Simultaneous Acquisition of Polarimetric SVBRDF and Normals

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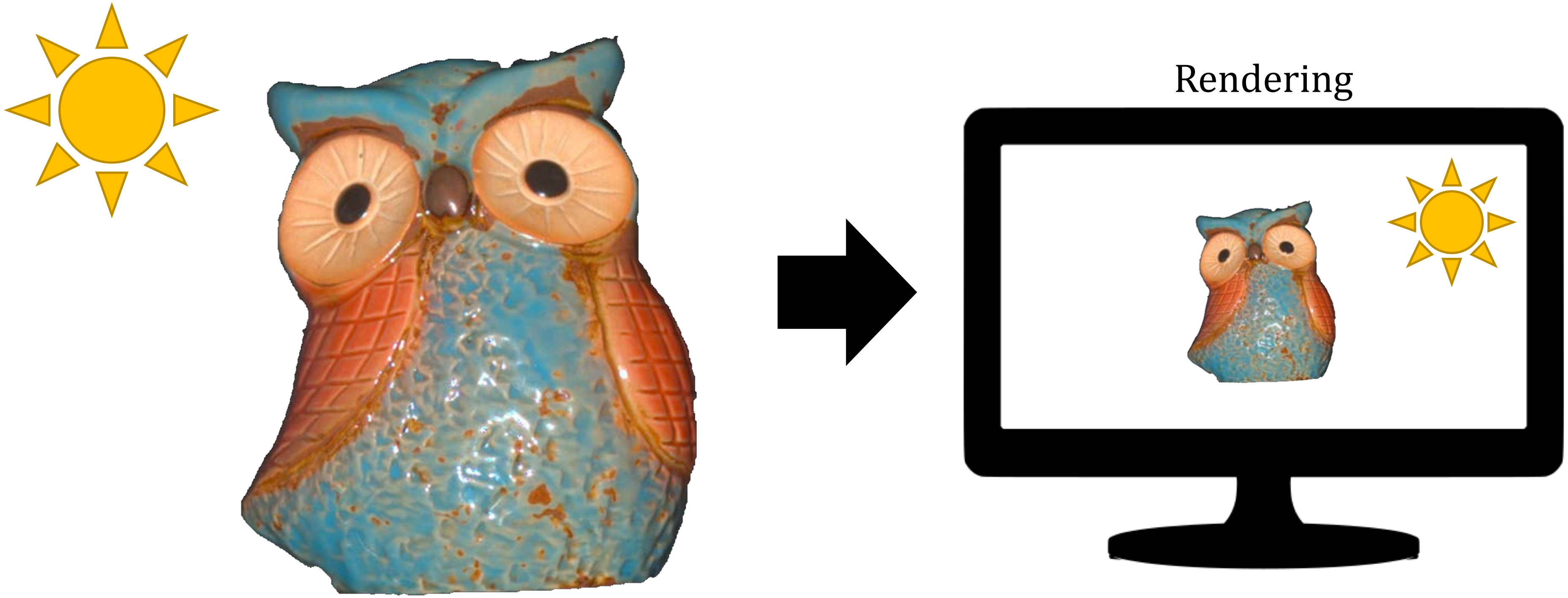
KAIST[†] Microsoft Research Asia[*]

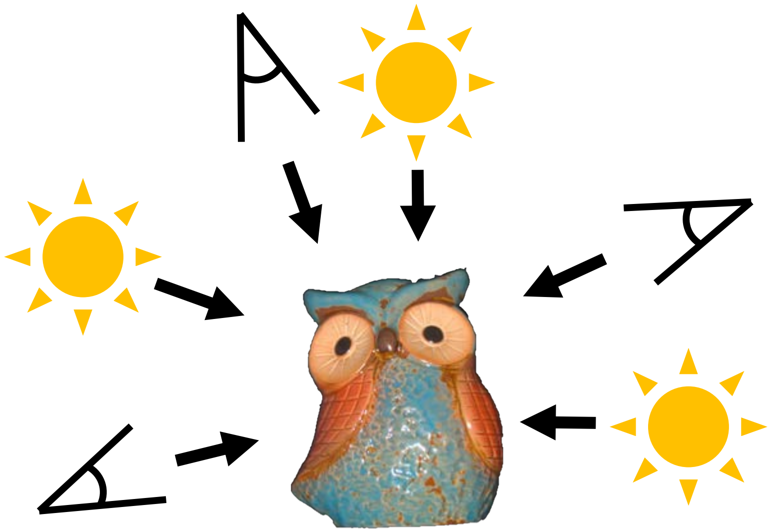
Surface Appearance

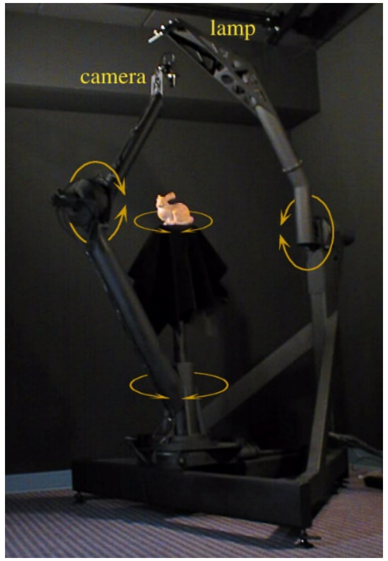


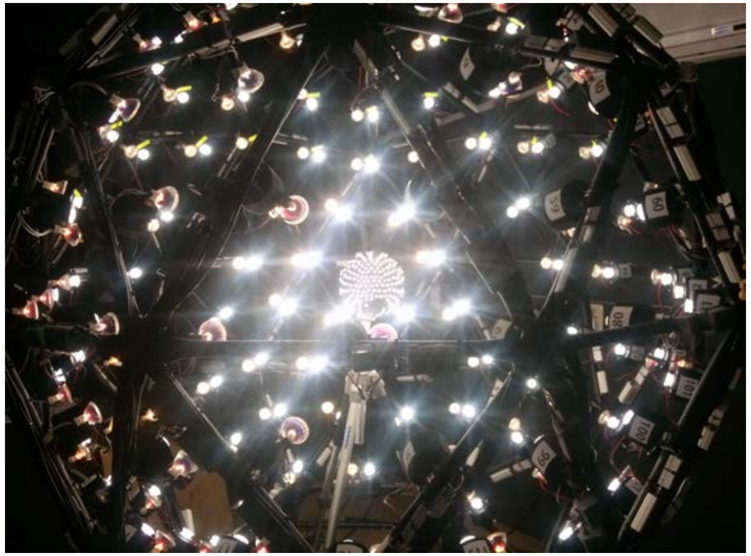
How the surface reflects light

- Surface normals
- Bidirectional reflectance distribution function (BRDF)

Surface Appearance from Intensity

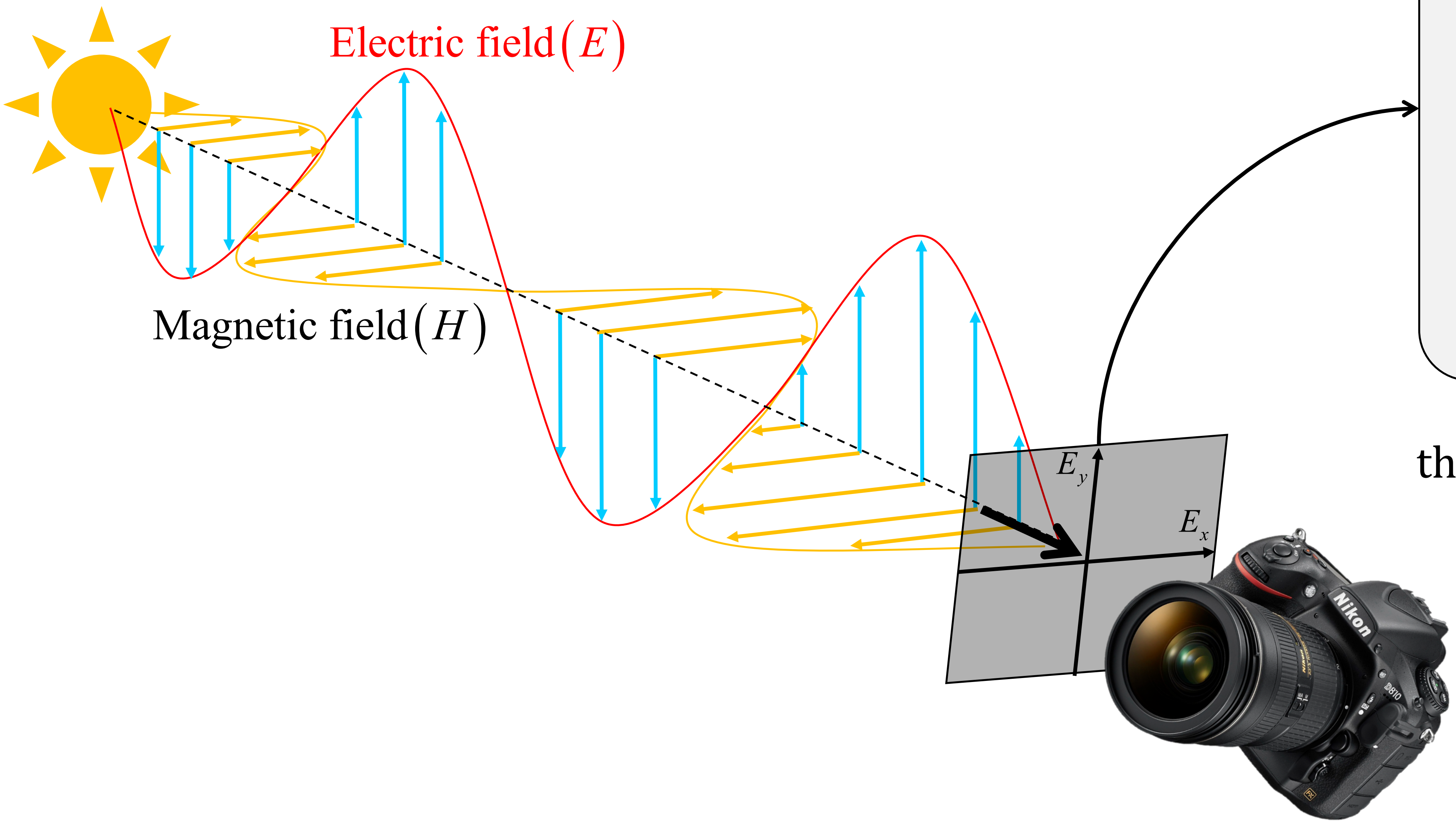


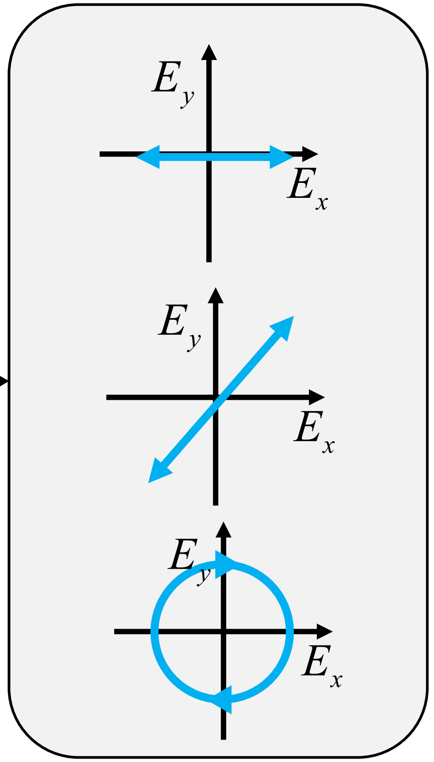




- Dense sampling of the light vector $\mathbf{i}$ and the view vector $\mathbf{o}$: $(\mathbf{i}, \mathbf{o})$
- Analyze the captured image intensity

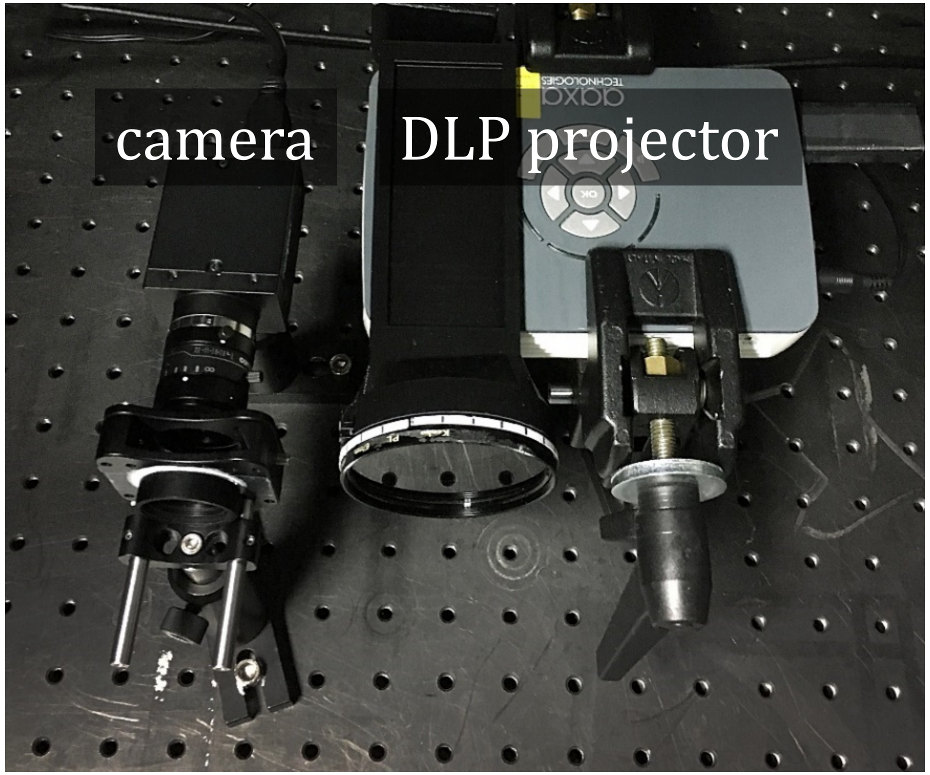
Wave Property: Polarization





Direction of the electric field

Motivation



Input

polarimetric images from single illumination and view vector $(\mathbf{i}, \mathbf{o})$

