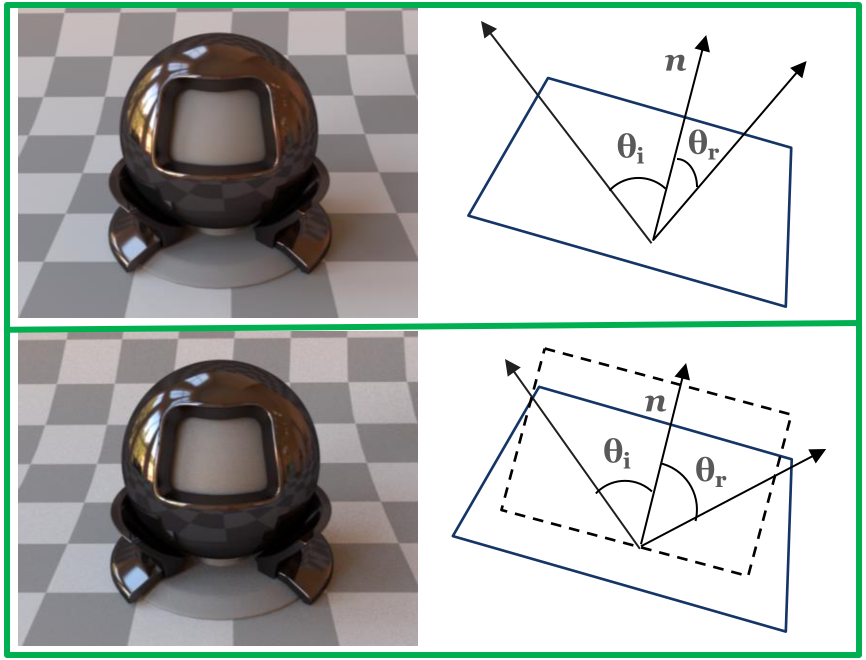
Simplifying BRDF Acquisition

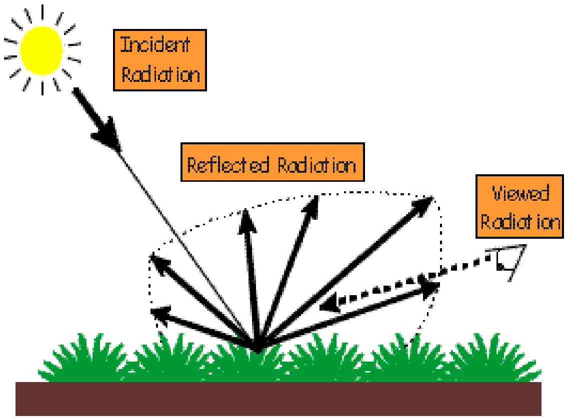
Dual Degree Project



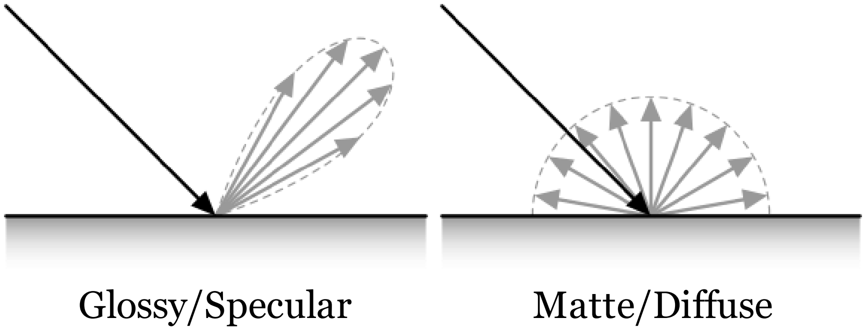
Presented by: Shubham Chitnis

Supervised by: Prof. Sharat Chandran

What is BRDF?



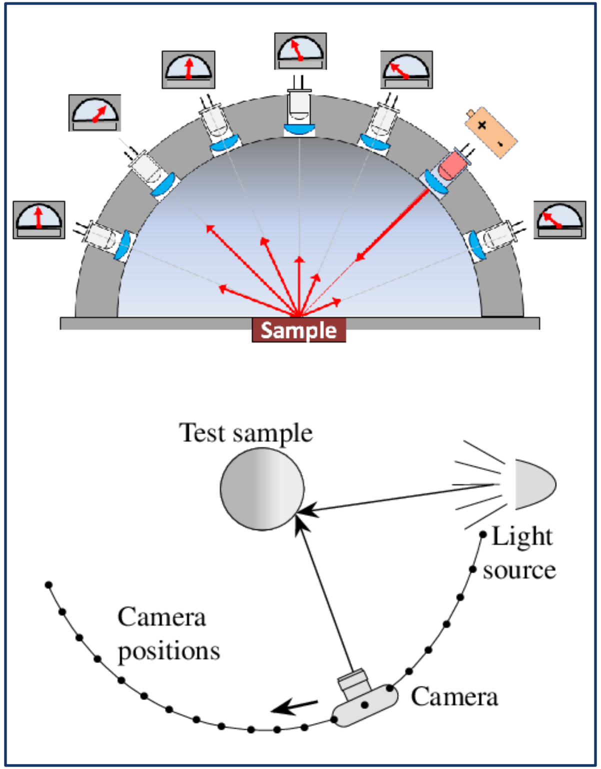
Determines how we perceive objects

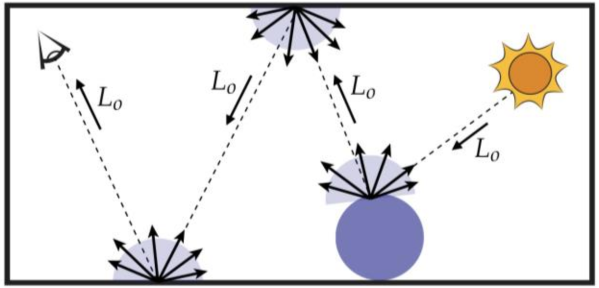


Formal definition	The ratio of the outgoing radiance from a point on the material to the incoming irradiance for a given *incidence and reflection angle pair*.

[1, 2, 3, 4]

Why measure BRDF?

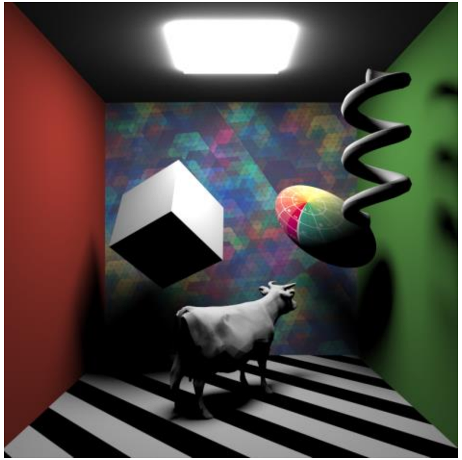




$$\underbrace{L(x, \vec{\omega}_o)}_{\text{radiance (unknown!)}} = \int_{\mathcal{H}^2} f_r(x, \vec{\omega}_i, \vec{\omega}_o) \underbrace{L(x, -\vec{\omega}_i)}_{\text{radiance (unknown!)}} \cos\theta \, d\omega_i$$

BRDF data

Laborious!



[5, 6, 7, 8]

Problem Description

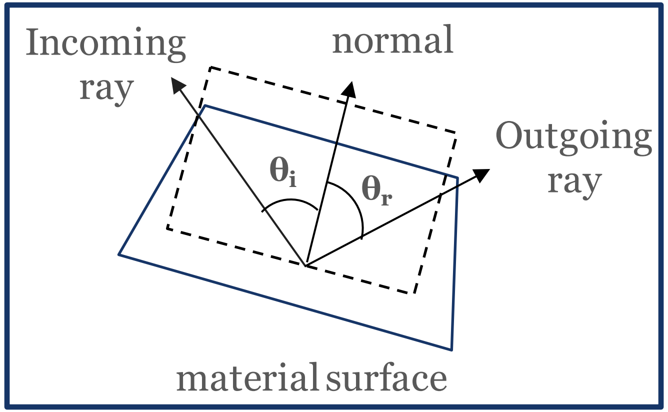
BRDF acquisition is expensive, requiring multiple hours (even days) for material capture forcing us to devise more efficient ways for BRDF capture.

