Comparative study of layered material models

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Inria

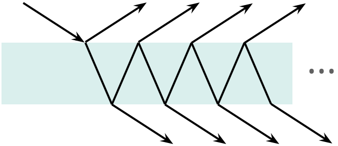
Multi-layered materials



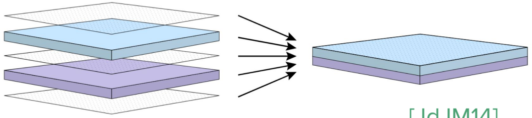



Multi-layered materials

- Smooth interfaces :
  ➡ Analytical solution (Matrix transfer) [Yeh05]



- Rough interfaces :
  ➡ Numerical simulation :
    - Monte Carlo path-tracing [GHZ18]
    - LayerLab representation [JdJM14, ZJ18]



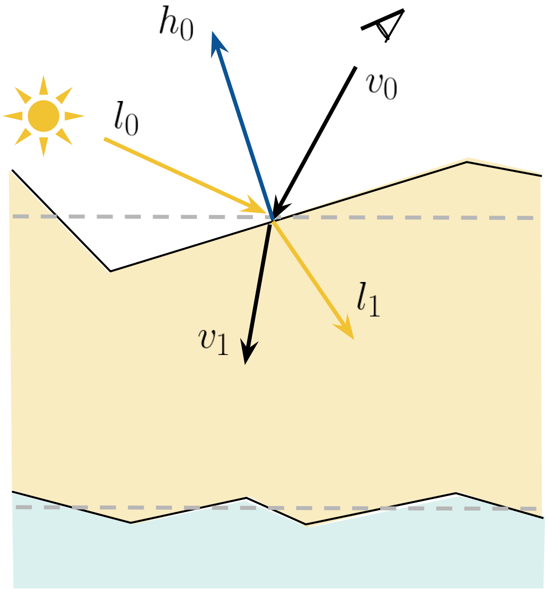
[JdJM14]

✅ Accuracy

❌ Time & memory consumption

Multi-layered models - Weidlich and Wilkie [WW07]

- Recursive composition of BRDFs
- Rely on Microfacets theory [CT82]



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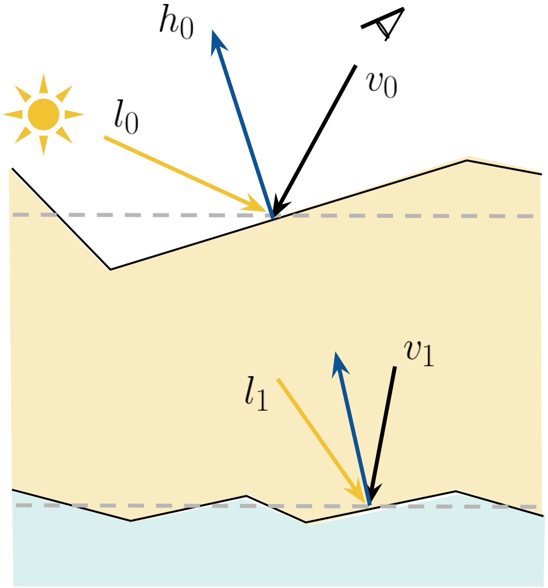

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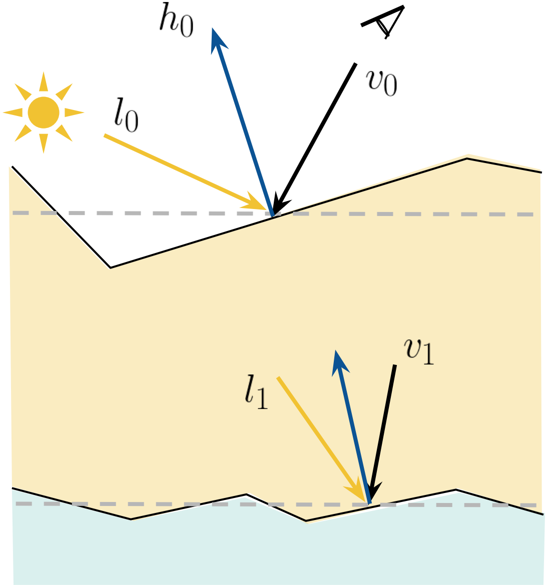
$$f_r = f_{r_0}(\boldsymbol{l}_0, \boldsymbol{v}_0) + T_{01} \cdot f_{r_1}(\boldsymbol{l}_1, \boldsymbol{v}_1) \cdot a \cdot t$$

Beer-Lambert absorption

Total internal reflection

⚠ no inter-reflections



Multi-layered models - Weidlich and Wilkie

[WW07]

Implementations :

2 variants [WW09] and [Ele10]

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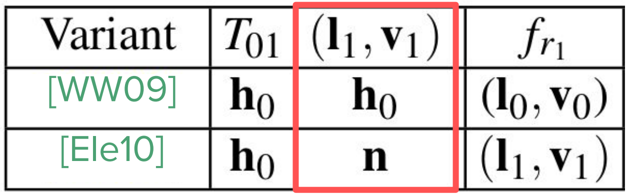

Variant	T_{01}	$(\mathbf{l}_1, \mathbf{v}_1)$	f_{r_1}
[WW09]	$\mathbf{h}_0$	$\mathbf{h}_0$	$(\mathbf{l}_0, \mathbf{v}_0)$
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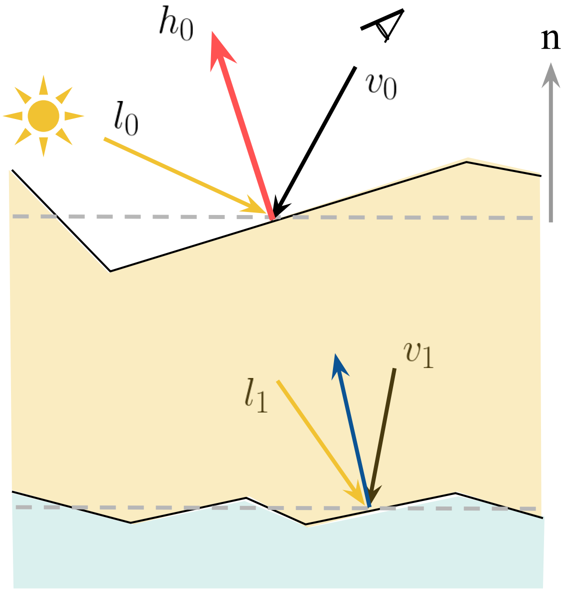

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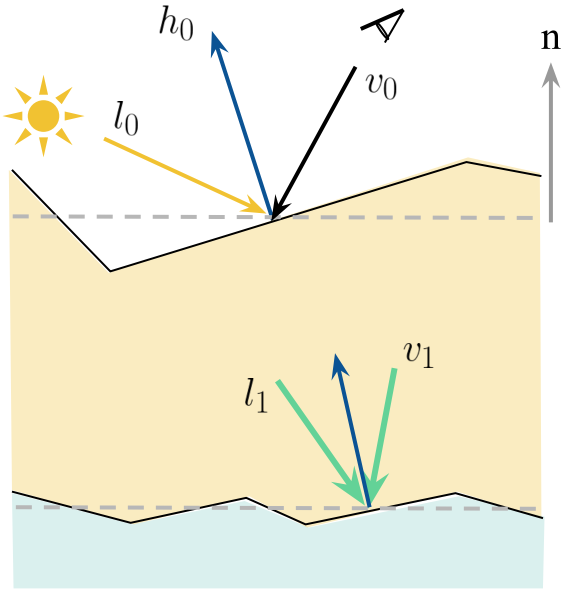
← **bug / feature ?**

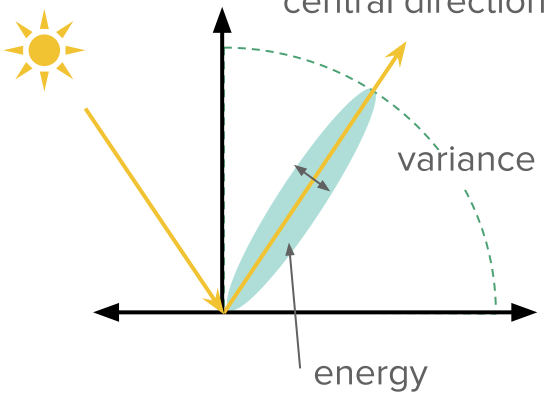


[Ele10]: $\text{roughness}_1 \leftarrow \text{MAX}(\text{roughness}_0, \text{roughness}_1)$

Multi-layered models - Belcour

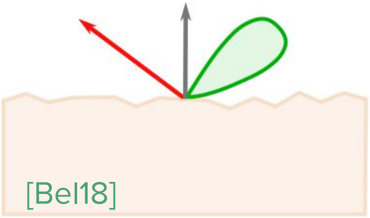
[Bel18]

- Tracing of (Gaussian) light beam through layers



- Impact of reflection, transmission, absorption & scattering

  with inter-reflections & multiple scattering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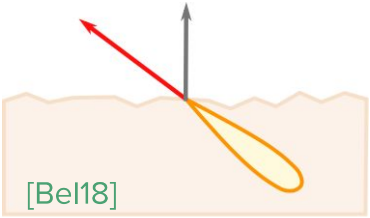
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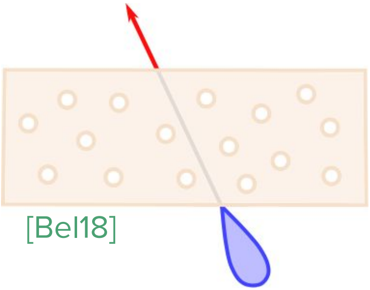

[Bel18]

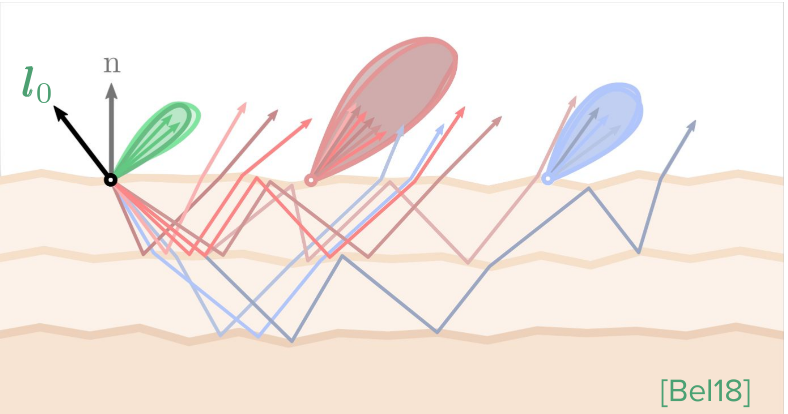
⚠ only forward propagation for scattering

Multi-layered models - Belcour

[Bel18]

- Resulting BRDF = weighted sum of GGX lobes

$$f_r^B(\boldsymbol{l}_0, \boldsymbol{v}_0) = \sum_{\text{layer } k} \underset{\underset{\text{energy}}{\uparrow}}{e_k(\boldsymbol{l}_0)} \cdot GGX(\boldsymbol{l}_0, \boldsymbol{v}_0; \underset{\underset{\text{variance}}{\uparrow}}{\alpha_k}(\boldsymbol{l}_0))$$



