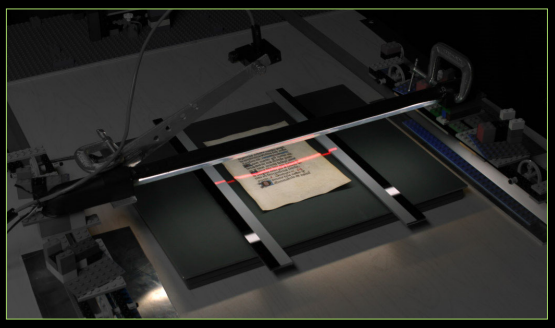
Spatially Varying Reflectance Modeling



70001 – Advanced Computer Graphics: Photographic Image Synthesis

Abhijeet Ghosh

Lecture 13, Feb. 16th 2024

1

SVBRDF (Spatially Varying BRDFs)

SVBRDF

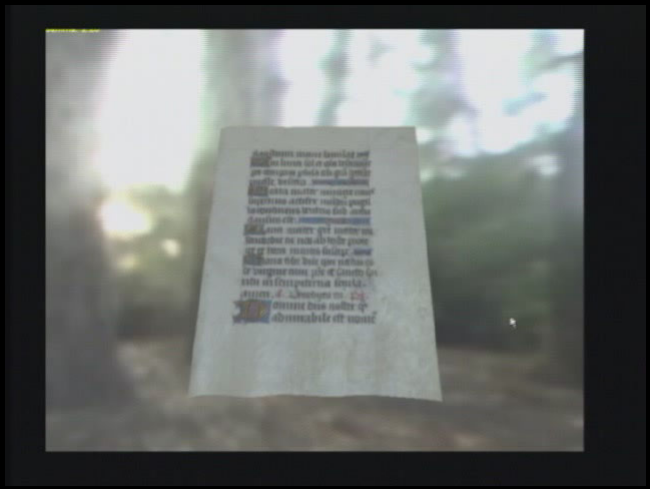
- 6D function (Surface position, incident, exitant)
- Planar surfaces
- Many independent surface points with different BRDFs
- Not a simple texture!

Question

- How to efficiently capture and model?
  - Analytic
  - Data-driven
  - Statistical modeling

2

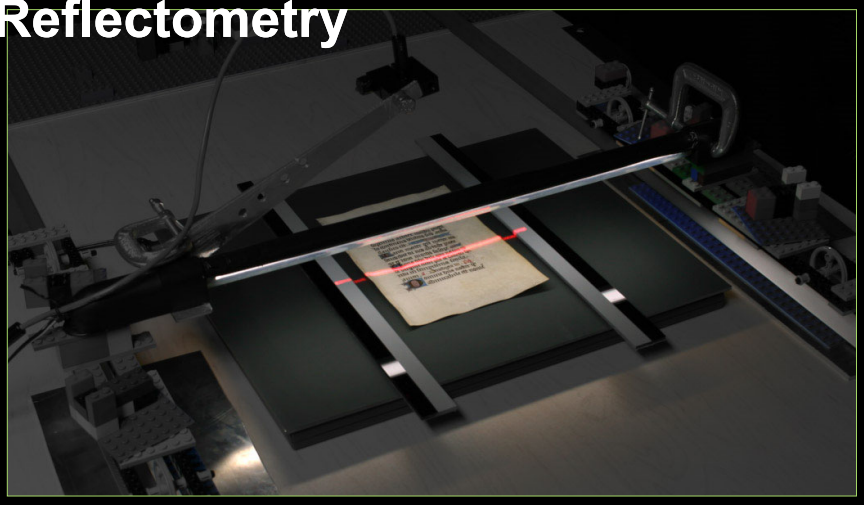
SVBRDF (Spatially Varying BRDFs) [Gardner et al. 03]



Spatially varying properties:
- Diffuse Color
- Specular Color
- Specular Roughness

3

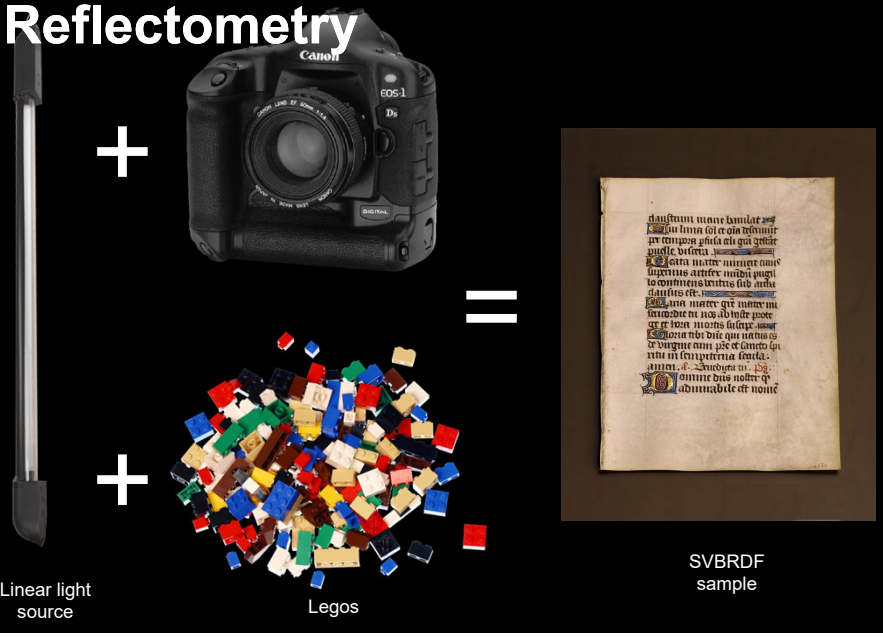
Linear Light Source Reflectometry



Andrew Gardner, Chris Tchou, Tim Hawkins, and Paul Debevec, SIGGRAPH 2003

4

Linear Light Source Reflectometry



Linear light source

Legos

SVBRDF sample

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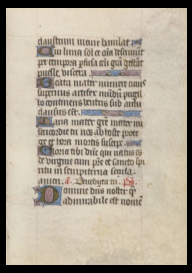
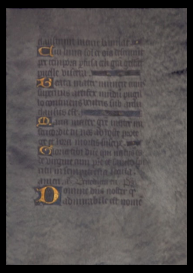
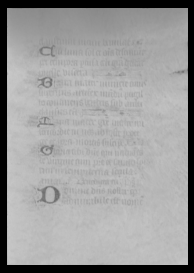
SVBRDF Parameters



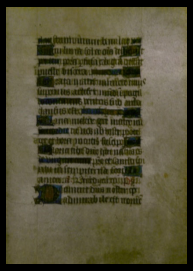
Diffuse Intensity



Specular Intensity

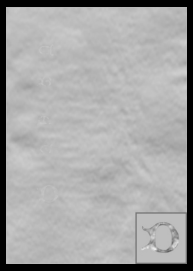


Specular Roughness



Translucency

Normals (X & Y gradients)



Displacement

6

Motivation: Linear Light Source

- Fewer images needed to cover planar samples with linear light source
- Dynamic range compression compared to point light source
  - can be photographed with single exposure instead of HDR
- Simple machinery of linear 1D translation to cover entire sample

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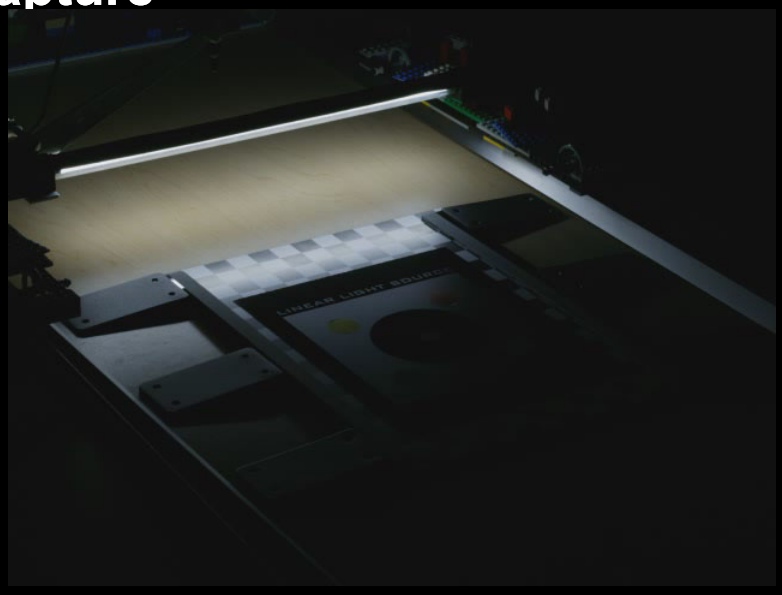
Capture



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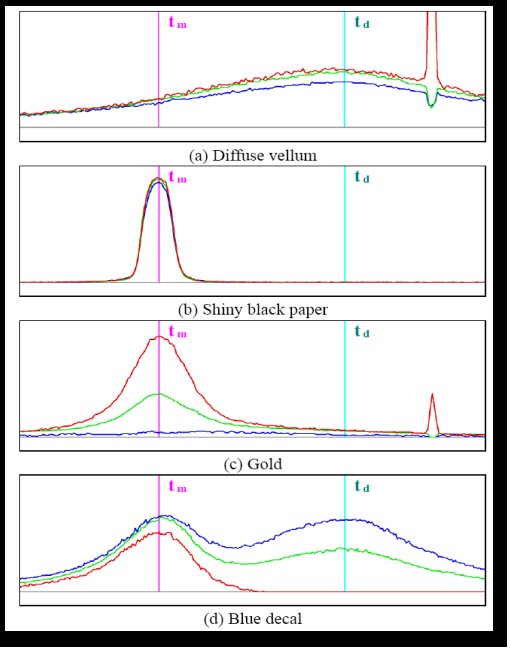
Reflectance trace for each pixel

X-axis: time (light motion)

Y-axis: reflectance

Diffuse peak td coincides with light aligned with surface normal

Specular peak tm coincides with light aligned with mirror reflection



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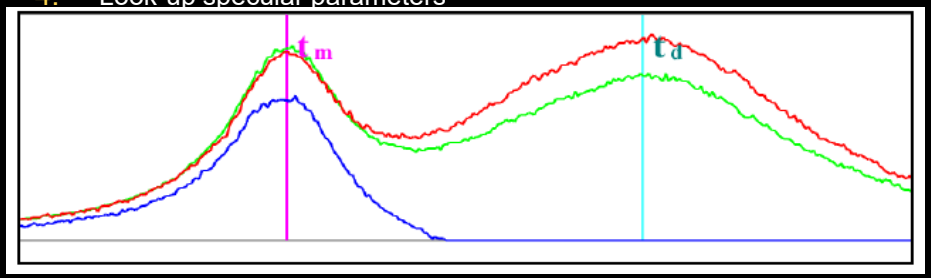
BRDF Fitting

1. Fit diffuse
2. Subtract diffuse
3. Estimate mean and variance of specular
4. Look-up specular parameters



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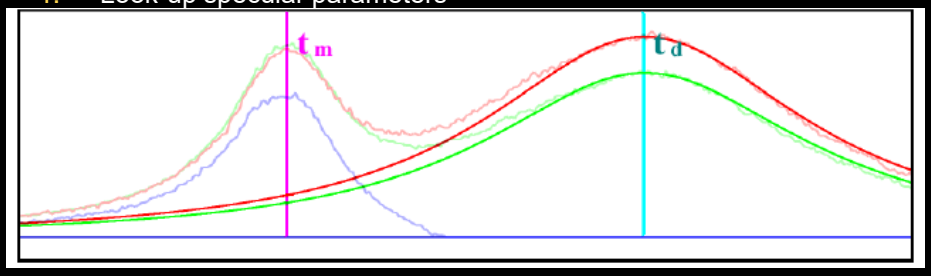
BRDF Fitting

