BMVC 2016 Tutorial:
Measurement Based Appearance Modelling

Abhijeet Ghosh
Imperial College London
Material reflectance capture techniques

BRDF

SVBRDF
Surface appearance

- Bidirectional Reflectance Distribution Function (BRDF)
  - 4D general case, 3D isotropic
  - Surface reflection at one surface point

- Spatially Varying BRDF (SVBRDF)
  - 6D, BRDF per surface point

- Bidirectional Texture Function (BTF)
  - 6D, more general includes inter-reflection & scattering
  - Data-driven representation of reflectance functions
BRDF

- Defined as the ratio of reflected radiance to incident irradiance:

\[ f_r(x, \omega_r, \omega_i) = \frac{dL_r(x, \omega_r)}{dE_i(x, \omega_i)} = \frac{dL_r(x, \omega_r)}{L_i(x, \omega_i) \cos \theta \, d\omega_i}. \]

- The units of a BRDF are inverse steradian [1/sr].
Physically based BRDFs have 2 important properties:

**Helmholtz Reciprocity:** \( f_r(x, \omega_r, \omega_i) = f_r(x, \omega_i, \omega_r) \).

and

**Energy Conservation:** \( \int_{\Omega} f_r(x, \omega_r, \omega_i) \cos \theta_i \, d\omega_i \leq 1 \), for all \( \omega_r \) in \( \Omega \).
Reflection Models

• Mathematical representation a class of BRDFs
  – typically with a small number of parameters

• Types of BRDF models
  – Phenomenological
  – Physically based

• Parameter fitting
  – Measured data
Phenomenological Models

• Equations that describe the “qualitative behavior” of surfaces
  – matte, glossy or plastic, roughness

• Examples
  – Lambertian diffuse reflection
  – Phong specular reflection [Phong75]
Lambertian Reflection

- $f_r(\omega_r, \omega_i) = \rho_d / \pi$
  - $\rho_d$ is the diffuse reflection coefficient $[0, 1]$
  - $\pi = \int_\Omega \cos \theta \, d\omega$, is the normalization constant!
  - Well suited for measurements
Glossy and Retro-reflective

- Glossy surfaces – plastic, high gloss paints, polished wood
- Retro-reflective – velvet, moon’s surface, road signs, bike reflectors
**Blinn-Phong Model**

\[ \omega_h = \frac{\omega_i + \omega_o}{||\omega_i + \omega_o||} \]

- \[ f_r(\omega_o, \omega_i) = \frac{\rho_d}{\pi} + \frac{\rho_s (n \cdot \omega_h)^s}{n \cdot \omega_i} \]
  \[ = \frac{\rho_d}{\pi} + \rho_s (\cos \theta)^s / (n \cdot \omega_i) \]
Lafortune Generalized Cosine Lobe

\[ f_r(\omega_r, \omega_i) = \rho_d / \pi + \sum_j \left[ C_{x,j} (\omega_{i.x} \cdot \omega_{r.x}) + C_{y,j} (\omega_{i.y} \cdot \omega_{r.y}) + C_{z,j} (\omega_{i.z} \cdot \omega_{r.z}) \right]^{s,j} \]

- Off-specularity, retro-reflection, anisotropy
- Well suited for measured data!
Ward Anisotropic Model

Generlization of microfacet model to account for anisotropy!

\[
f_r(\omega_r, \omega_i) = \frac{\rho_d}{\pi} + \rho_s \frac{1}{\sqrt{\cos\theta_i \cos\theta_r}} \exp[-\tan^2 \delta (\cos^2 \varphi/\alpha_x^2 + \sin^2 \varphi/\alpha_y^2)]
\]

- elliptical Gaussians, \( \alpha_x \) & \( \alpha_y \) control standard deviation in \( x \) & \( y \)
- energy preserving & reciprocal
Physically Based: Microfacet Model

\[ f_r(\omega_r, \omega_i) = D(\omega_h) \frac{G(\omega_r, \omega_i) F_r(\omega_h)}{4 \left( n \cdot \omega_i \right) \left( n \cdot \omega_i \right)} \]

- \( D \), the distribution term
- \( G \), the geometric term
- \( F \), the Fresnel term
Torrance-Sparrow Model

