

Passive Reflectometry

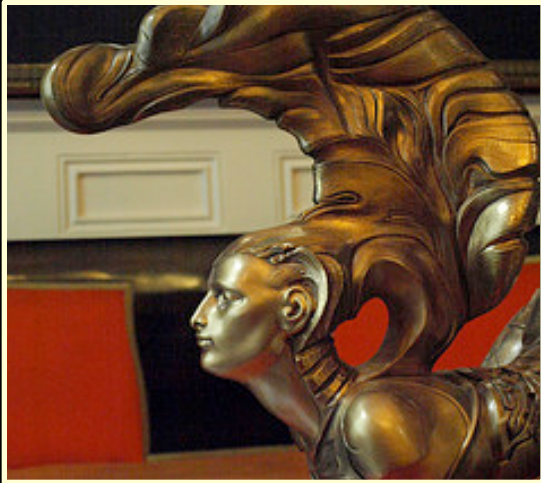
Fabiano Romeiro, Yuriy Vasilyev and Todd Zickler

School of Engineering and Applied Sciences
Harvard University

Surface Reflectance



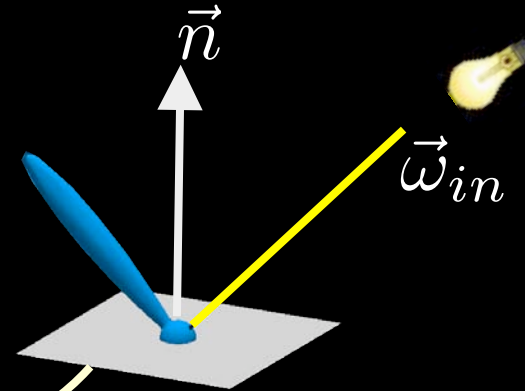
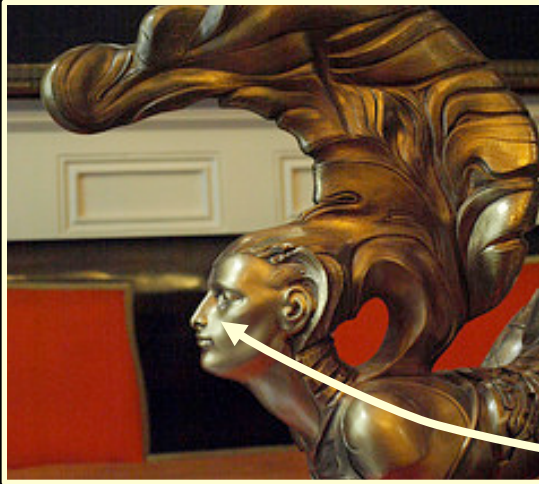
Surface Reflectance



Surface Reflectance: BRDF



Surface Reflectance: BRDF



$$f(\vec{\omega}_{in}, \vec{\omega}_{out})$$

Bi-directional Reflectance Distribution Function

Surface Reflectance: BRDF

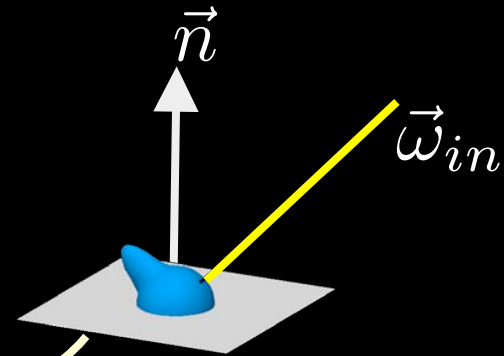
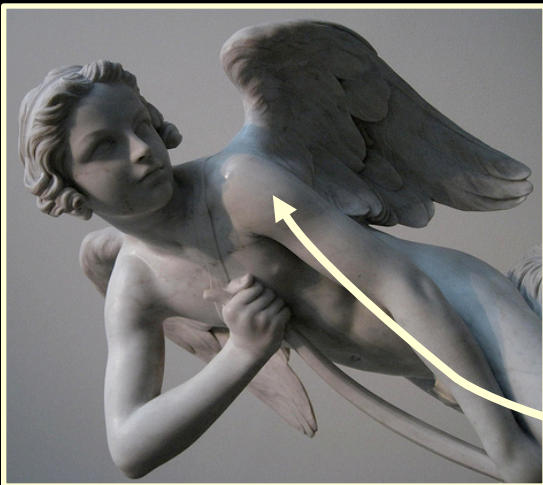
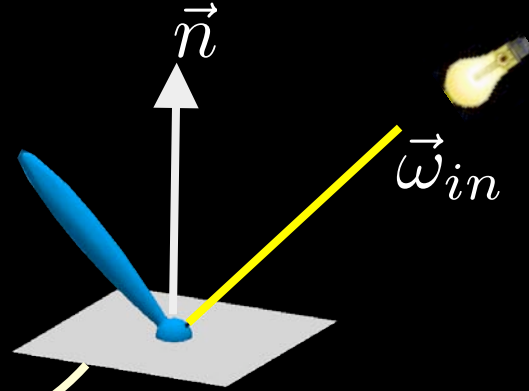
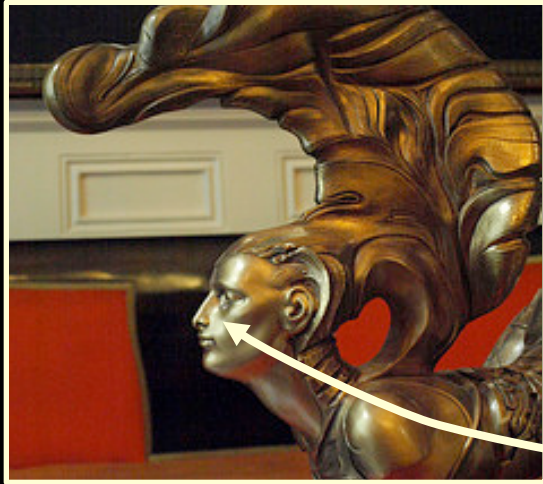


Image-based Reflectometry



Image-based Reflectometry

- ◆ Active Approach:



Image-based Reflectometry

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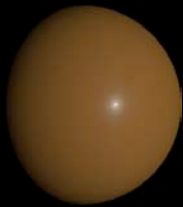


Image-based Reflectometry

◆ Active Approach:

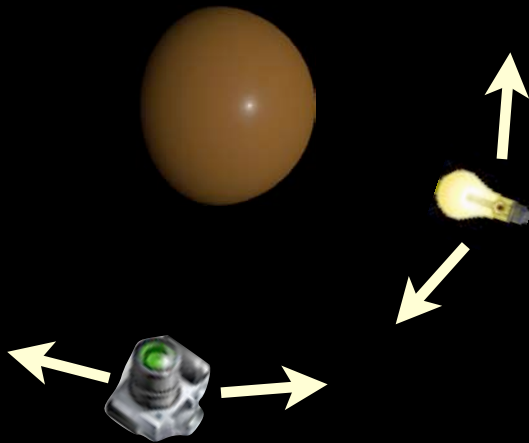


Image-based Reflectometry

◆ Active Approach:

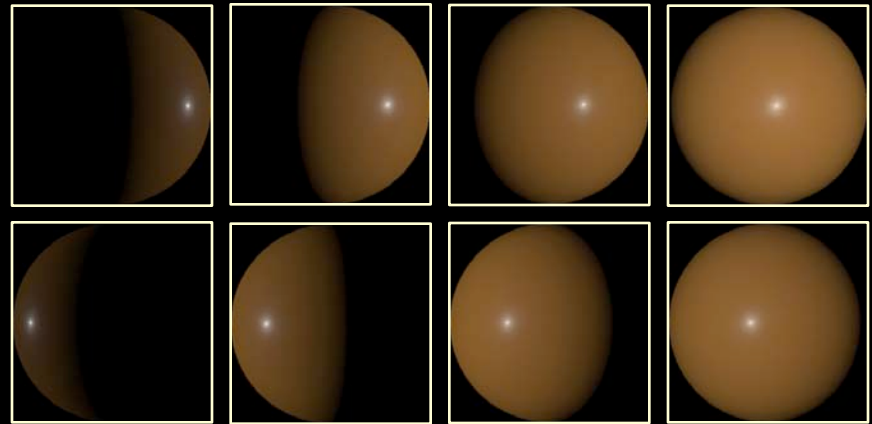
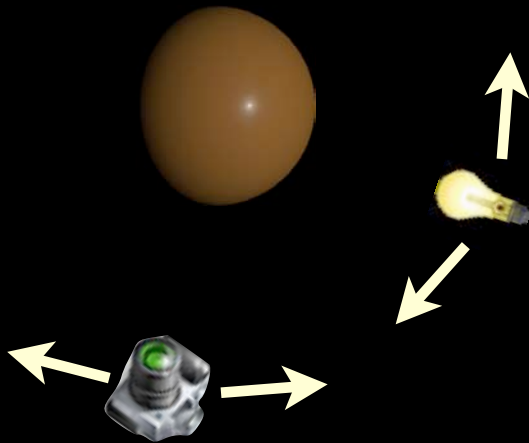


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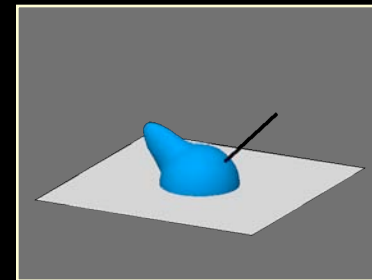
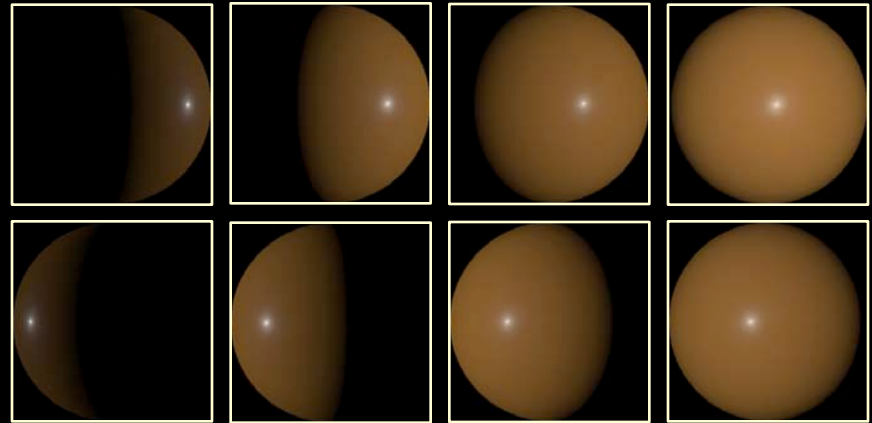
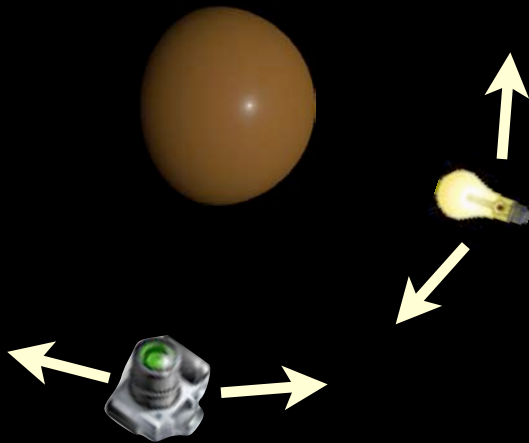


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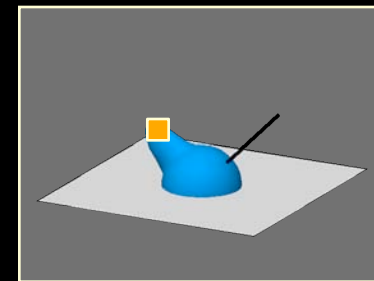
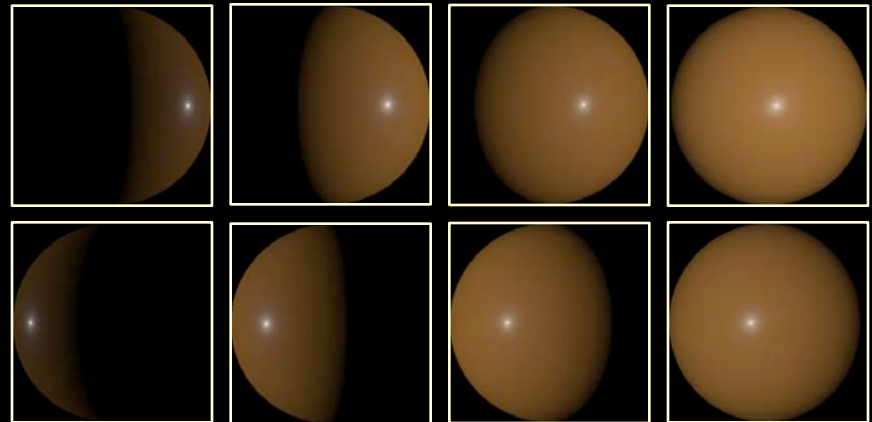
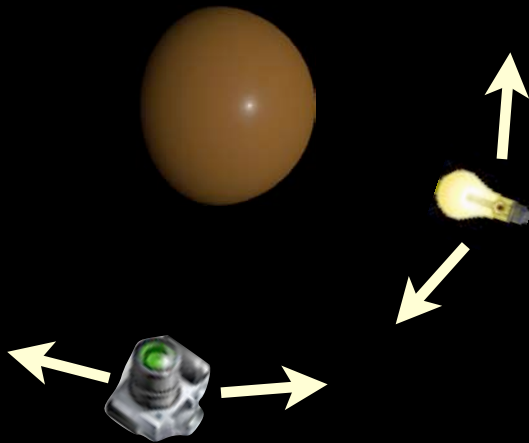


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◆ Active Approach:

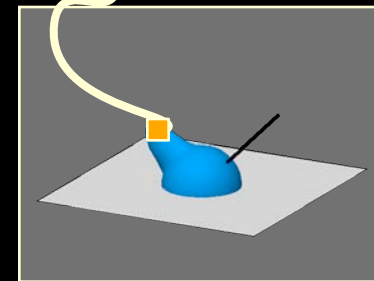
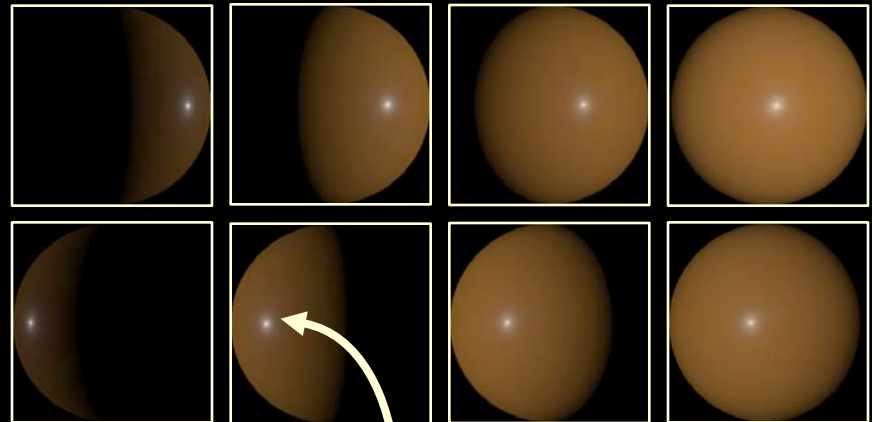
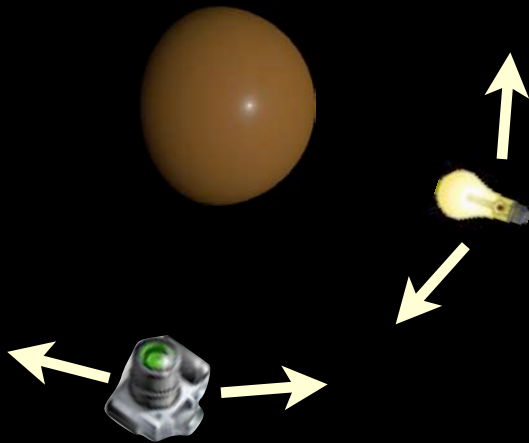


Image-based Reflectometry



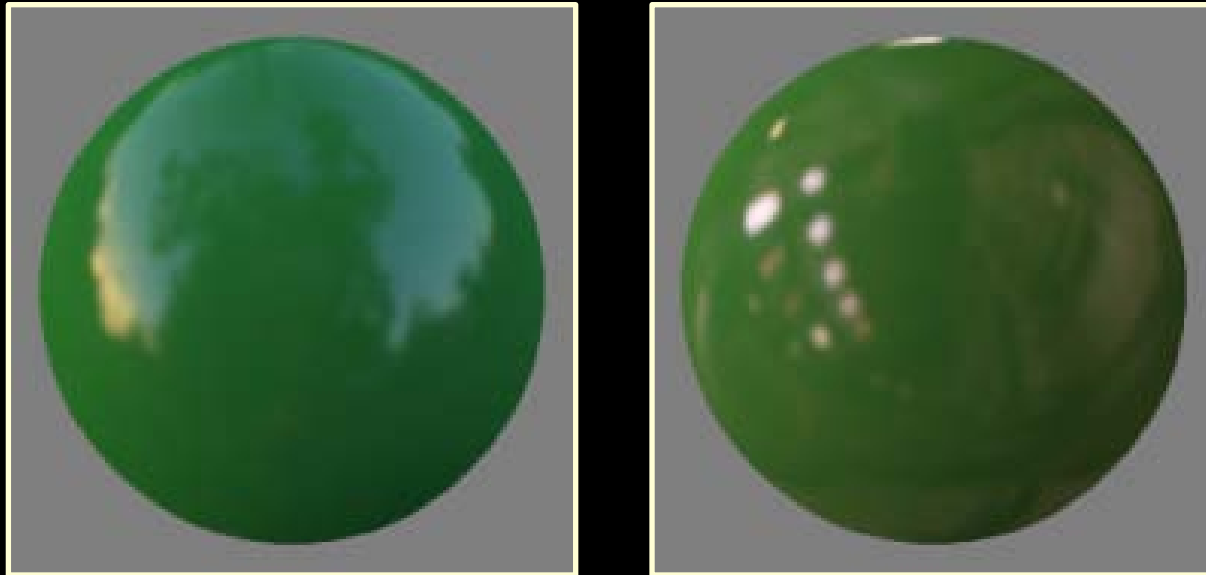
Image-based Reflectometry

- ◆ Human Approach:



Image-based Reflectometry

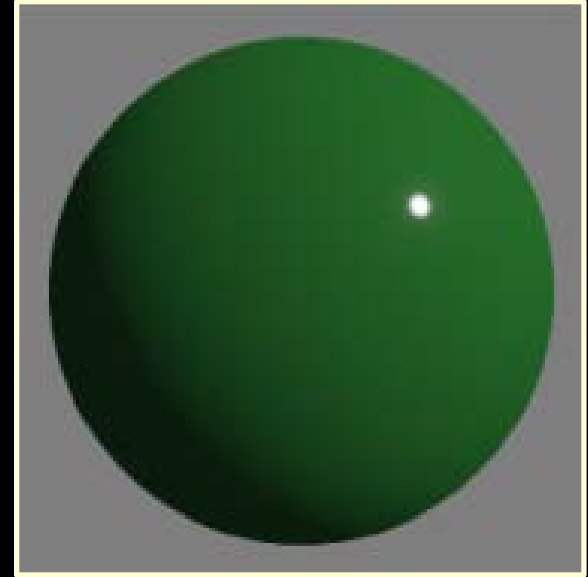
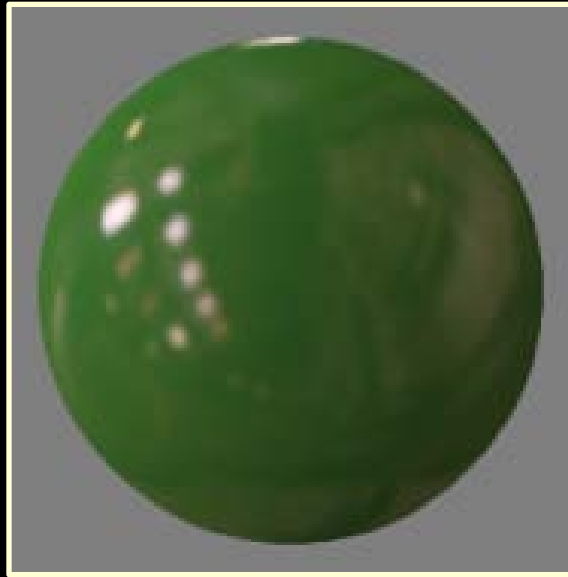
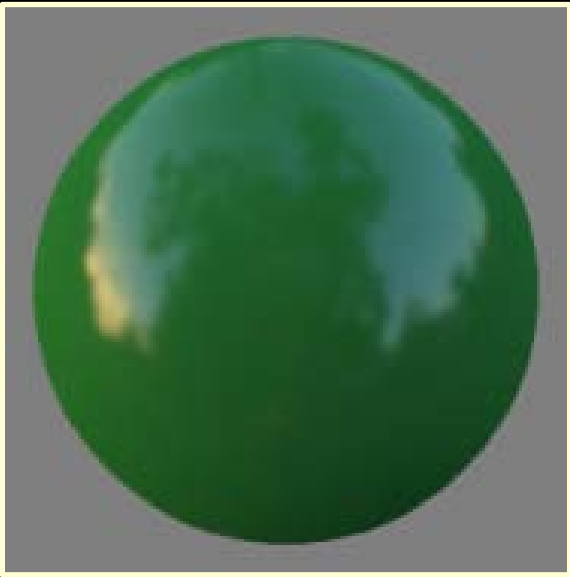
◆ Human Approach:



[Fleming et al, 2003]

Image-based Reflectometry

◆ Human Approach:



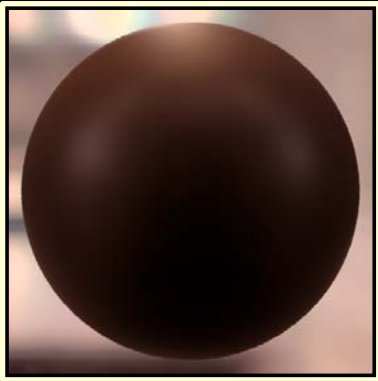
[Fleming et al, 2003]

Our goal: Passive Reflectometry



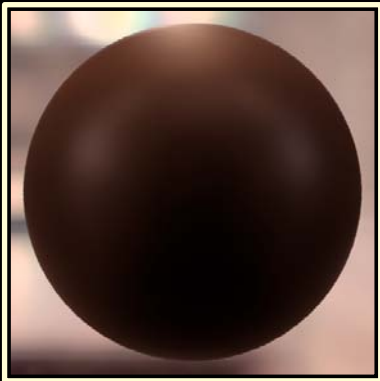
Our goal: Passive Reflectometry

- Known shape
- Image (I)



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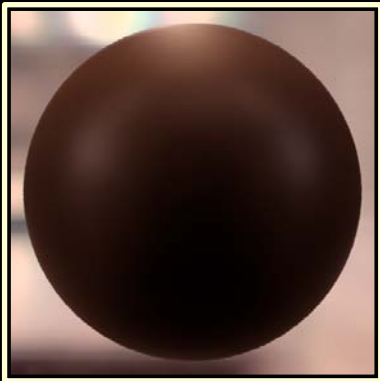


- Environment (L)

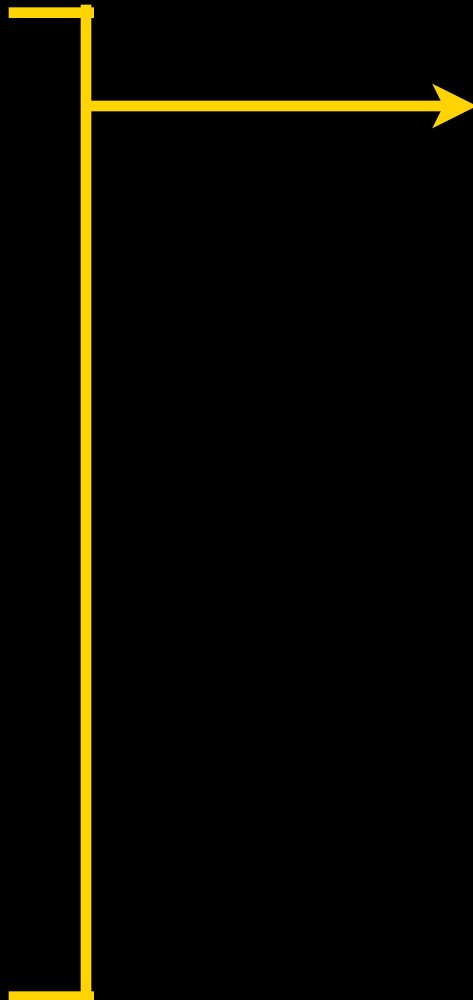


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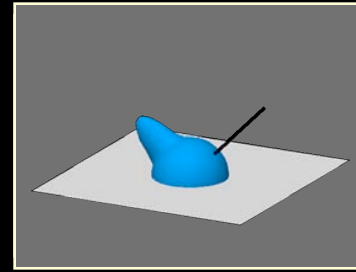


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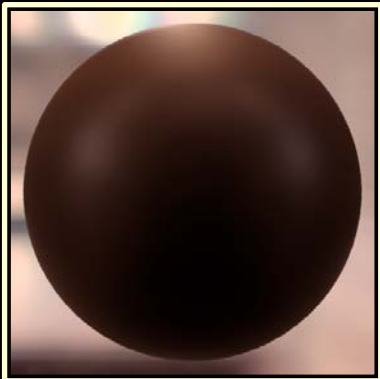


- Environment (L)

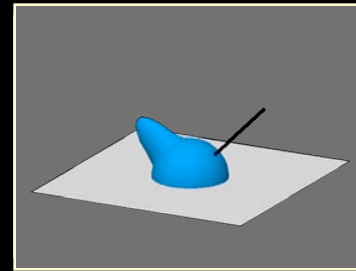


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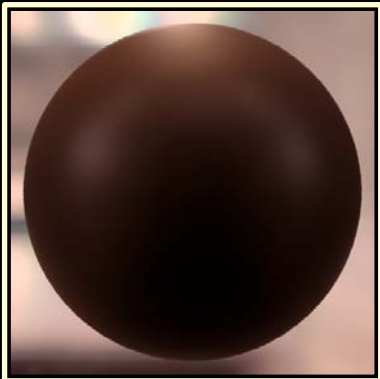
- Environment (L)



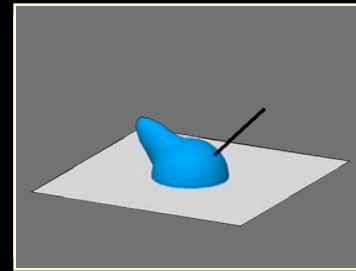
1. No Active Illumination

Our goal: Passive Reflectometry

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- Image (I)



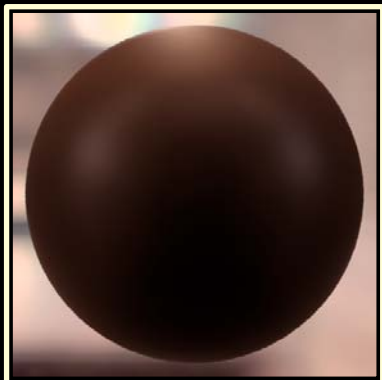
- Environment (L)



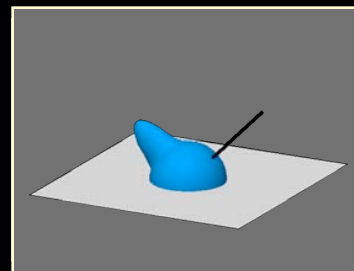
1. No Active Illumination
2. General reflectance

Related Work: Parametric BRDFs

- Known shape
- Image (I)

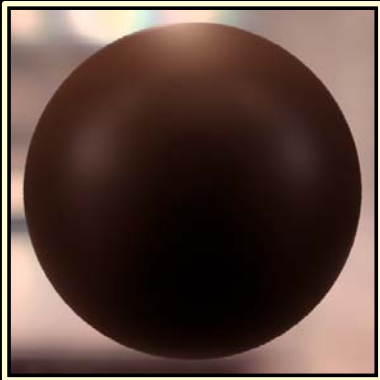


- Environment (L)