This could be done using:

a) Better data (smartly chosen angles)
b) Better ways to represent data

For (a), we suggest using in-plane angles

For (b), *existing* BRDF representations suffice

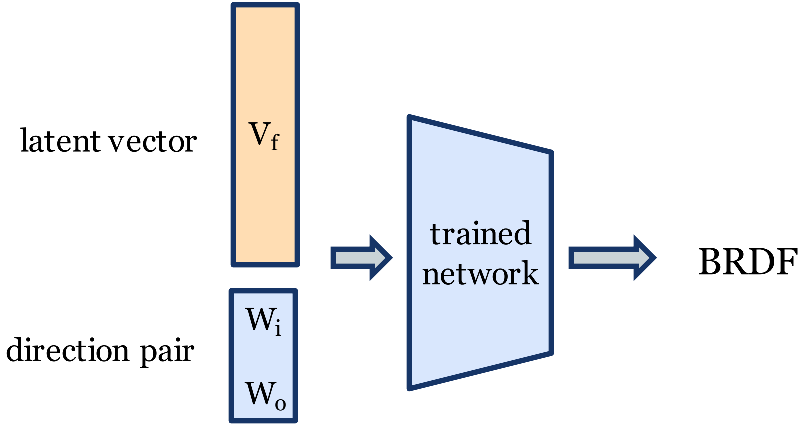


Existing BRDF representations

Physics based

$$\text{BRDF} = \frac{k_d}{\pi} + \frac{F(\theta_h)G(\mathbf{n}\cdot\mathbf{l},\mathbf{n}\cdot\mathbf{v})S(\sqrt{1-(\mathbf{n}\cdot\mathbf{h})}}{(\mathbf{n}\cdot\mathbf{l})(\mathbf{n}\cdot\mathbf{v})}$$

Network based



Input: Directions, Material-specific parameters
Output: BRDF

Contributions

- We demonstrate that a small subset of *in-plane* angles sufficiently represents isotropic BRDFs.
- We also generate reduced BRDF datasets and compare their fit qualities using *existing representations*.

Scope	Show that fitting in-plane angles is comparable to fitting unrestricted-data	Test BRDF representations with reduced datasets
Out-of-scope	Propose completely new BRDF representations	Compare between existing BRDF representations

Data Description (MERL)

Publicly available dataset for 100 isotropic materials

BRDF datapoints in millions (tristimulus domain, unrestricted)

Granularity (polar and azimuthal angles):

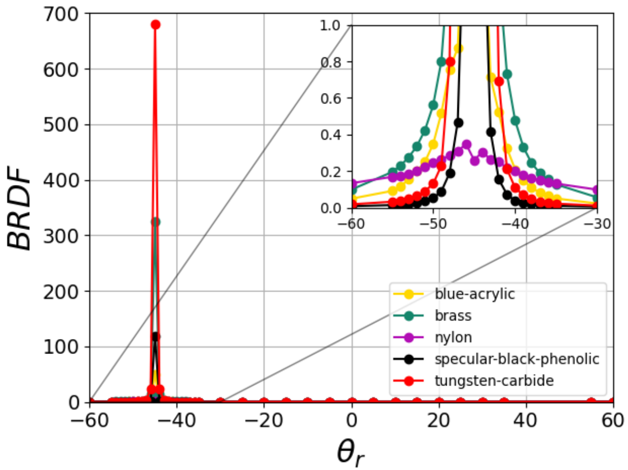
- 10° intervals for incoming polar angle
- 1° intervals for outgoing polar angle
- 1° intervals for outgoing azimuthal angle

Samples: *tungsten carbide, blue acrylic, brass, nylon, specular black phenolic*

Dataset and Measurement setup from "*A Data-Driven Reflectance Model*"

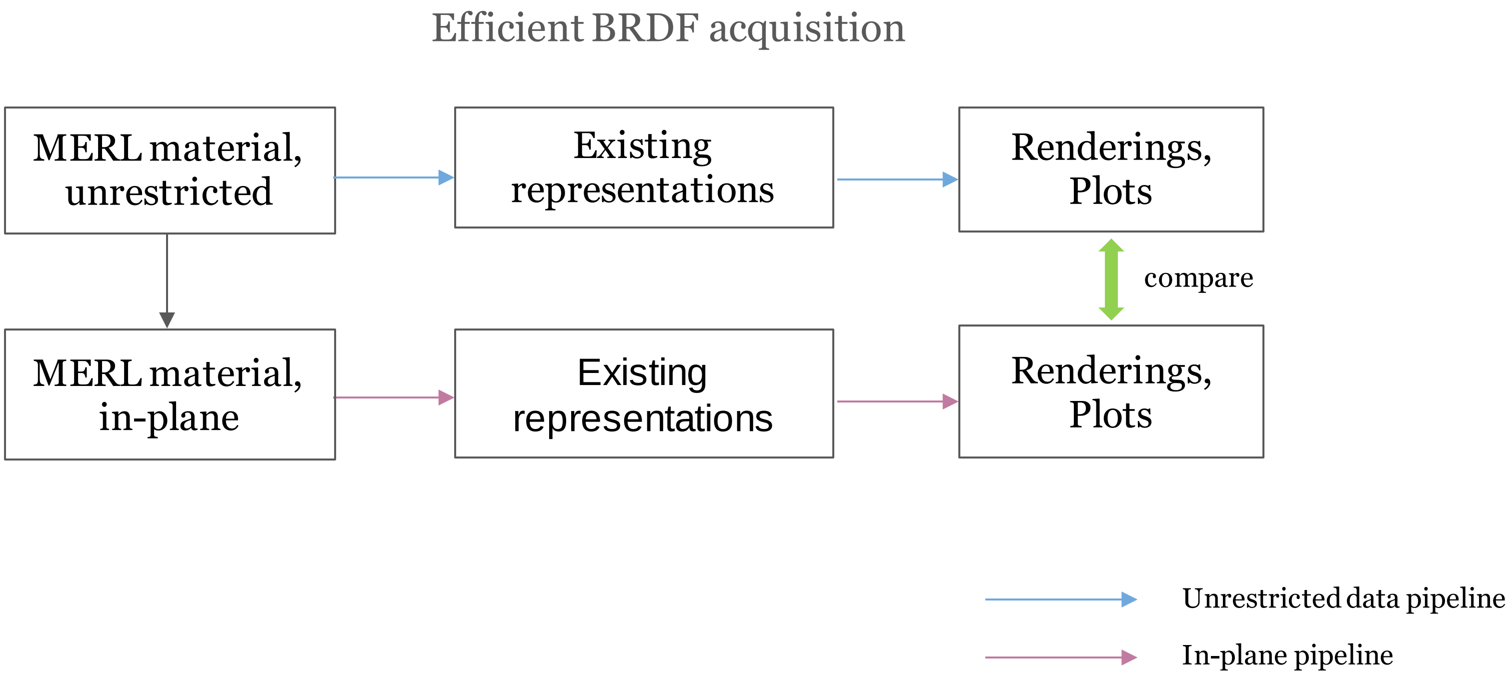
Data Description (MERL)

Picked materials with diverse optical properties: diffuse, light-specular, heavy-specular



Here, we have fixed incoming angle to -45° and varied the outgoing angle, querying the BRDF for each pair

Problem Description



Parametric Representation

ABC model based on **Microfacet theory**

Parameter estimation: 9 total (k_d^{RGB}, A^{RGB}, B, C, *eta*) estimated using least squares optimization on BRDF data with a weighted L2 loss function.

$$L^2_{\text{cus}} = \frac{1}{N}\sum_{n=1}^{N}(g_{\text{mea}} - g_{\text{pred}})^2 \sin\theta_r$$

$$g_{\text{mea}} = \ln(1 + \cos\theta_i f_{\text{mea}})$$

$$g_{\text{pred}} = \ln(1 + \cos\theta_i f_{\text{pred}})$$

ABC distribution variant of Cook-Torrance

$$f_r(\mathbf{l},\mathbf{v}) = \frac{k_d}{\pi} + \frac{F(\theta_h)G(\mathbf{n}\cdot\mathbf{l},\mathbf{n}\cdot\mathbf{v})S(\sqrt{1-(\mathbf{n}\cdot\mathbf{h})}}{(\mathbf{n}\cdot\mathbf{l})(\mathbf{n}\cdot\mathbf{v})}$$

(Geometric attenuation)

$$G = \min\left\{1, \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{v})}{(\mathbf{v}\cdot\mathbf{h})}, \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{l})}{(\mathbf{v}\cdot\mathbf{h})}\right\}$$

(Fresnel factor)

$$F = \frac{(g-c)^2}{2(g+c)^2}\left\{1 + \frac{[c(g+c)-1]^2}{[c(g-c)+1]^2}\right\}$$

(ABC distribution)

