Position-Free Monte Carlo Simulation for Arbitrary Layered BSDFs

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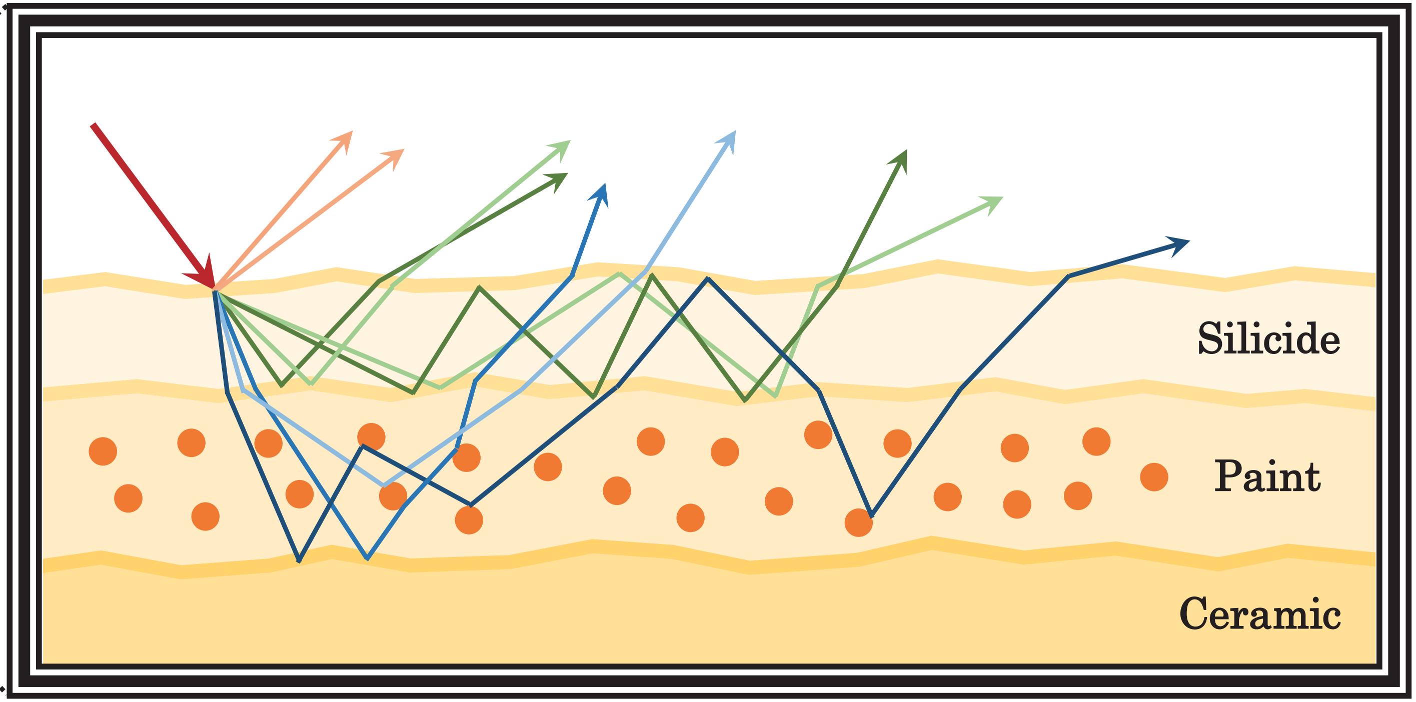
Layered Materials

Metal Wood Plastic Ceramics Glass

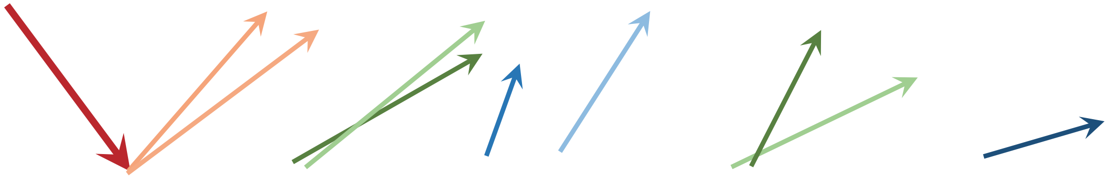
Small Displacement Assumption

Ceramic pot



Small Displacement Assumption

Ceramic pot



Small Displacement Assumption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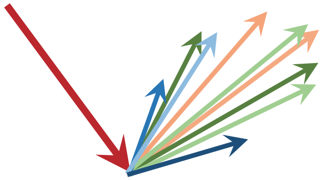
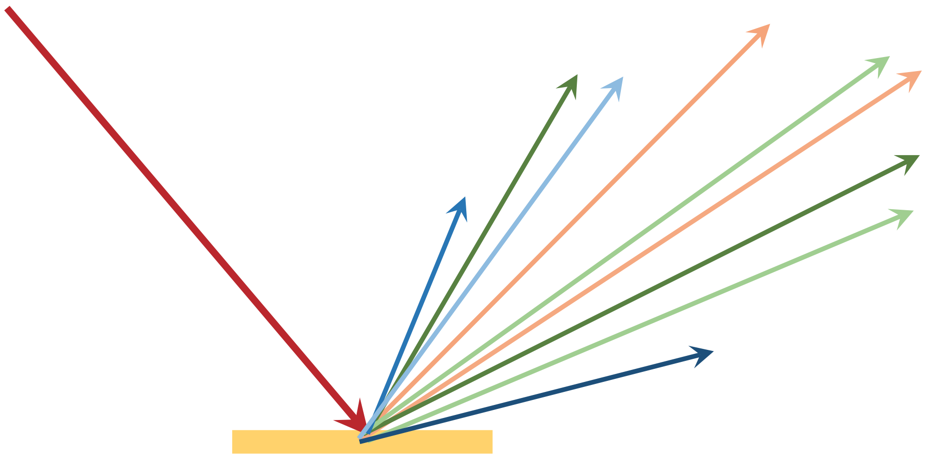


Small Displacement Assumption

Ceramic pot

BSSRDF ≈ BSDF



Prior Work

Analytical models

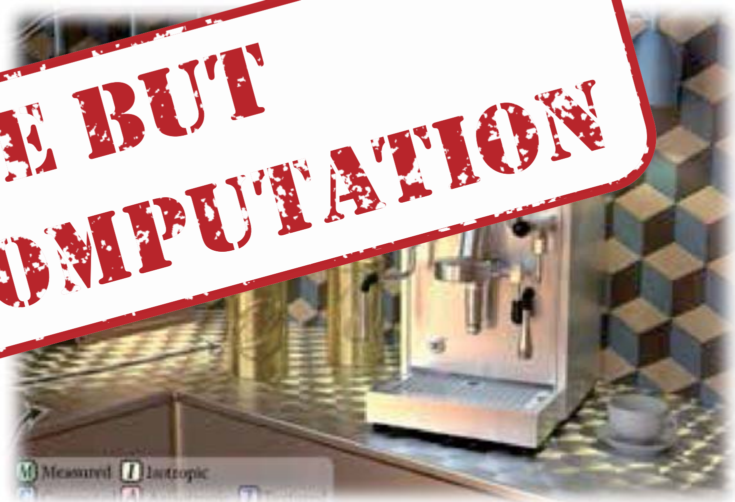
[Weidlich and Wilkie, 2007]

[Belcour, 2018]

Prior Work

Discretized models

[Jakob et al., 2014]



[Zeltner and Jakob, 2018]

ACCURATE BUT REQUIRE PRECOMPUTATION

Benefits of Our Work

Unbiased

"Reference" solution

General

Spatially variance & Arbitrary layer properties

Efficient

Faster than standard Monte Carlo methods

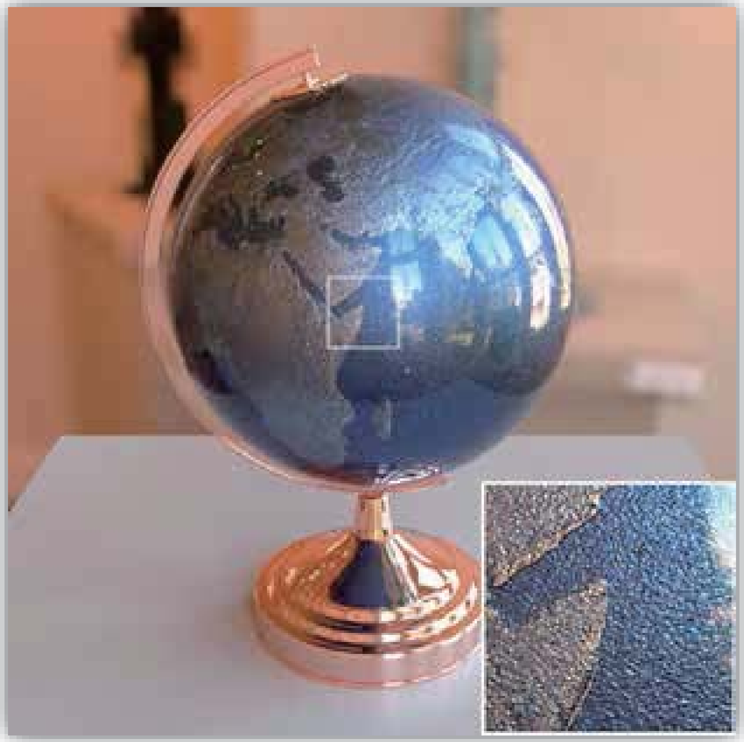
Our Contribution

Position-free formulation

$$L(z, \omega)$$

Monte Carlo estimators

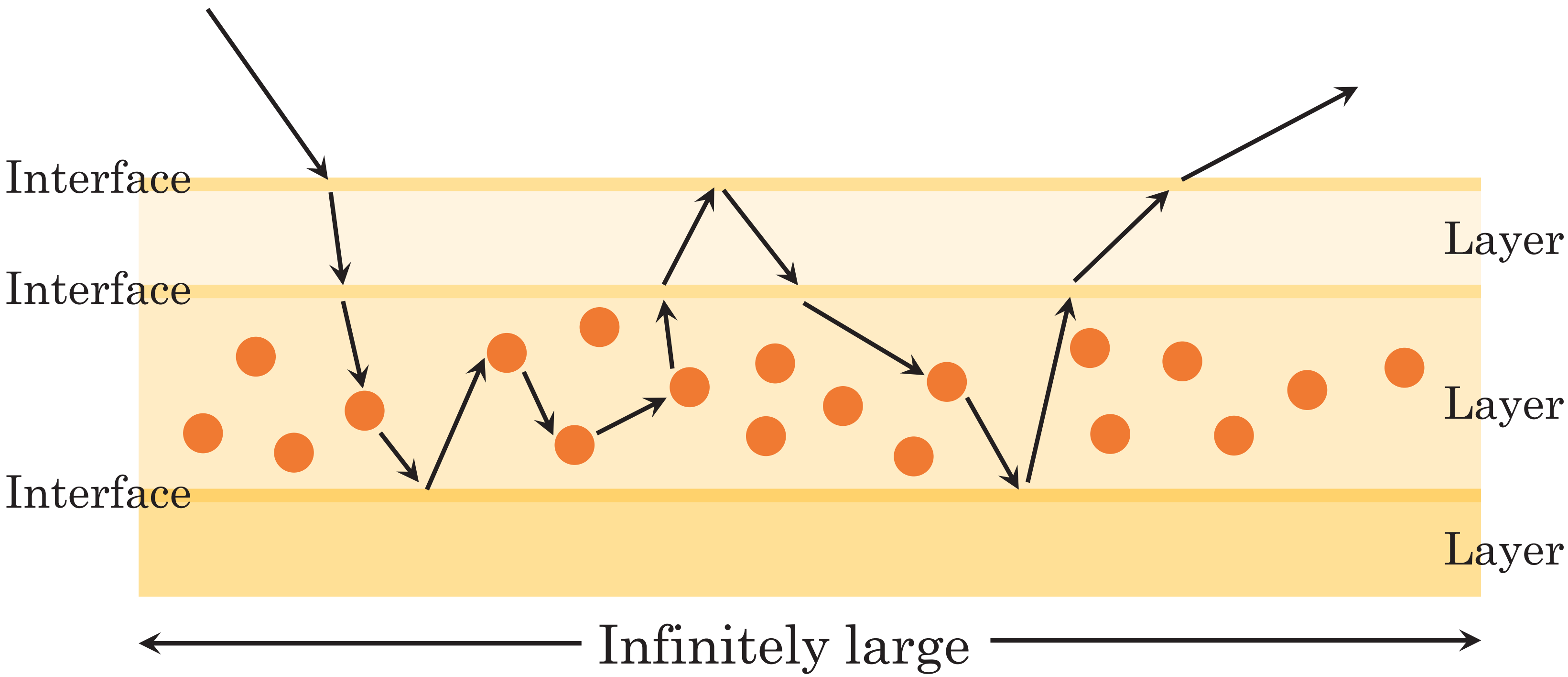
Results (Preview)