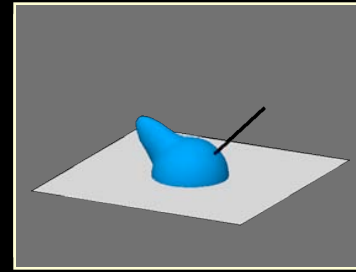


Related Work: Parametric BRDFs

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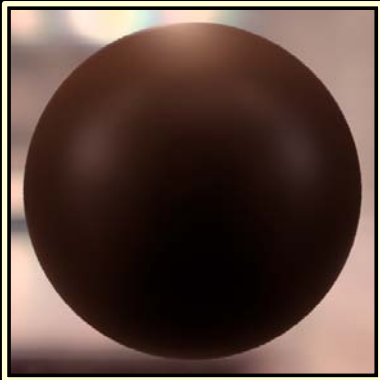
- Environment (L)



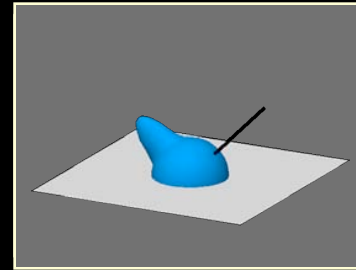
$$f(\vec{\omega}_{in}, \vec{\omega}_{out}) = f_{\vec{\alpha}}(\vec{\omega}_{in}, \vec{\omega}_{out})$$

Related Work: Parametric BRDFs

- Known shape
- Image (I)



- Environment (L)



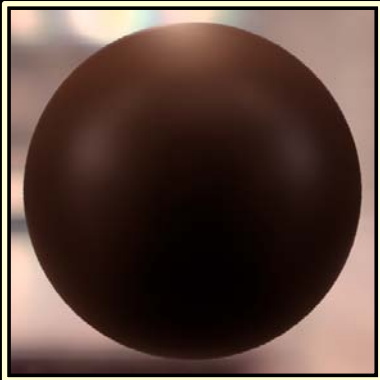
$$f(\vec{\omega}_{in}, \vec{\omega}_{out}) = f_{\vec{\alpha}}(\vec{\omega}_{in}, \vec{\omega}_{out})$$

Example: Lafortune model

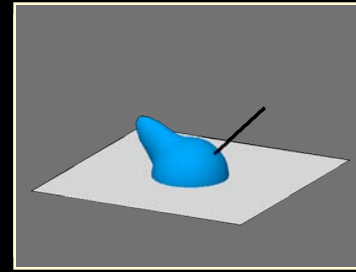
$$f_{\vec{\alpha}}(\vec{\omega}_{in}, \vec{\omega}_{out}) = (\vec{\omega}_{in}^T \begin{bmatrix} \alpha_1 & 0 & 0 \\ 0 & \alpha_2 & 0 \\ 0 & 0 & \alpha_3 \end{bmatrix} \vec{\omega}_{out})^{\alpha_4}$$

Related Work: Parametric BRDFs

- Known shape
- Image (I)



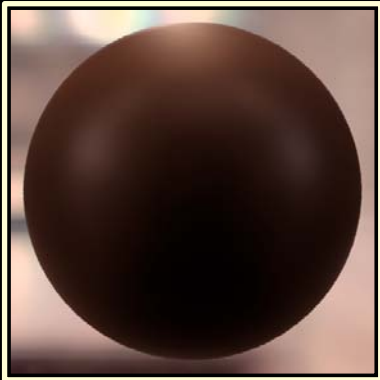
- Environment (L)



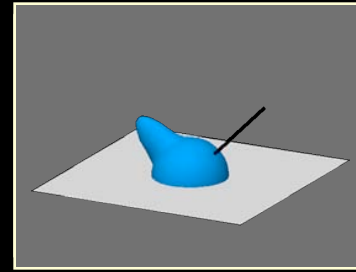
$$f(\vec{\omega}_{in}, \vec{\omega}_{out}) = f_{\vec{\alpha}}(\vec{\omega}_{in}, \vec{\omega}_{out})$$

Related Work: Parametric BRDFs

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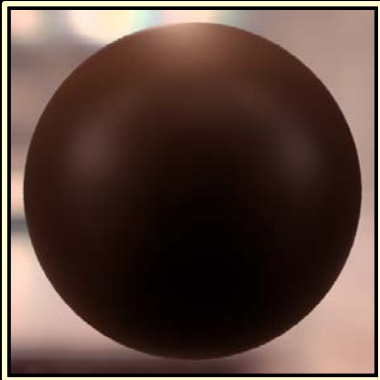


$$f(\vec{\omega}_{in}, \vec{\omega}_{out}) = f_{\vec{\alpha}}(\vec{\omega}_{in}, \vec{\omega}_{out})$$

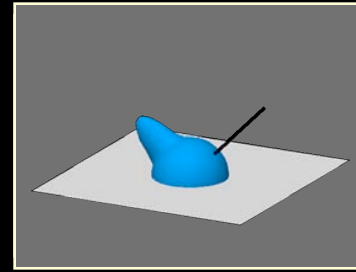
$$I = render(L, \vec{\alpha})$$

Related Work: Parametric BRDFs

- Known shape
- Image (I)



- Environment (L)



$$f(\vec{\omega}_{in}, \vec{\omega}_{out}) = f_{\vec{\alpha}}(\vec{\omega}_{in}, \vec{\omega}_{out})$$

$$I = render(L, \vec{\alpha})$$

$$\vec{\alpha}^* = \arg \min_{\alpha} ||I - render(L, \vec{\alpha})||^2$$

[Boivin and Cagalowicz, 2001]

Related Work: Parametric BRDFs



Related Work: Parametric BRDFs

Problems:



Related Work: Parametric BRDFs

Problems:

- Susceptible to local minima



Related Work: Parametric BRDFs

Problems:

- Susceptible to local minima
- Parametric models too restrictive



Ground Truth



Cook-Torrance



Ward



Lafortune

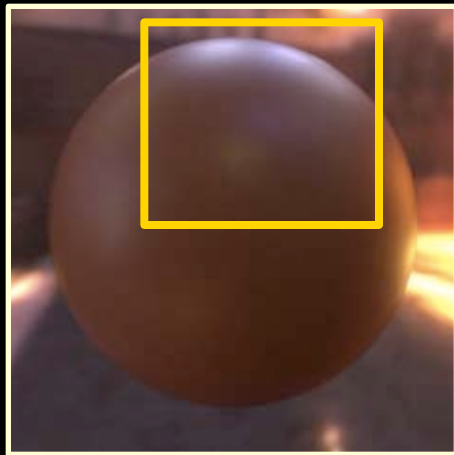
[Ngan et al, 2005]



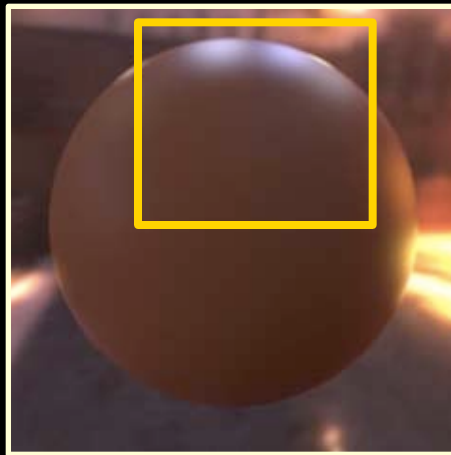
Related Work: Parametric BRDFs

Problems:

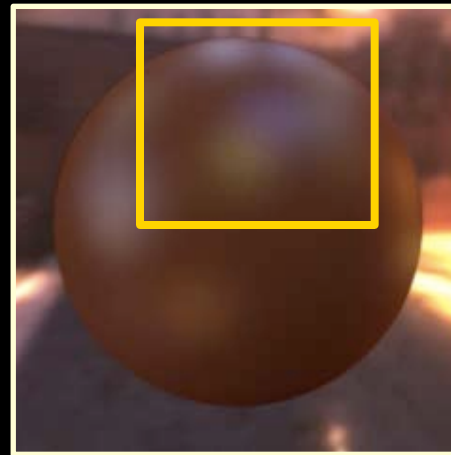
- Susceptible to local minima
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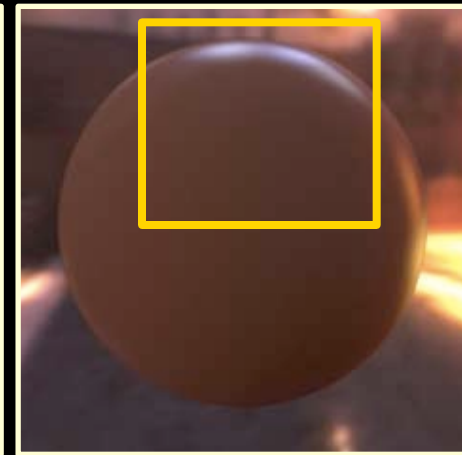
Ground Truth



Cook-Torrance



Ward



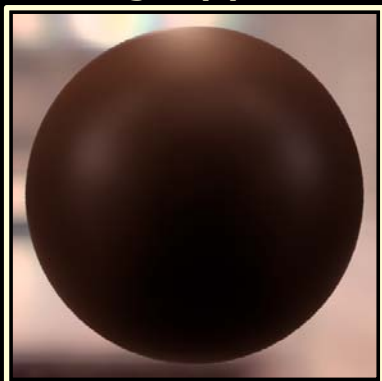
Lafortune

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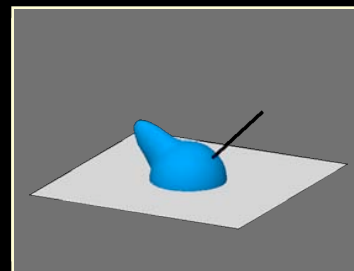


Related Work: Univariate BRDFs

- Known shape
- Image (I)



- Environment (L)

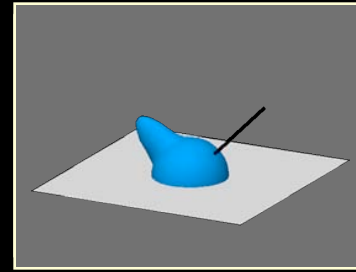


Related Work: Univariate BRDFs

- Known shape
- Image (I)



- Environment (L)



Univariate (radially-symmetric):

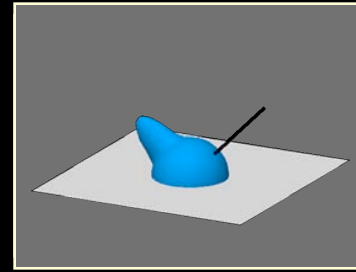
$$f(\vec{\omega}_{in}, \vec{\omega}_{out}) \rightarrow f(\theta_r)$$

Related Work: Univariate BRDFs

- Known shape
- Image (I)



- Environment (L)



Univariate (radially-symmetric):

$$f(\vec{\omega}_{in}, \vec{\omega}_{out}) \rightarrow f(\theta_r)$$

$$\hat{f} = \frac{\hat{I}}{\hat{L}}$$

[Ramamoorthi et al, 2001]

Related Work: Univariate BRDFs



Related Work: Univariate BRDFs

Problem:



Related Work: Univariate BRDFs

Problem:

- Univariate (radially symmetric) BRDFs too restrictive.



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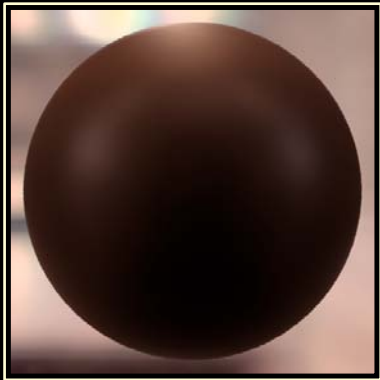
Ground Truth



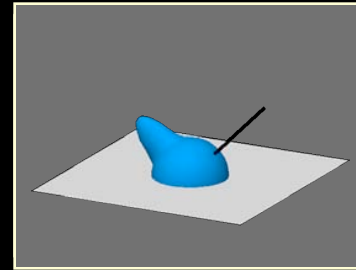
Radially Symmetric

Our approach

- Known shape
- Image (I)

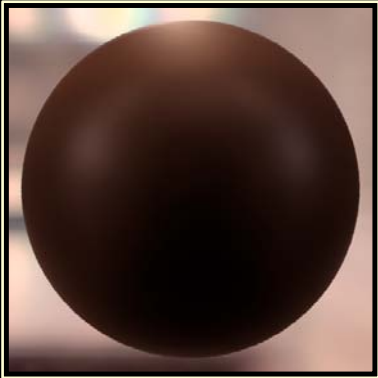


- Environment (L)

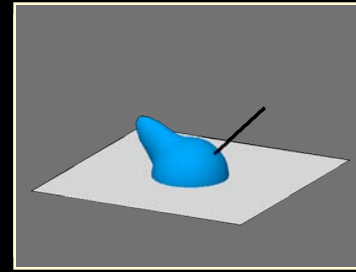


Our approach

- Known shape
- Image (I)



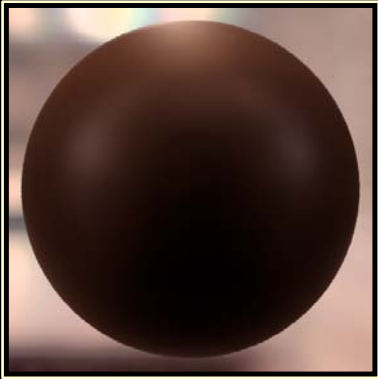
- Environment (L)



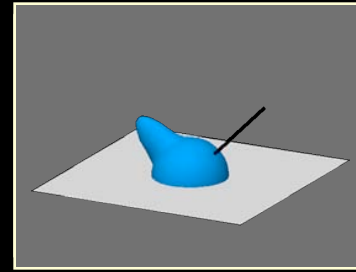
We introduce a BRDF model that is:

Our approach

- Known shape
- Image (I)



- Environment (L)

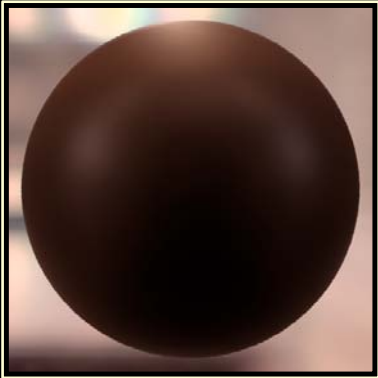


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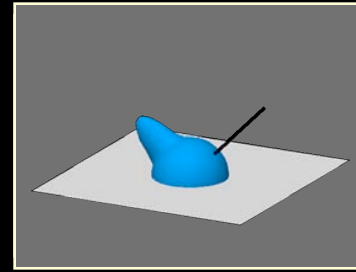
- General enough to capture important effects

Our approach

- Known shape
- Image (I)



- Environment (L)



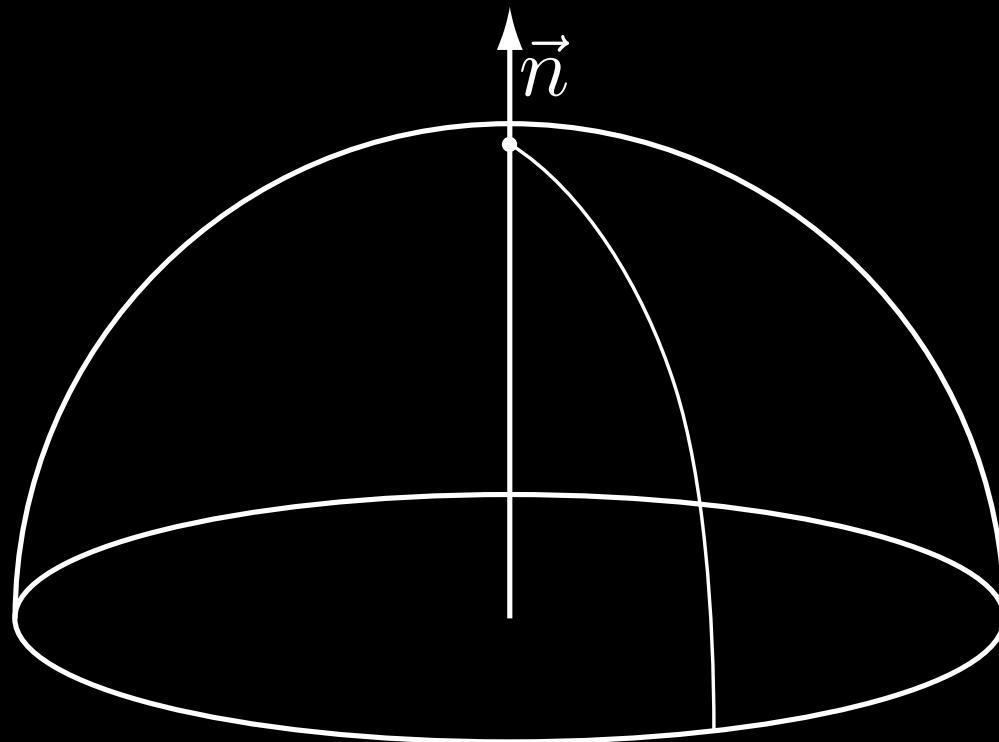
We introduce a BRDF model that is:

- General enough to capture important effects
- Simple enough to allow tractability

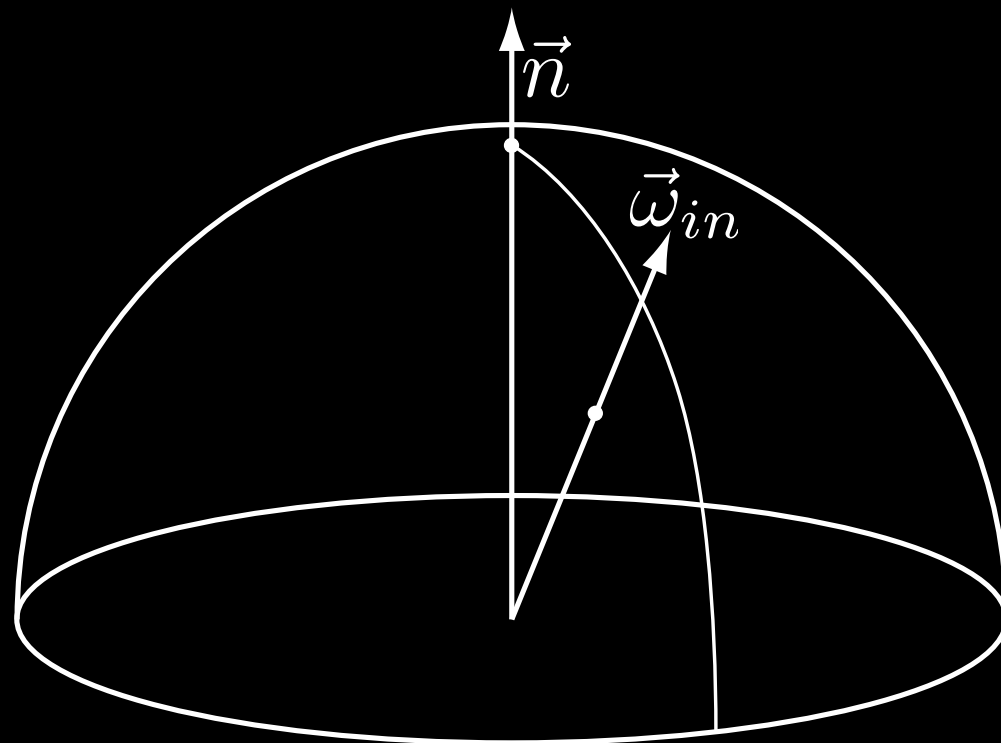
Bivariate BRDF Representation



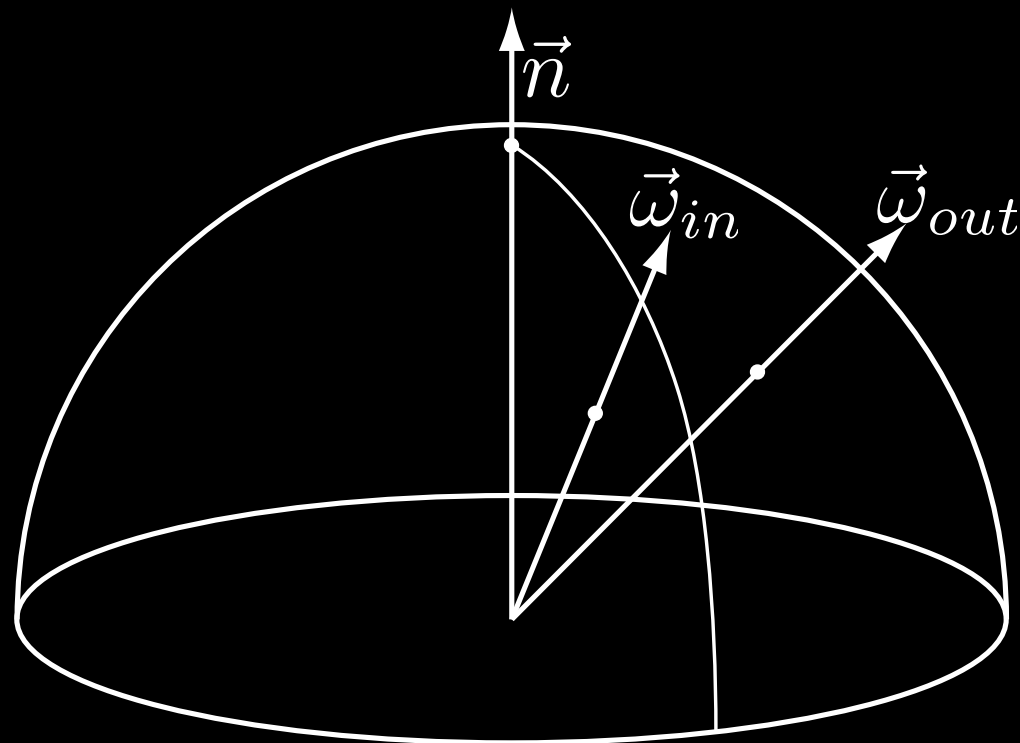
Bivariate BRDF Representation



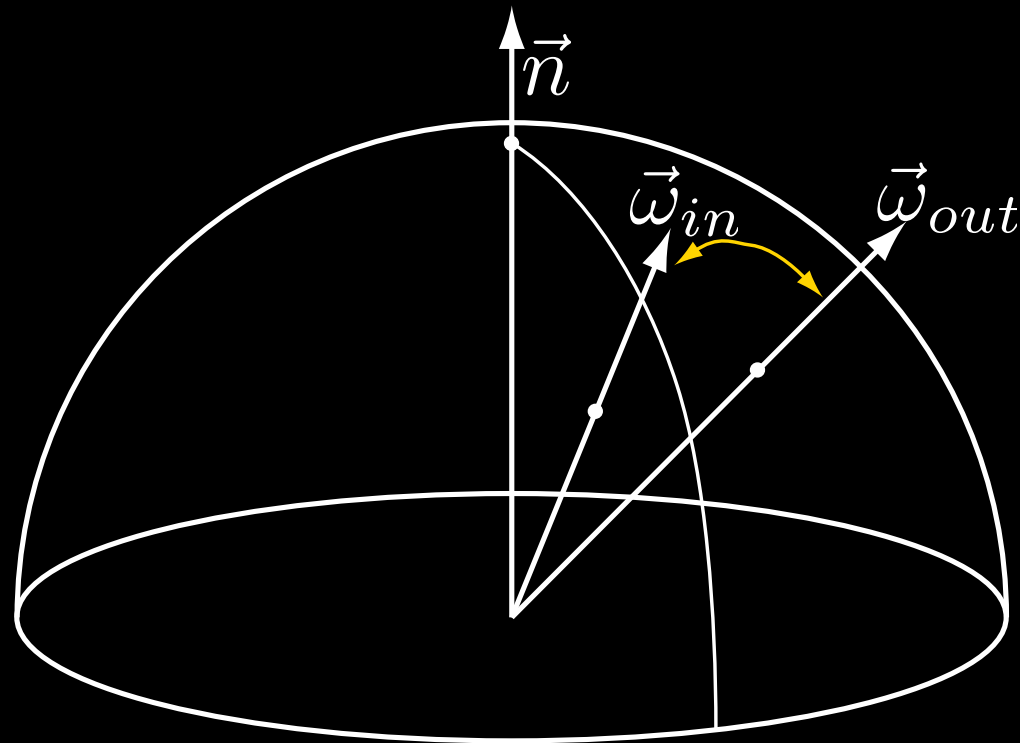
Bivariate BRDF Representation



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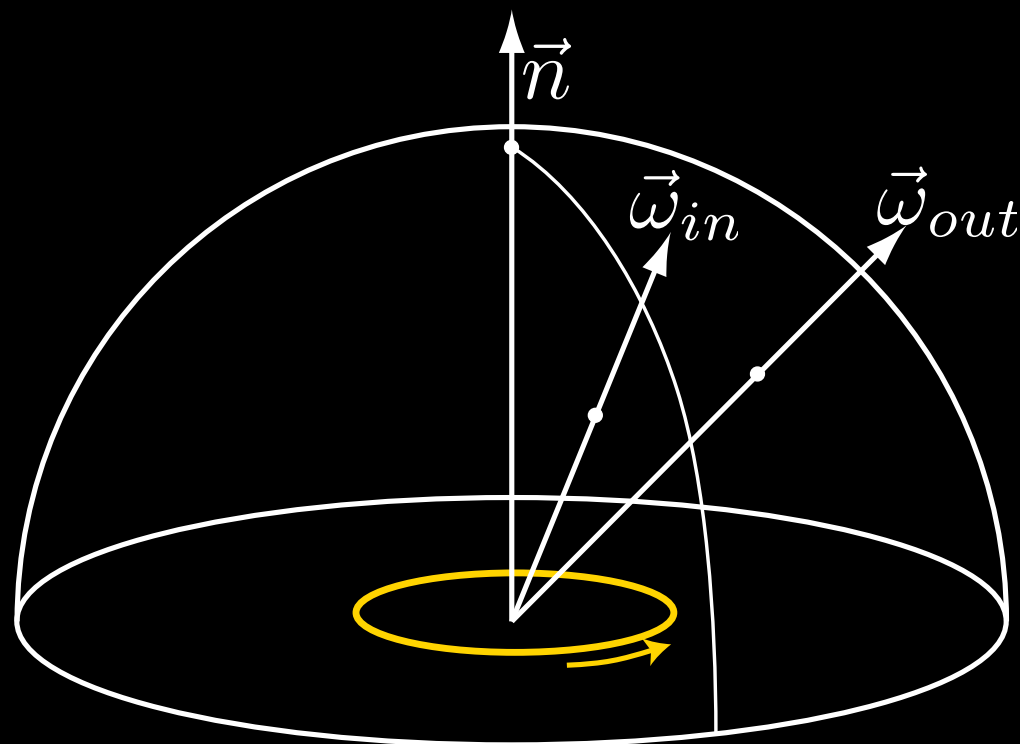