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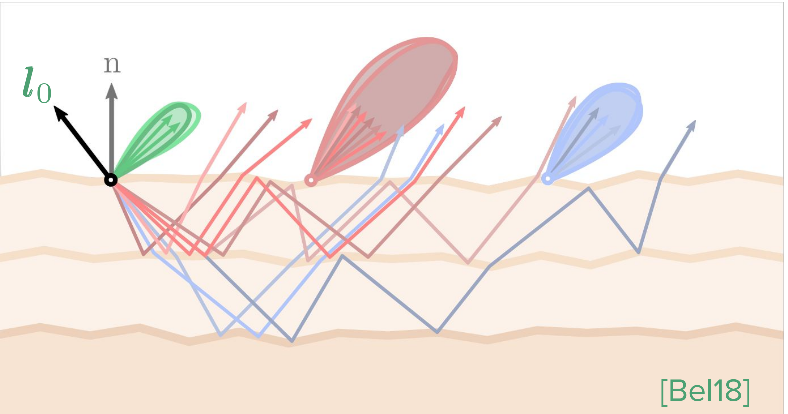


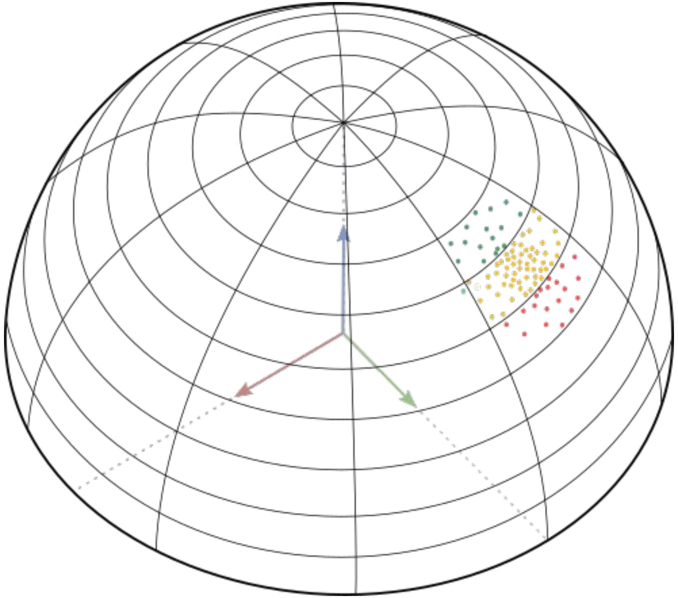
- *Forward* and *symmetric* variants

✓ Reciprocal

✗ No obvious interpretation, no BTDF

How accurate are these models ?

Numerical evaluation



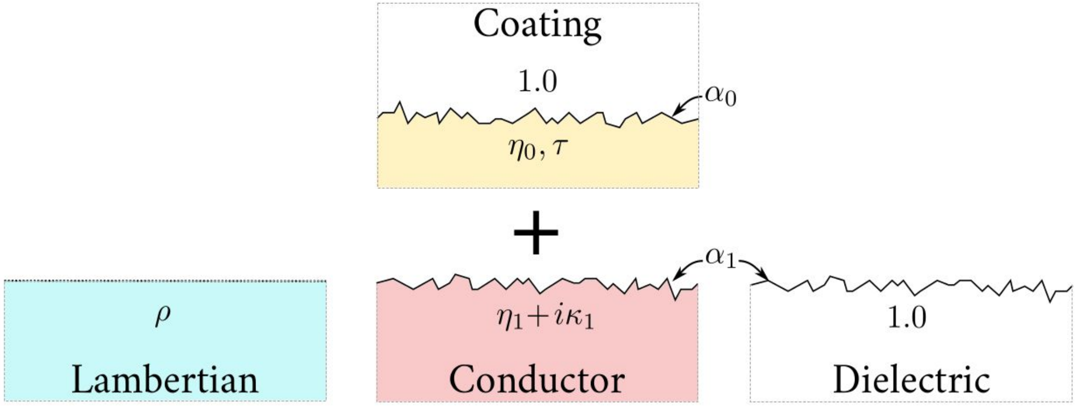
- Virtual goniospectrophotometer
  - Particles tracing through layers: Monte-Carlo
  - Interactions with
    - interfaces: Microfacet theory
    - media: Beer-Lambert law

  - BRDF / BTDF obtained with **density estimation**
    - discretized hemisphere

- Compared to
  - Numerical Integration of models on **same discretized hemisphere**

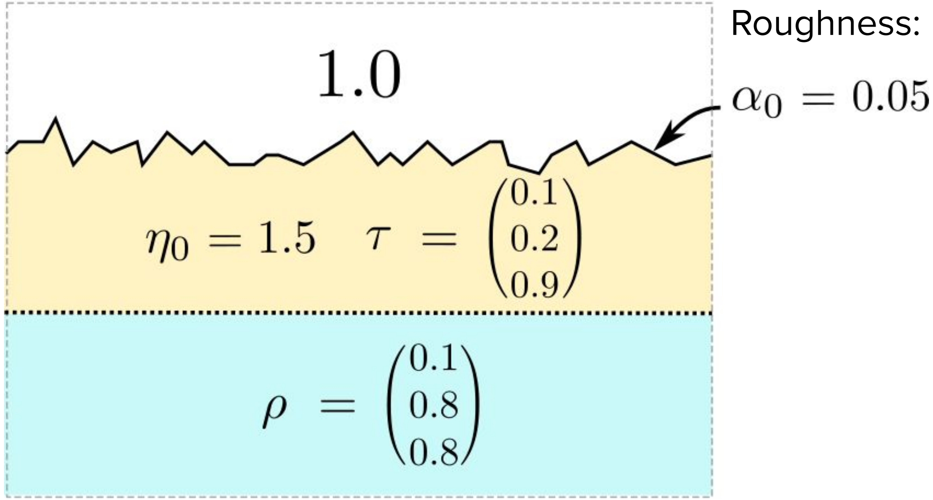
Numerical evaluation

- 3 layered material categories with 2 interfaces ➜ 60 configurations



	Plastics	Metals	Slabs
#configurations =	12	36	12

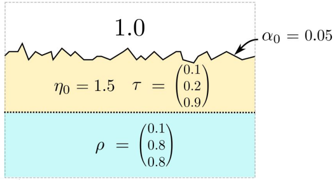
Plastic Configuration



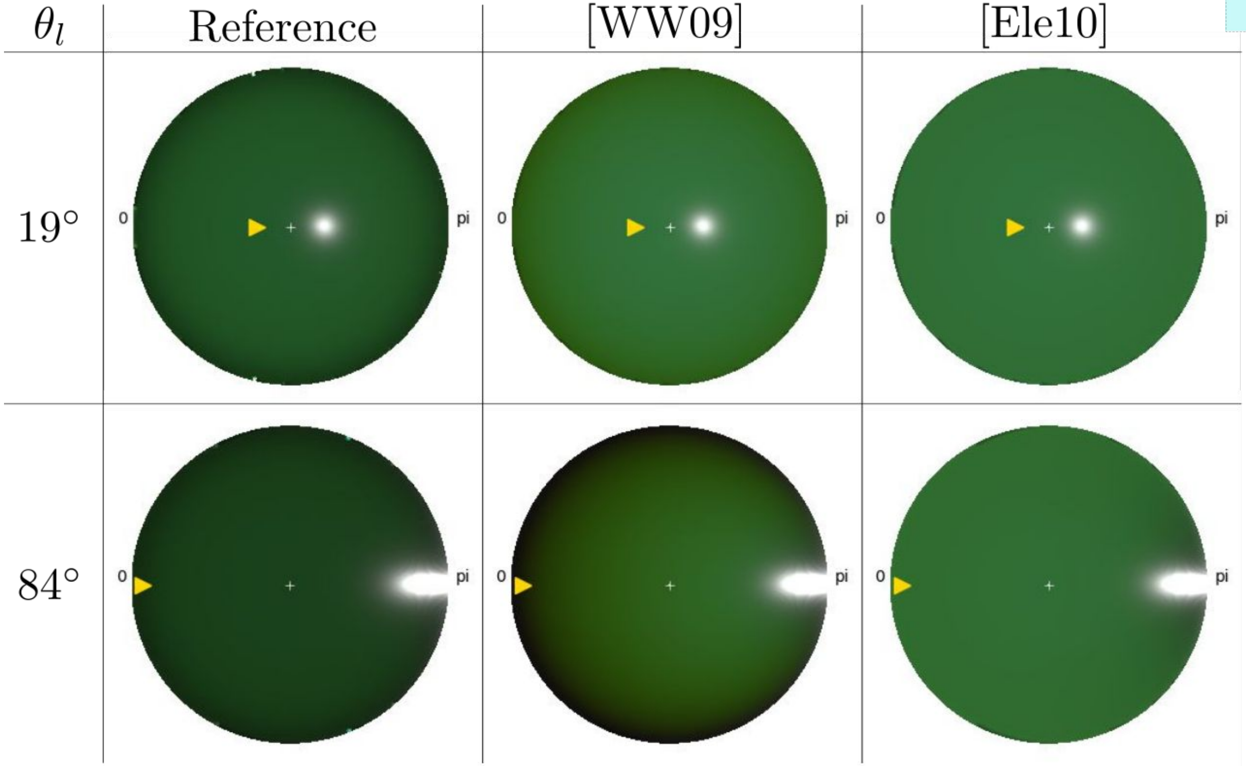
Dielectric

Lambertian

Plastic

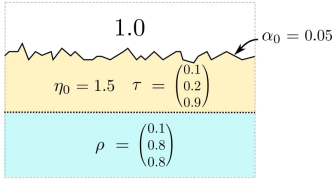


1.0
$\alpha_0 = 0.05$
$\eta_0 = 1.5 \quad \tau = \begin{pmatrix} 0.1 \\ 0.2 \\ 0.9 \end{pmatrix}$
$\rho = \begin{pmatrix} 0.1 \\ 0.8 \\ 0.8 \end{pmatrix}$