- \( D(\omega_h) = \exp[-\tan(\delta/m)]^2 \)  \hspace{1cm} \text{Beckman distribution}  
  \[
  m^2 \cos^4 \delta
  \]
  \[
  \delta, \text{ angle between } n \text{ and } \omega_h
  \]
  \[
  m, \text{ root-mean-square slope of microfacets}
  \]

- \( G(\omega_r, \omega_i) = \min\{1, \frac{2 (n \cdot \omega_h) (n \cdot \omega_r)}{(\omega_r \cdot \omega_h)}, \frac{2 (n \cdot \omega_h) (n \cdot \omega_i)}{(\omega_r \cdot \omega_h)} \} \)

- \( \text{V-shaped grooves} \)
Fresnel Reflectance

- Reflection from a surface is view dependent

- **Fresnel** equations
  - Maxwell’s equations at smooth surfaces
  - index of refraction and polarization!

- Two kinds of Fresnel equations:
  - Dielectric materials (insulators) – reflection & transmission
  - Conductors (metals) – only reflection & some absorption
Dielectric Fresnel

- Fresnel reflectance for parallel polarized light $r_{\parallel}$:
  \[
  R_{\parallel} = \left( \frac{\eta_t \cos \theta_i - \eta_i \cos \theta_t}{\eta_t \cos \theta_i + \eta_i \cos \theta_t} \right)^2
  \]

- Fresnel reflectance for perpendicular polarized light $r_{\perp}$:
  \[
  R_{\perp} = \left( \frac{\eta_i \cos \theta_i - \eta_t \cos \theta_t}{\eta_i \cos \theta_i + \eta_t \cos \theta_t} \right)^2
  \]

- Unpolarized reflectance $F_r = \frac{1}{2} (R_{\parallel} + R_{\perp})$.
  - Transmittance $T_r = 1 - F_r$. 
Dielectrics

- $R_p$ – parallel polarized, $R_s$ – perpendicular polarized
- Schlick approximation given reflectance $R_0$
Conductors Fresnel

- No transmission, but some absorption $k$:

\[
R_{\parallel} = \frac{(\eta^2 + k^2) \cos \theta_i^2 - 2\eta \cos \theta_i + 1}{(\eta^2 + k^2) \cos \theta_i^2 + 2\eta \cos \theta_i + 1}
\]

And

\[
R_{\perp} = \frac{(\eta^2 + k^2) - 2\eta \cos \theta_i + \cos \theta_i^2}{(\eta^2 + k^2) + 2\eta \cos \theta_i + \cos \theta_i^2}
\]
Conductors Fresnel

- No transmission, complex index of refraction: $\eta$, $k$
- High reflectance across angles of incidence
BRDF Measurement

• Analytical models have limitations
  – describe specific kinds of surfaces
  – appropriate parameters not easy to obtain!

• Measurement of BRDFs a solution
  – direct usage as tabulated data
  – fit to analytic models or basis functions
Dense Measurements

- Gonioreflectometer
  - Cornell, CUReT, NIST
  - Missing measurements interpolation!
Goneo-reflectometer

DMS 803
6 motorised axis

SOC210-BDR
LED-based Measurement

- LEDs as emitters as well as sensors!
- Parallel measurements with point sampling

[Ben-Ezra et al. 08]
Image-based Measurements

Isotropic 100 BRDFs

[Marschner et al. 00]

[Matusik et al. 03]

100 BRDFs MERL database
Data-driven BRDF Representation

Spherical Sample
(Isotropic BRDF = 3D function)
Data-driven BRDF Representation

Camera (fixed position)
Data-driven BRDF Representation

Light Source

measurement every 0.5 degree rotation
Data-driven BRDF Representation

More than 100 different BRDFs

20-80M Reflectance Measurements per Material
Reparameterization

Standard
Reparameterization

Incident: $\omega_i = (\theta_i, \Phi_i)$
Reparameterization

\[ \omega_i = (\theta_i, \Phi_i) \]

\[ \omega_o = (\theta_o, \Phi_o) \]
Reparameterization

Incident: \( \omega_i = (\theta_i, \Phi_i) \)
Exitant: \( \omega_o = (\theta_o, \Phi_o) \)

Halfway: \( \omega_h = (\theta_h, \Phi_h) \)
Reparameterization

Incident: $\omega_i = (\theta_i, \Phi_i)$
Exitant: $\omega_o = (\theta_o, \Phi_o)$
Halfway: $\omega_h = (\theta_h, \Phi_h)$
Difference: $\omega_d = (\theta_d, \Phi_d)$
Reparameterization