1. Fit diffuse
2. Subtract diffuse
3. Estimate mean and variance of specular
4. Look-up specular parameters



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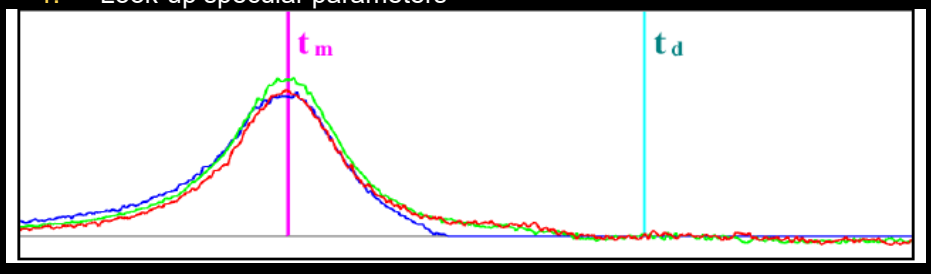
BRDF Fitting

1. Fit diffuse
2. Subtract diffuse
3. Estimate mean and variance of specular
4. Look-up specular parameters



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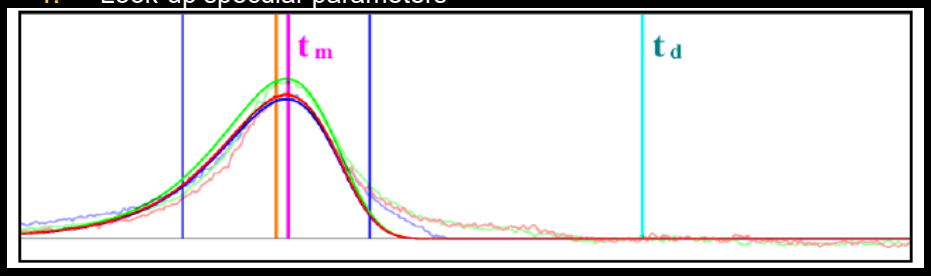
BRDF Fitting

1. Fit diffuse
2. Subtract diffuse
3. Estimate mean and variance of specular
4. Look-up specular parameters



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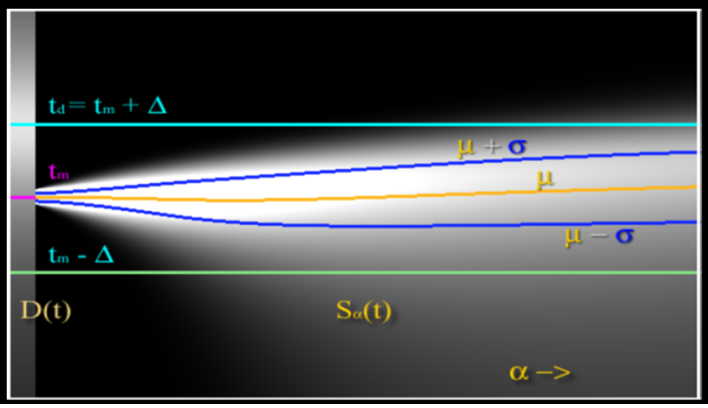
BRDF Fitting

1. Fit diffuse
2. Subtract diffuse
3. Estimate mean and variance using precomputed lookup table



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Results

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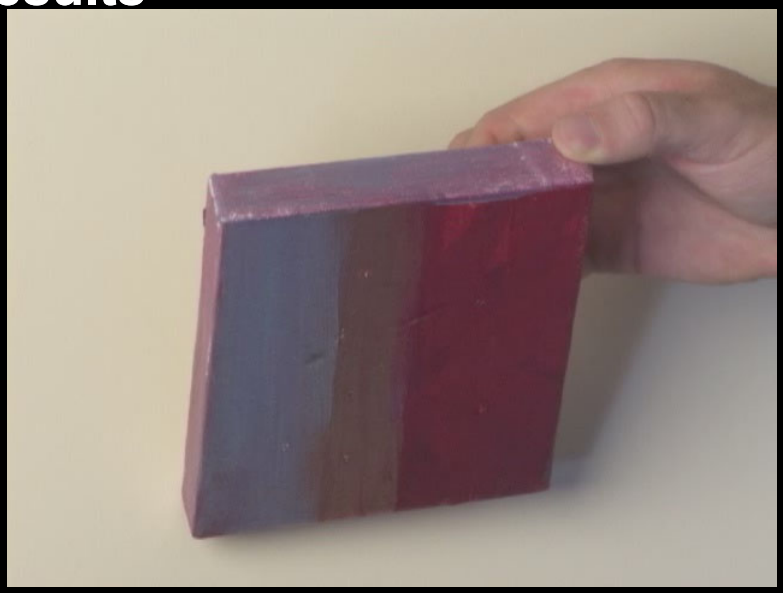
Results



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Pocket Reflectometry

Ren et al. SIGGRAPH 2011

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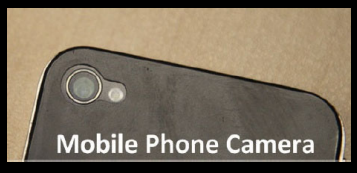
Pocket Reflectometry

+

+



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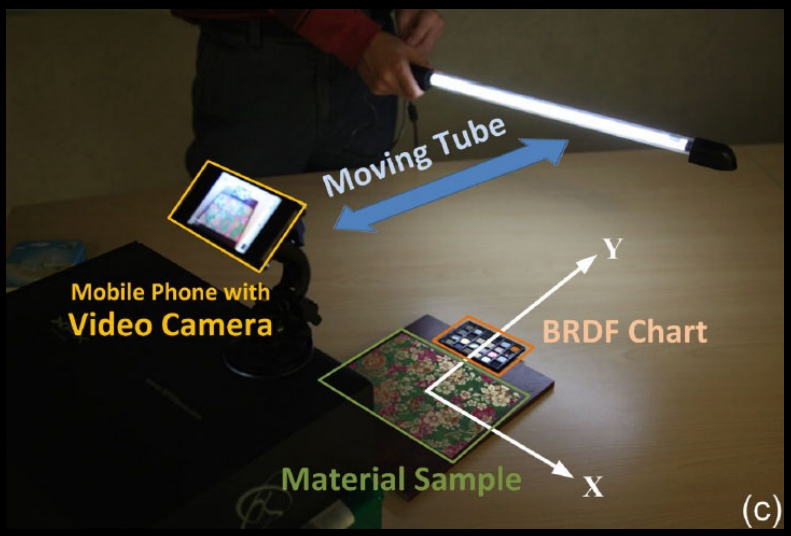
Pocket Reflectometry



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BRDF chart

plaster	sliver paint	rubber	polished acrylic	aluminium	fluorescent paint
matte tape	black paper	polished resin	bronze	bronze metallic paint	acrylic
plastic	brass	coated metallic paint	polyethylene	red metallic paint	alumina
80% Spectralon	leather	matte golden paint	alum-bronze	tinfoil	lactoprene

- Exemplar materials inspired by the MERL BRDF database!
- Data-driven BRDF modelling

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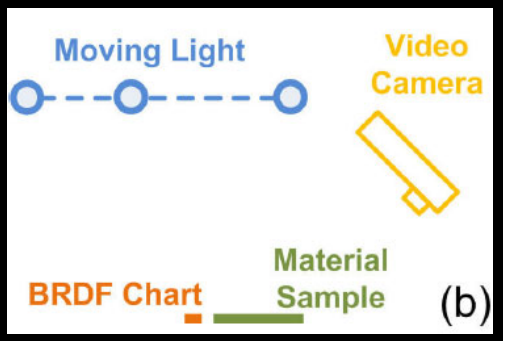
Pocket Reflectometry



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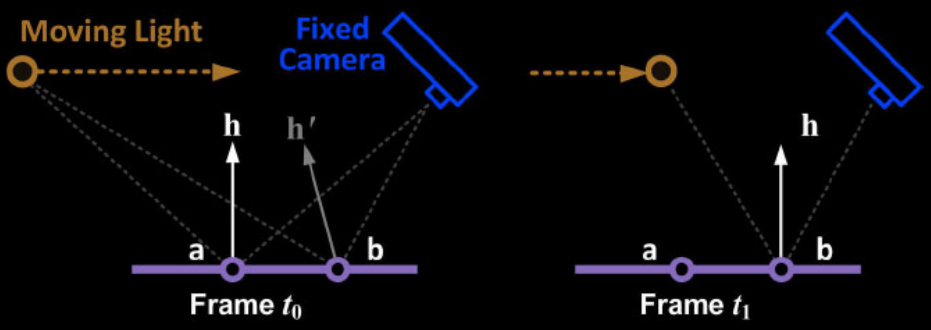
Time-shift compensation



- Different surface points will have their peaks at different time (frame)
- Reflectance trace of BRDF chart cannot be directly compared with sample

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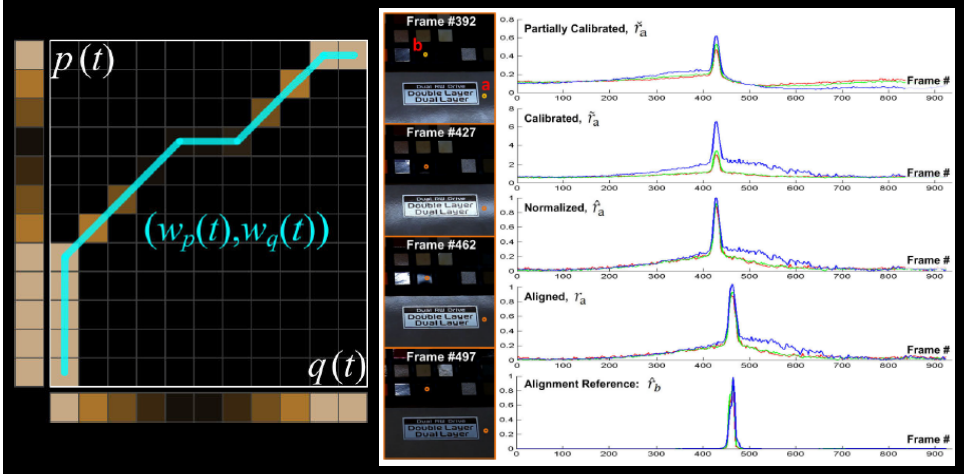
Dynamic time warping



- Alignment of reflectance traces of BRDF chart with sample

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Reflectance estimation from chart

$$\mathbf{r} = d\,\mathbf{a} + s\,\mathbf{b},$$

$$a(t) = \int_{\Omega^+} L_t(\mathbf{i})\,\alpha(\mathbf{i},\mathbf{o})\,(\mathbf{n}\cdot\mathbf{i})\,\mathrm{d}\mathbf{i}, \quad b(t) = \int_{\Omega^+} L_t(\mathbf{i})\,\beta(\mathbf{i},\mathbf{o})\,(\mathbf{n}\cdot\mathbf{i})\,\mathrm{d}\mathbf{i},$$

$$\min_{u_0,u_1,\cdots,u_k} \left\| \mathbf{r} - u_0\,\mathbf{a} - \sum_{j=1}^{k} u_j\,\mathbf{b}_j \right\|, \quad u_j \geq 0, \quad \mathbf{b}_j \in \Phi(\mathbf{r})$$

- a diffuse BRDF with albedo d
- b specular BRDF with parameters s
- Instead of direct estimation of s, estimate a linear combination of k exemplar BRDFs in BRDF chart that fits the observed data per-pixel