Our Method

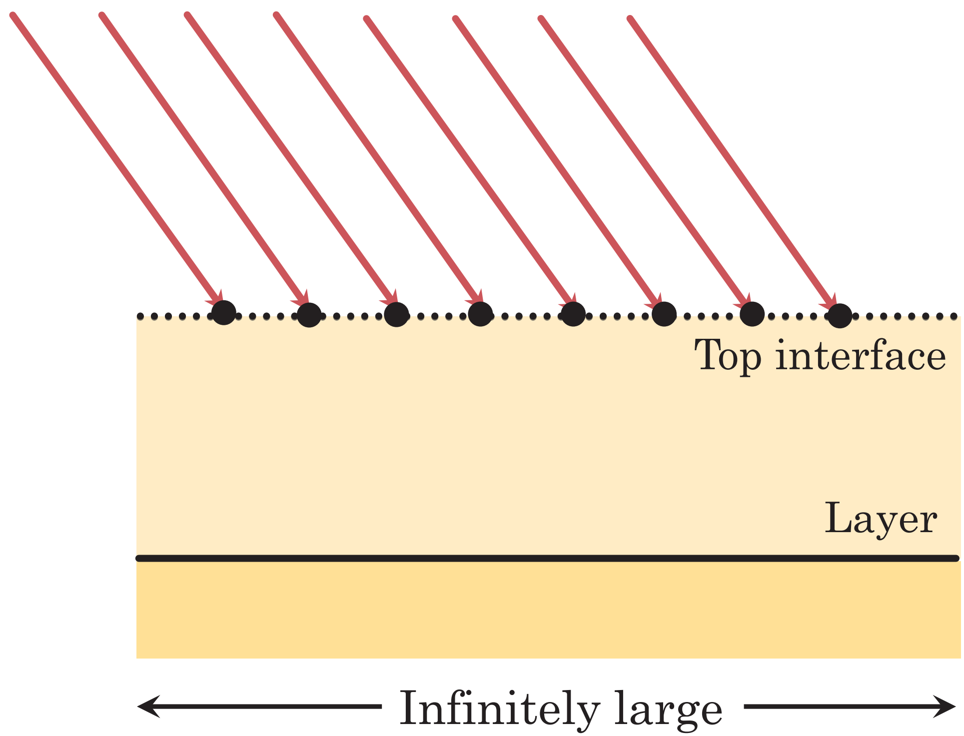
Position-Free Monte Carlo Simulation for Arbitrary Layered BSDFs

Layer Configuration



Position-Free Formulation

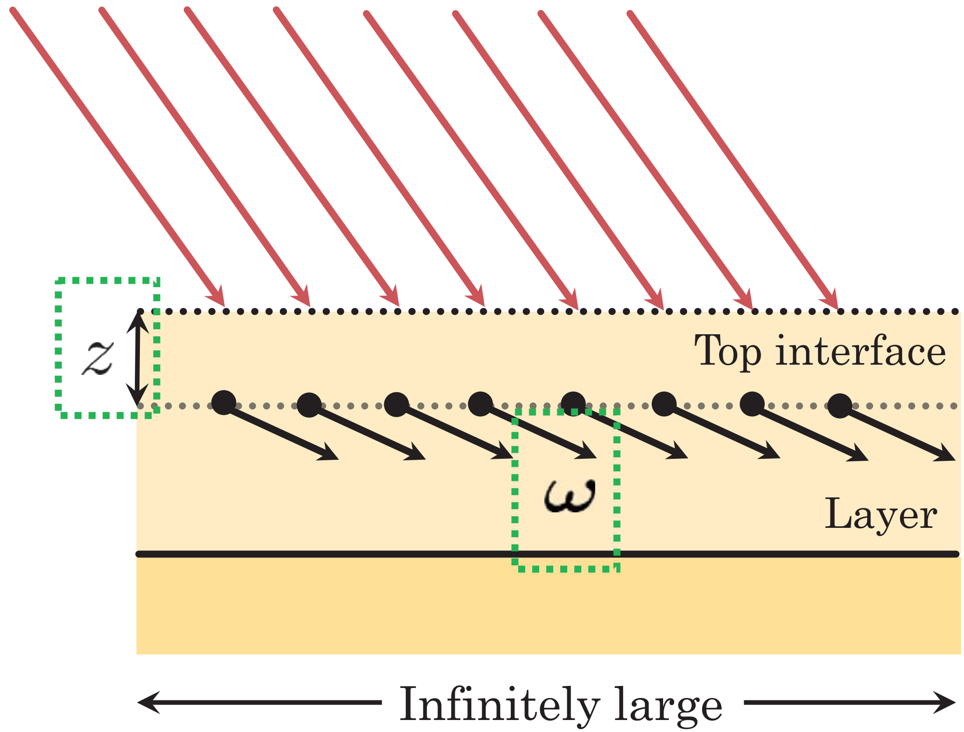
Light enters the layer from one given direction



Position-Free Formulation

Key observation:

$$\begin{aligned} L(\boldsymbol{r}, \boldsymbol{\omega}) &= L(x, y, \boxed{z}, \boxed{\boldsymbol{\omega}}) \\ &= L(0, 0, \boxed{z}, \boxed{\boldsymbol{\omega}}) \\ &= L(\boxed{z}, \boxed{\boldsymbol{\omega}}) \end{aligned}$$



Position-Free Formulation

Standard Radiative transfer equation

$$L_v(\boldsymbol{r},\boldsymbol{\omega}) = S(\boldsymbol{r},\boldsymbol{\omega}) + \int_0^{t'} \underbrace{\boxed{\tau(\boldsymbol{r},\boldsymbol{r}')}}_{\text{Transmittance}} \int_{S^2} \underbrace{\boxed{\hat{f}_p(\boldsymbol{\omega}',\boldsymbol{\omega})}}_{\text{Scaled phase function}} L_v(\boldsymbol{r}',\boldsymbol{\omega}')\,\mathrm{d}\boldsymbol{\omega}'\,\mathrm{d}t$$

Transmittance

Scaled phase function

Position-free radiative transfer equation

$$L_v(z,\boldsymbol{\omega}) = S(z,\boldsymbol{\omega}) + \int_0^{1} \frac{\boxed{\tau(z',z,\boldsymbol{\omega})}}{\underbrace{\boxed{|\cos\boldsymbol{\omega}|}}_{\text{Change of variable}}} \int_{S^2} \boxed{\hat{f}_p(\boldsymbol{\omega}',\boldsymbol{\omega})} L_v(z',\boldsymbol{\omega}')\,\mathrm{d}\boldsymbol{\omega}'\,\mathrm{d}z'$$

Change of variable

BSDF Value as Path Integral

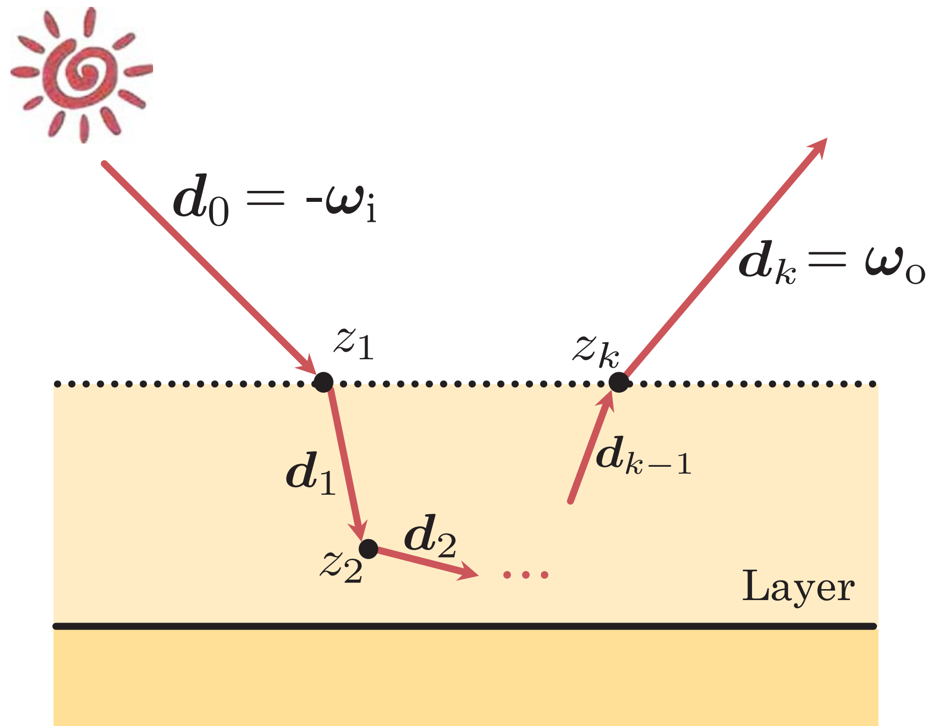
Position-free light path:

$\bar{x} = (\boldsymbol{d}_0, z_1, \boldsymbol{d}_1, \ldots, z_k, \boldsymbol{d}_k)$

Layered BSDF value:

$f_l(\boldsymbol{\omega}_\mathrm{i}, \boldsymbol{\omega}_\mathrm{o})$

$\Omega(\boldsymbol{\omega}_\mathrm{i}, \boldsymbol{\omega}_\mathrm{o})$: the space of all paths with $\boldsymbol{d}_0 = \text{-}\boldsymbol{\omega}_\mathrm{i}, \boldsymbol{d}_k = \boldsymbol{\omega}_\mathrm{o}$



BSDF Value as Path Integral

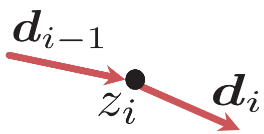
Layered BSDF value:

$$f_l(\boldsymbol{\omega}_\mathrm{i}, \boldsymbol{\omega}_\mathrm{o}) = \int_{\Omega(\boldsymbol{\omega}_\mathrm{i}, \boldsymbol{\omega}_\mathrm{o})} f(\bar{x}) \mathrm{d}\mu(\bar{x})$$

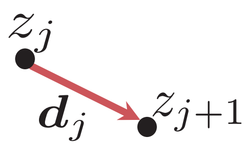
Path contribution:

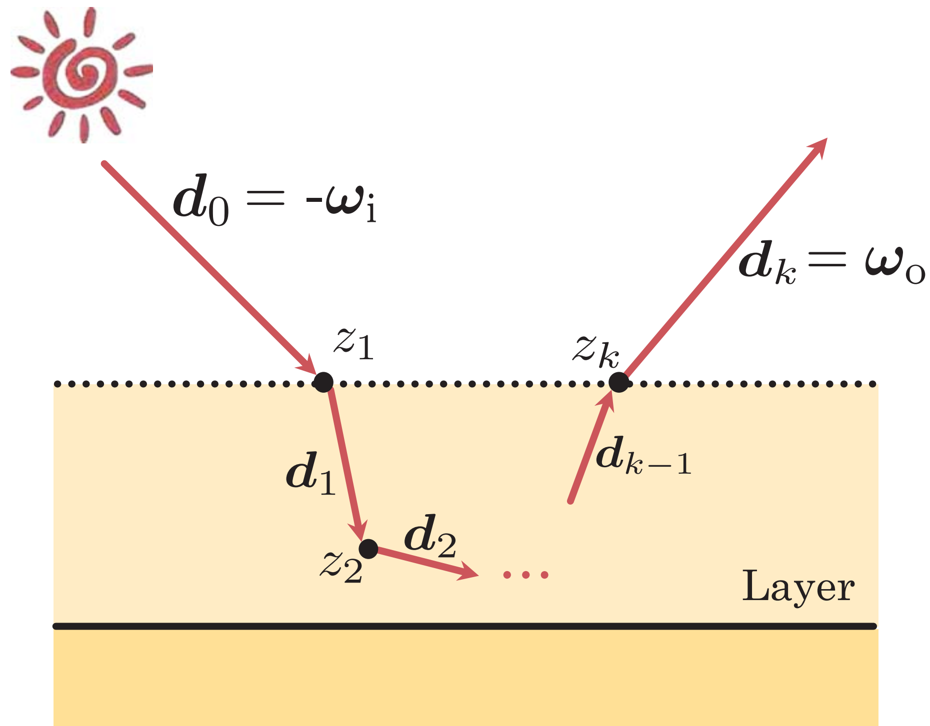
$$f(\bar{x})$$

Vertex contribution v_i:



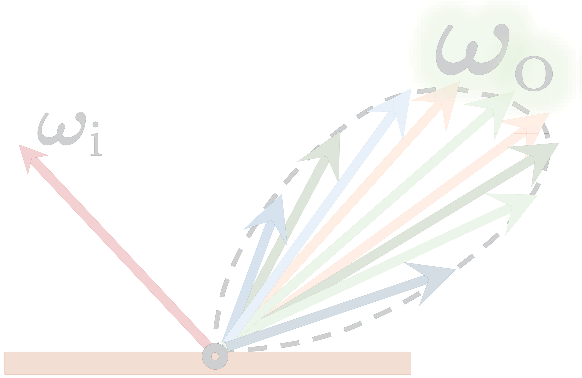
Segment contribution s_j:





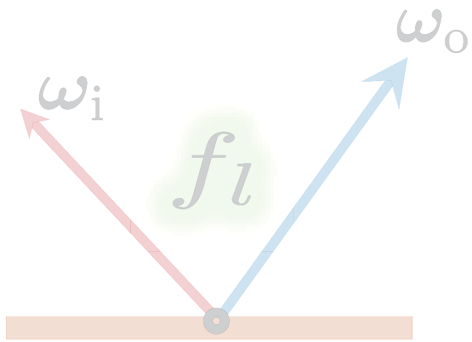
Key Operations for BSDF Model

Sample(ω_i):



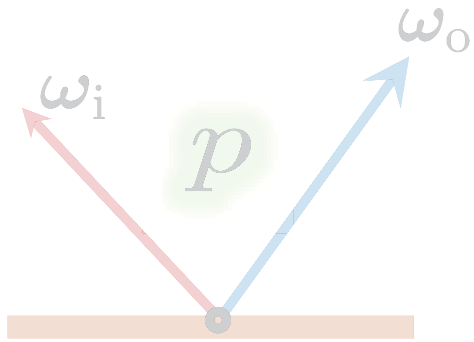
Returns randomly drawn ω_o given ω_i

Eval(ω_i, ω_o):



Evaluate the BSDF value given ω_i, ω_o

pdf($\omega_o|\omega_i$):



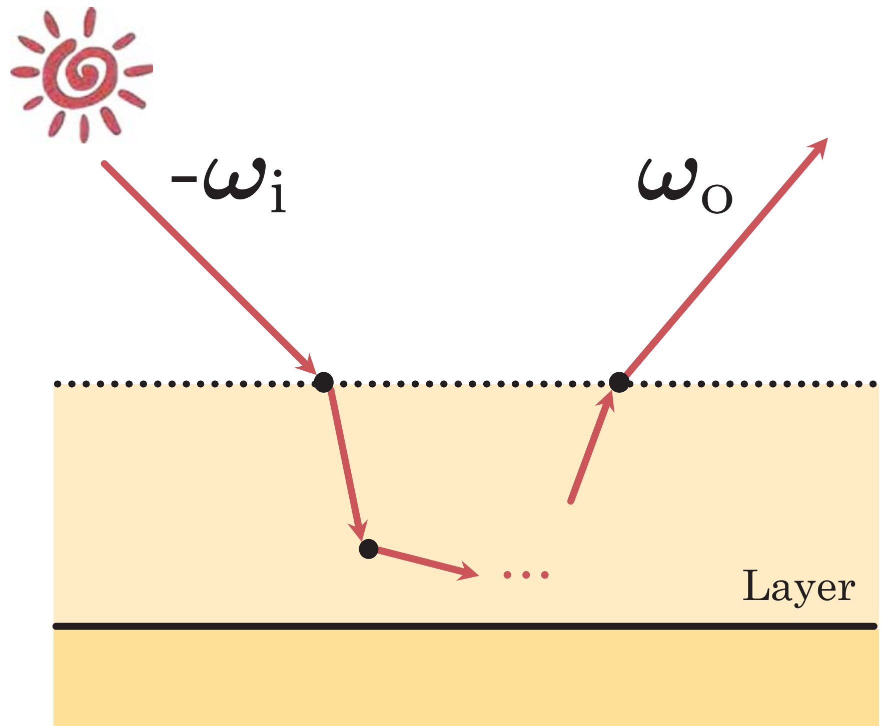
Returns the probability density for drawing ω_o given ω_i

Layered BSDFs Sampling

Start a ray with direction $-\omega_i$

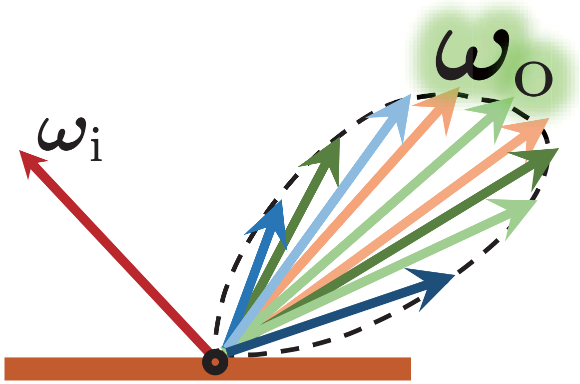
Ray travels in the layers

Return its final direction as ω_o when ray leaves



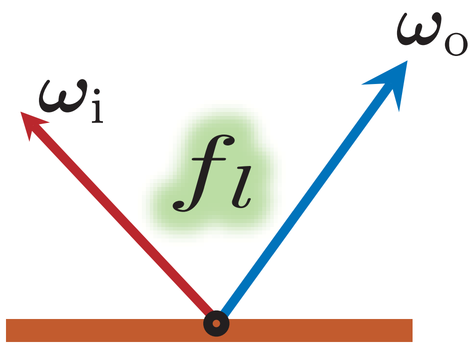
Key Operations for BSDF Model

Sample(ω_i):



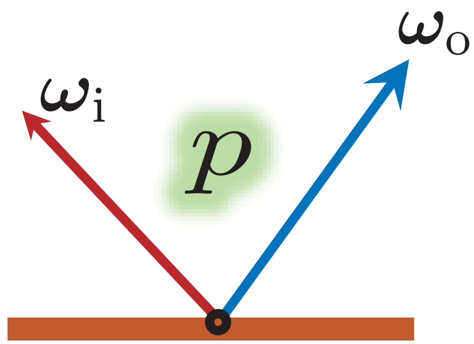
Returns randomly drawn ω_o given ω_i

Eval($\omega_\mathrm{i}, \omega_\mathrm{o}$):



Evaluate the BSDF value given $\omega_\mathrm{i}, \omega_\mathrm{o}$

pdf($\omega_\mathrm{o} | \omega_\mathrm{i}$):



Returns the probability density for drawing ω_o given ω_i

Layered BSDFs Evaluation

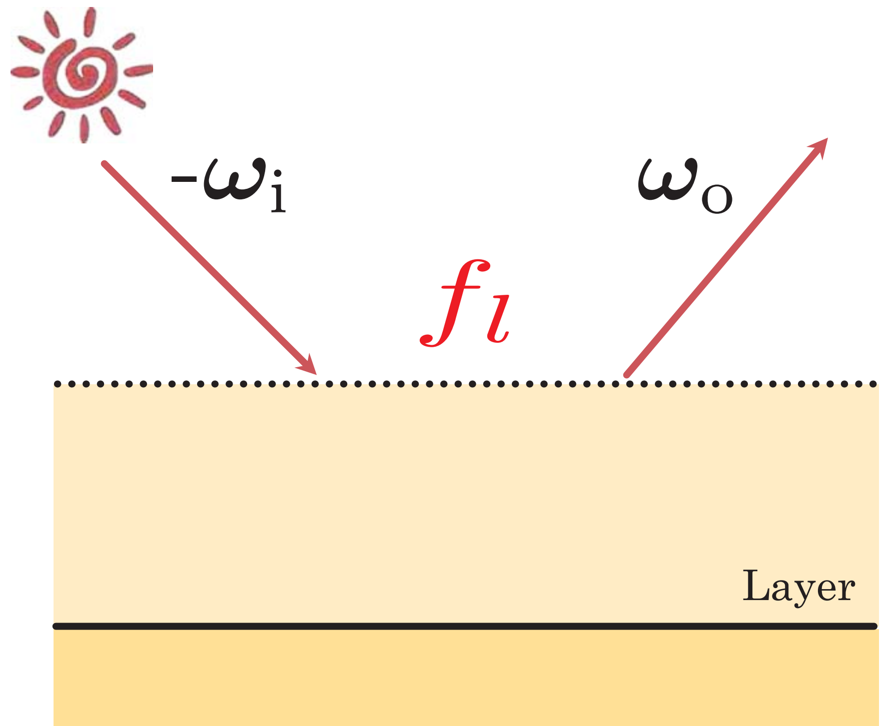
Position-free path integral:

$$f_l(\boldsymbol{\omega}_\mathrm{i}, \boldsymbol{\omega}_\mathrm{o}) = \int_{\Omega(\boldsymbol{\omega}_\mathrm{i}, \boldsymbol{\omega}_\mathrm{o})} f(\bar{x}) \mathrm{d}\mu(\bar{x})$$

Challenge: No analytical solution

Solution: Monte Carlo integration

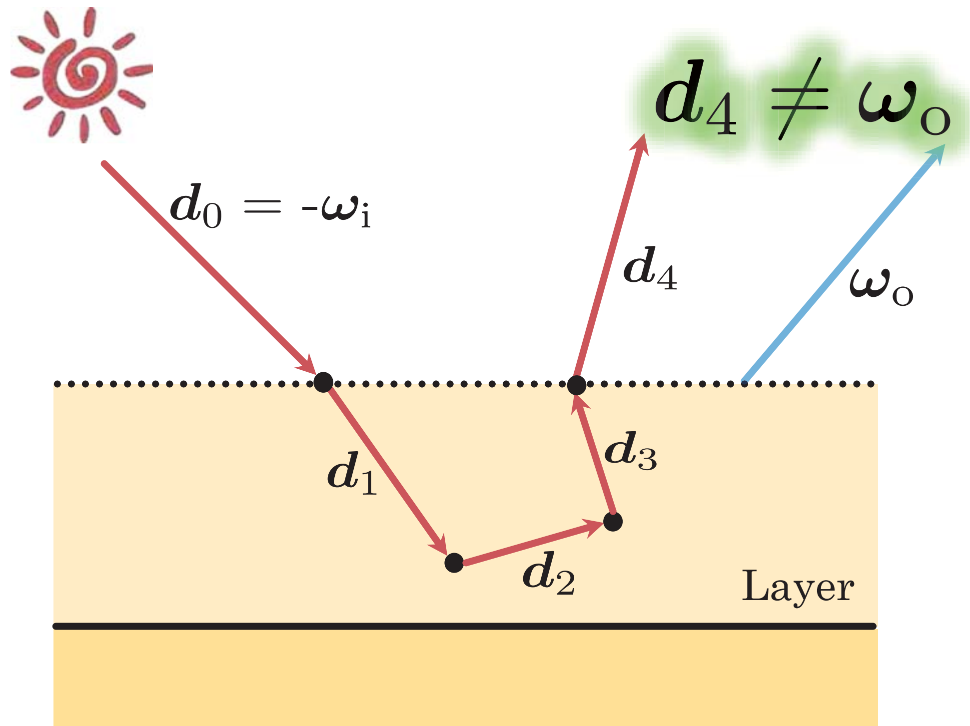
- Unidirectional estimator
- Bidirectional estimator