Advantage:

Specular highlight

Around halfway vector

\( \omega_h = 0 \)

\[ \omega_h = (\theta_h, \Phi_h) \]

Difference:

\[ \omega_d = (\theta_d, \Phi_d) \]
Reparameterization

\[ \omega_i \]

\[ \omega_0 \]

Standard
Reparameterization

Full Rank!
Reparameterization

\[ \omega_i \]

\[ \omega_d \]

\[ \omega_o \]

\[ \omega_h \]

Standard

Rusinkiewicz
Reparameterization

Standard

Rusinkiewicz

Low Rank!
Reparameterization

Sample Densely
Reparameterized data

Tabulated: $90 (\theta_h) \times 90 (\theta_d) \times 360 (\phi_d)$

• Easy to use in rendering system

Disadvantages:

• Requires 17Mb / BRDF
• 12 Hours to capture
Direct Visualization (Tabulated)

nickel

hematite

gold paint

pink fabric
Data-driven BRDF Representations

Data-driven Analysis

- Linear Data Analysis (PCA)
- Non-linear Data Analysis
- BRDFs as data driven basis

[Matusik et al. 2003]
Linear Data Analysis (PCA)

- Linearize each BRDF in a (long) vector
- Apply PCA on all these vectors
- Keep n largest principal vectors

45 components = approx. 1% error
Linear Data Analysis (PCA)

- Linearize each BRDF in a (long) vector
- Apply PCA on all these vectors
- Keep $n$ largest principal vectors

![Images depicting the linear data analysis process with different angles and means.]
PCA space exploration
Problem: non-physical BRDFs

45D space contains non-physical BRDFs

Measured BRDF
(point A in 45D space)

Non-physical BRDF
(point close to A in 45D space)
Why does it fail?
Why does it fail?

PCA
Why does it fail?

PCA
Why does it fail?

Move a little => fall outside measured space
Why does it fail?

non-linear manifold
Why does it fail?

non-linear manifold
Why does it fail?

Only move over manifold!
Non-linear Data Analysis

Local Linear Projections

Local Linear Embedding
Non-linear Data Analysis

Local Linear Projections

Minimize projection Error

Local Linear Embedding
Non-linear Data Analysis

Charter Method [Brand 2003]: kernel-based mixtures of projections that minimizes distortions of local neighborhoods

15 components = approx. 1% error
Non-linear manifold exploration
BRDFs as Basis Functions

Representing a new BRDF as a linear combination of the 100 measured BRDFs

\[
\sum_{i=1}^{N} \alpha_i \]
Solution

Linear equation: $b = Pa$

$b =$ linearized BRDF (4M x 1) (new data)

$P =$ matrix of all BRDFs (4M x 100) (MERL database)

$a =$ unknowns (100 x 1)

Hugely over-constrained

(many more knowns than unknowns)
Alternate randomized solution

- 800 rows from the original P (randomly selected)

\[ b' = P'a \]

- \( b' = 800 \times 1 \) vector
- \( P' = 800 \times 100 \) vector
- \( a = 100 \times 1 \) vector

- 800 \((\omega_i, \omega_o)\) samples (measurements)
BRDFs as Basis Functions

BRDFs based on 800 samples

Dark-red paint: 1.8%
Gold paint: 1.8%
Orange plastic: 4.3%
Aluminum bronze: 2.5%
Optimal BRDF sampling

- Up to 5 views sufficient for spherical samples
- Fitting based on projection to space spanned by 100 MERL BRDFs
# Optimal BRDF sampling

[Neilson et al. 15]

