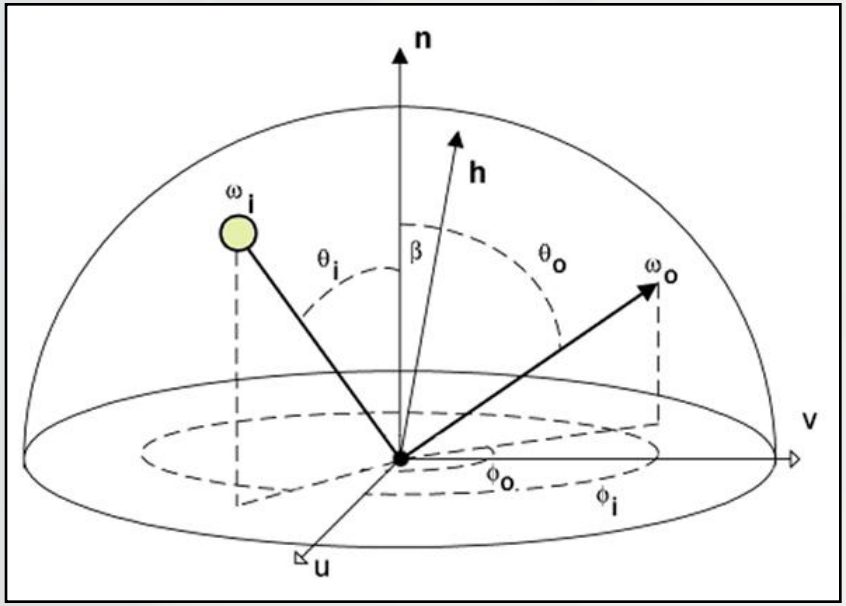

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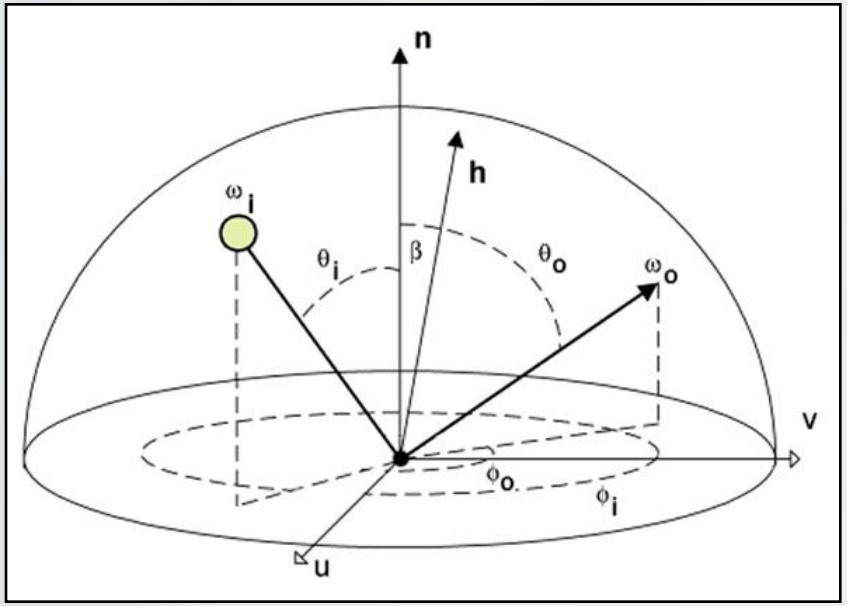
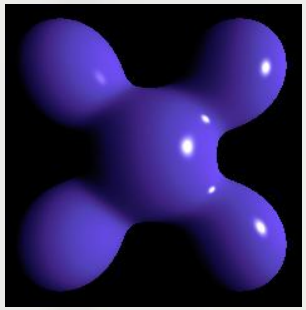


BRDF - Types

- Empirical models
  - Phong/Blinn-Phong, Ward, Strauss, Lafortune



BRDF - Types

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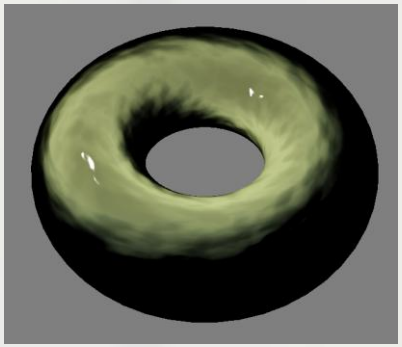
- **Analytical first principles models**
  - **Torrance-Sparrow/Cook-Torrance, Oren-Nayar**



BRDF - Types

- Empirical models
  - Phong/Blinn-Phong, Ward, Strauss, Lafortune
- Analytical first principles models
  - Torrance-Sparrow/Cook-Torrance, Oren-Nayar
- **Simulation from first principles**
  - **Cabral et al., Westin et al., Gondek et al.**

BRDF - Types

- Empirical models
  - Phong/Blinn-Phong, Ward, Strauss, Lafortune
- Analytical first principles models
  - Torrance-Sparrow/Cook-Torrance, Oren-Nayar
- Simulation from first principles
  - Cabral et al., Westin et al., Gondek et al.
- **Actual measurement**
  - **e.g. with gonioreflectometer**

BRDF - Properties

- Energy conservation (!)

$$f_r(\Theta_i, \Theta_r, x, y, \lambda) = \frac{d^2 L_r(\Theta_r, x, y, \lambda)}{L_i(\Theta_i, x, y, \lambda)\cos\theta_i dA d\omega_i}$$

BRDF - Properties

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BRDF - Properties

- Energy conservation (!)
- Helmholtz reciprocity principle (!)
- **Good Monte-Carlo sampling properties**

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BRDF - Properties

- Energy conservation (!)
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- **Reasonable amount of storage**

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BRDF - Properties

- Energy conservation (!)
- Helmholtz reciprocity principle (!)
- Good Monte-Carlo sampling properties
- Reasonable amount of storage
- **Good appearance reproduction**

$$f_r(\Theta_i, \Theta_r, x, y, \lambda) = \frac{d^2 L_r(\Theta_r, x, y, \lambda)}{L_i(\Theta_i, x, y, \lambda)\cos\theta_i dA d\omega_i}$$

BRDF - Sampling

- Path propagation vs. BRDF evaluation

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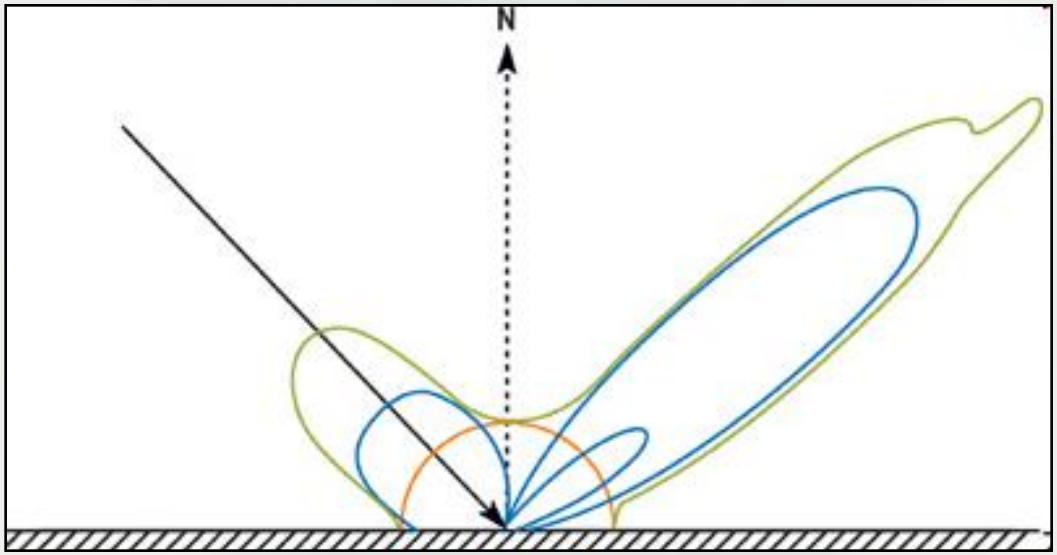
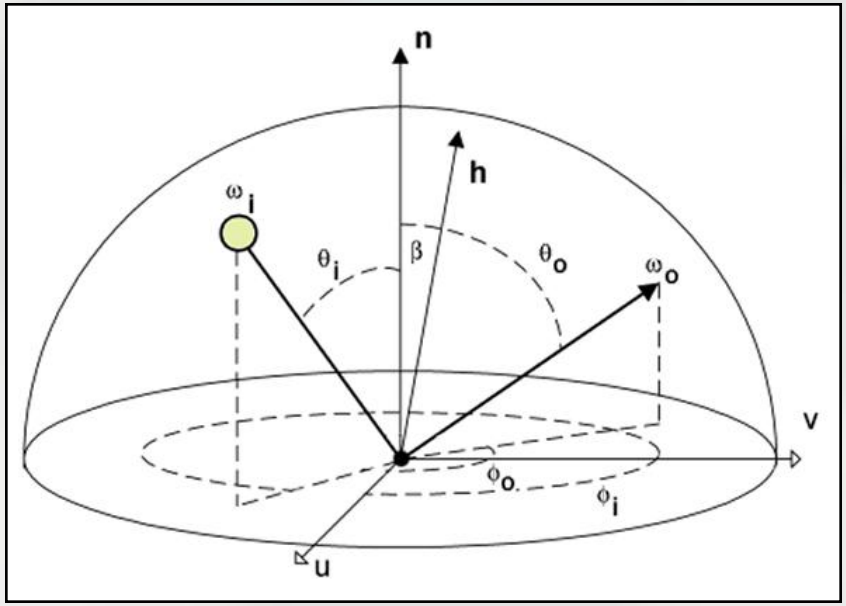
- Path propagation vs. BRDF evaluation
- **Path propagation (global model):**



BRDF - Sampling

- Path propagation vs. BRDF evaluation
- Path propagation (global model)
- **Combined BRDF evaluation (local model):**



BRDF - Perspectives

- Non-RT vs. RT applications...