θ_l
Reference
[WW09]
[Ele10]
19°
84°
0
pi

Plastic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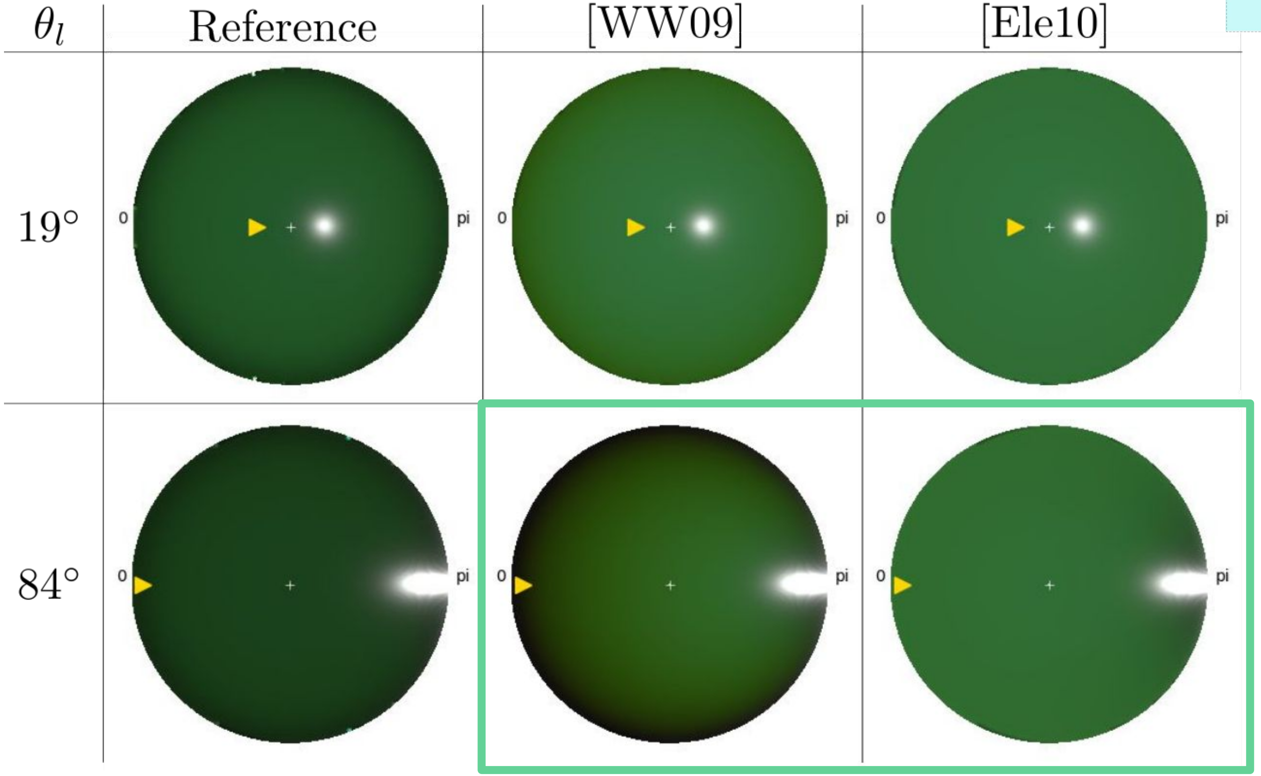
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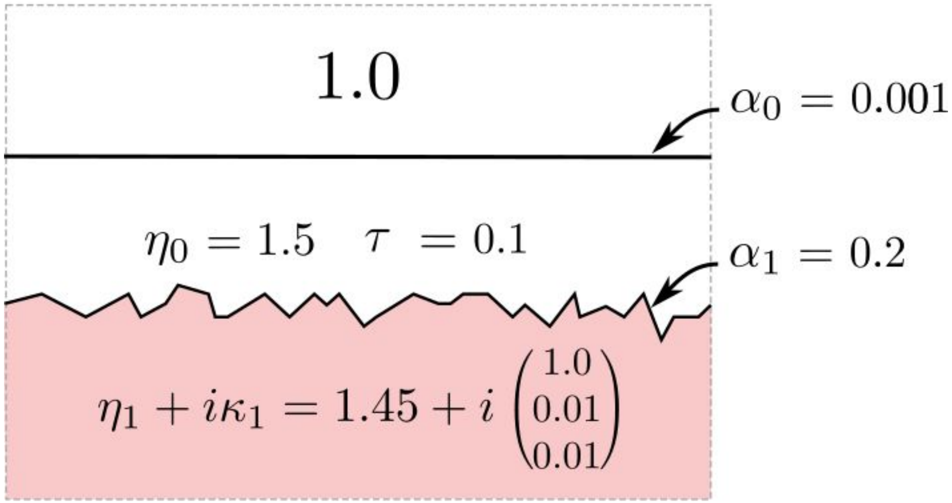
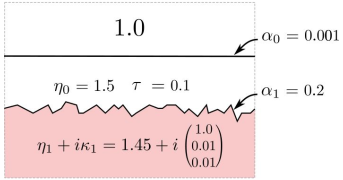
Metallic paint

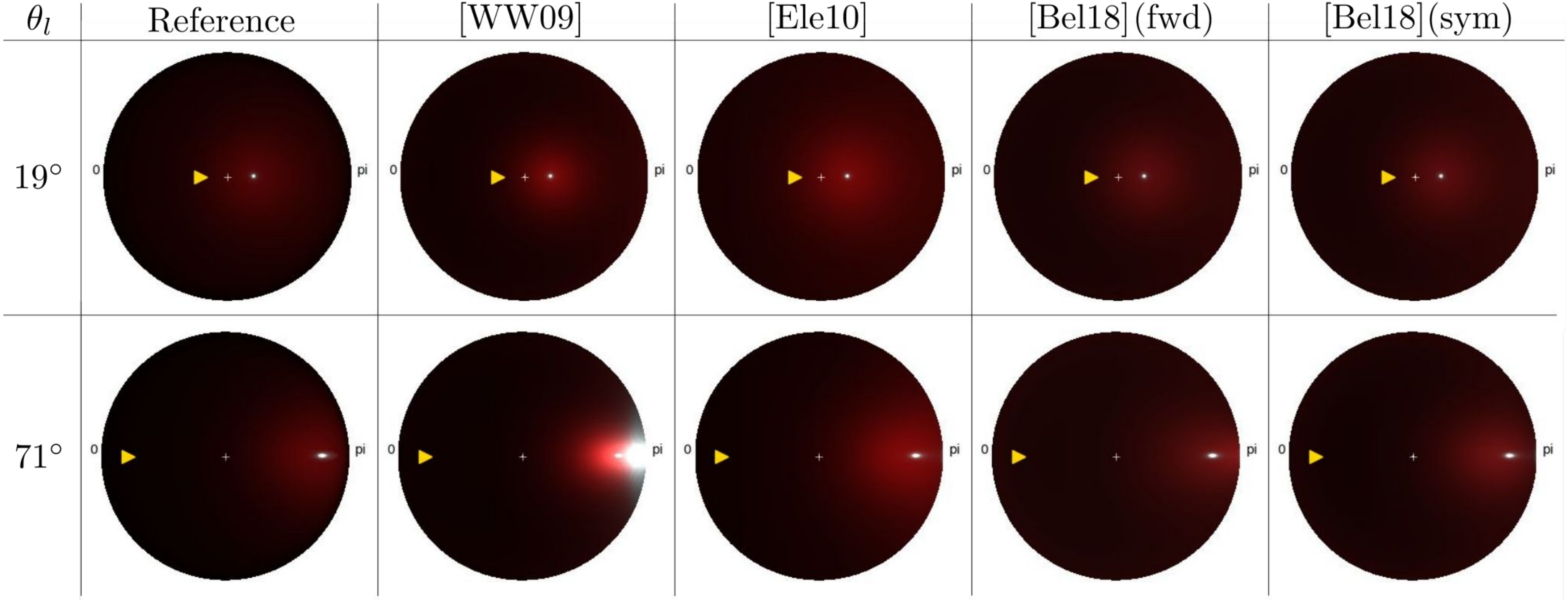


Smooth
dielectric

Rough
conductor

Metallic paint





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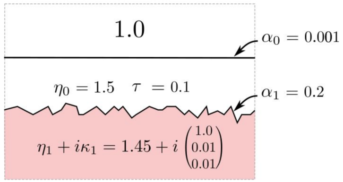

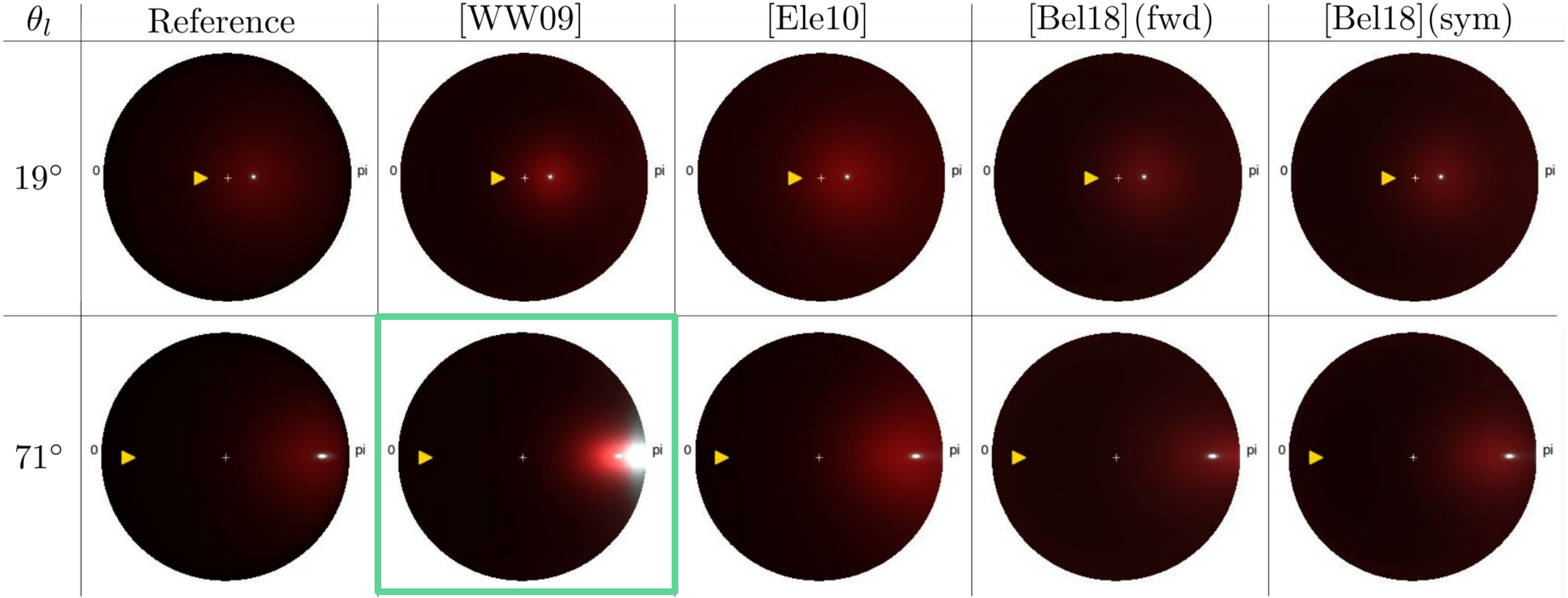

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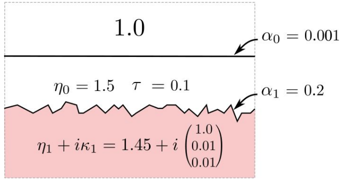