## Suggested minimal measurements

<table>
<thead>
<tr>
<th>Material</th>
<th>$n = 1$</th>
<th>$n = 2$</th>
<th>$n = 5$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>black-soft-plastic</td>
<td><img src="black-soft-plastic.png" alt="Image" /></td>
<td><img src="black-soft-plastic.png" alt="Image" /></td>
<td><img src="black-soft-plastic.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>blue-acrylic</td>
<td><img src="blue-acrylic.png" alt="Image" /></td>
<td><img src="blue-acrylic.png" alt="Image" /></td>
<td><img src="blue-acrylic.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>blue-metallic-paint2</td>
<td><img src="blue-metallic-paint2.png" alt="Image" /></td>
<td><img src="blue-metallic-paint2.png" alt="Image" /></td>
<td><img src="blue-metallic-paint2.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>green-fabric</td>
<td><img src="green-fabric.png" alt="Image" /></td>
<td><img src="green-fabric.png" alt="Image" /></td>
<td><img src="green-fabric.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>cayman [Cornell]</td>
<td><img src="cayman.png" alt="Image" /></td>
<td><img src="cayman.png" alt="Image" /></td>
<td><img src="cayman.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>garnet-red [Cornell]</td>
<td><img src="garnet-red.png" alt="Image" /></td>
<td><img src="garnet-red.png" alt="Image" /></td>
<td><img src="garnet-red.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>krylon-blue [Cornell]</td>
<td><img src="krylon-blue.png" alt="Image" /></td>
<td><img src="krylon-blue.png" alt="Image" /></td>
<td><img src="krylon-blue.png" alt="Image" /></td>
<td></td>
</tr>
</tbody>
</table>
Image-based Measurements

Anisotropic

[Ward 92]

[Ward 92] 

[Ngan et al. 05] 

Cylinder (1D normal variation) with stripes of the material at different orientations (1D)

Rotation of cylinder (1D)

Light source path (1D)
Catadioptric Measurements

Mirrors

Kuthirummal & Nayar 06

Dana 01

Concave parabolic mirror
(reflected rays)
(incident ray)
(surface point)
Catadioptric Measurements

[Image of a diagram showing a setup with a camera, projector, beam-splitter, mirrored dome, parabolic mirror, and sample, labeled accordingly.]
Catadioptric Measurements

- Mukaigawa et al. point sample the BRDF
- Ghosh et al. project basis functions
Basis Illumination

- Zonal basis functions (related to spherical harmonics)
- Coefficients of BRDF in the basis recorded

\[ \hat{f}_r(\omega_i, \omega_o) = f_r(\omega_i, \omega_o) \cos \theta_i \approx \sum_k z_k(\omega_i) z_k(\omega_o), \]

\[ z_k(\omega_o) = \int_{\Omega} z_k(\omega_i) f_r(\omega_i, \omega_o) \cos \theta_i \, d\omega_i. \]

Measurement Zone

[Ghosh et al. 07]
Basis Illumination

- Zonal basis functions (related to spherical harmonics)
- Coefficients of BRDF in the basis recorded

[Image of a setup with labels: Camera, Beam-splitter, Projector, Mirrored dome, Parabolic mirror, Sample]

[Colorful spheres in a grid]

[Reference: Ghosh et al. 07]
SVBRDF (Spatially Varying BRDFs)

- 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/Frequency domain modeling
Linear Light Source Reflectometry

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

Diffuse Intensity  Specular Intensity  Specular Roughness

Translucency  Normals (X & Y gradients)  Displacement
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
Reflectance trace for each pixel

X-axis: time (light motion)

Y-axis: reflectance

Diffuse peak $t_d$ coincides with light aligned with surface normal

Specular peak $t_m$ coincides with light aligned with mirror reflection
BRDF Fitting

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

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

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

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

1. Fit diffuse
2. Subtract diffuse
3. Estimate mean and variance of specular
Pocket Reflectometry

+ BRDF Chart

+ Mobile Phone Camera

Ren et al. SIGGRAPH 2011
Pocket Reflectometry
# BRDF Chart

<table>
<thead>
<tr>
<th>Material</th>
<th>Material</th>
<th>Material</th>
<th>Material</th>
<th>Material</th>
<th>Material</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>plaster</td>
<td>sliver paint</td>
<td>rubber</td>
<td>polished acrylic</td>
<td>aluminium</td>
<td>fluorescent paint</td>
<td></td>
</tr>
<tr>
<td>matte tape</td>
<td>black paper</td>
<td>polished resin</td>
<td>bronze</td>
<td>bronze metallic paint</td>
<td>acrylic</td>
<td></td>
</tr>
<tr>
<td>plastic</td>
<td>brass</td>
<td>coated metallic paint</td>
<td>polyethylene</td>
<td>red metallic paint</td>
<td>alumina</td>
<td></td>
</tr>
<tr>
<td>80% Spectralon</td>
<td>leather</td>
<td>matte golden paint</td>
<td>alum-bronze</td>
<td>tinfoil</td>
<td>lactoprene</td>
<td></td>
</tr>
</tbody>
</table>
Pocket Reflectometry