Challenges

Forward sampling does not work

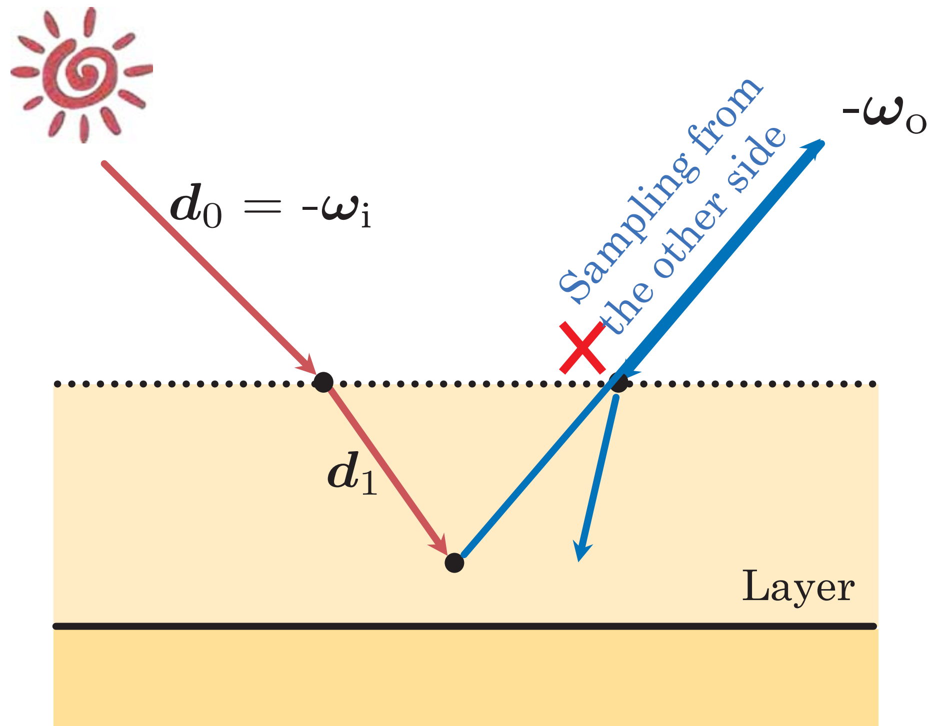
since the final direction will not be exactly ω_o



Uni-directional Estimator

Next-event estimation

- **Challenge**: refractive boundaries
- **Solution**: sample one-step from the other direction



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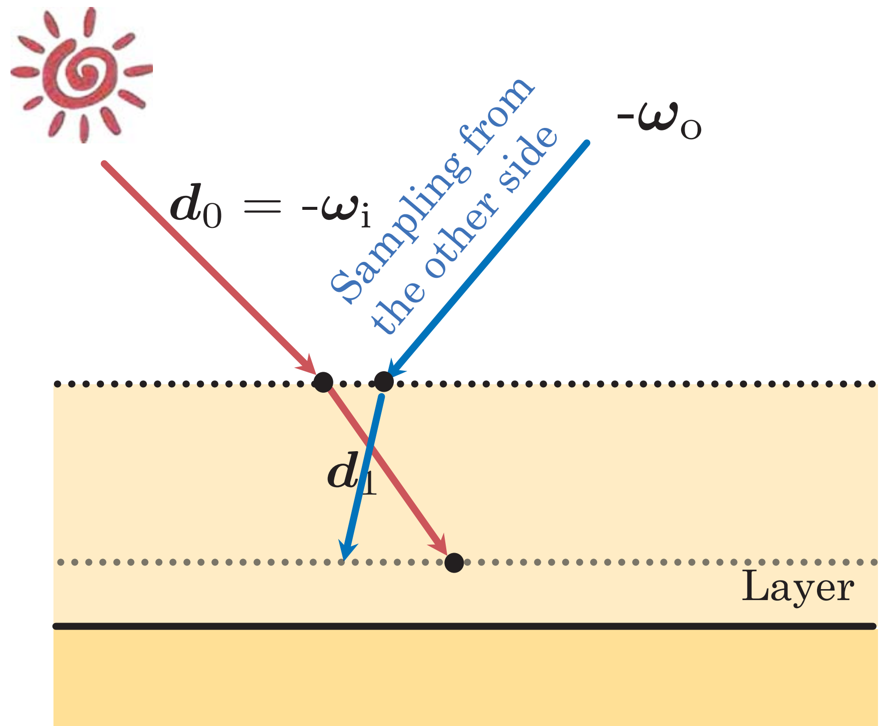

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Next-event estimation

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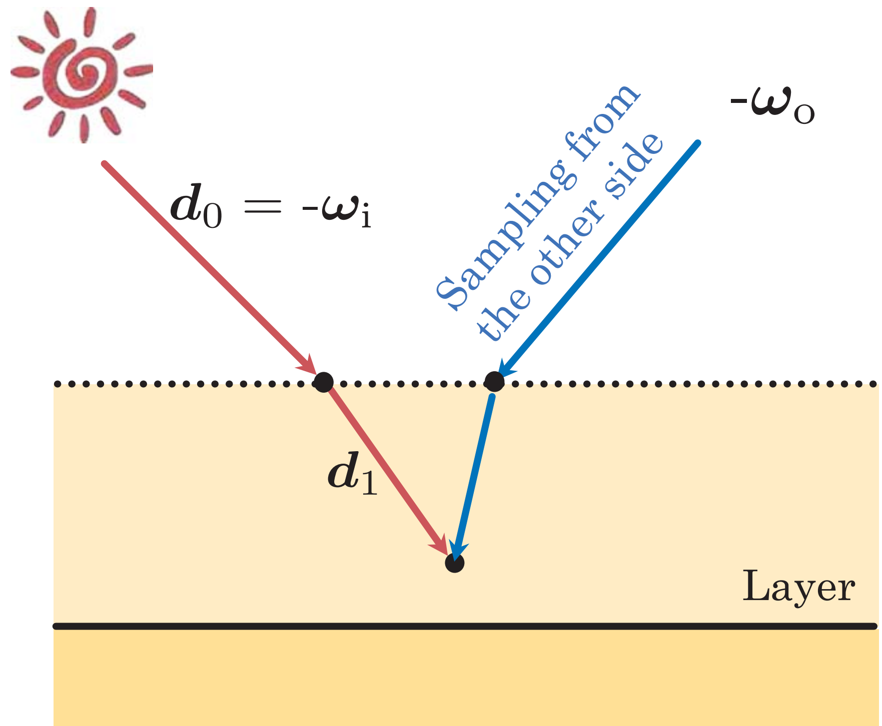
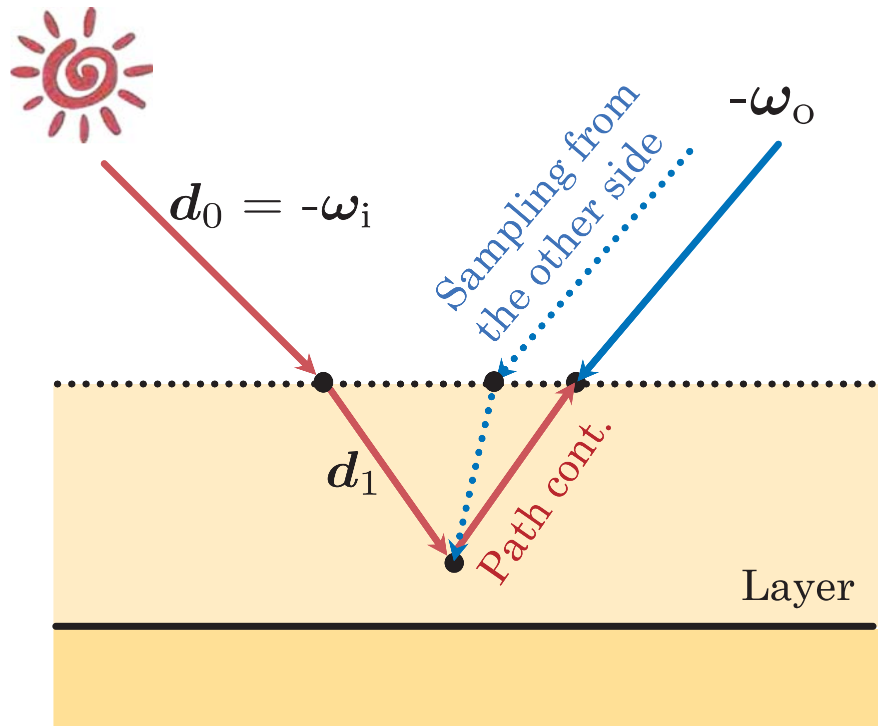


Uni-directional Estimator

Next-event estimation

Path continuation

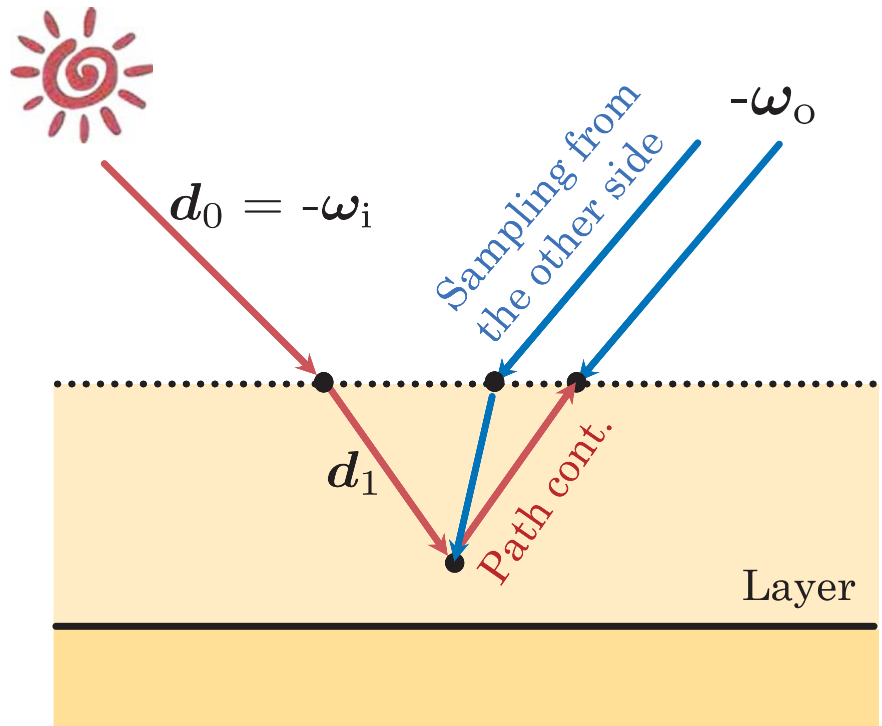


Uni-directional Estimator

Next-event estimation

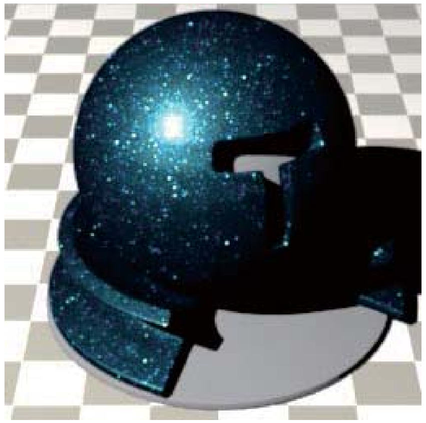
Path continuation

Combined using multiple importance sampling (MIS)



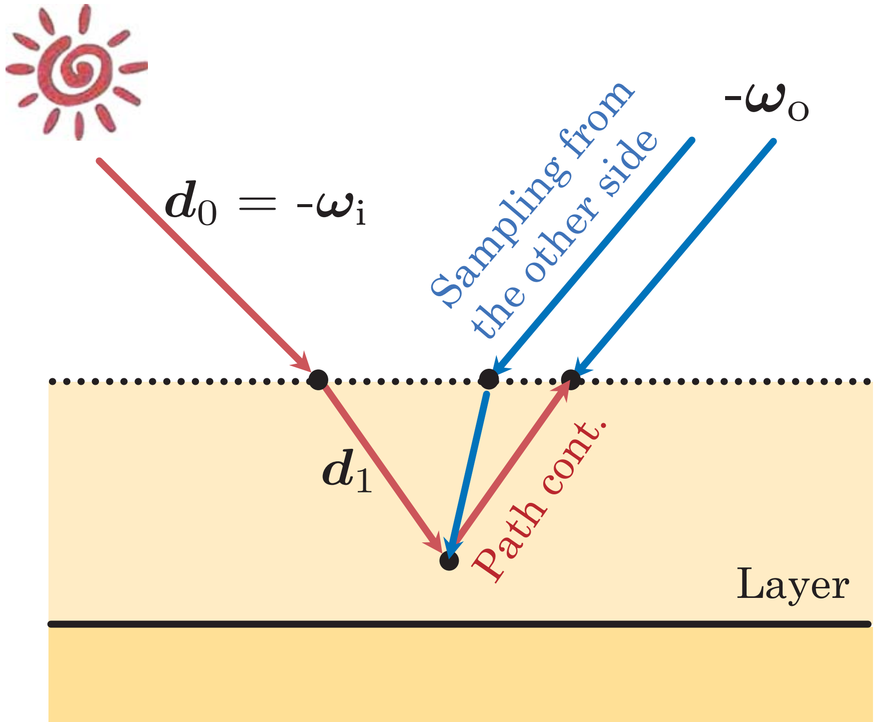
Uni-directional Estimator

Limitation:



Unidir.