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- Non-RT vs. RT applications
- **Non-RT renderer:**
  - **Local and global sampling (incl. PDF)**
  - **High-quality reproduction**
  - **Good storage possibilities**
  - **Speed not crucial**

BRDF - Perspectives

- Non-RT vs. RT applications
- Non-RT renderer:
  - Local and global sampling (incl. PDF)
  - High-quality reproduction
  - Good storage possibilities
  - Speed not crucial
- **RT renderer:**
  - **Only local model**
  - **Best-effort reproduction**
  - **Only closed form**
  - **Speed is crucial**

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- **Sample BRDF**
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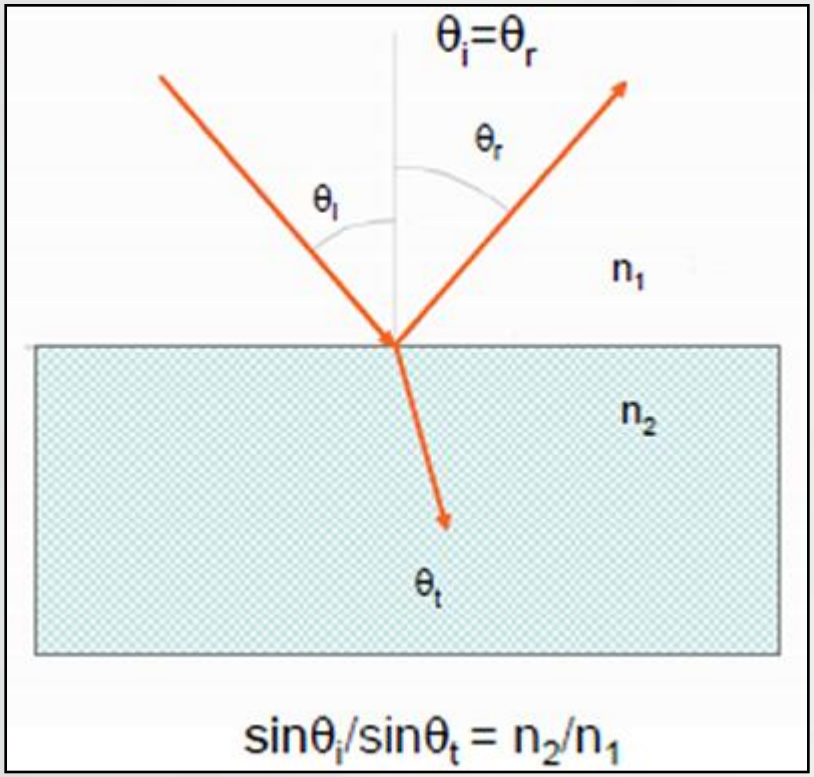
Sample BRDF – Lambert and mirror reflection

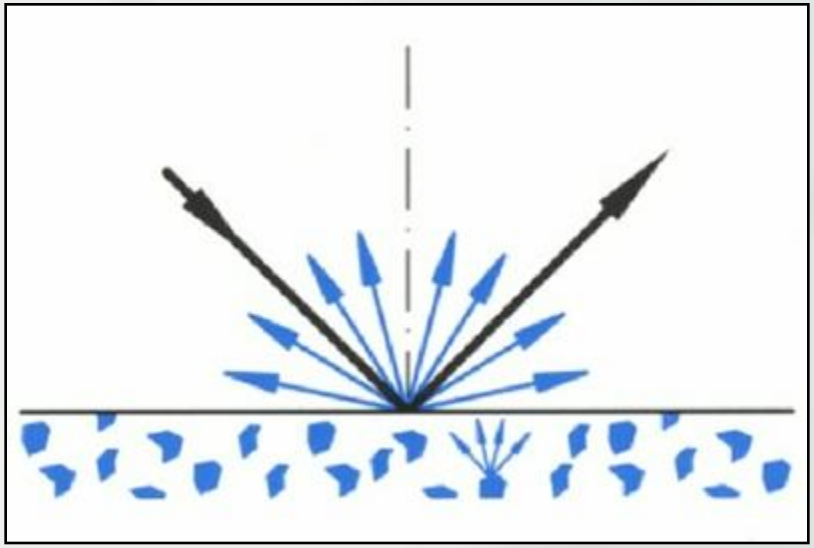
- Ideal mirror reflection/transmission
  - Fresnel term
  - Snell's law

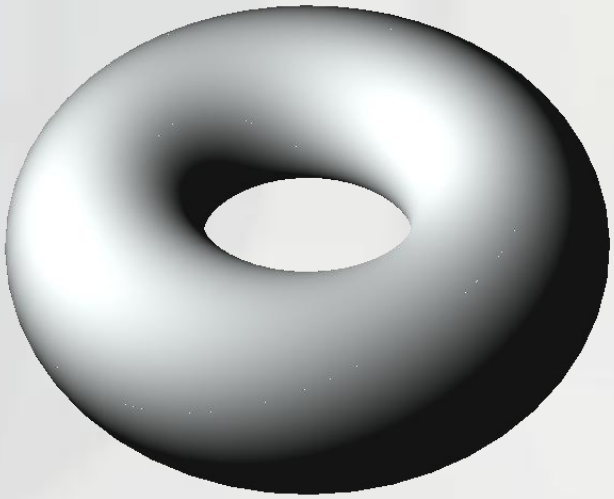


Sample BRDF – Lambert and mirror reflection

- Ideal mirror reflection/transmission
  - Fresnel term
  - Snell's law
- **Lambertian (diffuse) reflection**

$$L_r = \frac{\rho}{\pi} \cdot \cos\theta_i \cdot L_i$$





Sample BRDF – Phong/Blinn-Phong

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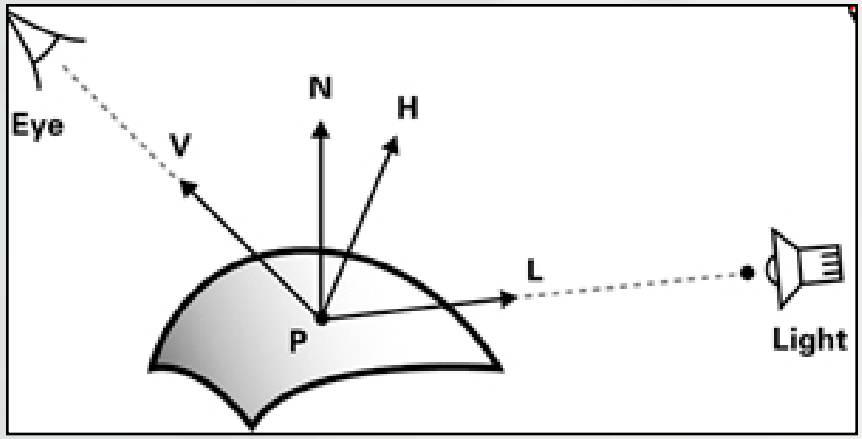
- **Phong:**

$$k_{spec} = \cos^n(R, V)$$

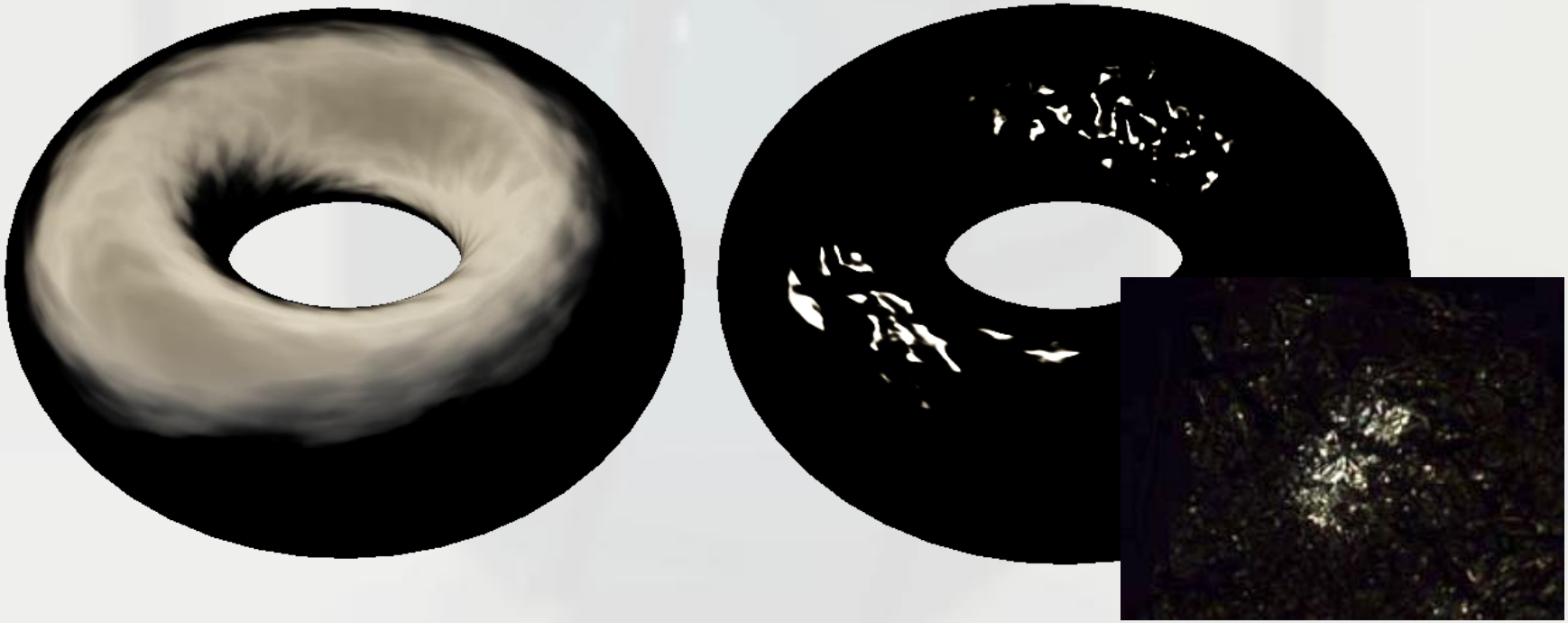


- **Blinn-Phong**

$$k_{spec} = \cos^n(N, H)$$

Sample BRDF – Torrance-Sparrow

- Analytical first principles model
  - Rough surface, V-shaped **specular** microfacets
- Cook-Torrance similarity



Sample BRDF – Torrance-Sparrow

- Analytical first principles model
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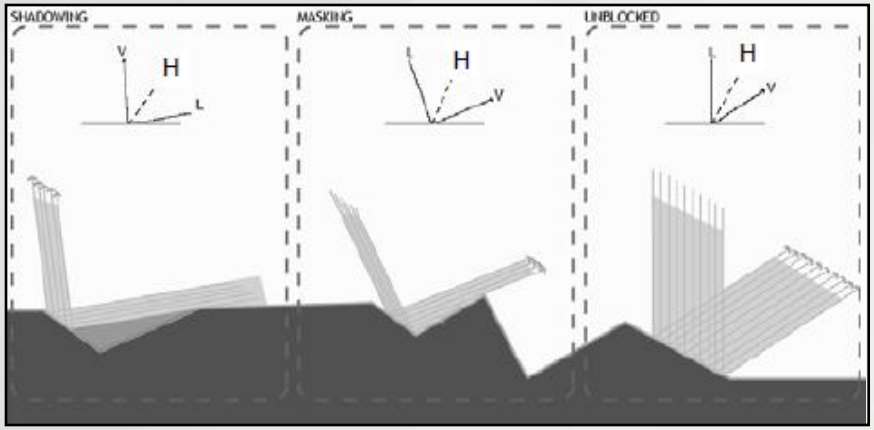
$$f_r = \frac{FDG}{4 \cdot (N \cdot L)(N \cdot V)}$$