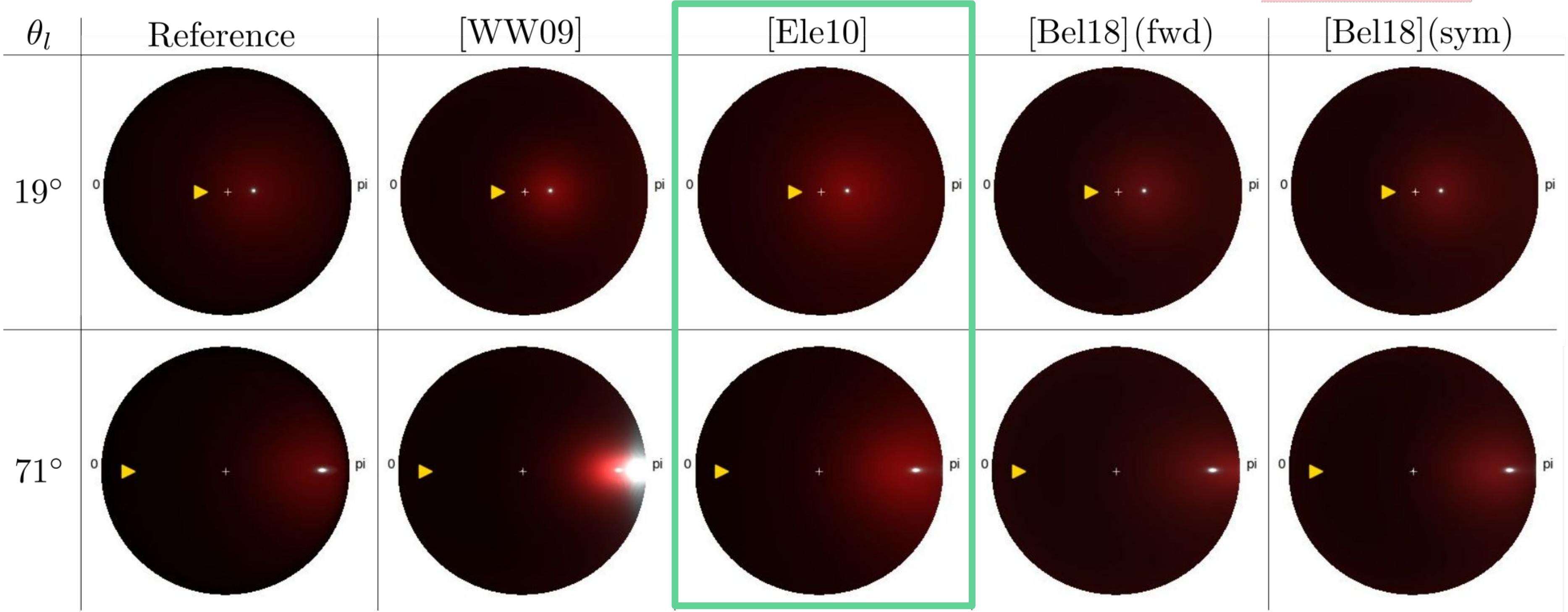

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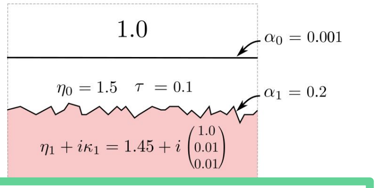
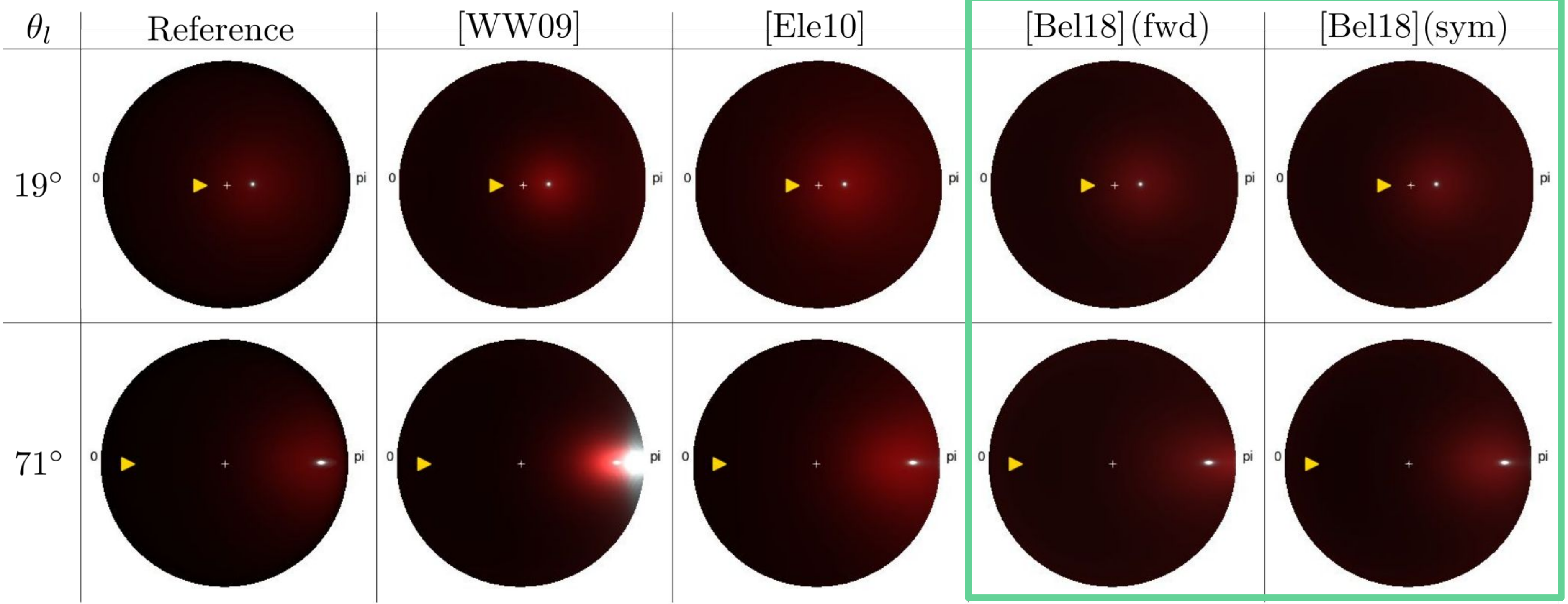
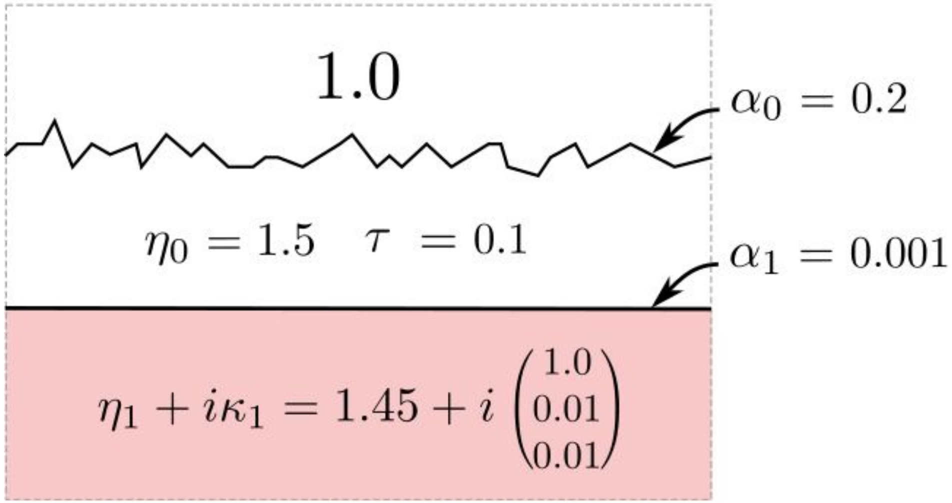




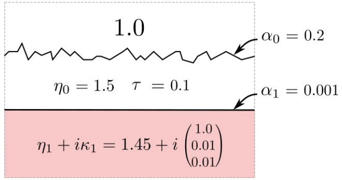
Frosted metal

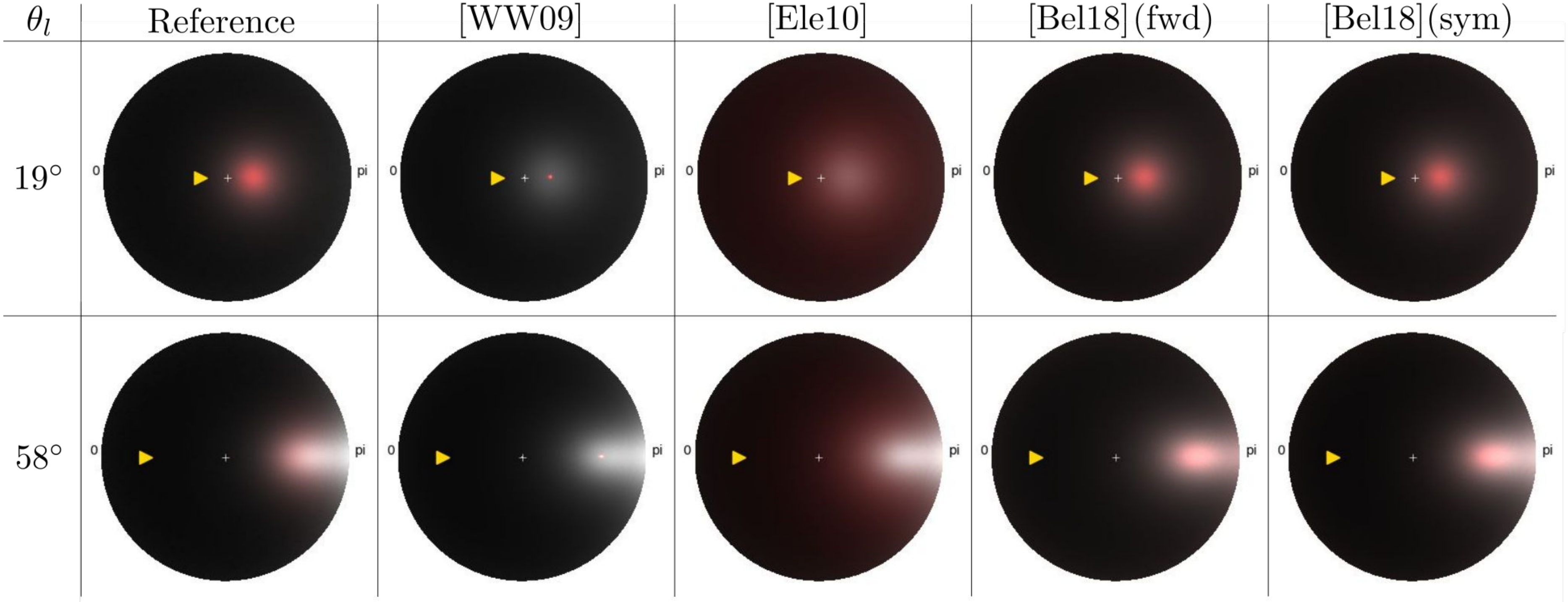


Rough dielectric

Smooth conductor

Frosted metal





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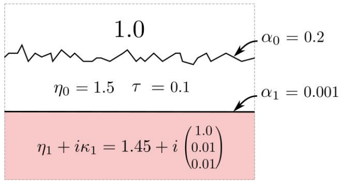

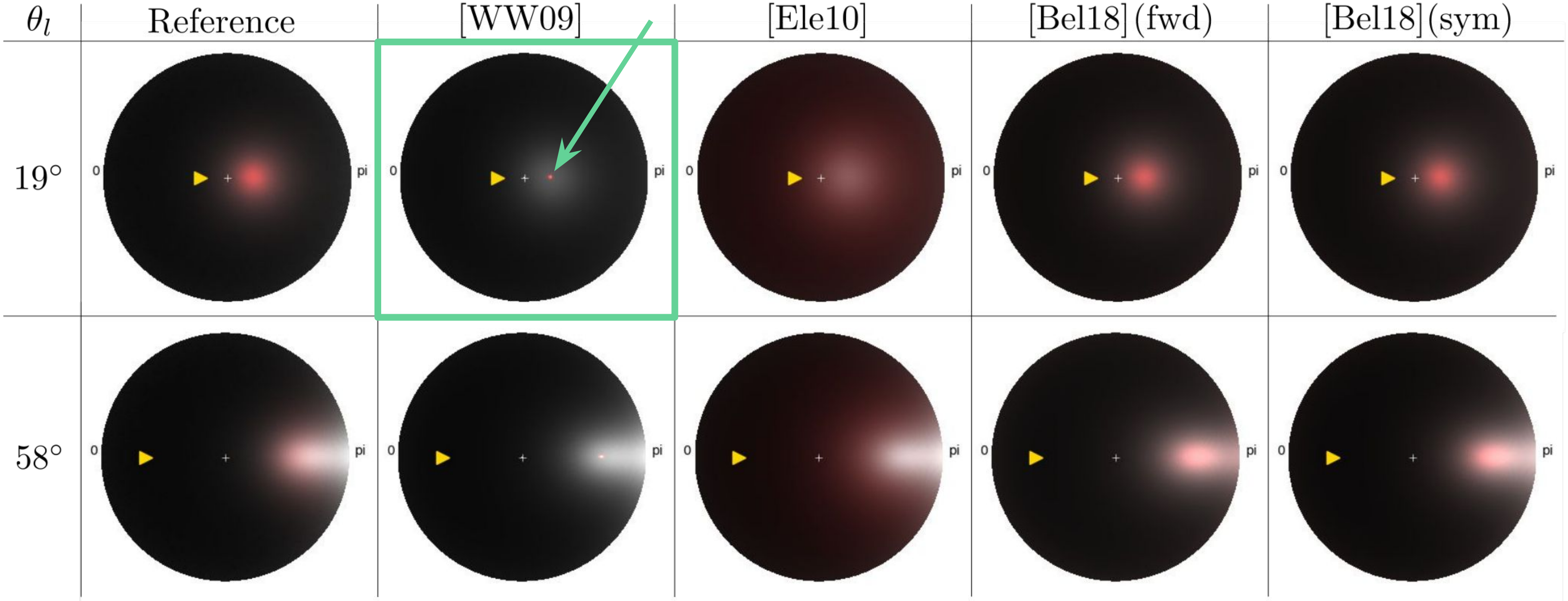

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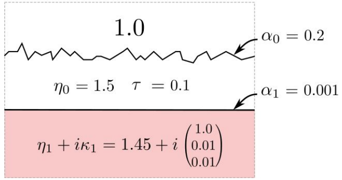