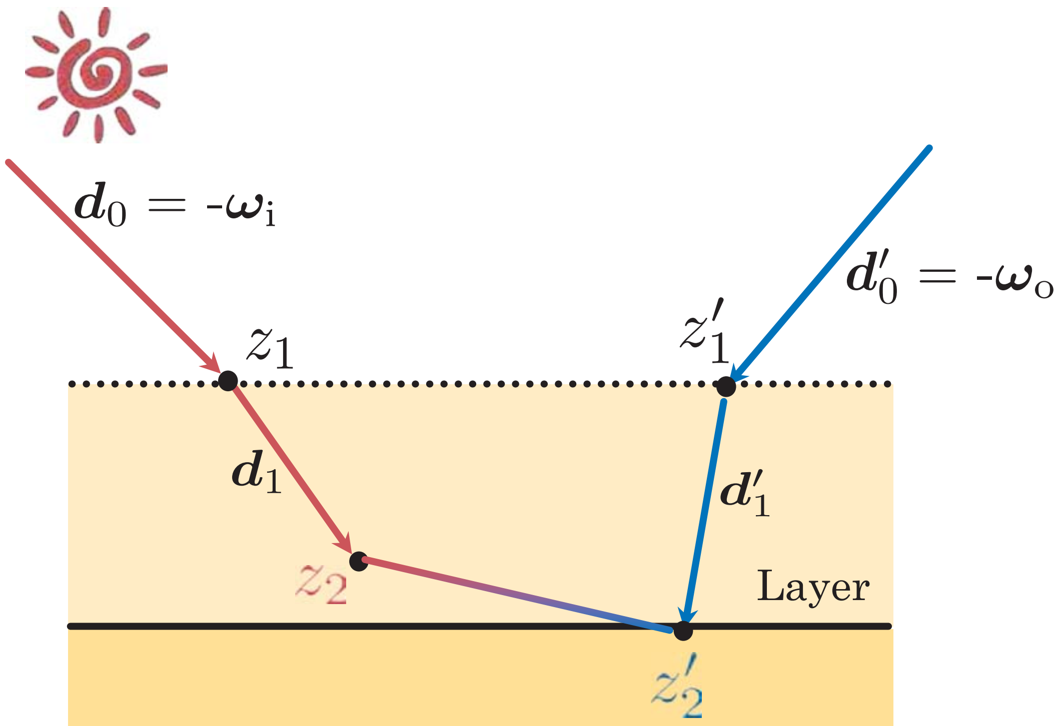
Bidir.



Bi-directional Estimator

Similar to traditional BDPT

Infinitely many connections between z_2 and z_2'



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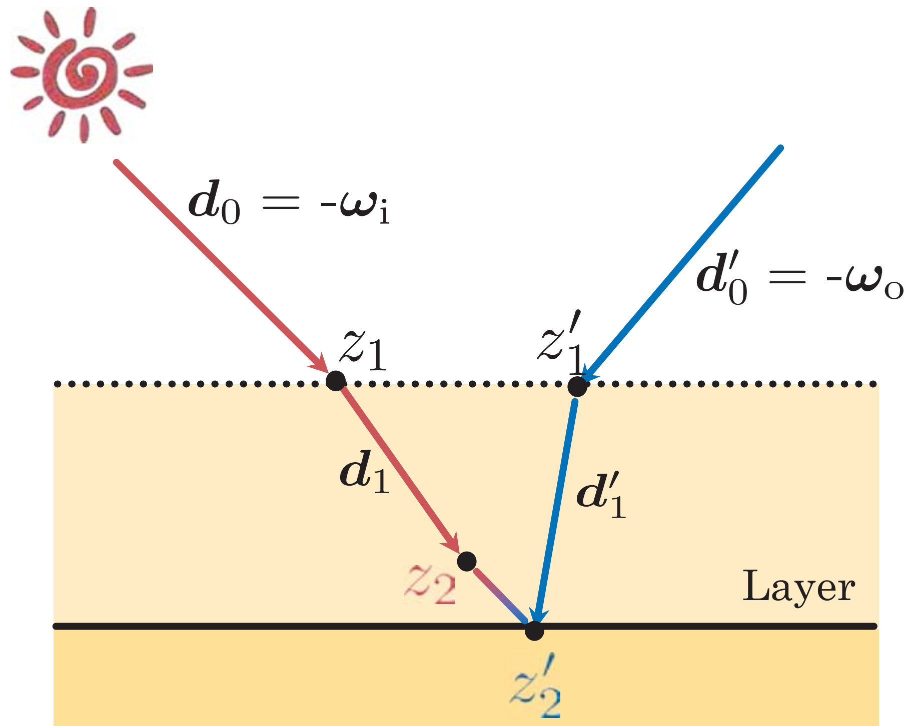

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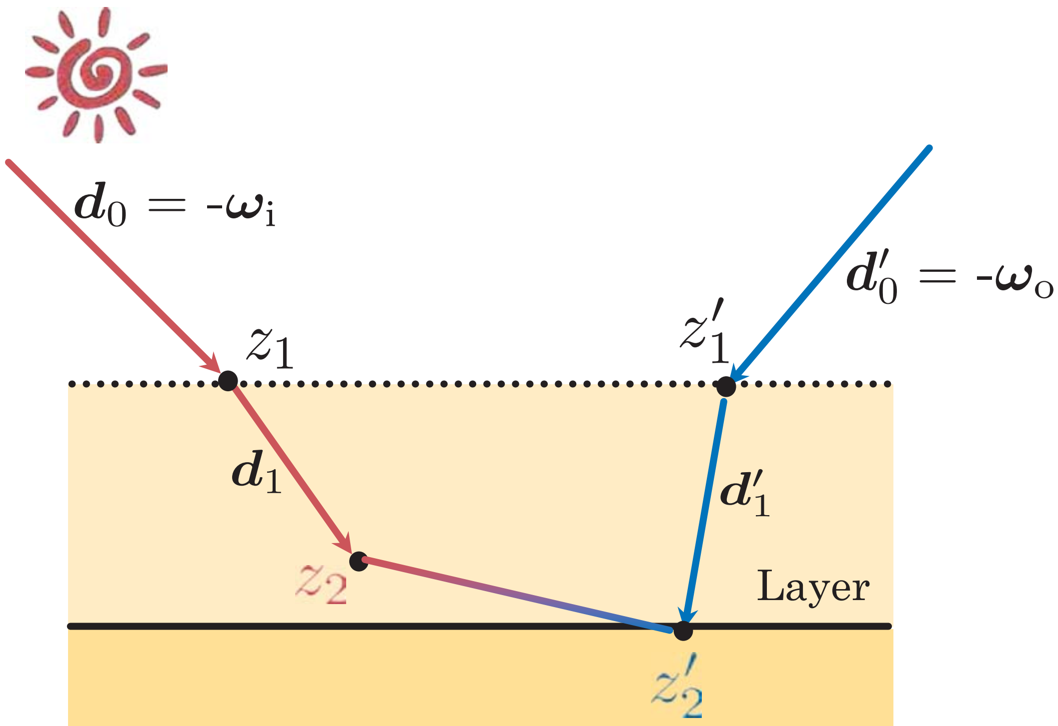
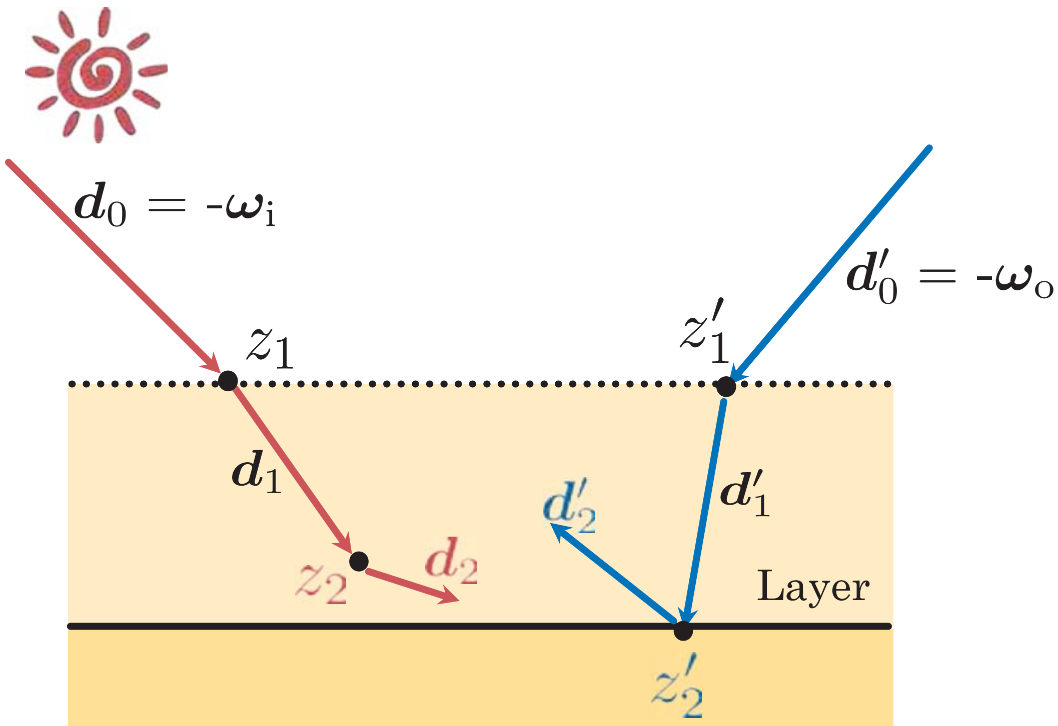


Bi-directional Estimator

Similar to traditional BDPT

Infinitely many connections between z_2 and z_2'

We draw $\boldsymbol{d}_2$ and $\boldsymbol{d}_2'$ and combine using MIS



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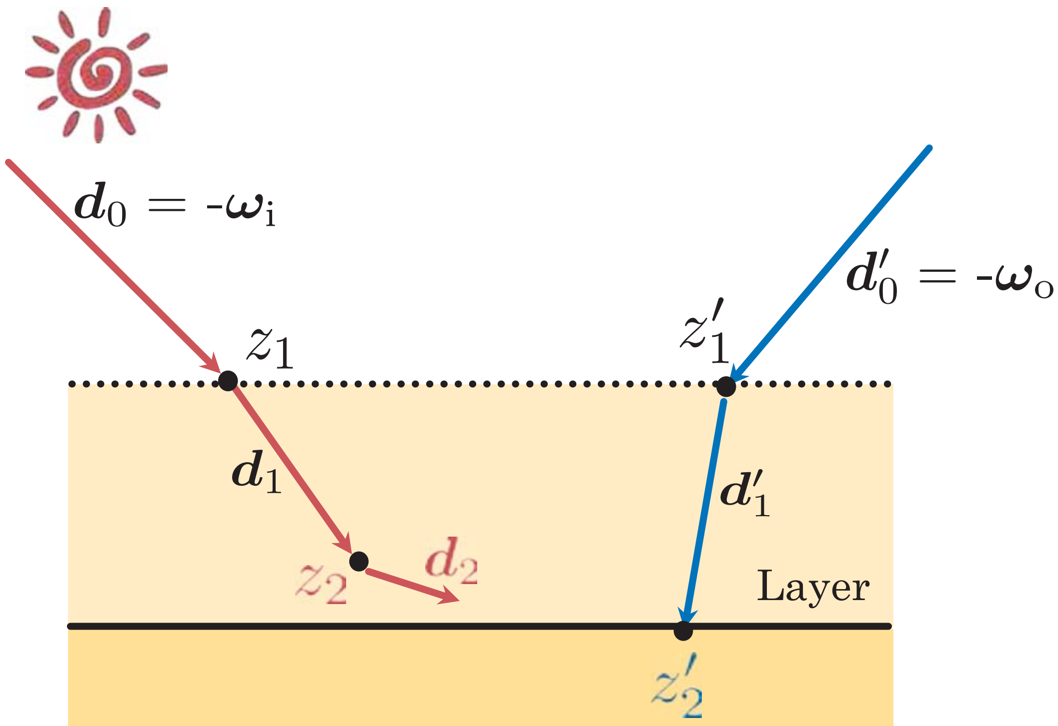