(a)

(b)
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
Dynamic time warping

- Alignment of reflectance traces of BRDF chart with sample
Reflectance estimation from chart

\[ r = d a + s b, \]

\[ a(t) = \int_{\Omega^+} L_t(i) \alpha(i, o) (n \cdot i) di, \quad b(t) = \int_{\Omega^+} L_t(i) \beta(i, o) (n \cdot i) di, \]

\[ \min_{u_0, u_1, \ldots, u_k} \left\| r - u_0 a - \sum_{j=1}^{k} u_j b_j \right\|, \quad u_j \geq 0, \quad b_j \in \Phi(r) \]

- a diffuse BRDF with albedo d
- b specular BRDF with parameters s
- Instead of direction estimation of s, estimate a linear combination of k exemplar BRDFs in BRDF chart
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
Bumpy surface results
Flat surface results
Measure and fit

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

- Is DIRECT estimate possible?
2nd order statistics of reflectance

[ Ghosh et al. 09 ]

- Specular reflection
  - measure of variance $\sigma^2$ about mean $\mu$
  - reflection vector and specular roughness
  - computational illumination for optical measurement of reflectance statistics!
In 1D, the moments of $f(x)$:

- total energy $\alpha$
- mean $\mu$
- variance $\sigma^2$

\[\alpha = \int f(x) \, dx = L_0,\]
\[\mu = \int x \frac{f(x)}{\alpha} \, dx,\]
\[= \frac{1}{\alpha} \int x f(x) \, dx = \frac{L_1}{L_0},\]
\[\sigma^2 = \int (x - \mu)^2 \frac{f(x)}{\alpha} \, dx,\]
\[= \frac{L_2}{L_0} - \frac{L_1^2}{L_0^2}.\]
0th spherical moment

\[ L_0 = \int_{\Omega} f(\bar{\omega}) \, d\bar{\omega}, \]

parallel

cross

\( \alpha \)
1st spherical moment

\[ L_1 = \int_{\Omega} \bar{\omega} f(\bar{\omega}) d\bar{\omega}, \]

\( \mu \)
2\textsuperscript{nd} spherical moment

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

\( \sigma^2 \)
Need to compute statistics in local shading frame!

- Isotropic material
- Anisotropic material
Spherical harmonics

- 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
Spherical harmonics

- Anisotropic material
  - $\sigma_x^2$ and $\sigma_y^2$
Isotropic reflectance

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

spec. normal  spec. albedo  anisotropy \((\sigma_x/\sigma_y)\)  tangent  bitangent  rendering  photograph
Flat sample

- Project 2\textsuperscript{nd} order gradients from LCD screen
  - Sufficient to cover specular lobe of flat samples

- Screen is already polarized
  - Diffuse specular separation
Flat sample

- Project 2\textsuperscript{nd} order gradients from LCD screen
  - Sufficient to cover specular lobe of flat samples

- Screen is already polarized
  - Diffuse specular separation
Specular materials!
Specular materials!

LED sphere
Continuous spherical harmonic illumination

[Tunwattanpong et al. 2013]
Hardware setup

- LED arm
- object
- turntable
- cameras -

continuous illumination
SH illumination
Diffuse-specular separation

98% of diffuse
[Ramamoorthi and Hanrahan 2002]
Specular response only!

0\textsuperscript{th} order

1\textsuperscript{st} order

2\textsuperscript{nd} order

3\textsuperscript{rd} order
Diffuse-specular separation
0th order energy

\[ E_0 = \left( K_0 \sum_{m=0}^{0} L_m^2 \right)^{\frac{1}{2}} \]
$E_1 = \left( K_1 \sum_{m=1}^{-1} L_{1}^{m^2} \right)^{1/2}$
$2^{\text{nd}}$ order energy

\[ E_2 = \left( K_2 \sum_{m=2}^{-2} L_2^m \right)^{\frac{1}{2}} \]
3rd order energy!

\[ E_3 = \left( K_3 \sum_{m=3}^{-3} L_3^m \right)^{\frac{1}{2}} \]
$E_5 = (K_5 \sum_{m=5}^{-5} L_5^{m^2})^{\frac{1}{2}}$
Constant illumination
Diffuse albedo
Reflectometry from SH

- $0^{th}$ order
- $1^{st}$ order
- $2^{nd}$ order
- $3^{rd}$ order
- $5^{th}$ order