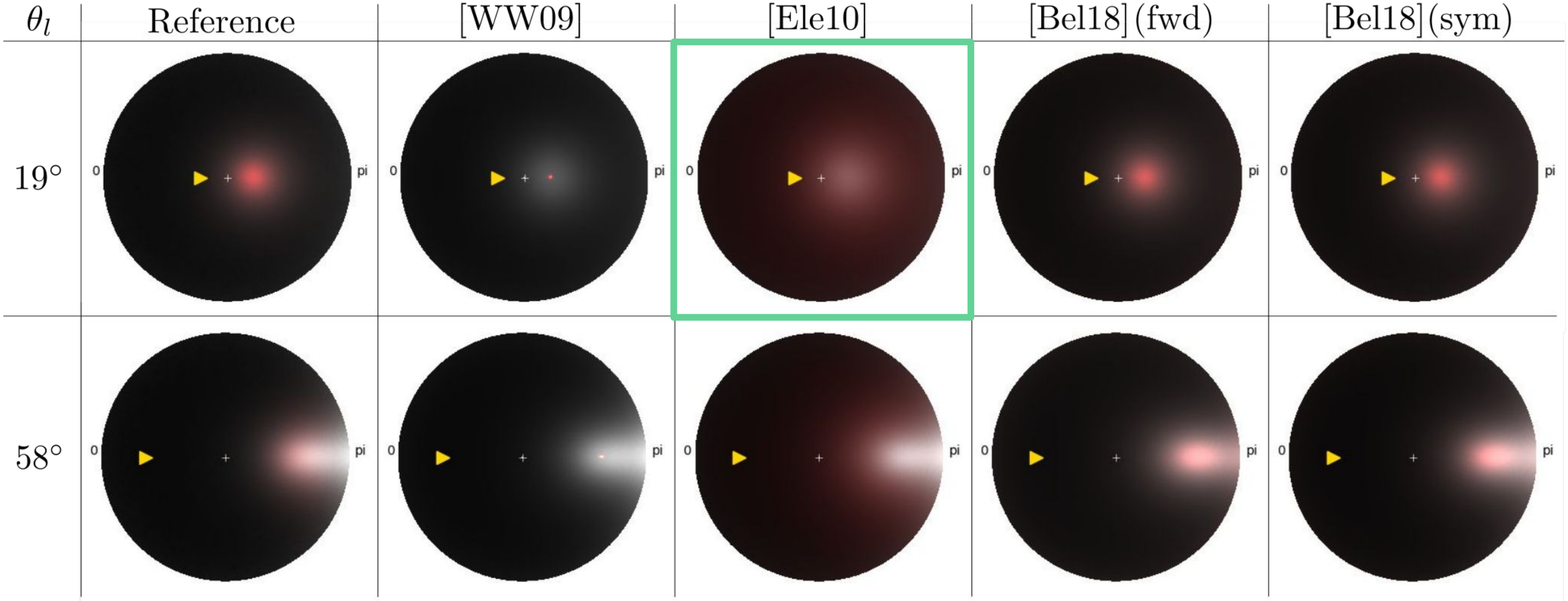

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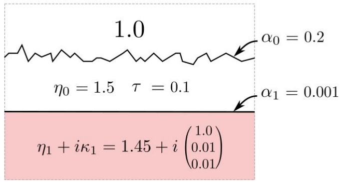

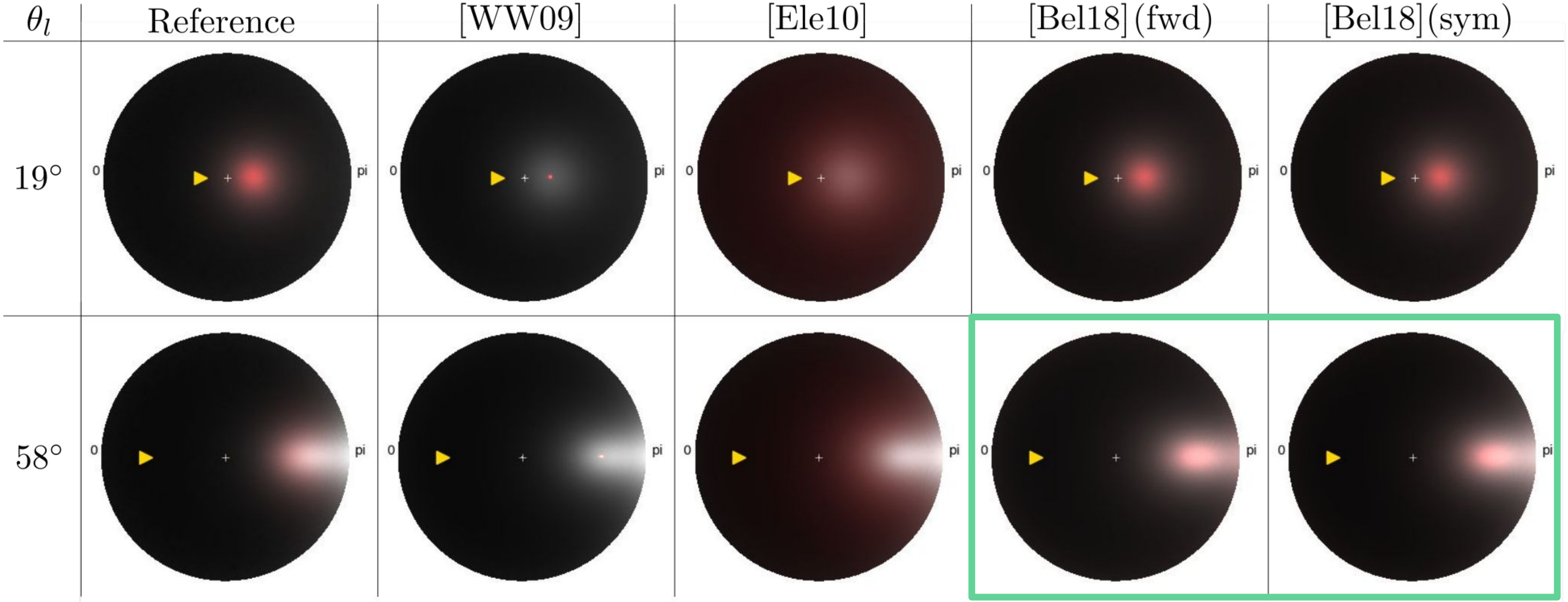

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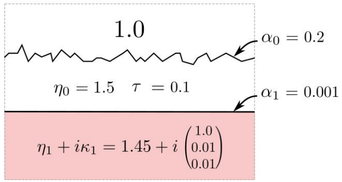
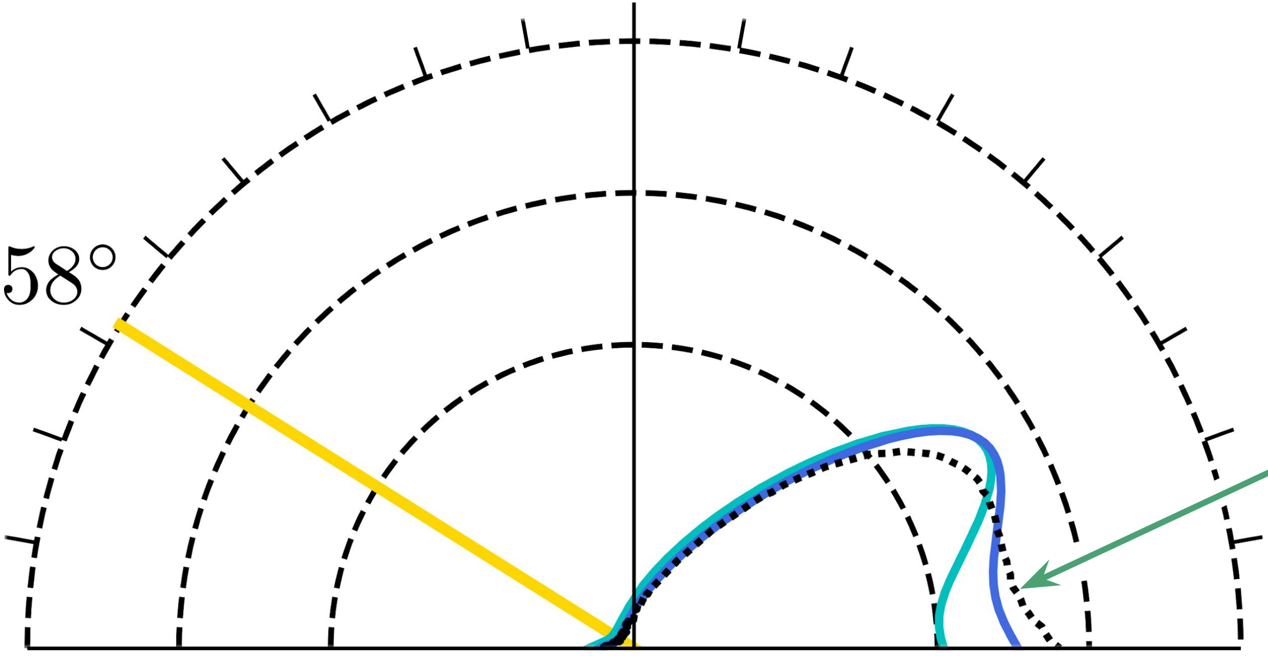
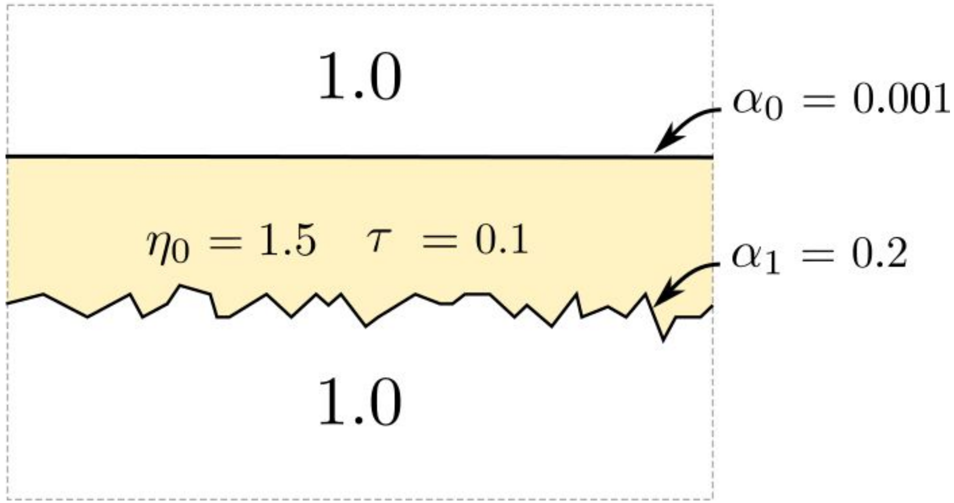




Reference

[Bel18] (fwd) [Bel18] (sym)

