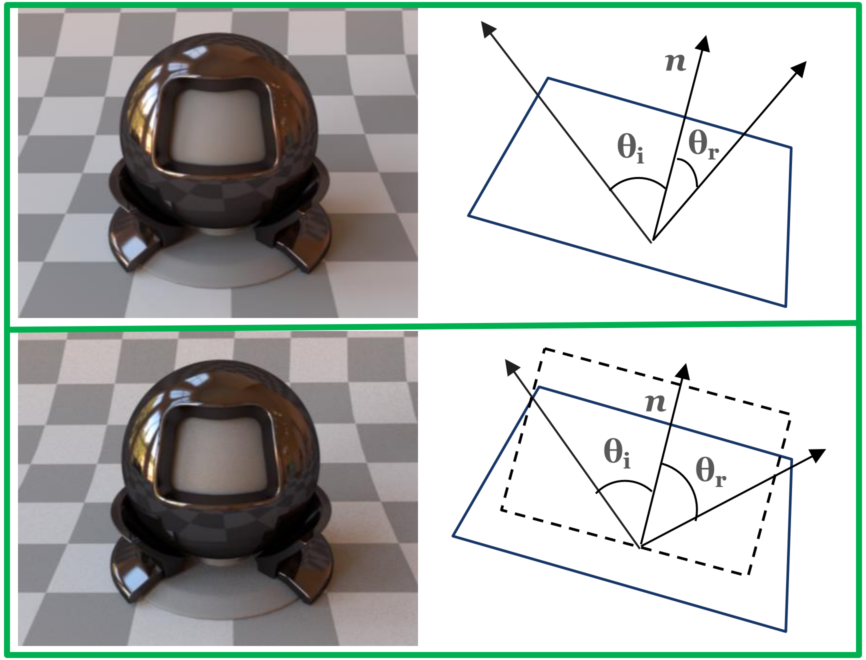
Simplifying BRDF Acquisition

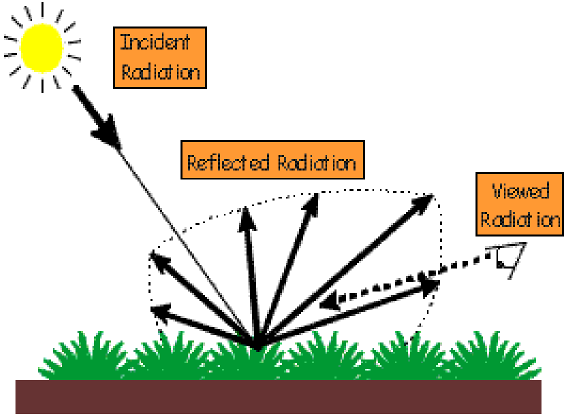
Dual Degree Project Presentation



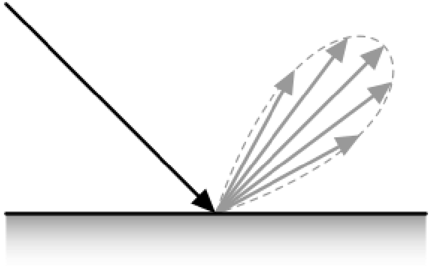
Shubham Chitnis (190020033)

10/06/2024

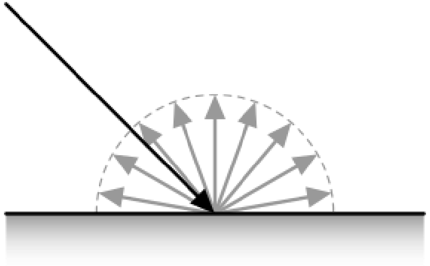
What is BRDF?



Important precursor to object perception



Glossy/Specular

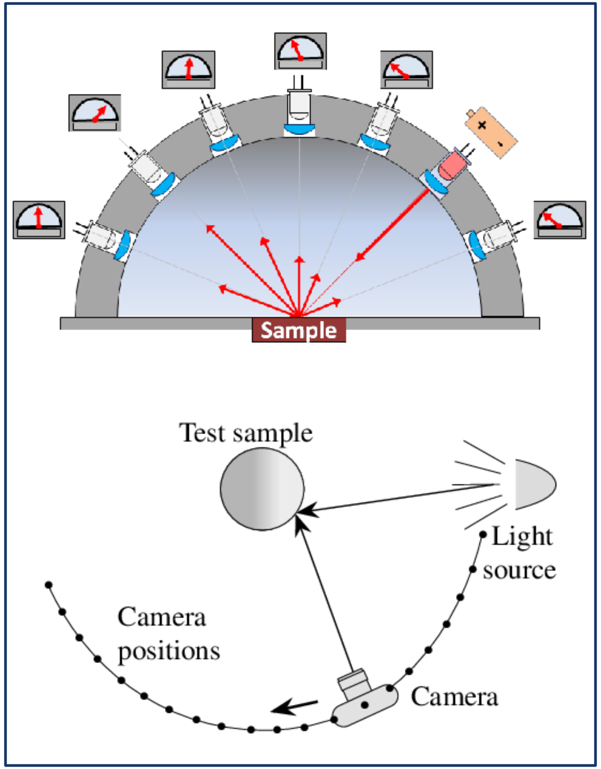


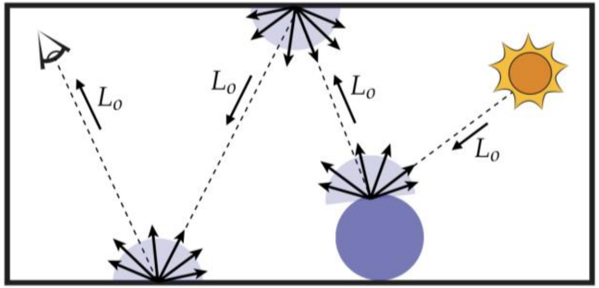
Matte/Diffuse

Definition	The ratio of the outgoing radiance from a point on the material to the incoming irradiance for a given *incoming and outgoing angle pair* and specific to a certain *wavelength*

[1, 2, 3, 4]

Why measure BRDF?



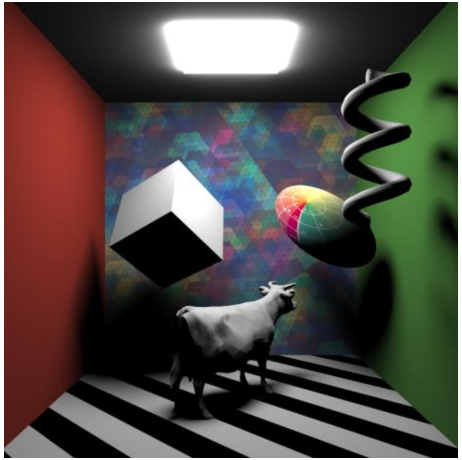


$$\boxed{L(x, \vec{\omega}_o)} = \int_{\mathcal{H}^2} f_r(x, \vec{\omega}_i, \vec{\omega}_o) \boxed{L(x, -\vec{\omega}_i)} \cos\theta \, d\omega_i$$

radiance (unknown!) — radiance (unknown!)

BRDF data

Laborious!



[5,6,7,8]

Objective 1/2

Problem Description

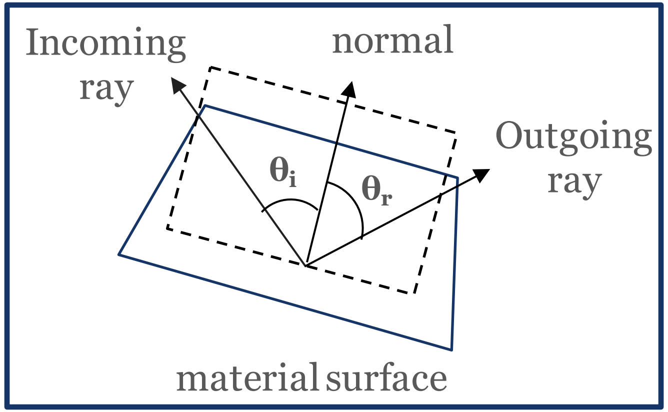
BRDF acquisition is expensive, requiring multiple hours (even days) for material capture. We need more efficient ways for BRDF capture.