Output

surface normals and BRDF parameters

Contributions

- In addition to the intensity, analyze the **polarization** state of light

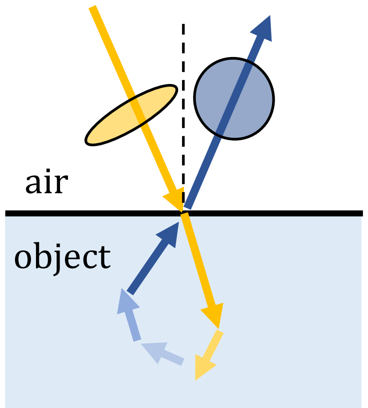
Polarimetric
Reflectance Model

Polarimetric
Imaging System

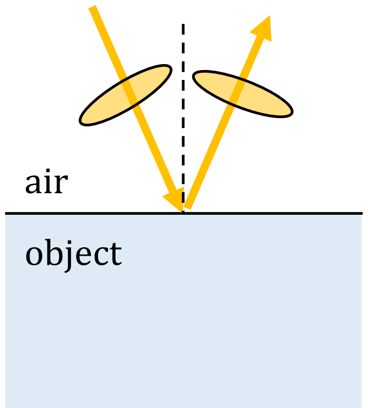
Polarimetric
Inverse-rendering Method

Previous Work

Polarimetric BRDF
[Hyde IV 2009, Priest and Gerner 2000]



Diffuse reflection



Specular reflection

Specular polarization ○
Diffuse polarization ✕

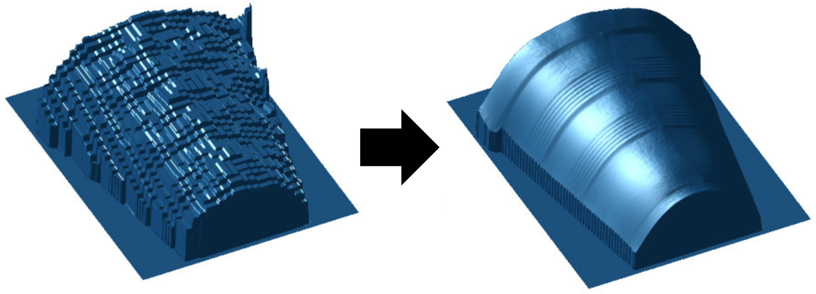
Appearance from Polarization
[Ma 2007, Ghosh 2010, Riviere 2017]

Photograph   Diffuse   Specular

Specular polarization ○
Diffuse polarization ✕

Diffuse polarization is weaker than specular polarization

Shape from Polarization
[Kadambi 2015, Cui 2017]

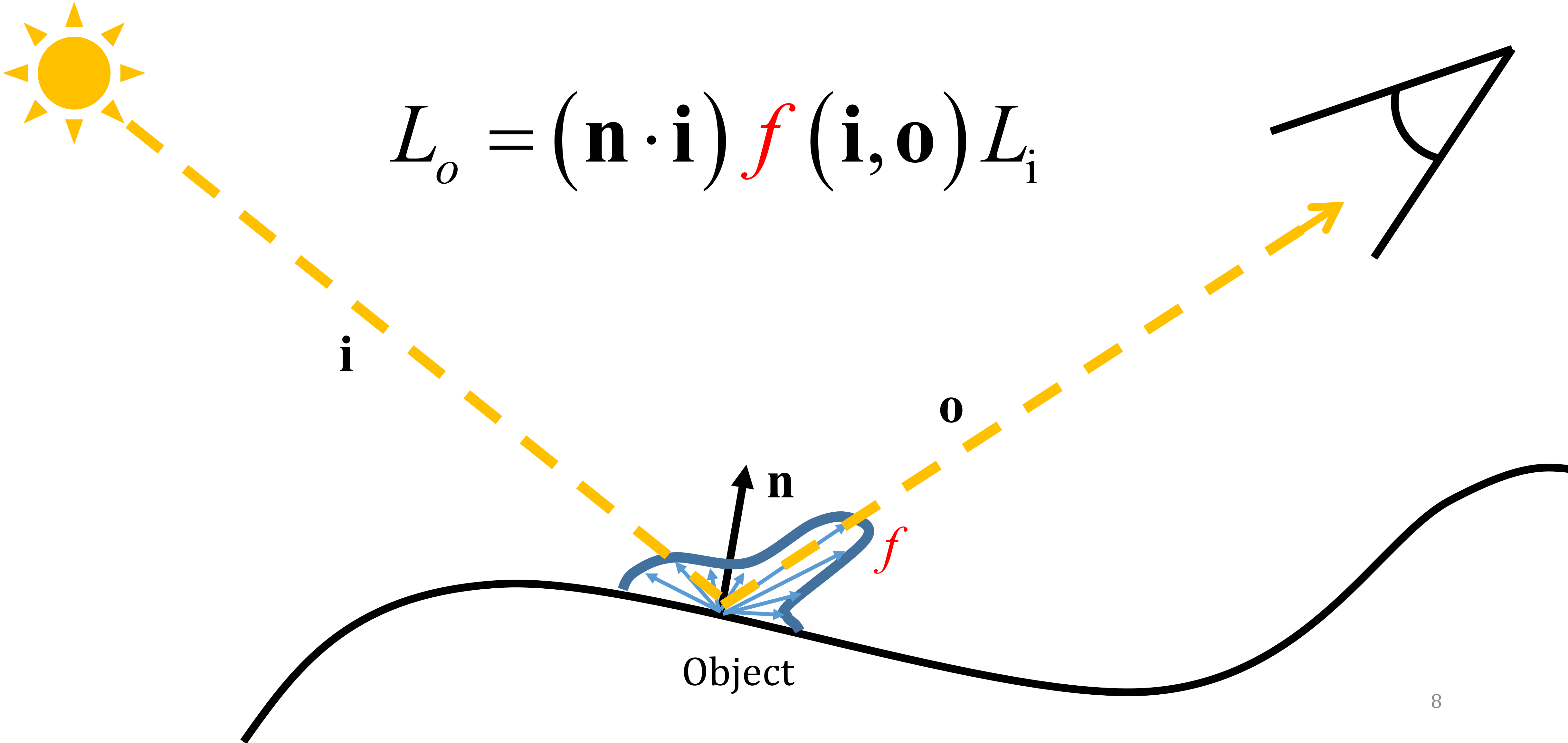


Specular polarization ✕ or ○
Diffuse polarization ○ or ✕

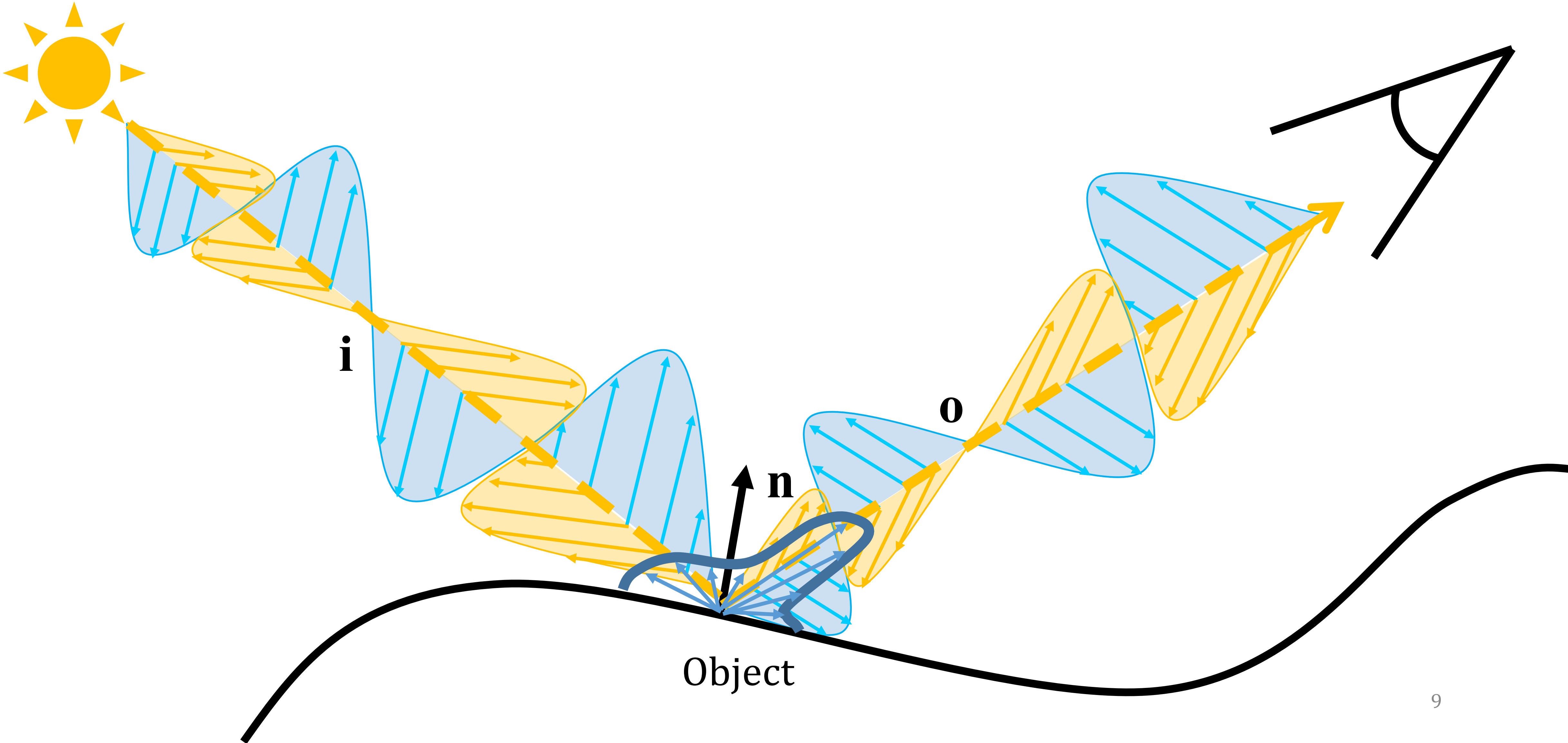
Modality problem:
Either one of them is allowed

BRDF

$$L_o = (\mathbf{n} \cdot \mathbf{i})\, f(\mathbf{i}, \mathbf{o})\, L_\mathrm{i}$$

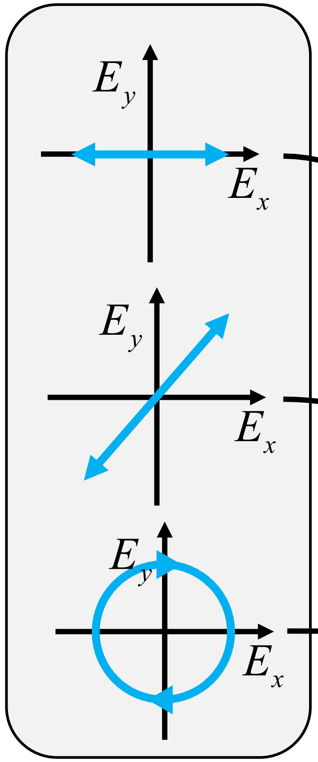


Polarimetric BRDF (pBRDF)



Backgrounds

Stokes vector

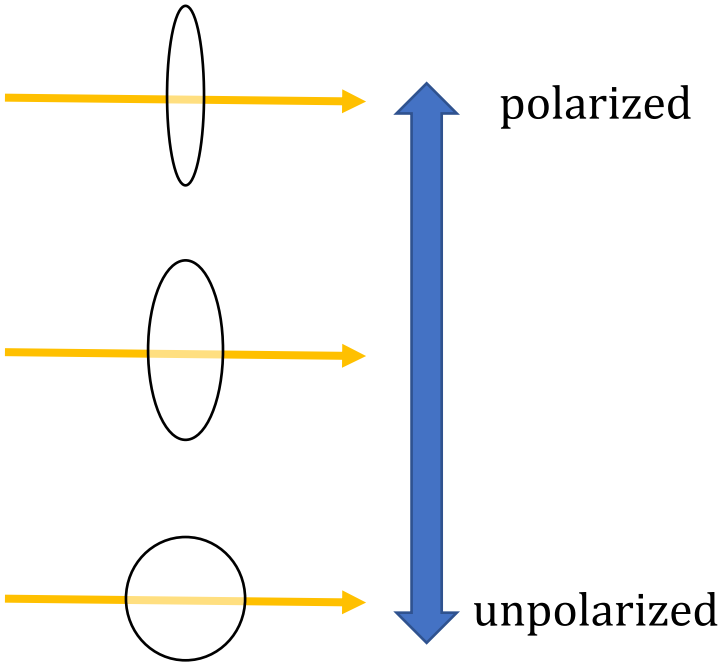


Direction of the electric field

$$\mathbf{s} = \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix}$$

- s_0: Overall Intensity
- s_1: Linear 0 deg.
- s_2: Linear 45 deg.
- s_3: Circular