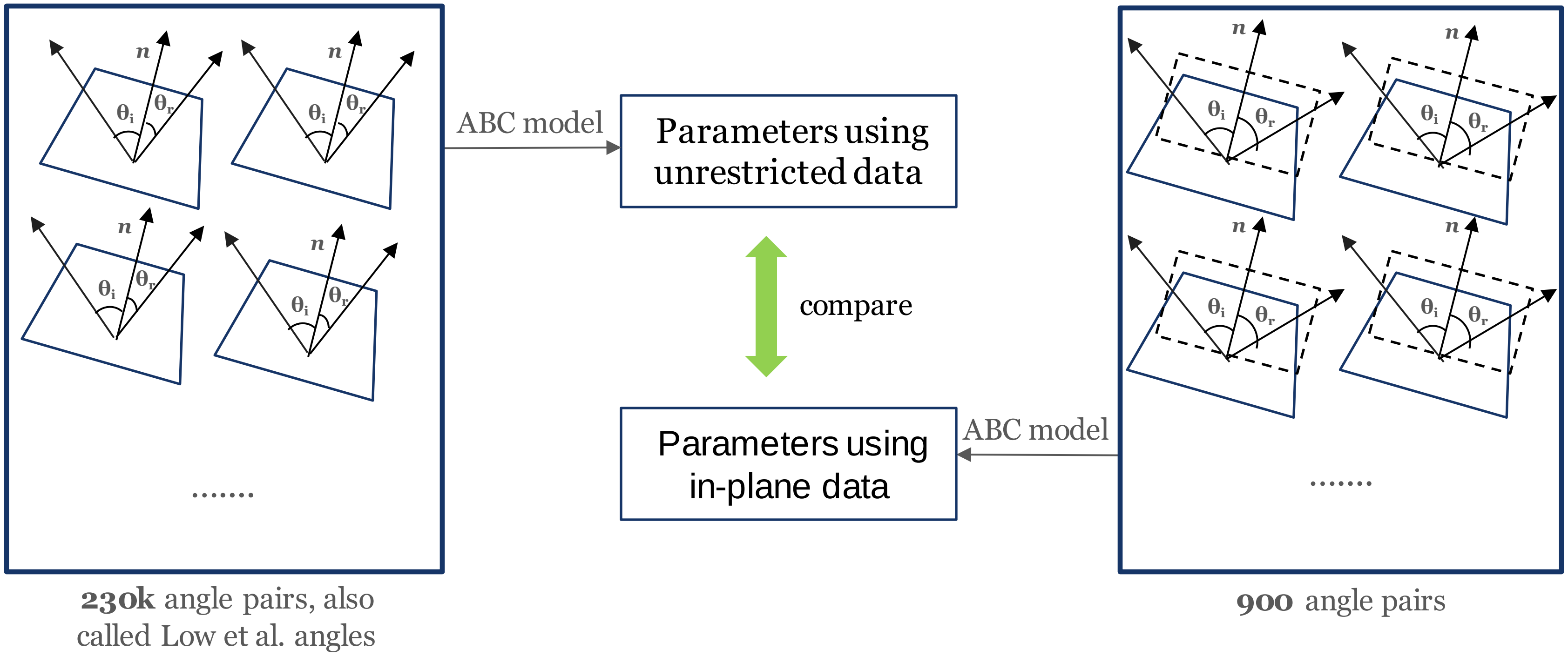
$$S(f) = \frac{A}{(1+Bf^2)^C}$$

n: surface normal
l: incoming angle
v: outgoing angle
h: half angle

c: **v.h**
g: $\eta^2 + c^2 - 1$
η: index of refraction

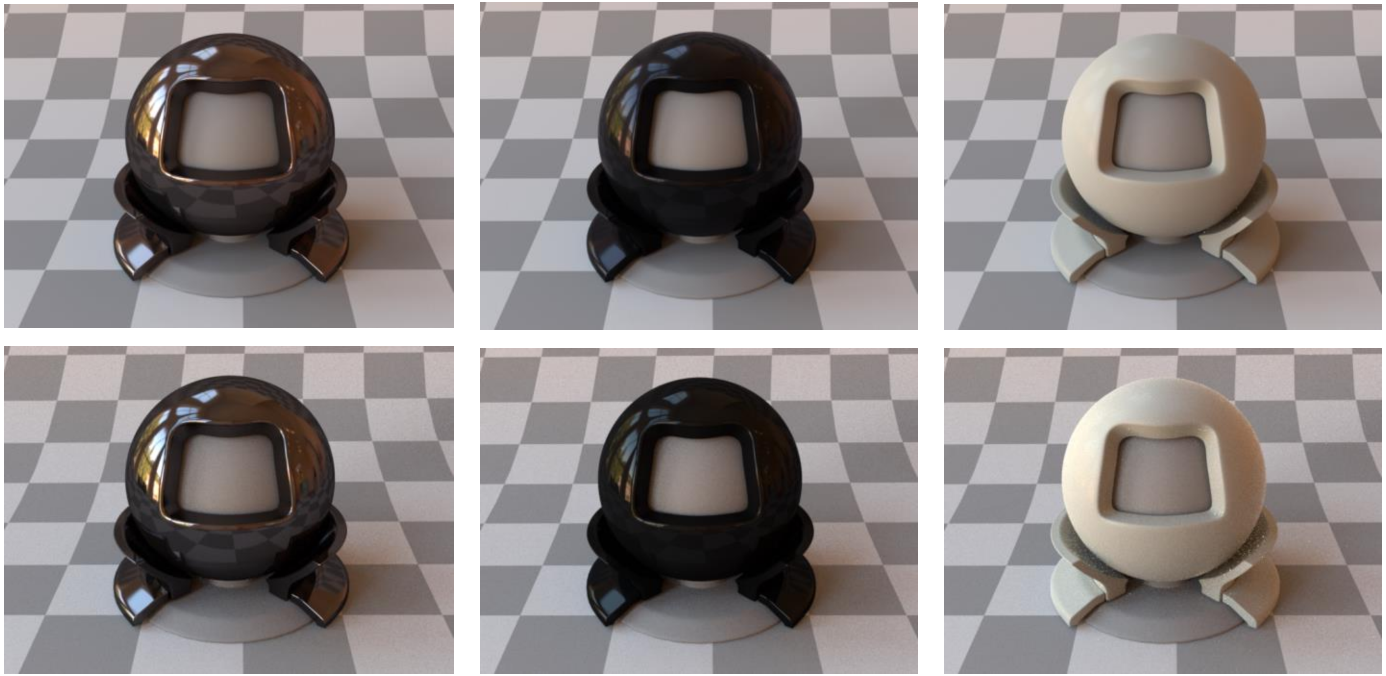
Equation based on the work Low et al. "*BRDF models for accurate and efficient rendering of glossy surfaces*"

In-plane vs Unrestricted (ABC Model)



Renderings (MERL)

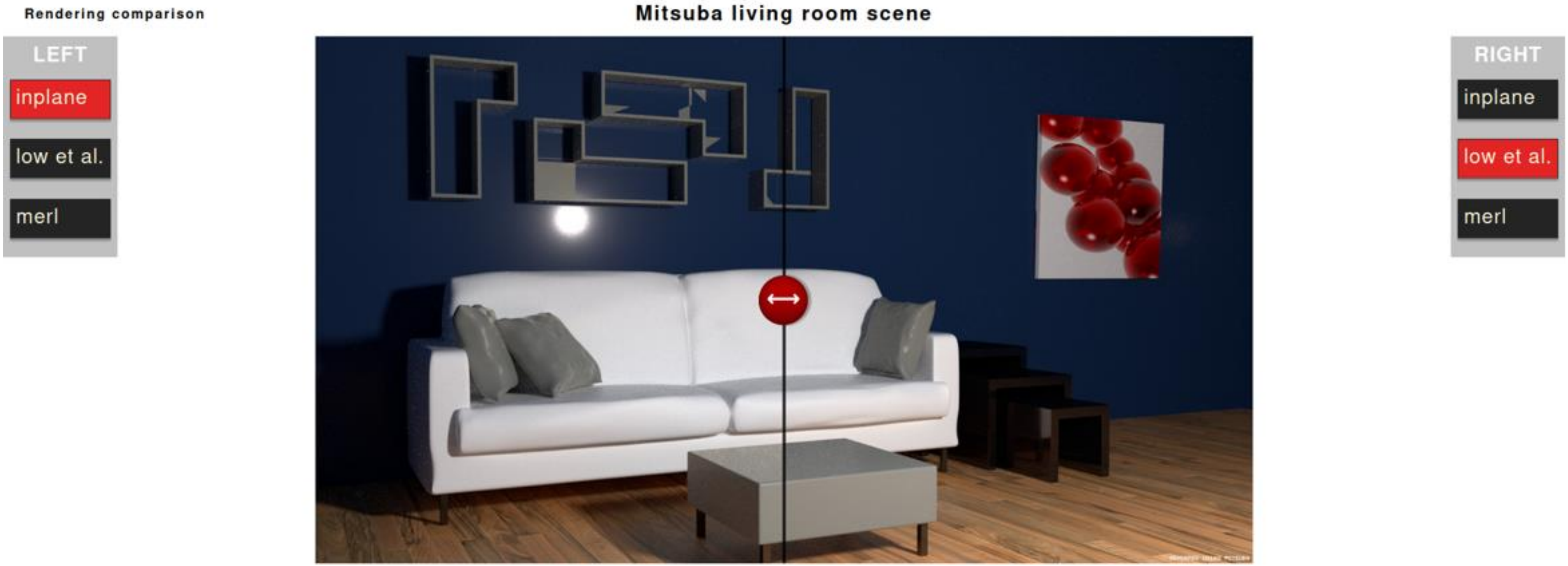
tungsten-carbide specular-black-phenolic nylon