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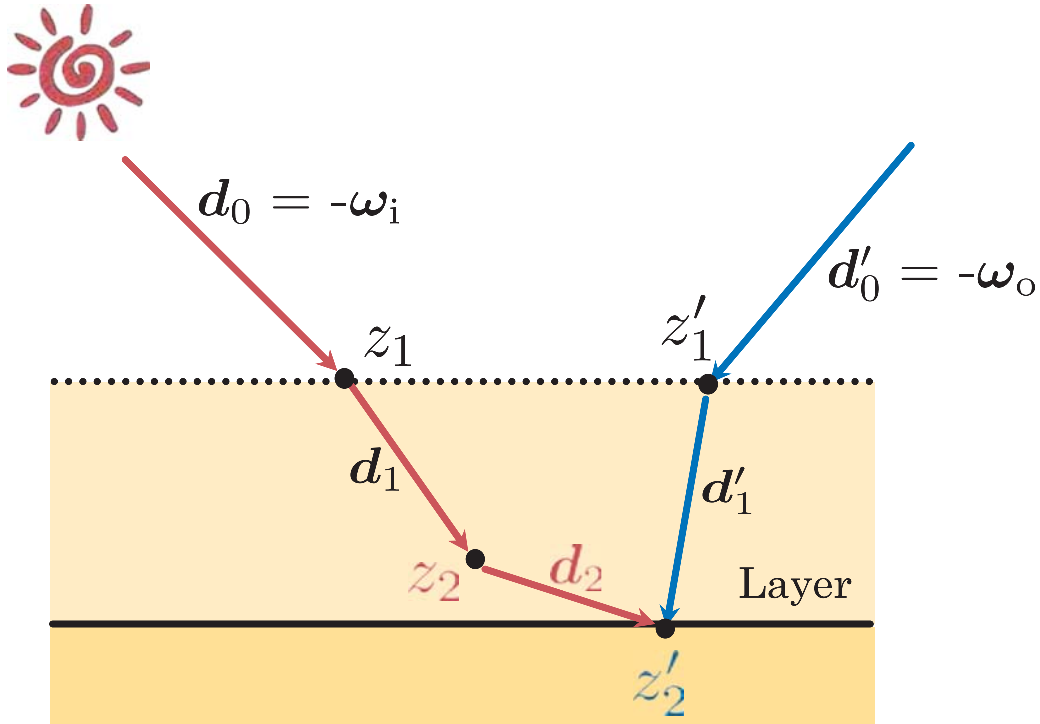

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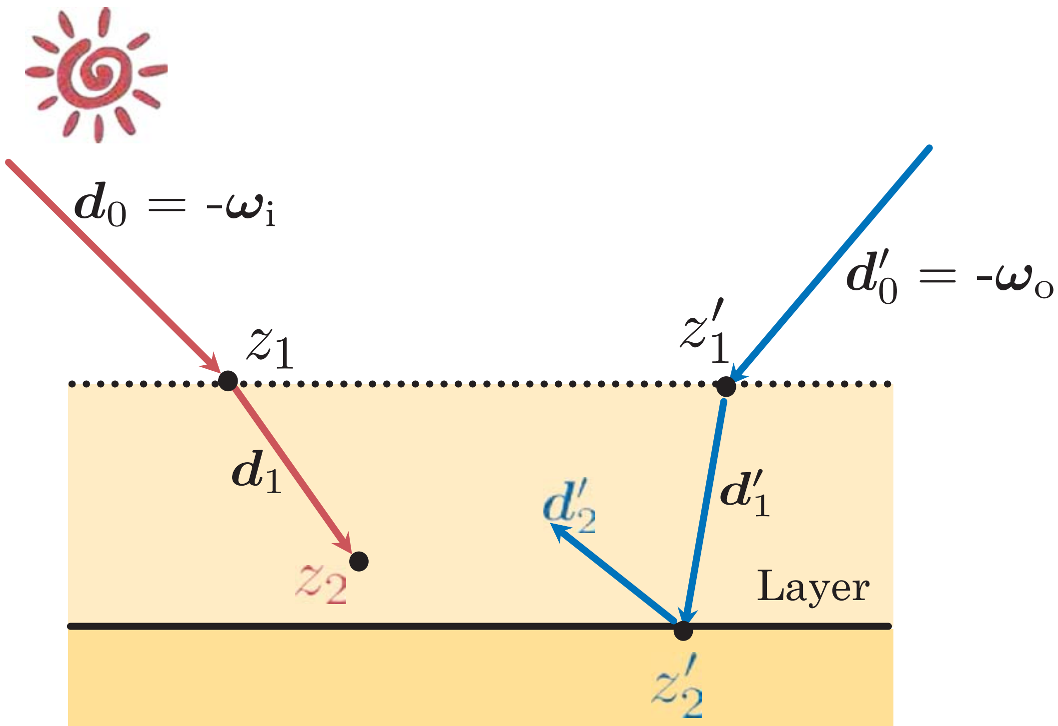

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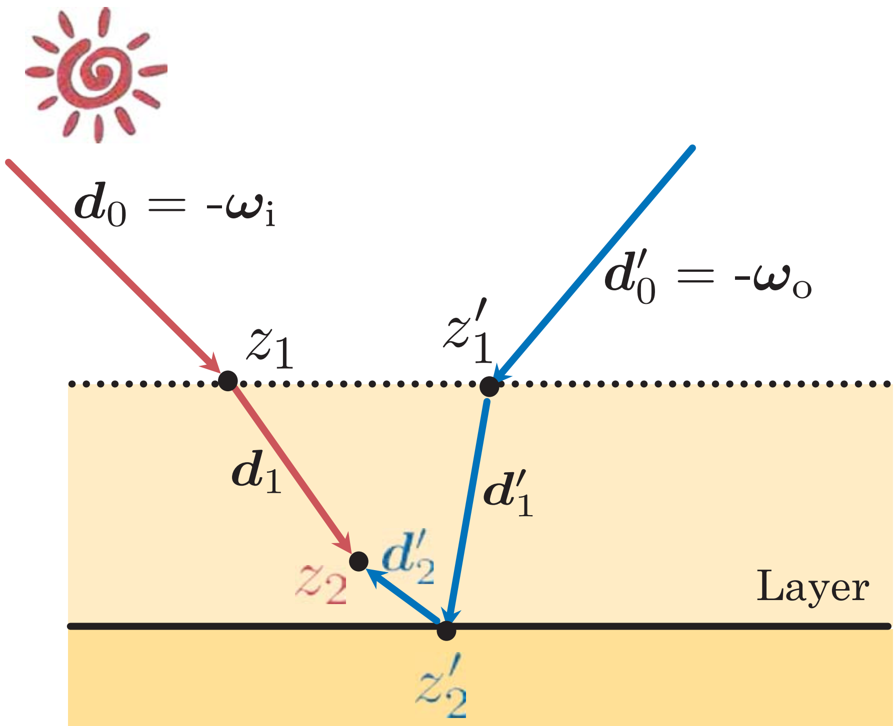
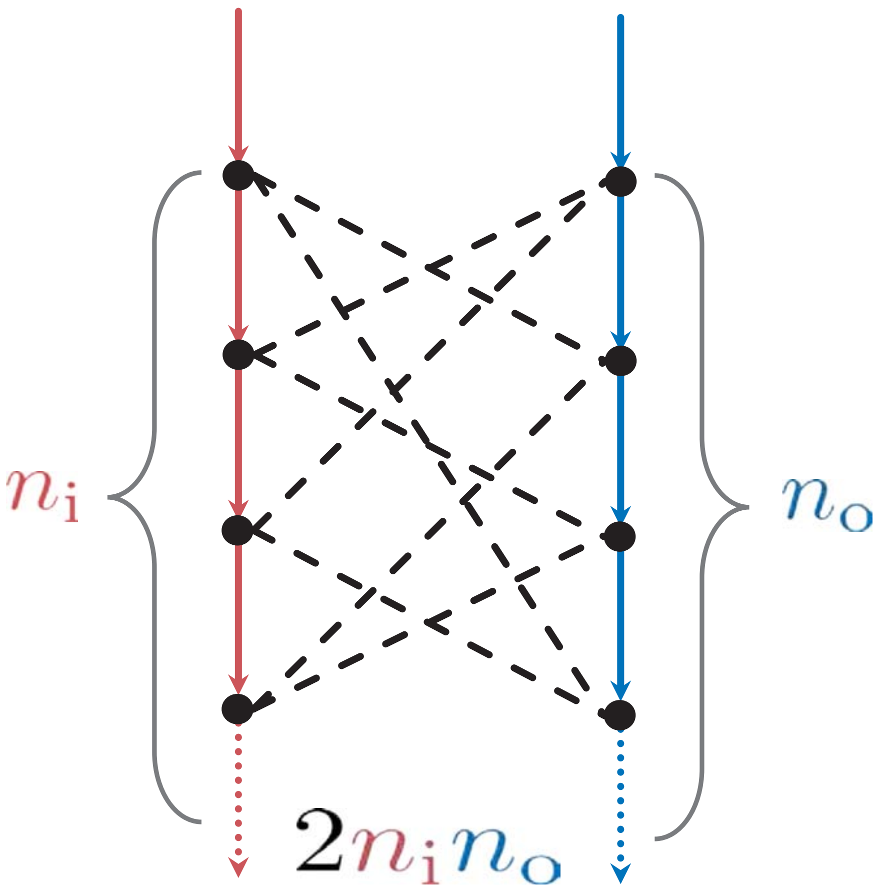
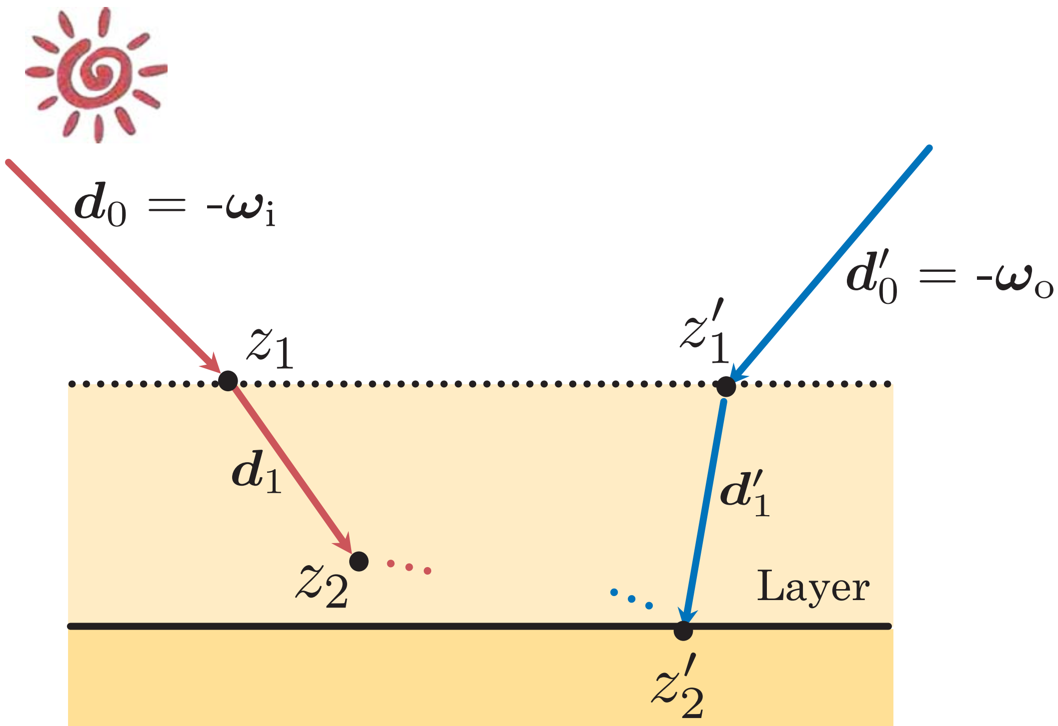