Degree of polarization (DOP)



$$\mathrm{DOP}(\mathbf{s}) = \frac{\sqrt{s_1^2 + s_2^2 + s_3^2}}{s_0}$$

Mueller matrix

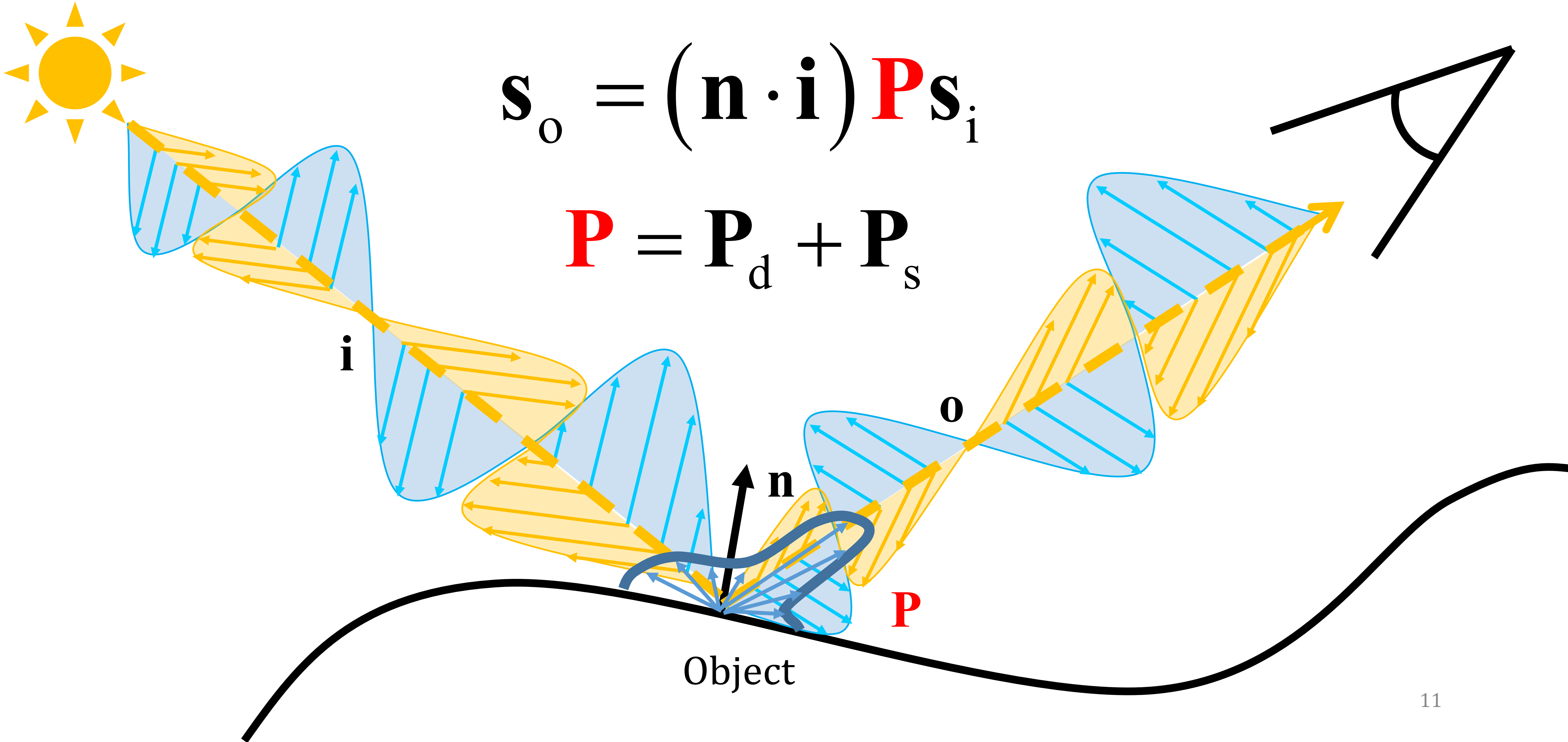
$$\mathbf{s}_{\text{after}} = \mathbf{M}\mathbf{s}_{\text{before}}$$

$$\mathbf{M} = \begin{bmatrix} M_{00} & M_{01} & M_{02} & M_{03} \\ M_{10} & M_{11} & M_{12} & M_{13} \\ M_{20} & M_{21} & M_{22} & M_{23} \\ M_{30} & M_{31} & M_{32} & M_{33} \end{bmatrix}$$

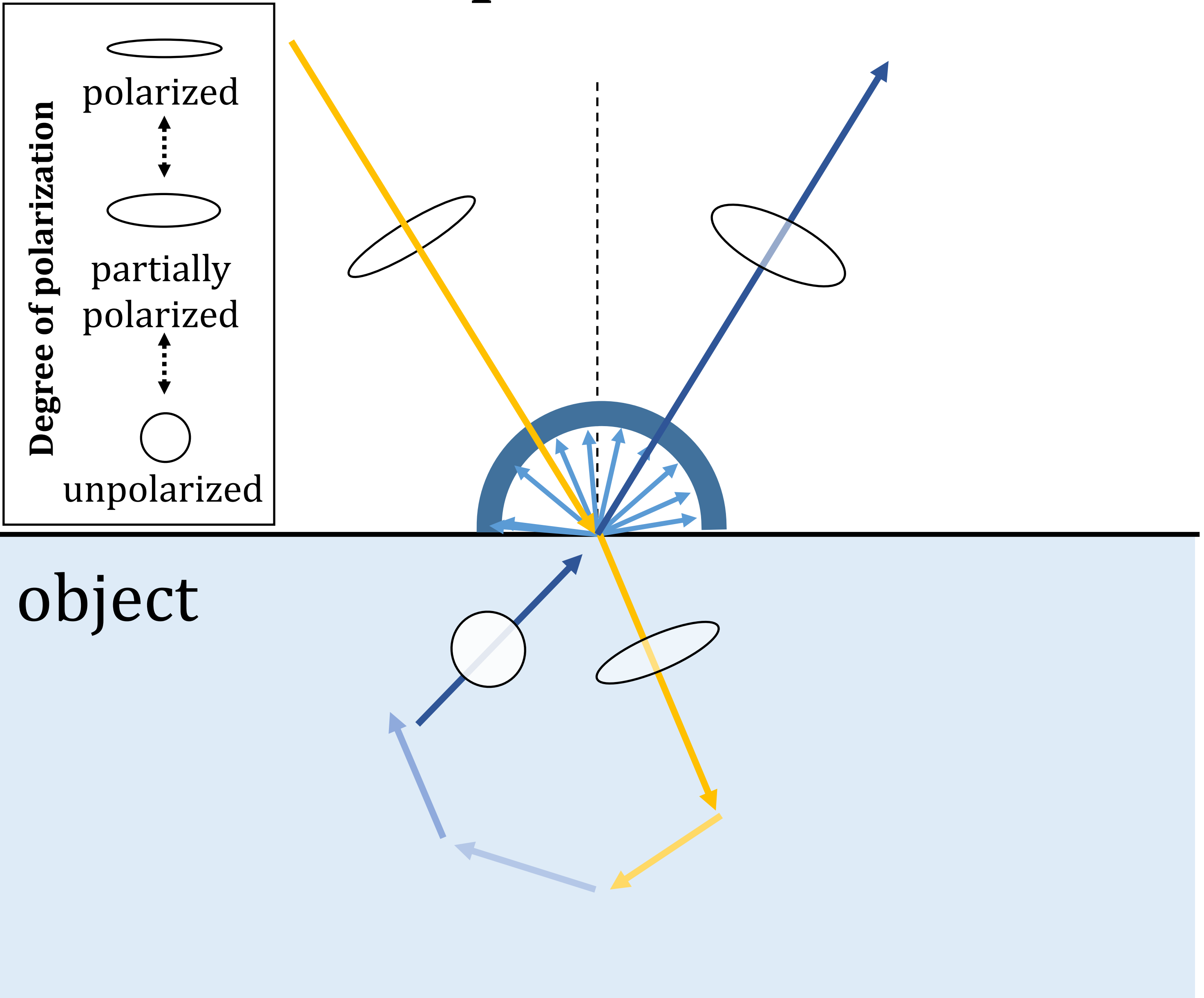
Polarimetric BRDF (pBRDF)

$$\mathbf{s}_o = (\mathbf{n} \cdot \mathbf{i})\,\mathbf{P}\,\mathbf{s}_i$$

$$\mathbf{P} = \mathbf{P}_d + \mathbf{P}_s$$



Diffuse pBRDF

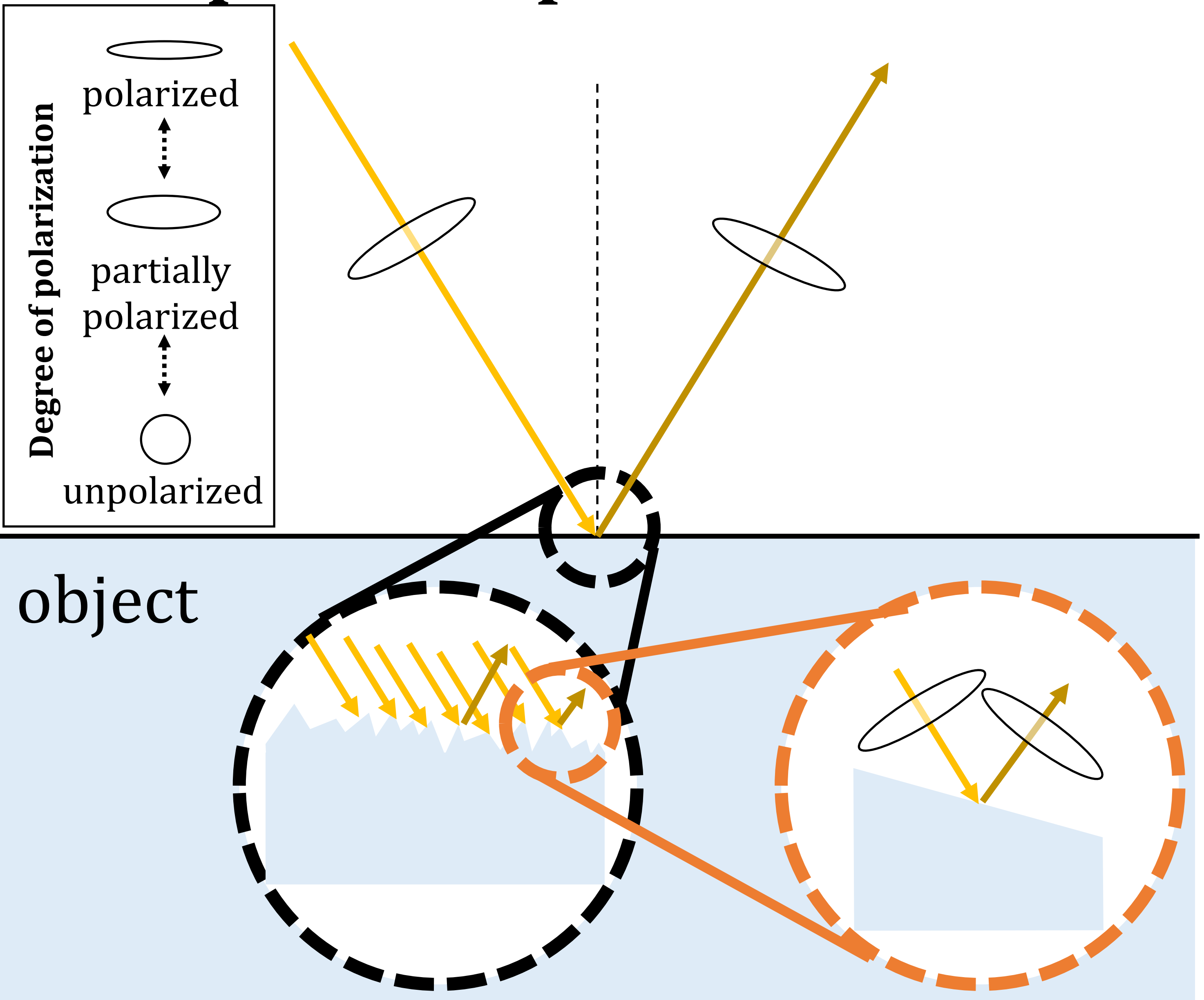


Depolarization

$\mathbf{P}^{d} =$

polarization polarization

Specular pBRDF



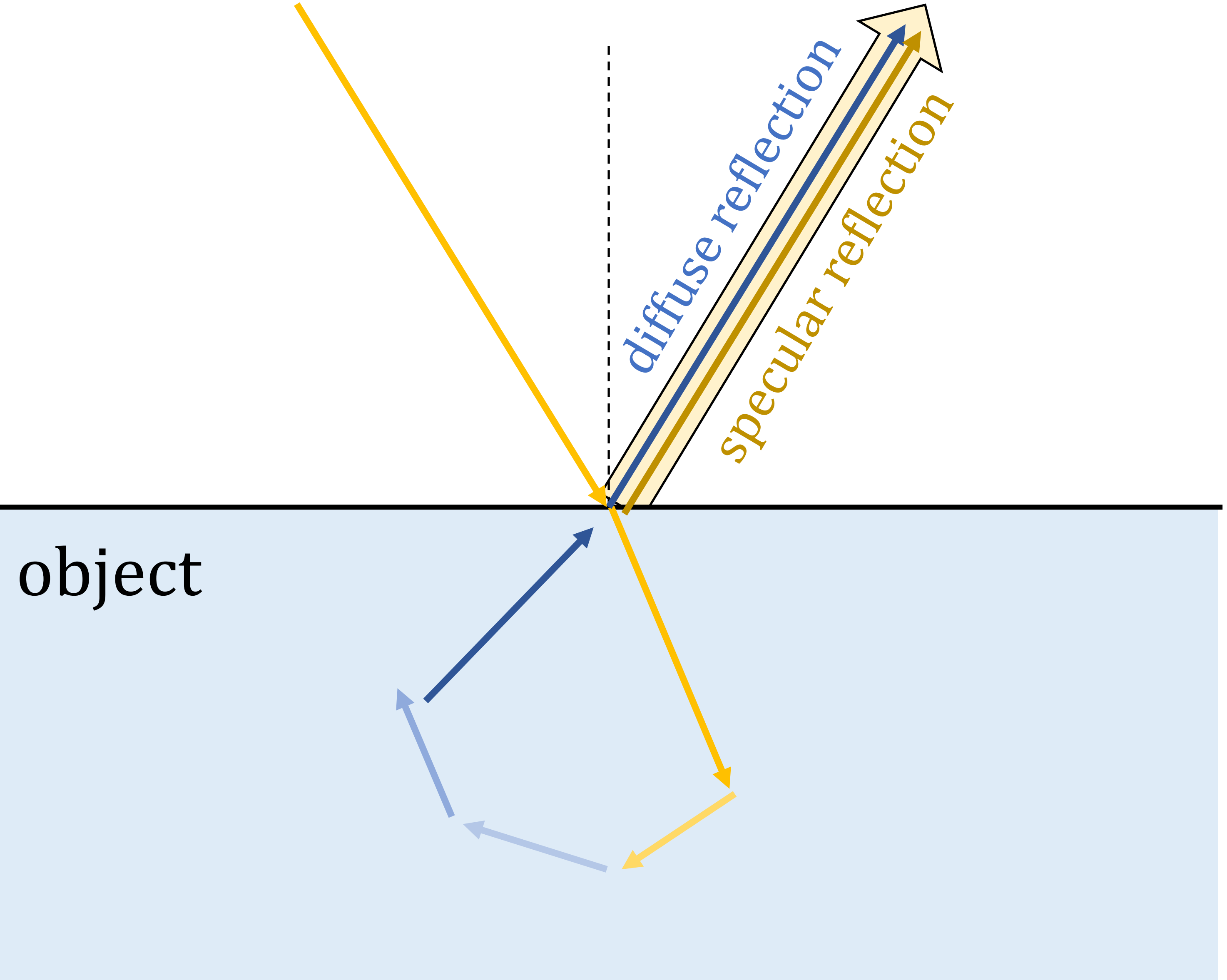
Coordinate conversion | Fresnel reflection | Coordinate conversion

$$\mathbf{P}^{s} = \mathcal{K}\,\mathbf{C}_{h\to o}\,\mathbf{F}^{R}\,\mathbf{C}_{i\to h}$$