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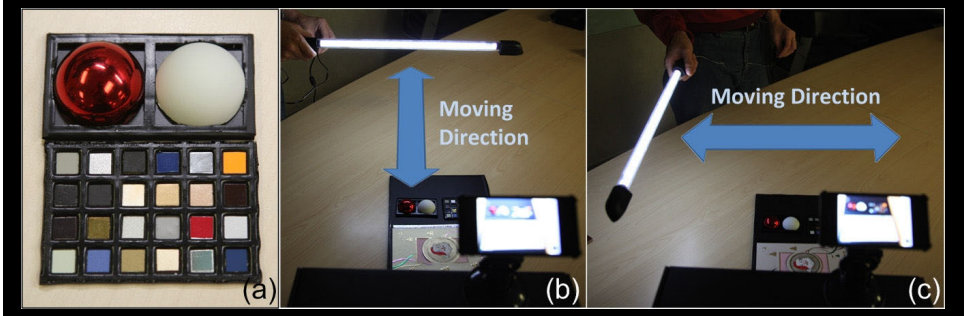
Bumpy surface estimation



- Compute surface normal as intersection of two orthogonal passes of light source to estimate X & Y components of surface normals
- Assumption mostly flat surface, so no need to estimate z component

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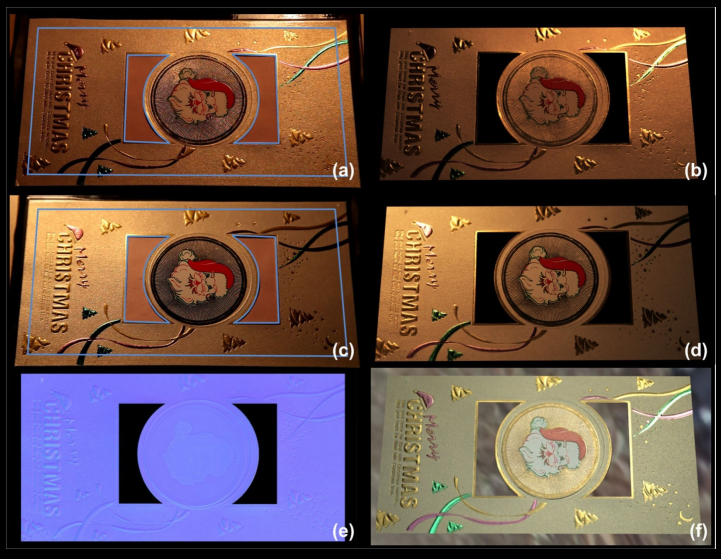
Bumpy surface results



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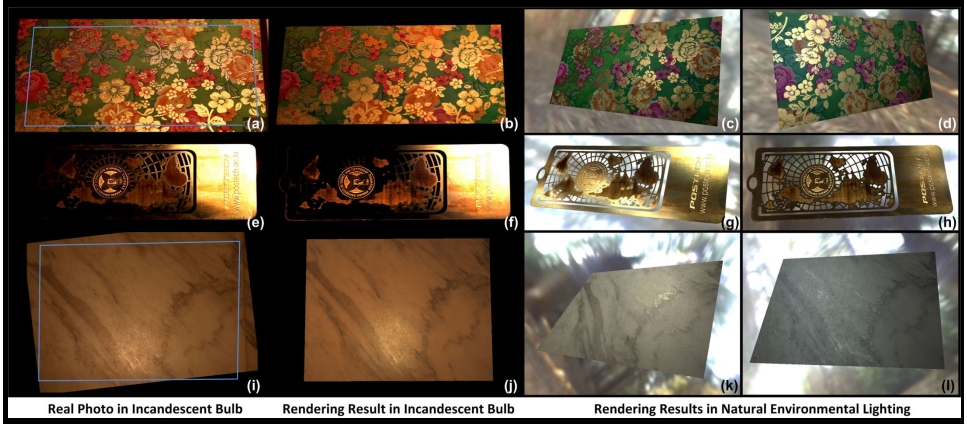
Flat surface results



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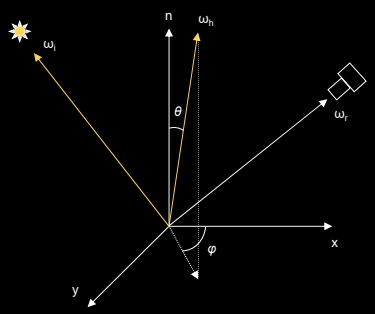
Measure and fit

- Analytic BRDF models
  - albedo
  - specular roughness
  - normal and tangent directions



- Is DIRECT estimate possible?

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Second order statistics of reflectance

Ghosh et al. EGSR 2009

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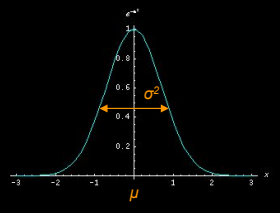
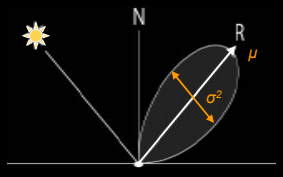
2nd order statistics of reflectance

- Specular reflection
  - measure of variance σ^2 about mean μ
  - reflection vector and specular roughness
  - computational illumination for optical measurement of reflectance statistics!





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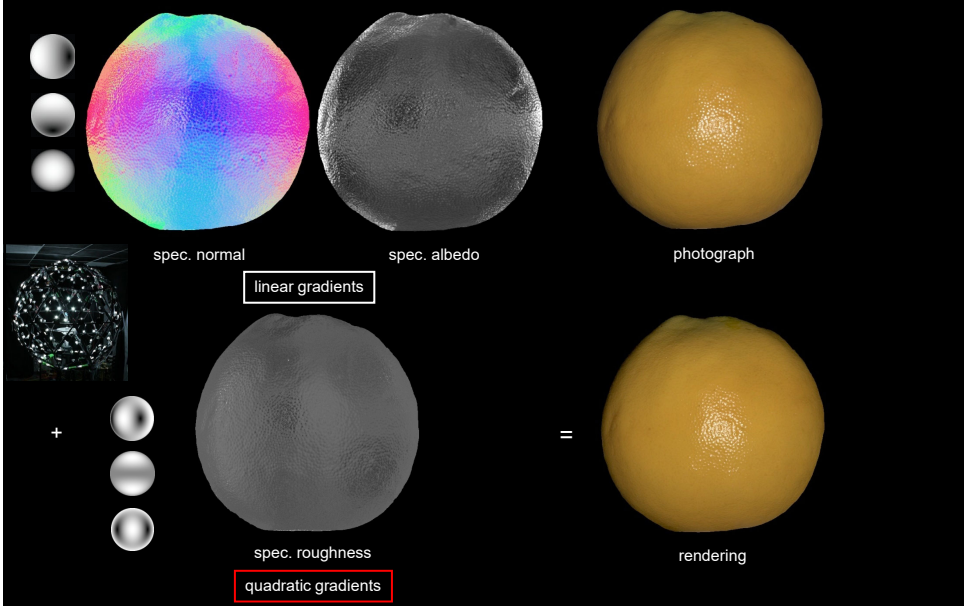
2nd order statistics



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0th, 1st & 2nd moments

- In 1D, the moments of f(x):
  - total energy α
  - mean μ
  - variance σ^2

$$\begin{aligned}
\alpha &= \int \mathbf{f}(x)\,dx = L_0, \\
\mu &= \int x \frac{\mathbf{f}(x)}{\alpha}\,dx, \\
&= \frac{1}{\alpha}\int x\mathbf{f}(x)\,dx = \frac{L_1}{L_0}, \\
\sigma^2 &= \int (x-\mu)^2 \frac{\mathbf{f}(x)}{\alpha}\,dx, \\
&= \frac{L_2}{L_0} - \frac{L_1^2}{L_0^2}.
\end{aligned}$$

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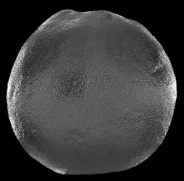
0th spherical moment



$$L_0 = \int_\Omega \mathbf{f}(\vec{\omega})\, d\vec{\omega},$$

α

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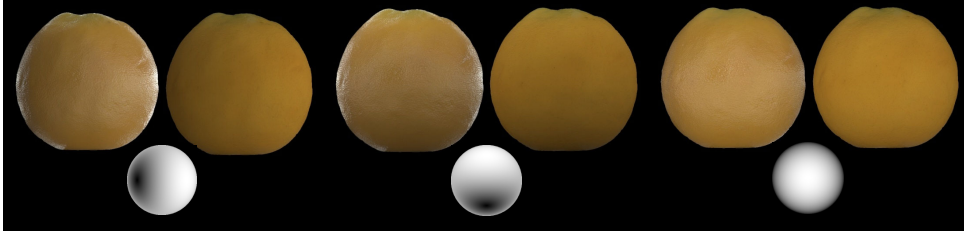
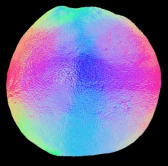
1st spherical moment





$$L_1 = \int_\Omega \vec{\omega}\mathbf{f}(\vec{\omega})\, d\vec{\omega},$$

μ

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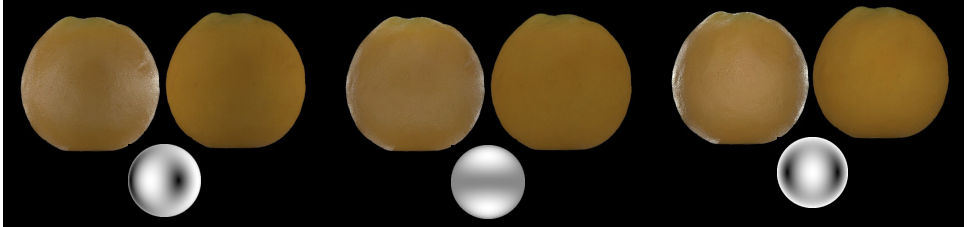
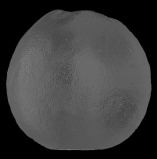
2nd spherical moment





$$L_2 = \int_\Omega \vec{\omega}\vec{\omega}^T \mathbf{f}(\vec{\omega})\, d\vec{\omega},$$

σ^2

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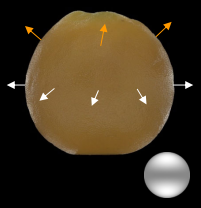
Need to compute statistics in local shading frame!