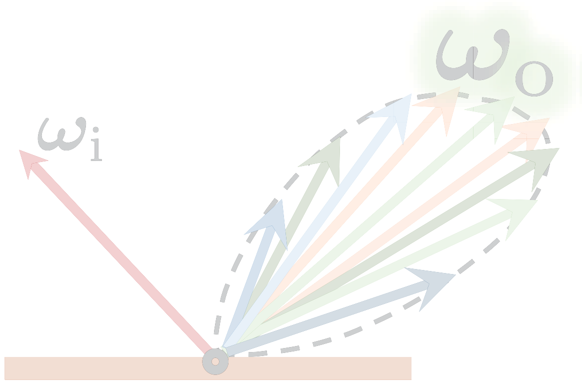
Bi-directional Estimator





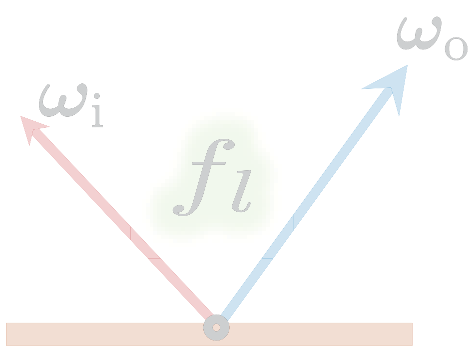
Basic Operations for a BSDF Model

Sample(ω_i):



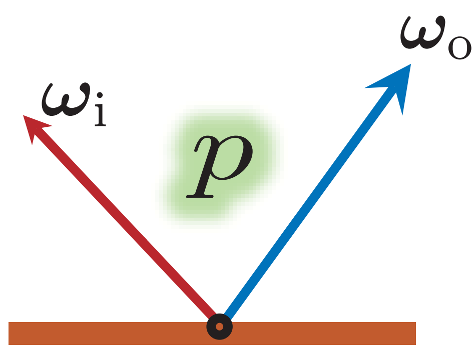
Returns randomly drawn ω_o given ω_i

Eval(ω_i, ω_o):



Evaluate the BSDF value given ω_i, ω_o

pdf($\omega_o | \omega_i$):

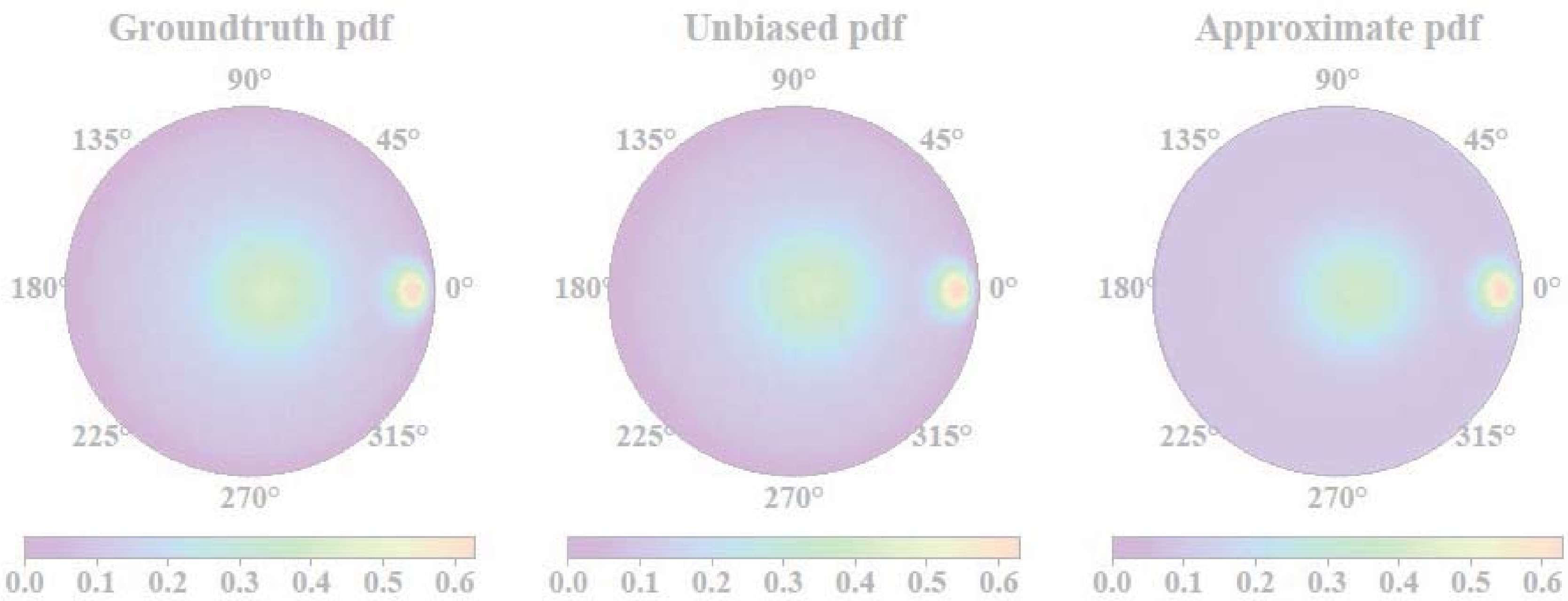


Returns the probability density for drawing ω_o given ω_i

PDF Evaluation

- Can be modeled as another path integral
- Unbiased method (slow)
  - Similar to our BSDF evaluation
- Approximated method (fast)
  - Neglects layer medium and limits max. path length
  - Good enough for computing MIS weights
- Both lead to unbiased global rendering

PDF Evaluation

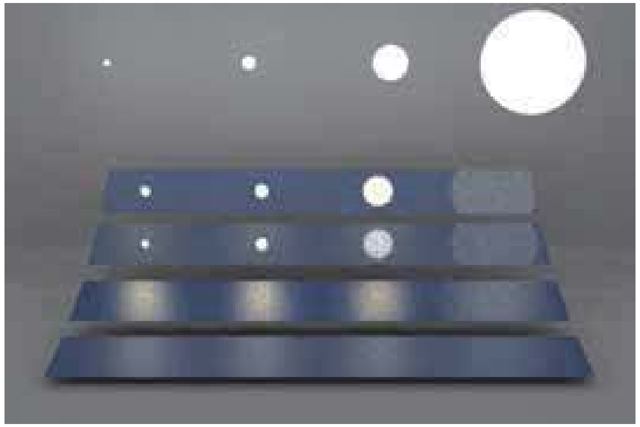


Sampling and binning

Point-wise Evaluate

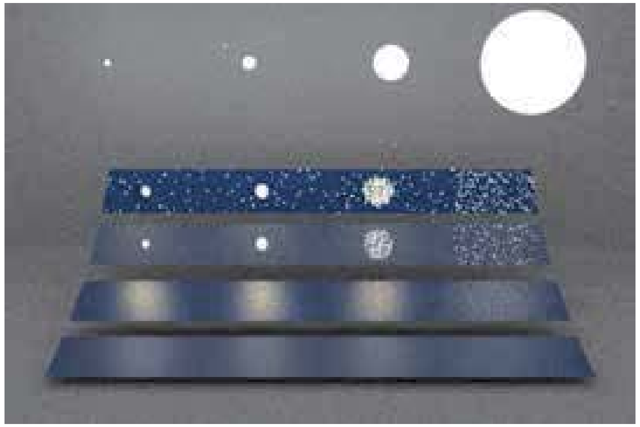
Point-wise Evaluate

PDF Evaluation for MIS



MIS + unbiased pdf
(14min)

MIS + approx. pdf
(4min)

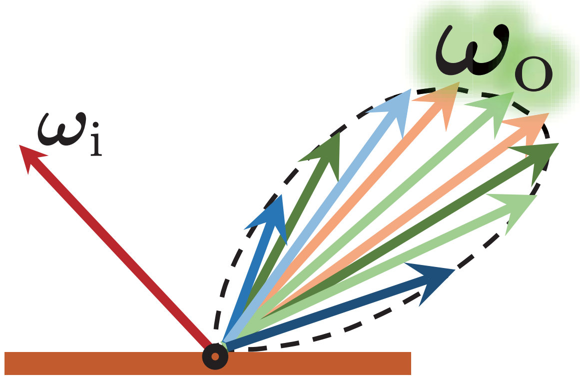


no MIS

Images rendered with equal spp

Key Operations for BSDF Model

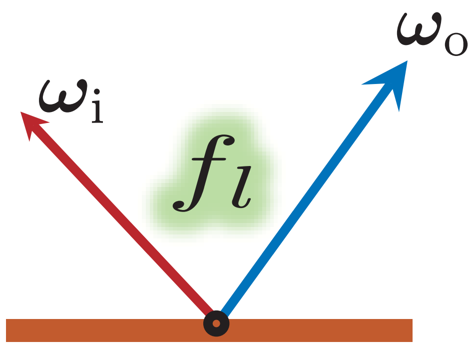
Sample(ω_{i}):



Returns randomly drawn ω_{o} given ω_{i}

EASY!

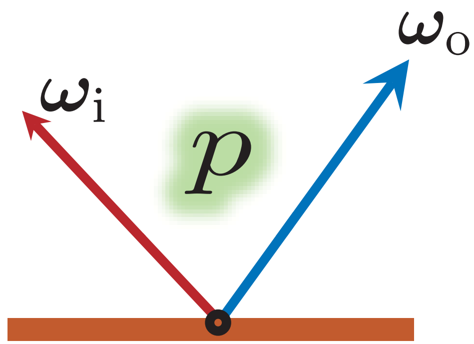
Eval($\omega_{\mathrm{i}}, \omega_{\mathrm{o}}$):



Evaluate the BSDF value given $\omega_{\mathrm{i}}, \omega_{\mathrm{o}}$

MC (unidir. & bidir.)

pdf($\omega_{\mathrm{o}} | \omega_{\mathrm{i}}$):



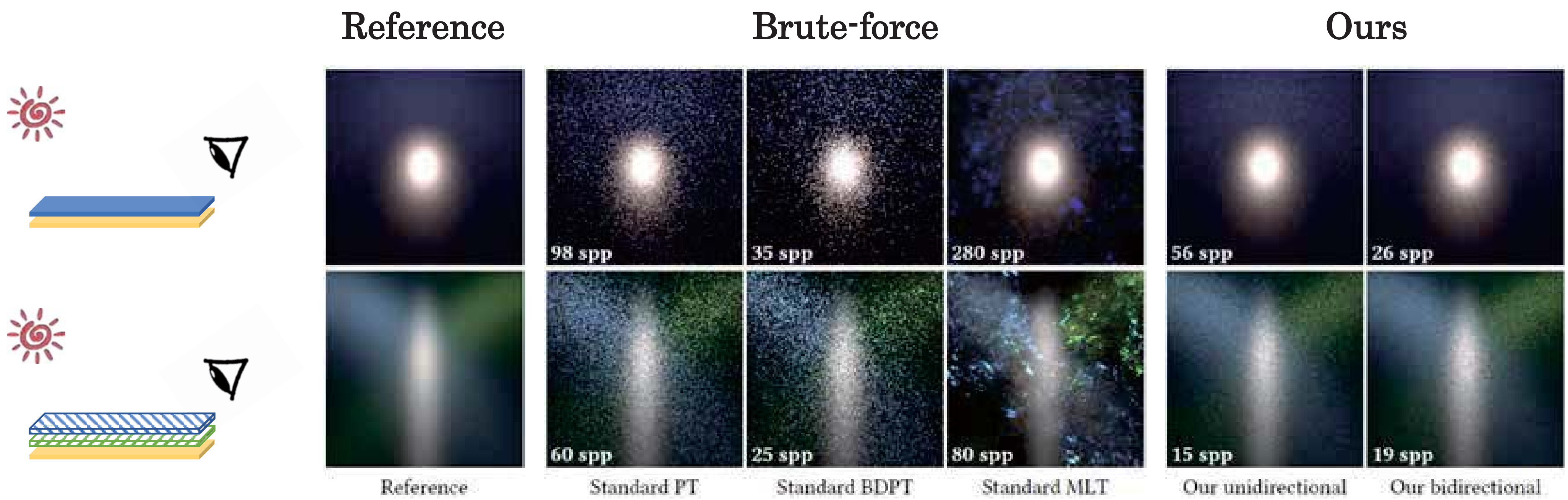
Returns the probability density for drawing ω_{o} given ω_{i}

MC (unbiased & approximated)

Results

Position-Free Monte Carlo Simulation for Arbitrary Layered BSDFs

Equal-Time Comparison



Converge faster!