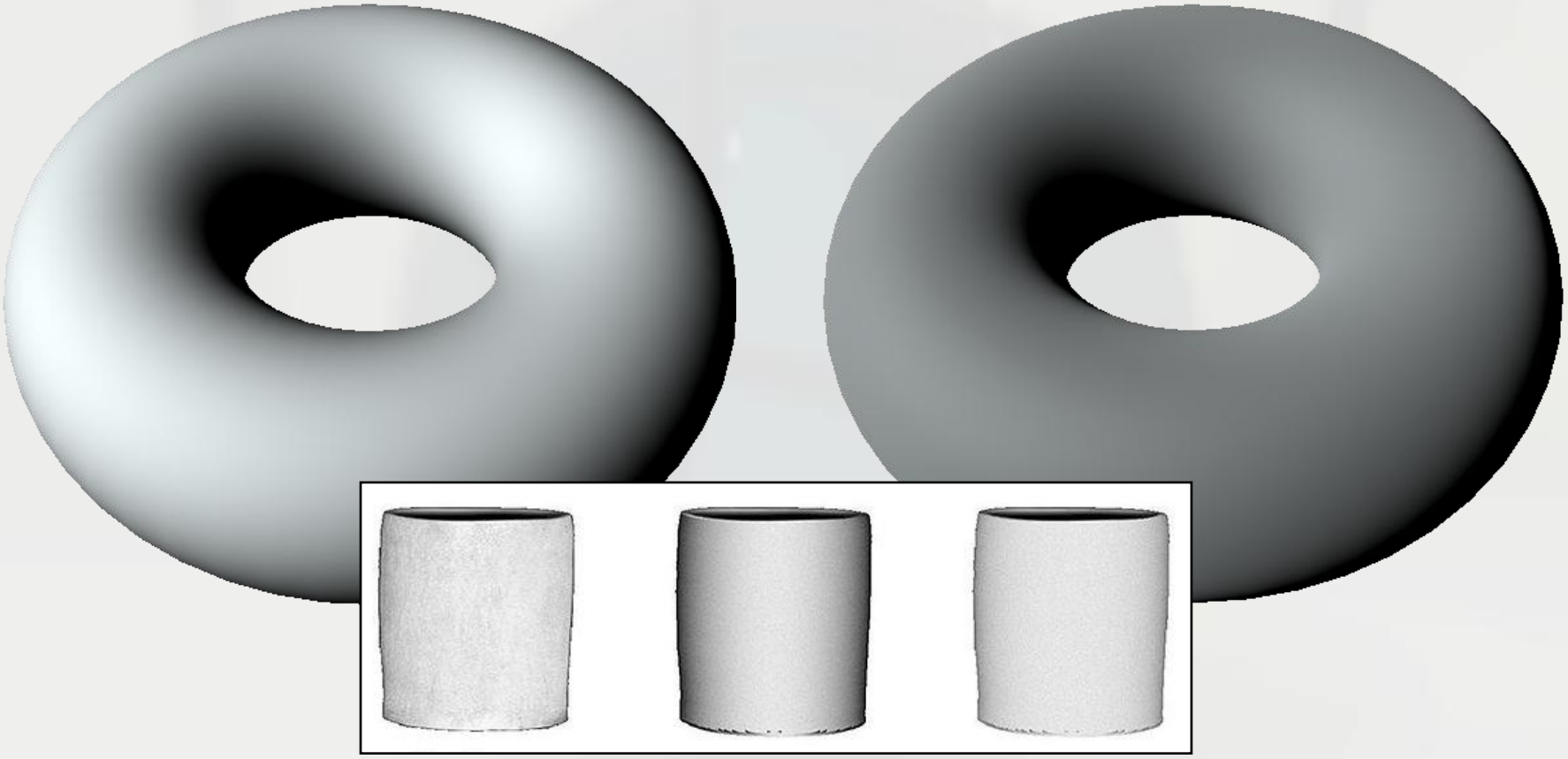
- **D – distribution term**
  - Gaussian, Beckmann, etc.
- **F – Fresnel term**
- **G – geometry attenuation term (masking)**

$$G = \min(1, \frac{2(H \cdot N)(E \cdot N)}{E \cdot H}, \frac{2(H \cdot N)(L \cdot N)}{E \cdot H})$$



Sample BRDF – Oren-Nayar

- Analytical first principles model
  - Rough surface, V-shaped **diffuse** microfacets



Sample BRDF – Oren-Nayar

- Analytical first principles model
  - Rough surface, V-shaped diffuse microfacets

$$\frac{\rho}{\pi} E_0 \cos\theta_i \left(A + B\, Max\left[0, \cos\left(\phi_r - \phi_i\right)\right] \sin\alpha \tan\beta \right)$$

$$A = 1.0 - 0.5 \frac{\sigma^2}{\sigma^2 + 0.33}$$

$$B = 0.45 \frac{\sigma^2}{\sigma^2 + 0.09}$$

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Layered microfacet model - Introduction

- Layering problem

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- Full solution complicated

Layered microfacet model - Assumptions

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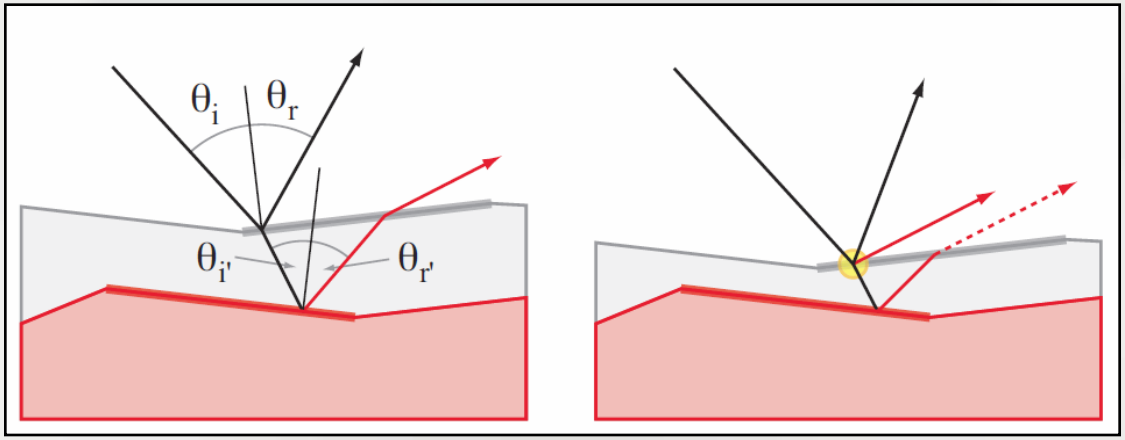
- Assumptions
  - (1) Large microfacets (~thin layers)



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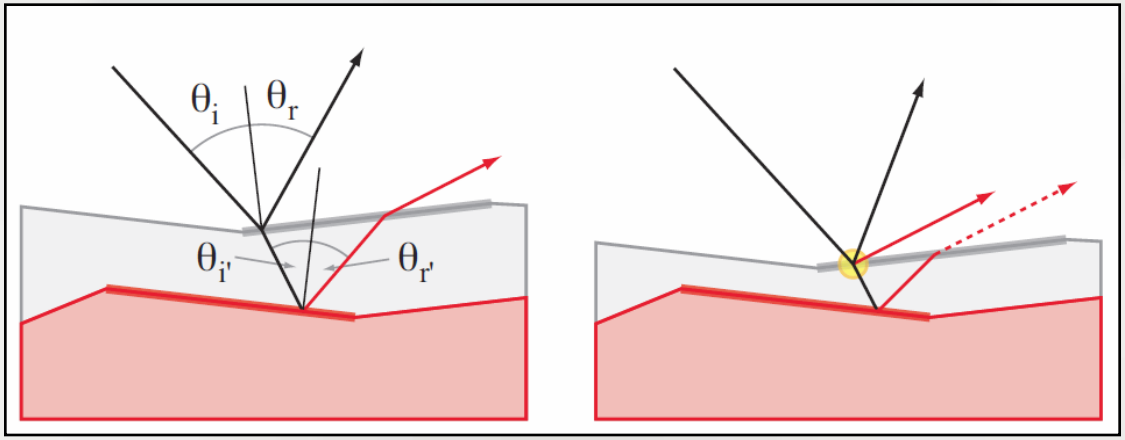

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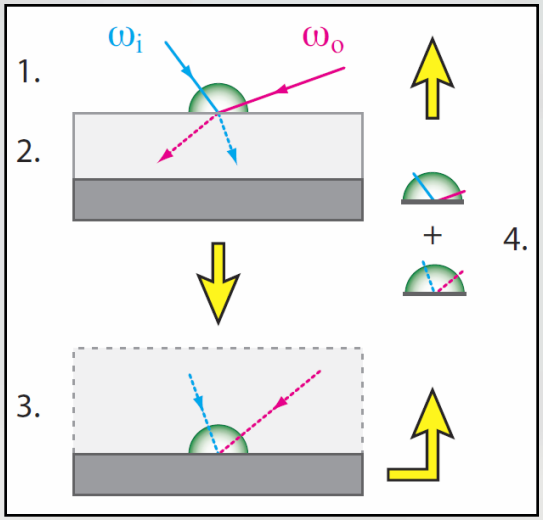

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- Assumptions
  - (1) Large microfacets (~thin layers)
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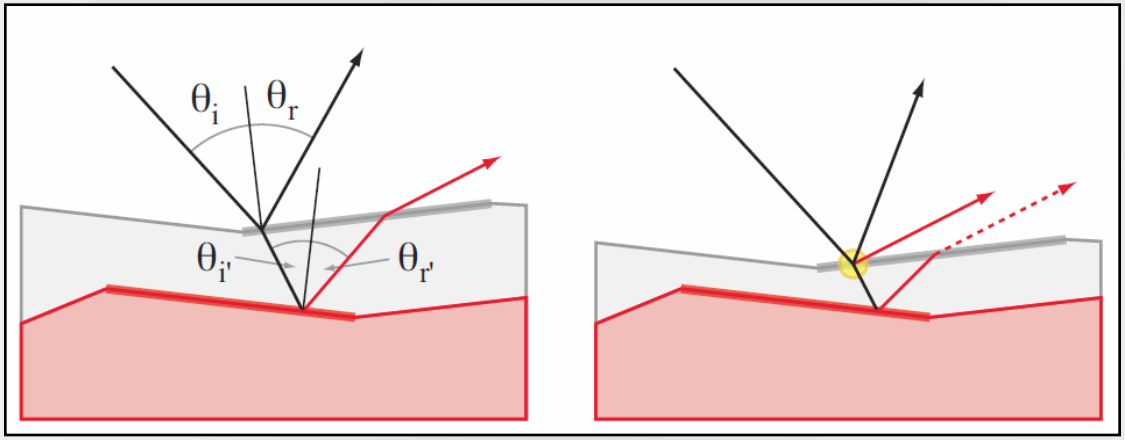
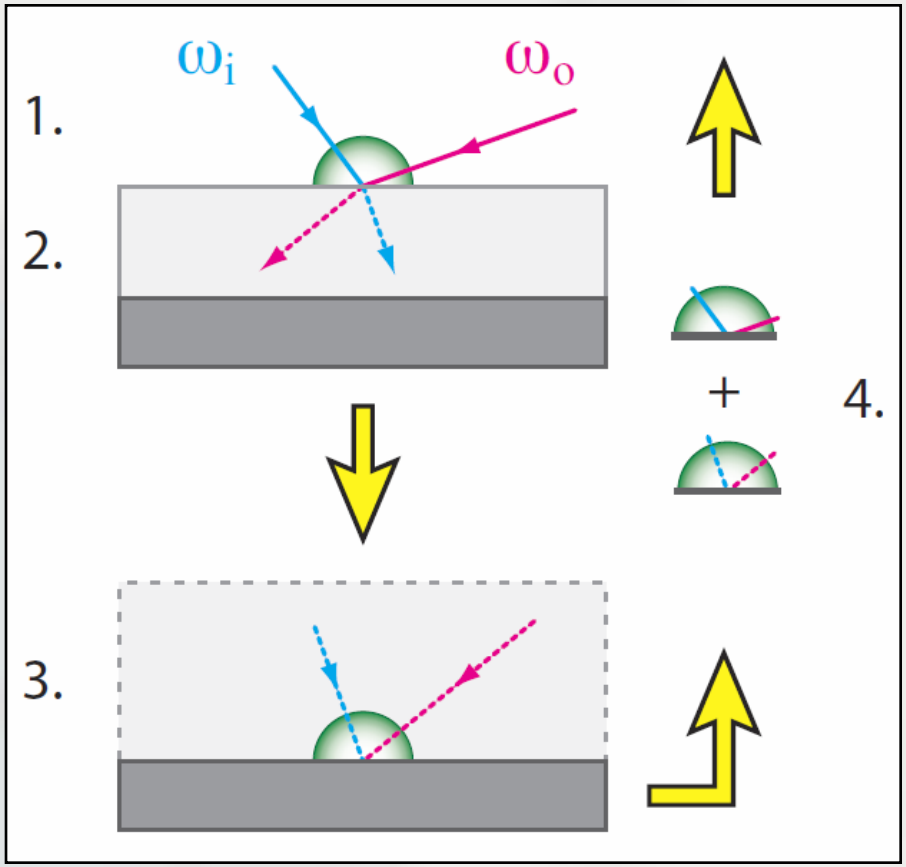
  - (3) Refracted rays meet at single point
  - (4) No scattering within layers