Bivariate BRDF Representation



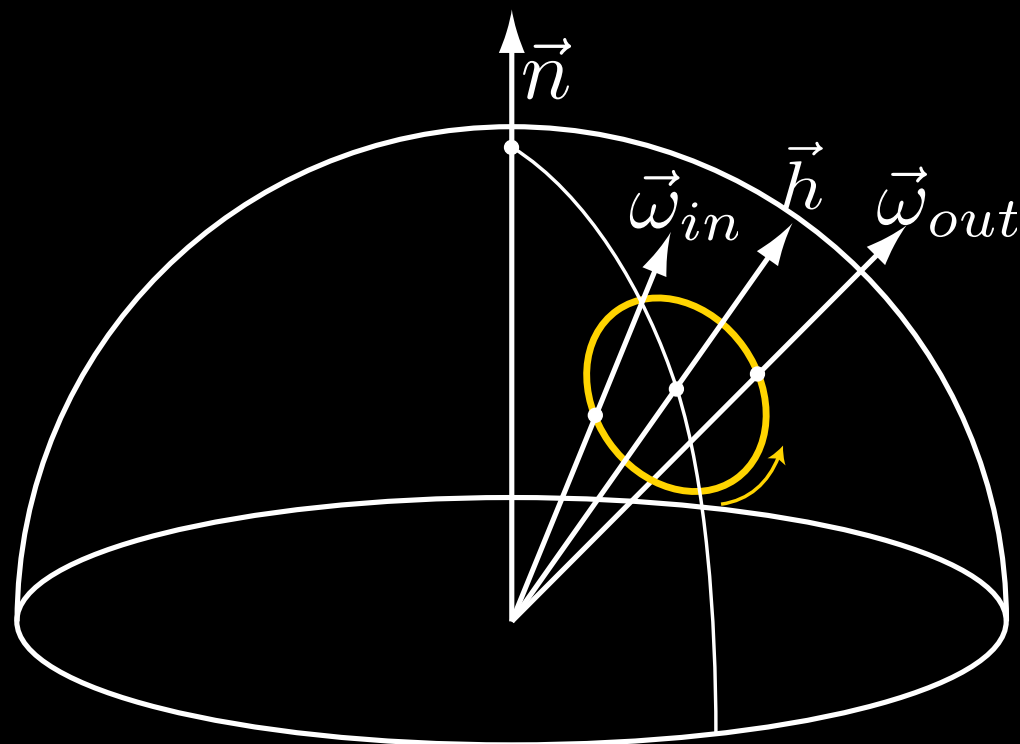
RECIPROcity

Bivariate BRDF Representation



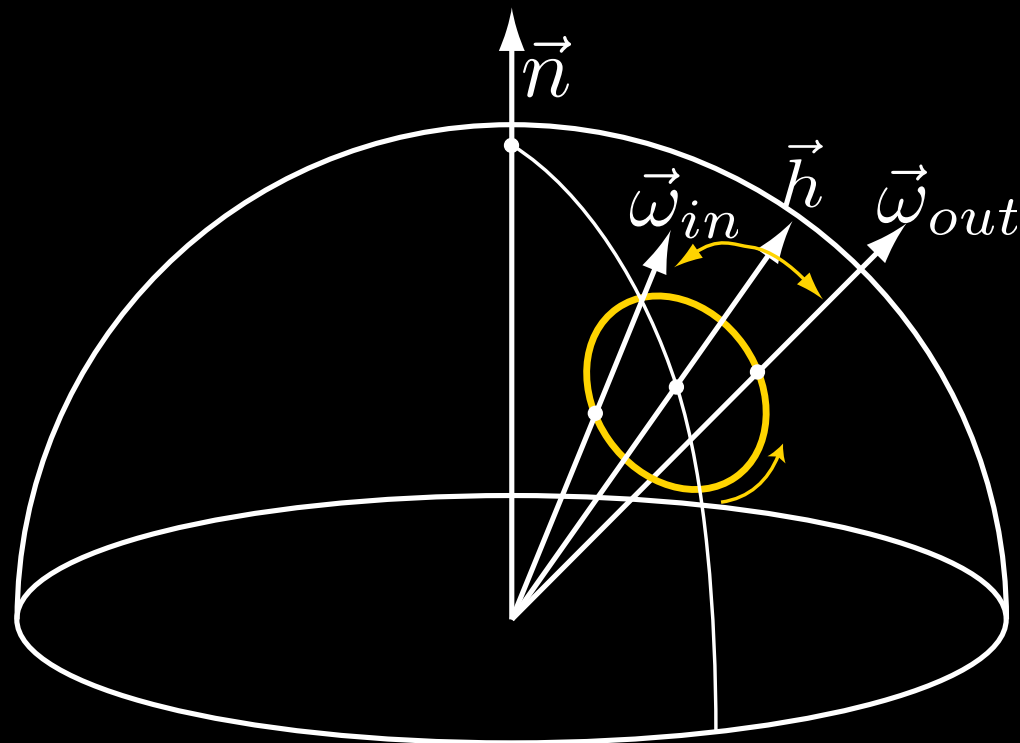
ISOTROPY

Bivariate BRDF Representation

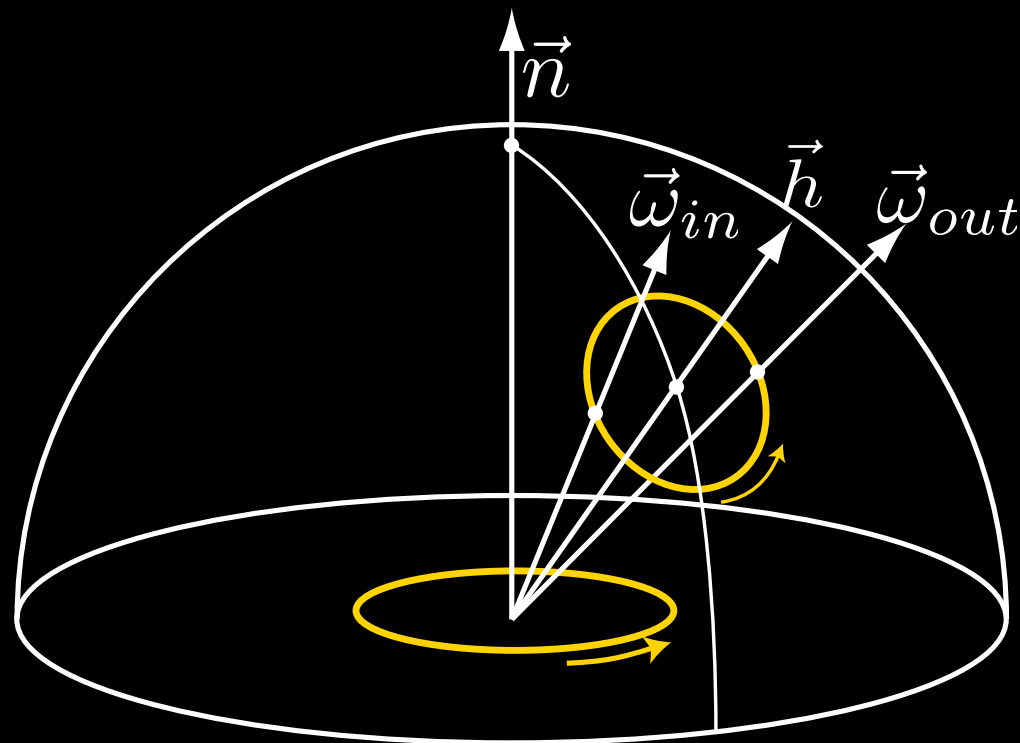


PROPOSED: ADDITIONAL SYMMETRY

Bivariate BRDF Representation

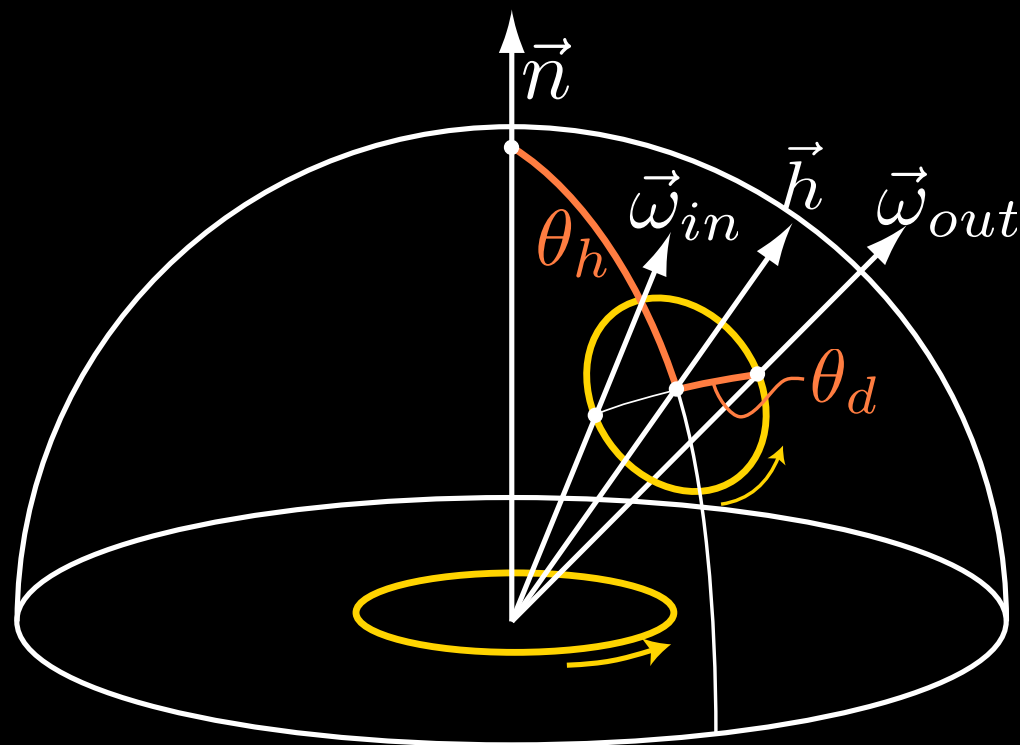


Bivariate BRDF Representation



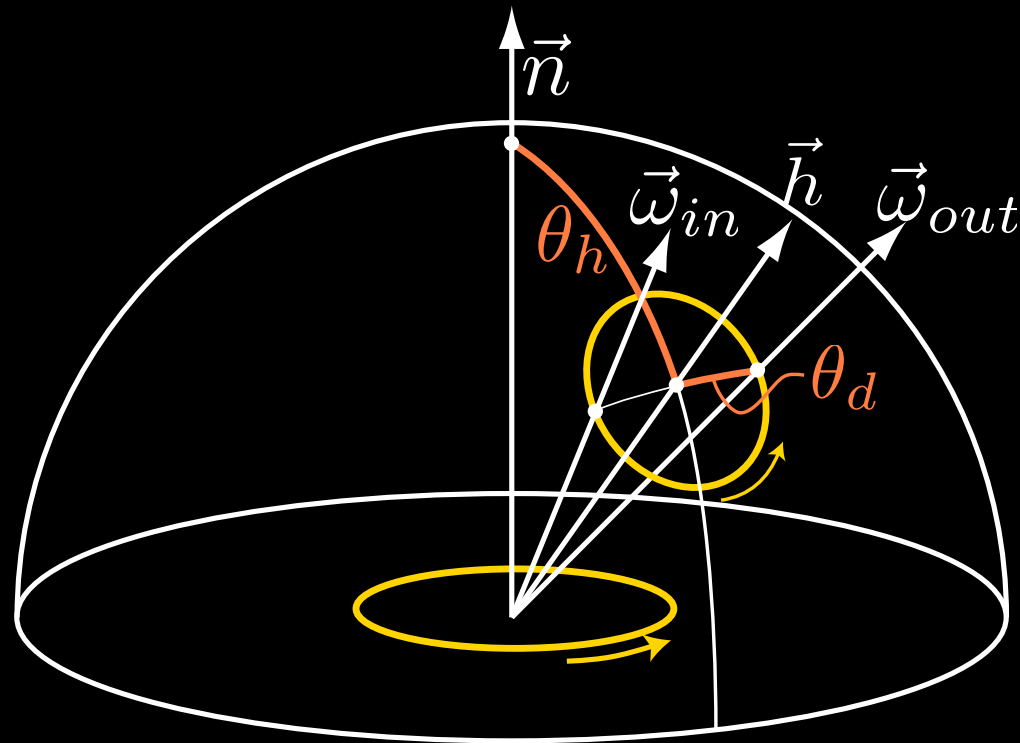
BIVARIATE

Bivariate BRDF Representation



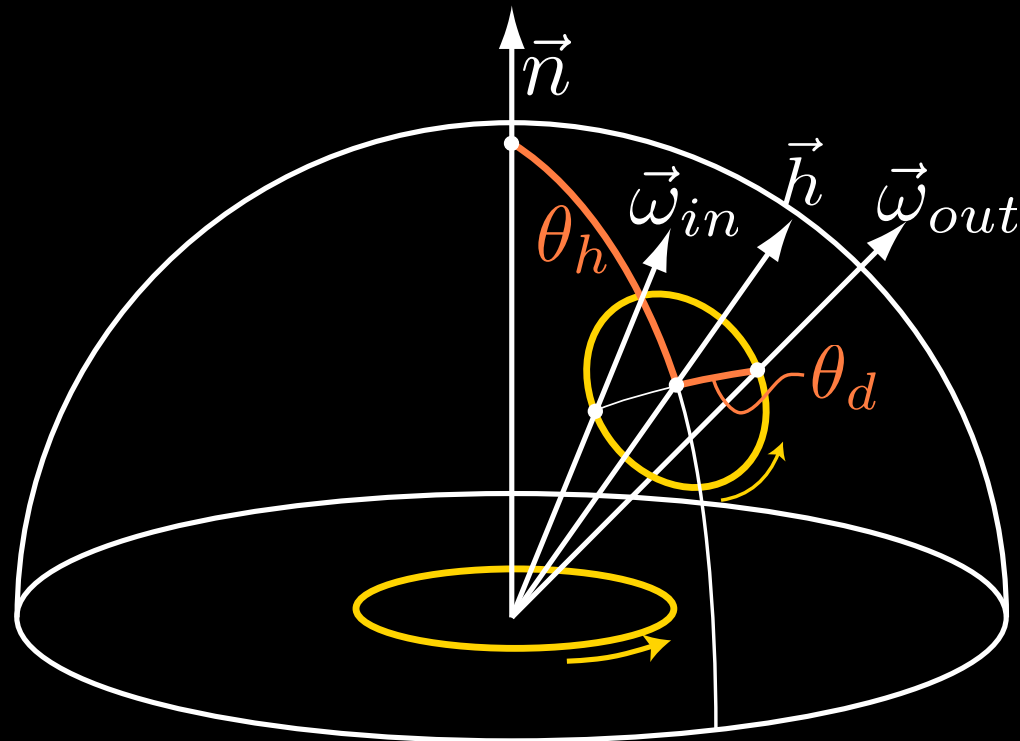
BIVARIATE

Bivariate BRDF Representation



$$f(\vec{\omega}_{in}, \vec{\omega}_{out}) \rightarrow f(\theta_h, \theta_d)$$

Bivariate BRDF Representation



$$f(\vec{\omega}_{in}, \vec{\omega}_{out}) \rightarrow f(\theta_h, \theta_d)$$

Halfway angle

Difference angle

[Rusinkiewicz, 1999]

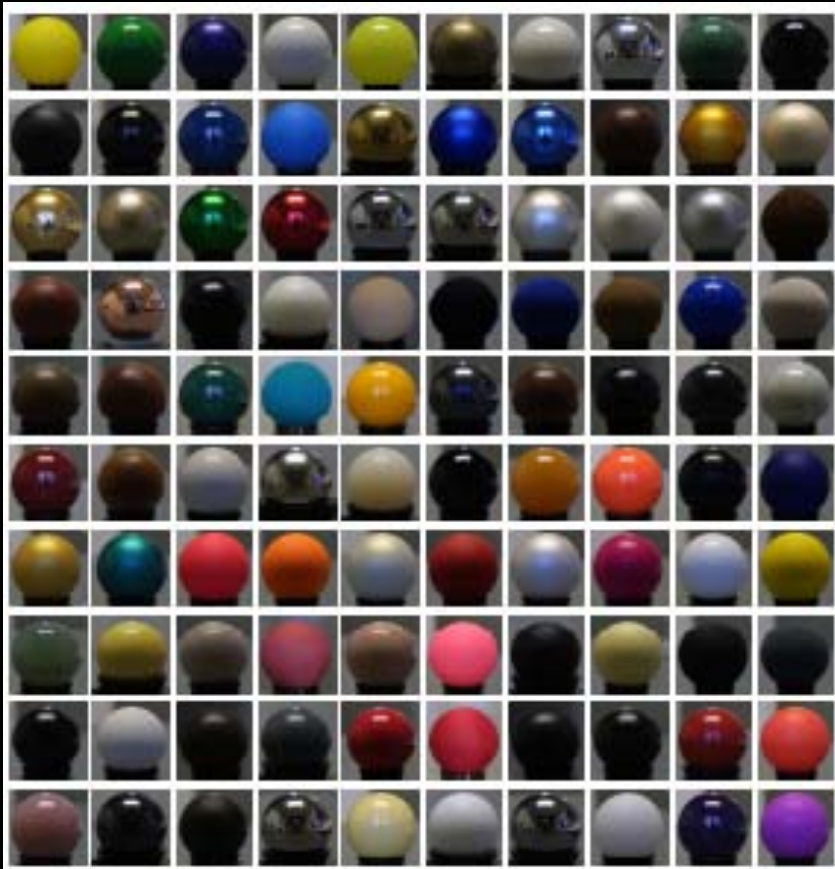


Bivariate Representation: Empirical Validation



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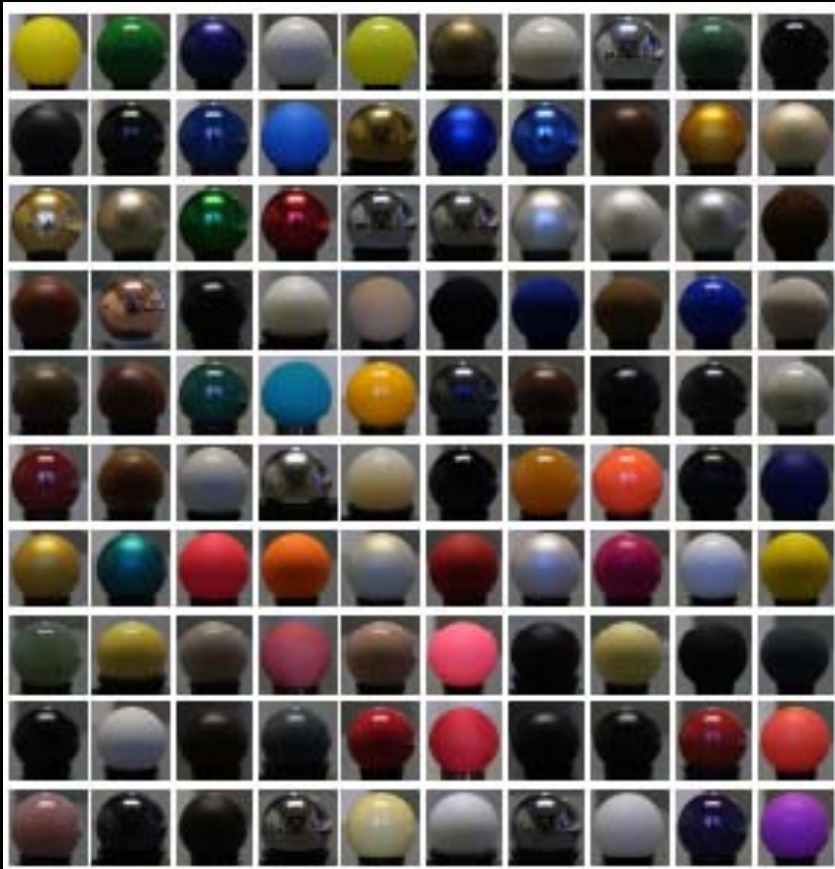
- ◆ MERL BRDF database (~ 100 isotropic materials)



[Matusik et al., 2003]

Bivariate Representation: Empirical Validation

- ◆ MERL BRDF database (~ 100 isotropic materials)



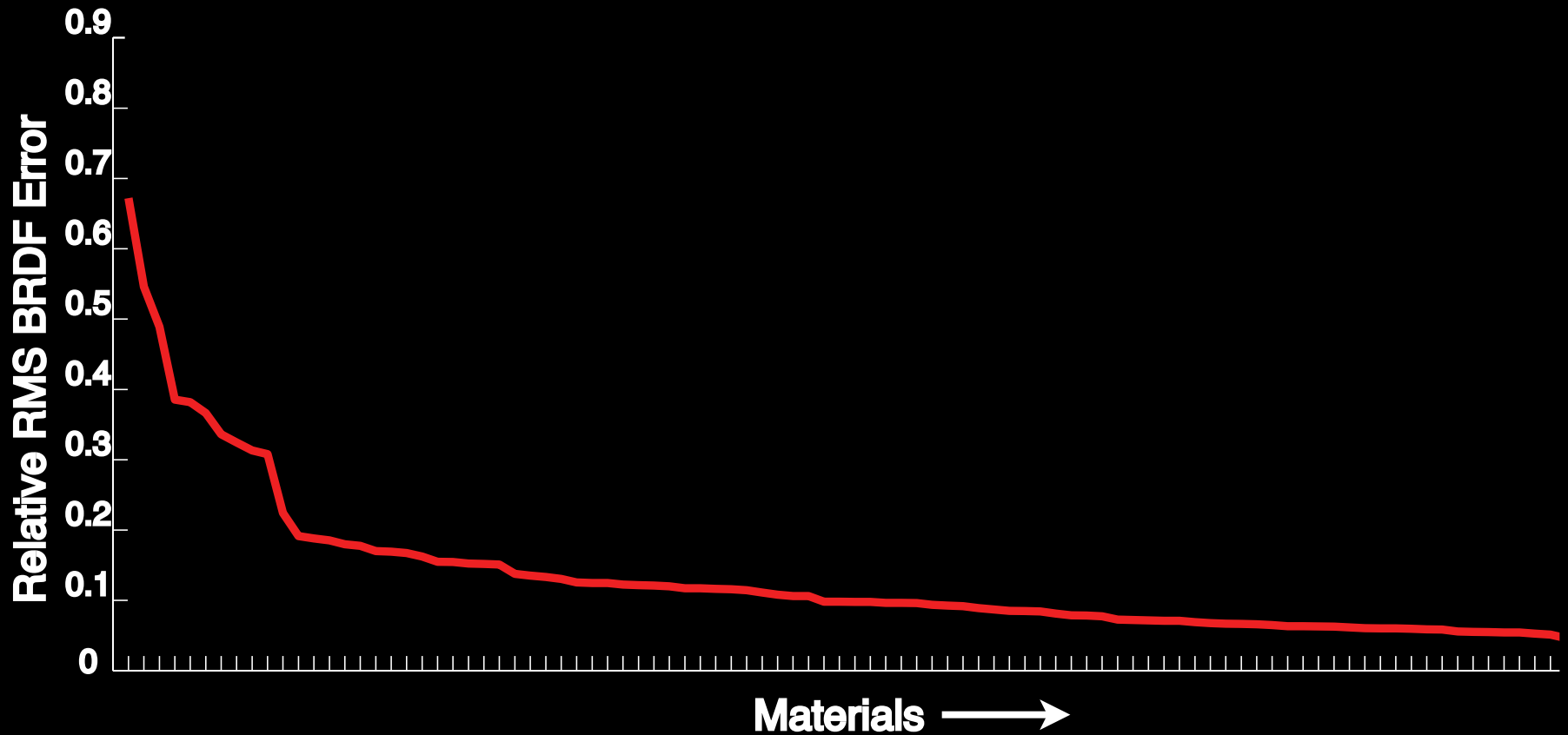
Isotropic BRDFs: 3D

[Matusik et al., 2003]

Bivariate Representation: Empirical Validation



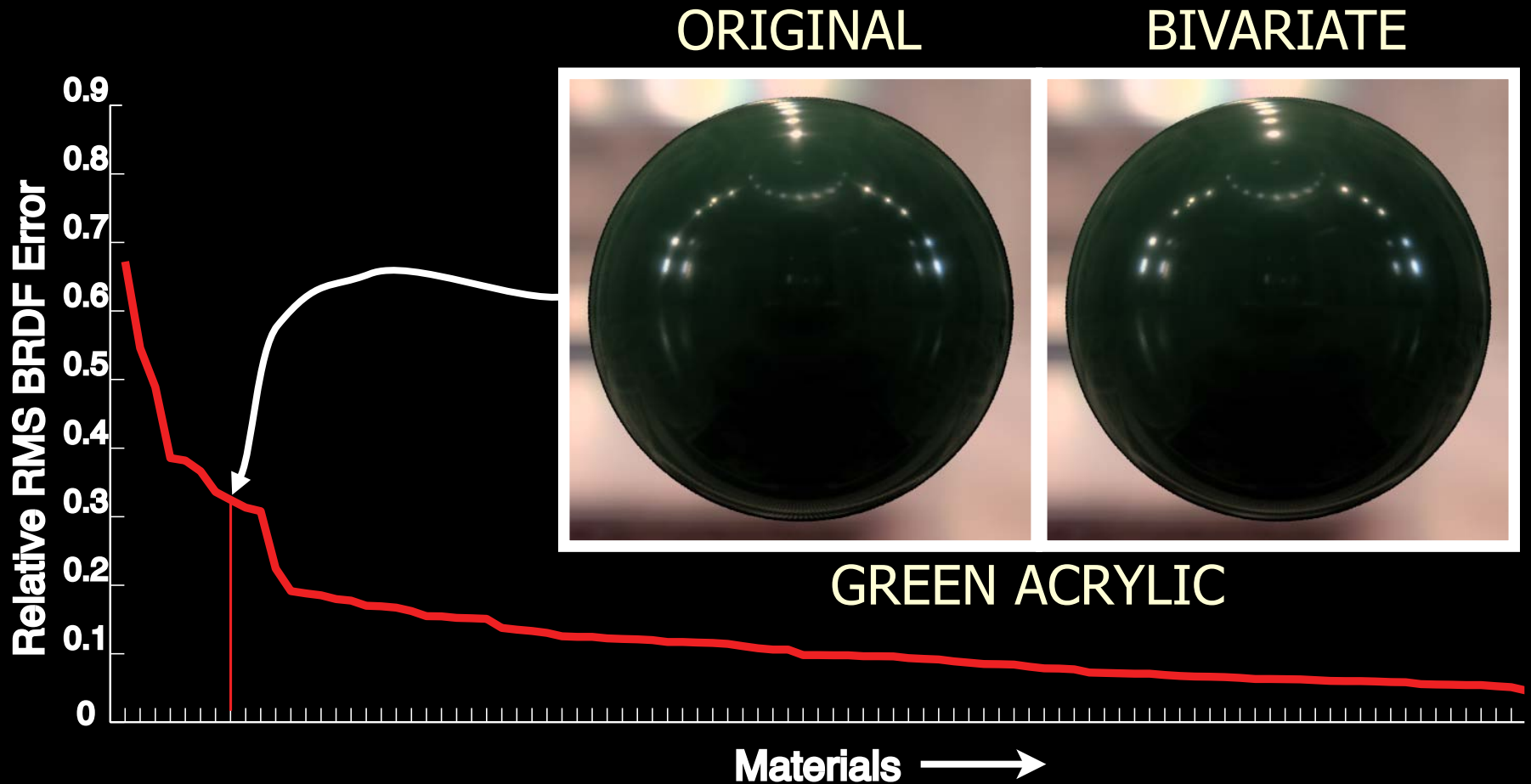
Bivariate Representation: Empirical Validation



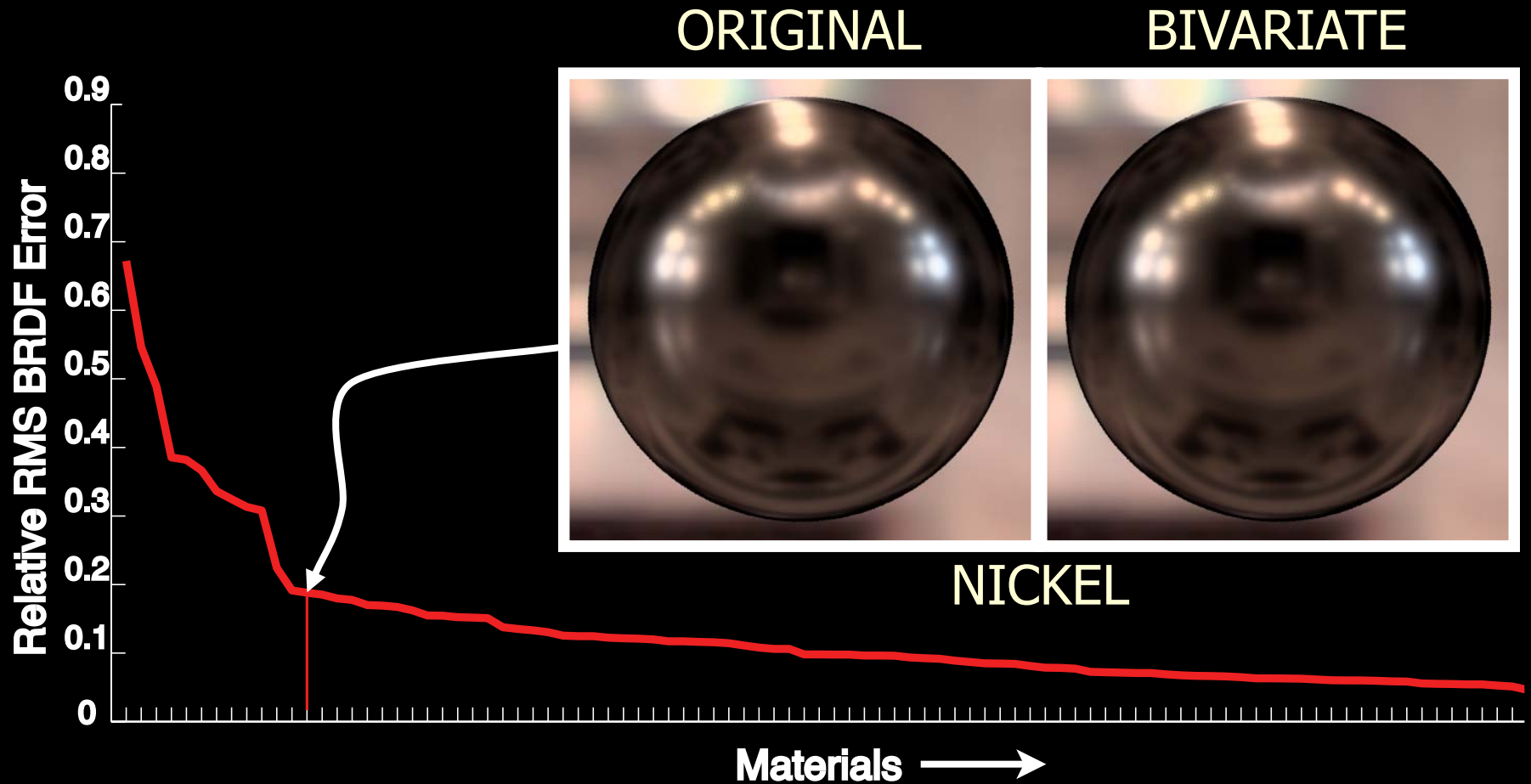
Bivariate Representation: Empirical Validation