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



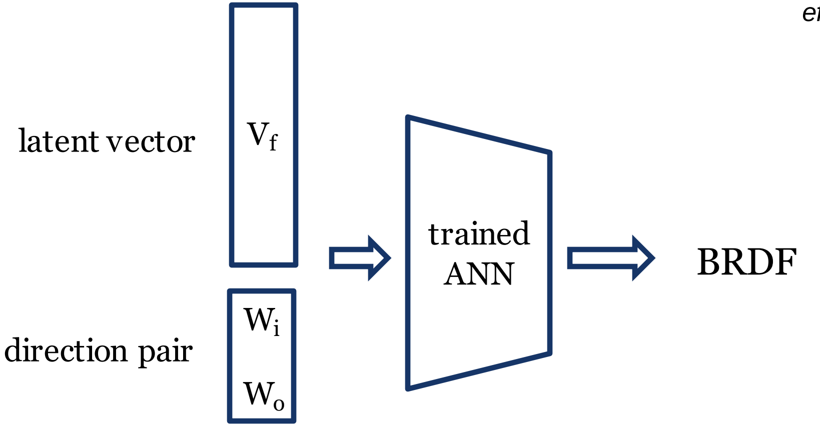
Existing BRDF representations

Physics based

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

Low et al. "*BRDF models for accurate and efficient rendering of glossy surfaces*"

ANN based



Fan et al. "*Neural layered BRDFs*"

Input: Directions, Material-specific parameters
Output: BRDF

Contributions

- We demonstrate that, for varied isotropic materials, a small subset of *in-plane* angles is able to represent the entire BRDF range sufficiently.

- We also check the fit qualities of *existing* representations by progressively reducing the fitting BRDF data from 900 angle pairs to as little as six angle pairs.

Scope

Show that fitting in-plane angles is comparable to fitting baseline data

Test BRDF representations with reduced datasets

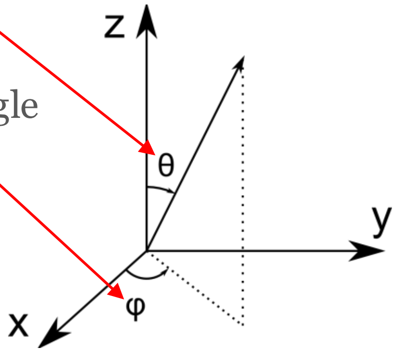
Data Description (MERL)

Publicly available dataset for 100 isotropic materials

BRDF datapoints in millions (tristimulus domain, baseline). Process takes roughly 3 hours per material

Granularity (polar and azimuthal angles):

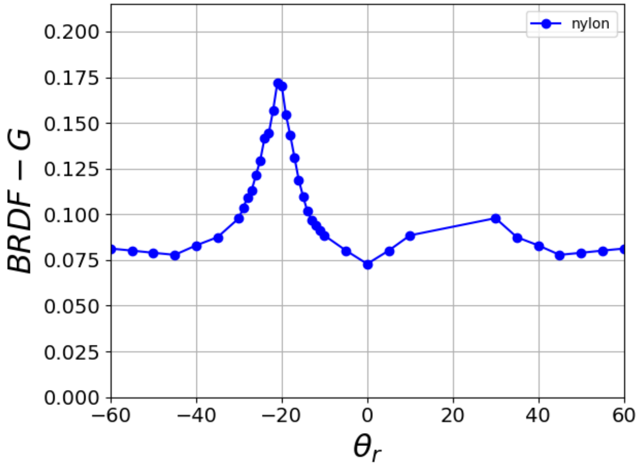
- 10° intervals for incoming polar angle
- 1° intervals for outgoing polar angle
- 1° intervals for outgoing azimuthal angle



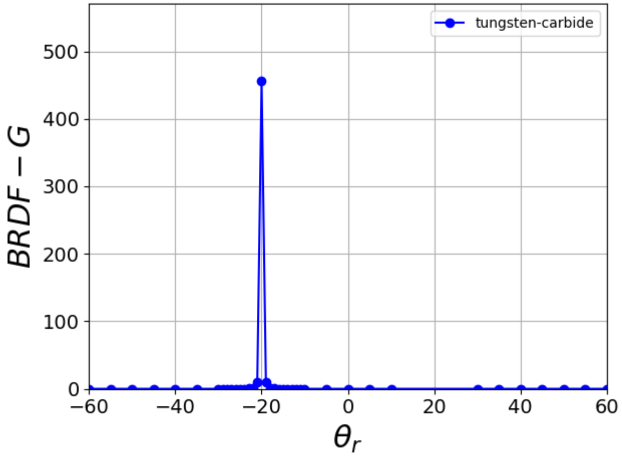
Dataset and Measurement setup from "*A Data-Driven Reflectance Model*"

Data Description (MERL)

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



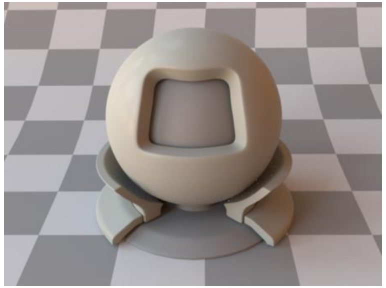
Nylon

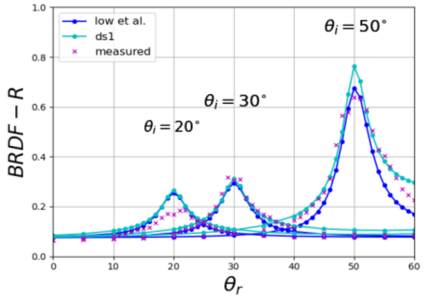


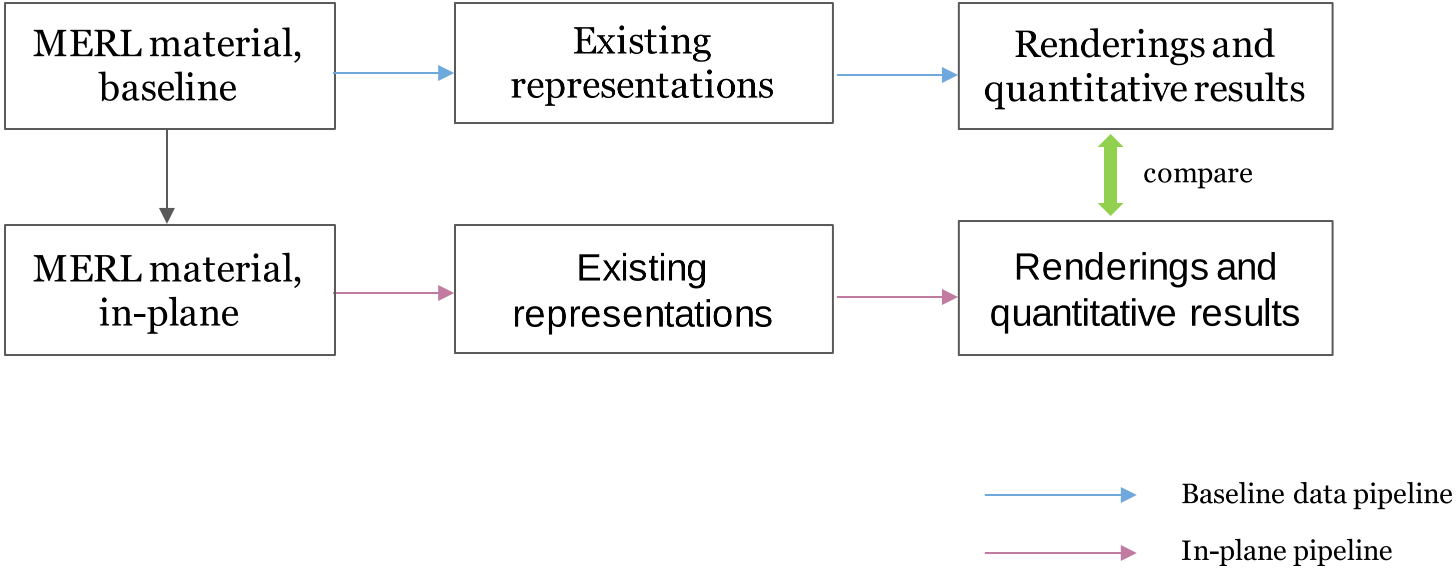
Tungsten-Carbide

Here, we have fixed incoming angle to -20° and varied the outgoing angle, querying the BRDF for each pair

Workflow




low et al.
ds1
measured
$\theta_i = 20^\circ$
$\theta_i = 30^\circ$
$\theta_i = 50^\circ$
$BRDF - R$
θ_r


MERL material, baseline
Existing representations
Renderings and quantitative results
compare
MERL material, in-plane
Existing representations
Renderings and quantitative results
Baseline data pipeline
In-plane pipeline

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.