Layered microfacet model - Description

- 1. Upper layer BRDF evaluation

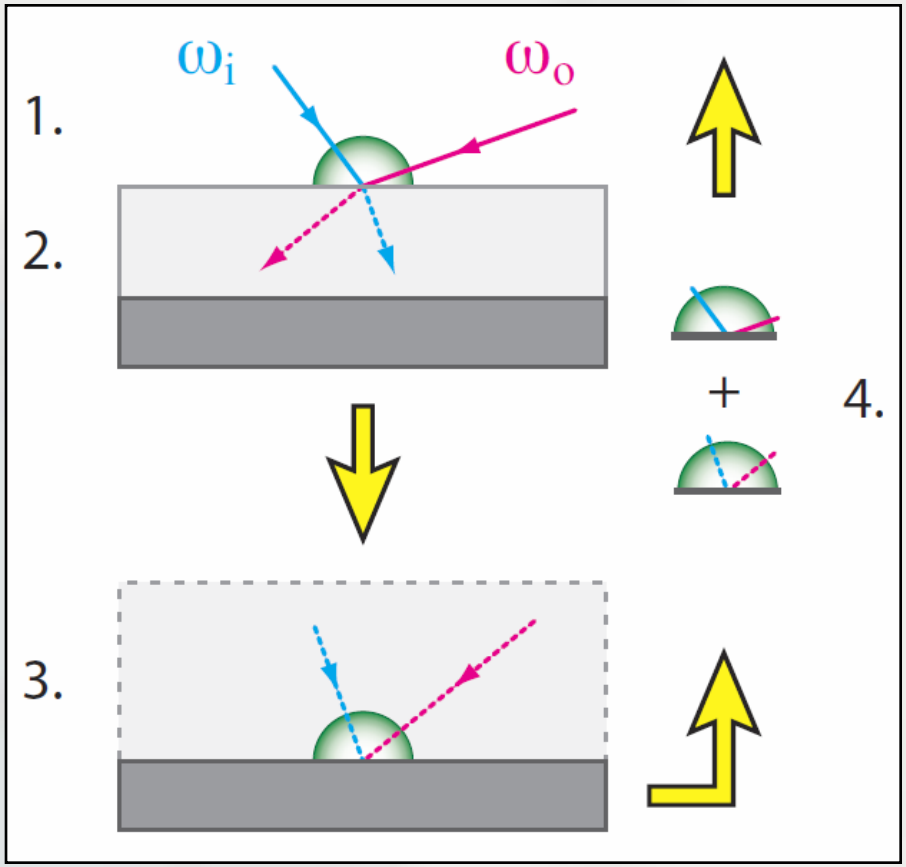
$$f_{r_1}(\theta_i, \theta_r)$$



Layered microfacet model - Description

- 1. Upper layer BRDF evaluation
- **2. Energy enters acc. to Fresnel's law and under-goes absorption**

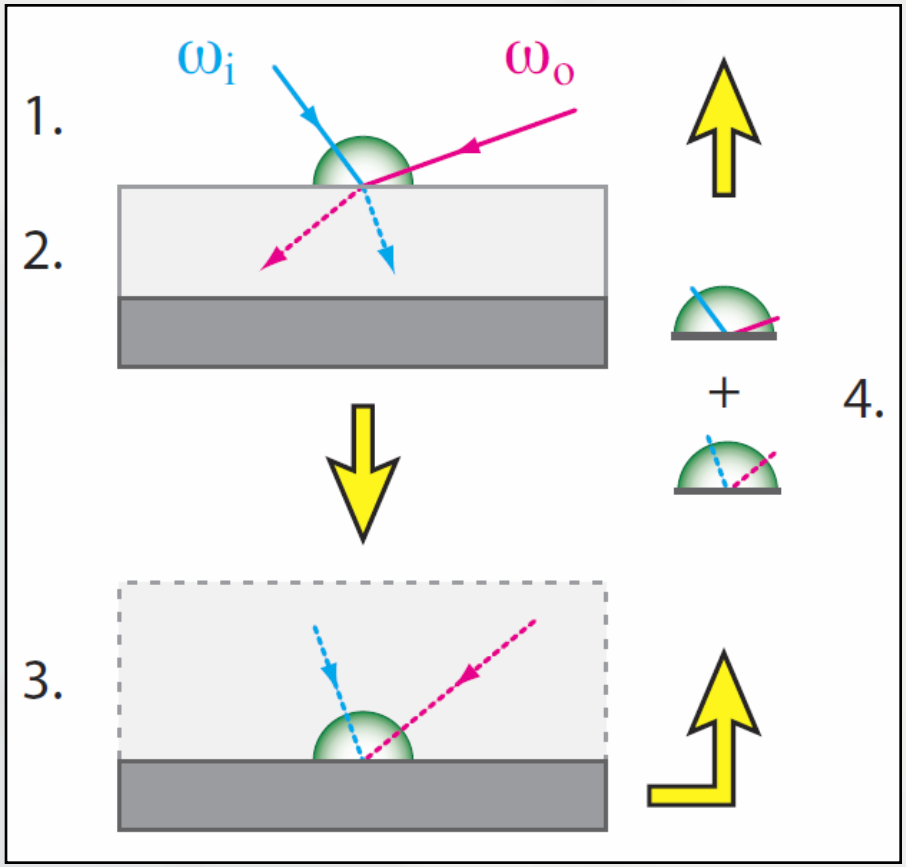
T_{12} a



Layered microfacet model - Description

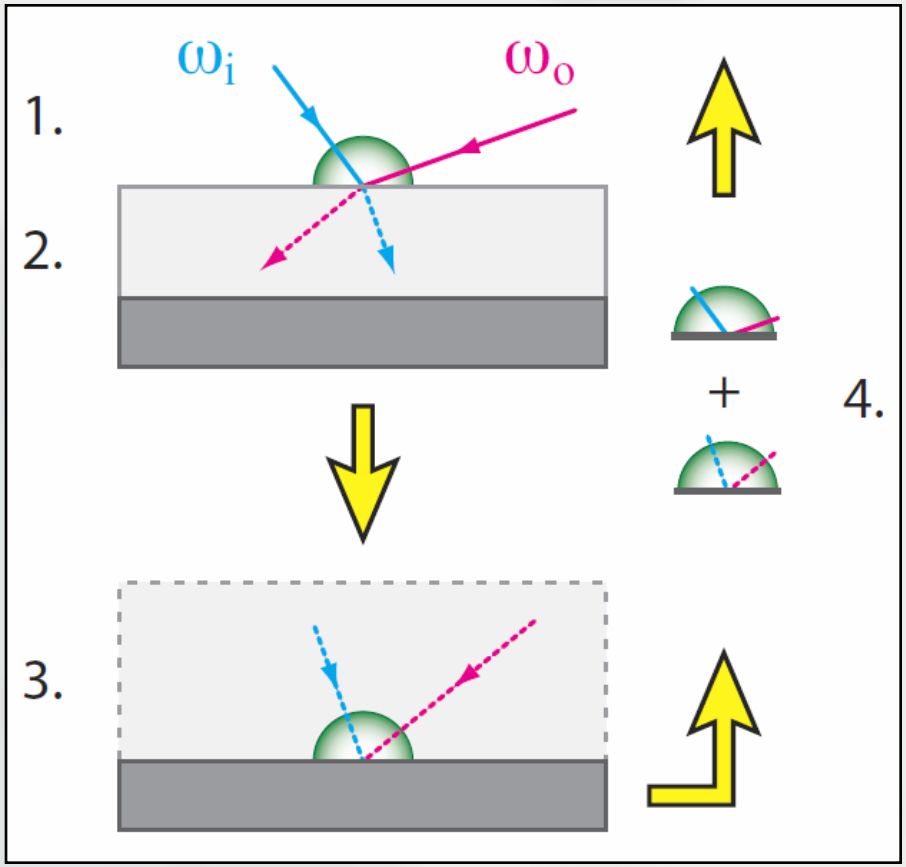
- 1. Upper layer BRDF evaluation
- 2. Energy enters acc. to Fresnel's law and under-goes absorption
- **3. Lower layer BRDF evaluation at single point**

$$f_{r_2}(\theta_{i'}, \theta_{r'})$$



Layered microfacet model - Description

- 1. Upper layer BRDF evaluation
- 2. Energy enters acc. to Fresnel's law and under-goes absorption
- 3. Lower layer BRDF evaluation at single point
- **4. Upward attenuation and recombination**



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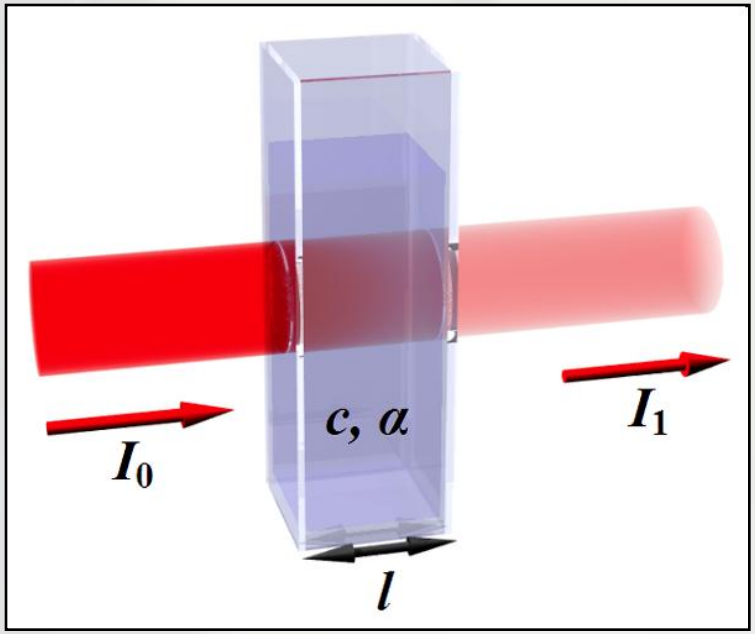
Layered microfacet model - Details