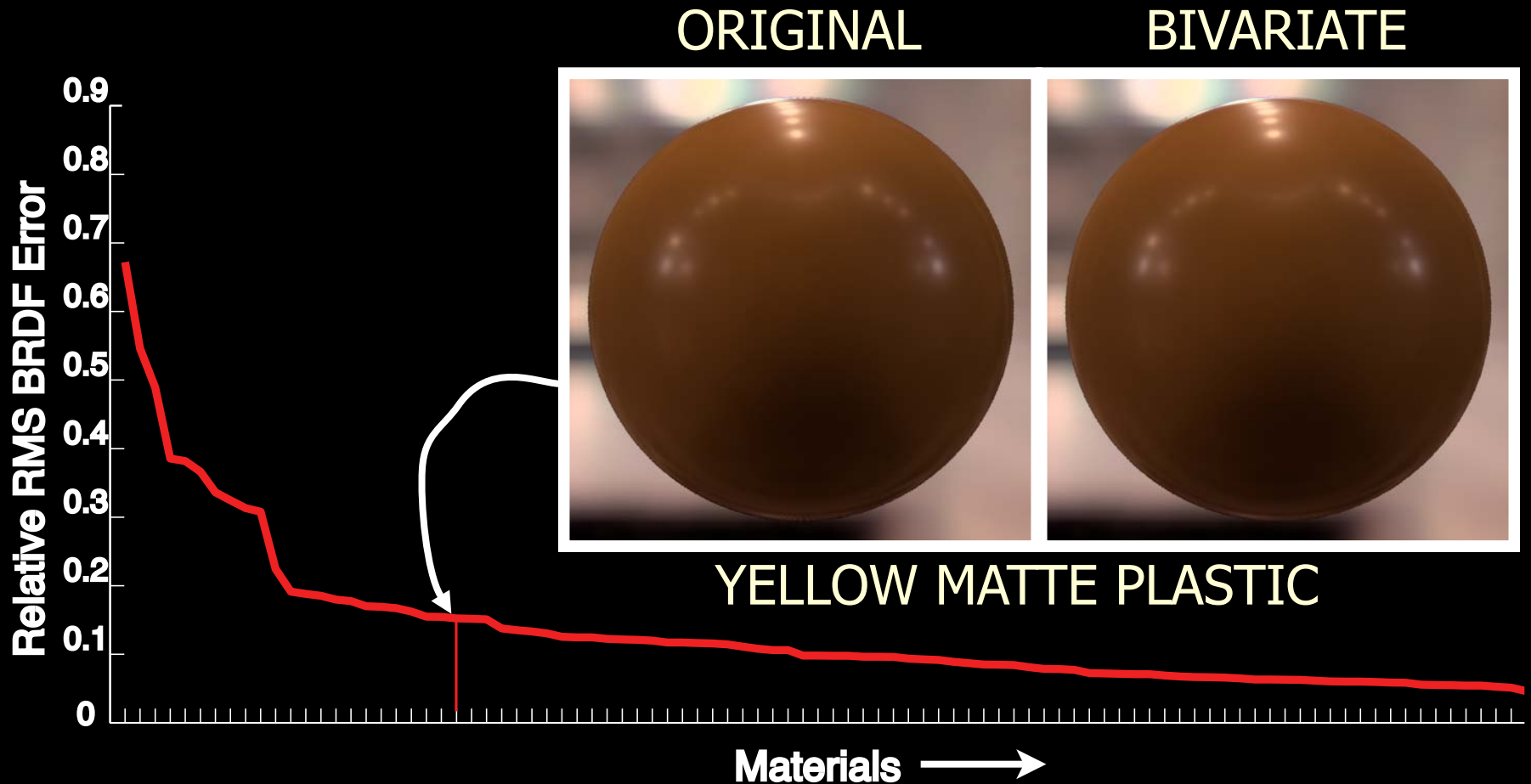
Bivariate Representation: Empirical Validation



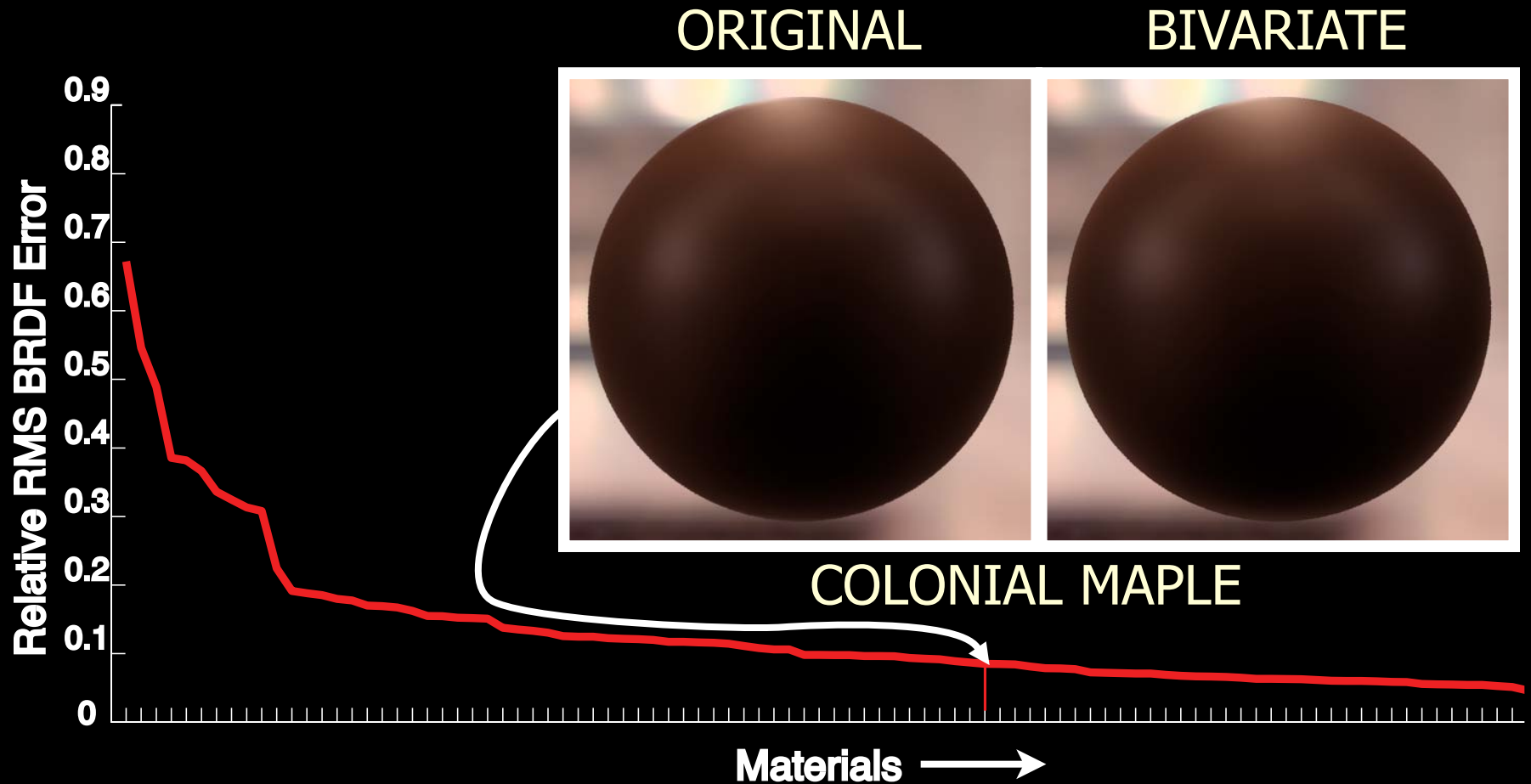
Bivariate Representation: Empirical Validation



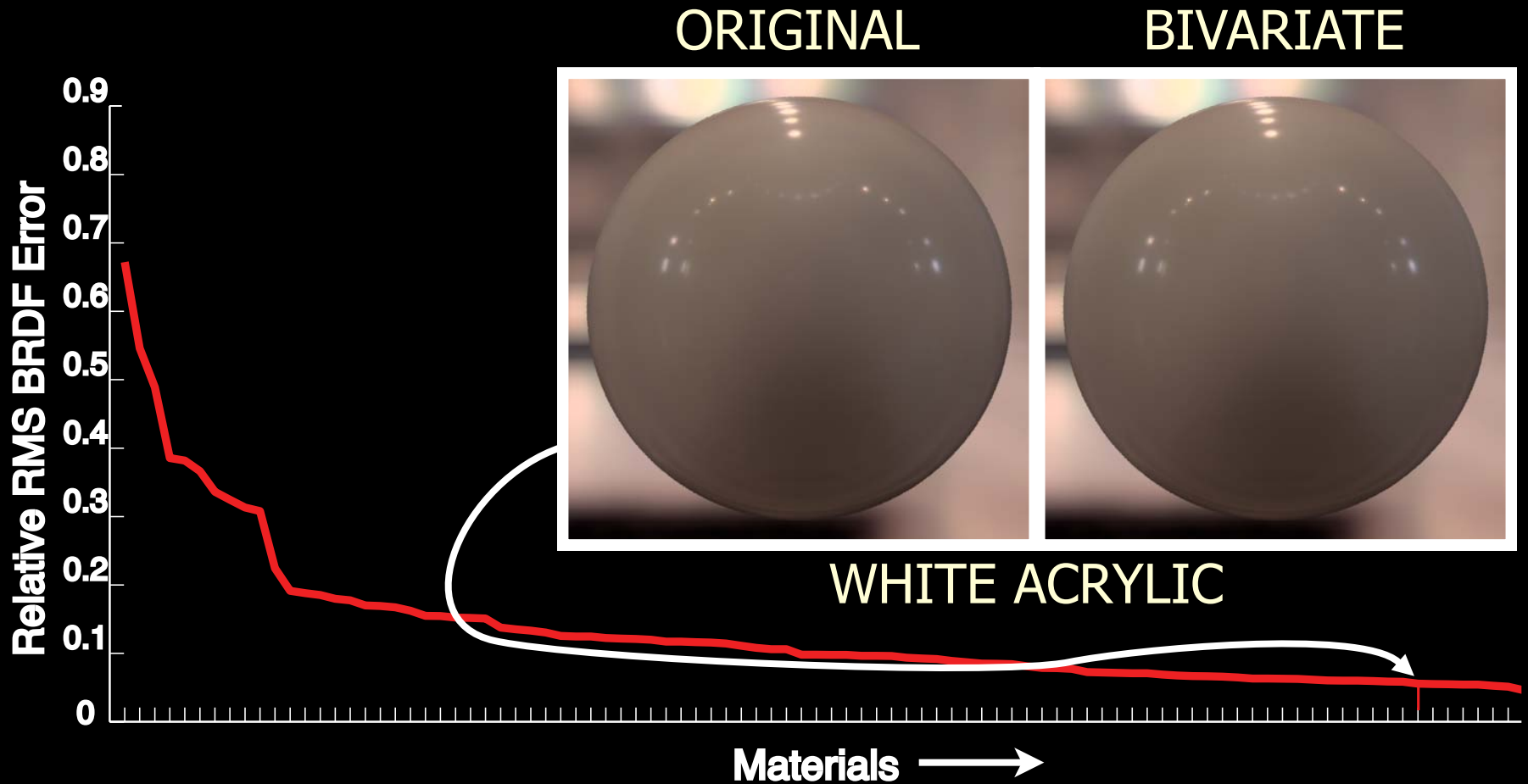
Bivariate Representation: Empirical Validation



Bivariate Representation: Empirical Validation



Bivariate Representation: Empirical Validation



Bivariate Representation: Conclusion



Bivariate Representation: Conclusion

- ◆ Isotropic materials: approximately bivariate



Bivariate Representation: Conclusion

- ◆ Isotropic materials: approximately bivariate
- ◆ Supports earlier findings [Stark et al, 2005]