ABC BRDF Model

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

(Geometric attenuation)

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

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

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

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

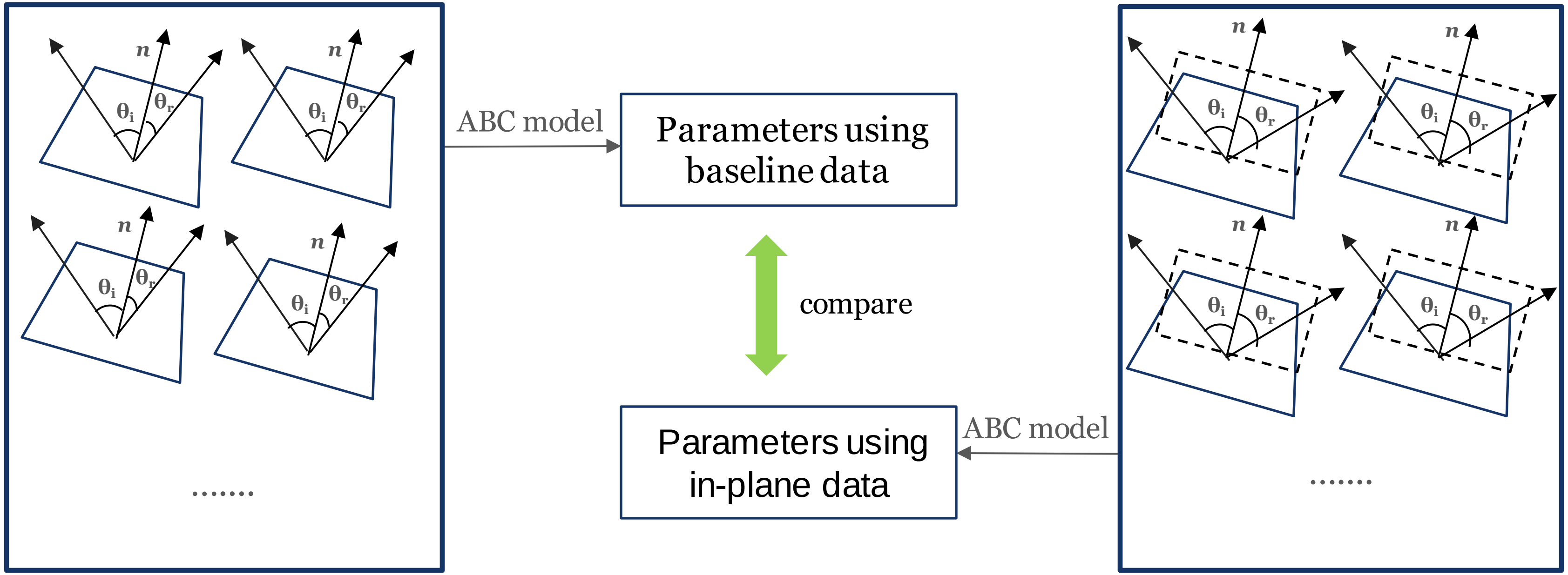
$$g_{\text{pred}} = \ln(1 + \cos\theta_i f_{\text{pred}})$$

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

c: **v.h**
g: η^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 Baseline (ABC Model)



2,30,000 angle pairs, also called Low et al. angles

$$\frac{2,30,000}{900} \approx 256$$

900 angle pairs

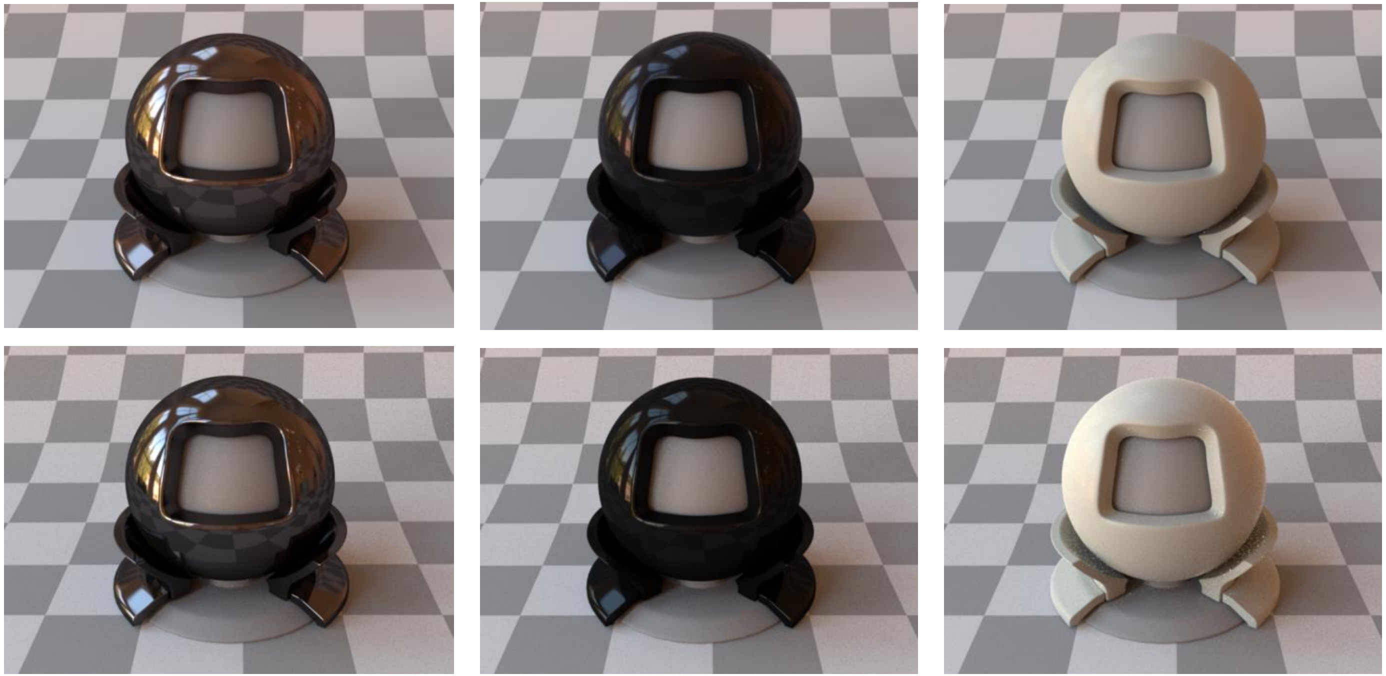
Renderings (MERL)

link

"Modern living room" by Wig42

Renderings (MERL)