unrestricted

in-plane

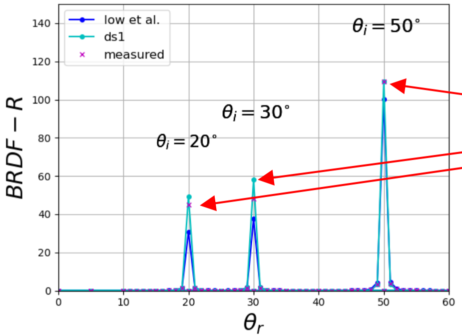
Renderings (MERL)



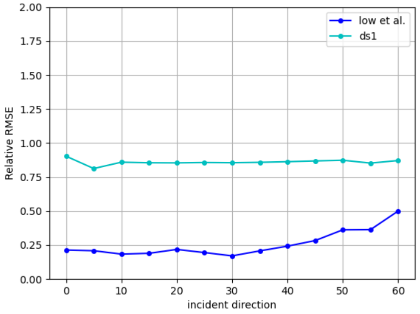
[link](#)

"Modern living room" by [Wig42](#)

BRDF and relative-rmse plots



3 separate plots superimposed

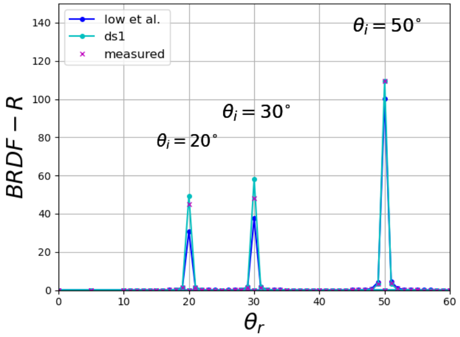


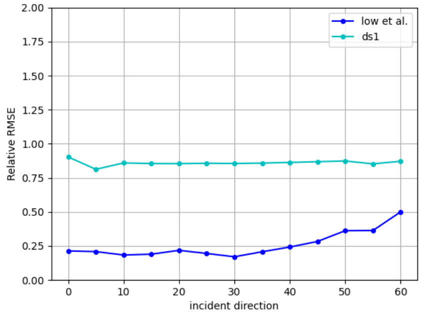
$$\text{Relative-rmse} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\frac{f_{\text{pred}} - f_{\text{mea}}}{f_{\text{mea}}}\right)^2}$$

(for a particular incoming directions, values are aggregated over all the outgoing directions and the three channels)

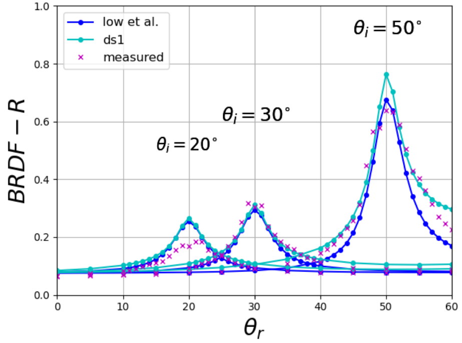
BRDF and relative-rmse plots

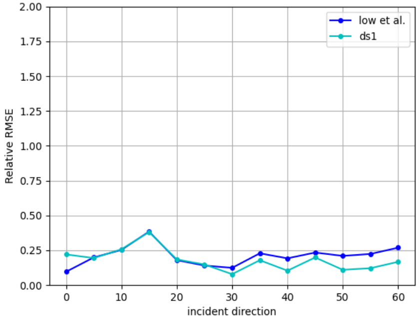
specular-black-phenolic



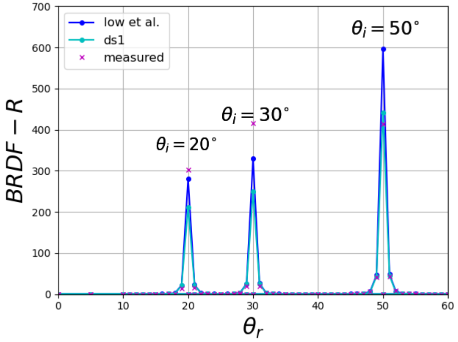


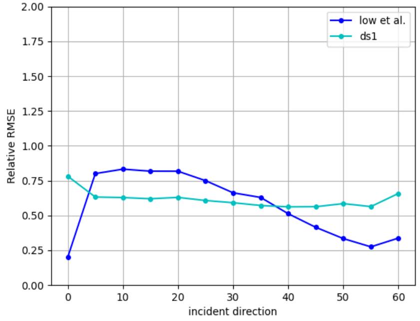
nylon





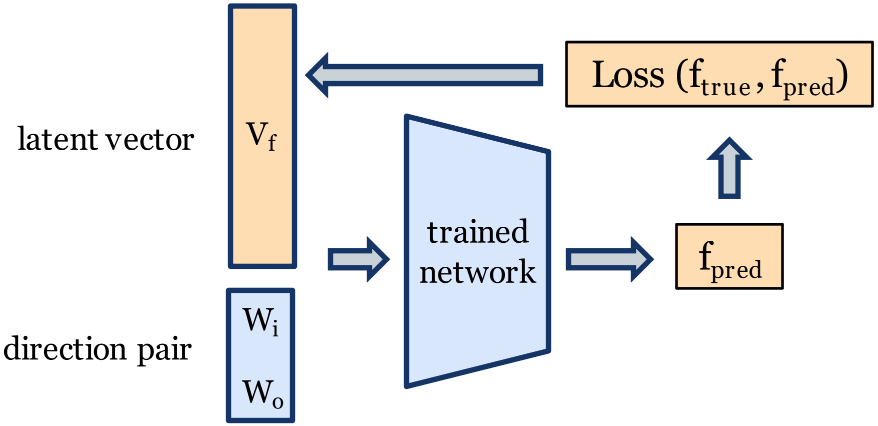
tungsten-carbide





Low et al. (unrestricted angle) fits produce superior relative-rmse plots for only 20/100 MERL materials