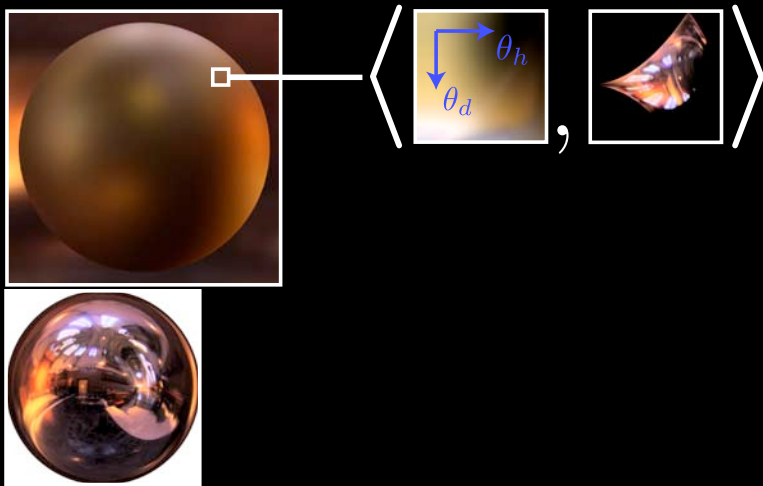
Passive Reflectometry



Passive Reflectometry

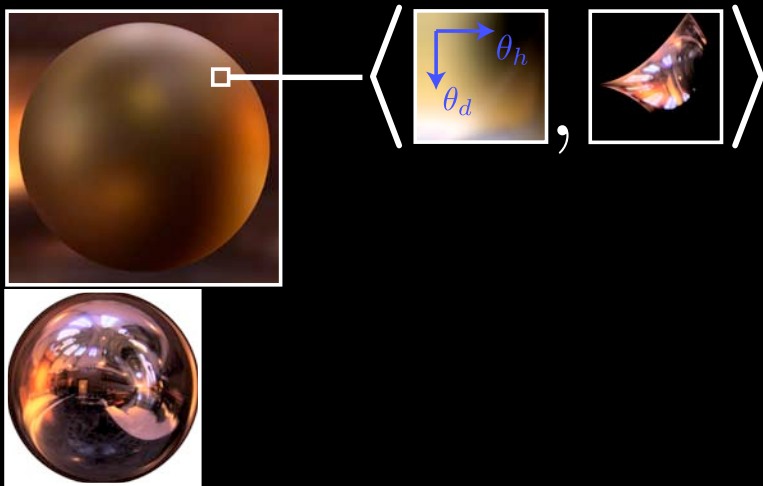


Passive Reflectometry

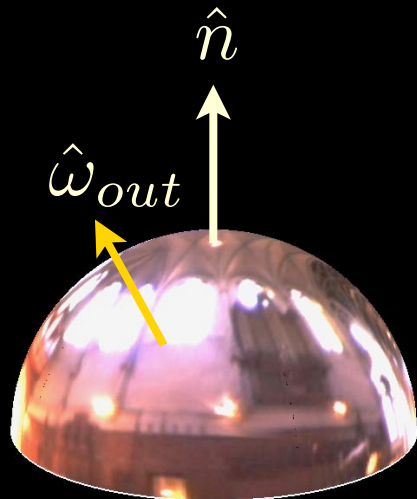


$$I_1 = L_1^T f$$

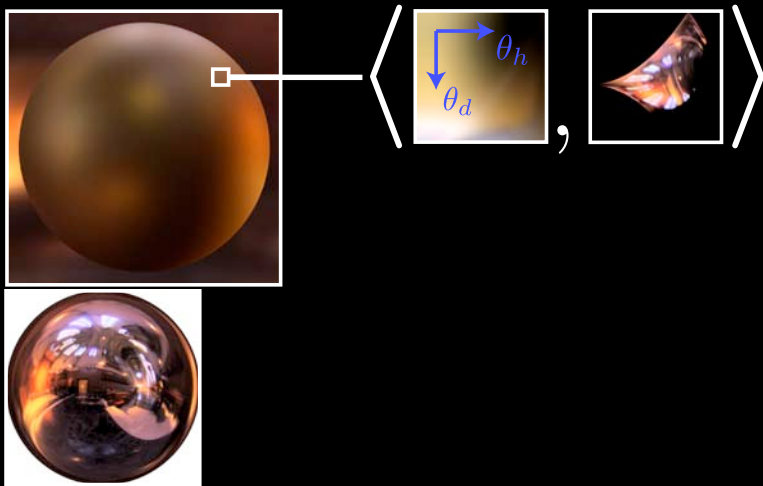
Passive Reflectometry



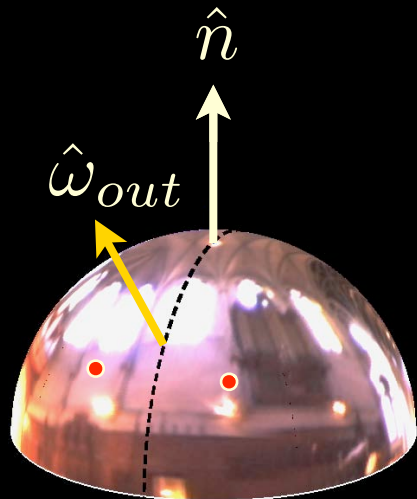
$$I_1 = L_1^T f$$



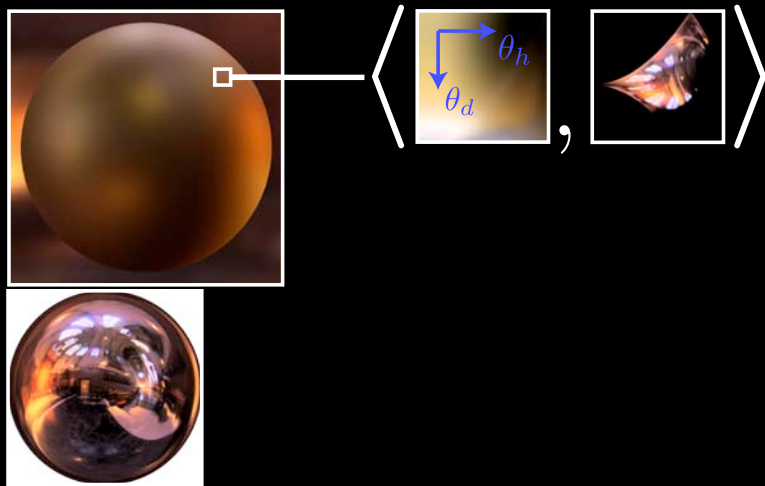
Passive Reflectometry



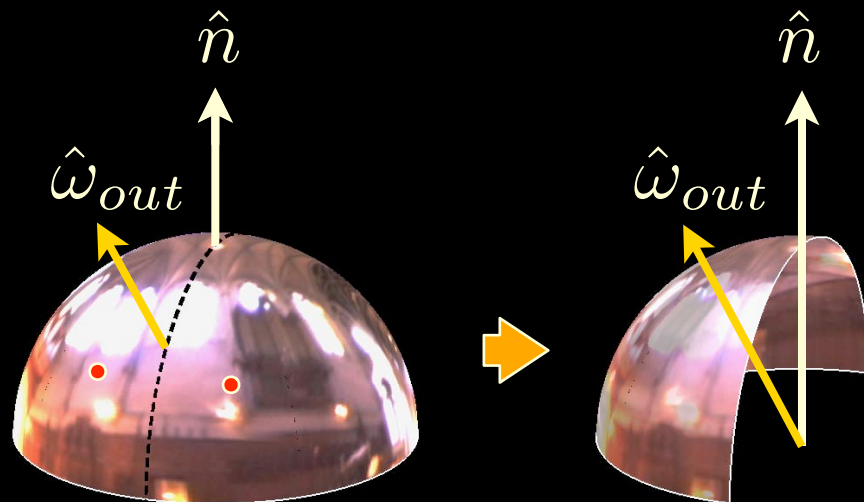
$$I_1 = L_1^T f$$



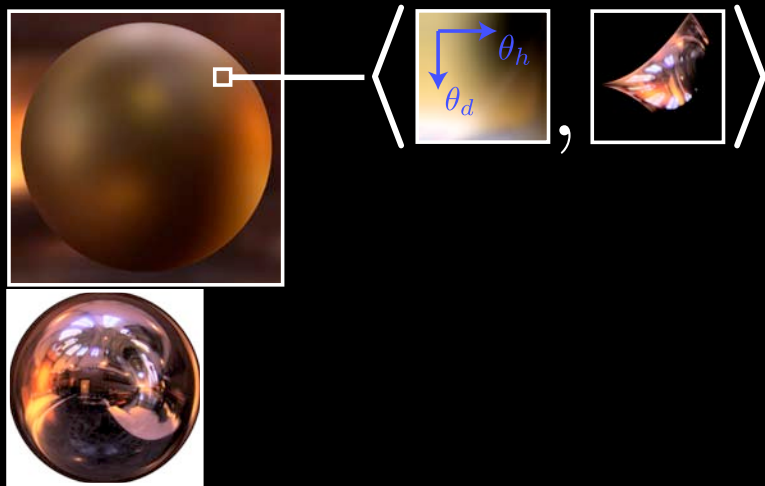
Passive Reflectometry



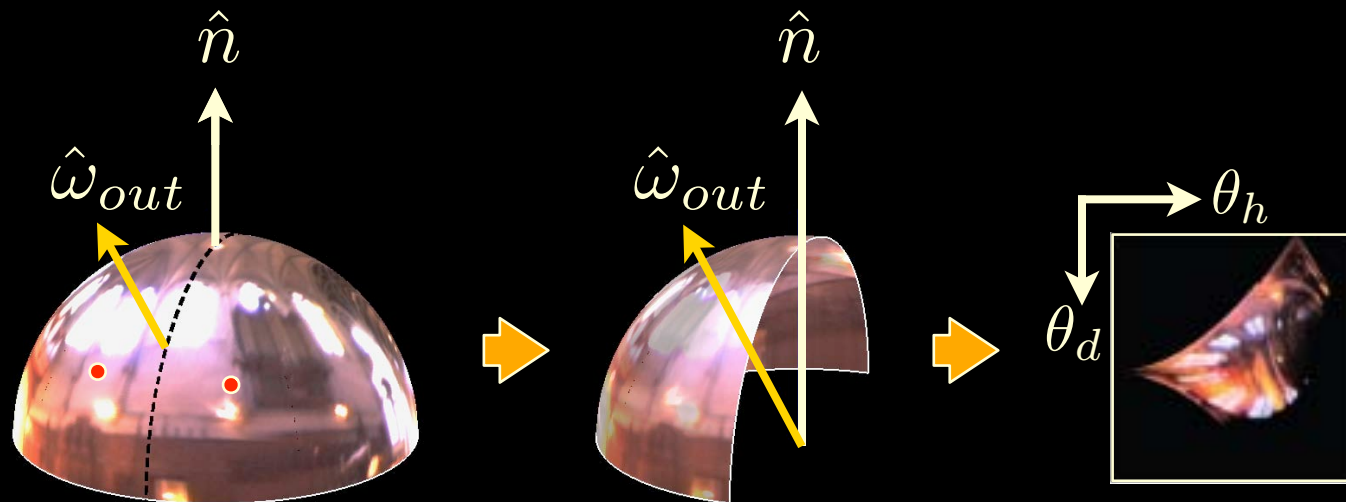
$$I_1 = L_1^T f$$



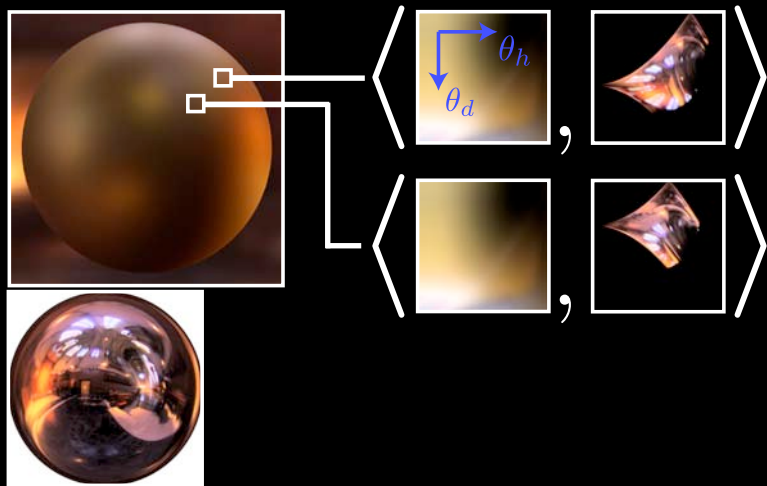
Passive Reflectometry



$$I_1 = L_1^T f$$

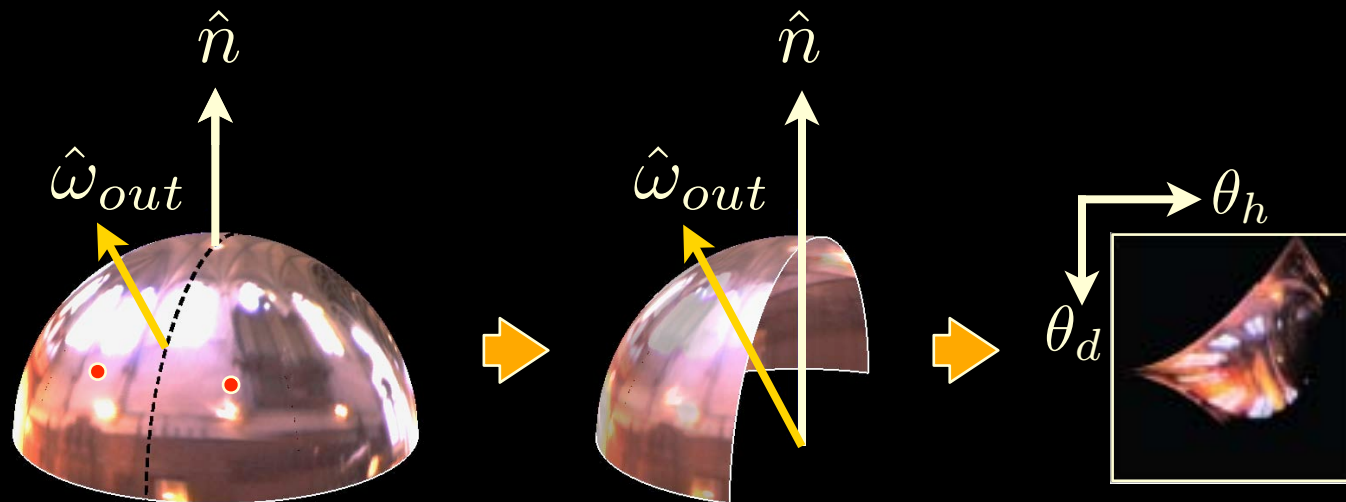


Passive Reflectometry

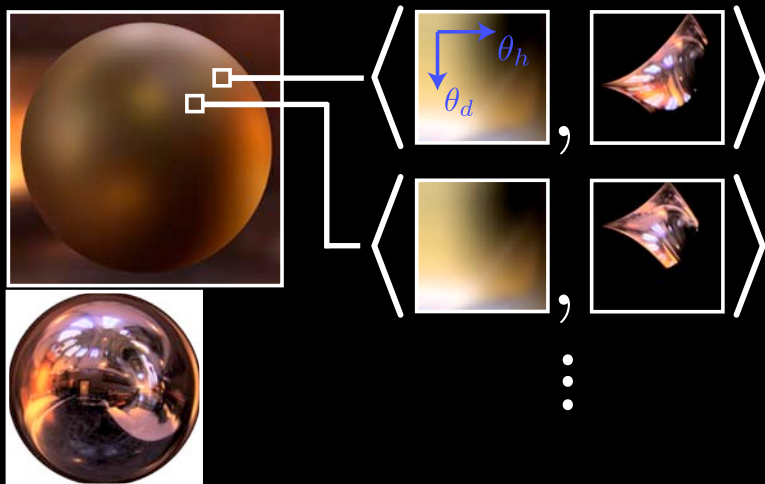


$$I_1 = L_1^T f$$

$$I_2 = L_2^T f$$



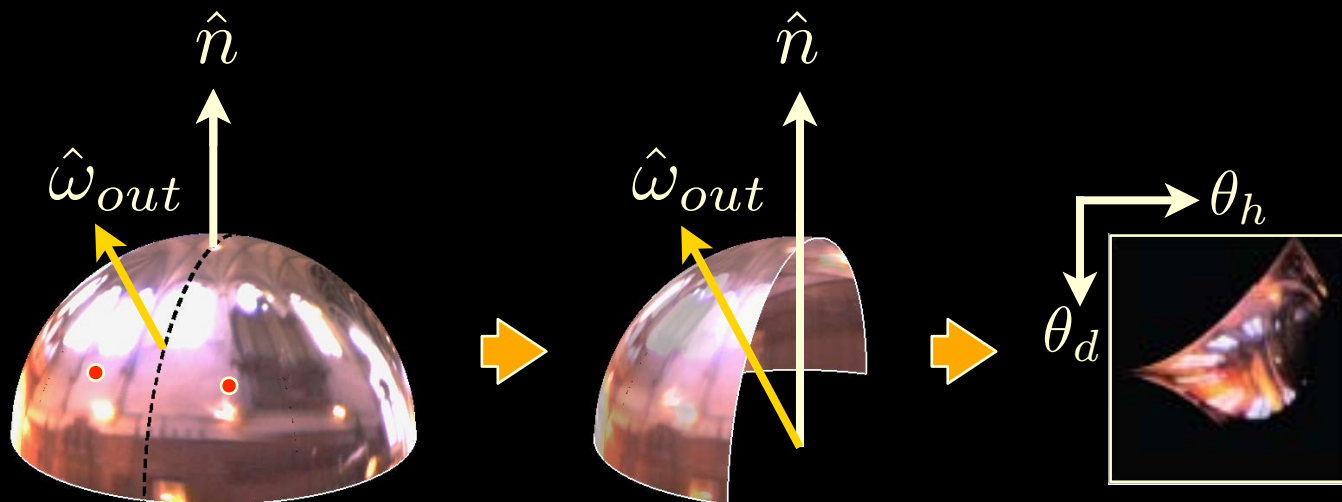
Passive Reflectometry



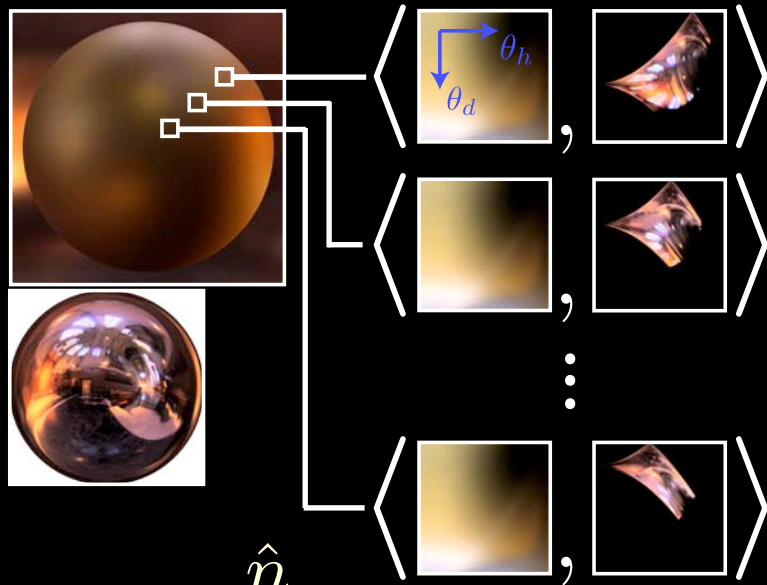
$$I_1 = L_1^T f$$

$$I_2 = L_2^T f$$

⋮



Passive Reflectometry

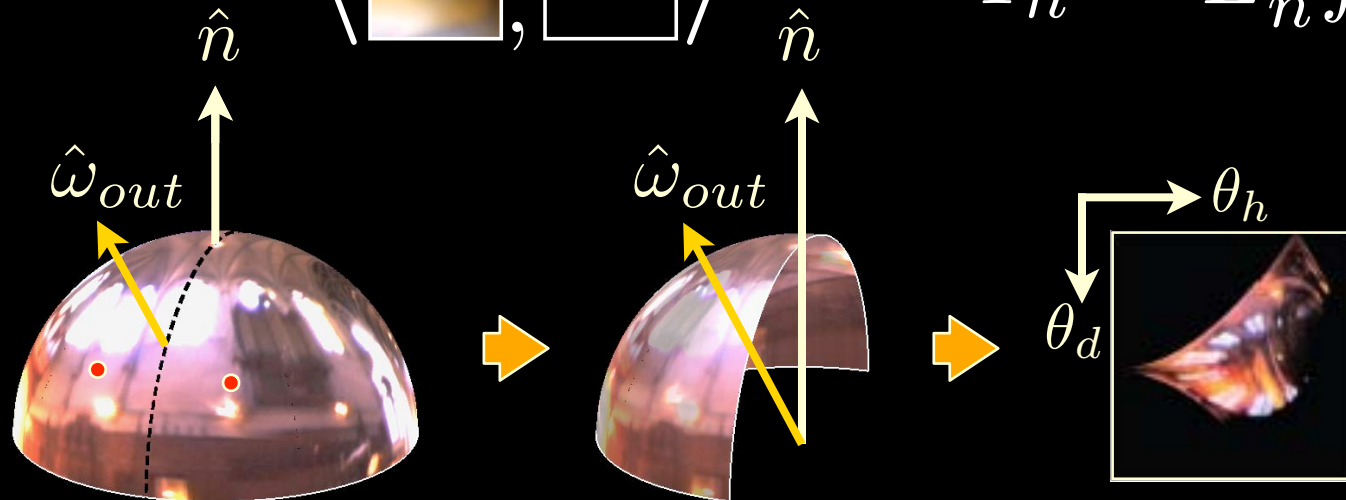


$$I_1 = L_1^T f$$

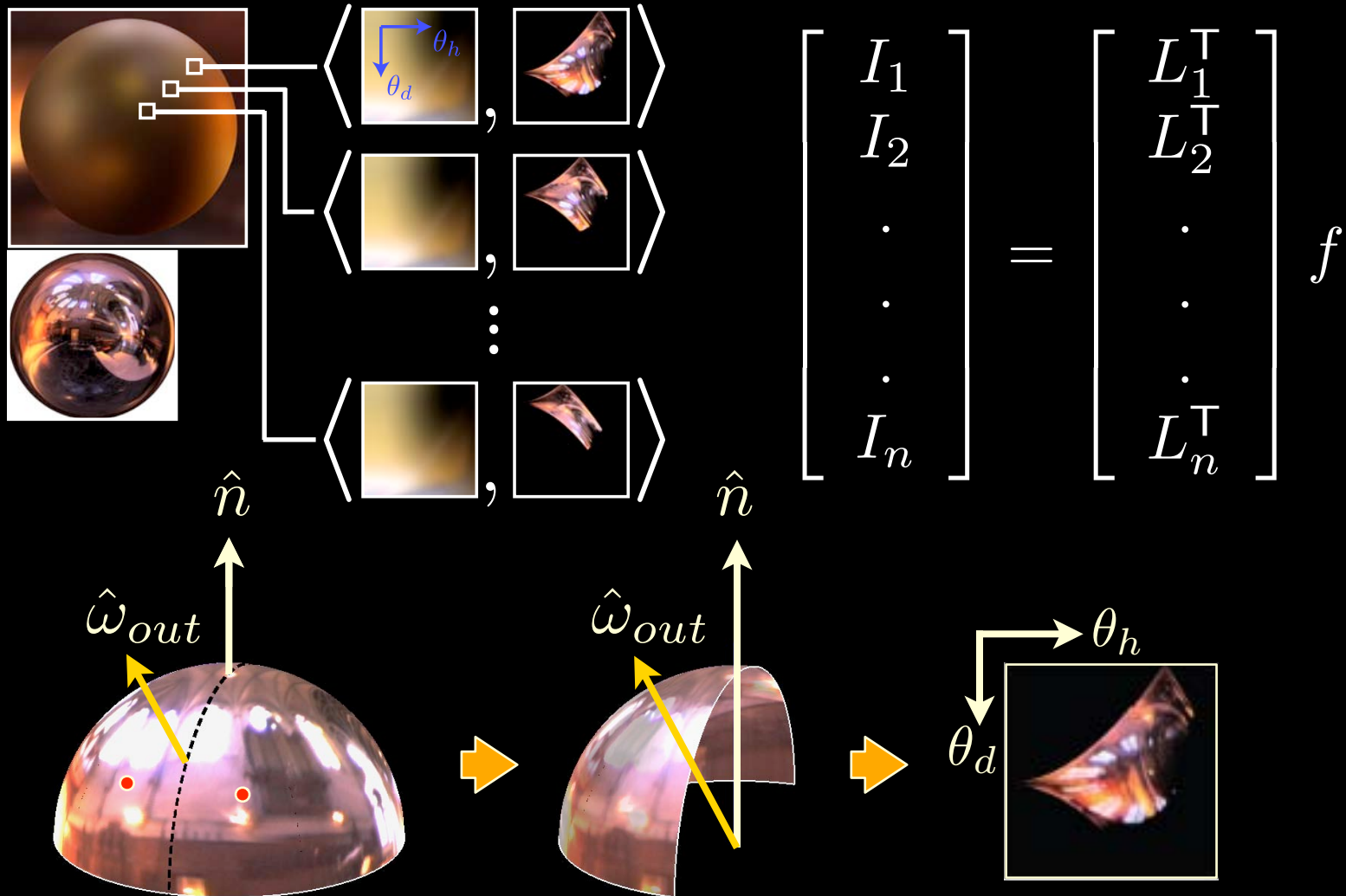
$$I_2 = L_2^T f$$

⋮

$$I_n = L_n^T f$$



Passive Reflectometry



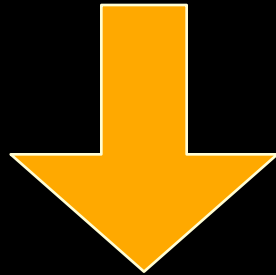
Passive Reflectometry

$$I = Lf$$



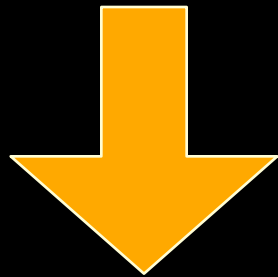
Passive Reflectometry

$$I = Lf$$



Passive Reflectometry

$$I = Lf$$



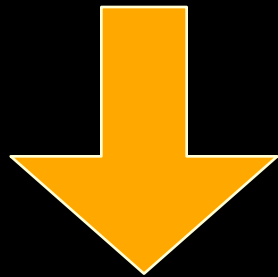
$$f^* = \mathit{arg} \min_f ||I - Lf||_2^2$$

subject to $f \geq 0$



Passive Reflectometry

$$I = Lf$$



$$f^* = \arg \min_f \|I - Lf\|_2^2 + \alpha E_{smooth}(f)$$

subject to $f \geq 0$



Non-uniform Regularization

$$E_{smooth}(f) = \|\Lambda_h D_h f\|_2^2 + \|\Lambda_d D_d f\|_2^2$$



Non-uniform Regularization

$$E_{smooth}(f) = \|\Lambda_h \underbrace{D_h f}_{\text{partial derivatives w.r.t. } \theta_h}\|_2^2 + \|\Lambda_d \underbrace{D_d f}_{\text{partial derivatives w.r.t. } \theta_d}\|_2^2$$

partial derivatives
w.r.t. θ_h, θ_d

Non-uniform Regularization

$$E_{smooth}(f) = \|\underbrace{\Lambda_h}_{\text{diagonal matrix}} D_h f\|_2^2 + \|\underbrace{\Lambda_d}_{\text{diagonal matrix}} D_d f\|_2^2$$

- diagonal matrices
- non-uniform weights
- learned from statistics of derivatives in MERL database

Results: Synthetic Data



Results: Synthetic Data

Input Environment



Results: Synthetic Data

Input Image



Input Environment



Results: Synthetic Data

Input Image



Input Environment



Eval. Environment



Results: Synthetic Data

Input Image



Recovered



Input Environment



Eval. Environment



Results: Synthetic Data

Input Image



Recovered



Ground Truth



Input Environment



Eval. Environment



Results: Synthetic Data

Input Image



Recovered



Ground Truth



100x Difference



Input Environment



Eval. Environment



Results: Synthetic Data

Input Image



Recovered






Ground Truth



100x Difference



Polar Plot

-  MERL Ground Truth (3D)
-  Bivariate Recovered
-  Bivariate Ground Truth

Results: Synthetic Data

Input Image



Recovered






Ground Truth



100x Difference



Polar Plot

-  MERL Ground Truth (3D)
-  Bivariate Recovered
-  Bivariate Ground Truth

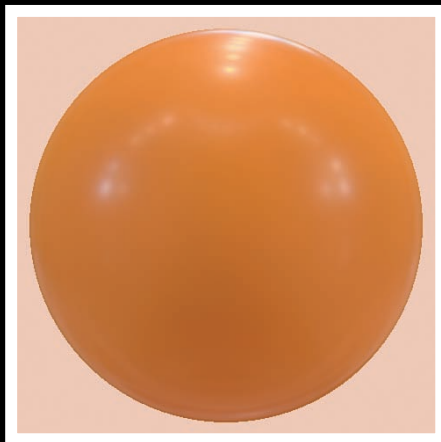


Results: Synthetic Data

Input Image



Recovered



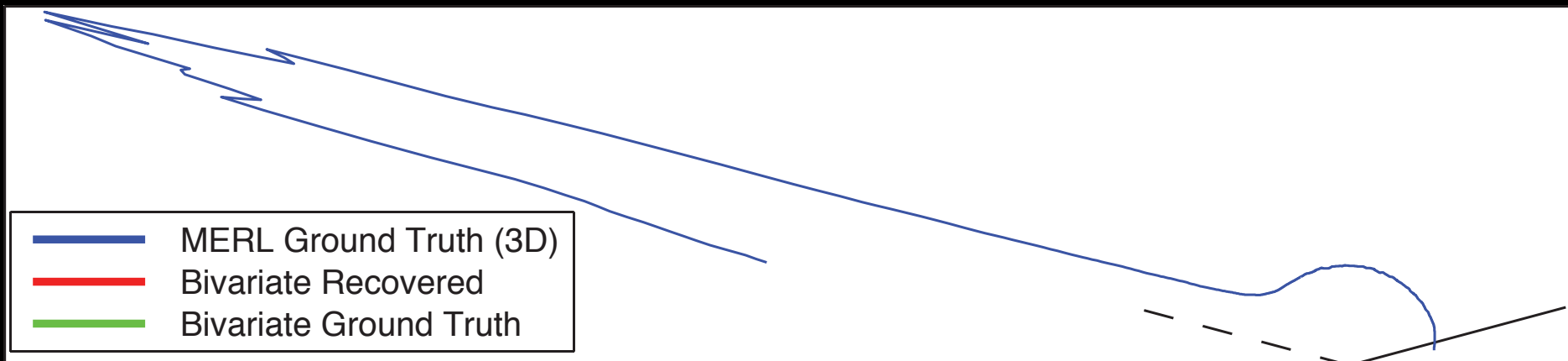
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data

Input Image



Recovered



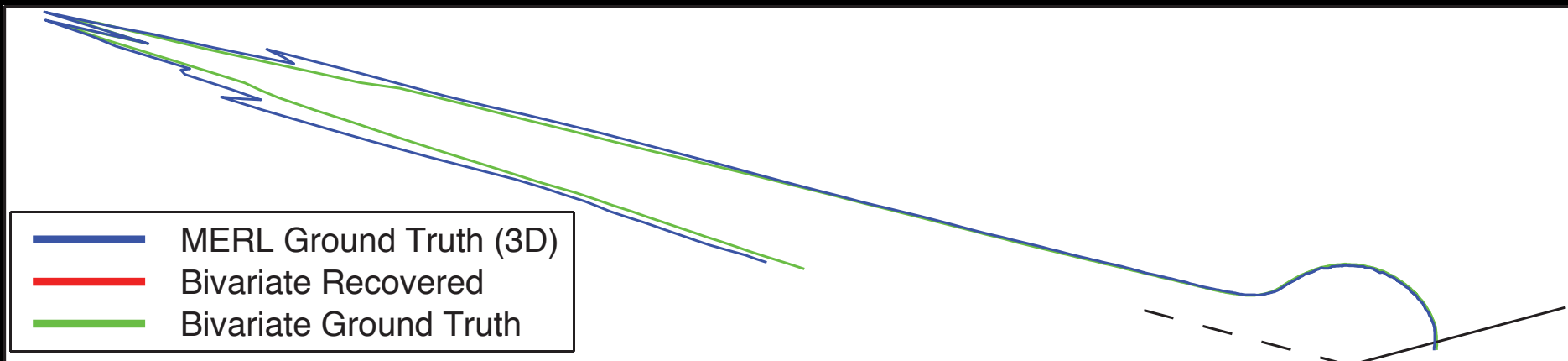
Ground Truth



100x Difference



Polar Plot

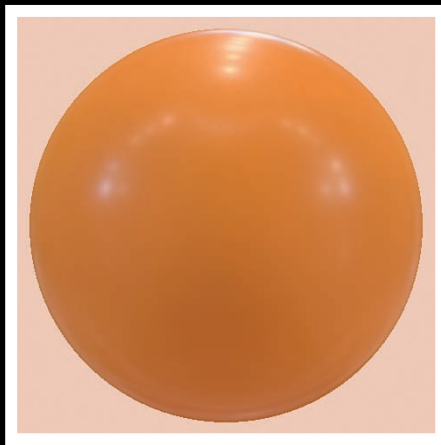


Results: Synthetic Data

Input Image



Recovered



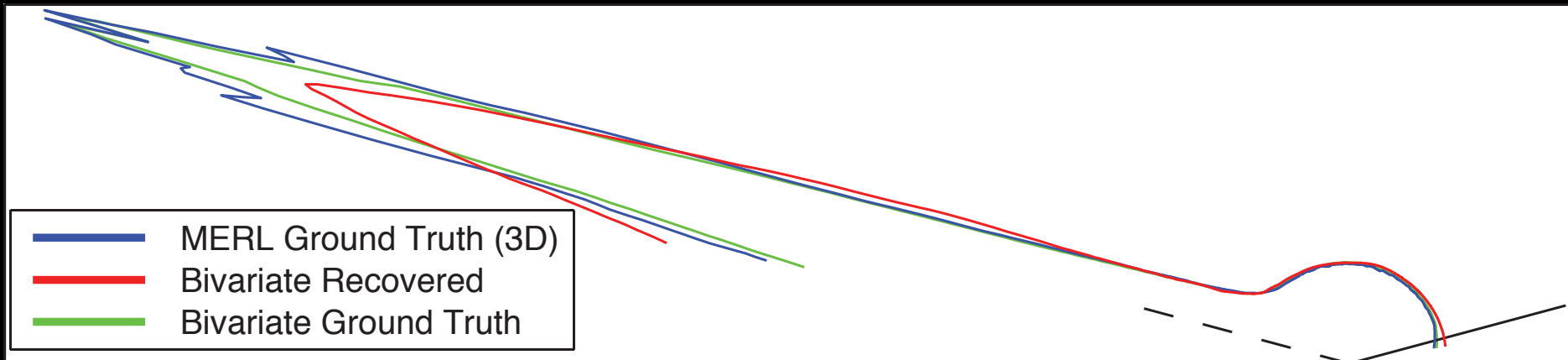
Ground Truth



100x Difference



Polar Plot

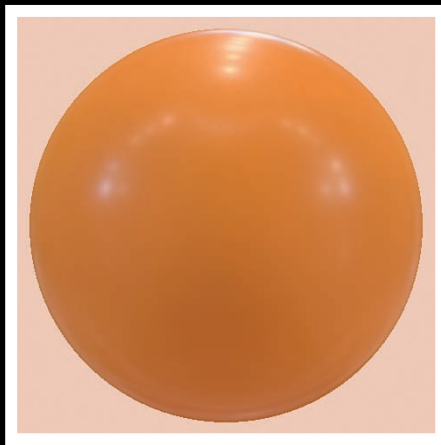


Results: Synthetic Data

Input Image



Recovered



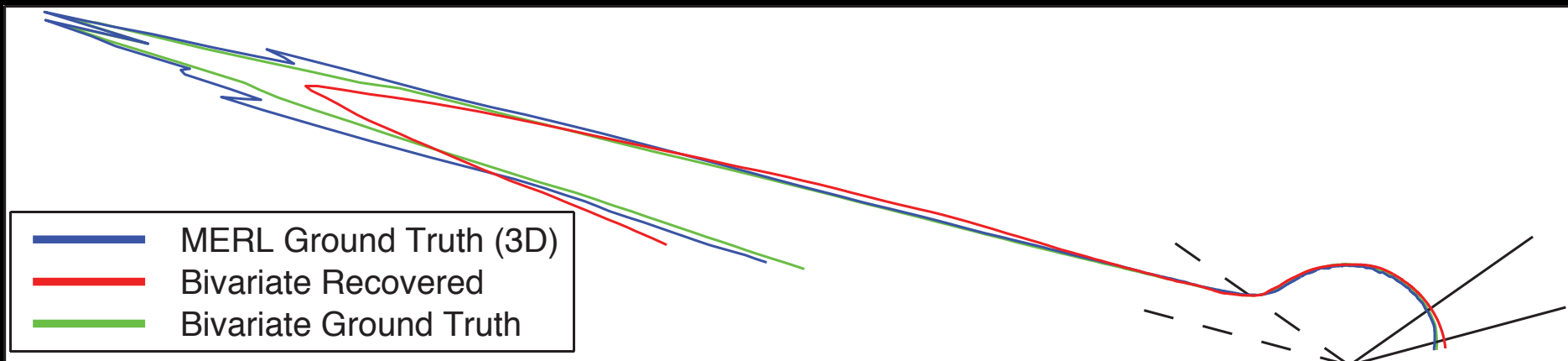
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data

Input Image



Recovered



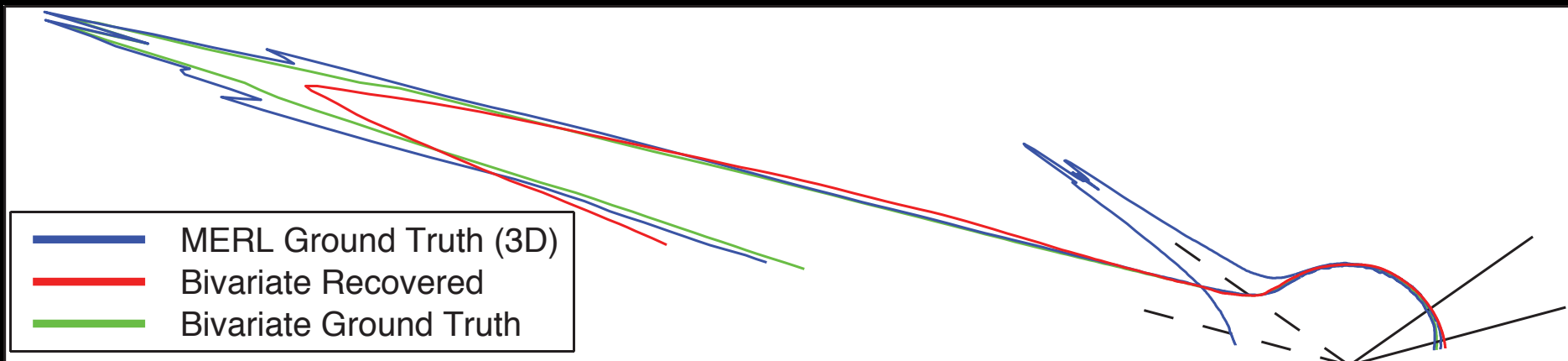
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data

Input Image



Recovered



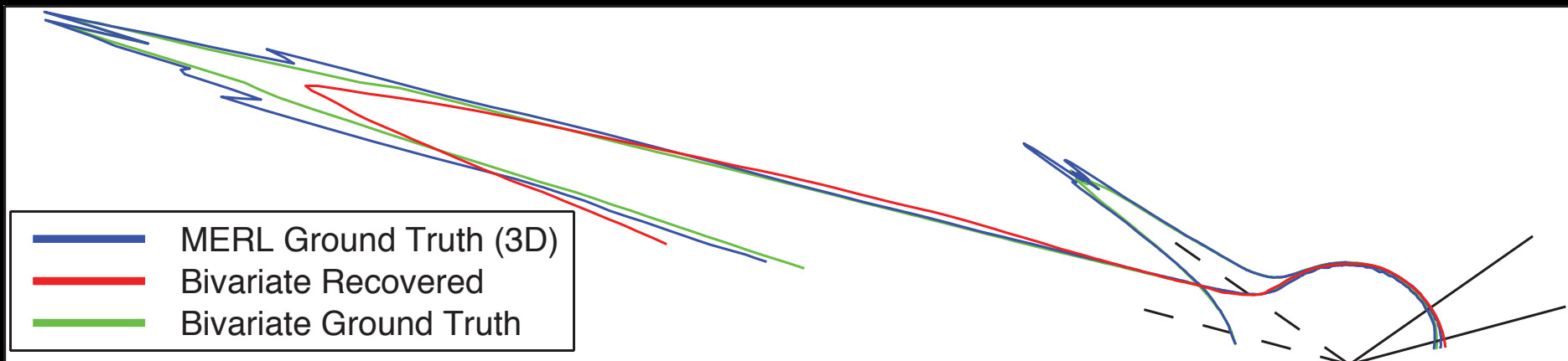
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data

Input Image



Recovered



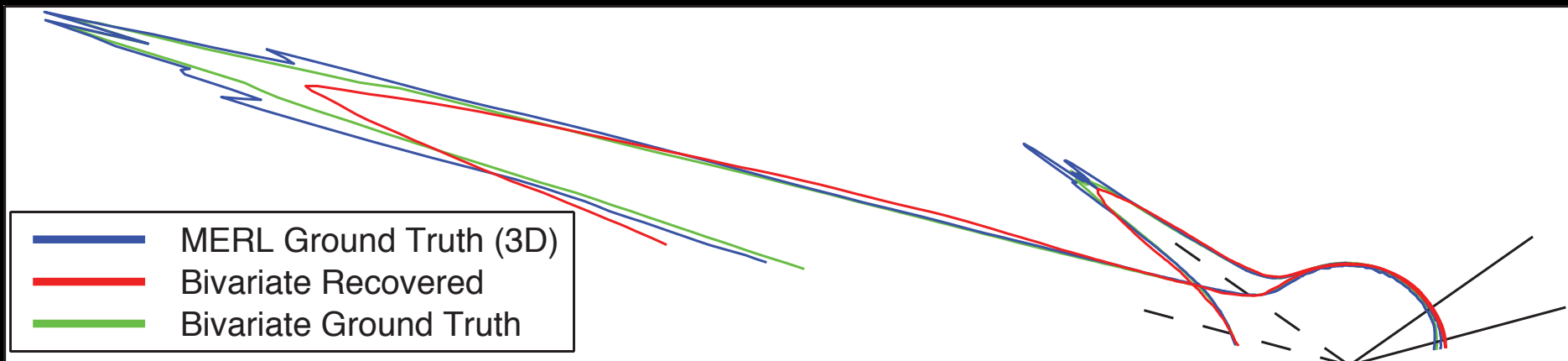
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data

Input Image



Recovered



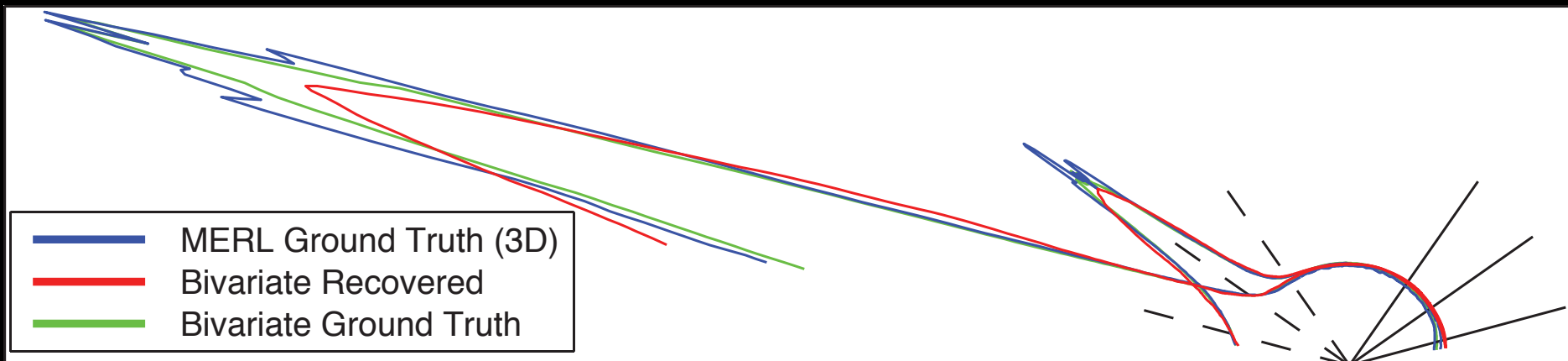
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data