tungsten-carbide | specular-black-phenolic | nylon

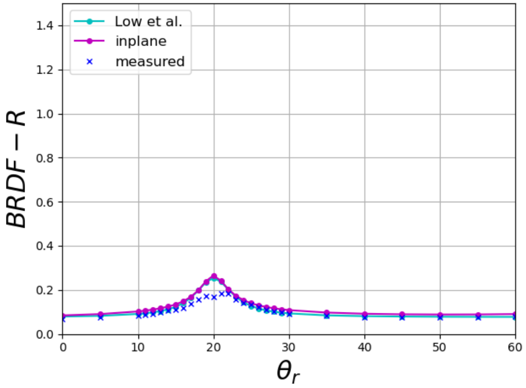


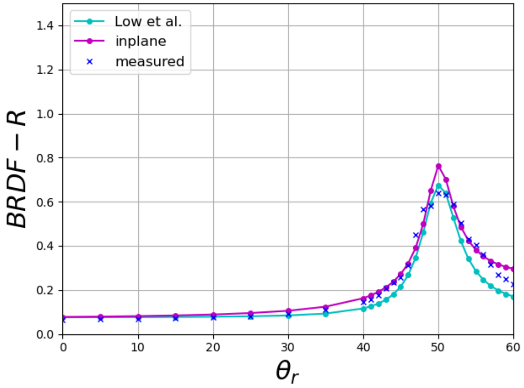
baseline

in-plane

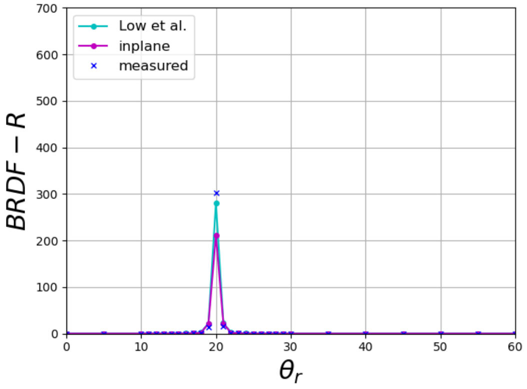
BRDF plots

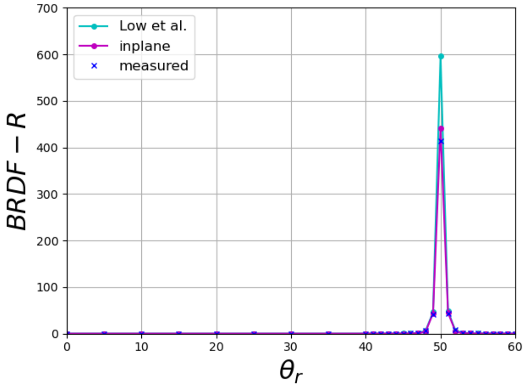
Nylon





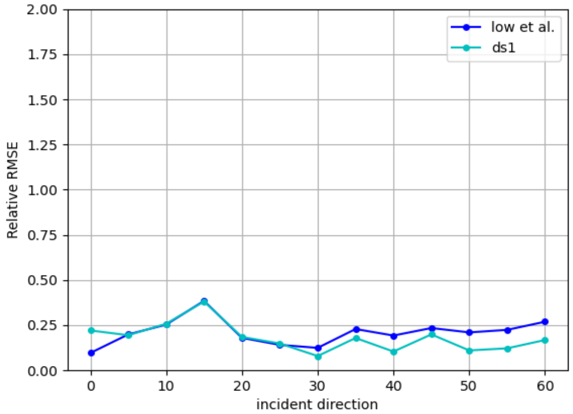
Tungsten carbide



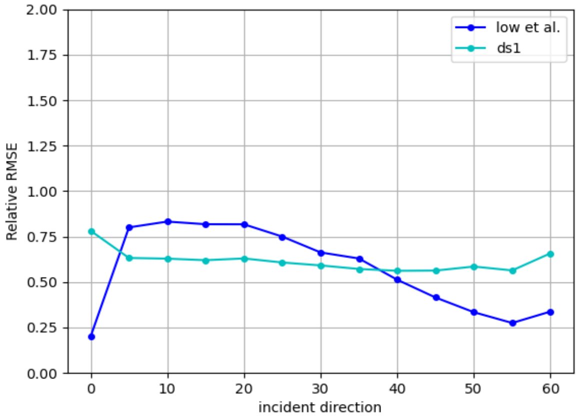


Relative-rmse plots

Nylon



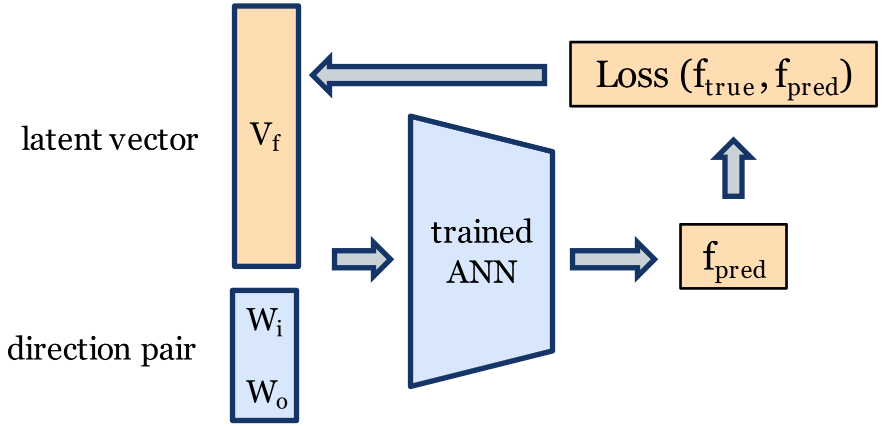
Tungsten carbide



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

For a particular incoming directions, values are aggregated over all the outgoing directions and the three channels

Neural Layered BRDF



Inputs

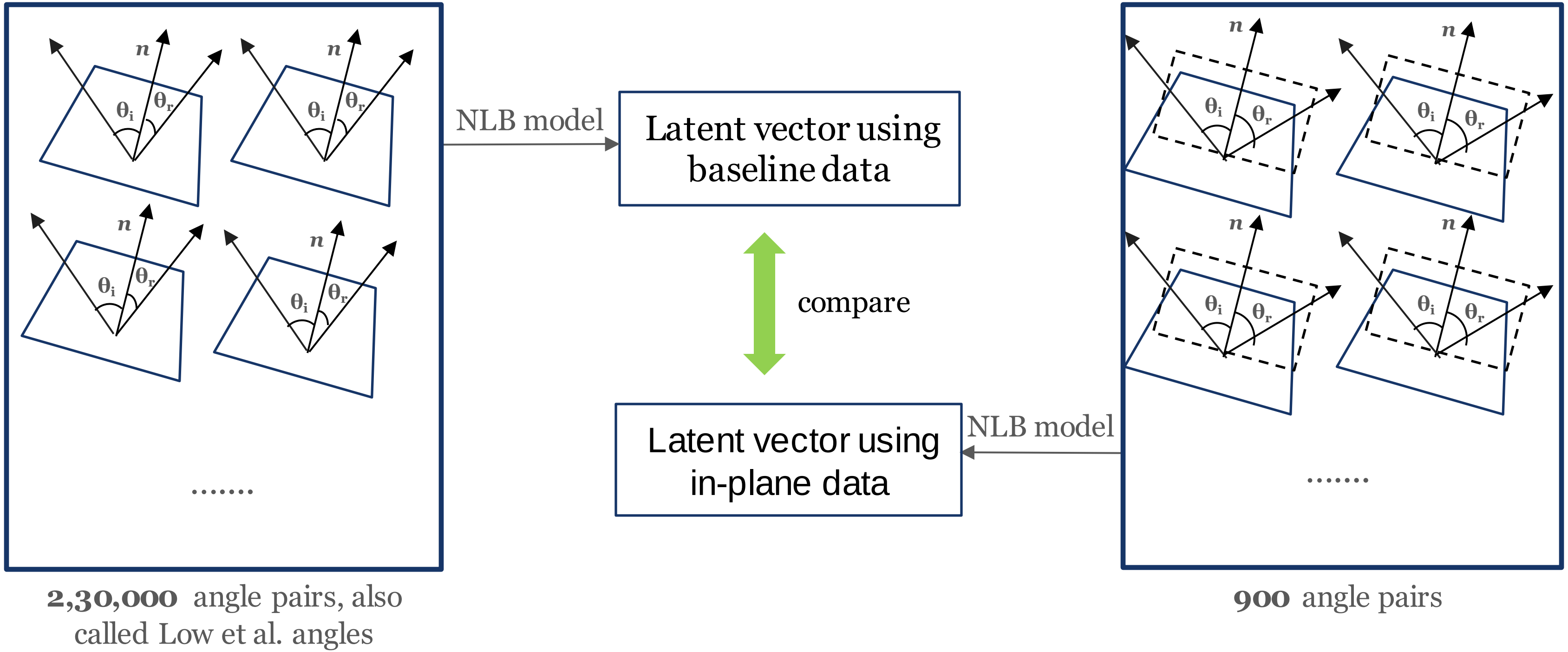
- Incoming direction
- Outgoing direction
- Material-specific latent vector