- Isotropic material



- Anisotropic material

normal

tangent

bitangent

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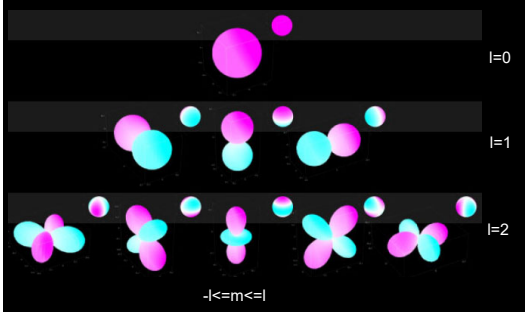
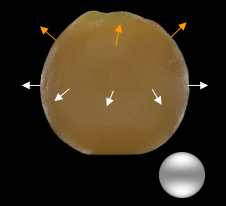
Spherical harmonics





normal

tangent

bitangent

- Steerable spherical basis
  - SH basis can be rotated over the 3D sphere
- Capture reflectance with fixed SH patterns
  - Computation steering in post-process for rotations

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Spherical harmonics

- Anisotropic material
  - σ_x^2 and σ_y^2

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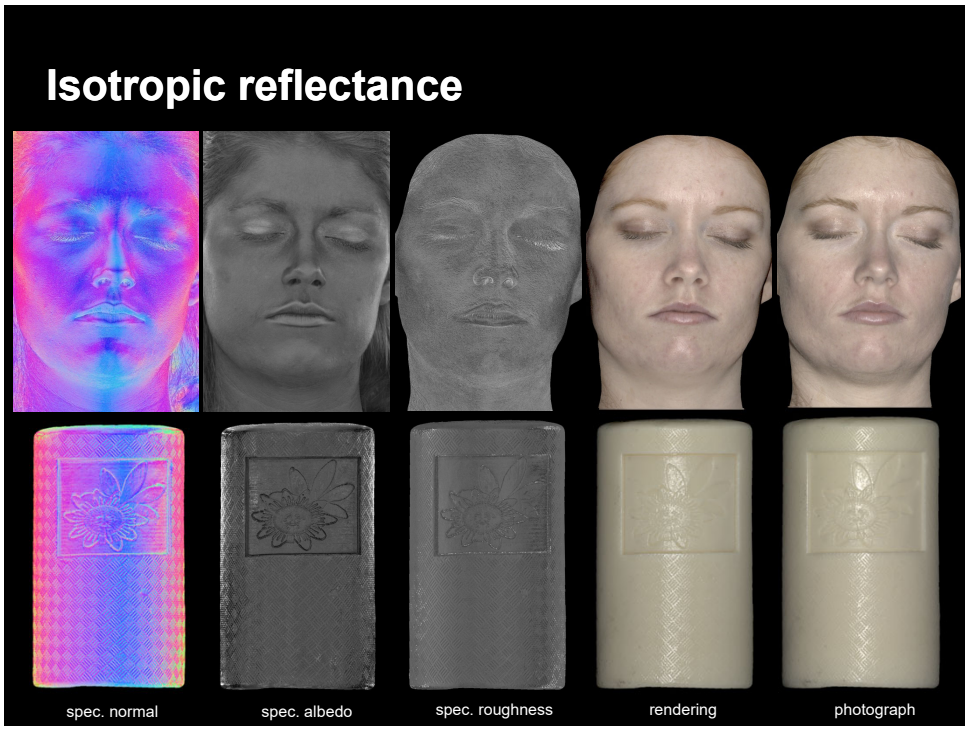
Isotropic reflectance
spec. normal
spec. albedo
spec. roughness
rendering
photograph

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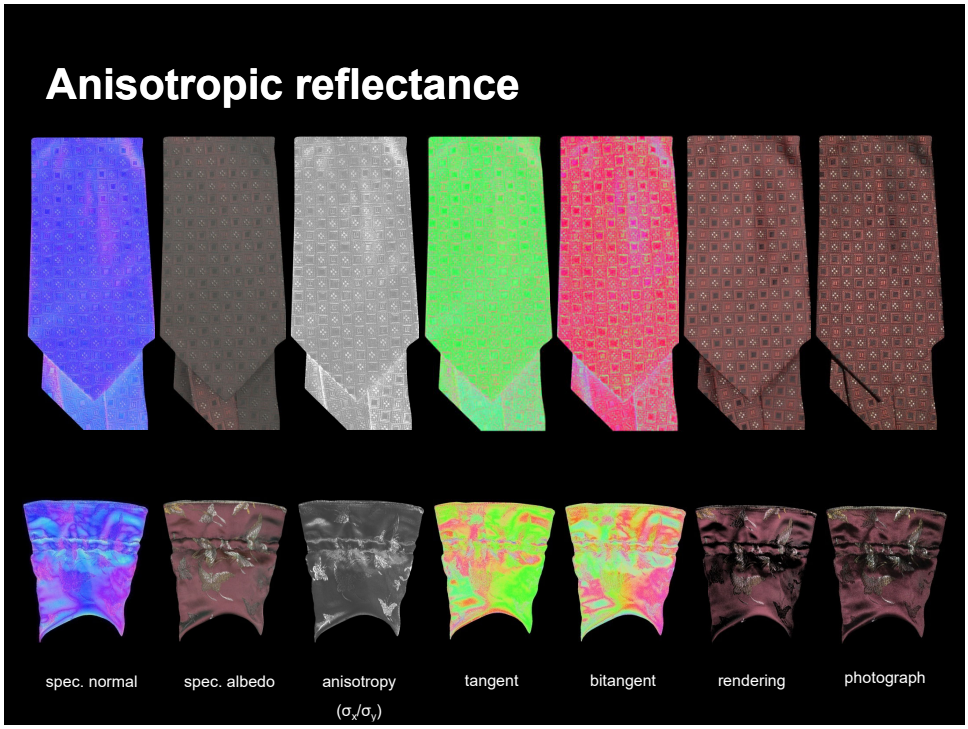
Anisotropic reflectance
spec. normal
spec. albedo
anisotropy
(σx/σy)
tangent
bitangent
rendering
photograph

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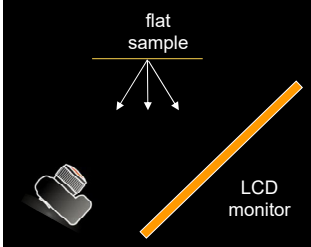
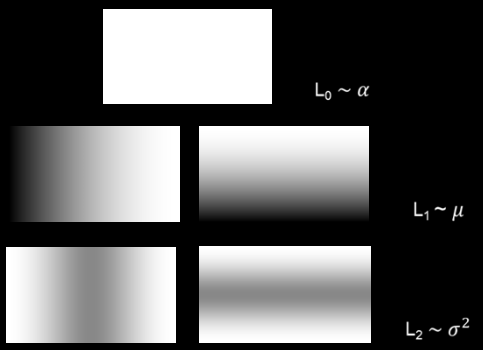
Flat sample





- Project 2nd order gradients from LCD screen
  - Sufficient to cover specular lobe of flat samples
- Screen is already polarized
  - Diffuse specular separation

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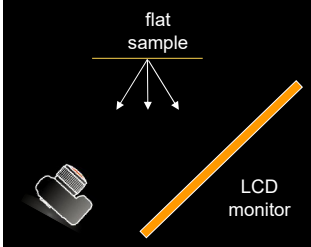
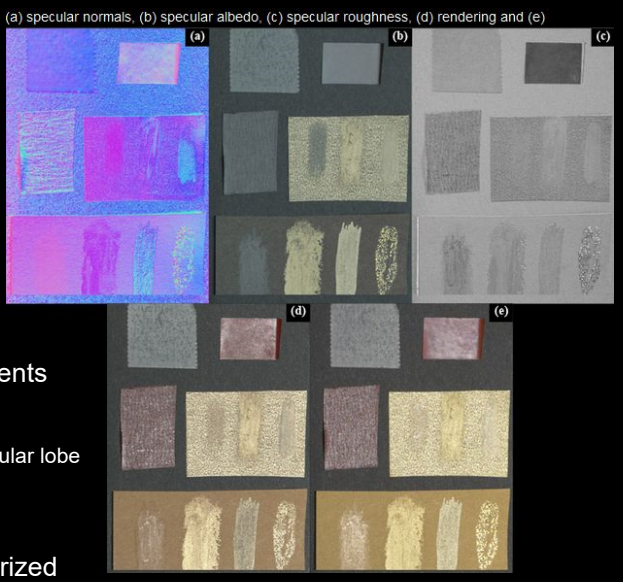
Flat sample





- Project 2nd order gradients from LCD screen
  - Sufficient to cover specular lobe of flat samples
- Screen is already polarized
  - Diffuse specular separation

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Specular materials!

- Highly specular objects difficult to acquire ☹
  - especially if not planar

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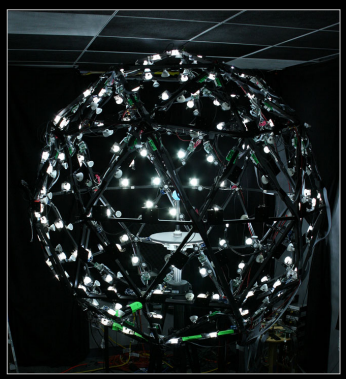
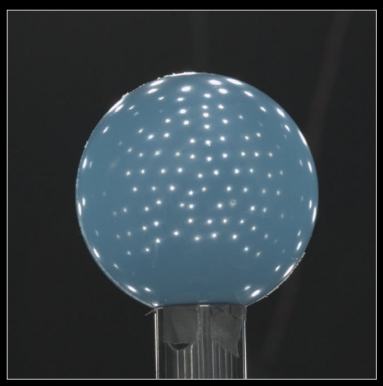
Specular materials!





LED sphere

- Discrete light stage results in hot spots of specular reflection
  - Niquist sampling problem!

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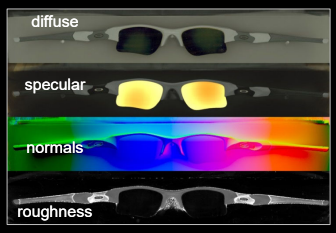
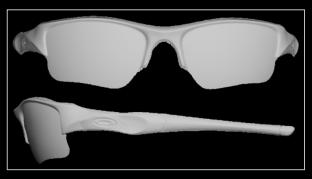
Continuous spherical harmonic illumination

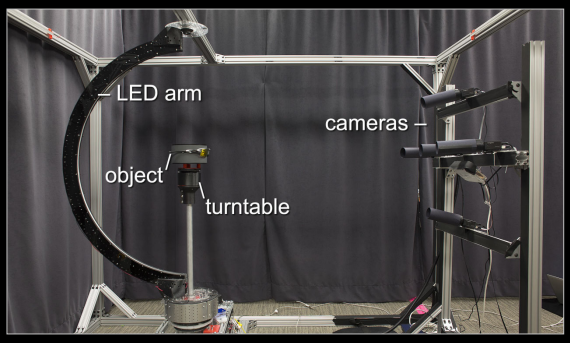
[Tunwattanpong et al. 2013]





45

Hardware setup



continuous illumination

- LED arc creates a full continuous sphere of light through rotation
  - Long exposure photography required to integrate over the entire sphere!