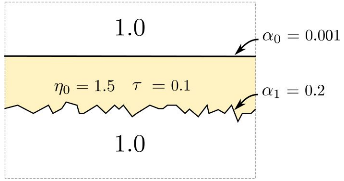
Slab (transmission)

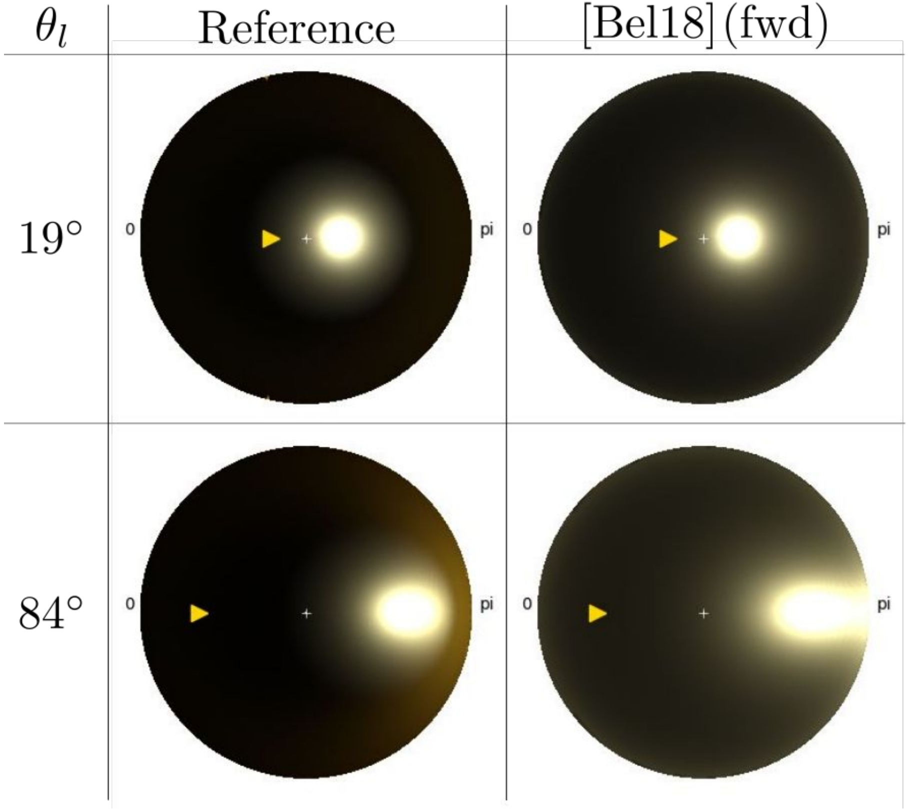


Smooth dielectric

Rough interface with **AIR**

Slab (transmission)





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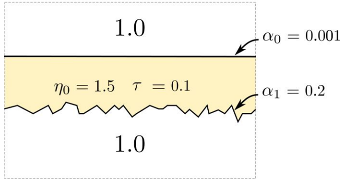

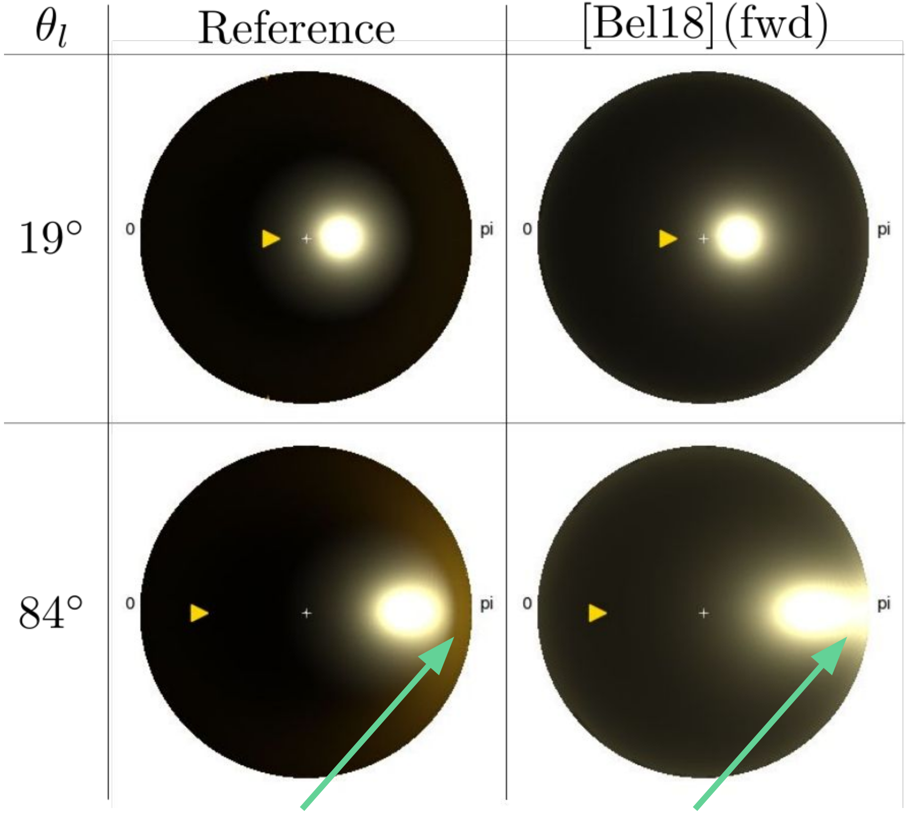

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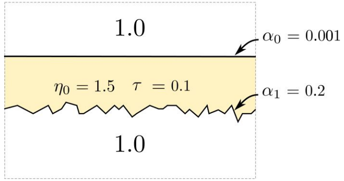

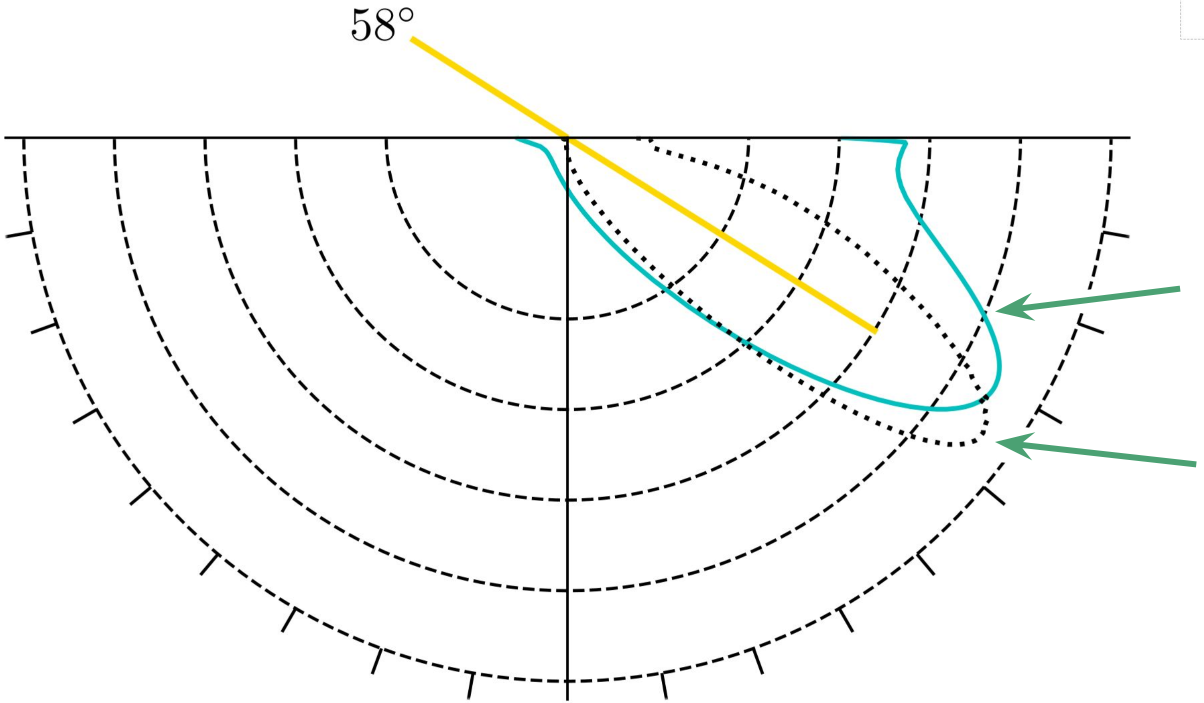

[Bel18] (fwd)

Reference

What can easily be fixed ?

(Slightly) Improved models

WW':

- Apply Snell's law to solid angles [HK93]
    - → $f_r^{WW'}(\mathbf{l}_0, \mathbf{v}_0) = f_{r_0}(\mathbf{l}_0, \mathbf{v}_0) + T_{01}\, f_{r_1}(\mathbf{l}_1, \mathbf{v}_1) \boxed{\frac{a}{\eta_1^2}} T_{10}$

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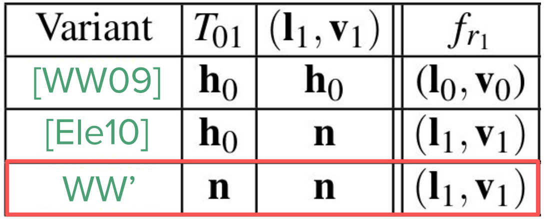
- Transmission based on geometric normal



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WW'	$\mathbf{n}$	$\mathbf{n}$	$(\mathbf{l}_1, \mathbf{v}_1)$

- [Ele10]'s max roughness

(Slightly) Improved models

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- Apply Snell's law to solid angles [HK93]

→ $f_r^{WW'}(\mathbf{l}_0, \mathbf{v}_0) \;=\; f_{r_0}(\mathbf{l}_0, \mathbf{v}_0) + T_{01}\, f_{r_1}(\mathbf{l}_1, \mathbf{v}_1)\, \frac{a}{\eta_1^2}\, T_{10}$

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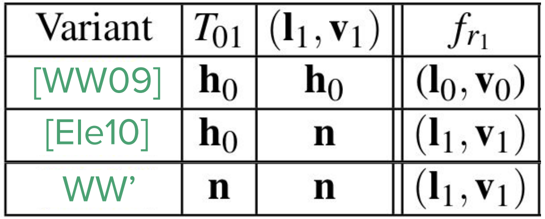

Variant	T_{01}	$(\mathbf{l}_1, \mathbf{v}_1)$	f_{r_1}
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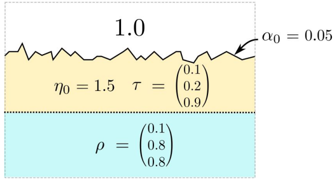
[Ele10]	$\mathbf{h}_0$	$\mathbf{n}$	$(\mathbf{l}_1, \mathbf{v}_1)$
WW'	$\mathbf{n}$	$\mathbf{n}$	$(\mathbf{l}_1, \mathbf{v}_1)$

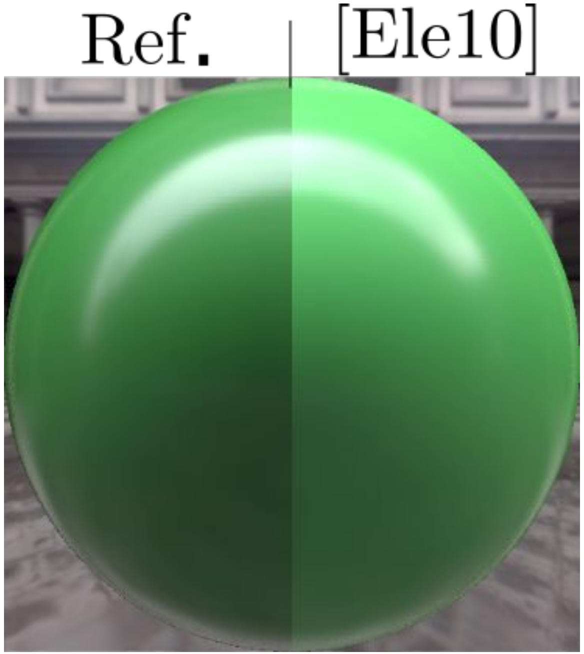
- [Ele10]'s max roughness

Bel' (fwd):