Normal distribution function | Geometric shading

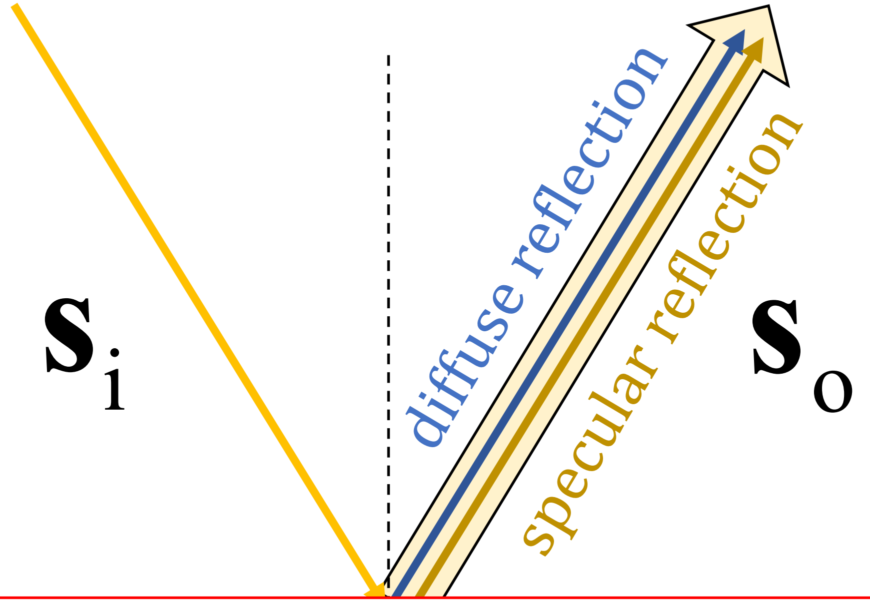
$$\mathcal{K} = k_s \frac{DG}{4(\mathbf{n}\cdot\mathbf{i})(\mathbf{n}\cdot\mathbf{o})}$$

Full pBRDF



$$\mathbf{P} =$$

Polarimetric Light Transport

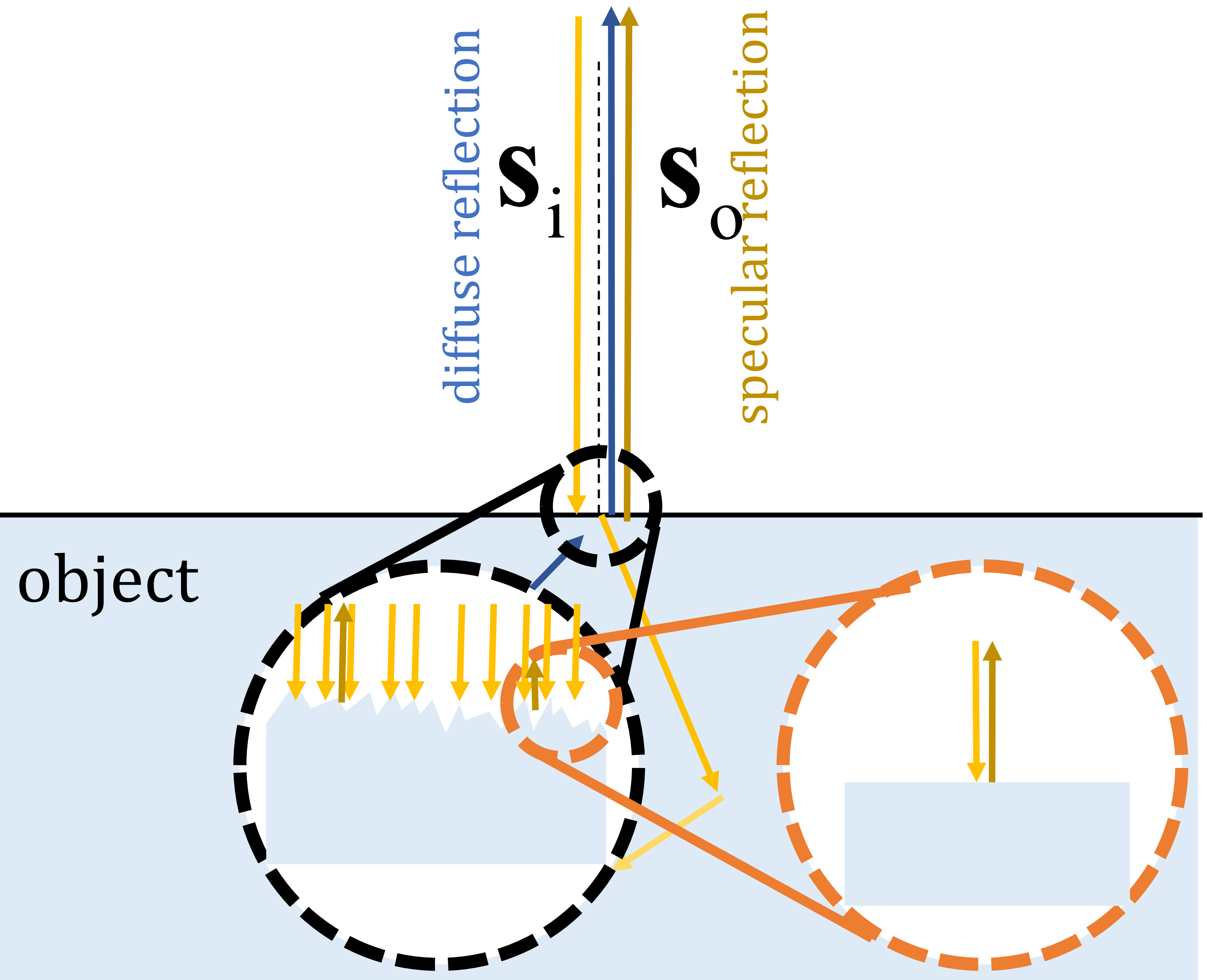


$$\mathbf{s}_{\mathrm{o}} = (\mathbf{n}\cdot\mathbf{i})\mathbf{P}\mathbf{s}_{\mathrm{i}}$$

$$\mathbf{H} = (\mathbf{n}\cdot\mathbf{i})\begin{bmatrix} \rho T_o^+ T_i^+ + \mathcal{K}R^+ & \rho T_o^+ T_i^- \beta_i + \mathcal{K}R^- \gamma_i & -\rho T_o^+ T_i^- \alpha_i - \mathcal{K}R^- \chi_i & 0 \\ \rho T_o^- T_i^+ \beta_o + \mathcal{K}R^- \gamma_o & \rho T_o^- T_i^- \beta_i \beta_o + \mathcal{K}R^+ \gamma_i \gamma_o + \mathcal{K}R^\times \chi_i \chi_o \cos\delta & -\rho T_o^- T_i^- \alpha_i \beta_o - \mathcal{K}R^+ \chi_i \gamma_o + \mathcal{K}R^\times \gamma_i \chi_o \cos\delta & \mathcal{K}\chi_o R^\times \sin\delta \\ -\rho T_o^- T_i^+ \alpha_o - \mathcal{K}R^- \chi_o & -\rho T_o^- T_i^- \alpha_o \beta_i - \mathcal{K}R^+ \gamma_i \chi_o + \mathcal{K}R^\times \chi_i \gamma_o \cos\delta & \rho T_o^- T_i^- \alpha_i \alpha_o + \mathcal{K}R^+ \chi_i \chi_o + \mathcal{K}R^\times \gamma_i \gamma_o \cos\delta & \mathcal{K}\gamma_o R^\times \sin\delta \\ 0 & -\mathcal{K}\chi_i R^\times \sin\delta & -\mathcal{K}\gamma_i R^\times \sin\delta & \mathcal{K}R^\times \cos\delta \end{bmatrix},$$

where $\mathcal{K} = k_s \dfrac{DG}{4(\mathbf{n}\cdot\mathbf{i})(\mathbf{n}\cdot\mathbf{o})}$

Coaxial Case



Simplification for Coaxial Setup

$$\mathbf{H} = (\mathbf{n}\cdot\mathbf{i})\begin{bmatrix} \rho T_o^+T_i^+ + \mathcal{K}R^+ & \rho T_o^+T_i^-\beta_i \cancel{+\mathcal{K}R^-}\gamma_i & -\rho T_o^+T_i^-\alpha_i \cancel{-\mathcal{K}R^-}\chi_i & 0 \\ \rho T_o^-T_i^+\beta_o \cancel{+\mathcal{K}R^-}\gamma_o & \rho T_o^-T_i^-\beta_i\beta_o + \mathcal{K}R^+\gamma_i\gamma_o + \mathcal{K}R^\times\chi_i\chi_o\cos\delta & \cancel{-\rho T_o^-T_i^-\alpha_i\beta_o - \mathcal{K}R^+\chi_i\gamma_o + \mathcal{K}R^\times\gamma_i\chi_o\cos\delta} & \cancel{\mathcal{K}\chi_o R^\times\sin\delta} \\ -\rho T_o^-T_i^+\alpha_o \cancel{-\mathcal{K}R^-}\chi_o & \cancel{-\rho T_o^-T_i^-\alpha_o\beta_i - \mathcal{K}R^+\gamma_i\chi_o + \mathcal{K}R^\times\chi_i\gamma_o\cos\delta} & \rho T_o^-T_i^-\alpha_i\alpha_o + \mathcal{K}R^+\chi_i\chi_o + \mathcal{K}R^\times\gamma_i\gamma_o\cos\delta & \cancel{\mathcal{K}\gamma_o R^\times\sin\delta} \\ 0 & \cancel{-\mathcal{K}\chi_i R^\times\sin\delta} & \cancel{-\mathcal{K}\gamma_i R^\times\sin\delta} & \mathcal{K}R^\times\cos\delta \end{bmatrix}$$

$$\Downarrow$$

$$\mathbf{H} \approx (\mathbf{n}\cdot\mathbf{i})\begin{bmatrix} \rho T_o^+T_i^+ + \mathcal{K}R^+ & \rho T_o^+T_i^-\beta_i & -\rho T_o^+T_i^-\alpha_i & 0 \\ \rho T_o^-T_i^+\beta_o & \mathcal{K}R^+ & 0 & 0 \\ -\rho T_o^-T_i^+\alpha_o & 0 & -\mathcal{K}R^+ & 0 \\ 0 & 0 & 0 & -\mathcal{K}R^+ \end{bmatrix}$$