Neural Layered BRDF

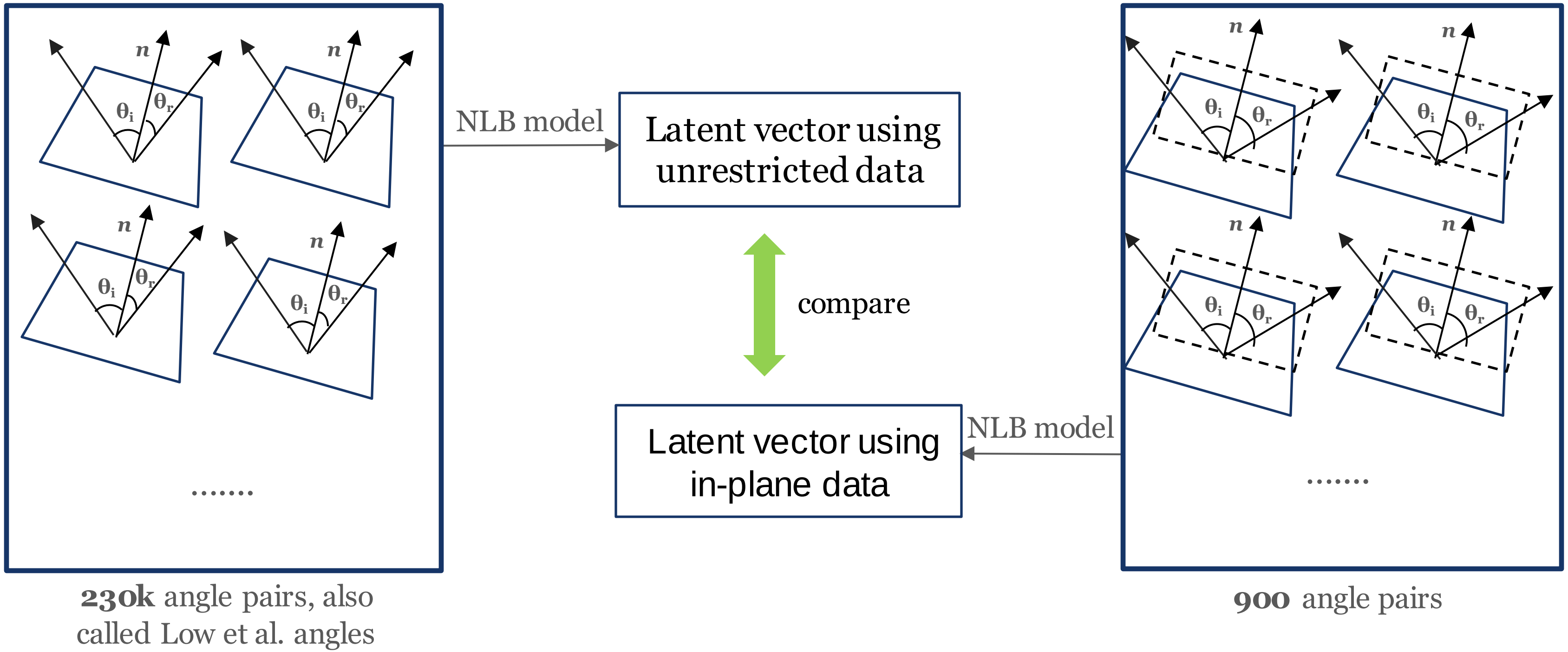


Inputs
- Incoming direction
- Outgoing direction
- Material-specific latent vector

Back-propagation
- For learning a new material
- Freeze network weights
- Optimize V_f using BRDF data

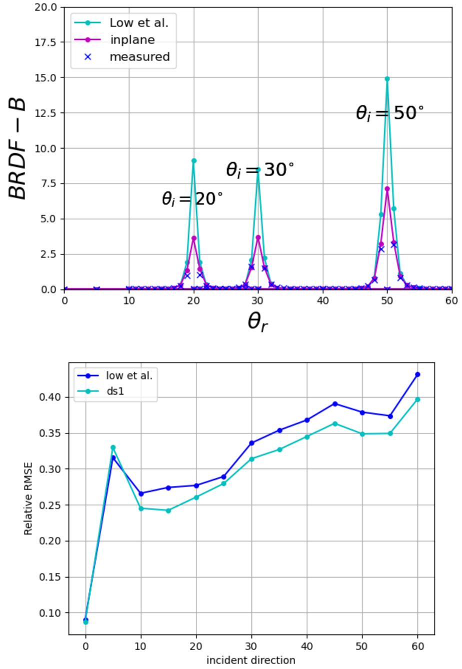
Model architecture based on the work Fan et al. "*Neural layered BRDFs*"

In-plane vs Unrestricted (NLB Model)

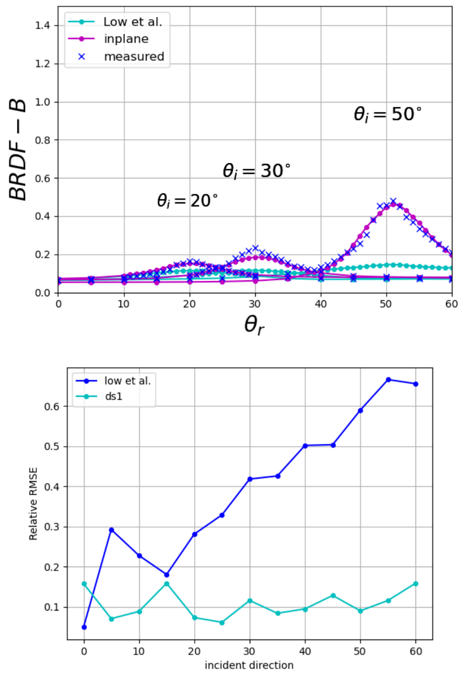


BRDF and relative-rmse plots

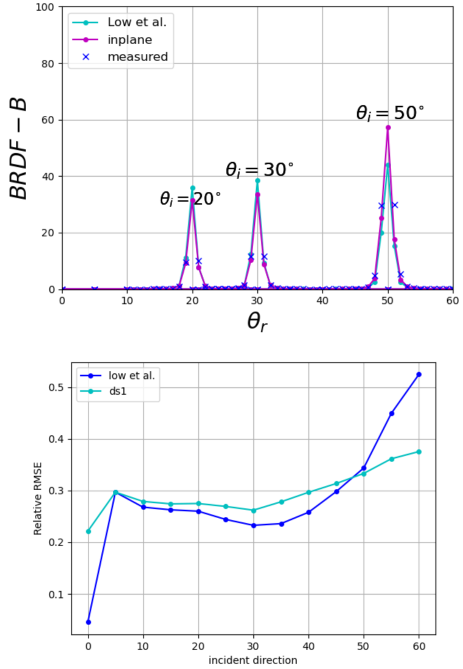
specular-black-phenolic



nylon



tungsten-carbide



Ablations

Progressively reduce dataset (DS1-DS4) from 900 angle pairs to 6 angle pairs

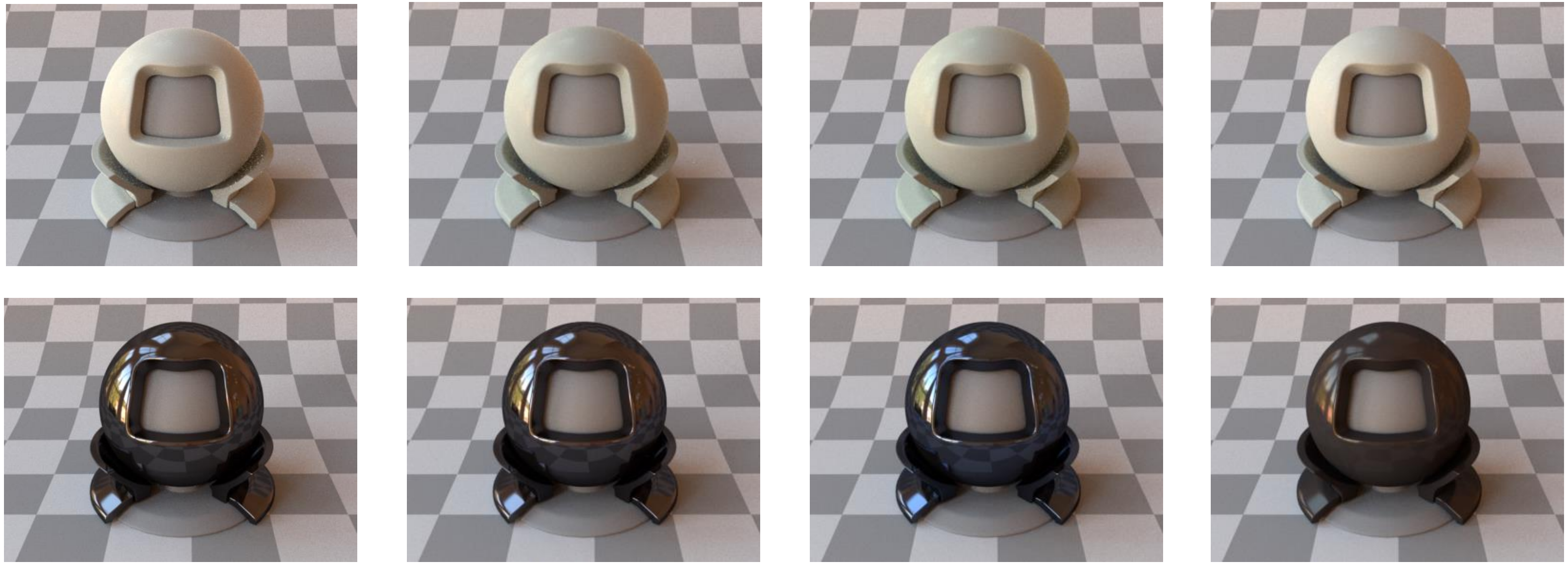
ABC parameters obtained through least squares optimization. NLB latent vector obtained using backprop shown earlier.