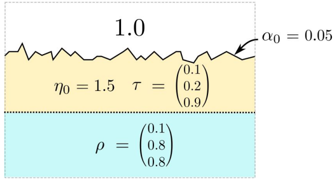
- Use exact model for 1st reflection

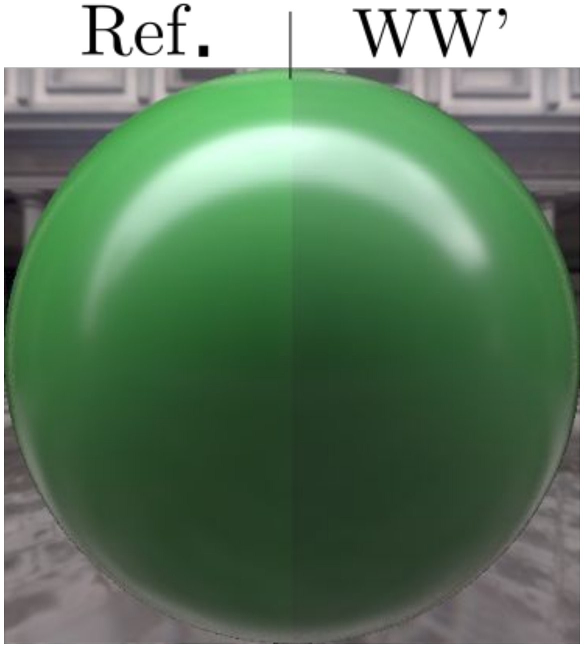
Improved models - Plastic



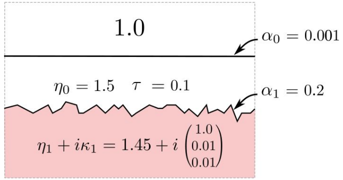


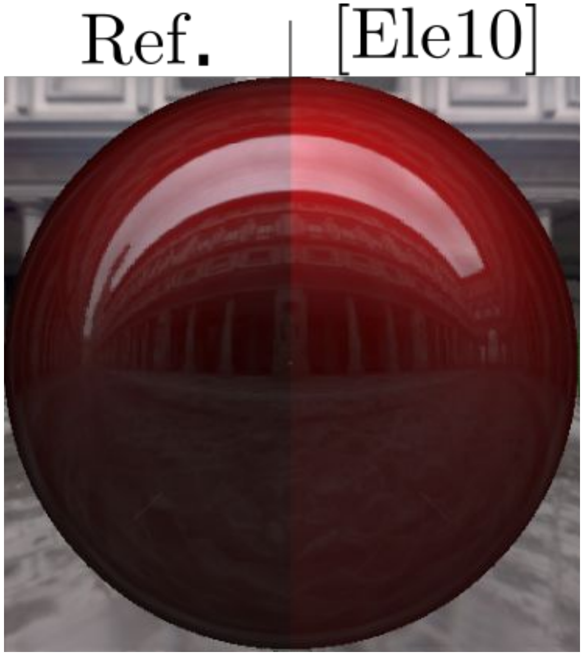
Improved models - Plastic





Improved models - Metallic paint





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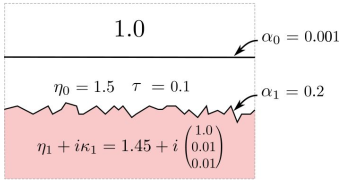
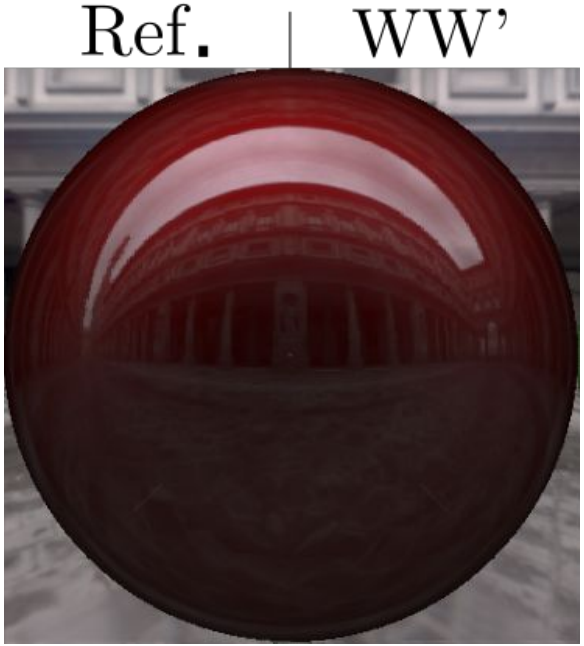
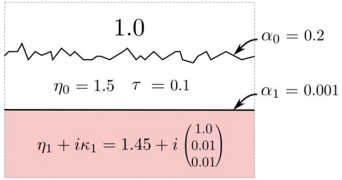
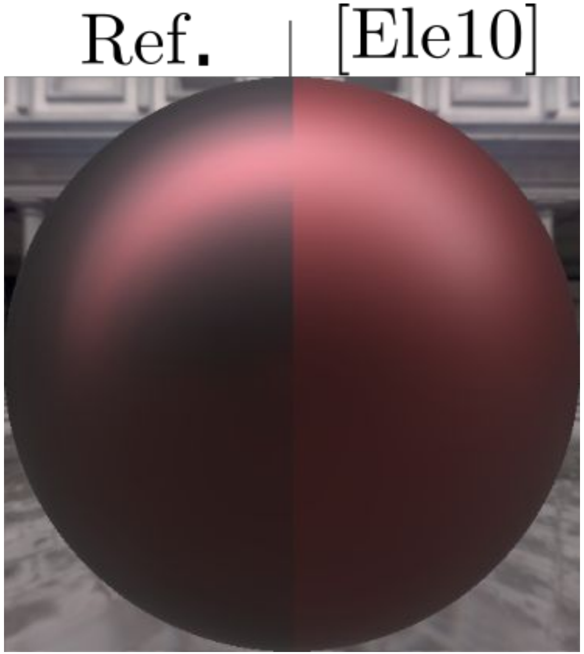




Improved models - Frosted metal





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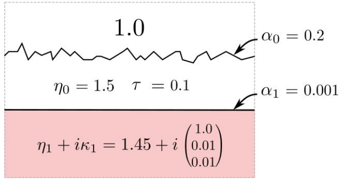

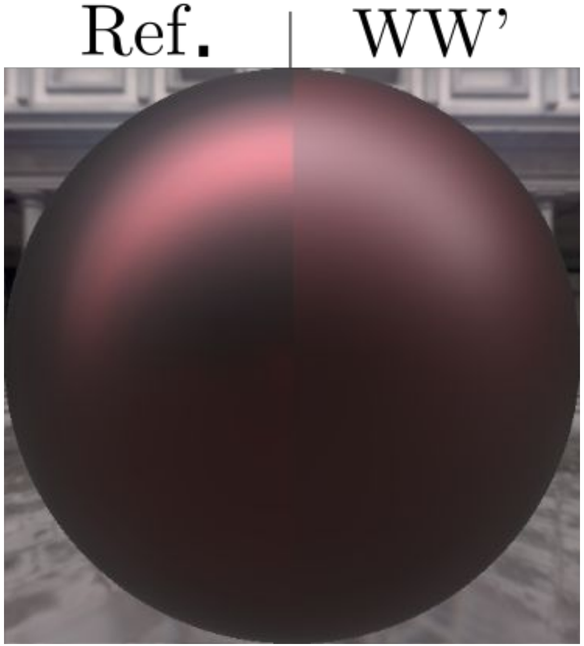

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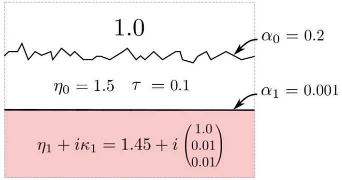

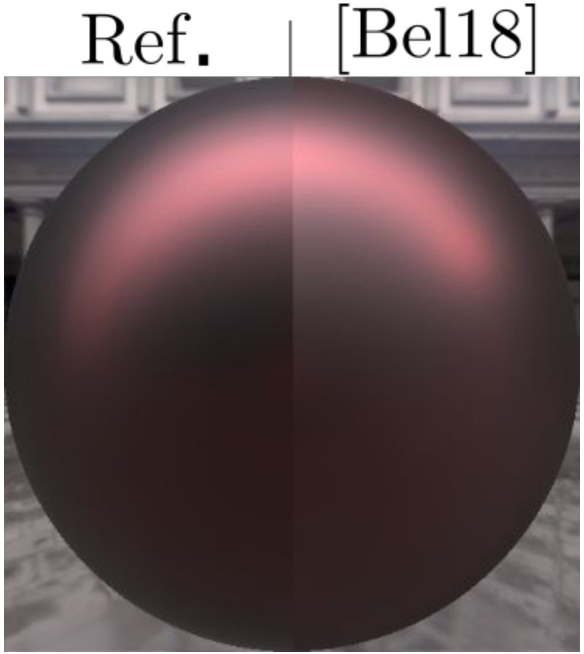

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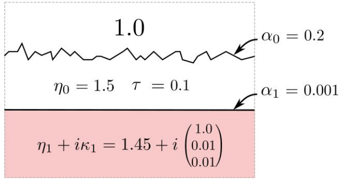
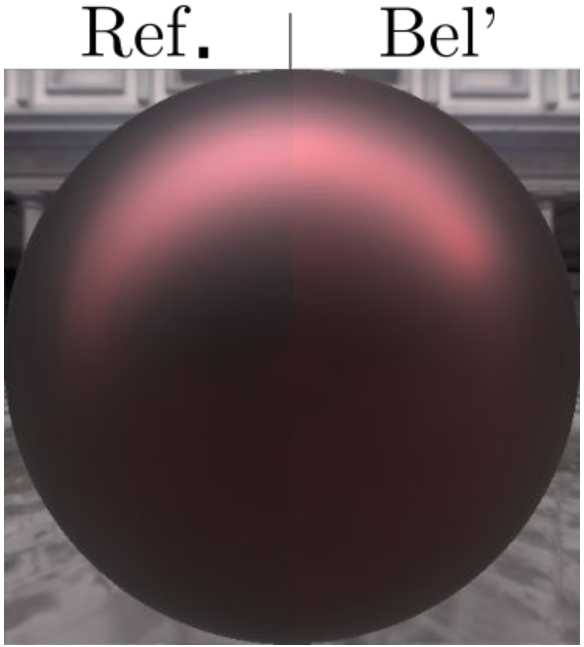


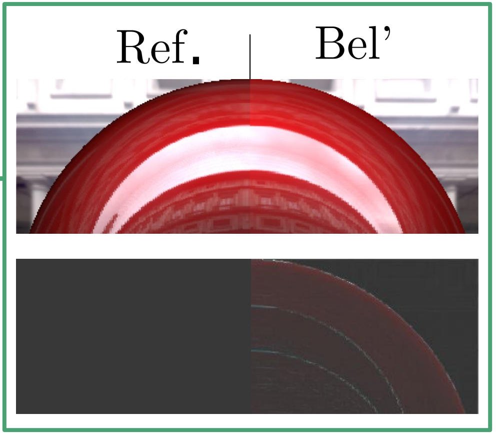


Conclusions - Supported layers

	WW’	Bel’
Slabs / BTDF	❌	✓
Lambertian / Plastics	✓	❌
Scattering in media	❌	only forward