Back-propagation

- For learning a new material
- Freeze ANN weights
- Optimize V_f using BRDF data

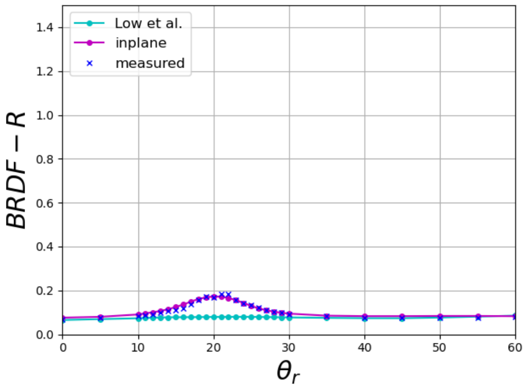
Model architecture based on the work Fan et al. "*Neural layered BRDFs*"

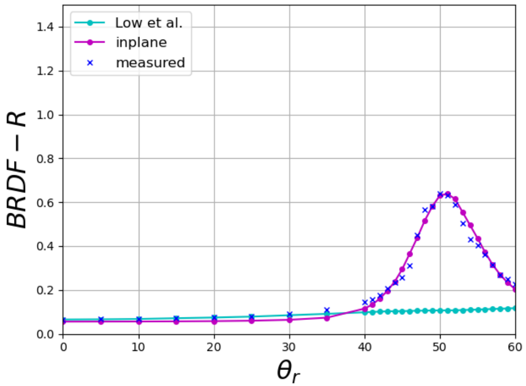
In-plane vs Baseline (NLB Model)



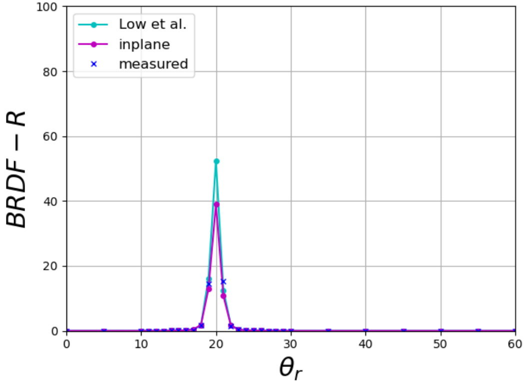
BRDF plots

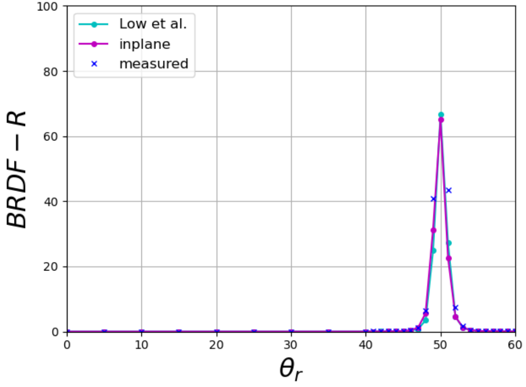
Nylon





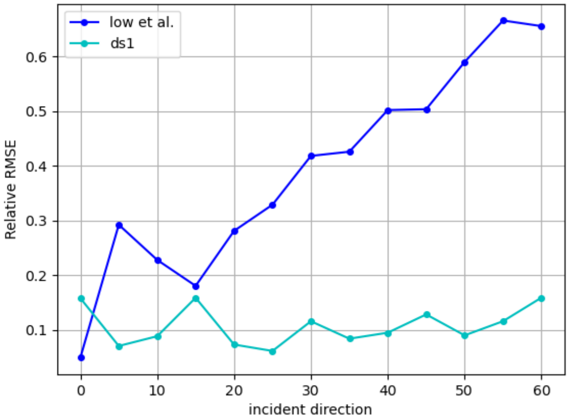
Tungsten carbide



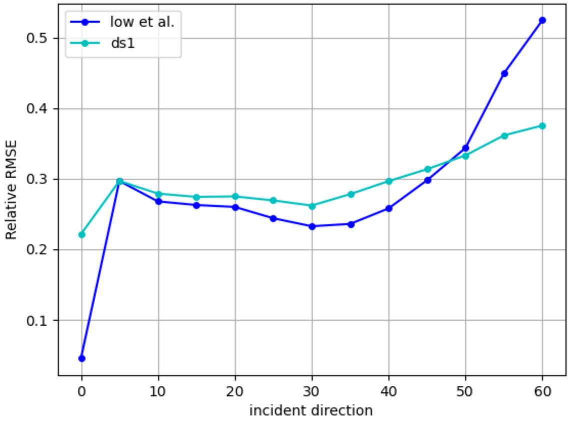


Relative-rmse plots

Nylon



Tungsten carbide



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

For a particular incoming directions, values are aggregated over all the outgoing directions and the three channels

Ablations

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

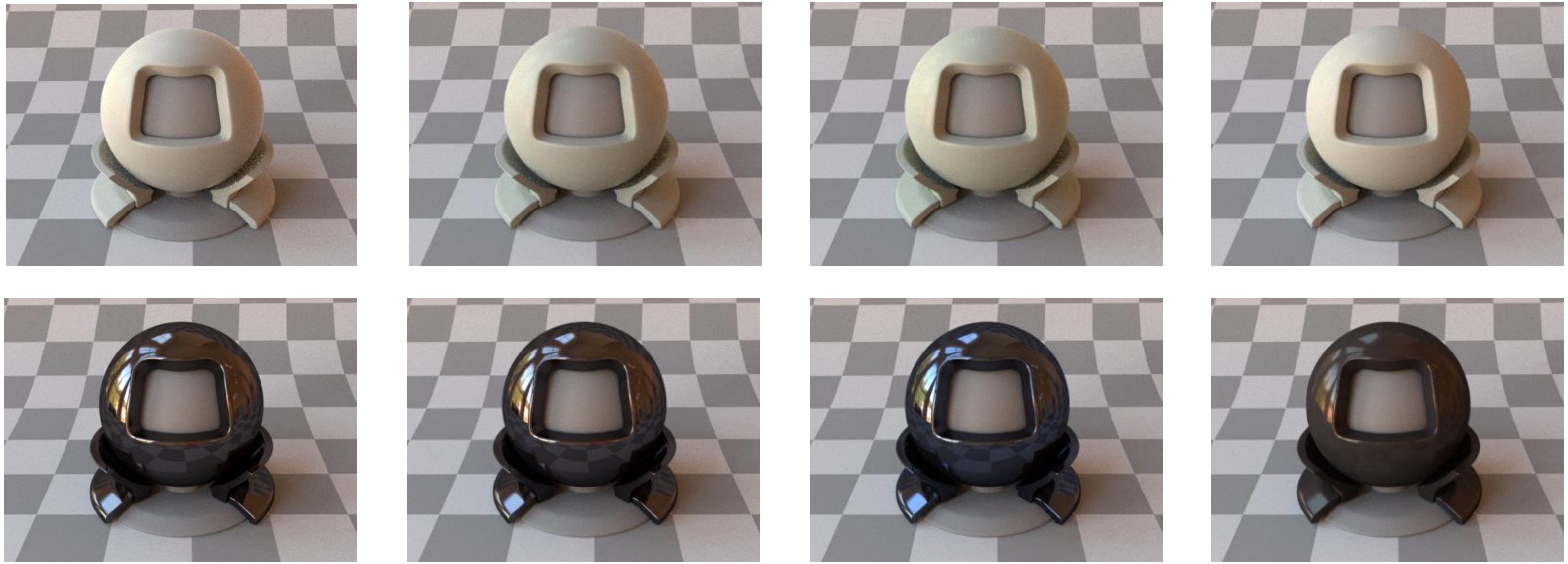
ABC parameters obtained through least squares optimization. NLB latent vector obtained using backprop shown earlier.