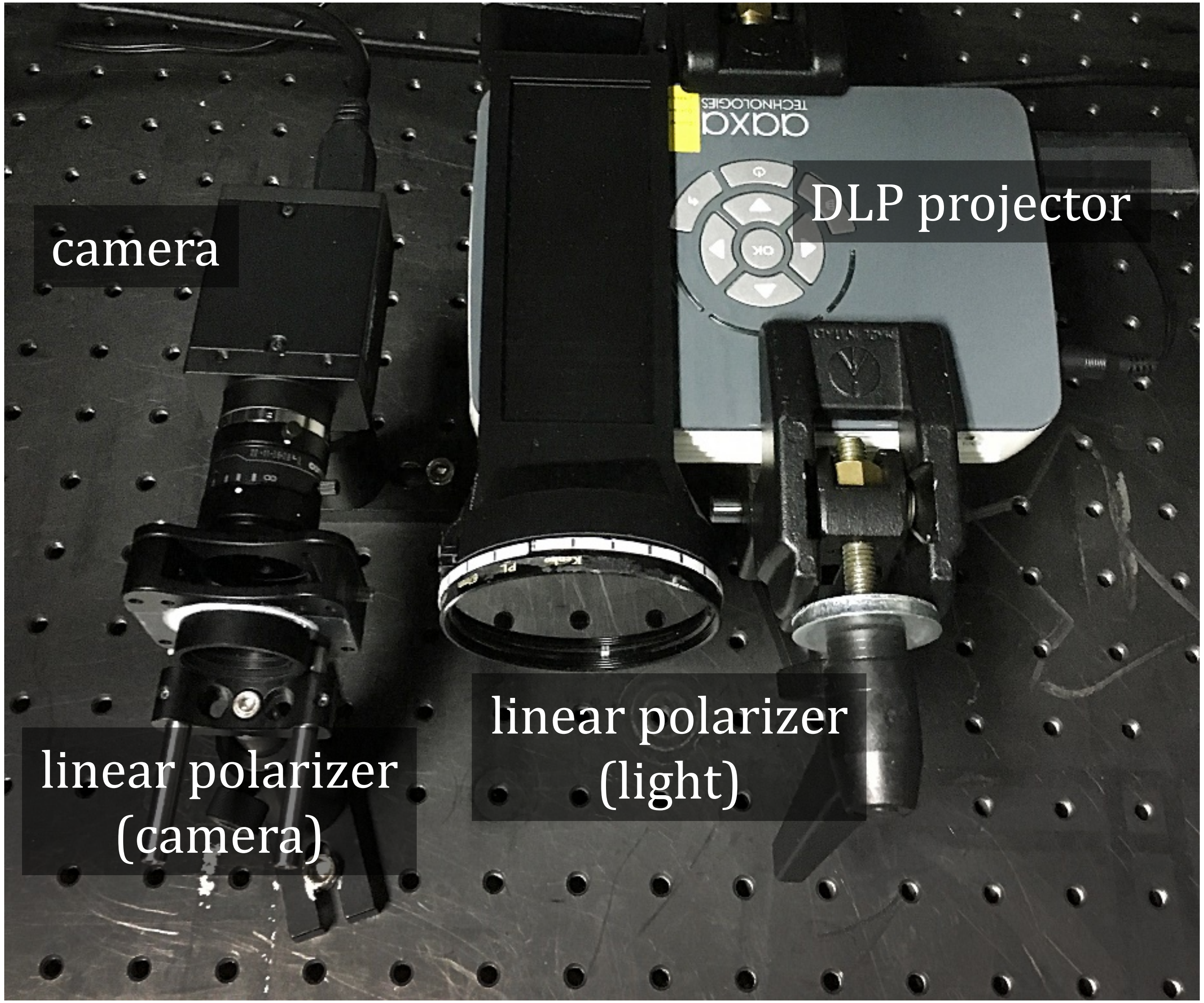
Simplification for Linear Polarization

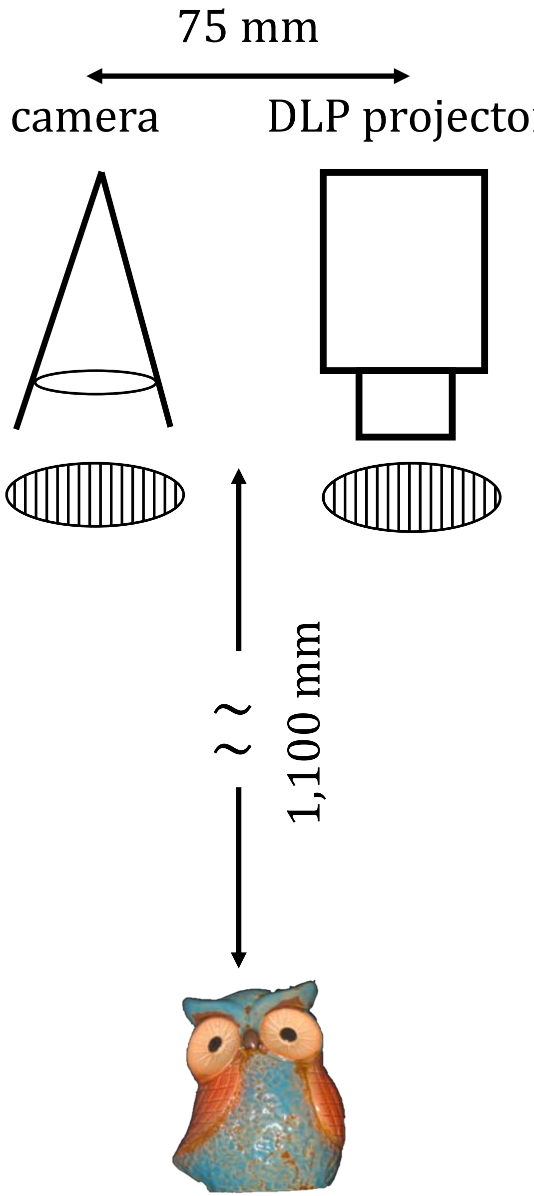
$$\mathbf{H} \approx (\mathbf{n}\cdot\mathbf{i})\begin{bmatrix} \rho T_o^+ T_i^+ + \mathcal{K}R^+ & \rho T_o^+ T_i^- \beta_i & -\rho T_o^+ T_i^- \alpha_i & 0 \\ \rho T_o^- T_i^+ \beta_o & \mathcal{K}R^+ & 0 & 0 \\ -\rho T_o^- T_i^+ \alpha_o & 0 & -\mathcal{K}R^+ & 0 \\ 0 & 0 & 0 & -\mathcal{K}R^+ \end{bmatrix}$$

Circular polaization

$$\mathbf{H}_{\mathrm{L}} \approx (\mathbf{n}\cdot\mathbf{i})\begin{bmatrix} \rho T_o^+ T_i^+ + \mathcal{K}R^+ & \rho T_o^+ T_i^- \beta_i & -\rho T_o^+ T_i^- \alpha_i \\ \rho T_o^- T_i^+ \beta_o & \mathcal{K}R^+ & 0 \\ -\rho T_o^- T_i^+ \alpha_o & 0 & -\mathcal{K}R^+ \end{bmatrix}$$

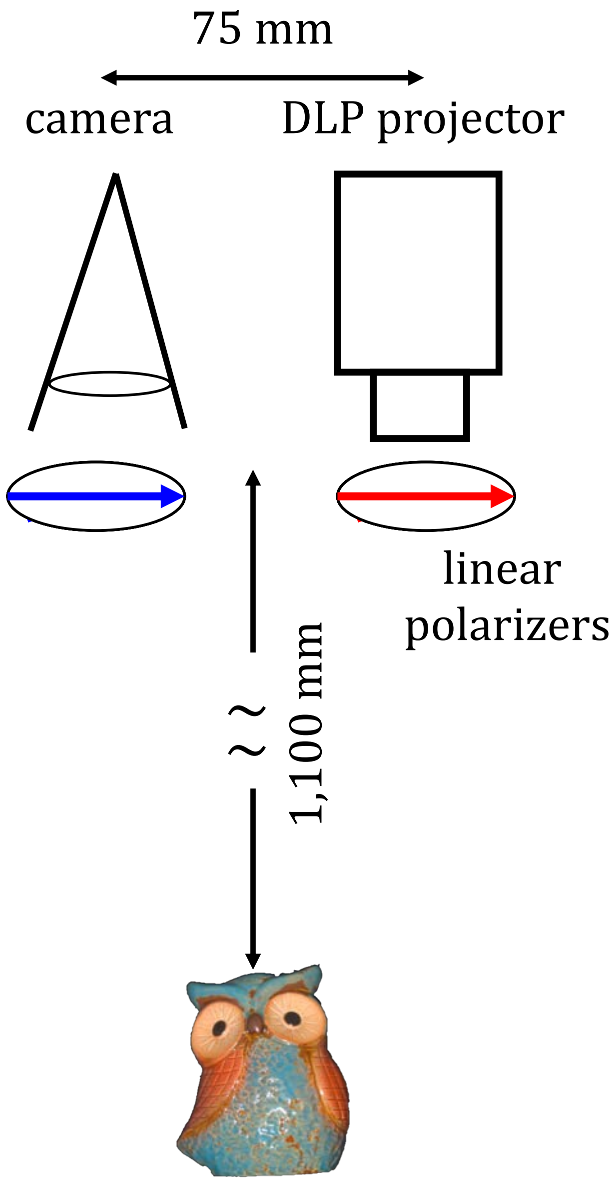
Polarimetric Imaging System





Rough normals

Polarimetric Imaging System



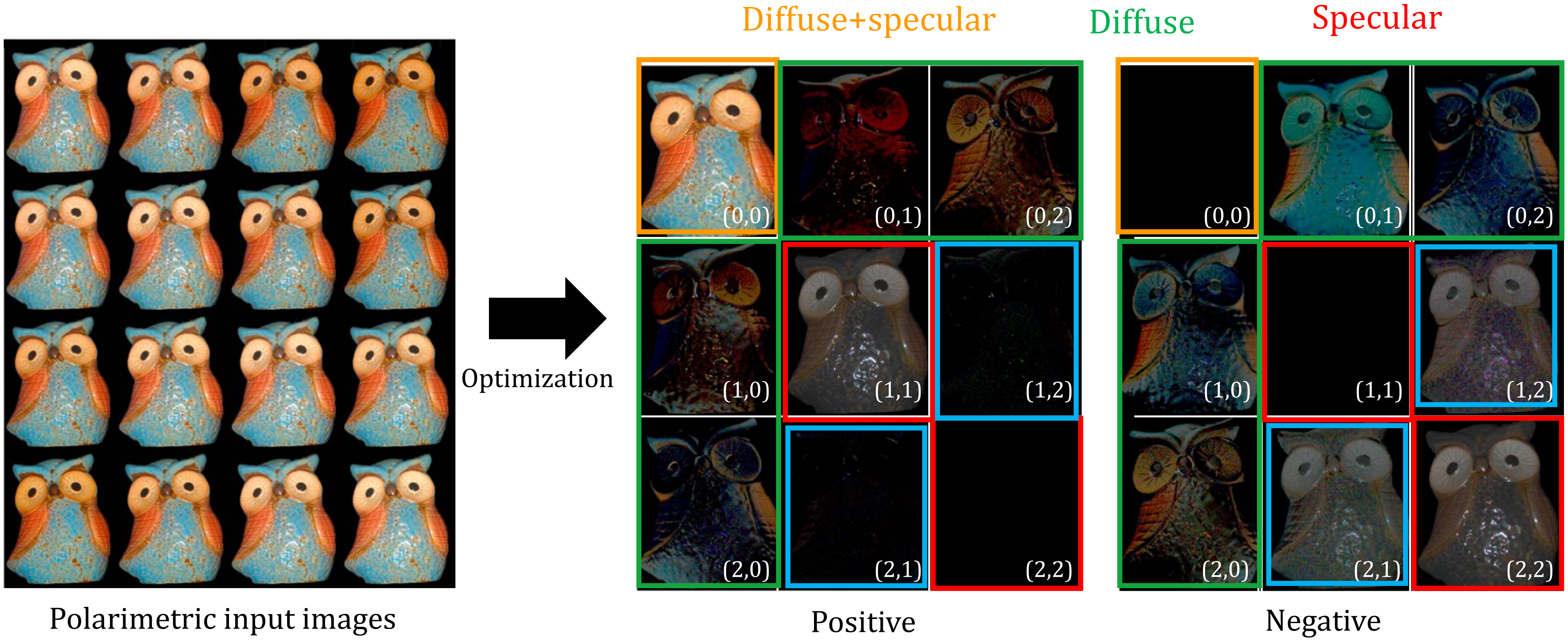
Light polarization [degree]

0 30 60 90

Camera polarization [degree]

0 30 60 90

Estimation of Polarimetric Shading Matrix



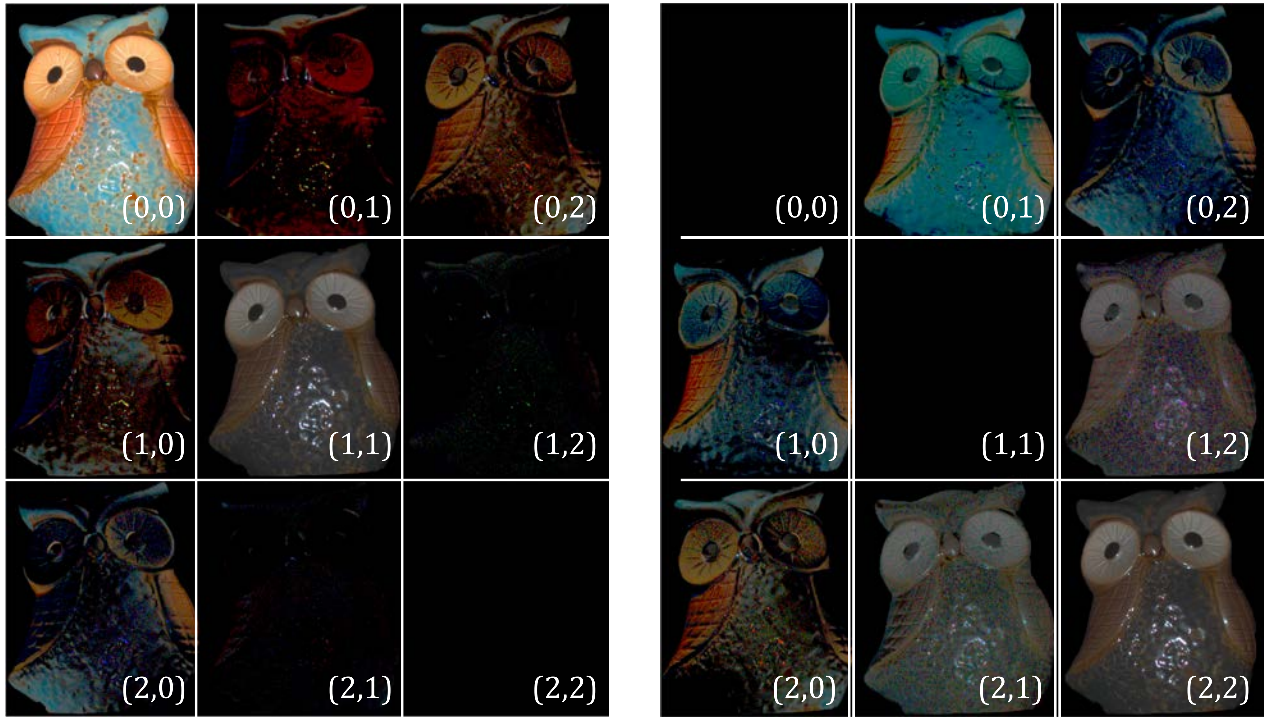
Polarimetric input images

T: Fresnel transmission (diffuse)