- Absorption term *a*
  - Bouguer-Beer-Lambert law

$$I = I_0 e^{-\alpha l}$$

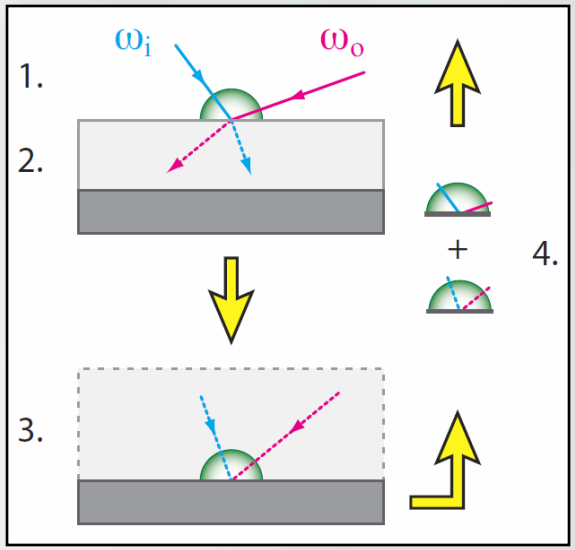


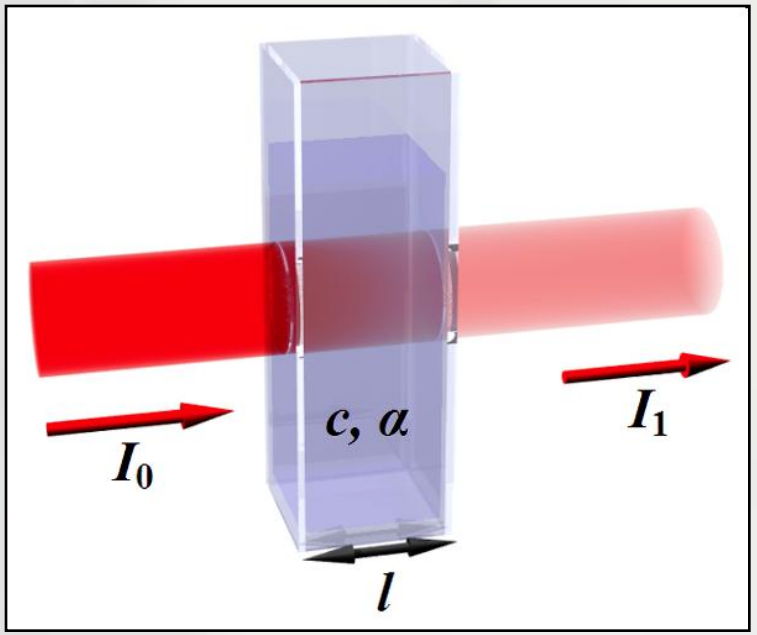
Layered microfacet model - Details

- Absorption term *a*
  - Bouguer-Beer-Lambert law

$$I = I_0 e^{-\alpha l}$$

$$a = e^{-\alpha d \cdot \left(\frac{1}{\cos \theta_{i'}} + \frac{1}{\cos \theta_{r'}} \right)}$$

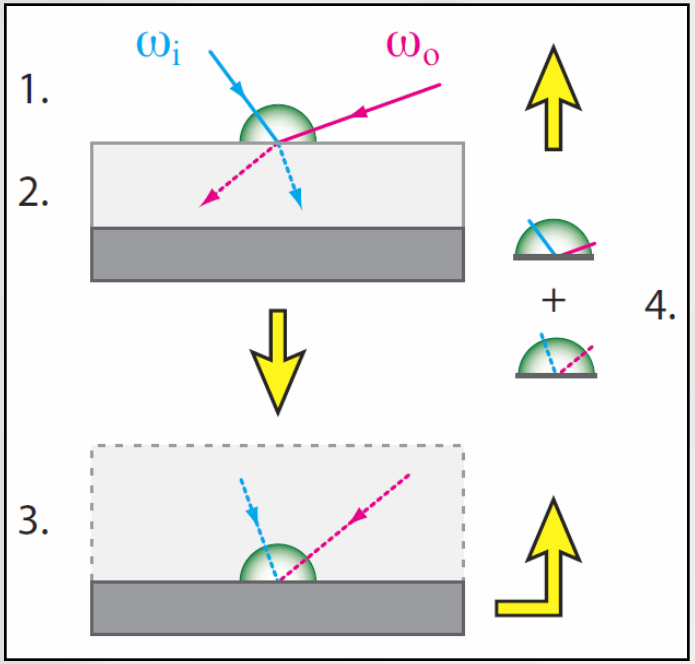




Layered microfacet model - Details

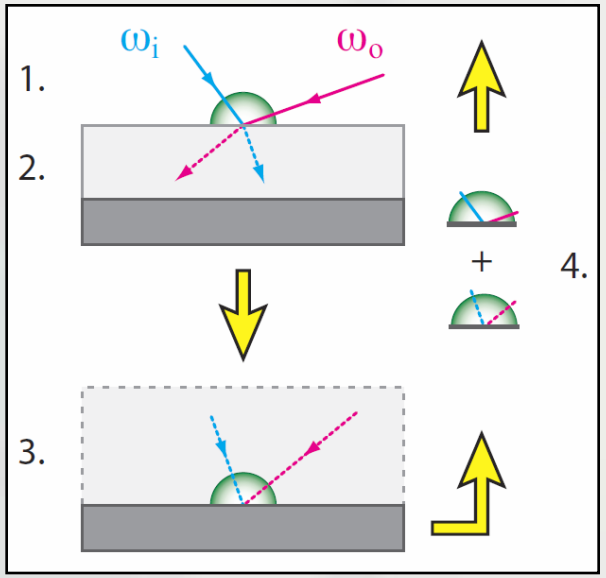
- Absorption term *a*
- **Total internal reflection term *t***
  - **Snell's law and upper layer microfacet distribution**

$$t = (1 - G) + T_{21} \cdot G$$



Layered microfacet model - Details

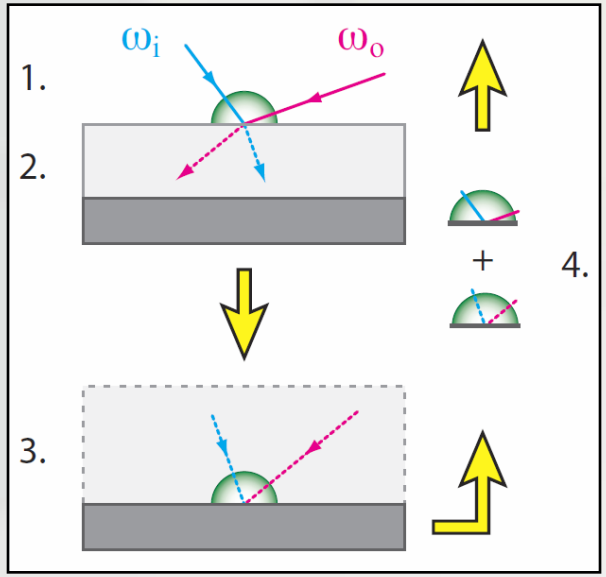
- Absorption term *a*
- Total internal reflection term *t*
- **Final combination**



$$f_r = f_{r_1}(\theta_i, \theta_r) + T_{12} \cdot f_{r_2}(\theta_{i'}, \theta_{r'}) \cdot a \cdot t$$

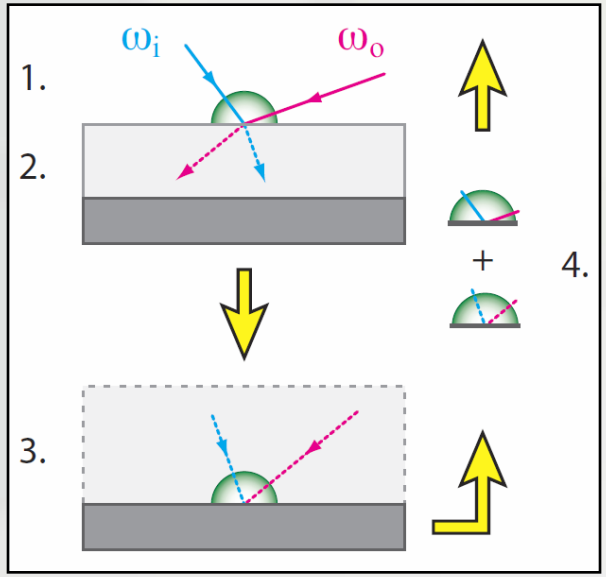
Layered microfacet model - Sampling

- Both local and global model



Layered microfacet model - Sampling

- Both local and global model
- **Importance sampling**
  - **Global model – per-layer evaluation**



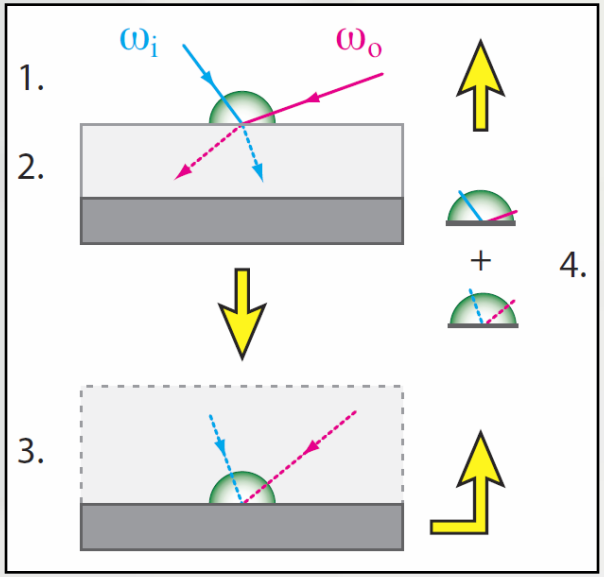
Layered microfacet model - Sampling

- Both local and global model
- Importance sampling
  - Global model – per-layer evaluation
  - Local model - weighting