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

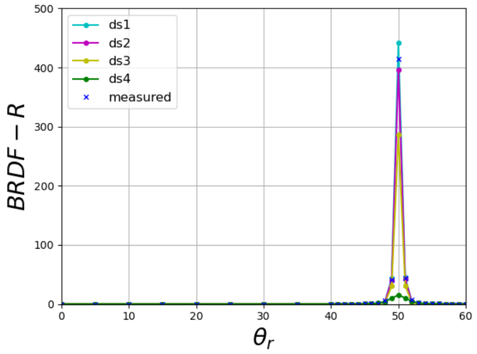


nylon

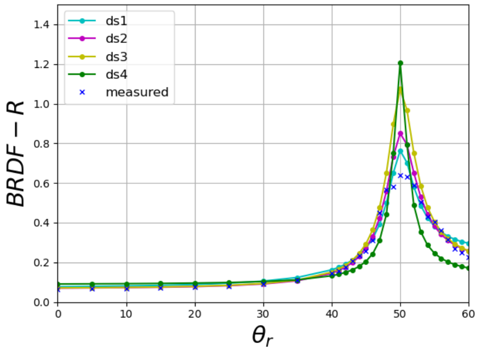
tungsten-carbide

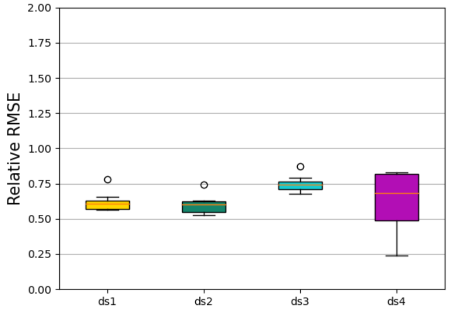
BRDF and relative-rmse plots (ABC Model)

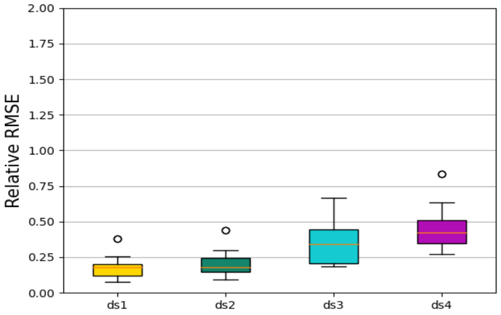
Tungsten-carbide



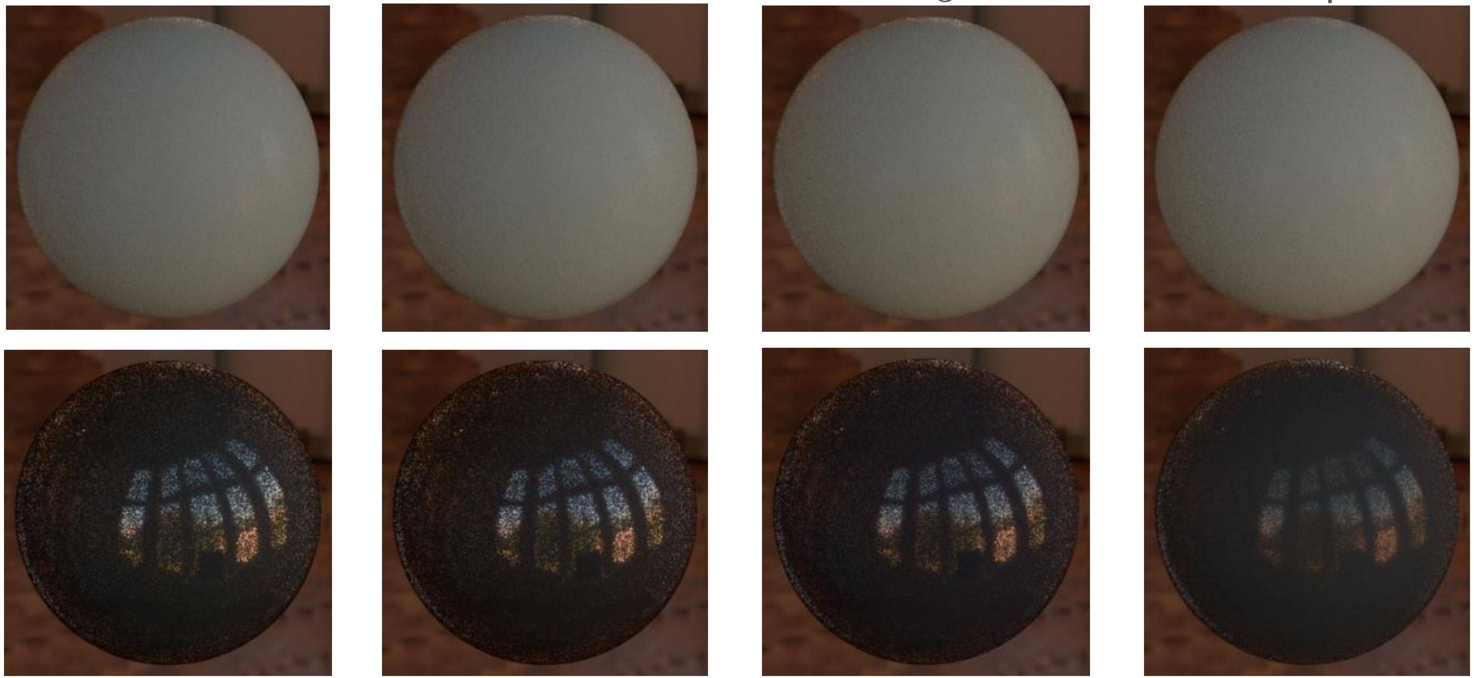
Nylon





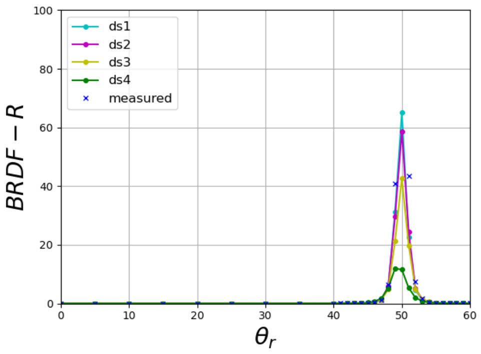


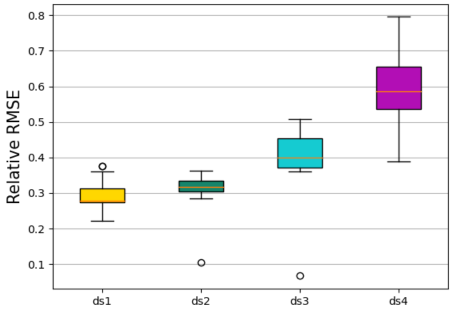
Renderings (NLB Model)



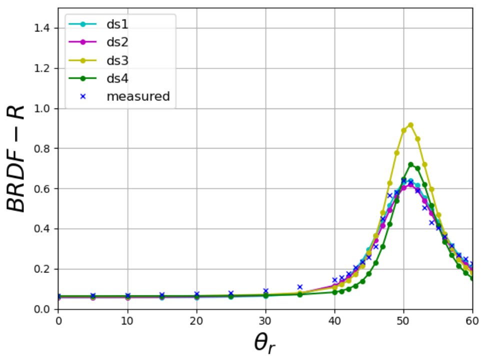
BRDF and relative-rmse plots (NLB Model)