R: Fresnel reflection (specular)

$$\mathbf{H}_{\mathrm{L}} \approx (\mathbf{n}\cdot\mathbf{i}) \begin{bmatrix} \rho T_o^+ T_i^+ + \mathcal{K} R^+ & \rho T_o^+ T_i^- \beta_i & -\rho T_o^+ T_i^- \alpha_i \\ \rho T_o^- T_i^+ \beta_o & \mathcal{K} R^+ & 0 \\ -\rho T_o^- T_i^+ \alpha_o & 0 & -\mathcal{K} R^+ \end{bmatrix}$$

Polarimetric Inverse Rendering



Positive

Negative

Optimization

Surface appearance

- Surface normals
- Specular coefficient
- Surface roughness
- Refractive index
- Diffuse albedo

$$\mathbf{H}_{\mathrm{L}} \approx (\mathbf{n}\cdot\mathbf{i})\begin{bmatrix} \rho T_o^+ T_i^+ + \mathcal{K}R^+ & \rho T_o^+ T_i^- \beta_i & -\rho T_o^+ T_i^- \alpha_i \\ \rho T_o^- T_i^+ \beta_o & \mathcal{K}R^+ & 0 \\ -\rho T_o^- T_i^+ \alpha_o & 0 & -\mathcal{K}R^+ \end{bmatrix}$$

Diffuse and Specular Decomposition

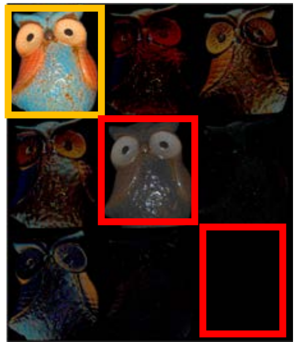
Diffuse + specular

Specular

Diffuse

Cluster

Positive



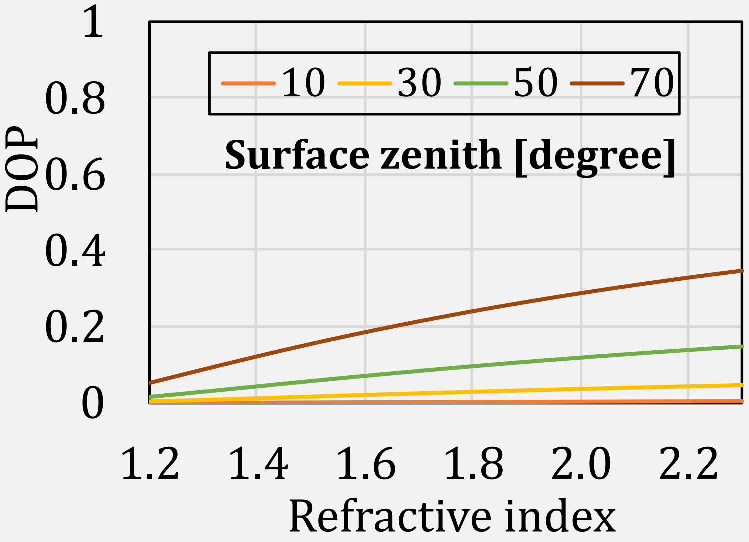
Negative

$$\mathbf{H}_{\mathrm{L}} \approx (\mathbf{n} \cdot \mathbf{i}) \begin{bmatrix} \rho T_o^+ T_i^+ + \mathcal{K} R^+ & \rho T_o^+ T_i^- \beta_i & -\rho T_o^+ T_i^- \alpha_i \\ \rho T_o^- T_i^+ \beta_o & \mathcal{K} R^+ & 0 \\ -\rho T_o^- T_i^+ \alpha_o & 0 & -\mathcal{K} R^+ \end{bmatrix}$$

Refractive index

Diffuse cue

Diffuse DOP



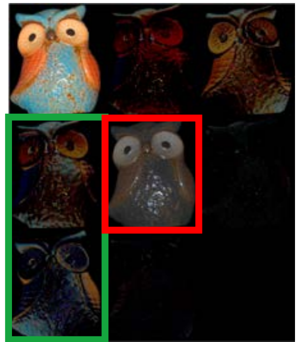
Rough normals

Specular cue

→

Refractive index

Positive



Negative

$$\mathbf{H}_{\mathrm{L}} \approx (\mathbf{n}\cdot\mathbf{i})\begin{bmatrix} \rho T_o^+ T_i^+ + \mathcal{K}R^+ & \rho T_o^+ T_i^- \beta_i & -\rho T_o^+ T_i^- \alpha_i \\ \rho T_o^- T_i^+ \beta_o & \mathcal{K}R^+ & 0 \\ -\rho T_o^- T_i^+ \alpha_o & 0 & -\mathcal{K}R^+ \end{bmatrix}$$

Surface Normals

Refractive index

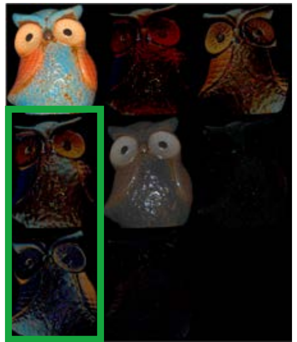
Normals from polarization

Rough normals

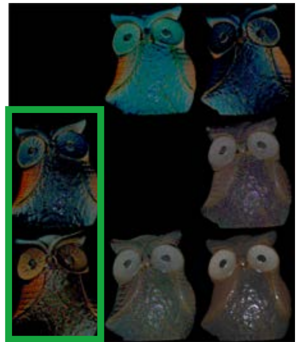
Optimized normals

- Polarization normals ➔ details
- Rough normals ➔ structures
- Smoothness prior

Positive



Negative



$$\mathbf{H}_{\mathrm{L}} \approx (\mathbf{n}\cdot\mathbf{i})\begin{bmatrix} \rho T_o^+ T_i^+ + \mathcal{K}R^+ & \rho T_o^+ T_i^- \beta_i & -\rho T_o^+ T_i^- \alpha_i \\ \rho T_o^- T_i^+ \beta_o & \mathcal{K}R^+ & 0 \\ -\rho T_o^- T_i^+ \alpha_o & 0 & -\mathcal{K}R^+ \end{bmatrix}$$

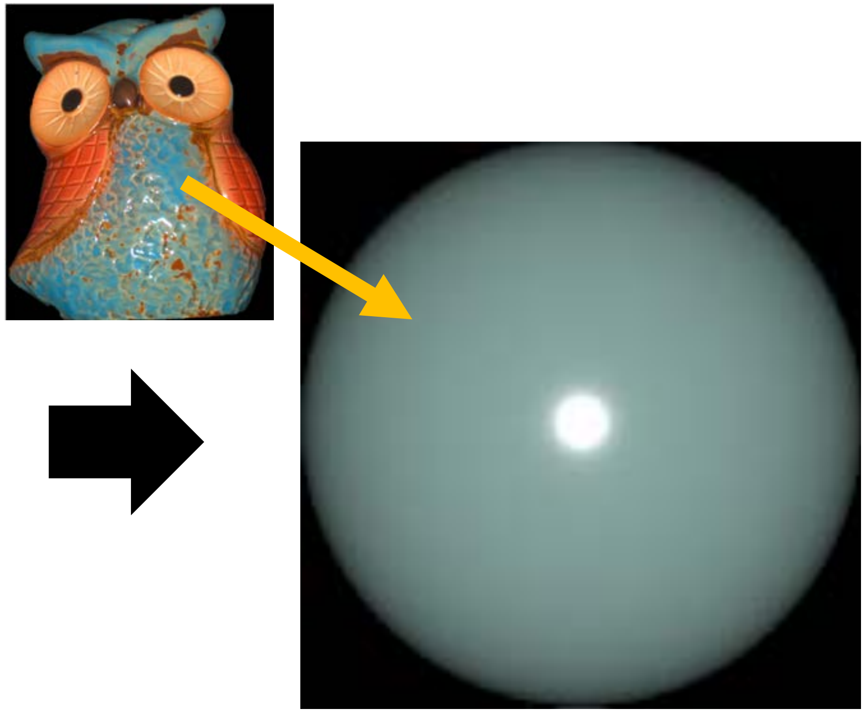
Surface Roughness and Specular Coefficient

Surface normals

Refractive index

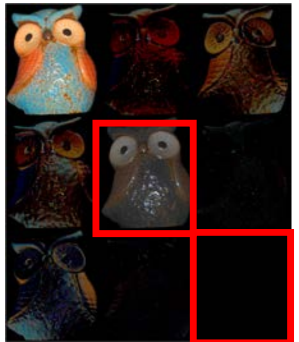
Fit

Specular intensity

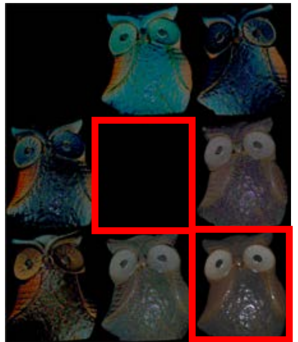


Estimated appearance

Positive

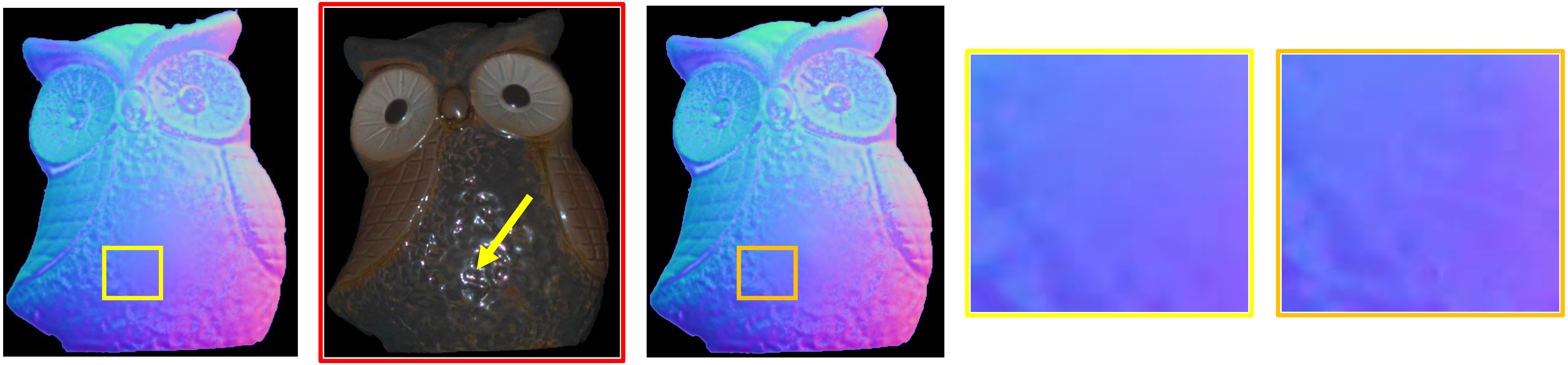


Negative

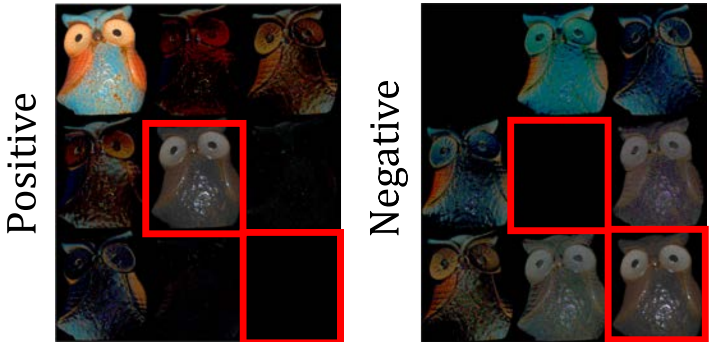


$$\mathbf{H}_{\mathrm{L}} \approx (\mathbf{n}\cdot\mathbf{i})\begin{bmatrix} \rho T_o^+ T_i^+ + \mathcal{K}R^+ & \rho T_o^+ T_i^- \beta_i & -\rho T_o^+ T_i^- \alpha_i \\ \rho T_o^- T_i^+ \beta_o & \boxed{\mathcal{K}R^+} & 0 \\ -\rho T_o^- T_i^+ \alpha_o & 0 & \boxed{-\mathcal{K}R^+} \end{bmatrix}$$

Refinement using Specular Intensity



Before refinement — Specular intensity — After refinement

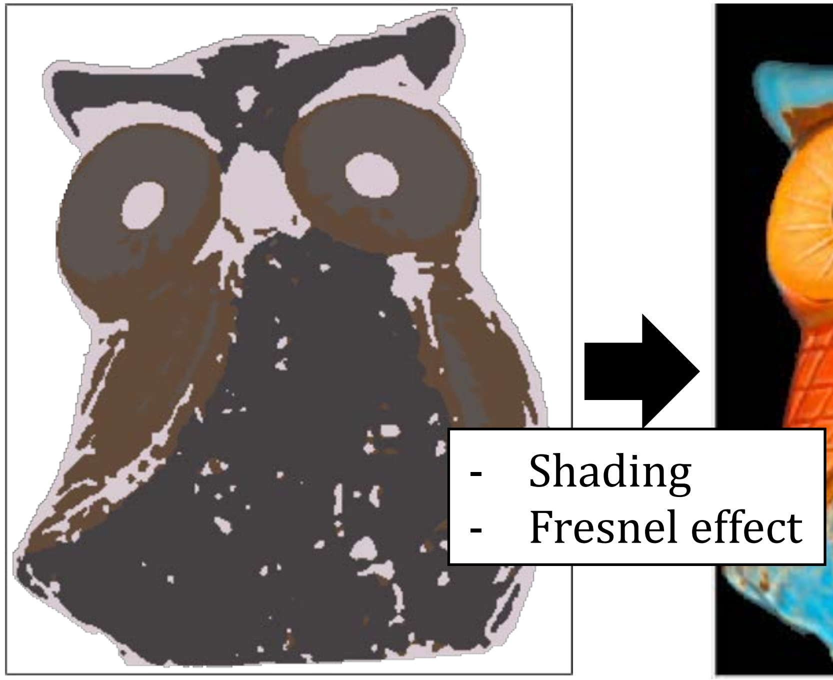


$$\mathbf{H}_{\mathrm{L}} \approx (\mathbf{n}\cdot\mathbf{i})\begin{bmatrix} \rho T_o^{+}T_i^{+} + \mathcal{K}R^{+} & \rho T_o^{+}T_i^{-}\beta_i & -\rho T_o^{+}T_i^{-}\alpha_i \\ \rho T_o^{-}T_i^{+}\beta_o & \boxed{\mathcal{K}R^{+}} & 0 \\ -\rho T_o^{-}T_i^{+}\alpha_o & 0 & \boxed{-\mathcal{K}R^{+}} \end{bmatrix}$$