Generality Comparison

Spatial
variation

Volumetric
scattering

Anisotropic
reflectance

Anisotropic
scattering

Generality Comparison

				
▪ Analytic models				
▪ [Weidlich and Wilkie, 2007]	*Approx*	*No*	*No*	*No*
▪ [Belcour, 2018]	*Yes*	*Yes*	*No*	*No*
▪ Discretized models				
▪ [Jakob et al., 2014]	*Costly*	*Yes*	*No*	*No*
▪ [Zeltner and Jakob, 2018]	*Costly*	*Yes*	*Yes*	*No*
▪ Ours	*Yes*	*Yes*	*Yes*	*Yes*

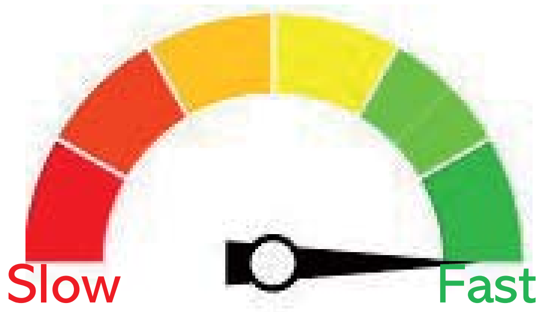
Performance

"Brute-force"

General
Slow

Ours

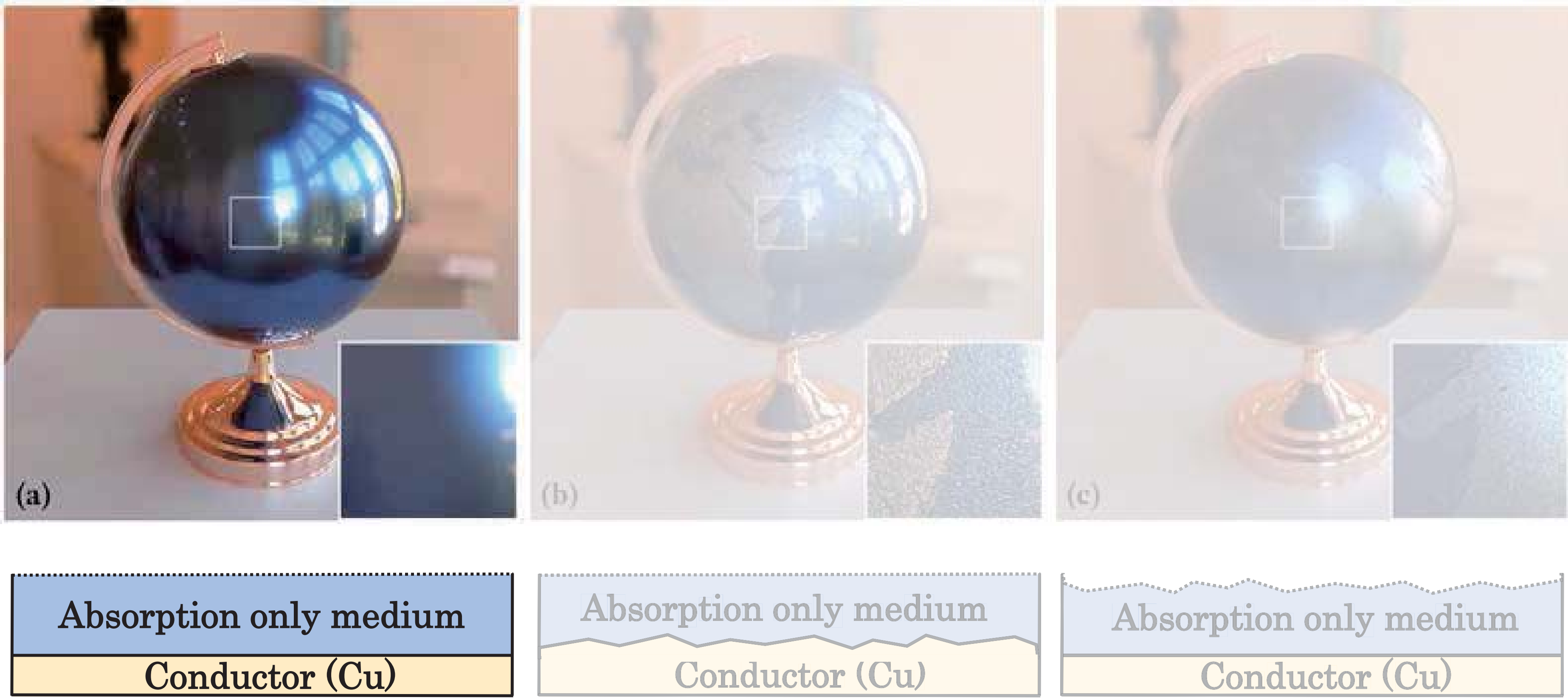
General
Faster



Analytical

Less general
Fastest

Top vs Bottom



Reflection and Transmission

Back-lit　Front-lit　Back-lit　Front-lit

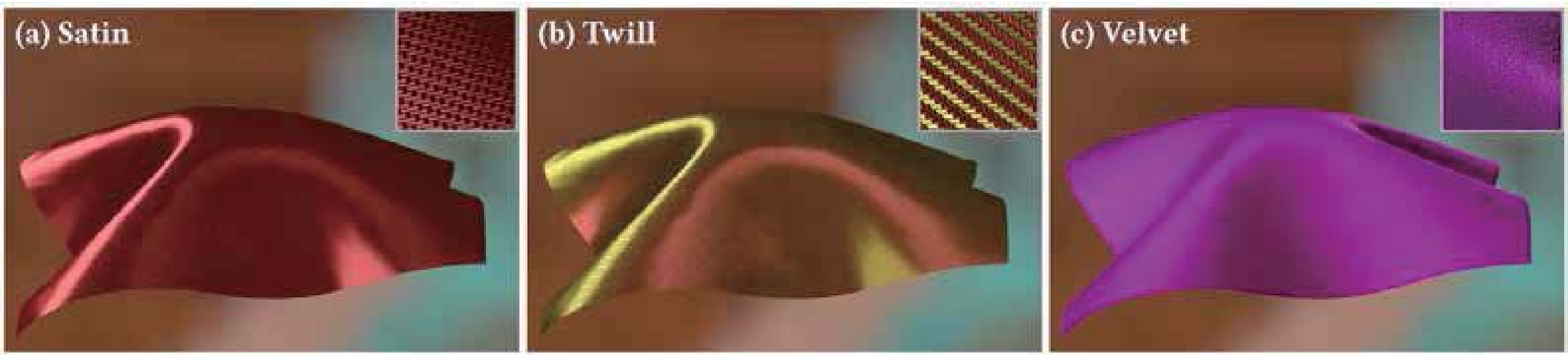
Spatial Thickness variation

$\eta = 1.65, \alpha = 0.01$

Spatially and spectrally varying scattering and absorption

$\alpha = 0.01$

Anisotropic Layer Media



Multiple layers

Summary

What we proposed

A new layered BSDF model

Monte Carlo simulations of light transport in flat slabs

Position-free path formulation

Key benefits

Unbiased BSDF estimation

Full generality in layer/interface properties

Run faster than explicitly method

Position-Free Monte Carlo Simulation for Arbitrary Layered BSDFs

Thank you!

Yu Guo UC, Irvine
Miloš Hašan Autodesk (Adobe)
Shuang Zhao UC, Irvine

Performance

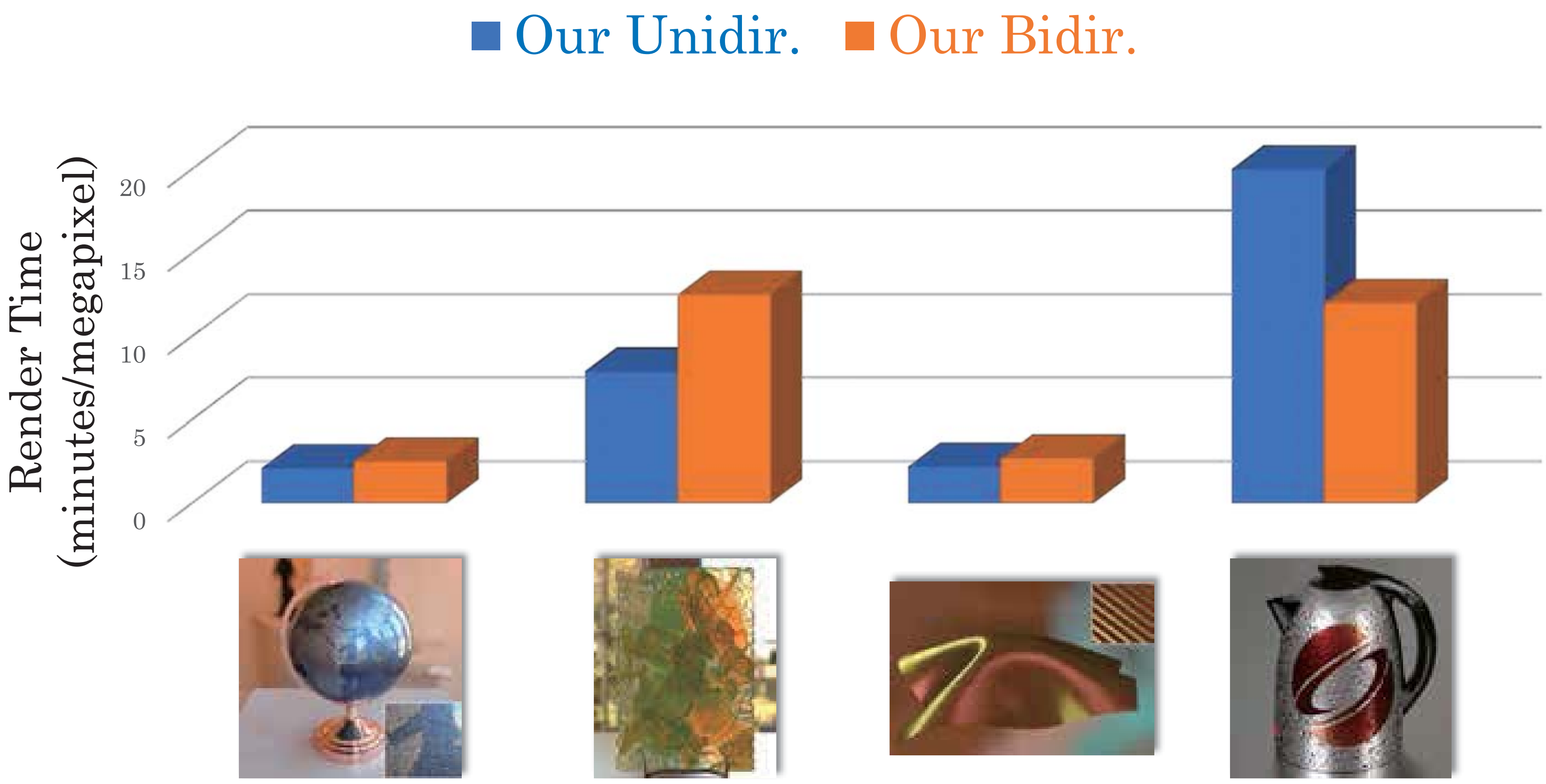


	Image size	Spp	Render time					
			Unidir.		Bidir.		Trivial	
Fig. 1 (a)	3000×2000	1024	2.5 h	(25 m)	**2.2 h**	**(22 m)**	38 m	(6.3 m)
Fig. 11 (b)	1024×1024	256	**2.2 m**	**(2.1 m)**	2.6 m	(2.5 m)	1.3 m	(1.2 m)
Fig. 12, top	800×1200	512	15.2 m	(7.9 m)	**24 m**	**(12.5 m)**	2.4 m	(1.3 m)
Fig. 12, bot.	512×512	1024	6.4 m	(6.1 m)	**13 m**	**(12.6 m)**	1.6 m	(1.5 m)
Fig. 13 (a)	876×584	256	**1.1 m**	**(2.2 m)**	1.4 m	(2.7 m)	0.6 m	(1.1 m)
Fig. 13 (b)	876×584	256	**1.1 m**	**(2.2 m)**	1.4 m	(2.7 m)	0.5 m	(0.9 m)
Fig. 13 (c)	876×584	256	**2.5 m**	**(4.9 m)**	5.4 m	(10.5 m)	0.5 m	(0.9 m)
Fig. 14 (b)	640×540	256	1.5 m	(4.3 m)	**1.9 m**	**(5.5 m)**	0.5 m	(1.4 m)
Fig. 15 (a)	1200×1400	256	**6.7 m**	**(4.0 m)**	12 m	(7.1 m)	3.7 m	(2.2 m)
Fig. 15 (b)	1200×1400	256	**7.0 m**	**(4.2 m)**	13 m	(7.7 m)	3.7 m	(2.2 m)
Fig. 15 (c)	1200×1400	256	67 m	(40 m)	**20 m**	**(12 m)**	4.7 m	(2.8 m)

White furnace tests