$$p(x) \geq 0$$

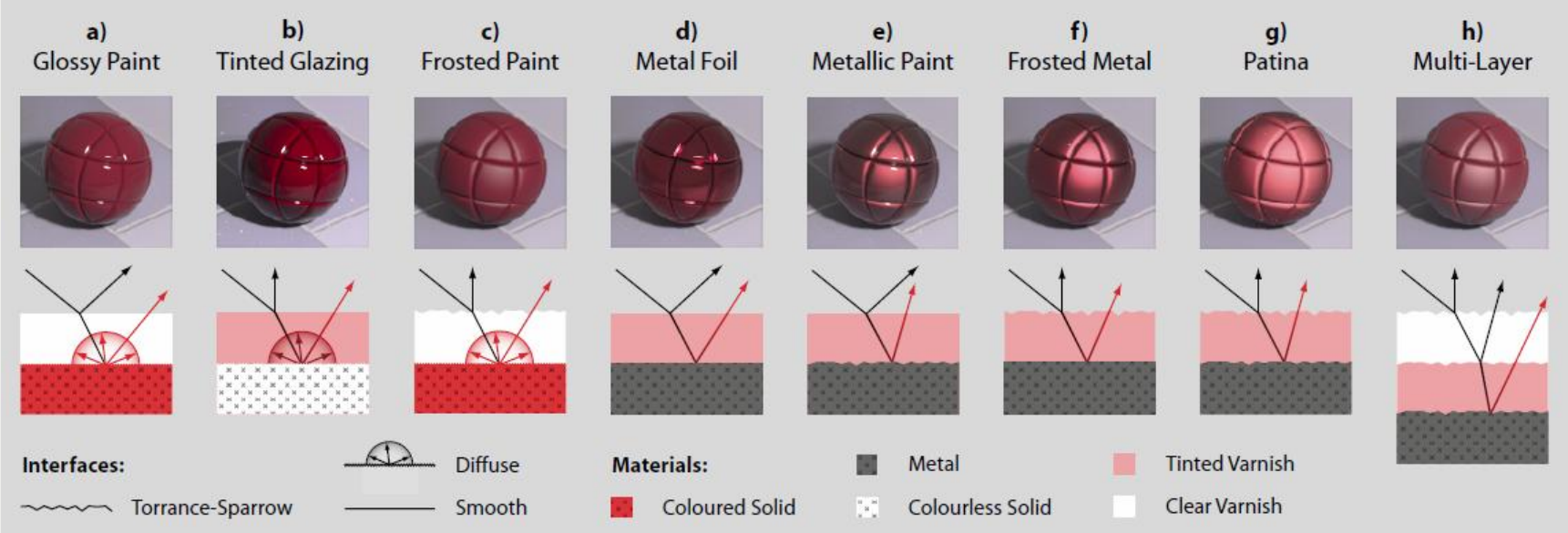
$$\int_D p(x) d\mu(x) = 1$$

$$p = \sum w_i p_i$$



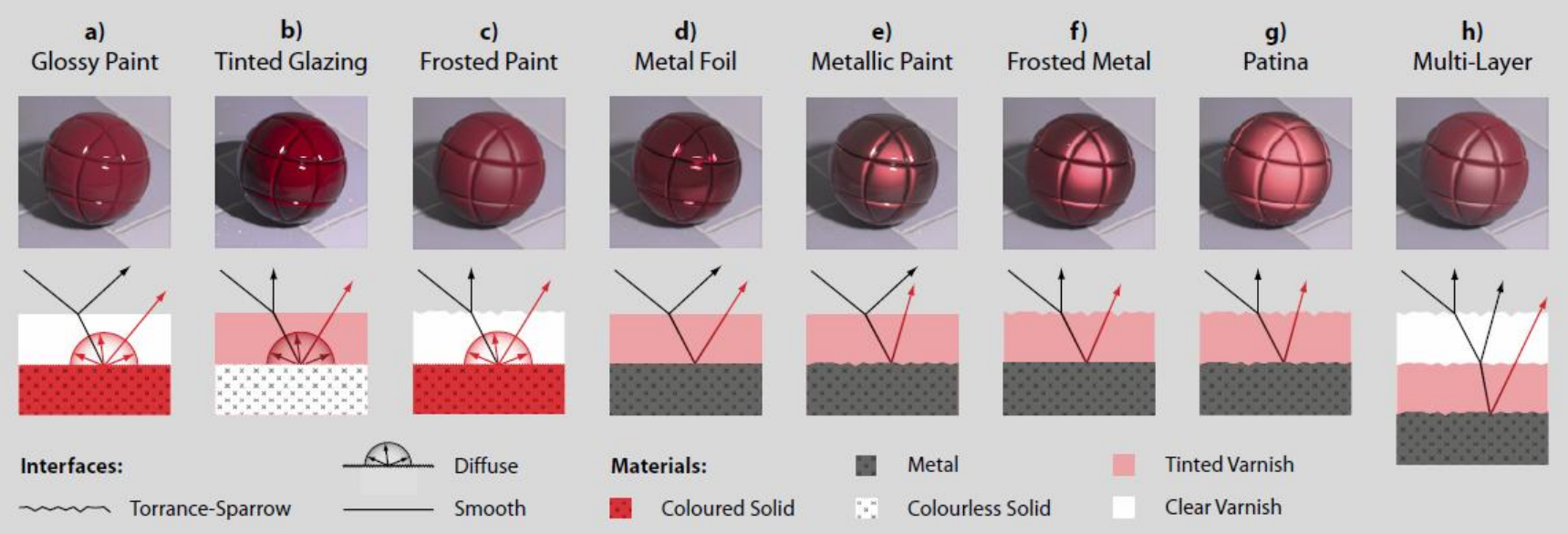
Layered microfacet model - Examples

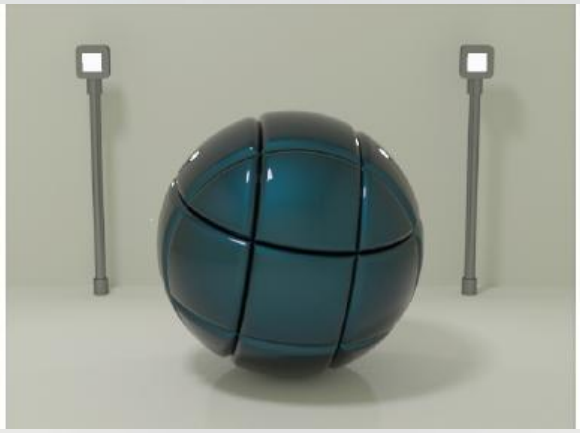
- GI renders



Layered microfacet model - Examples

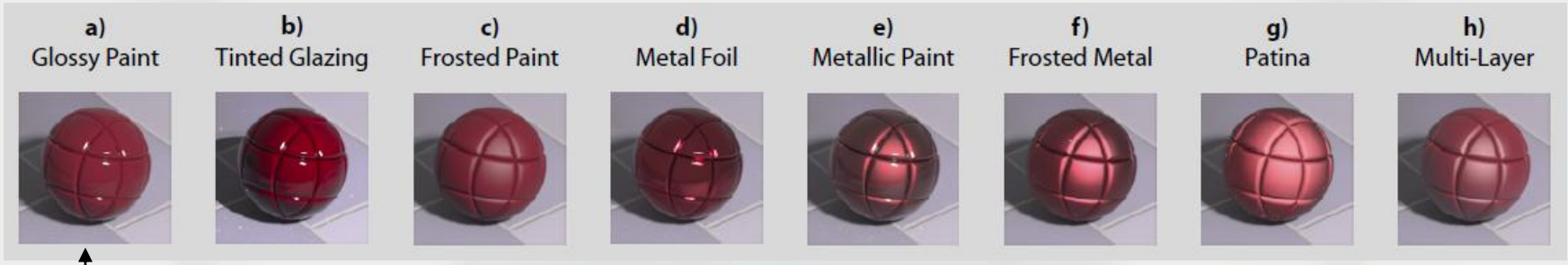
- GI renders

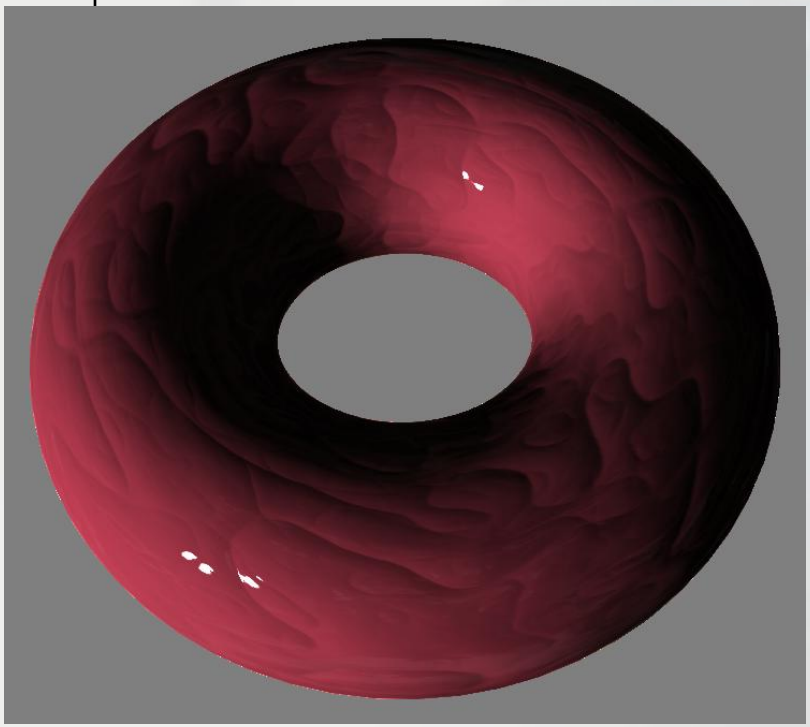




Layered microfacet model - Examples

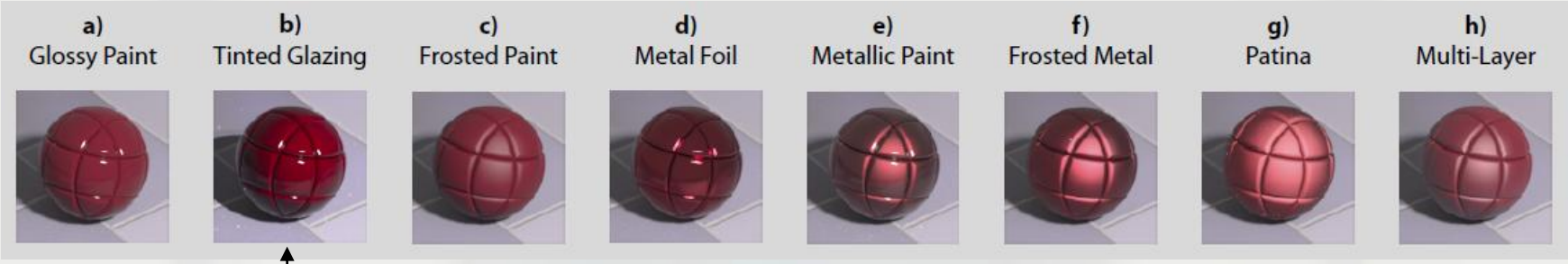
- RT results

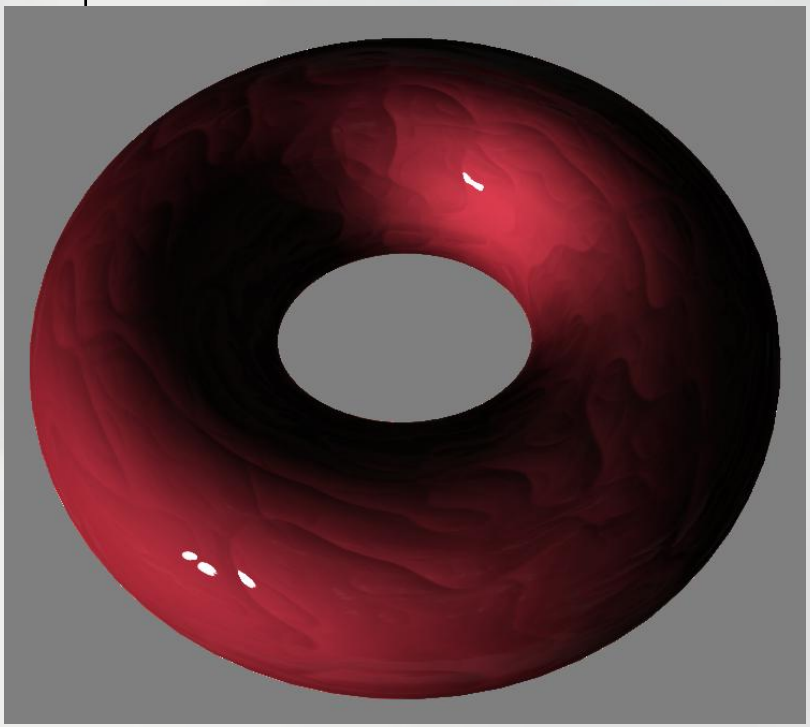




Layered microfacet model - Examples

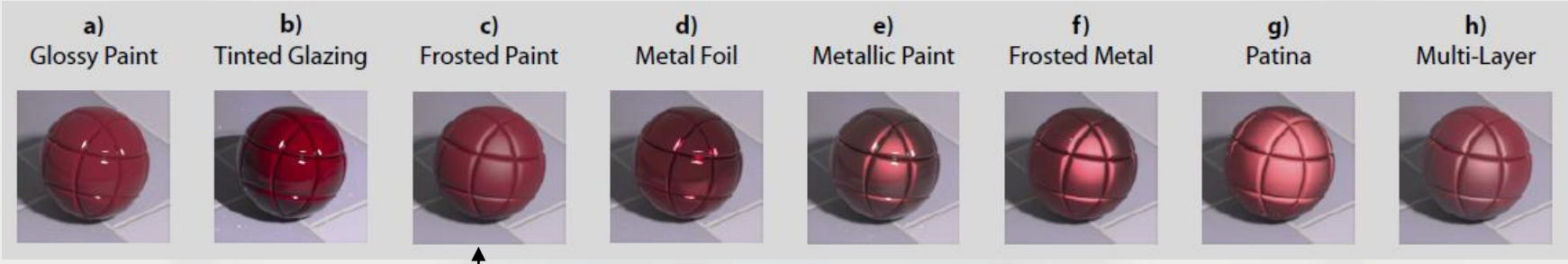
- RT results

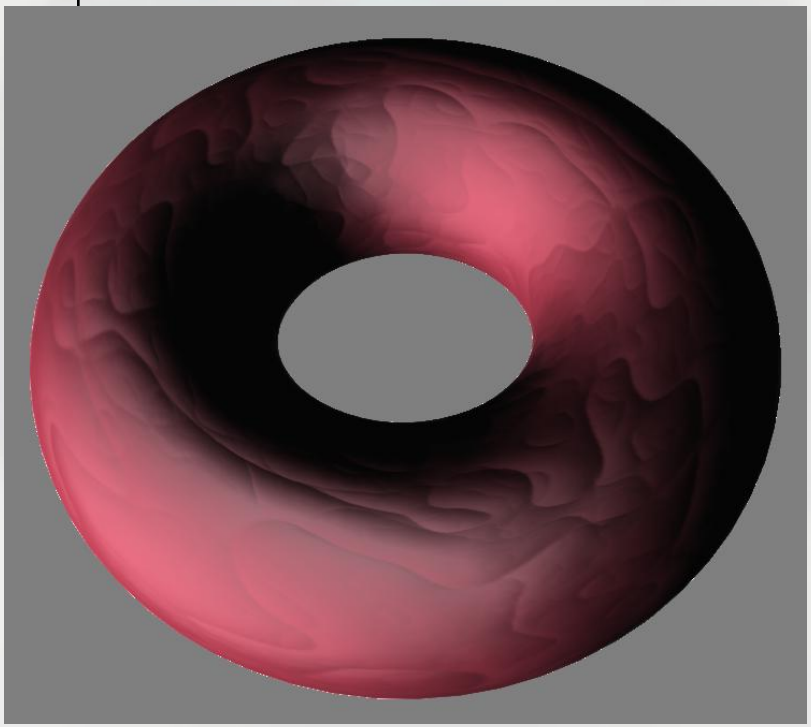




Layered microfacet model - Examples

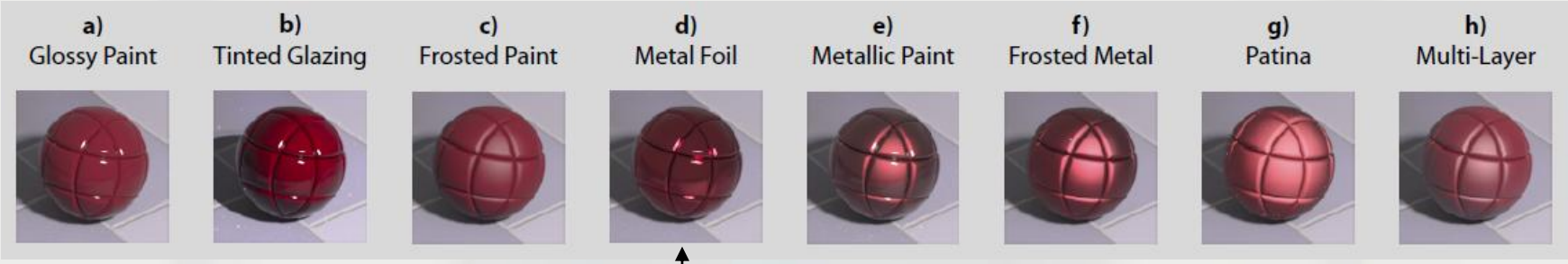