Diffuse Albedo

Diffuse reflection

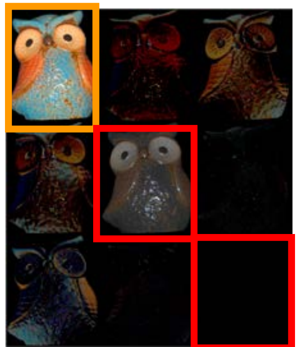
Surface normals



Refractive index

Diffuse albedo

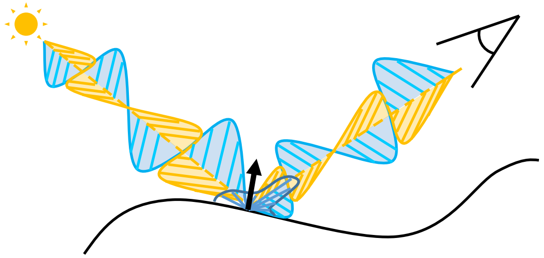
Positive

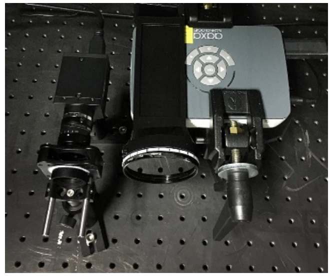


Negative

$$\mathbf{H}_{\mathrm{L}} \approx (\mathbf{n}\cdot\mathbf{i})\begin{bmatrix} \rho T_o^+ T_i^+ + \mathcal{K}R^+ & \rho T_o^+ T_i^- \beta_i & -\rho T_o^+ T_i^- \alpha_i \\ \rho T_o^- T_i^+ \beta_o & \mathcal{K}R^+ & 0 \\ -\rho T_o^- T_i^+ \alpha_o & 0 & -\mathcal{K}R^+ \end{bmatrix}$$