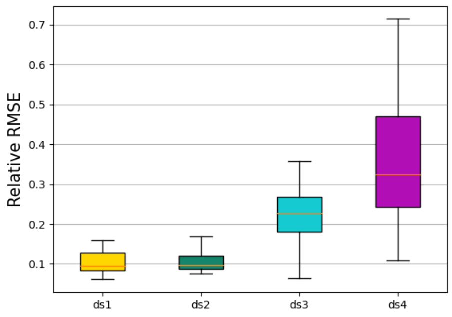
tungsten-carbide





nylon



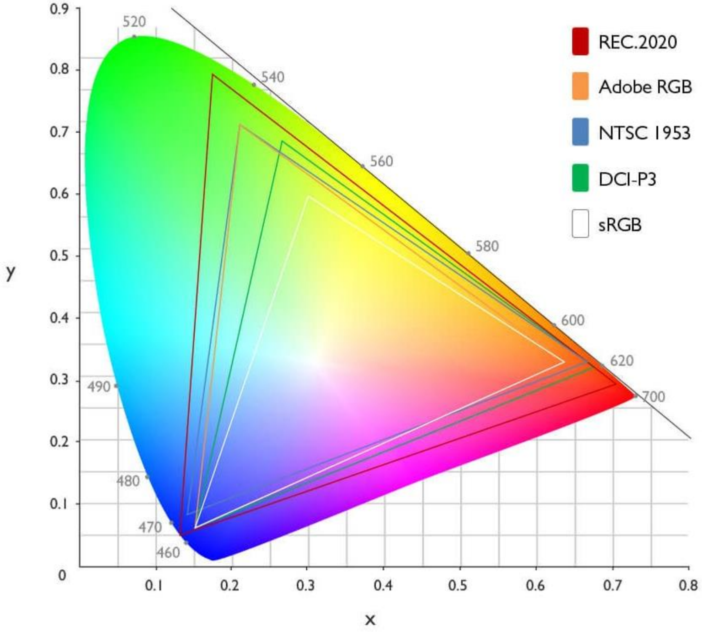


Objective 2/2

Problem Description

Existing representations for BRDFs lie in the tristimulus domain. Premature wavelength compression of spectral data is required to fit any material which leads to loss of information.

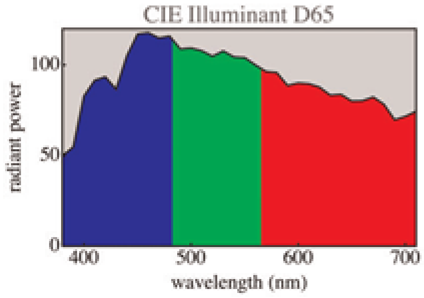
Contribution:
We propose an MLP architecture that learns underlying BRDF trends using a subset training data and provides suitable estimates for unseen angles and wavelengths.

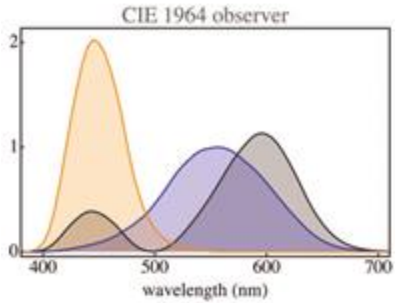


[9]

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





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

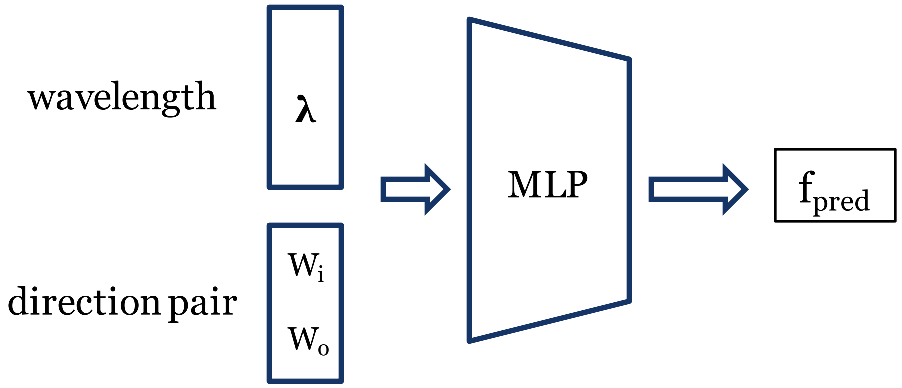
[10, 11]

Spectral BRDF matching

Input (normalized): Incoming angle, outgoing 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):

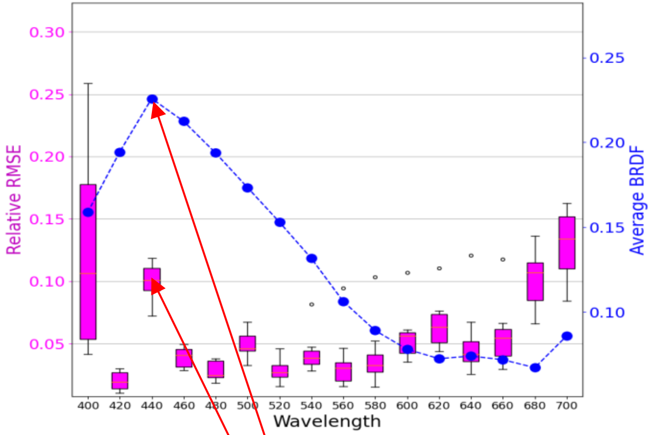
- 5° intervals for diffuse region
- 1° intervals for specular region.