- RT results

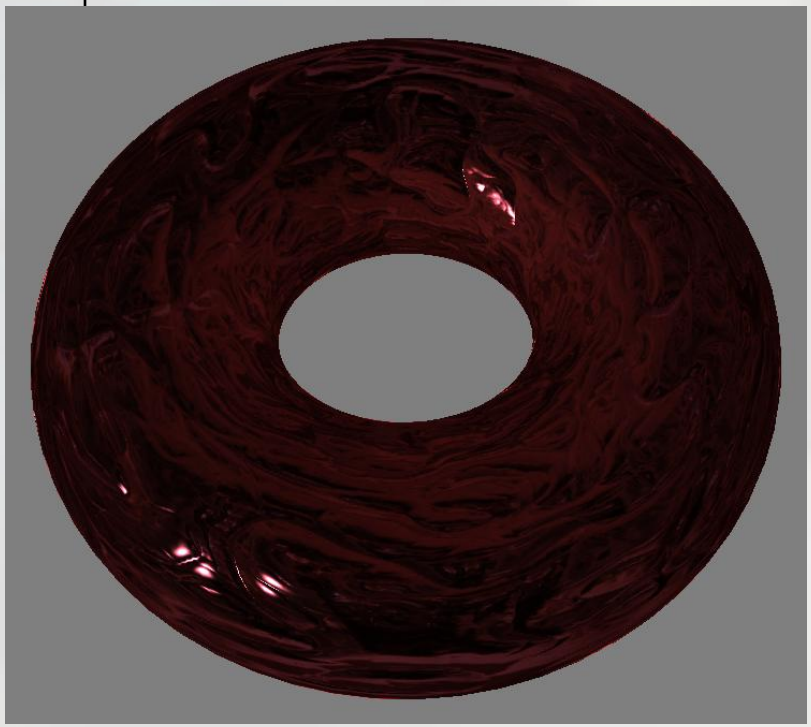




Layered microfacet model - Examples

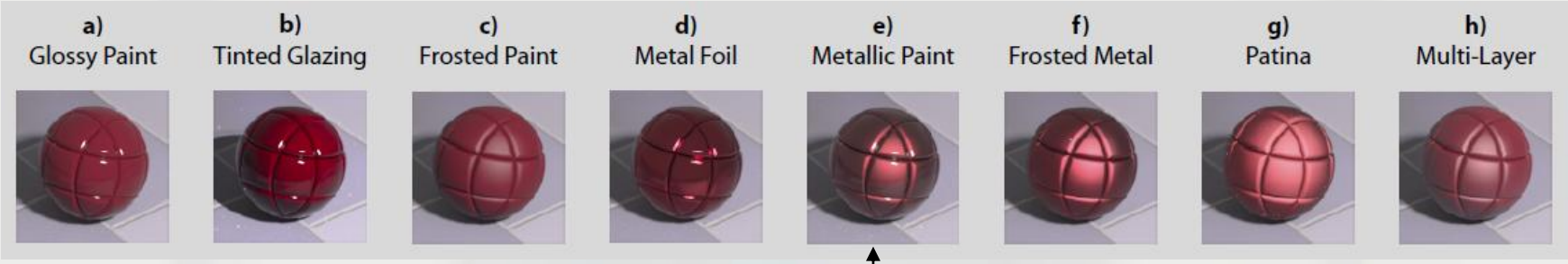
- RT results

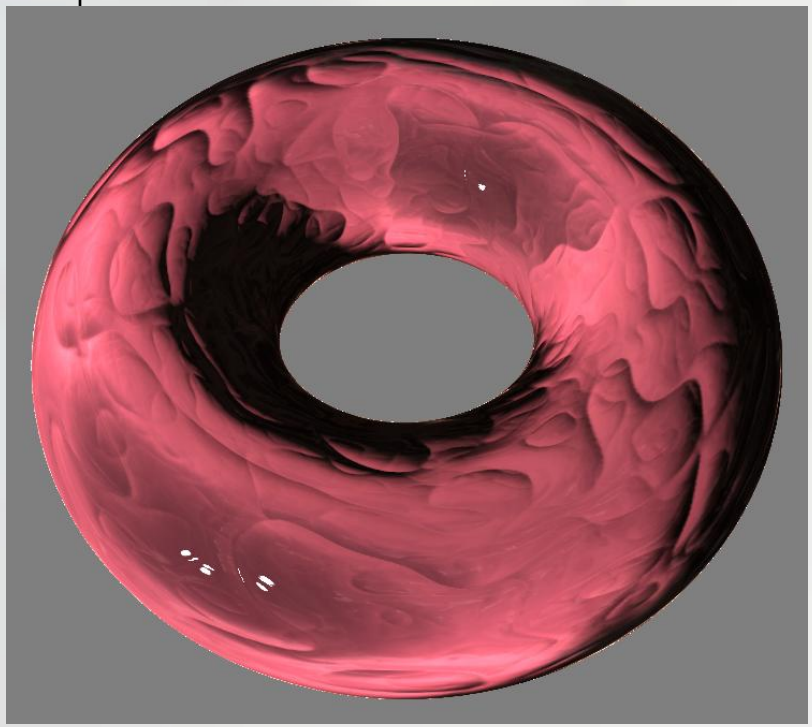




Layered microfacet model - Examples

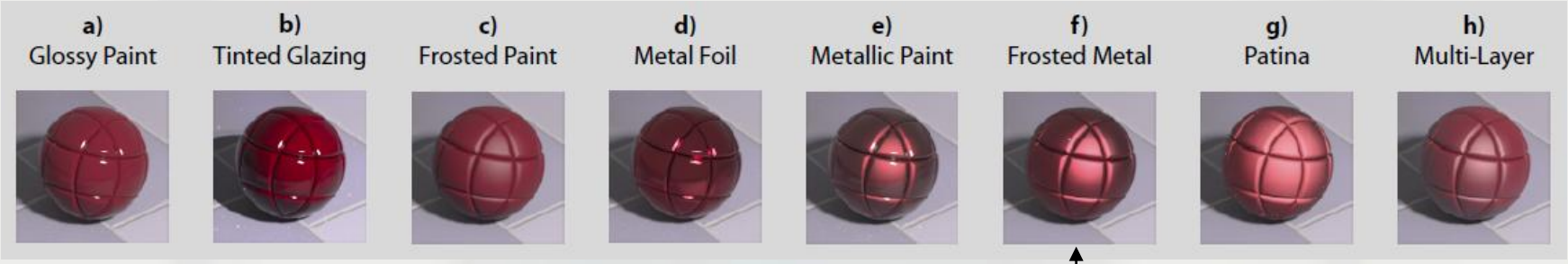
- RT results

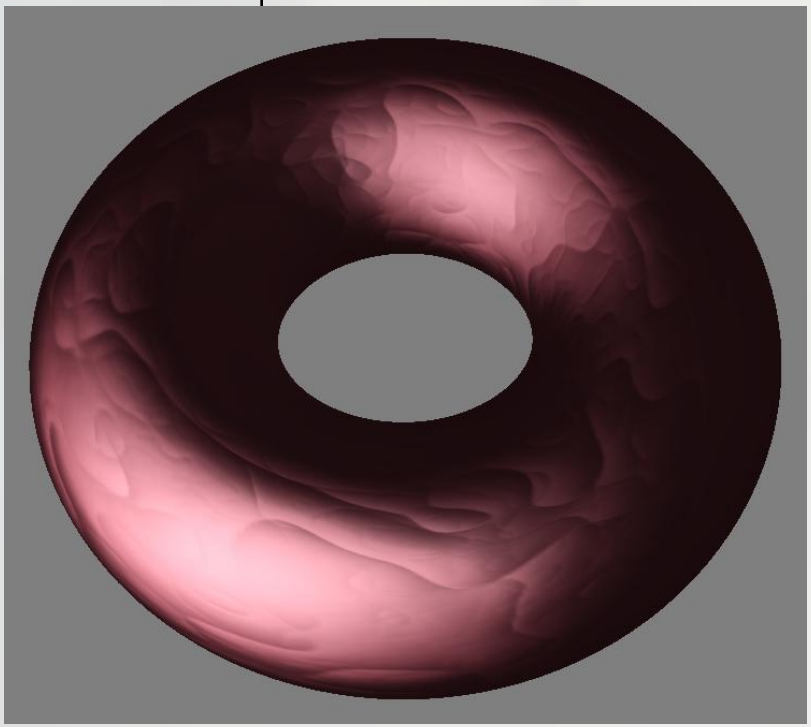




Layered microfacet model - Examples

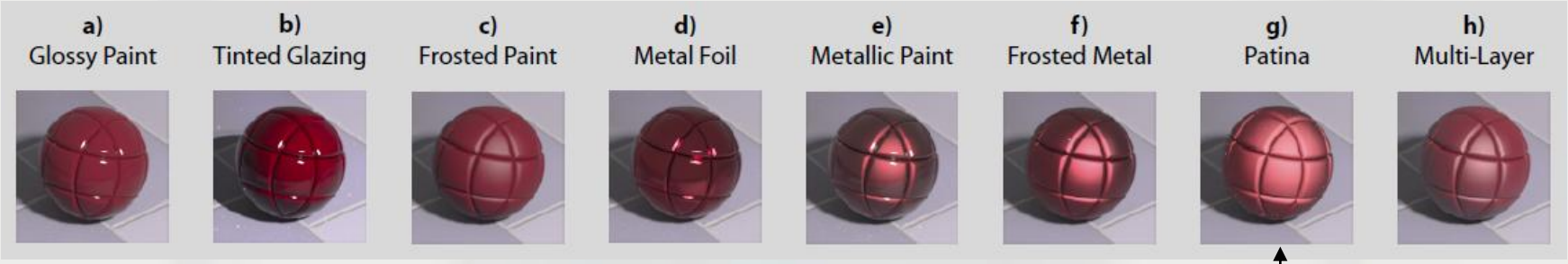
- RT results

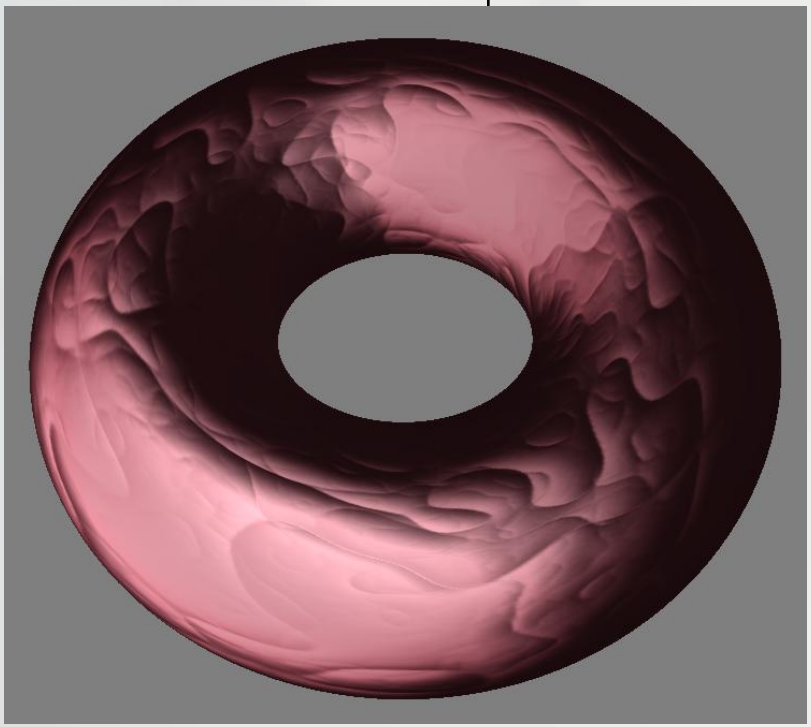




Layered microfacet model - Examples

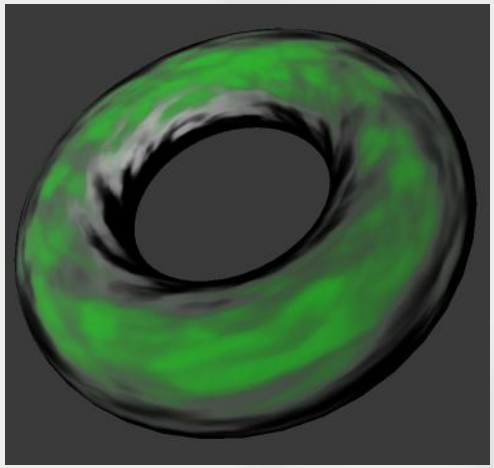
- RT results

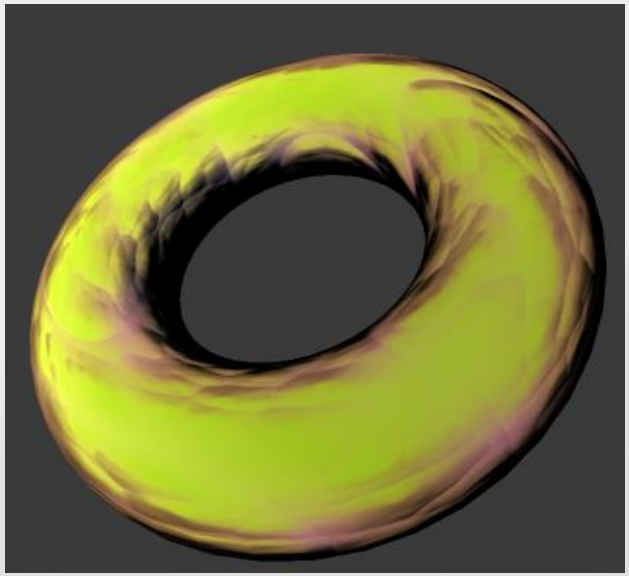


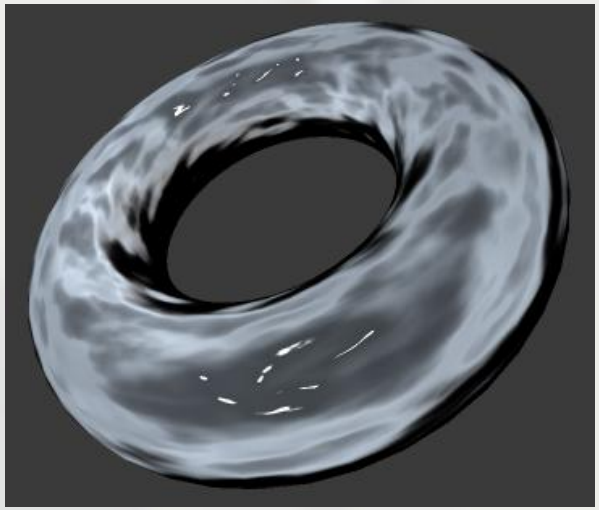


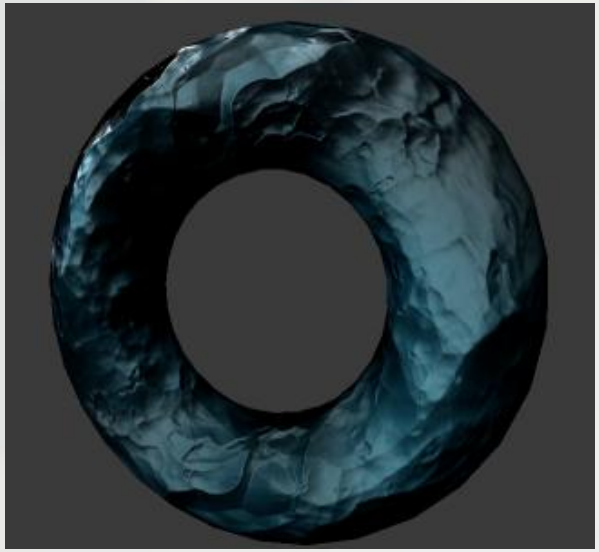
Layered microfacet model - Examples

- RT results









Layered microfacet model - Examples

- RT demo

The end

- Questions...

References

- A. Weidlich and A. Wilkie: Arbitrary Layered Micro-Facet Surfaces, 2007
- A. Weidlich and A. Wilkie: Exploring the Potential of Layered BRDF Models (SIGGRAPH ASIA Course), 2009
- J. Dorsey, H. Rushmeyer, F. Sillion: Digital Modelling of Material Appearance, 2007
- R. L. Cook and K. E. Torrance: A Reflectance Model for Computer Graphics, 1982
- M. Oren and S. K. Nayar: Generalization of Lambert's Reflectance Model, 1994
- K. E. Torrance and E. M. Sparrow: Theory for Off-Specular Reflection From Roughened Surfaces, 1966
- Related Wikipedia articles (mostly for images and formulas)