Input Image



Recovered



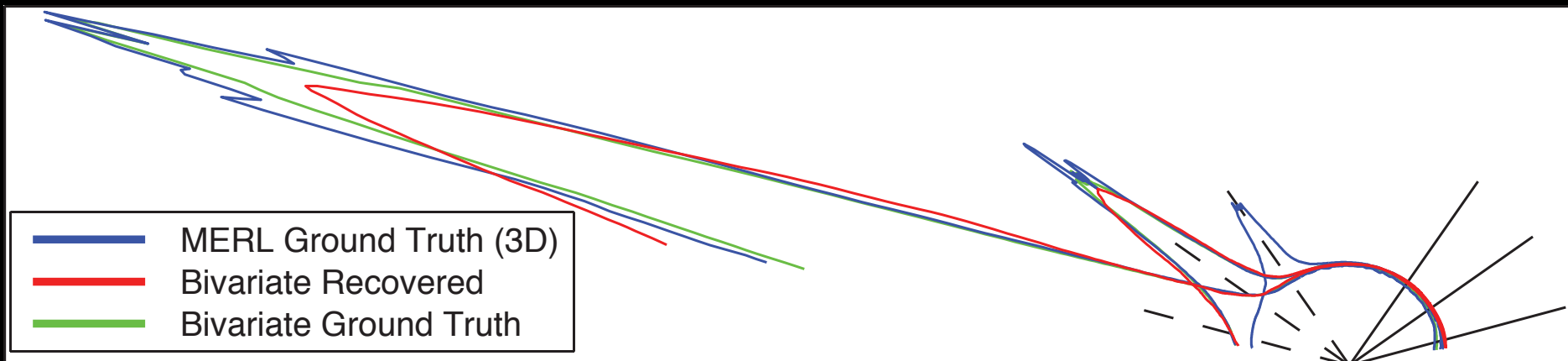
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data

Input Image



Recovered



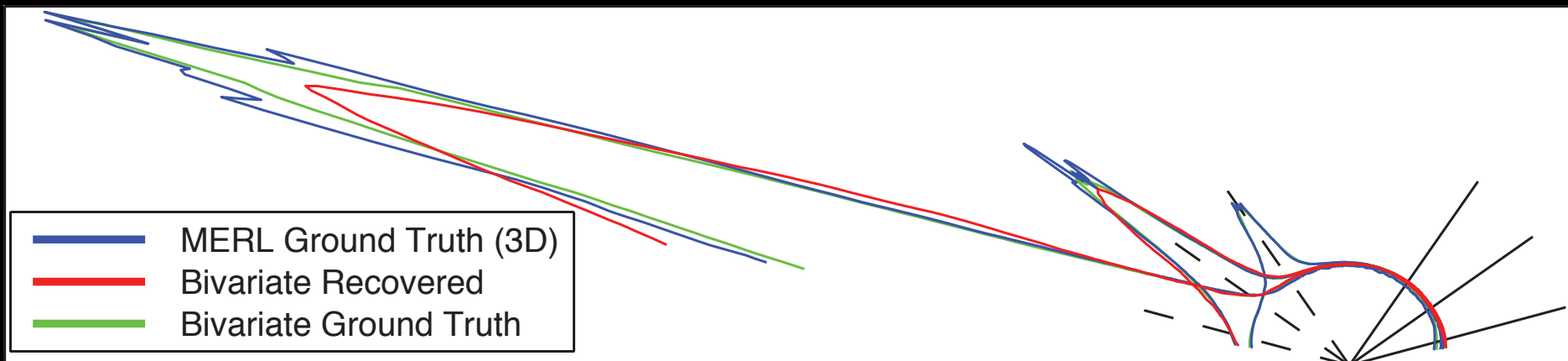
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data

Input Image



Recovered



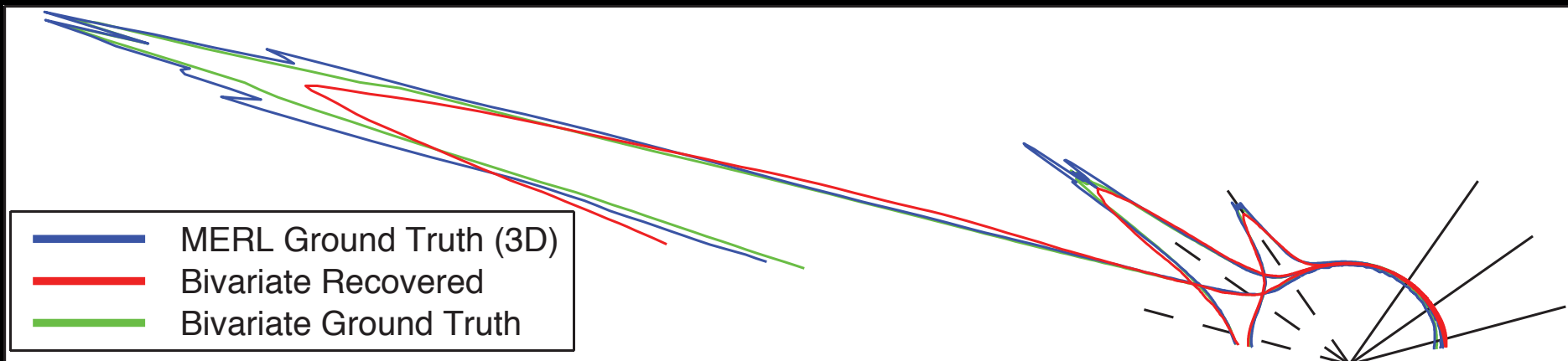
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data

Input Image



Recovered



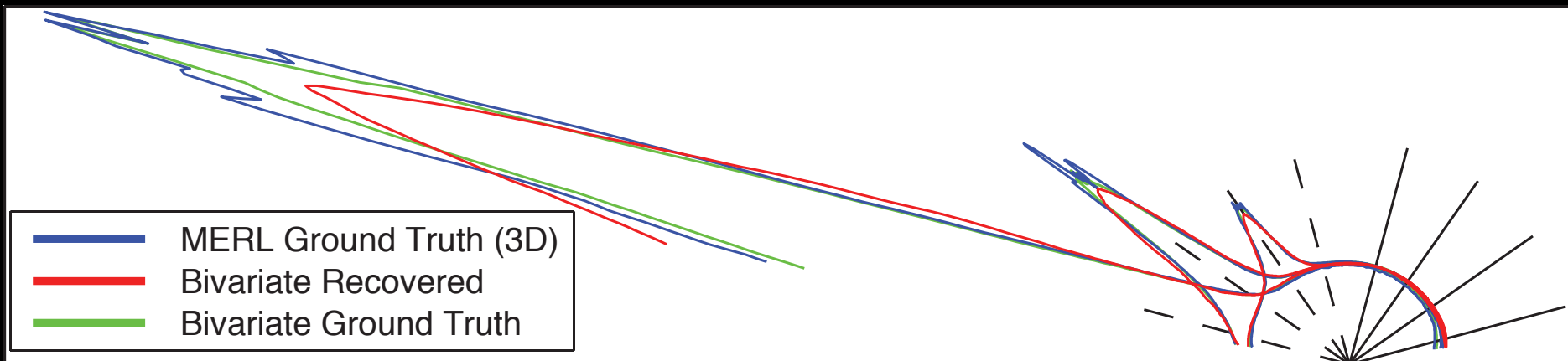
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data

Input Image



Recovered



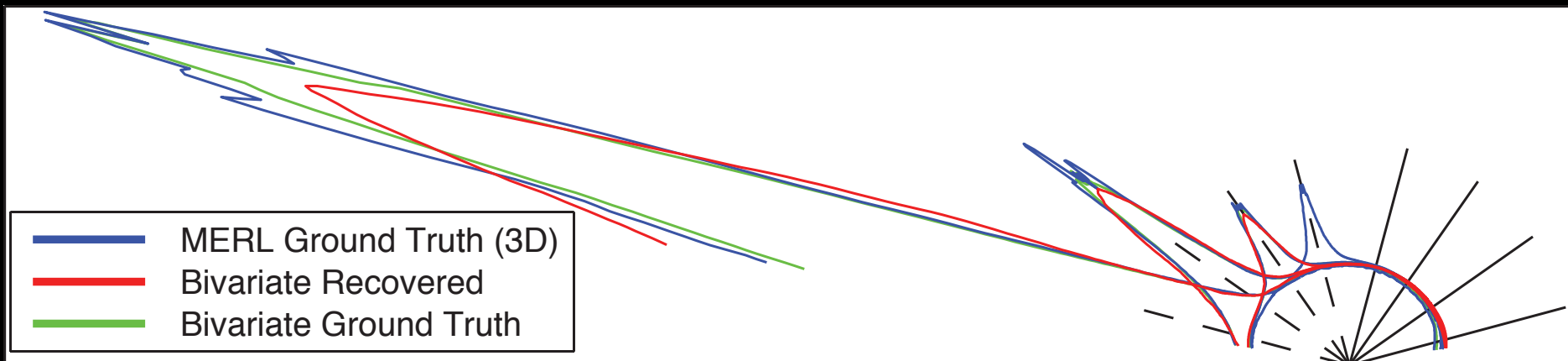
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data

Input Image



Recovered



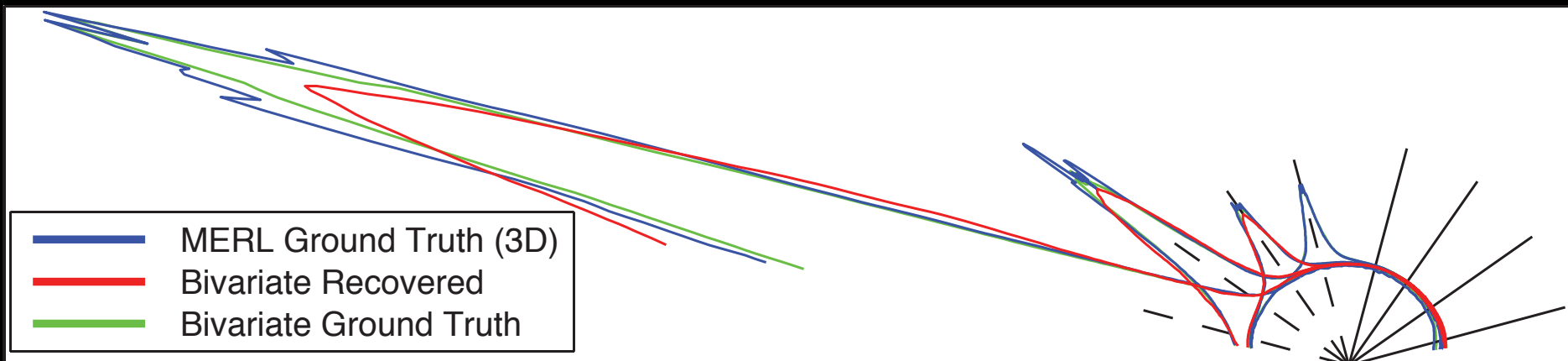
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data

Input Image



Recovered



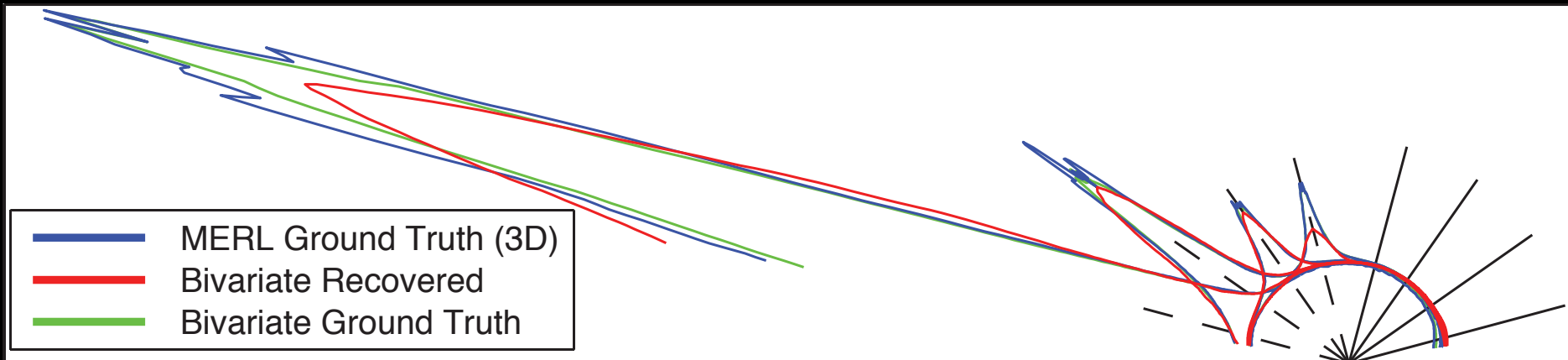
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data