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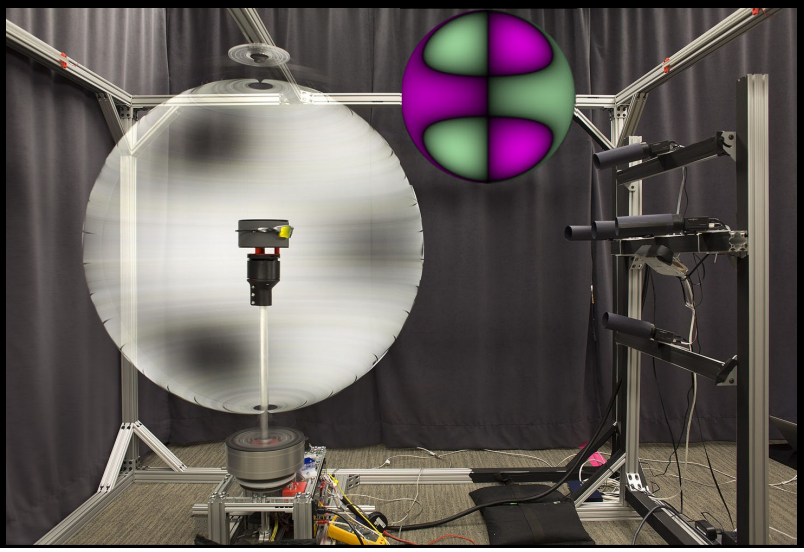
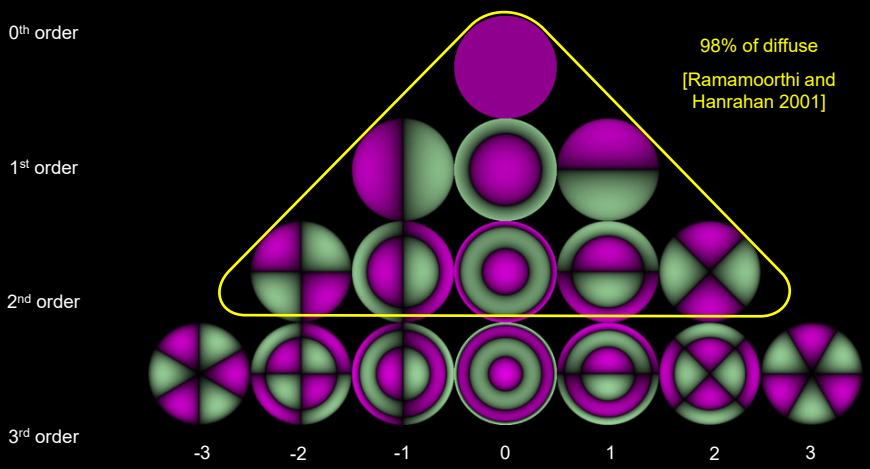
SH illumination



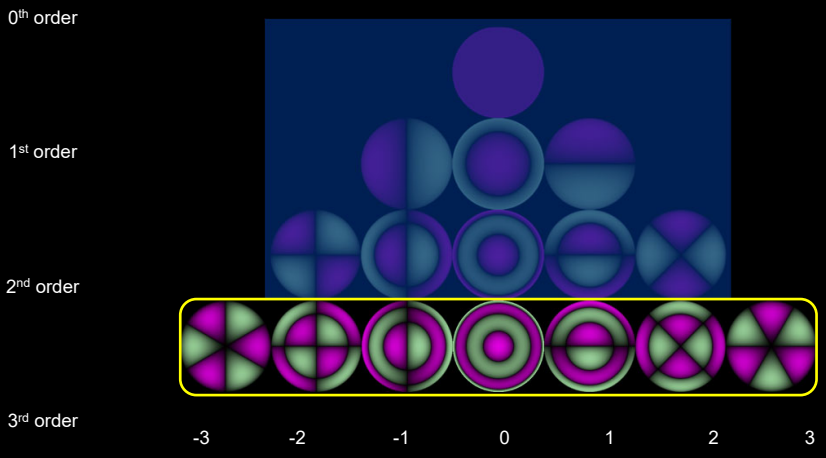
47

Diffuse-specular separation



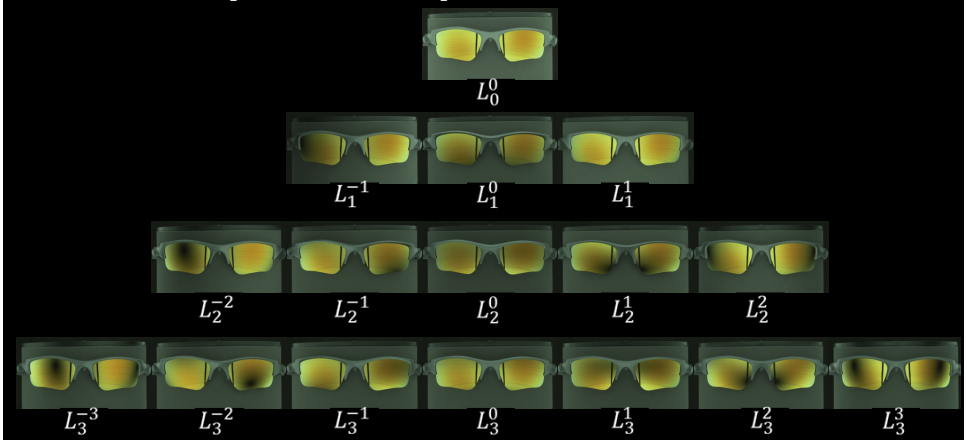
48

Specular response only!



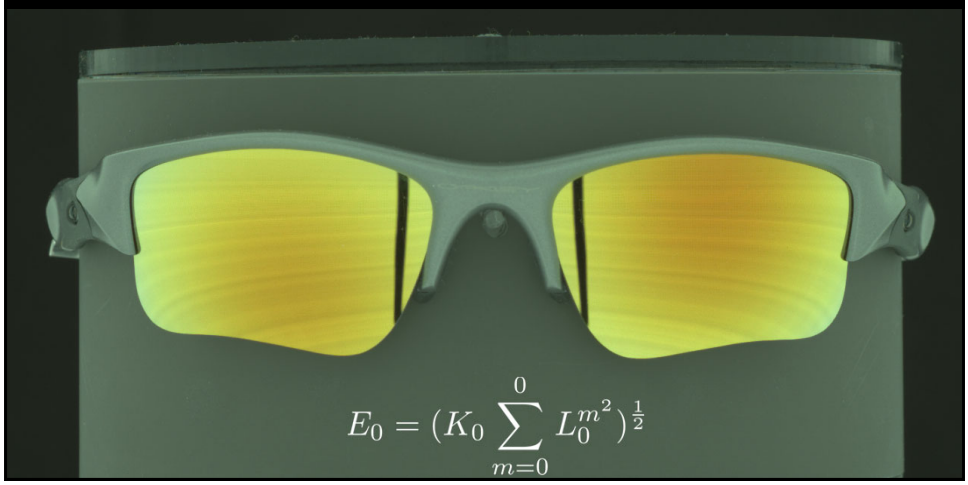
49

Diffuse-specular separation



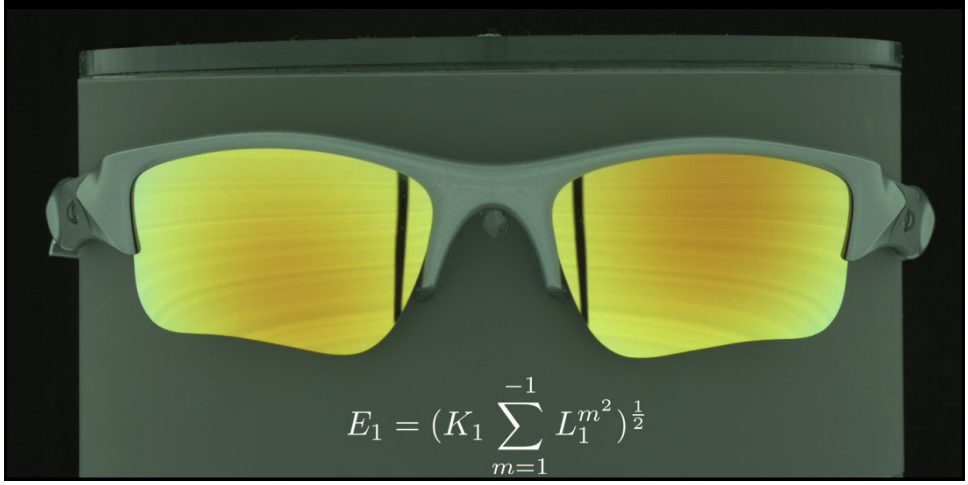
50

0th order energy



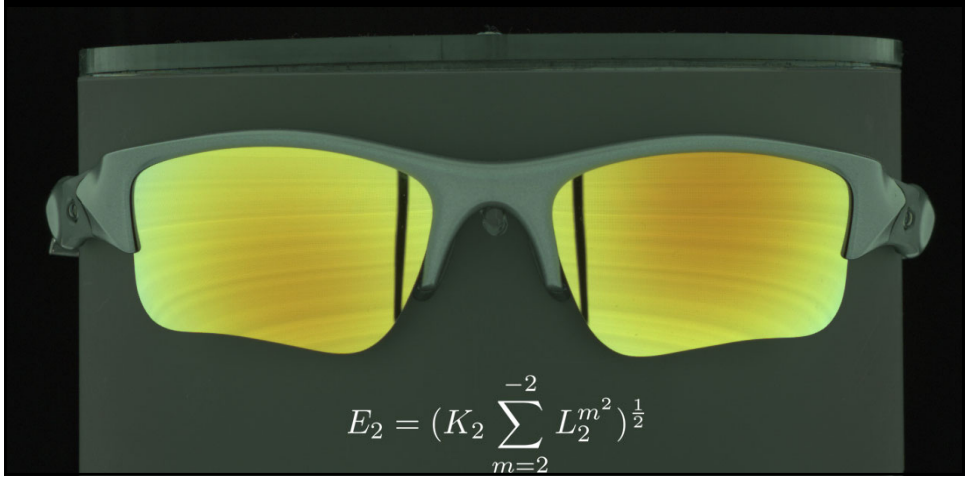
51

1st order energy



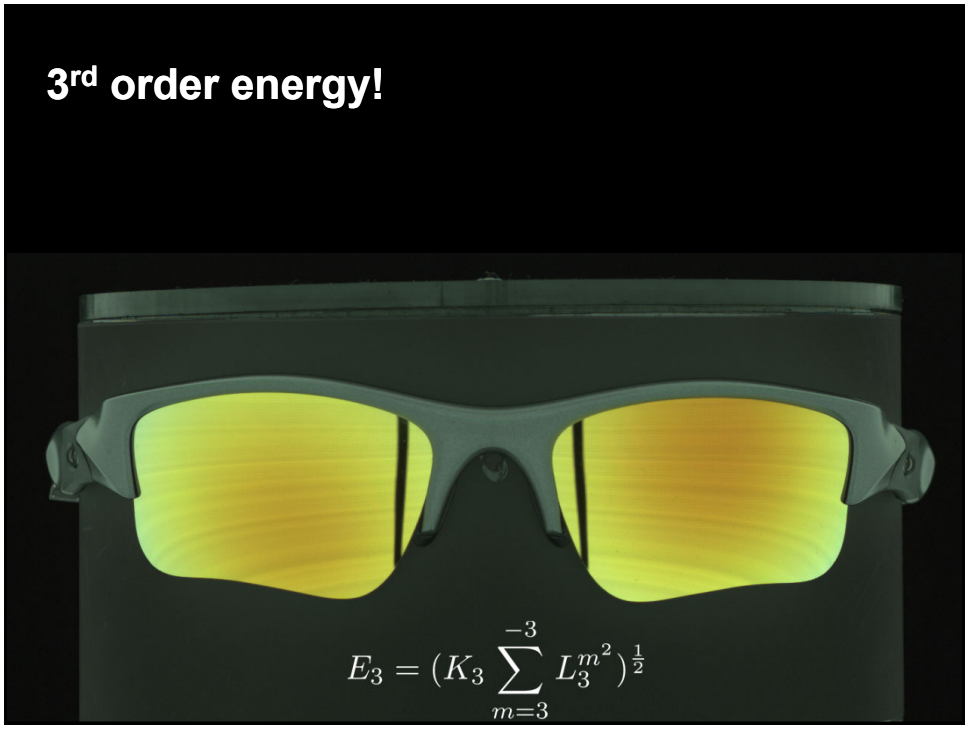
52

2nd order energy



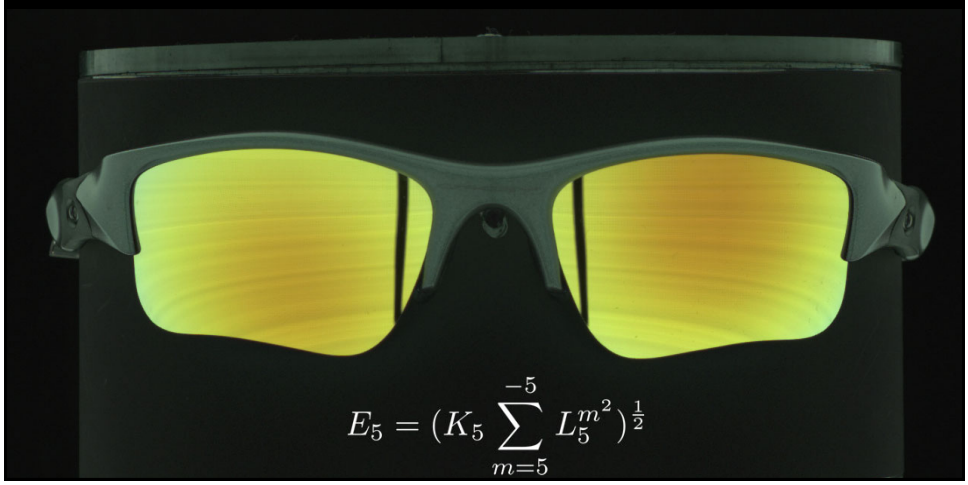
53

3rd order energy!