Dataset	θ_i **interval**	θ_r **interval: Diffuse**	θ_r **interval: Glossy**
DS1	$5°$	$5°$	$1°$
DS2	$15°$	$10°$	$2°$
DS3	$30°$	$20°$	$3°$

Dataset	**Incoming angle** (θ_i°)	**Outgoing angle** (θ_r°)
DS4	$30°$	$-60°, -20°, 20°, 28°, 36°, 60°$

Renderings (ABC Model)

ds1 ds2 ds3 ds4

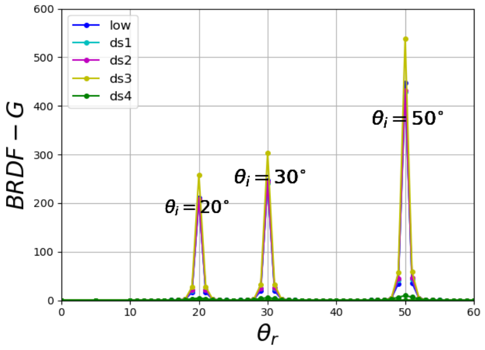


nylon

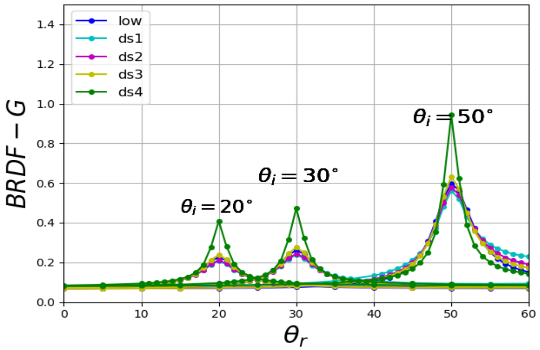
tungsten-carbide

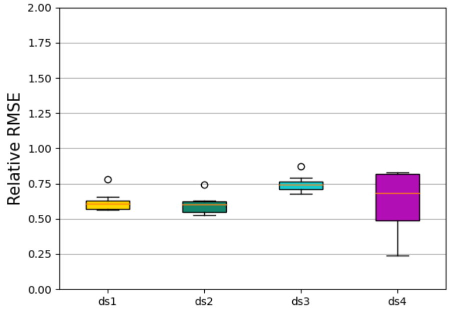
BRDF and relative-rmse plots (ABC Model)

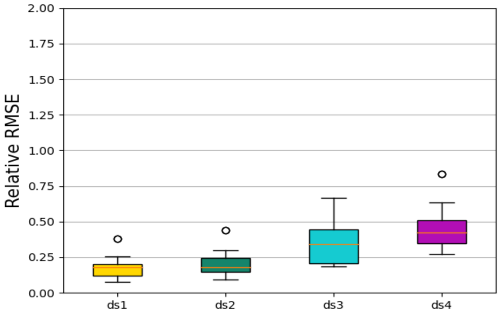
tungsten-carbide



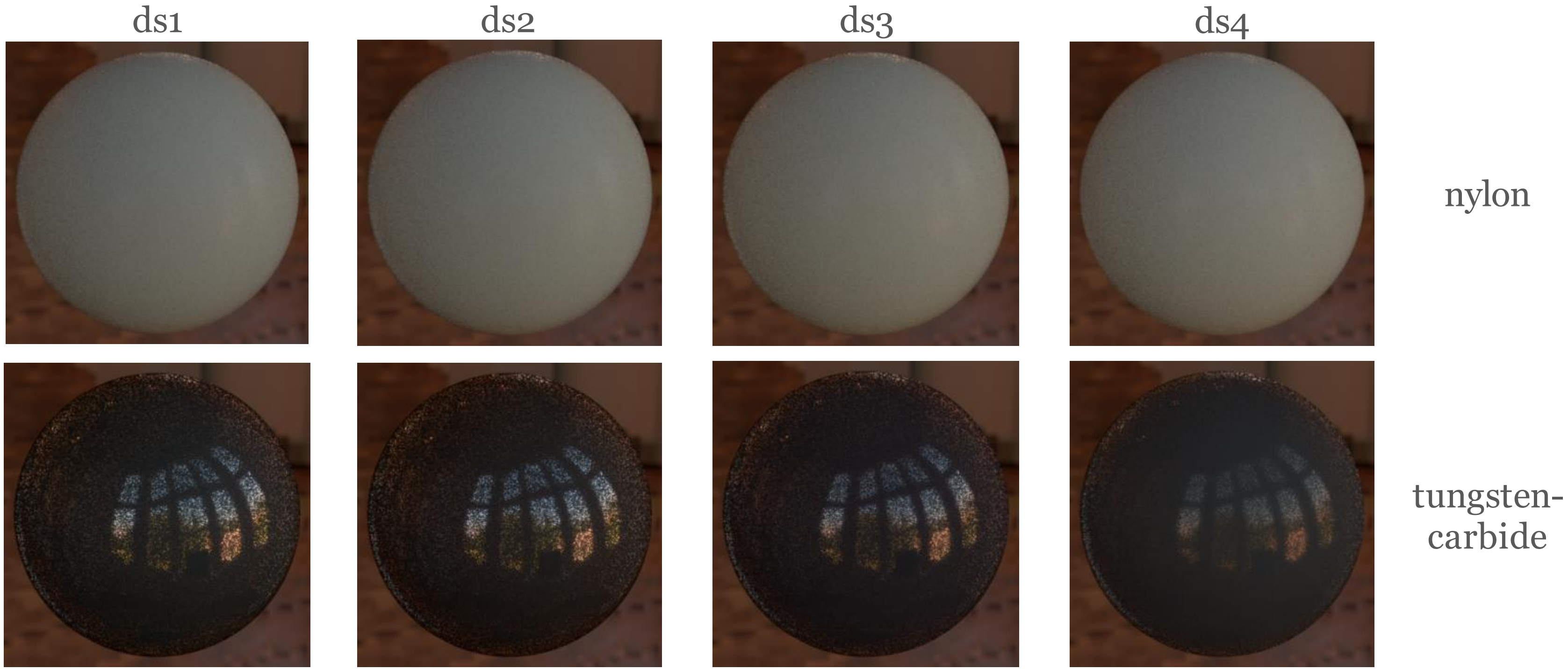
nylon





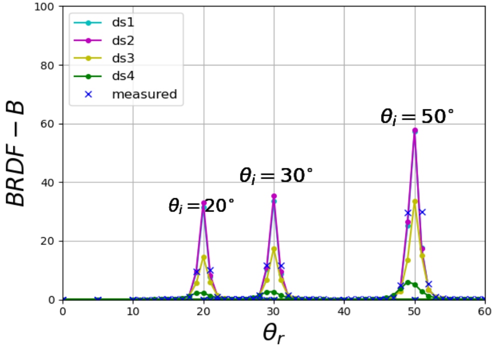


Renderings (NLB Model)

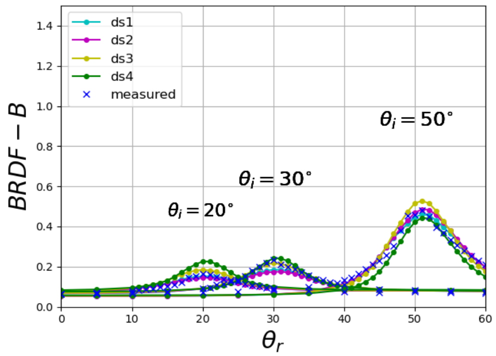


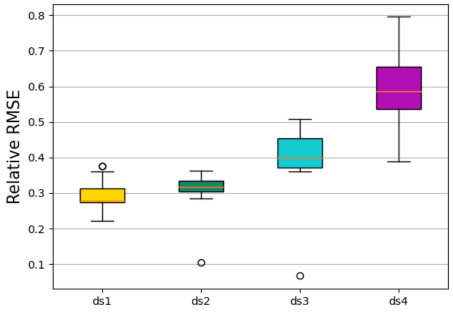
BRDF and relative-rmse plots (NLB Model)