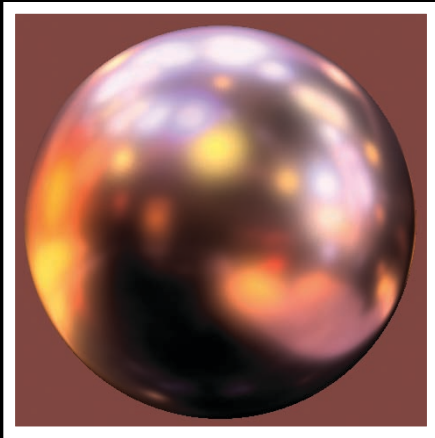
Results: Synthetic Data

Input Environment



Results: Synthetic Data

Input Image

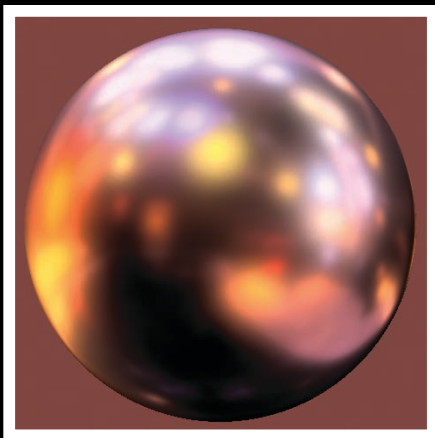


Input Environment



Results: Synthetic Data

Input Image



Input Environment

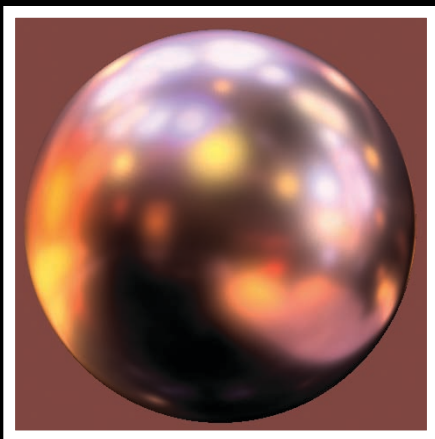


Eval. Environment



Results: Synthetic Data

Input Image



Recovered



Input Environment

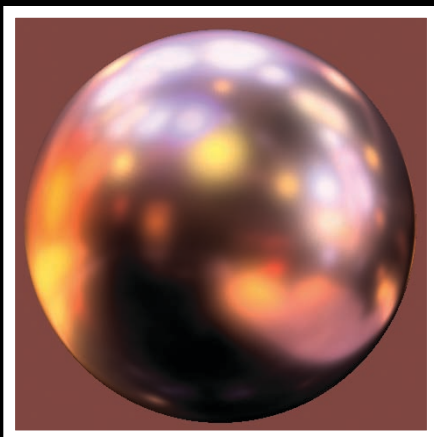


Eval. Environment

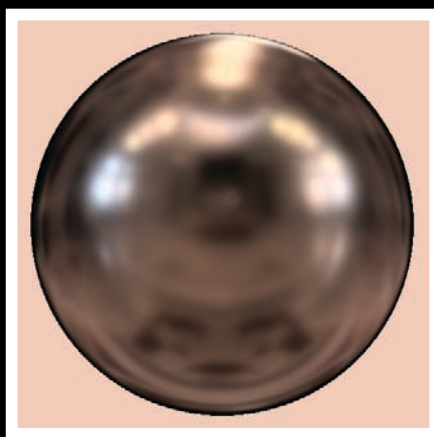


Results: Synthetic Data

Input Image



Recovered



Ground Truth



Input Environment

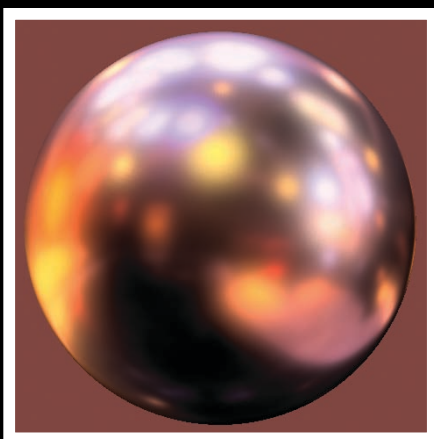


Eval. Environment



Results: Synthetic Data

Input Image



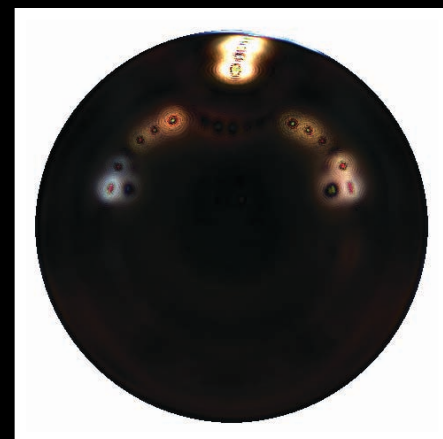
Recovered



Ground Truth



100x Difference



Input Environment

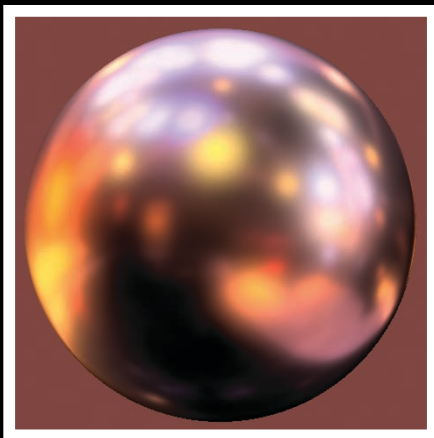


Eval. Environment



Results: Synthetic Data

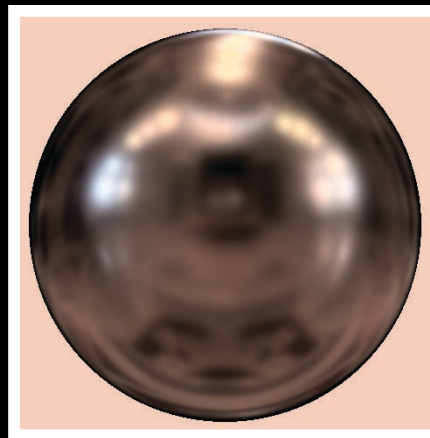
Input Image



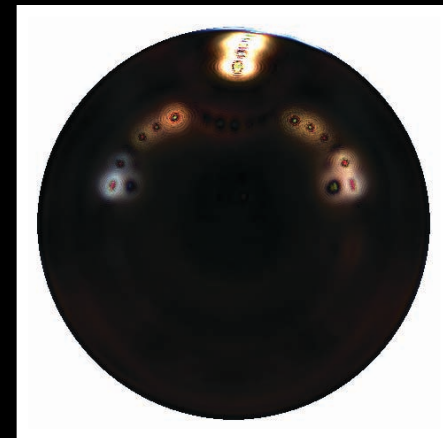
Recovered



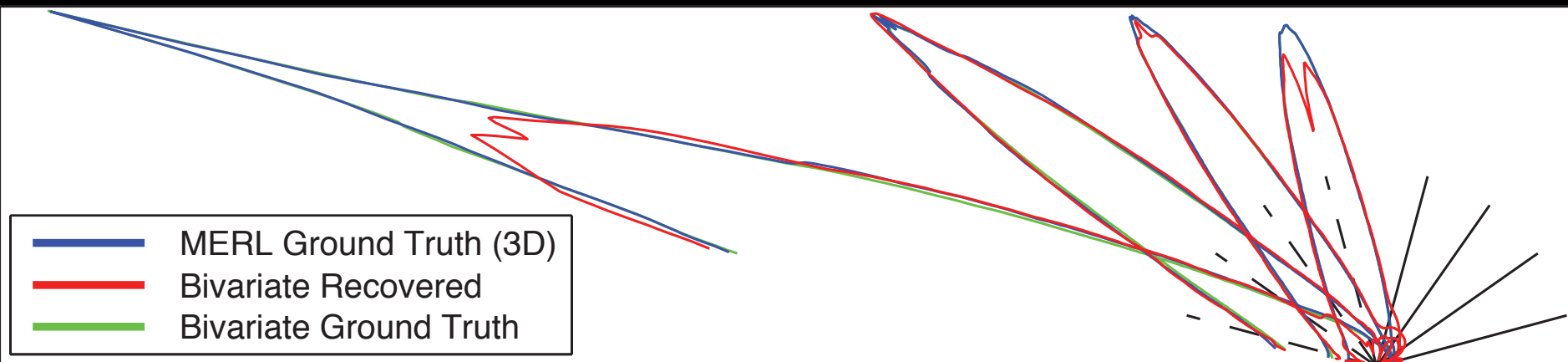
Ground Truth



100x Difference



Polar Plot



Results: Synthetic Data



Results: Synthetic Data

Input Environment



Results: Synthetic Data

Input Image



Input Environment



Results: Synthetic Data

Input Image



Input Environment



Eval. Environment

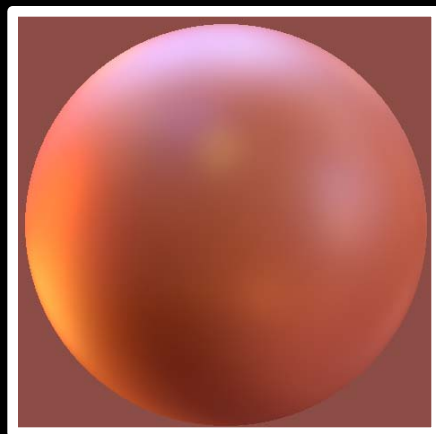


Results: Synthetic Data

Input Image



Recovered



Input Environment



Eval. Environment



Results: Synthetic Data

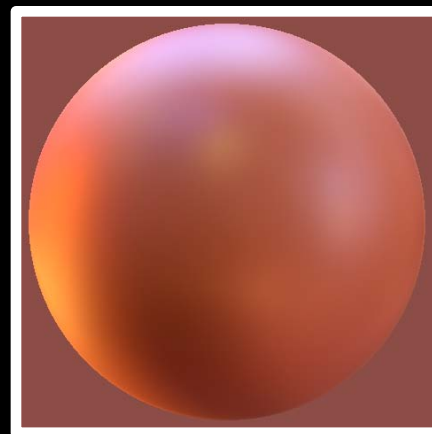
Input Image



Recovered



Ground Truth



Input Environment



Eval. Environment

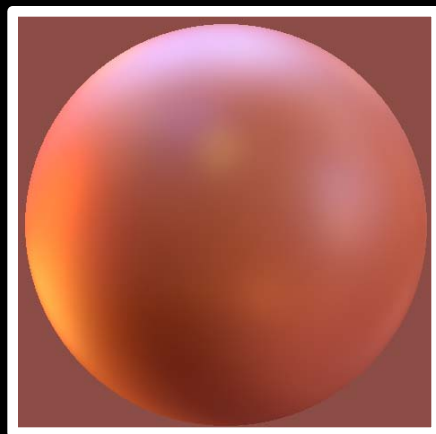


Results: Synthetic Data

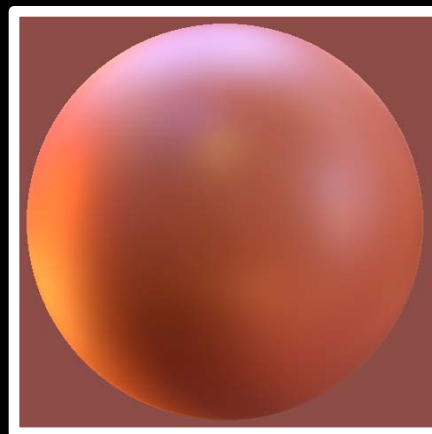
Input Image



Recovered



Ground Truth



100x Difference



Input Environment

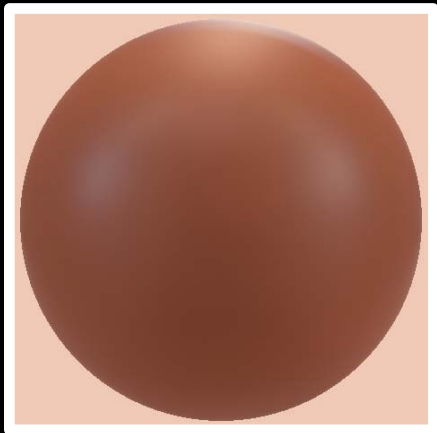


Eval. Environment

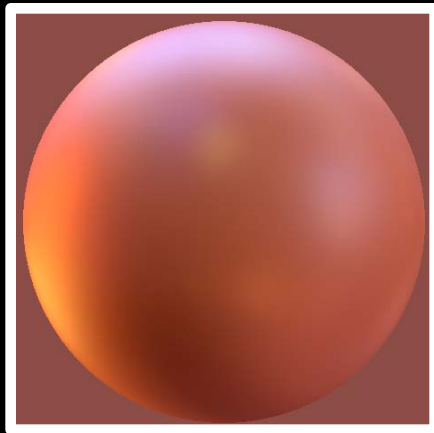


Results: Synthetic Data

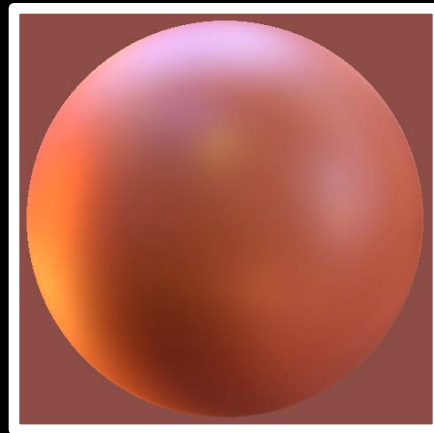
Input Image



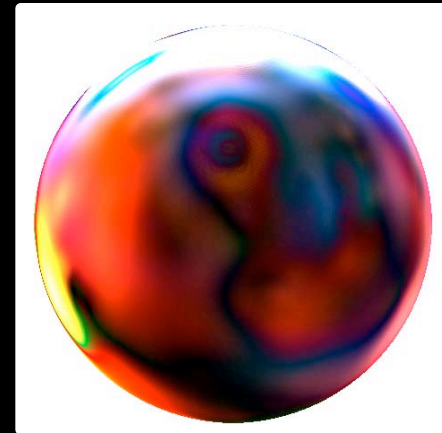
Recovered



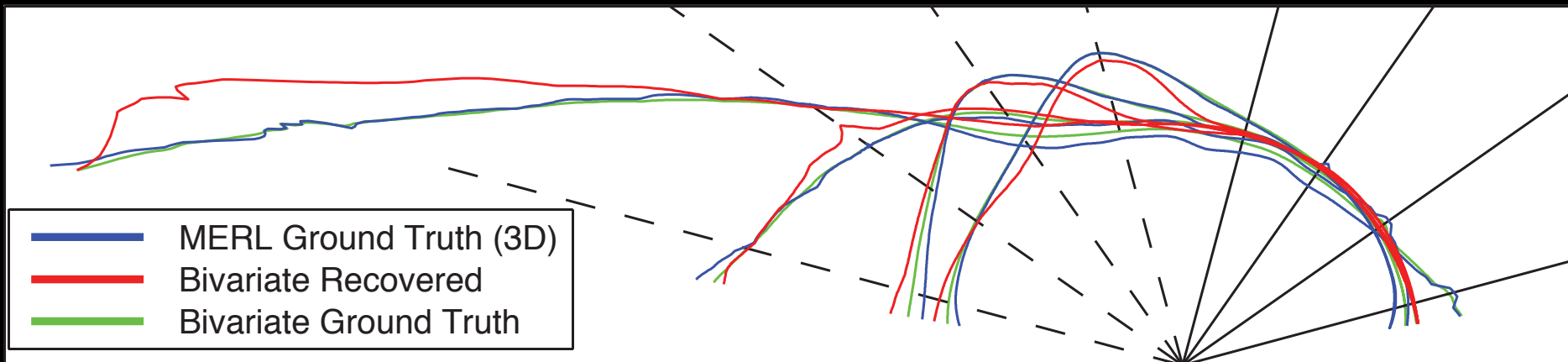
Ground Truth



100x Difference



Polar Plot

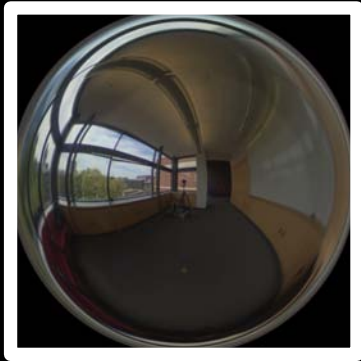


Results: Captured Data



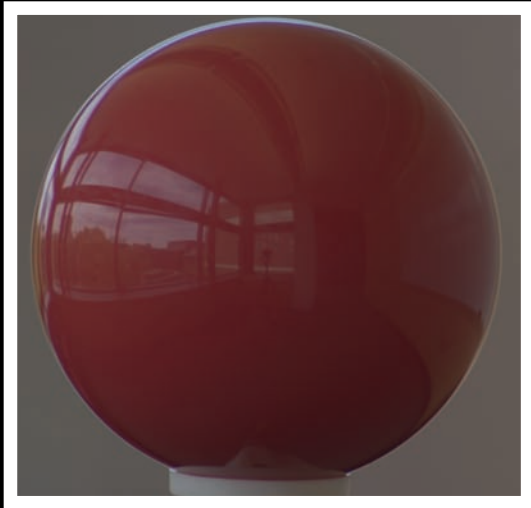
Results: Captured Data

Input Environment

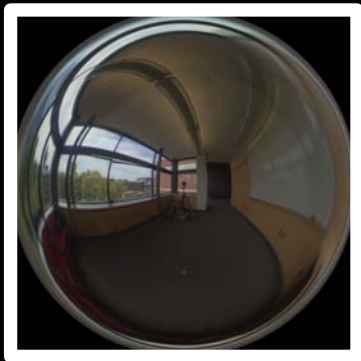


Results: Captured Data

Input Image

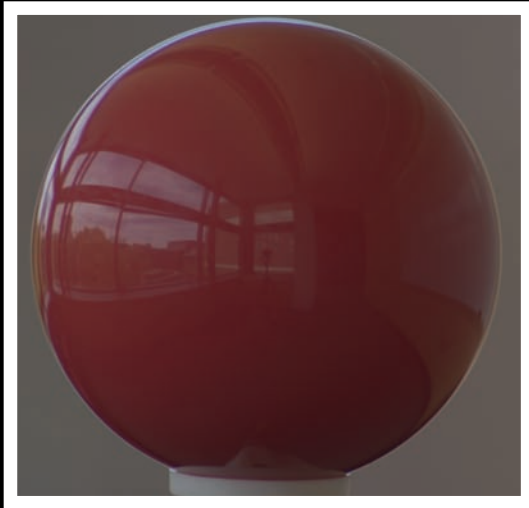


Input Environment

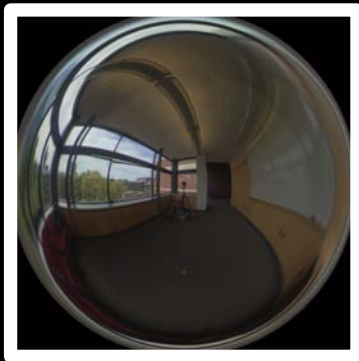


Results: Captured Data

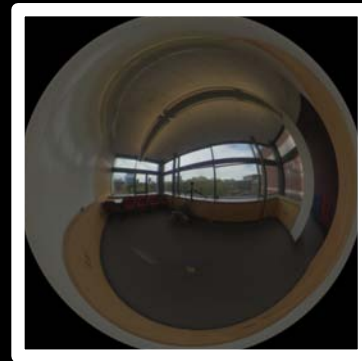
Input Image



Input Environment

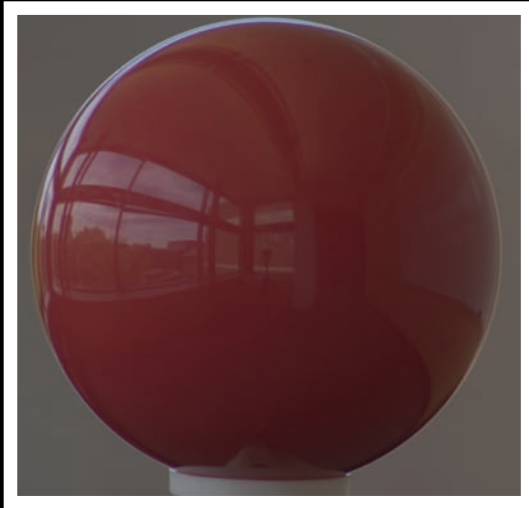


Eval. Environment



Results: Captured Data

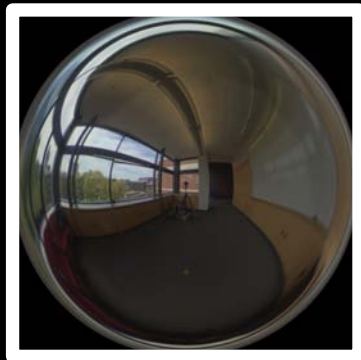
Input Image



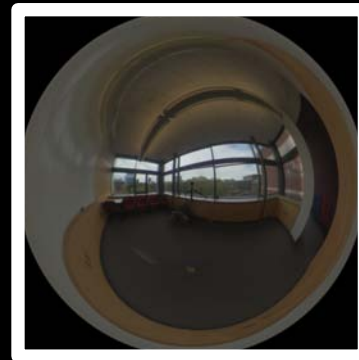
Recovered



Input Environment

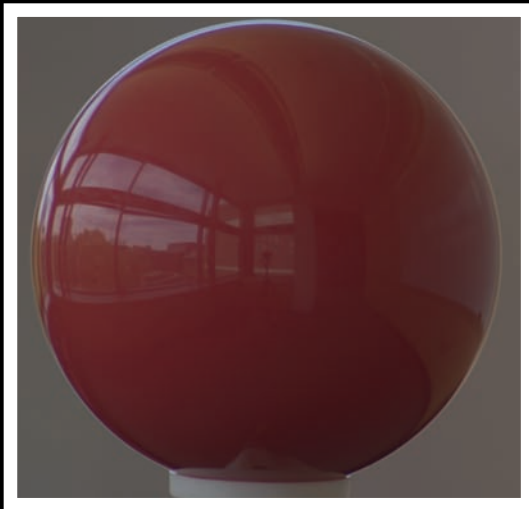


Eval. Environment



Results: Captured Data

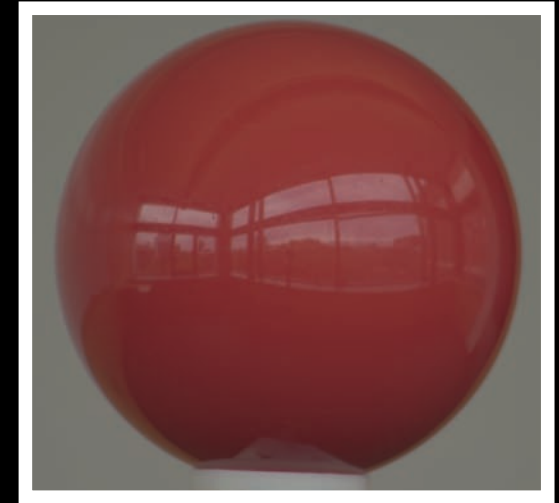
Input Image



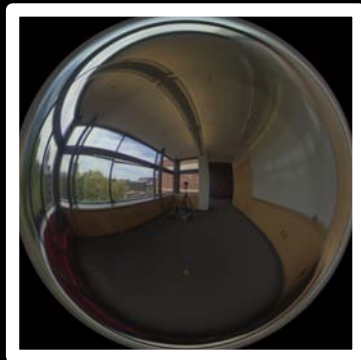
Recovered



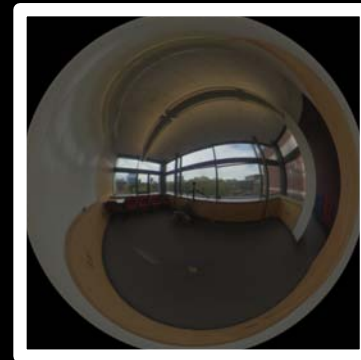
Ground Truth



Input Environment

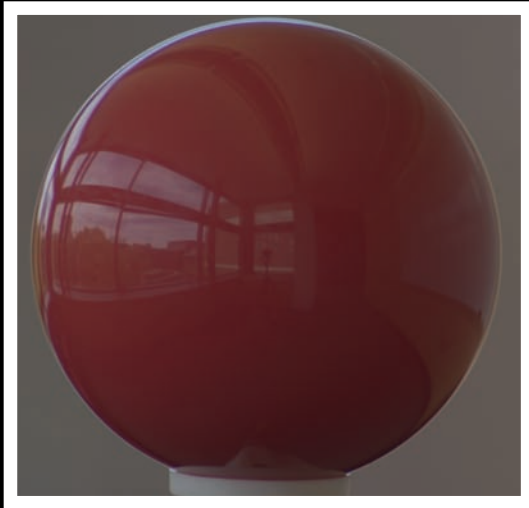


Eval. Environment



Results: Captured Data

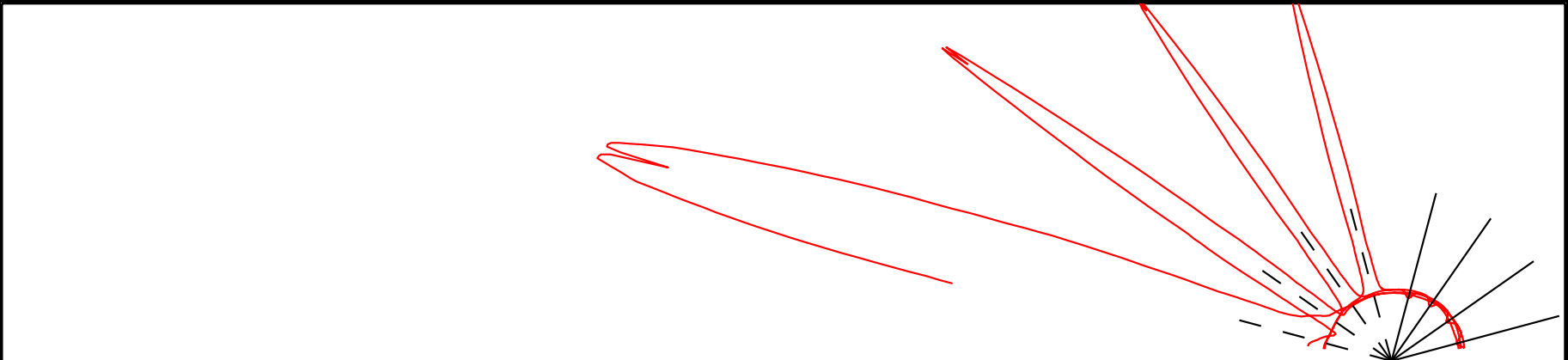
Input Image



Recovered



Ground Truth

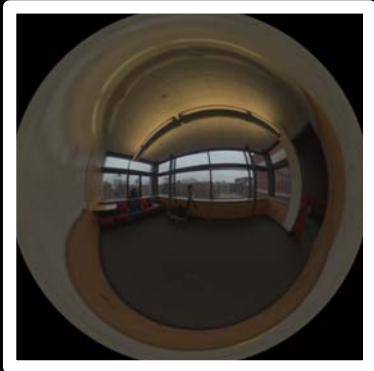


Results: Captured Data



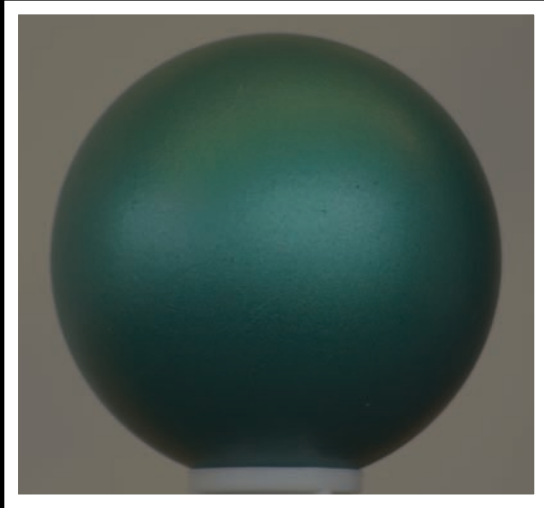
Results: Captured Data

Input Environment

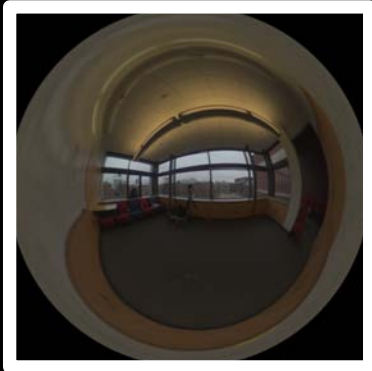


Results: Captured Data

Input Image

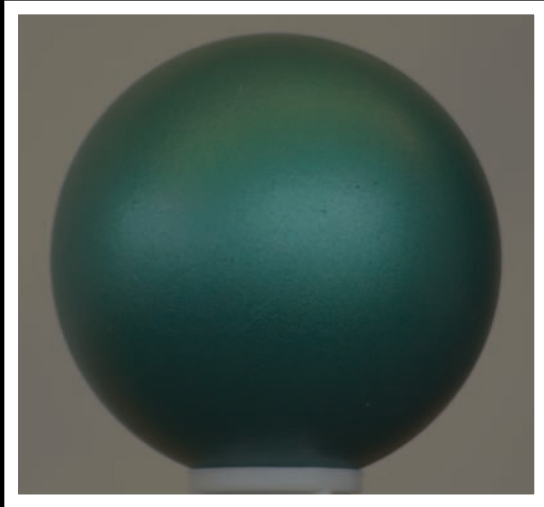


Input Environment

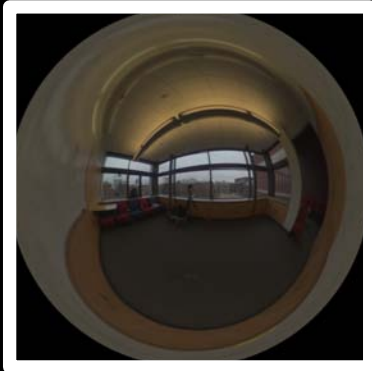


Results: Captured Data

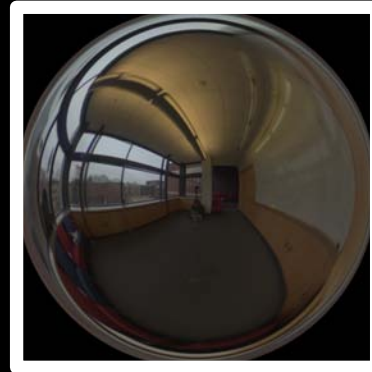
Input Image



Input Environment

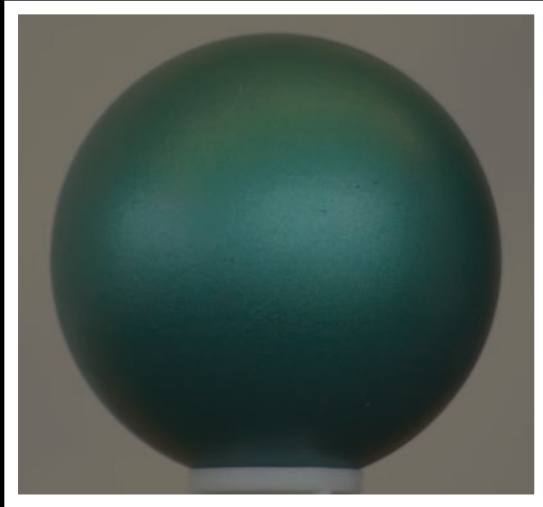


Eval. Environment



Results: Captured Data

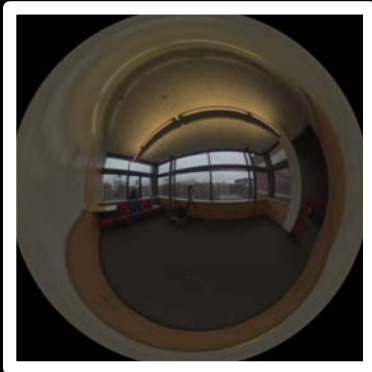
Input Image



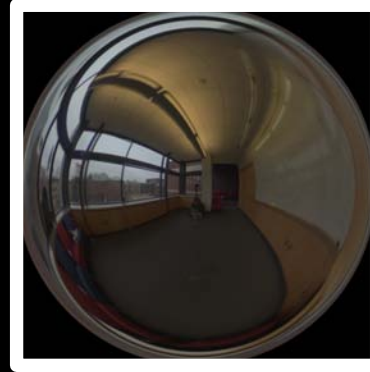
Recovered



Input Environment

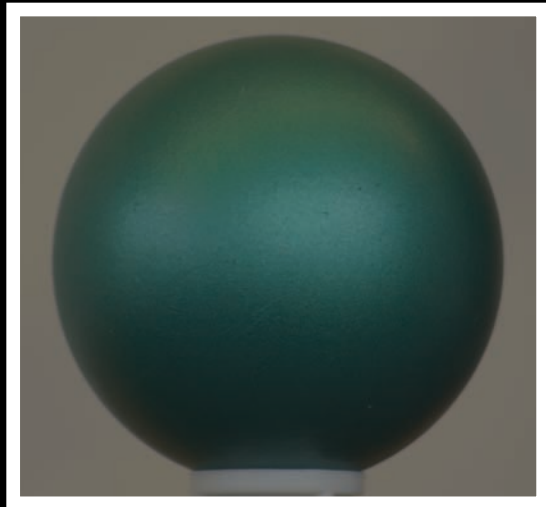


Eval. Environment



Results: Captured Data

Input Image



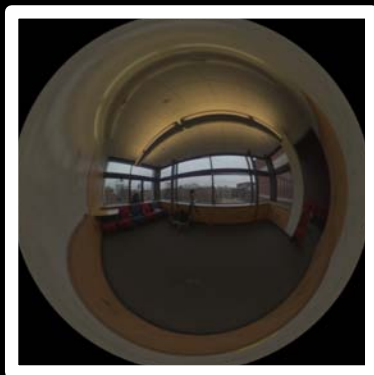
Recovered



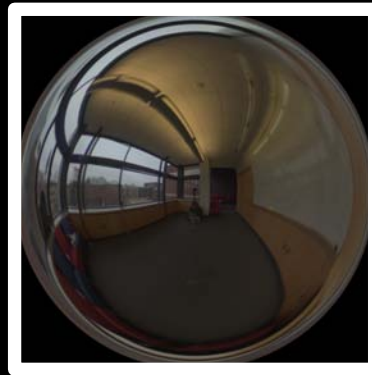
Ground Truth



Input Environment

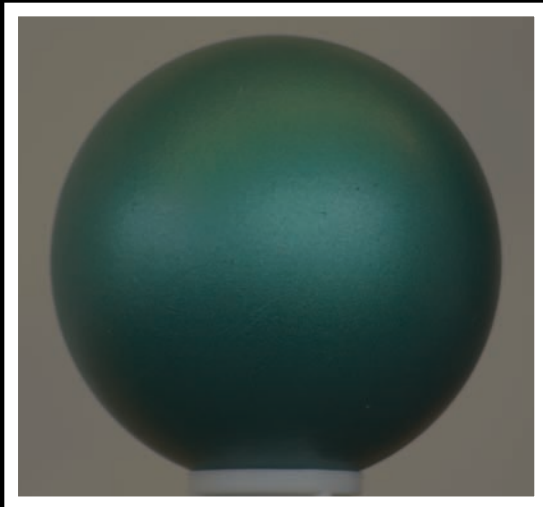


Eval. Environment



Results: Captured Data

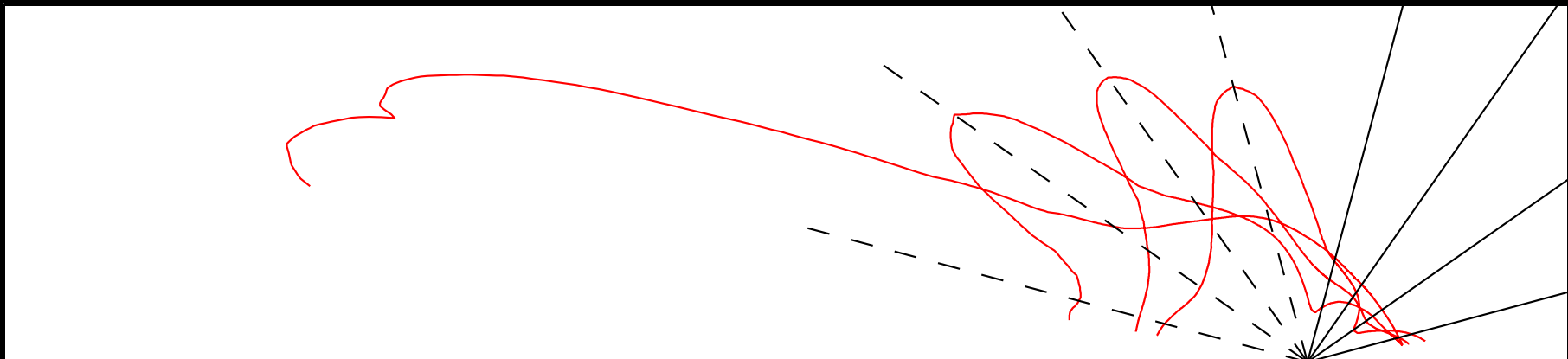
Input Image



Recovered



Ground Truth

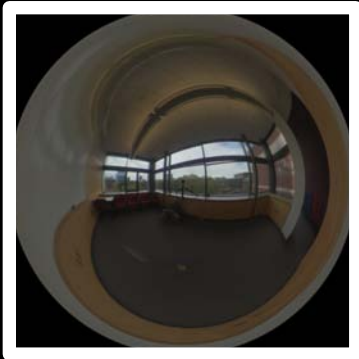


Results: Captured Data



Results: Captured Data

Input Environment

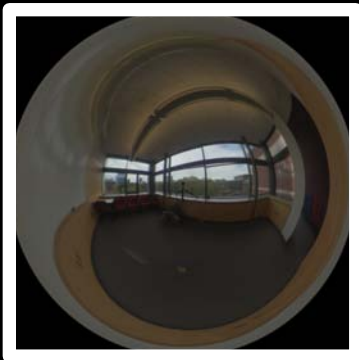


Results: Captured Data

Input Image



Input Environment

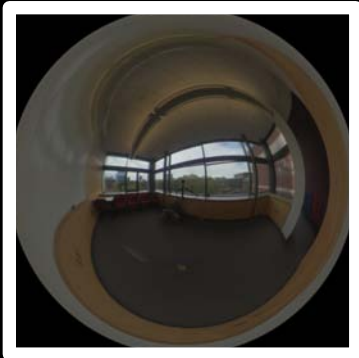


Results: Captured Data

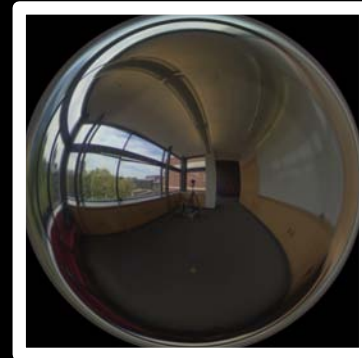
Input Image



Input Environment



Eval. Environment

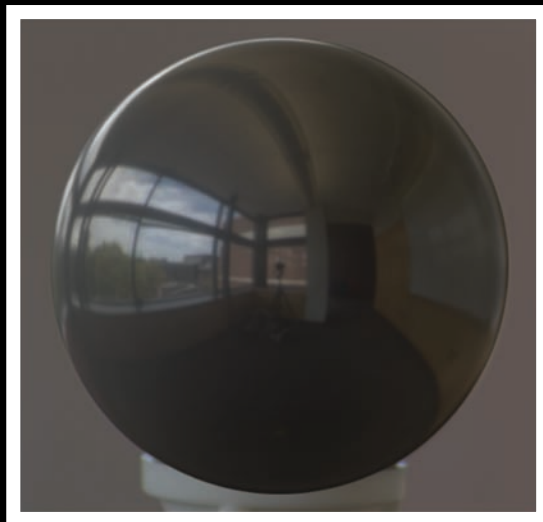


Results: Captured Data

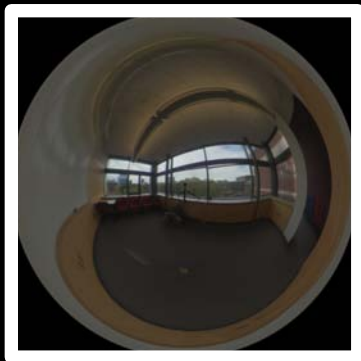
Input Image



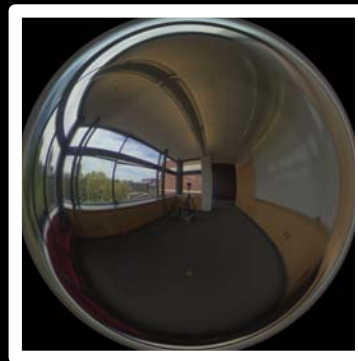
Recovered



Input Environment



Eval. Environment



Results: Captured Data

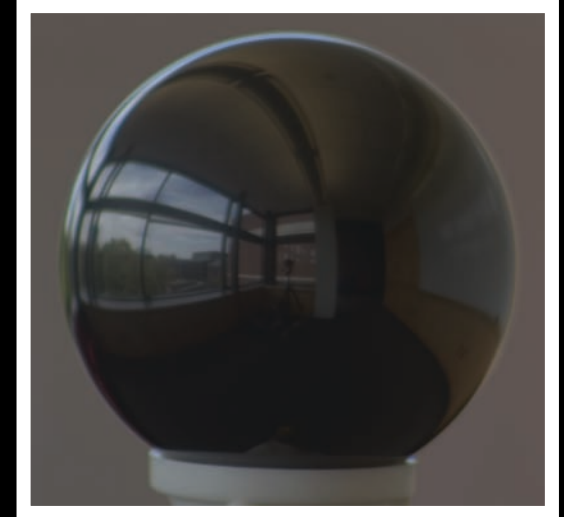
Input Image



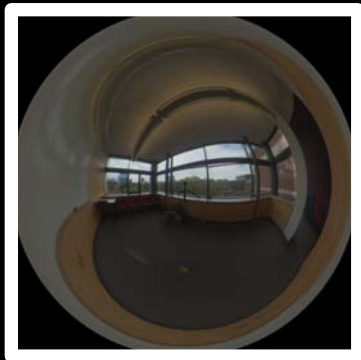
Recovered



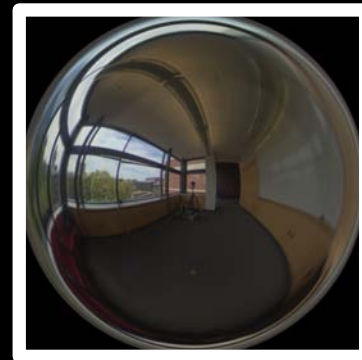
Ground Truth



Input Environment



Eval. Environment



Results: Captured Data

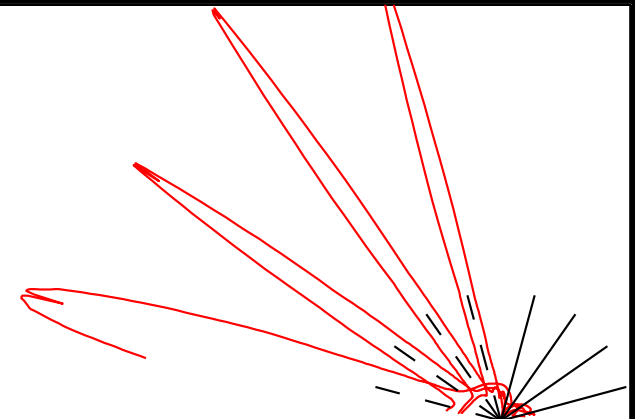
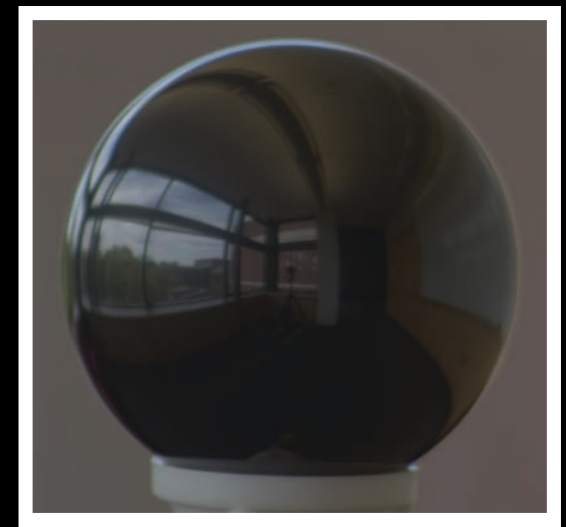
Input Image



Recovered



Ground Truth



Conclusions



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- ◆ Technique for “light-weight” reflectometry



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Conclusions

- ◆ Technique for “light-weight” reflectometry
 - eliminates need for active illumination
 - minimal infrastructure required
 - handles general isotropic reflectance
- ◆ Enabled by reduction of isotropic BRDF domain (from 3D to 2D)
 - “bivariate” BRDF



Discussion



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$$I = Lf$$



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- ◆ When does an environment provide “adequate illumination”?