Samples: *Gold, Cyan, Magenta, Gonio*

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

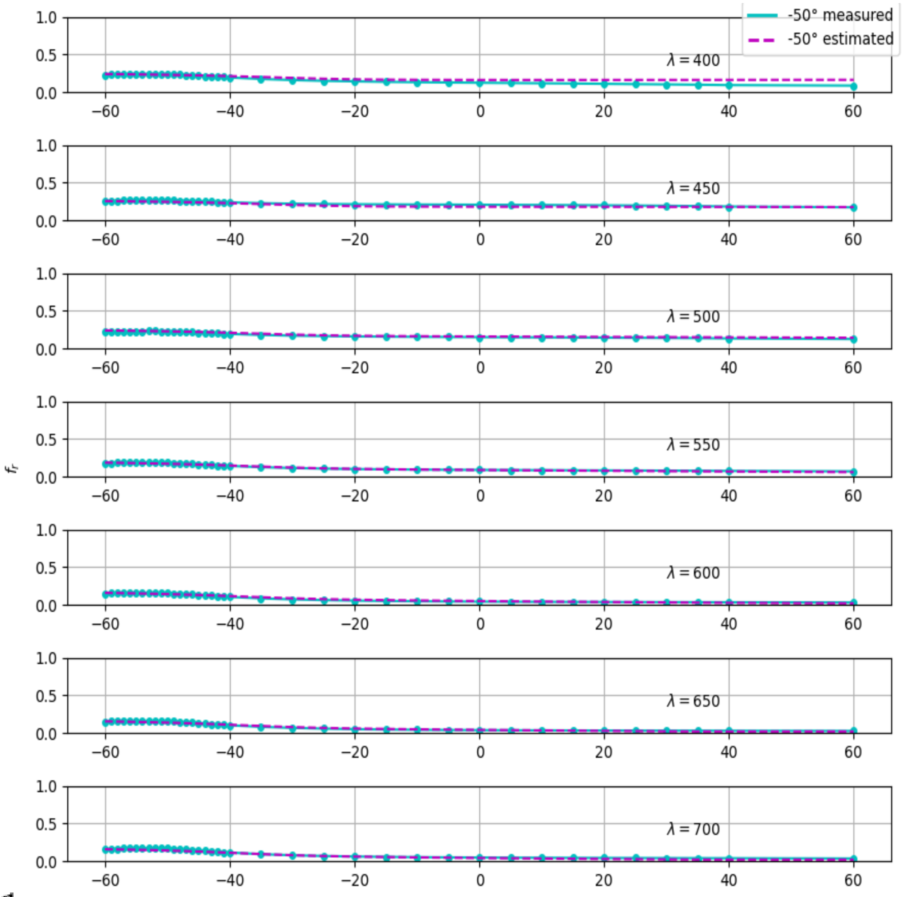
Spectral ANN results

Cyan Sample



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

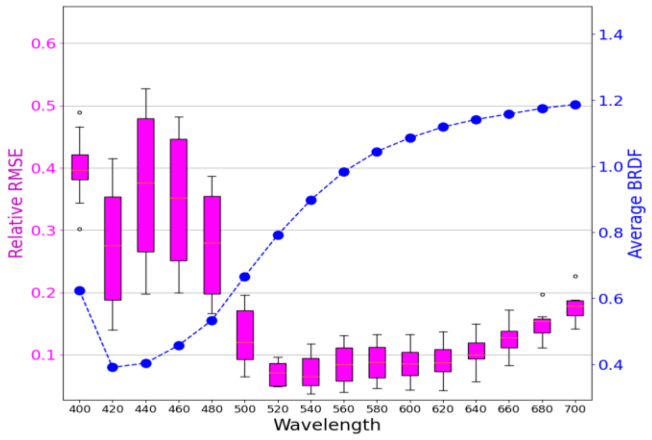
$$\frac{0.23 - 0.207}{0.23} = 0.1$$

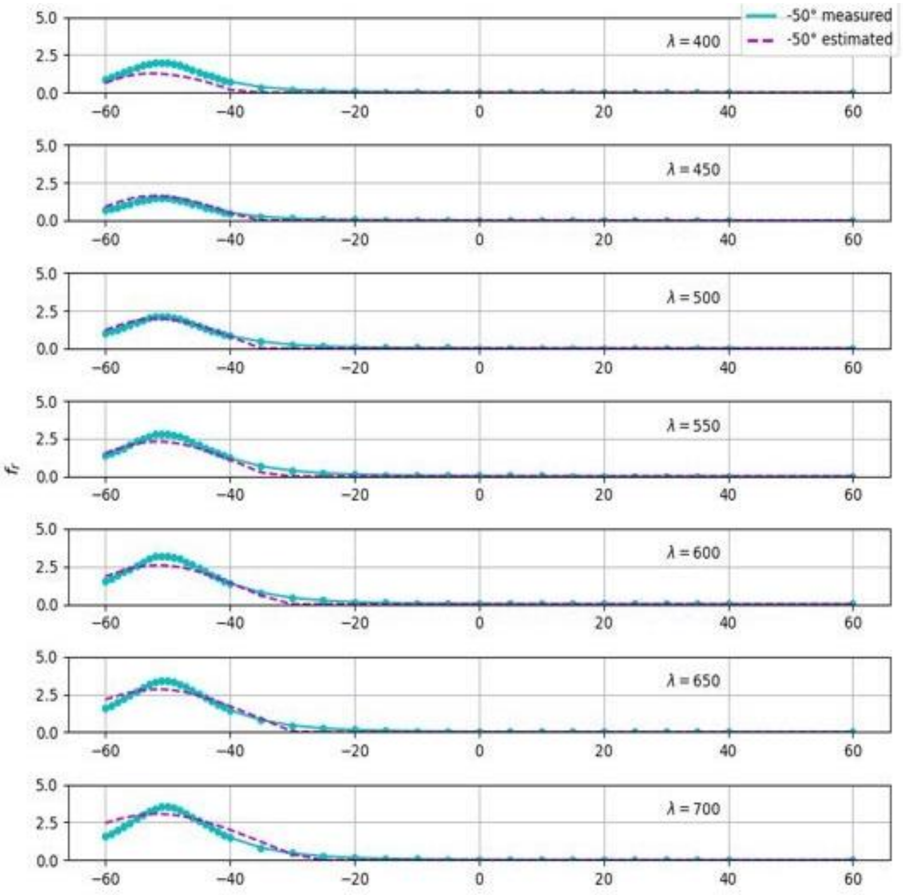


outgoing direction

Spectral ANN results

Gold Sample

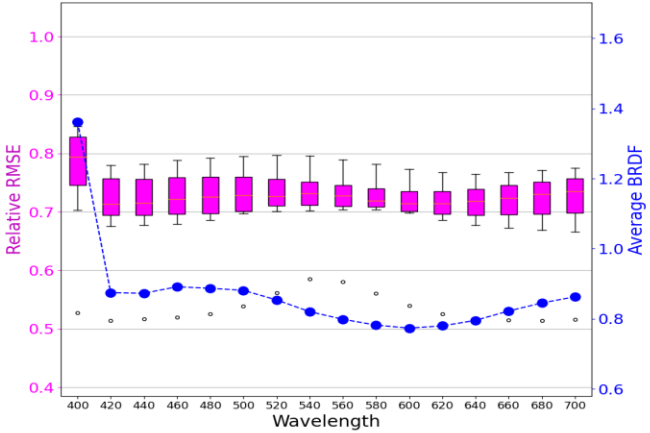


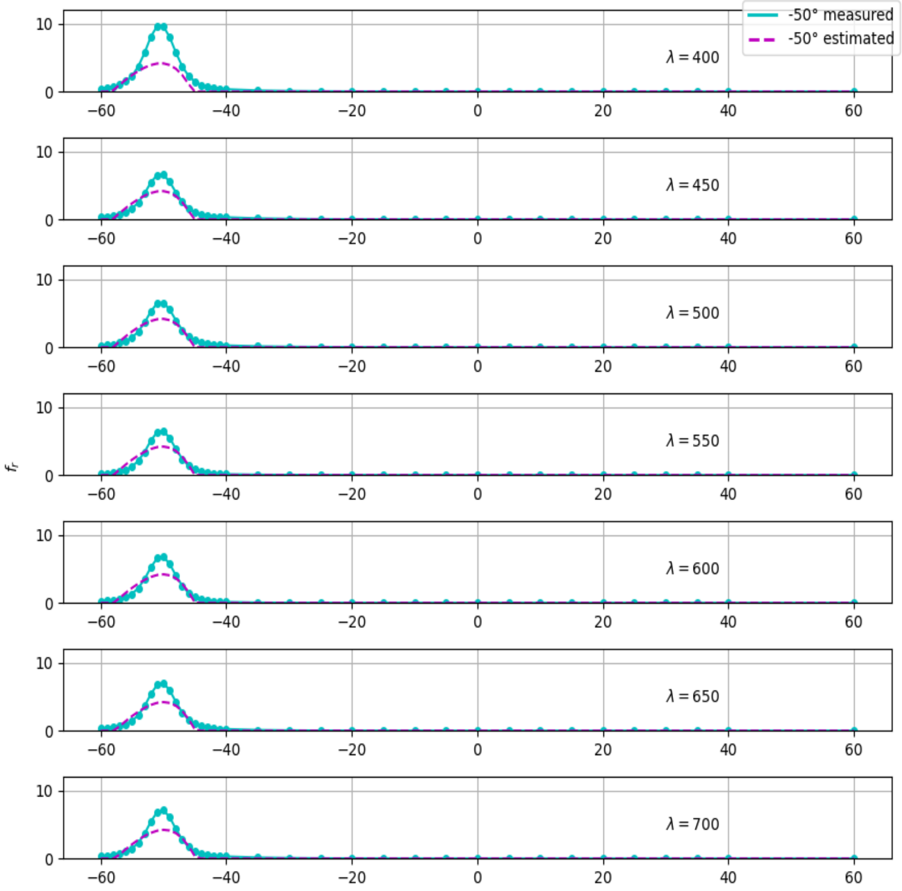


outgoing direction

Spectral ANN results

Gonio Sample





outgoing direction

Summarizing

- For isotropic materials that were considered, 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 the chosen in-plane angles and 256x larger baseline.
- The effect of data reduction on material capture was studied

Future work

- Extending this to materials with increasingly complex optical properties (anisotropy, spatial variance).
- A more exhaustive study could be conducted involving more representations.
- Think of adaptive strategies to pick "good" data instead of fixing a set of angles.

Acknowledgements

- My advisor: Prof. Sharat Chandran
- Collaborator: Prof. Aditya Sole, ColourLab, NTNU
- Prof. Parag Chaudhuri
- Pratik, Anant, and Akshat

Thank You!

References

[1] https://www.sciencedirect.com/topics/engineering/bidirectional-reflectance-distribution-function
[2] https://en.wikipedia.org/wiki/Bidirectional_reflectance_distribution_function
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