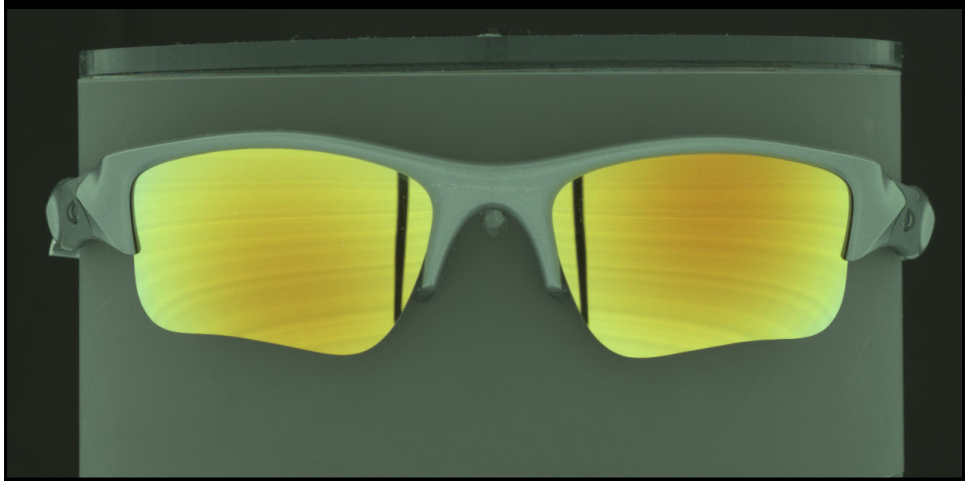
54

5th order energy!



55

Constant illumination



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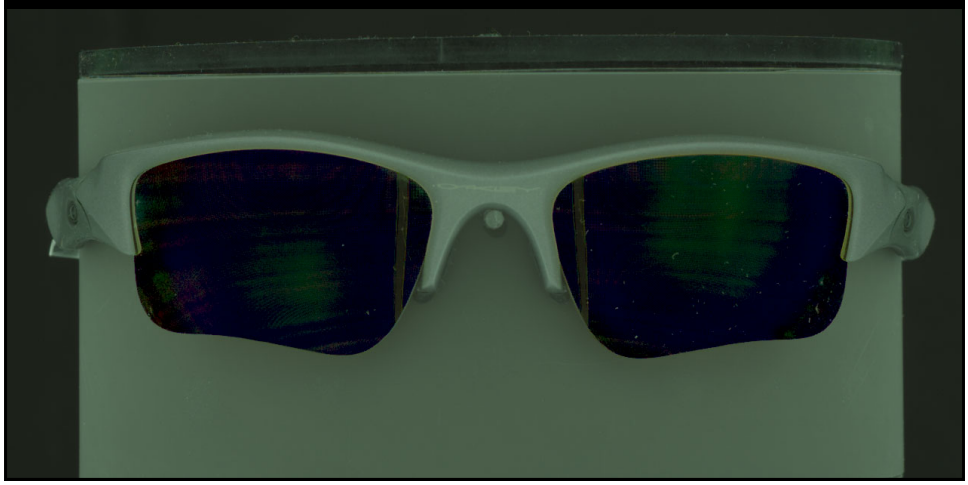
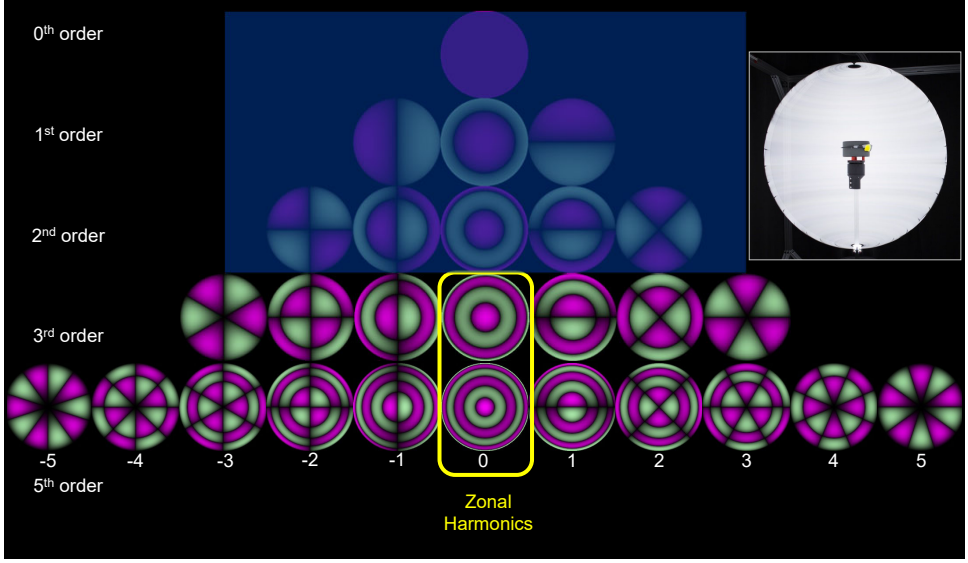
Diffuse albedo = constant - specular

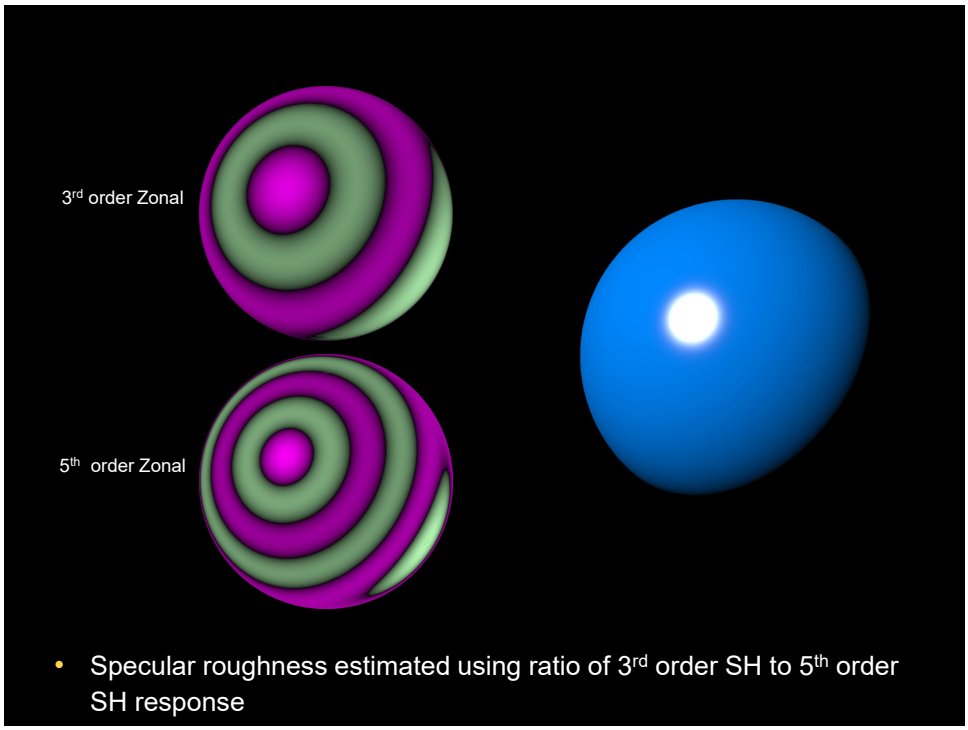


57

Reflectometry from SH



58



- Specular roughness estimated using ratio of 3rd order SH to 5th order SH response

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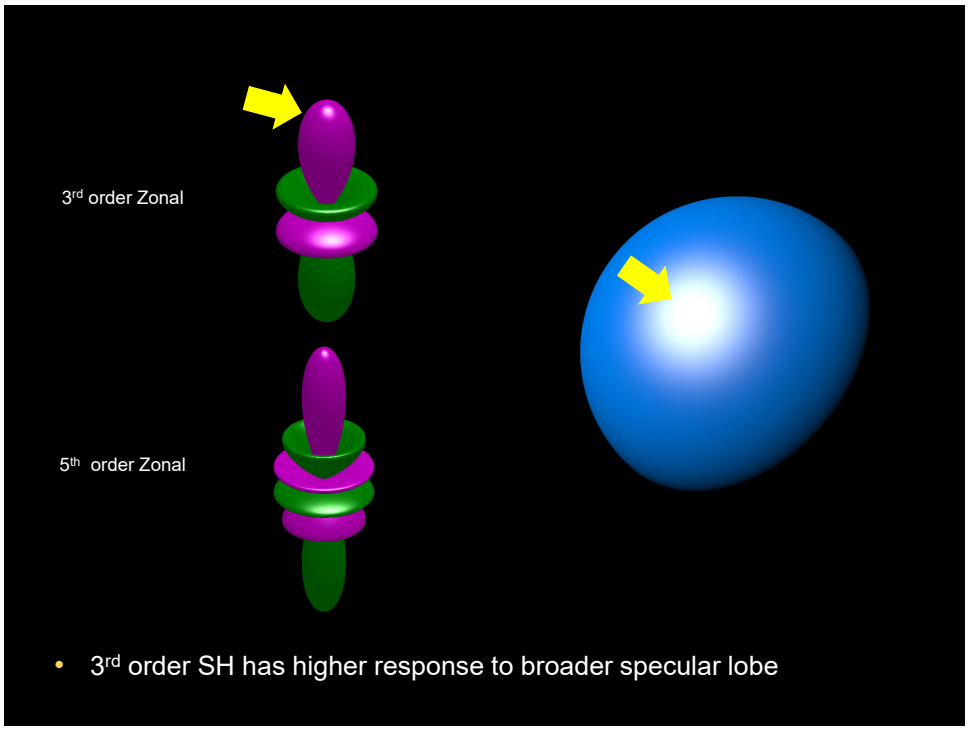
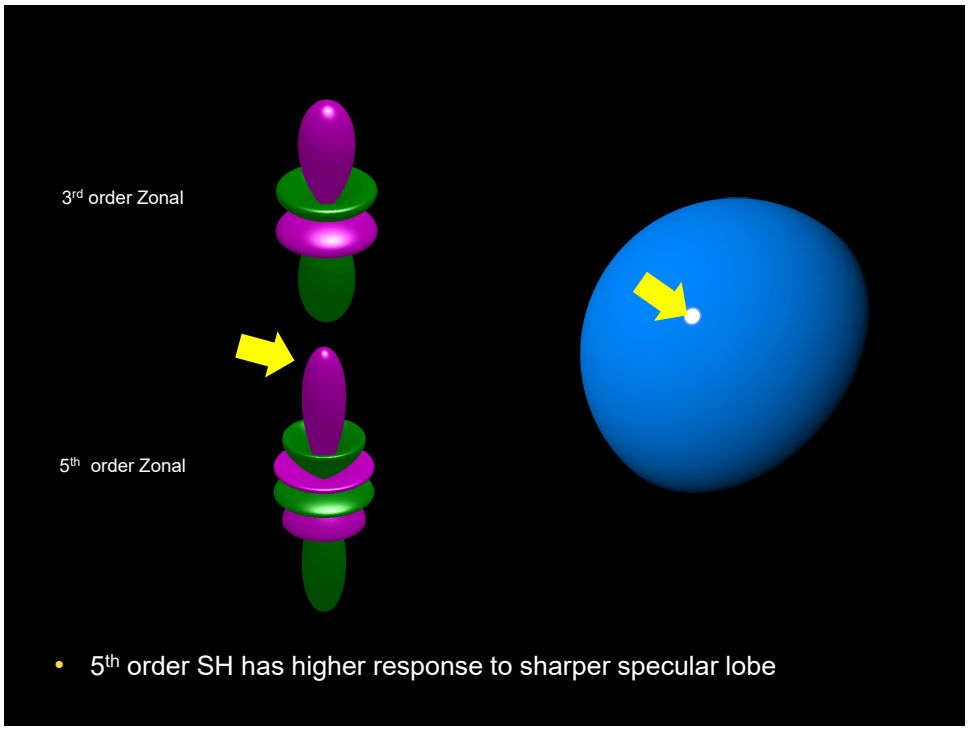