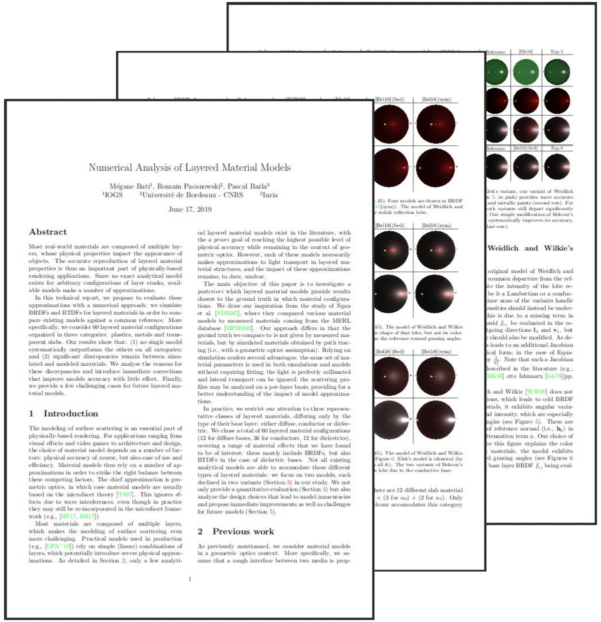
Conclusions - Approximations assessment

	WW’	Bel’
Smooth transmission	😃	🙂
Rough transmission	😞	🙂
Multiple bounces	❌	😐



Future Work

- Combine [WW07] and [Bel18] into a **new layered material model**
- Handle more complex materials / physical phenomena
  - Anisotropy & inter-reflections at interfaces
  - Back scattering in media
  - Spectral shift, polarisation, fluorescence
  - Thin films, interference, diffraction



Numerical Analysis of Layered Material Models

Mégane Bati[1], Romain Pacanowski[2], Pascal Barla[3]
[1]IOGS [2]Université de Bordeaux - CNRS [3]Inria

June 17, 2019

Abstract

Most real-world materials are composed of multiple layers, whose physical properties impact the appearance of objects. The accurate reproduction of layered material properties is thus an important part of physically-based rendering applications. Since no exact analytical model exists for arbitrary configurations of layer stacks, available models make a number of approximations.

In this technical report, we propose to evaluate these approximations with a numerical approach: we simulate BRDFs and BTDFs for layered materials in order to compare existing models against a common reference. More specifically, we consider 60 layered material configurations organized in three categories: plastics, metals and transparent slabs. Our results show that: (1) no single model systematically outperforms the others on all categories; and (2) significant discrepancies remain between simulated and modeled materials. We analyse the reasons for these discrepancies and introduce immediate corrections that improve models accuracy with little effort. Finally, we provide a few challenging cases for future layered material models.

1 Introduction

The modeling of surface scattering is an essential part of physically-based rendering. For applications ranging from visual effects and video games to architecture and design, the choice of material model depends on a number of factors: physical accuracy of course, but also ease of use and efficiency. Material models thus rely on a number of approximations in order to strike the right balance between these competing factors. The chief approximation is geometric optics, in which case material models are usually based on the microfacet theory [TS67]. This ignores effects due to wave interferences, even though in practice they may still be re-incorporated in the microfacet framework (e.g., [HP17, BB17]).

Most materials are composed of multiple layers, which makes the modeling of surface scattering even more challenging. Practical models used in production (e.g., [GPA+19]) rely on simple (linear) combinations of layers, which potentially introduce severe physical approximations. As detailed in Section 2, only a few analytical layered material models exist in the literature, with the *a priori* goal of reaching the highest possible level of physical accuracy while remaining in the context of geometric optics. However, each of these models necessarily makes approximations to light transport in layered material structures, and the impact of these approximations remains, to date, unclear.

The main objective of this paper is to investigate *a posteriori* which layered material models provide results closest to the ground truth in which material configurations. We draw our inspiration from the study of Ngan et al. [NDM05], where they compared various material models to measured materials coming from the MERL database [MPBM03]. Our approach differs in that the ground truth we compare to is not given by measured materials, but by simulated materials obtained by path tracing (i.e., with a geometric optics assumption). Relying on simulation confers several advantages: the same set of material parameters is used in both simulations and models without requiring fitting; the light is perfectly collimated and lateral transport can be ignored; the scattering profiles may be analyzed on a per-layer basis, providing for a better understanding of the impact of model approximations.

In practice, we restrict our attention to three representative classes of layered materials, differing only by the type of their base layer: either diffuse, conductor or dielectric. We chose a total of 60 layered material configurations (12 for diffuse bases, 36 for conductors, 12 for dielectrics), covering a range of material effects that we have found to be of interest: these mostly include BRDFs, but also BTDFs in the case of dielectric bases. Not all existing analytical models are able to accomodate these different types of layered materials: we focus on two models, each declined in two variants (Section 3) in our study. We not only provide a quantitative evaluation (Section 4) but also analyze the design choices that lead to model innacuracies and propose immediate improvements as well as challenges for future models (Section 5).

2 Previous work

As previously mentionned, we consider material models in a geometric optics context. More specifically, we assume that a rough interface between two media is prop-

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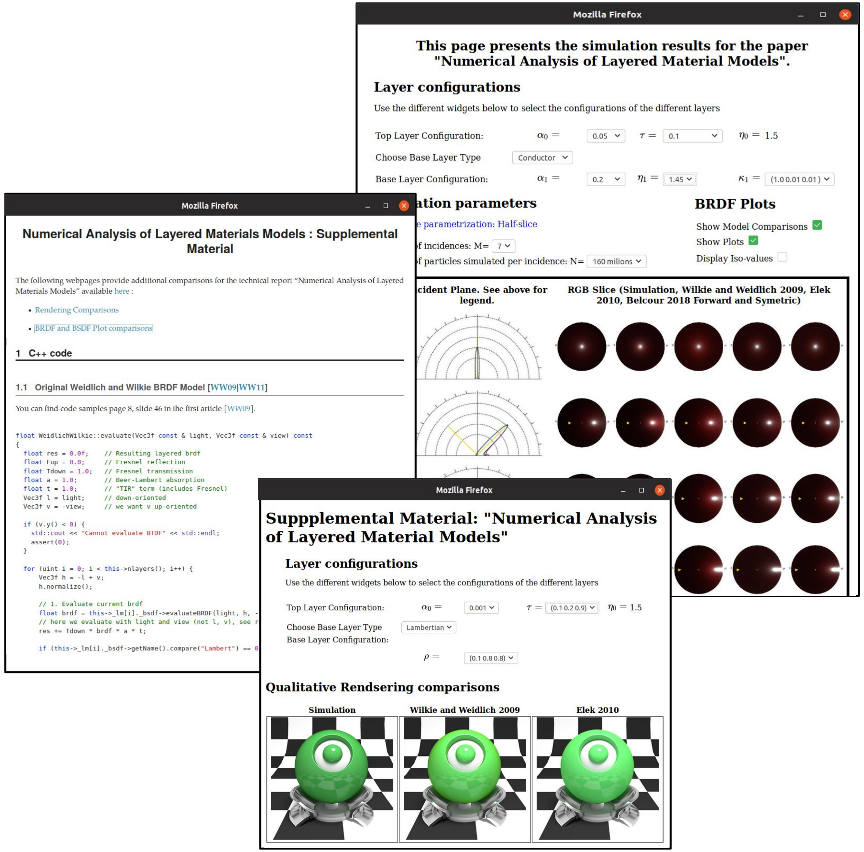

Mozilla Firefox

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BRDF Plots

Show Model Comparisons ☑

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Display Iso-values ☐

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Mozilla Firefox

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Qualitative Rendsering comparisons

Simulation

Wilkie and Weidlich 2009

Elek 2010

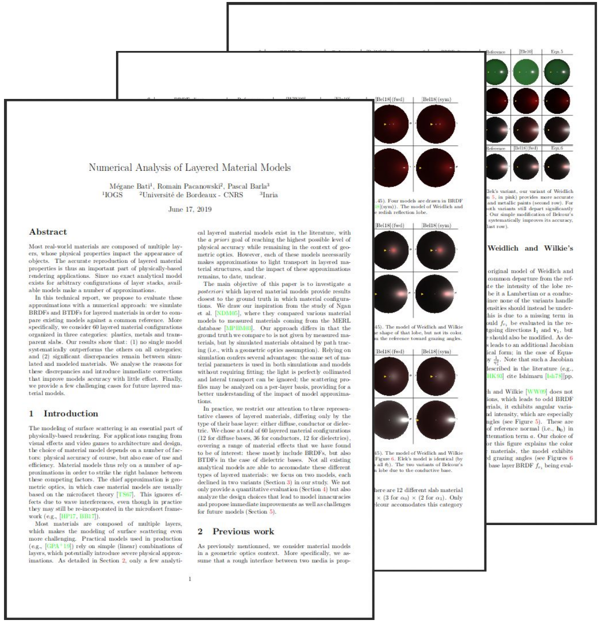
Technical report

https://hal.inria.fr/hal-02157966

Supplemental materials

Code samples, BSDF comparisons & renderings

Thank you ! Any question ?



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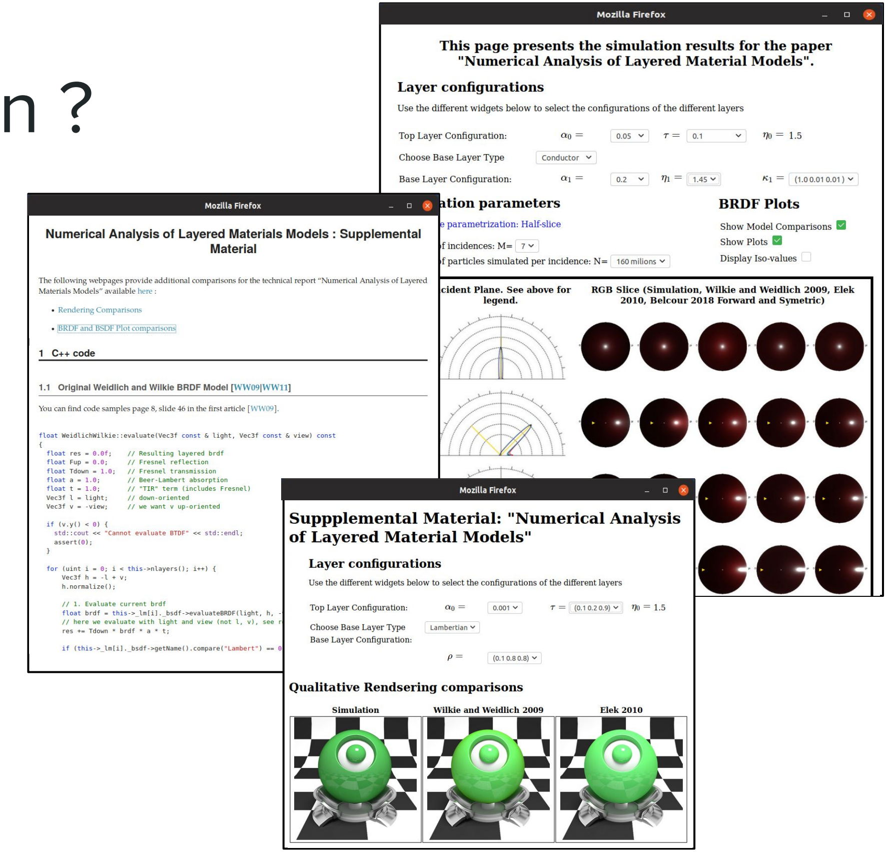

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Supplemental materials

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