Discussion

$$I = Lf$$

- ◆ When does an environment provide “adequate illumination”?
- ◆ Can we estimate a bivariate BRDF when the environment (L) is unknown?

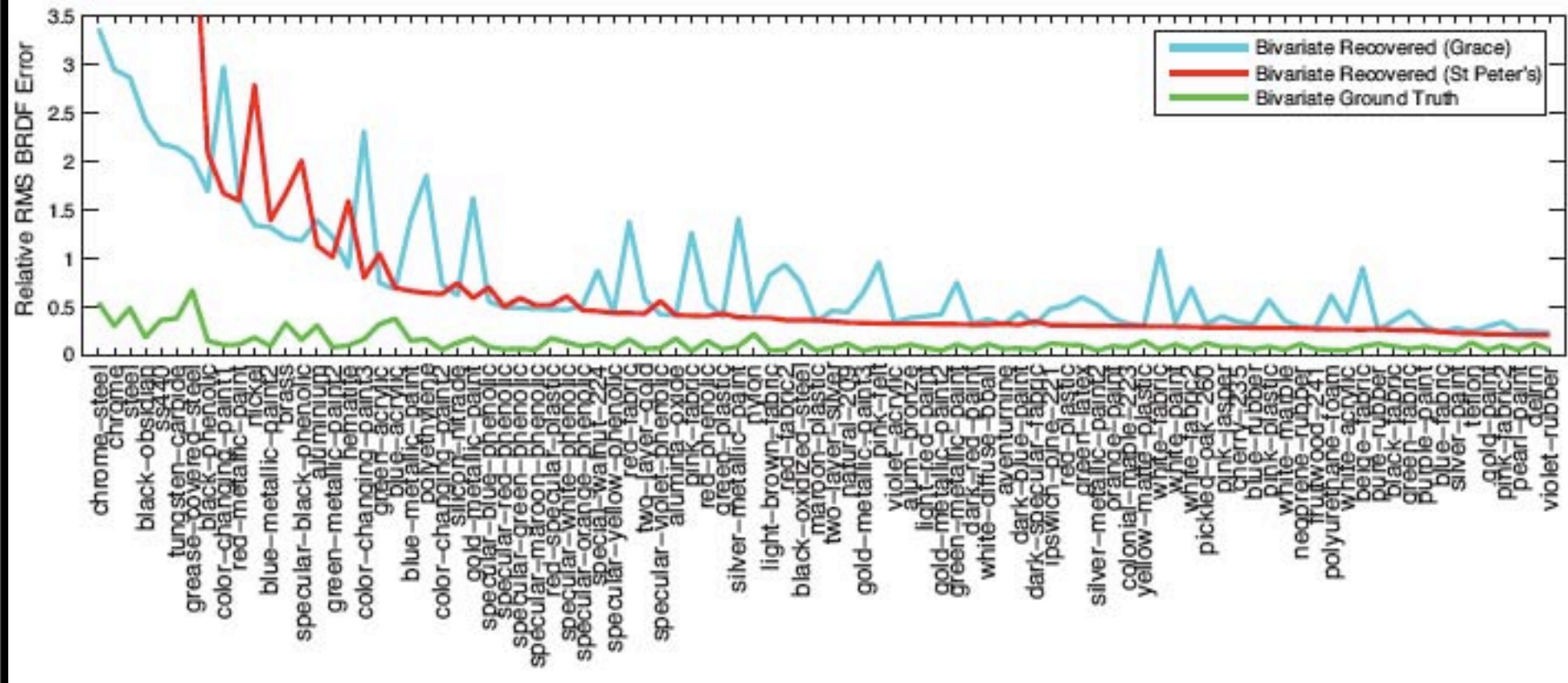




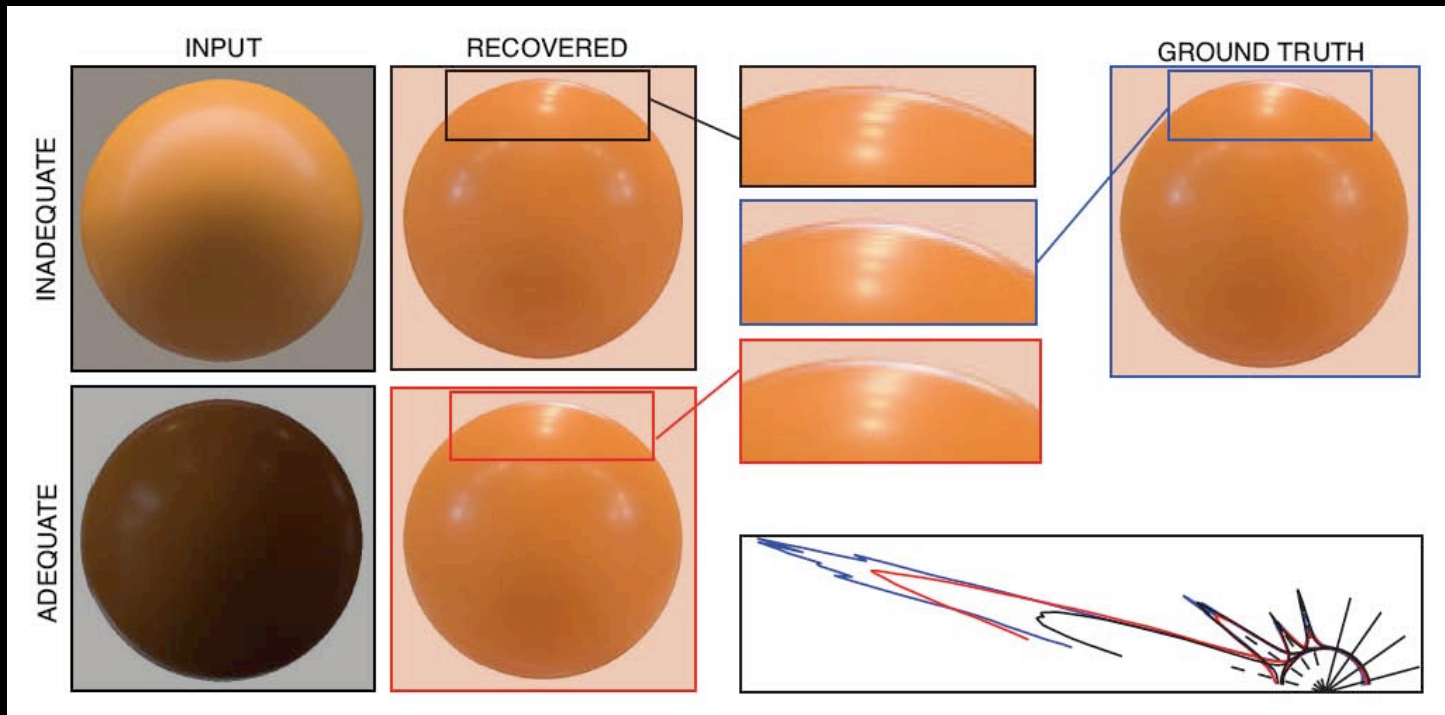
gvi.seas.harvard.edu



Results: Synthetic

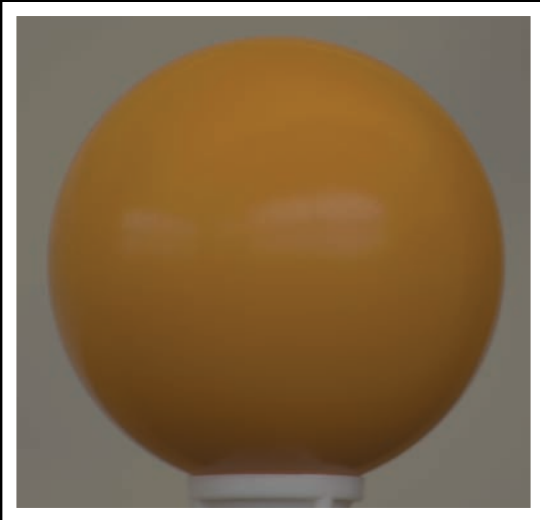


Results: Importance of L



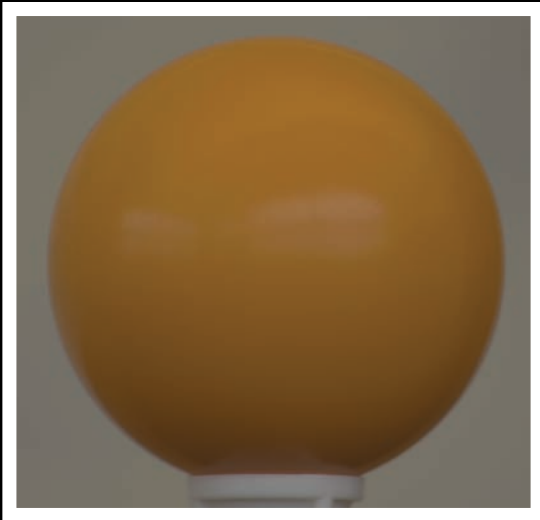
Results: Captured Data

Input Image

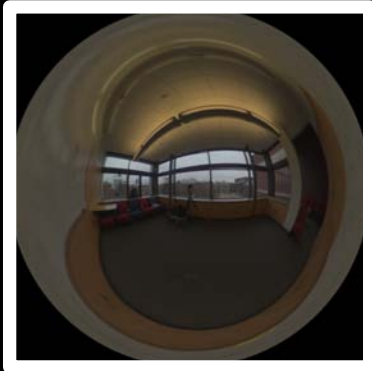


Results: Captured Data

Input Image

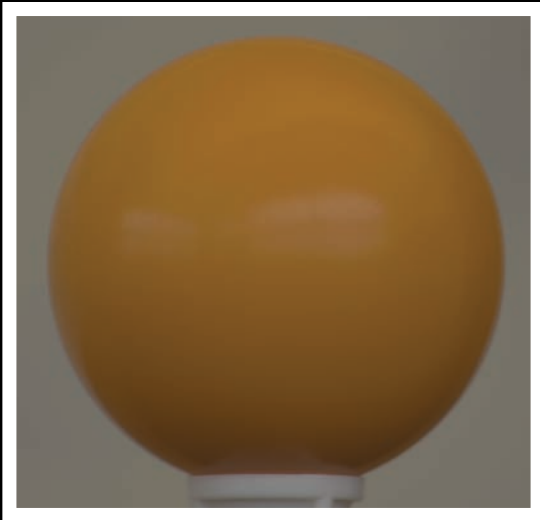


Input Environment

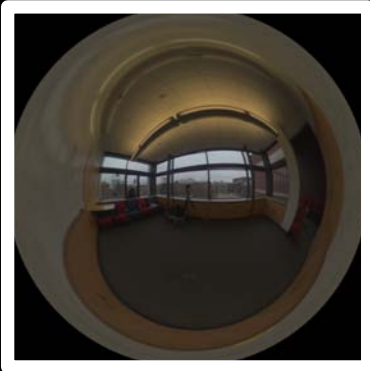


Results: Captured Data

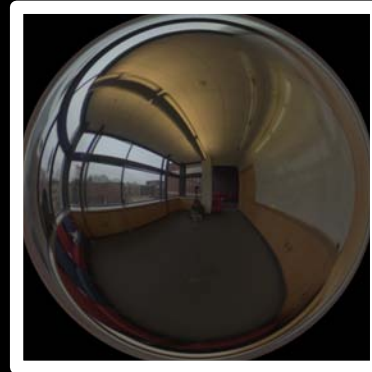
Input Image



Input Environment

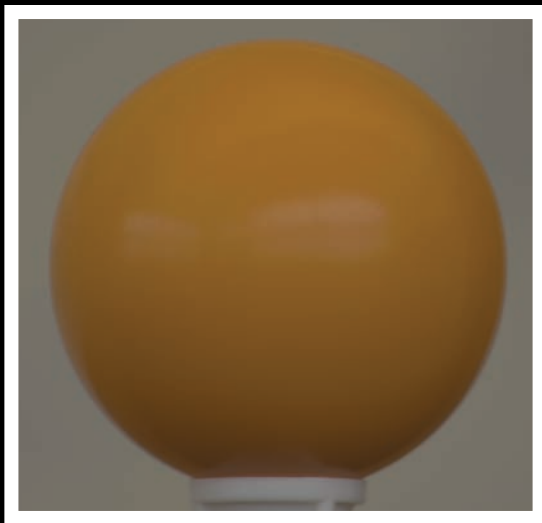


Eval. Environment

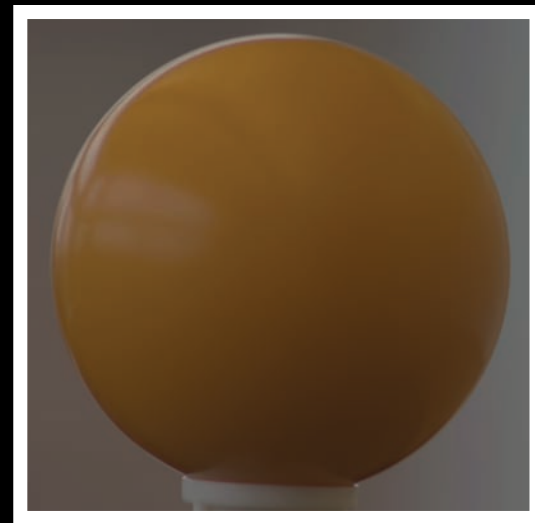


Results: Captured Data

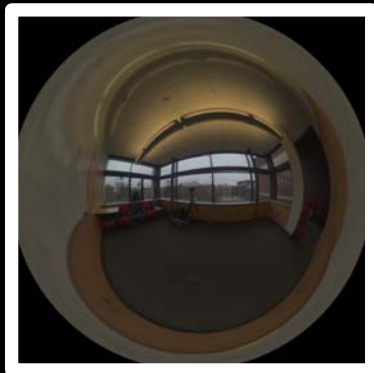
Input Image



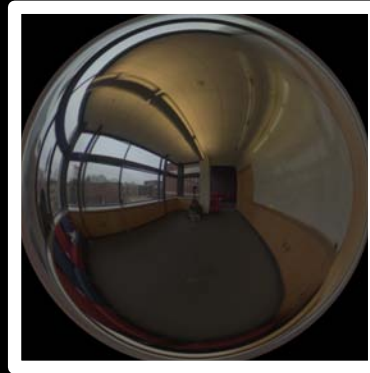
Ground Truth



Input Environment

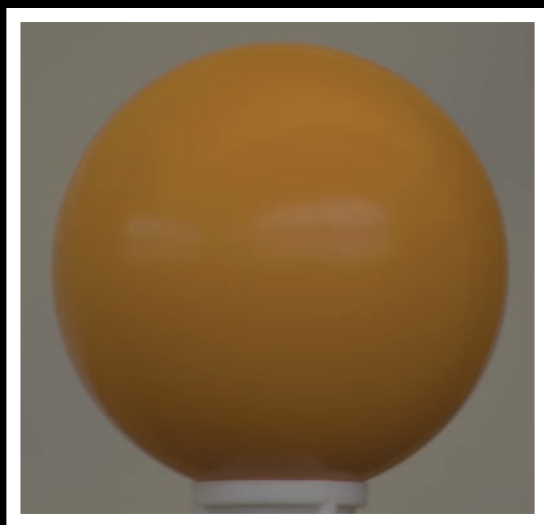


Eval. Environment

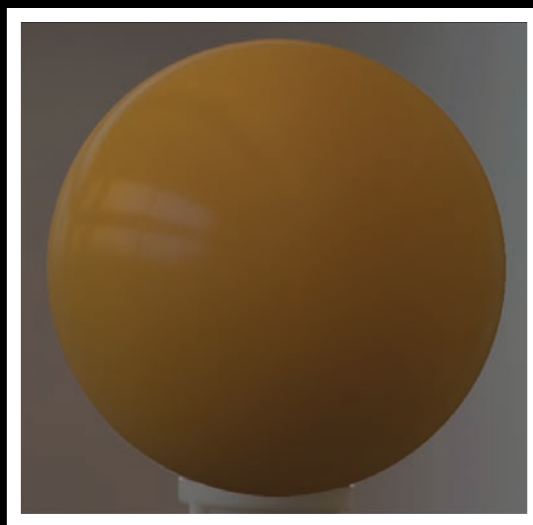


Results: Captured Data

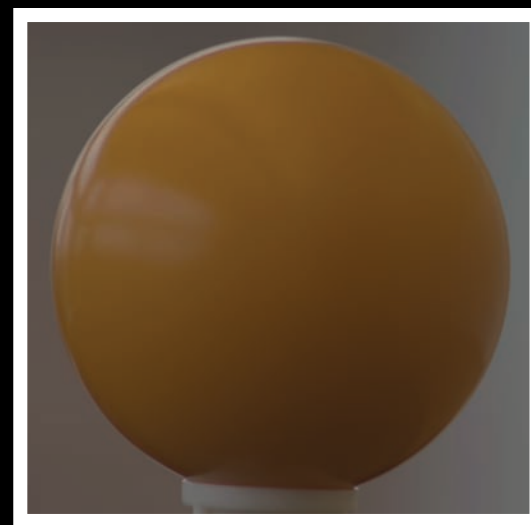
Input Image



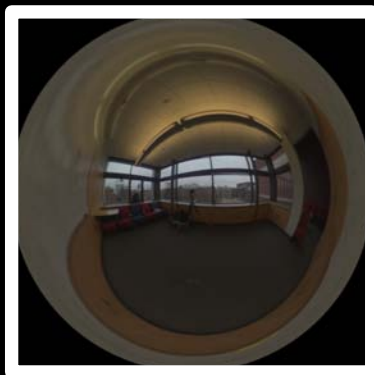
Recovered



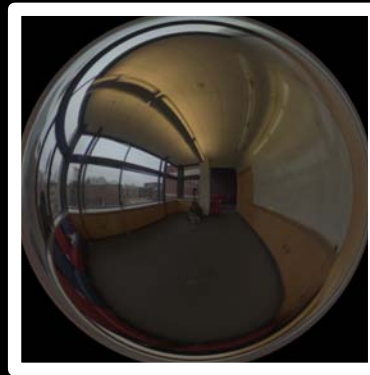
Ground Truth



Input Environment

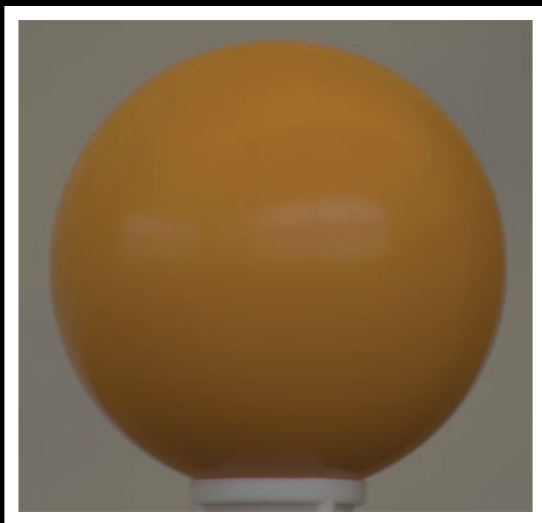


Eval. Environment

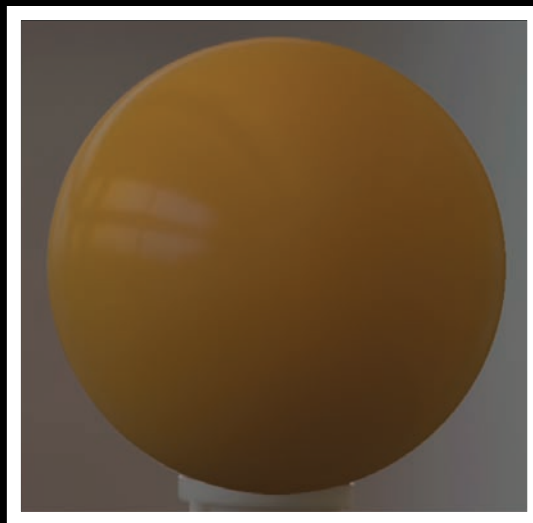


Results: Captured Data

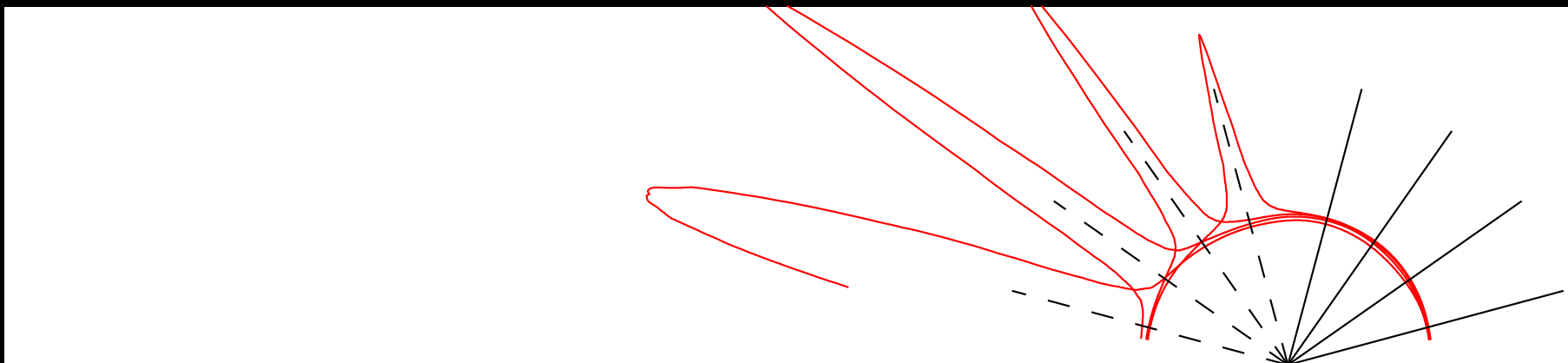
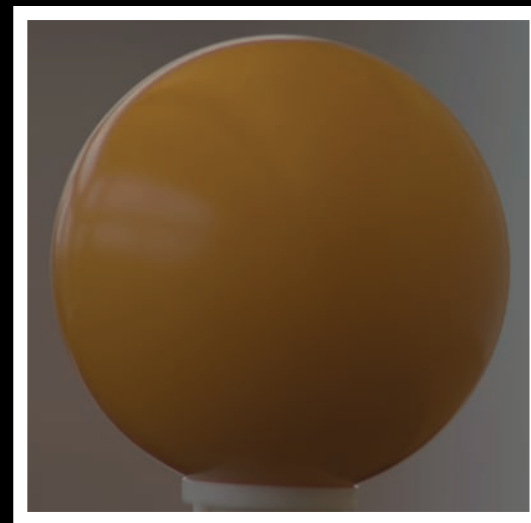
Input Image



Recovered



Ground Truth



Results: Synthetic Data

Input Image



Recovered



Ground Truth



100x Difference



Input Environment



Eval. Environment



Results: Synthetic Data

Input Image



Recovered



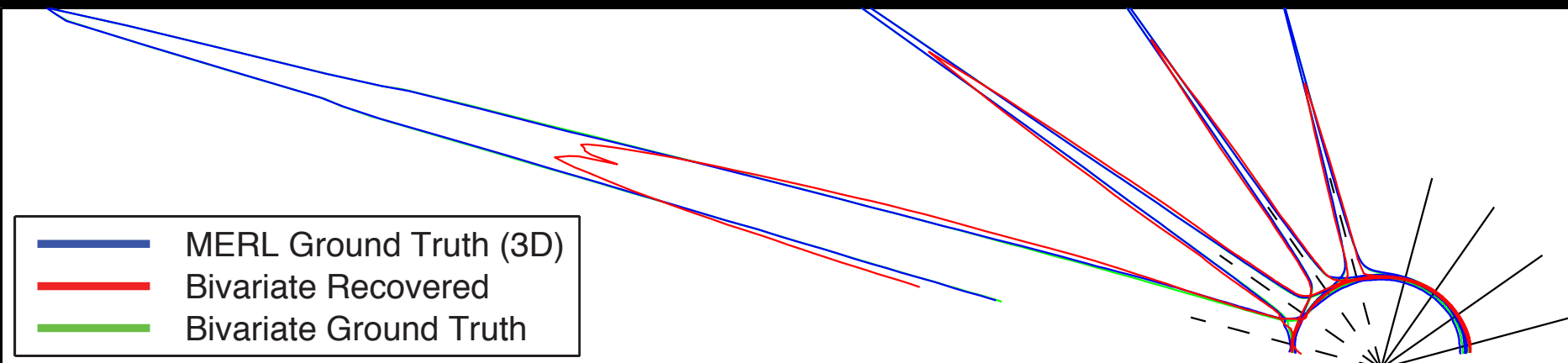
Ground Truth



100x Difference



Polar Plot

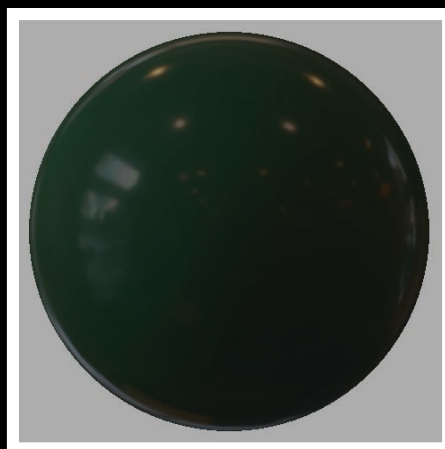


Results: Synthetic Data

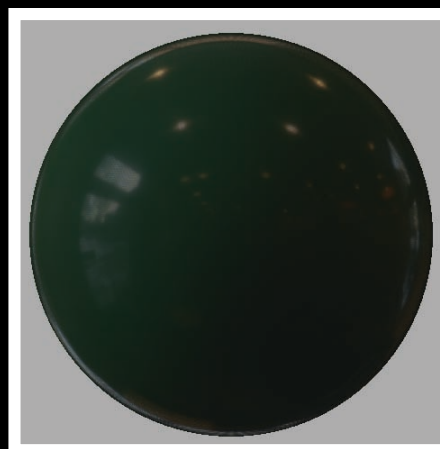
Input Image



Recovered



Ground Truth



100x Difference



Input Environment



Eval. Environment

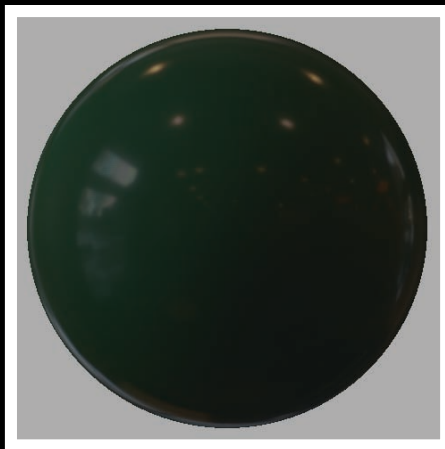


Results: Synthetic Data

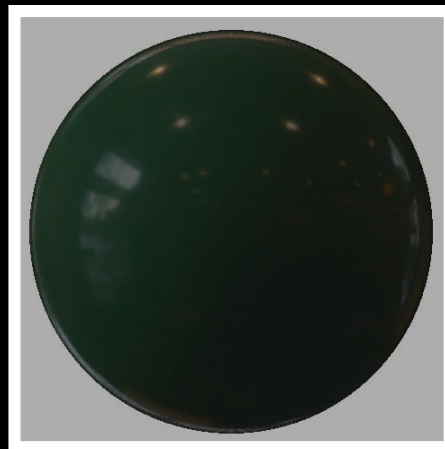
Input Image



Recovered



Ground Truth



100x Difference



Polar Plot