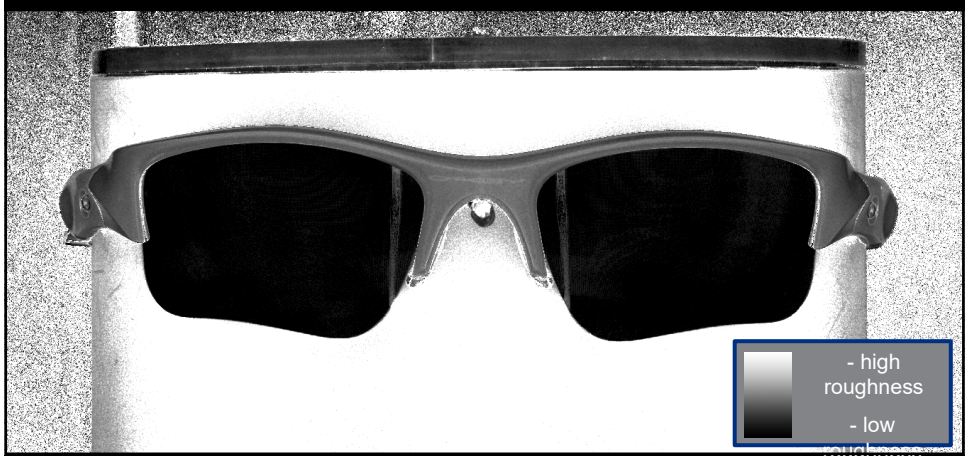
- 3rd order SH has higher response to broader specular lobe

60



61

Specular roughness



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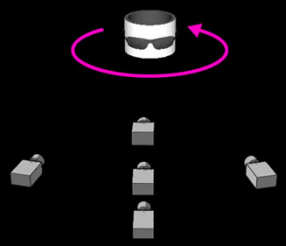
Stereo reconstruction

diffuse albedo | specular albedo | reflection vector

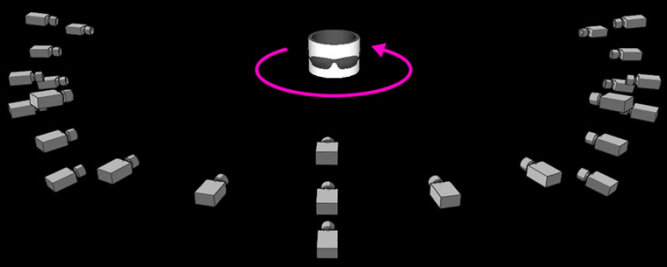


5 cameras = 5 views

63

Stereo reconstruction

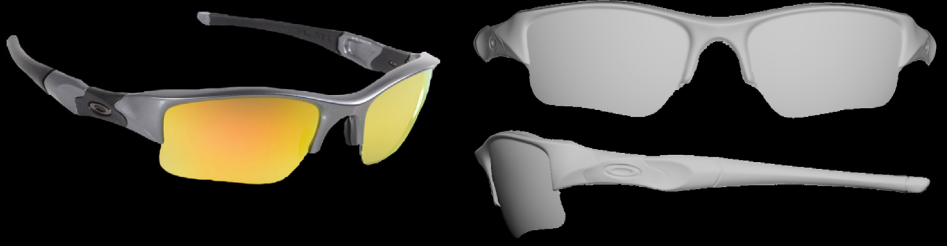
diffuse albedo | specular albedo | reflection vector



5 cameras × 5 rotations = 25 views

64

Stereo reconstruction



photograph reconstructed geometry

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Rendering with geometry & reflectance

66

Validation

rendering

photograph

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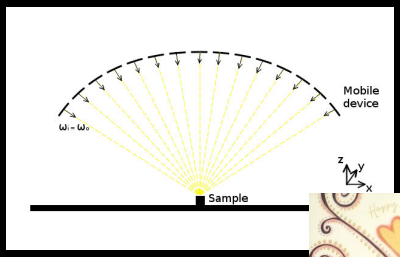
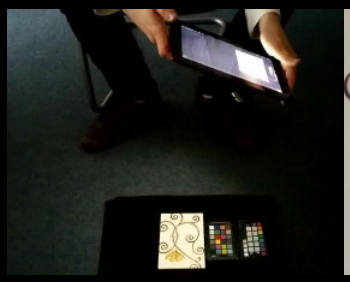
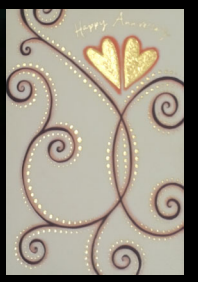
Mobile surface reflectometry

- Camera-flash pair
  - backscatter measurements
  - rough specular BRDFs

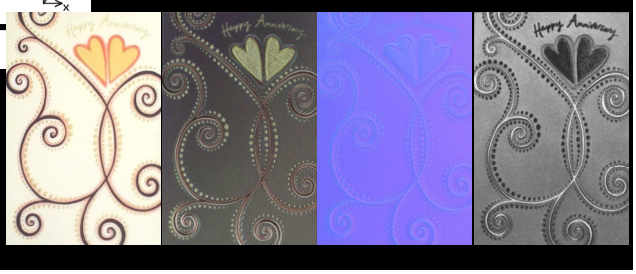






Hand-held acquisition

Rendering



J. Riviere, P. Peers, A. Ghosh

Computer Graphics Forum 2016

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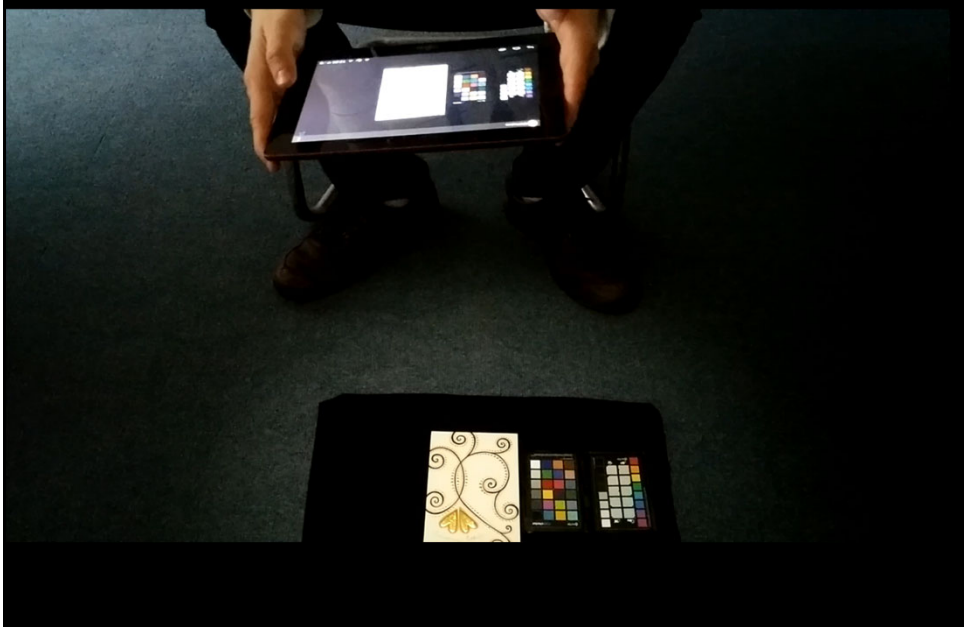
Mobile surface reflectometry

[Riviere et al. 16]



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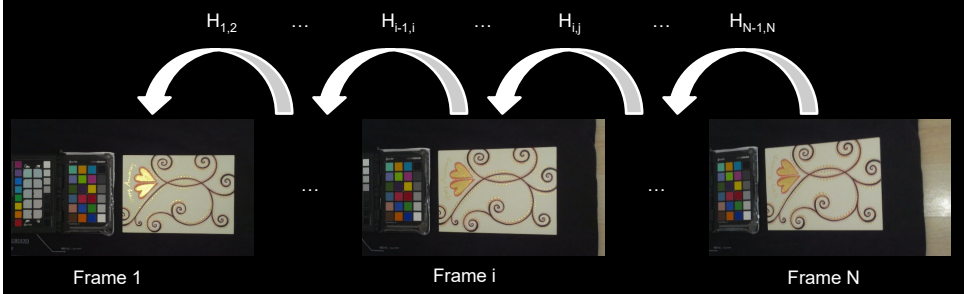
Data registration

[Riviere et al. 16]

- Feature extraction (Harris corners)
  - Matched with optical flow
- Homography-based warping



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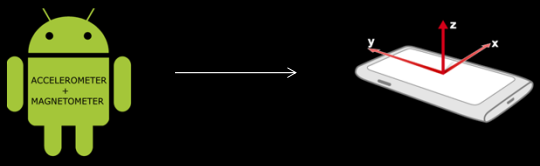
Light/view direction estimation

[Riviere et al. 16]

- $\omega_i = \omega_r$ (back scattering direction)
- Android standard API (getRotationMatrix)



- 3D tracking
  - Simultaneous Localisation And Mapping (PTAM [G. Klein and D. Murray 2007])
  - Limited to feature rich scenes
  - SfM alternate solution

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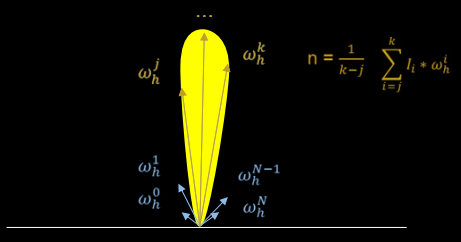
Mobile surface reflectometry

[Riviere et al. 16]

- Normal map: Weighted average



Normal map

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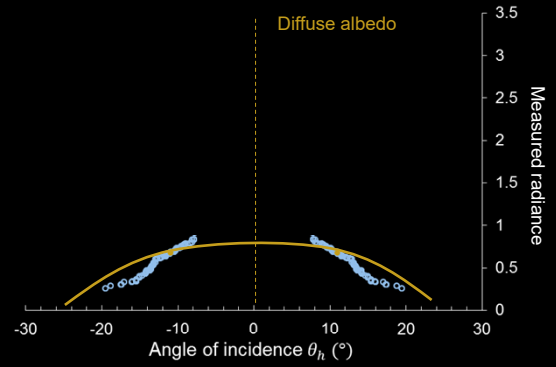
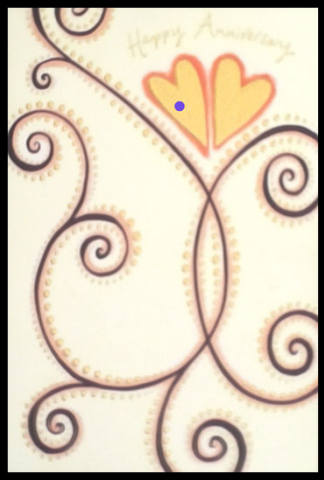
Mobile surface reflectometry