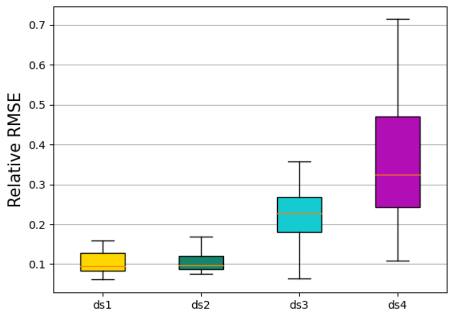
tungsten-carbide



nylon



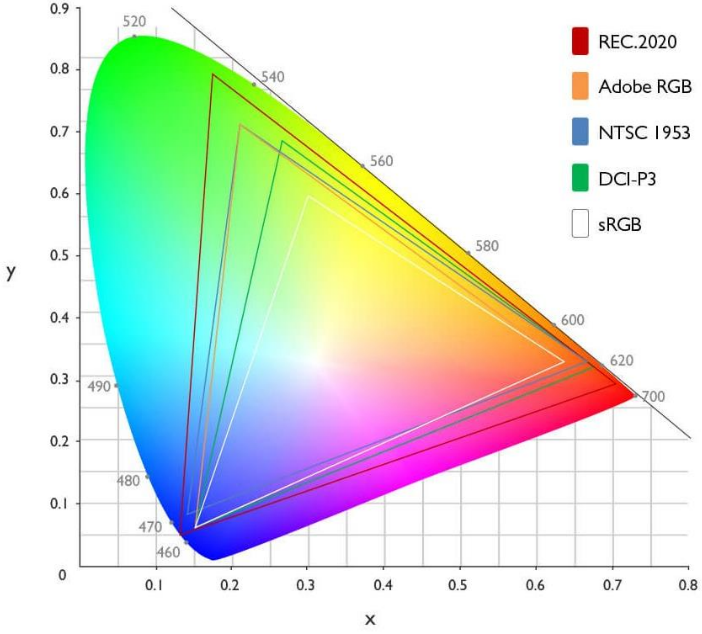




Problem Description

Parametric representations for BRDFs lie in the tristimulus domain, forcing premature wavelength compression of spectral data and loss of information.

Contribution:
We propose an MLP architecture that learns underlying BRDF trends using a subset training data and provides suitable estimates for unseen angles and wavelengths.



[9]

Spectral to RGB

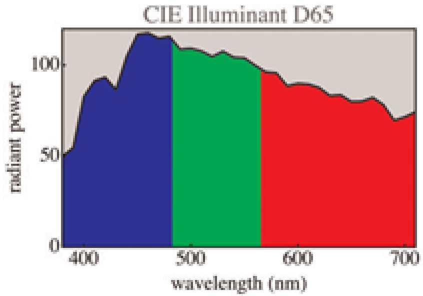
Spectral Data → **Radiance Values** → **Tone Reduction** → **XYZ to sRGB**

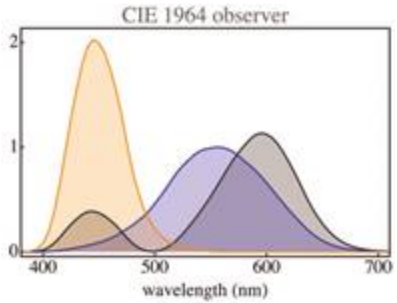
Data with 31 wavelengths for a sample

Weighting D65 spectral power distribution

CIE standard observer color matching functions applied across wavelength

Scaling and matrix (M) multiplication performed across tristimulus values





$$M = \begin{bmatrix} 3.2404542 & -1.5371385 & -0.4985314 \\ -0.9692660 & 1.8760108 & 0.0415560 \\ 0.0556434 & -0.2040259 & 1.0572252 \end{bmatrix}$$

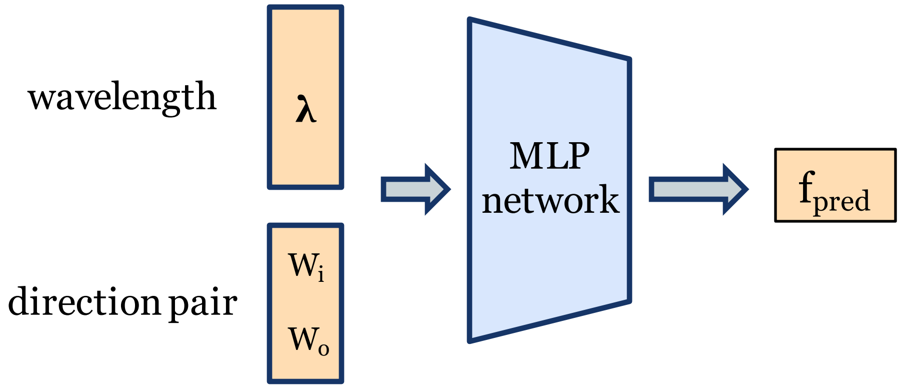
[10,11]

Spectral BRDF matching

Input (normalized): Incident angle, viewing angle, wavelength

Output: BRDF value

Network: 3 layer MLP, 10 nodes each layer



Data Description (Packaging print)

BRDF measured for 31 wavelengths (390–730 nm at 10 nm intervals, in-plane)

Granularity (incident and viewing angles):

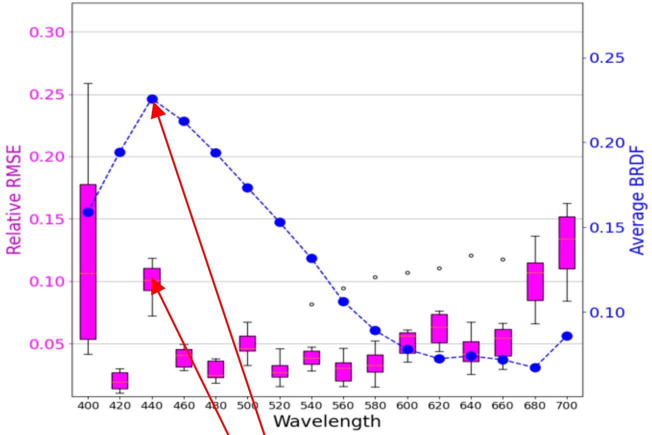
- 5° intervals for diffuse region
- 1° intervals for specular region.

Samples: *Gold, Cyan, Magenta, Gonio*

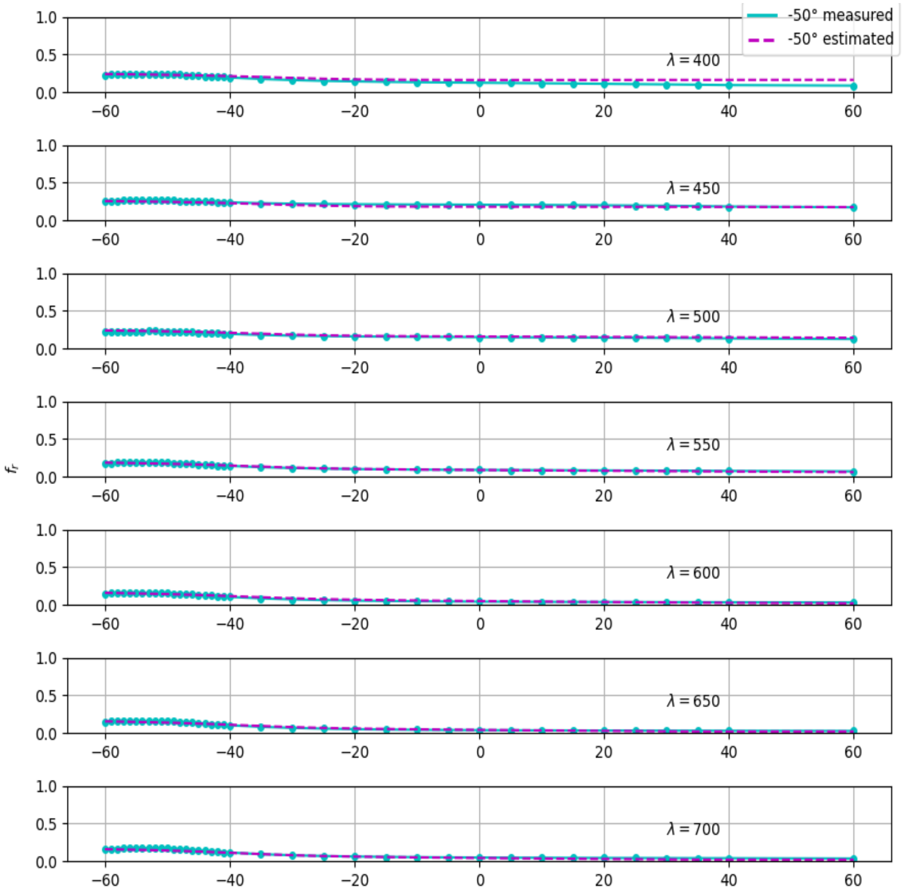
Dataset from "*Measurement and rendering of complex non-diffuse and goniochromatic packaging materials*" [12]