Summary





Input images

Positive Negative

Polarimetric shading matrix

Diffuse and specular reflection

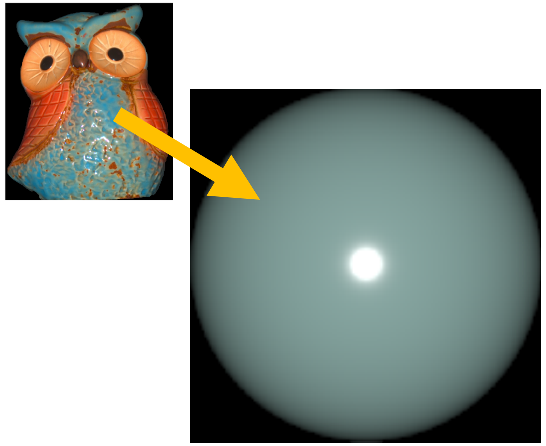
Cluster

Surface appearance

Surface normals

Diffuse albedo

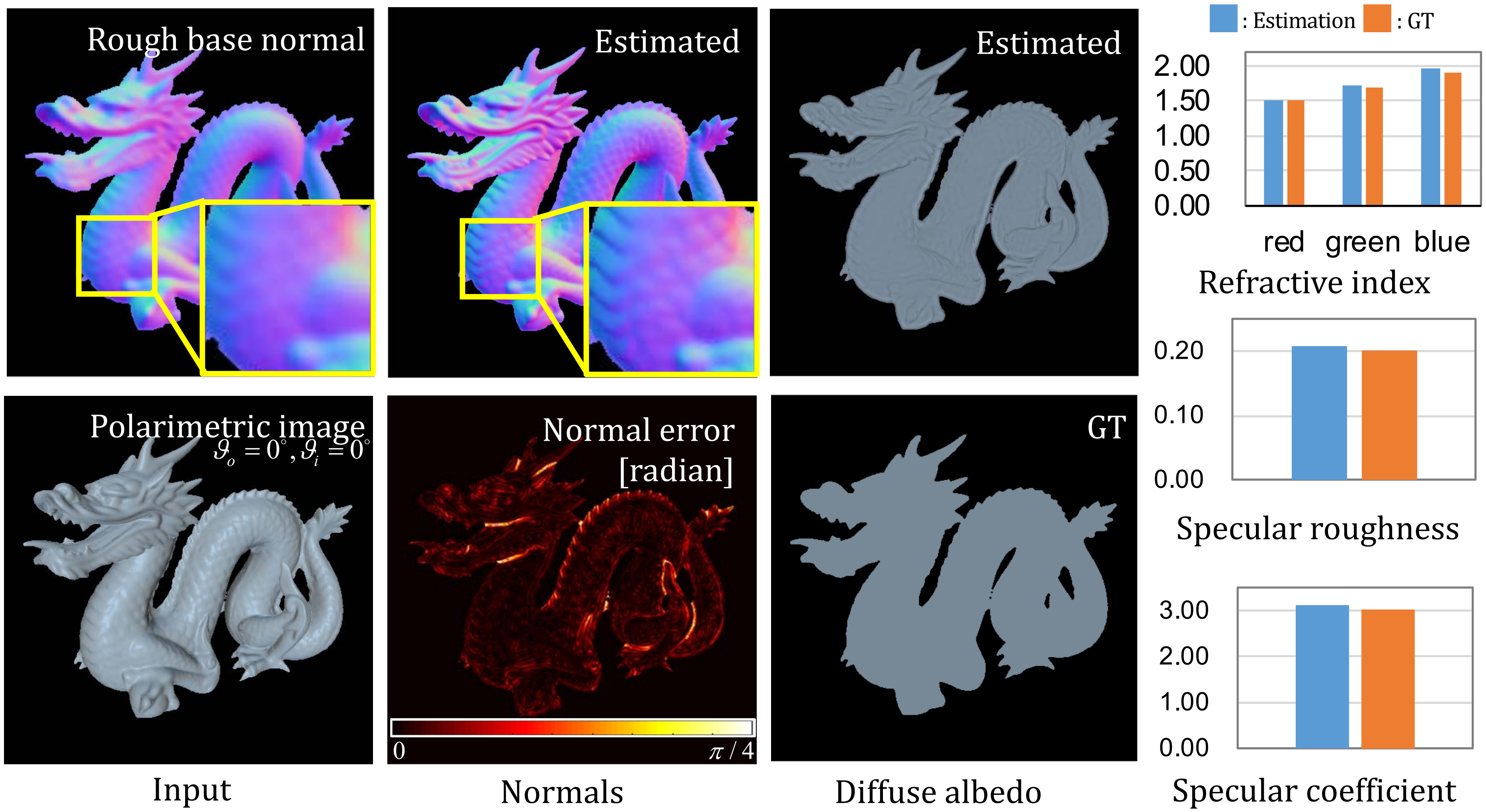
Refractive index



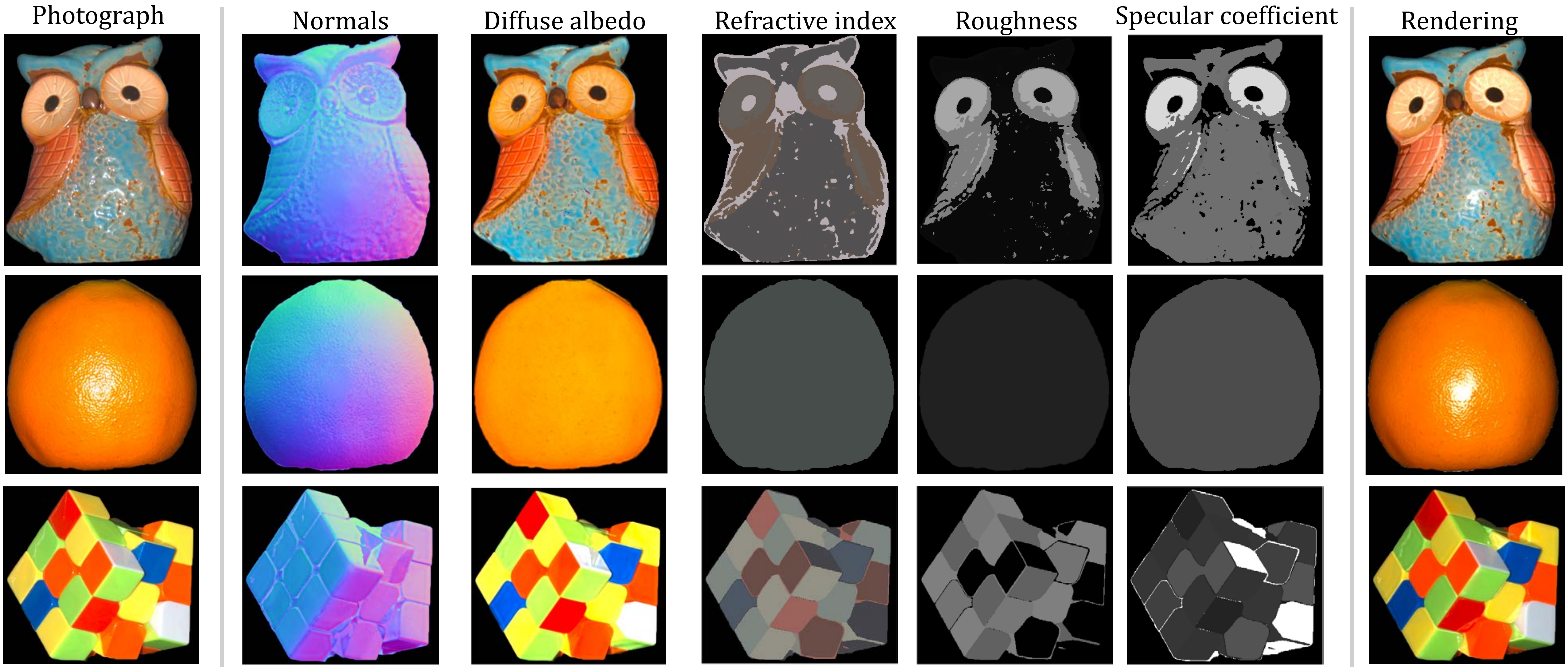
Specular coefficient and roughness

Results

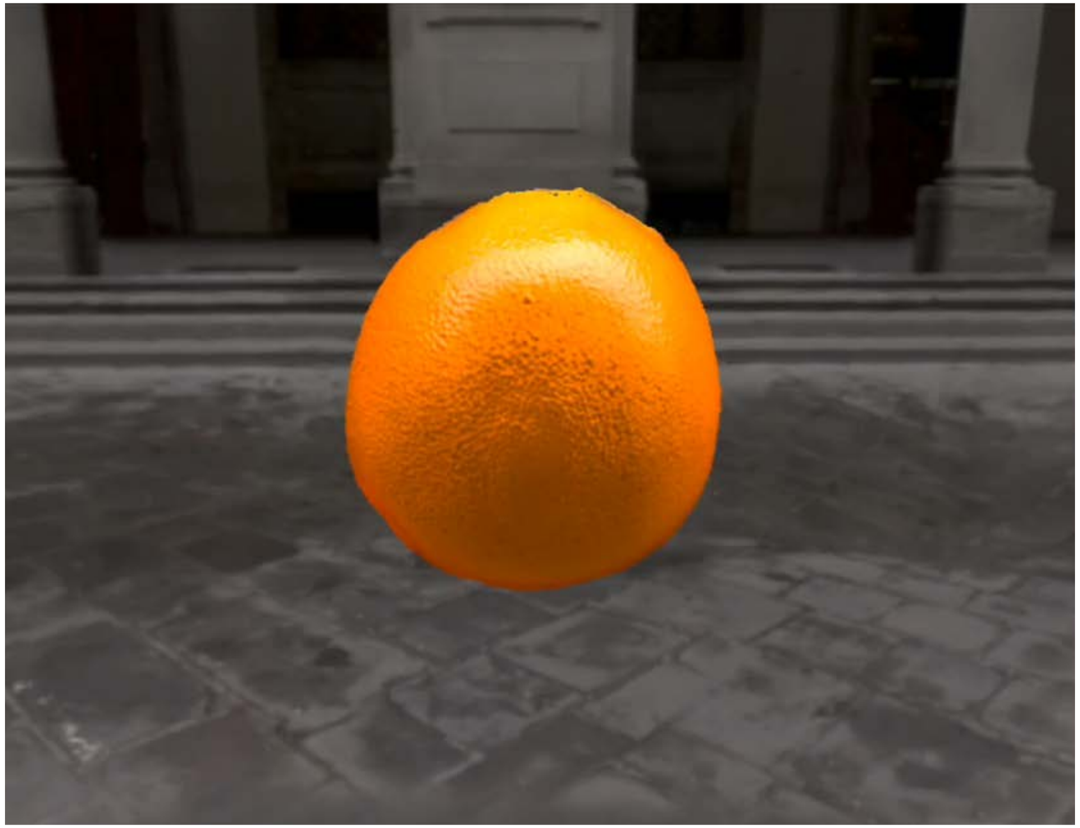
Synthetic Results



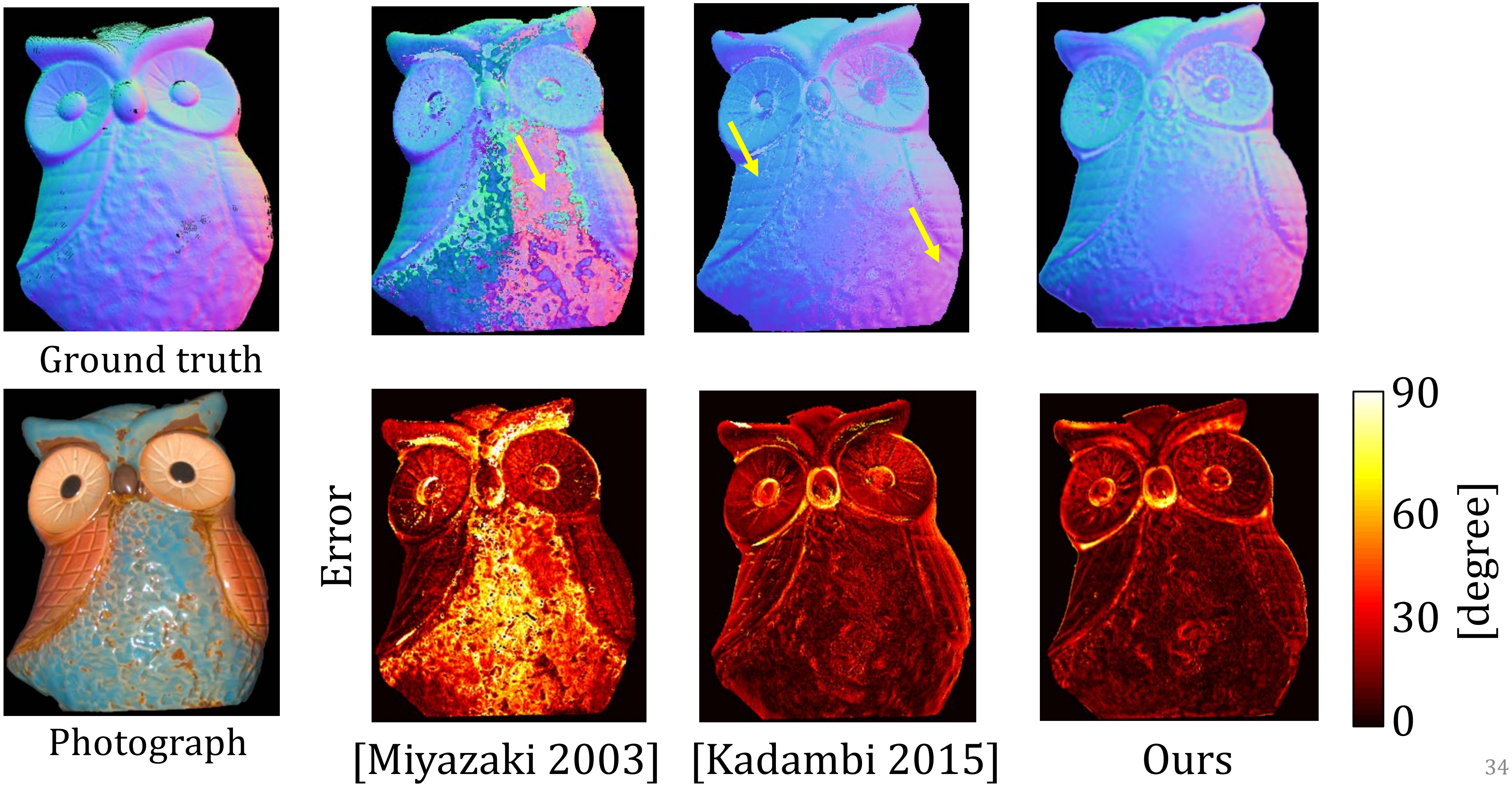
Real Results



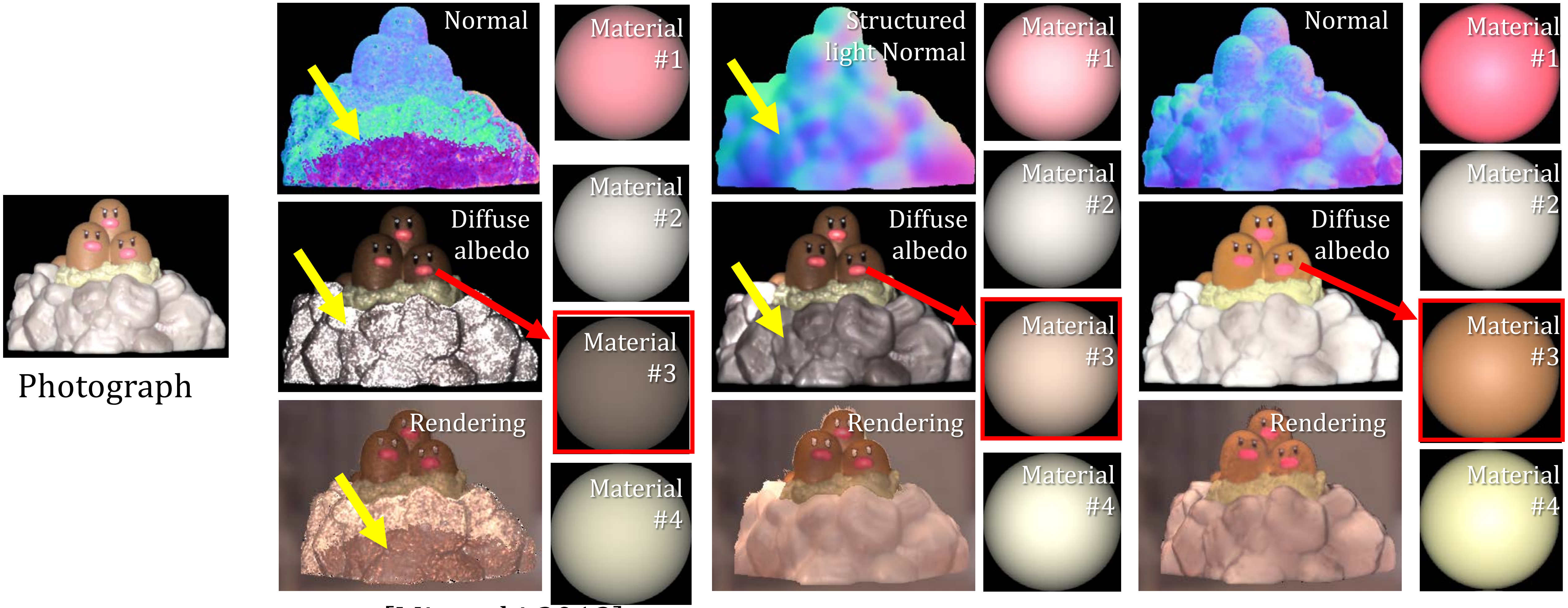
Environmental Rendering



Comparison with Other Shape-from-Polarization Methods



Comparison with Other Appearance-from-Polarization Methods



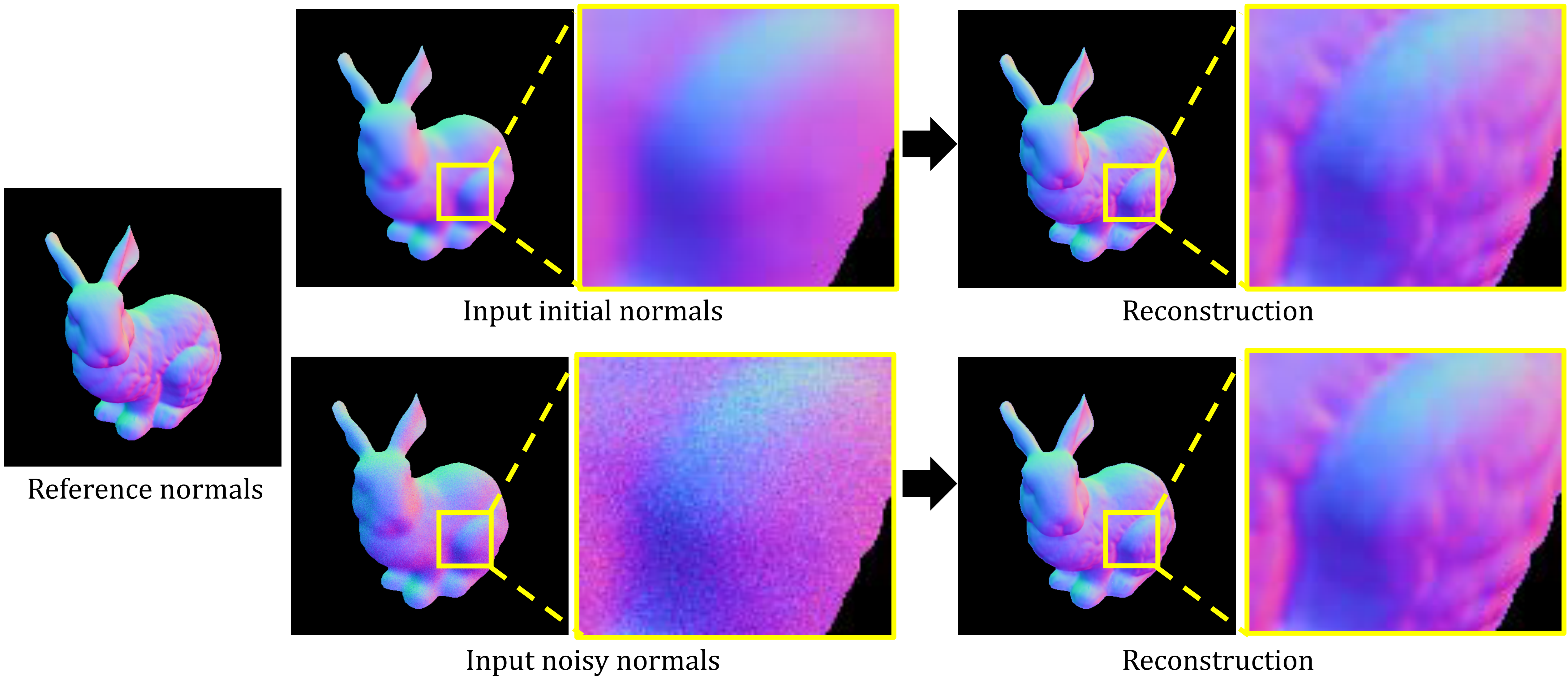
Photograph

[Miyazaki 2013]

Without polarization

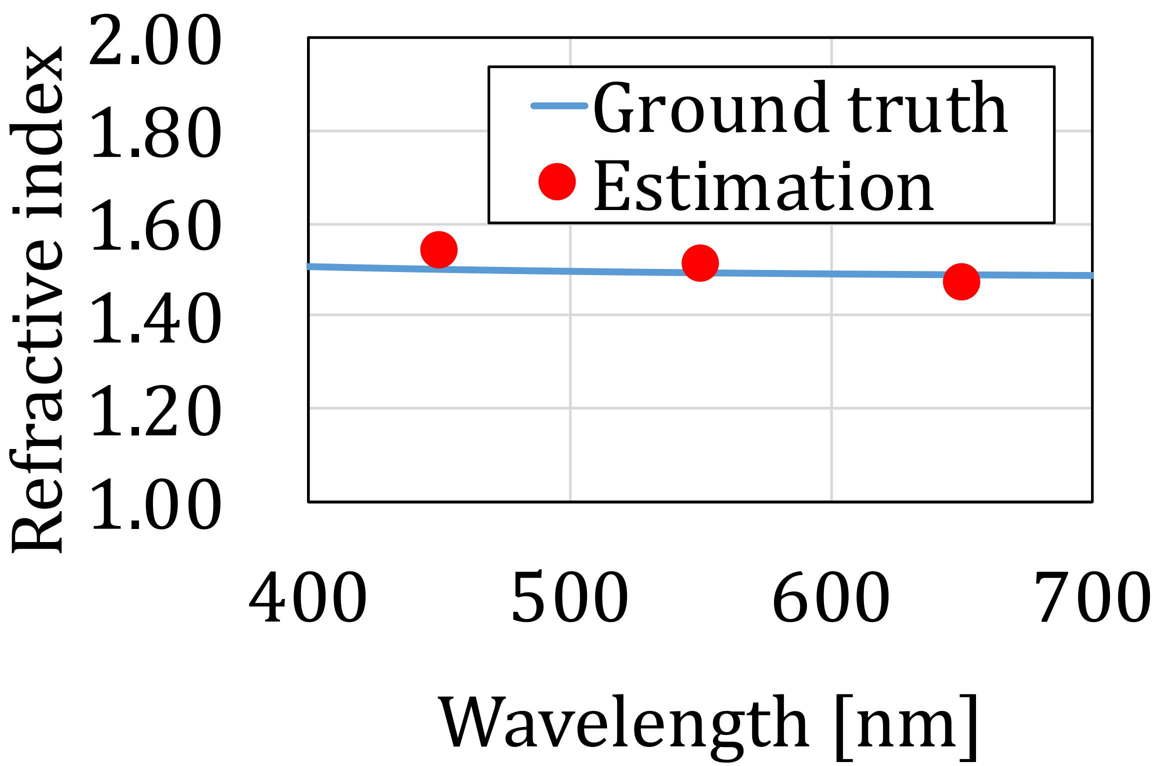
Ours

Impact of Initial Normals



Evaluation of Refractive Index

Real object (Acrylic paint)



Discussion

- pBRDF model
  - Multiple reflection among microfacets
  - Polarization-maintaining diffuse refraction
- Imaging setup
  - Circular polarization
  - No mechanical rotation of polarizers
- Inverse rendering method
  - Direct relation with material parameters with the polarization properties
  - Per-pixel estimation rather than using clustering

Conclusion

- Analyze the polarization state of the light in addition to its intensity to estimate surface appearance information
  - Normals
  - Diffuse and specular appearance parameters