[Riviere et al. 16]

- Diffuse albedo: Median operator





Diffuse albedo map

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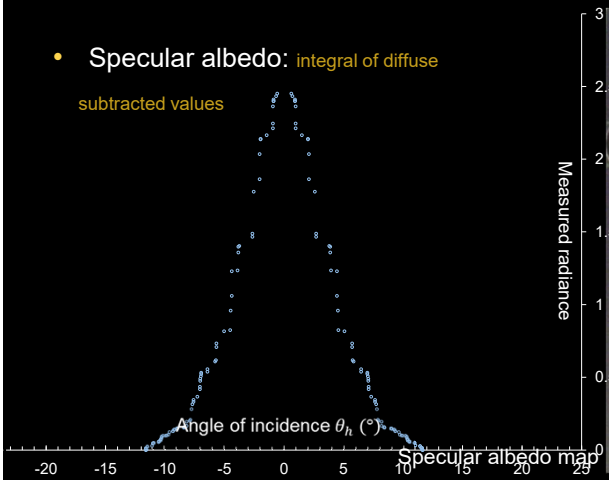
Mobile surface reflectometry

[Riviere et al. 16]

- Specular albedo: integral of diffuse subtracted values



Specular albedo map

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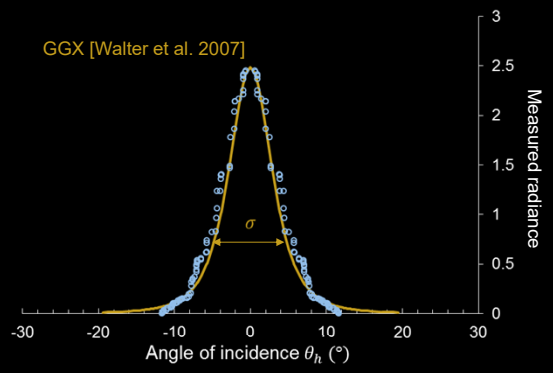
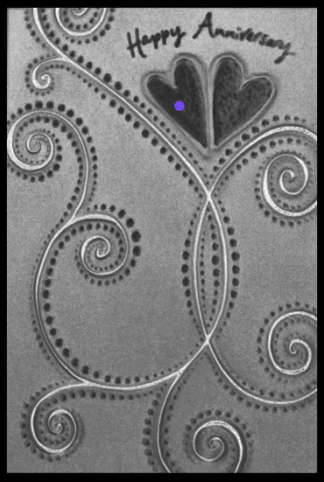
Mobile surface reflectometry

[Riviere et al. 16]

- Roughness: Microfacet BRDF fit





Roughness map

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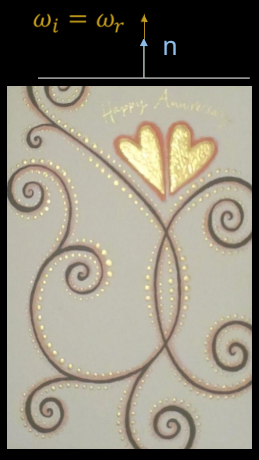
Mobile surface reflectometry

[Riviere et al. 16]

Rendering – frontal view

shaders



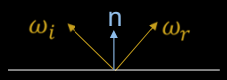
Rendering

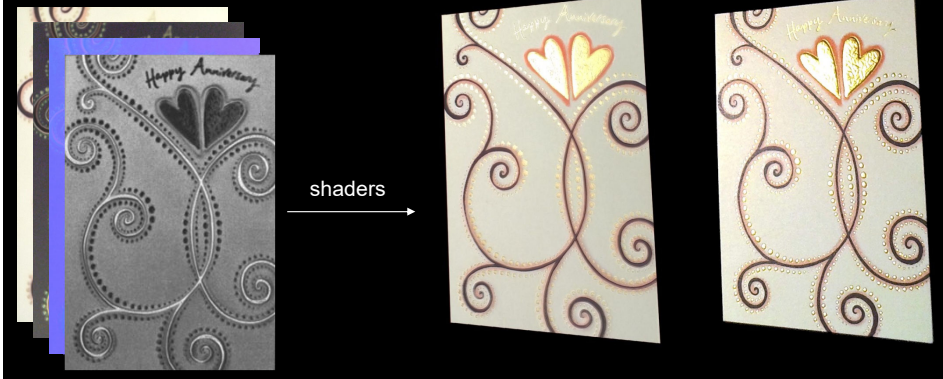
76

Mobile surface reflectometry

[Riviere et al. 16]

Rendering – novel view





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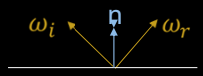
Mobile surface reflectometry

[Riviere et al. 16]

Rendering – novel view



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Summary for SVBRDF measurement

- Linear light sources
  - Hand held acquisition
  - Measure and fit – analytic or data-driven
- Frequency domain analysis
  - Second order statistics (with polarization)
  - Higher order spherical harmonics (without polarization)
- Hardware setups
  - LED sphere/arc, LCD panels
  - Mobile devices!

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Deep Learning SVBRDFs

[Deschaintre et al. 2018]

- U-net applied to predict the spatially varying appearance parameters of a planar sample seen under flash illumination.
- Estimated parameters of the planar sample include spatially varying diffuse albedo, surface normal, specular albedo and roughness.

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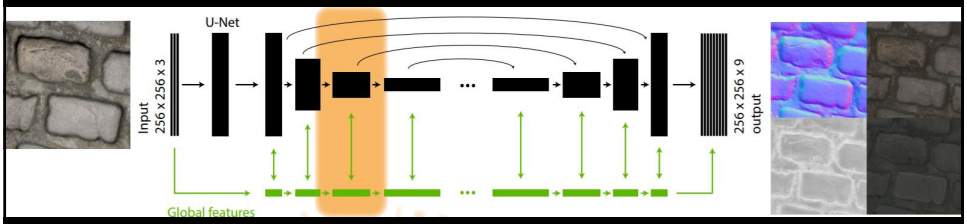
Deep Learning SVBRDFs

[Deschaintre et al. 2018]



- Unet like encoder-decoder architecture employed with skip connections
- Parallel network of global features (to deal with saturated specular highlights)
- Estimated parameters of the planar sample include spatially varying diffuse albedo, surface normal, specular albedo and roughness.

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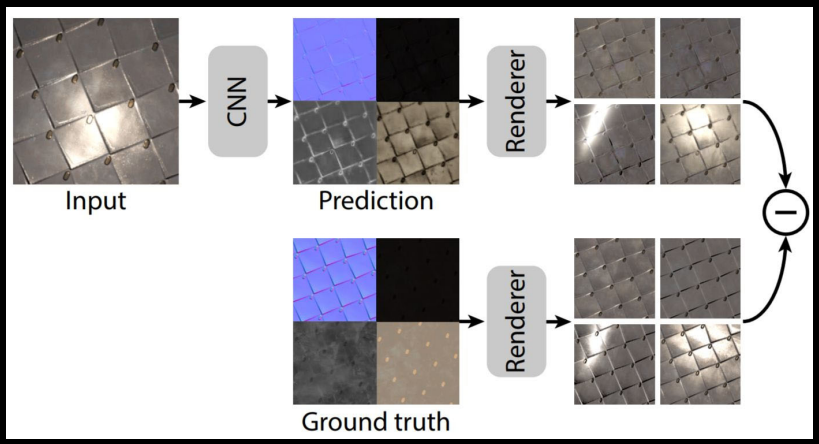
Deep Learning SVBRDFs

[Deschaintre et al. 2018]



- Training done on novel rendering loss function instead of just L1 or L2 error on the reflectance maps
- Synthetic training data – artist and procedurally created appearance maps

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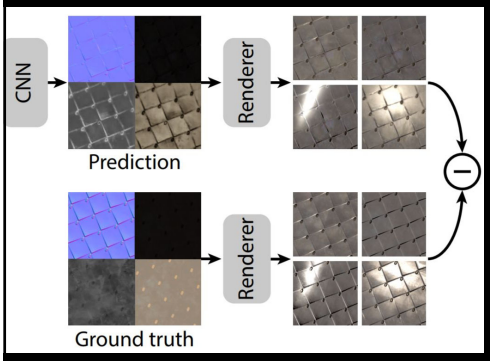
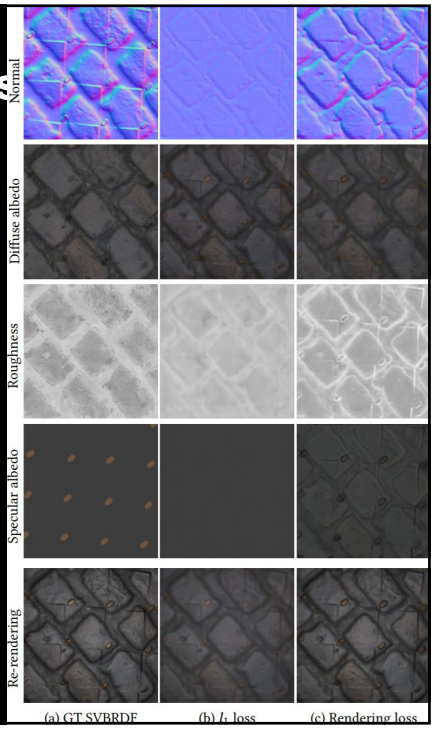
Deep Learning SVBRDFs



- Training done on novel rendering loss function instead of L1 or L2!



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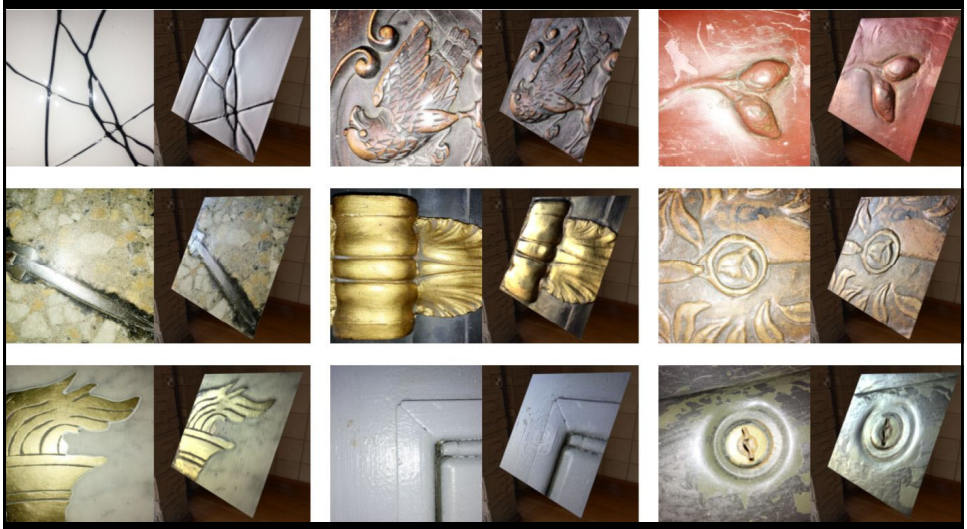
Deep Learning SVBRDFs

[Deschaintre et al. 2018]



Additional results of SVBRDF estimation from a single photograph under flash illumination

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