Results

Cyan Sample



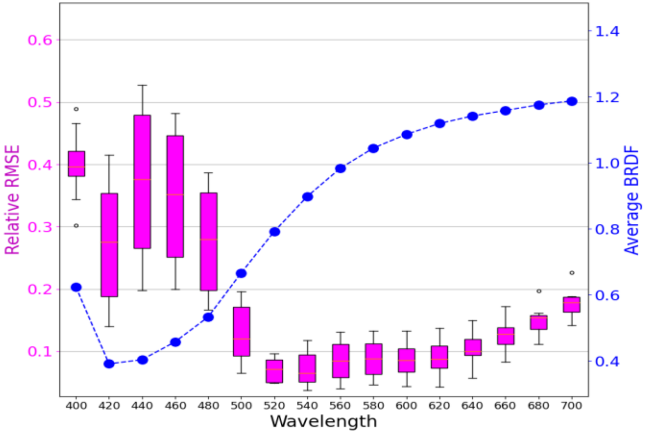
True value = 0.23
Model output = [0.207, 0.253]

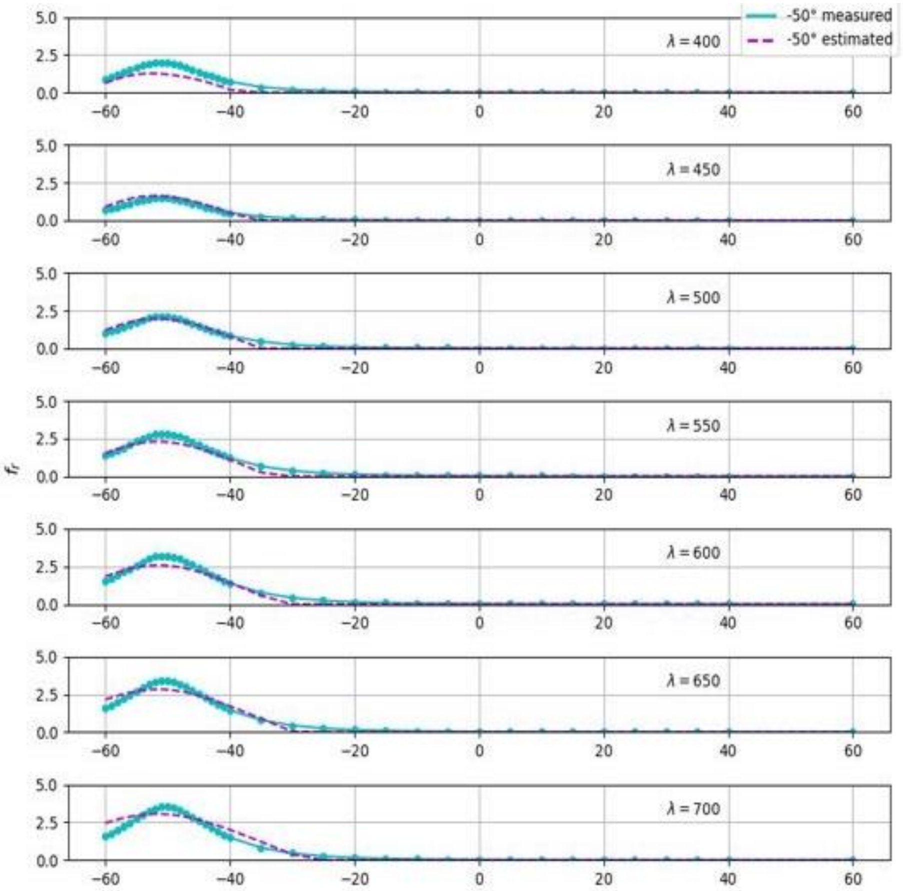


outgoing direction

Results

***Gold* Sample**

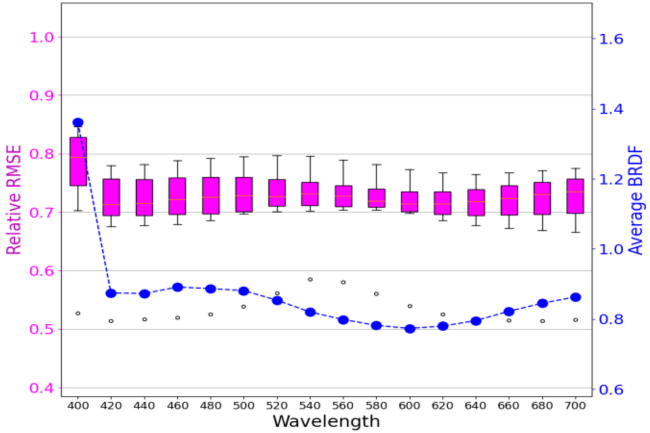


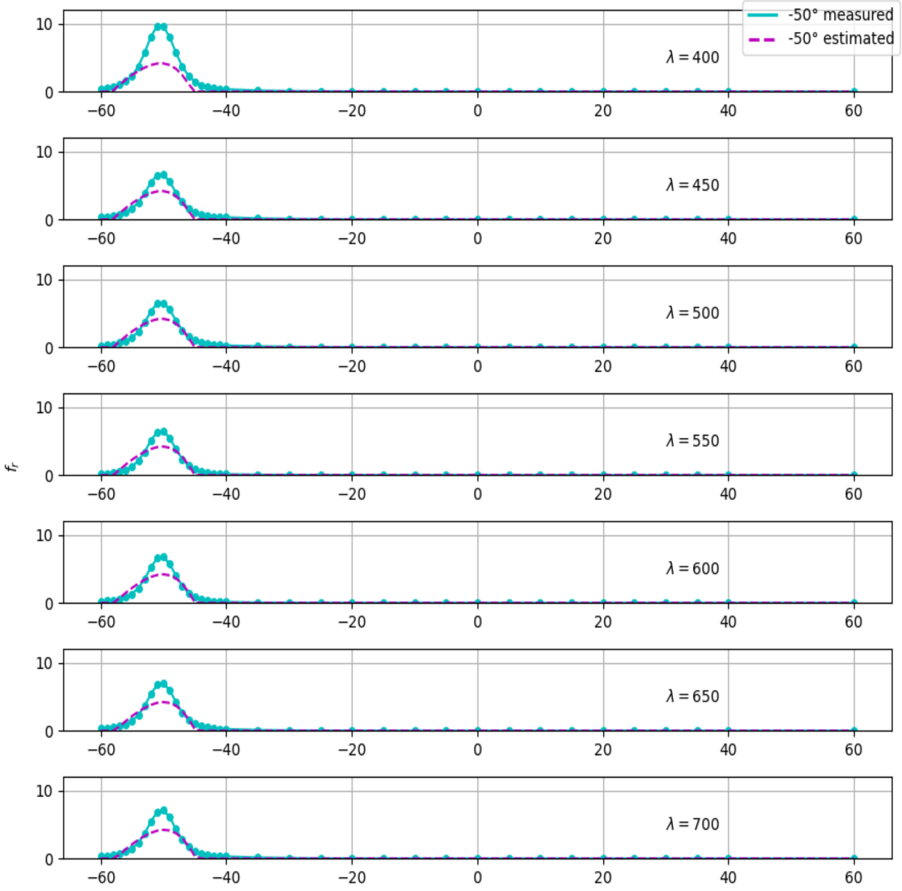


outgoing direction

Results

Gonio Sample





outgoing direction

Summarizing

- For isotropic materials, we demonstrate the sufficiency of in-plane angles for material capture.
- Both physics-based and network-based models were used to show comparable results between our chosen angles and 256x larger out-of-plane ones.
- The effect of data reduction on material capture was studied with the findings suggesting that even six angle pairs are enough in simpler materials.

Thank You!

References

[1] https://www.sciencedirect.com/topics/engineering/bidirectional-reflectance-distribution-function
[2] https://en.wikipedia.org/wiki/Bidirectional_reflectance_distribution_function
[3] https://snr.unl.edu/agmet/brdf/brdf-definition.asp
[4] https://tips.clip-studio.com/en-us/articles/4405
[5] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4587766&tag=1
[6] https://www.semanticscholar.org/paper/Image-Based-BRDF-Measurement-Including-Human-Skin-Marschner-Westin/c05c4b5238b8344d44de424811a4b2d8f6f99f48
[7] https://x.com/keenanisalive/status/1526158057151111169
[8] https://blog.yiningkarlli.com/2013/04/working-towards-importance-sampled-direct-lighting.html
[9] https://www.projector1.com/color-gamut-rec-2020-vs-dci-p3-vs-adobe-rgb-vs-ntsc/
[10] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5624368/
[11] https://www.researchgate.net/figure/At-left-the-CIE-illuminant-D65-average-daylight-The-colors-show-the-spectral-bins-for_fig2_320108906
[12] https://www.mcrl.co.jp/english/products/p_color_sp/detail/GCMS3B.html