Zonal Harmonics
$3^{rd}$ order Zonal

$5^{th}$ order Zonal
3rd order Zonal

5th order Zonal
3rd order Zonal

5th order Zonal
Specular roughness

- low roughness
- high roughness
Stereo reconstruction

diffuse albedo  specular albedo  reflection vector

5 cameras = 5 views
Stereo reconstruction

- diffuse albedo
- specular albedo
- reflection vector

5 cameras × 5 rotations = 25 views
Stereo reconstruction

photograph

reconstructed geometry
Rendering with geometry & reflectance
Fourier basis measurement [Aitalla et al. 2013]

- Fourier basis illumination
  - Spectrum decay measure of glossiness
Fourier basis measurement [Aitalla et al. 2013]

- Fourier basis illumination
  - Spectrum decay measure of glossiness
  - Surface normal inferred from position (phase of Fourier basis) on screen
Fourier basis measurement

[Aitalla et al. 2013]
Polarization imaging reflectometry [Ghosh et al. 2010]

- Constant uniform illumination!
  - Circularly polarized

- Measurement of Stokes parameters
Polarization imaging reflectometry  [Ghosh et al. 2010]

- Stokes parameters

\[
\begin{align*}
S_0 &= I \\
S_1 &= Ip \cos 2\psi \cos 2\chi \\
S_2 &= Ip \sin 2\psi \cos 2\chi \\
S_3 &= Ip \sin 2\chi
\end{align*}
\]

Poincare sphere

Right-hand circularly polarized
Polarization imaging reflectometry \[\text{[Ghosh et al. 2010]}\]

- Stokes reflectance field
  - Mueller calculus

\[ s' = C(\phi)D(\delta; n)R(\theta; n)C(-\phi)s \]

\[ C = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\phi & -\sin 2\phi & 0 \\ 0 & \sin 2\phi & \cos 2\phi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \]

\[ R = \begin{pmatrix} R_{||} + R_{\perp} & R_{||} - R_{\perp} & 0 & 0 \\ \frac{R_{||}^2 - R_{\perp}^2}{2} & \sqrt{R_{||} R_{\perp}} & 0 & 0 \\ 0 & 0 & \frac{R_{||}^2 + R_{\perp}^2}{2} & \sqrt{R_{||} R_{\perp}} \\ 0 & 0 & 0 & \sqrt{R_{||} R_{\perp}} \end{pmatrix} \]

Stokes Reflectance Field

Magnitude

Angle
Polarization imaging reflectometry [Ghosh et al. 2010]

- Stokes reflectance field
  - Mueller calculus

\[ s' = C(\phi)D(\delta; n)R(\theta; n)C(-\phi)s \]
Polarization imaging reflectometry [Ghosh et al. 2010]
Polarization imaging reflectometry [Ghosh et al. 2010]
Mobile camera-flash measurements!

Stationary materials [Aittala et al. 15]

Isotropic SVBRDFs [Riviere et al. 16]
Stationary materials [Aitalla et al. 2015]

- Two shot capture!
  - Ambient + flash image
  - Repeating texture/material
  - Statistical appearance sharing
Stationary materials [Aitalla et al. 2015]
## Stationary materials [Aitalla et al. 2015]

<table>
<thead>
<tr>
<th>Diffuse albedo</th>
<th>Specular albedo</th>
<th>Anisotropy</th>
<th>Glossiness</th>
<th>Normals</th>
<th>Photo (center)</th>
<th>Relit master (center illum.)</th>
<th>Photo (side)</th>
<th>Relit master (side illum.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fabric_orange</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wood_dark</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>book_brown</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>paint_black</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wood_door</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>metal_scratches</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Mobile surface reflectometry

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

[Riviere et al. 16]
Data registration

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

\[ H_{1,2} \quad \ldots \quad H_{i-1,i} \quad \ldots \quad H_{i,j} \quad \ldots \quad H_{N-1,N} \]

Frame 1  \quad \ldots \quad \text{Frame } i \quad \ldots \quad \text{Frame } N

[Riviere et al. 16]
Light/view direction estimation

- $\omega_i = \omega_r$ (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
Mobile surface reflectometry

- Normal map: **Weighted average**

\[
n = \frac{1}{k-j} \sum_{i=j}^{k} I_i \ast \omega_{i}^k
\]
• Diffuse albedo: Median operator
Mobile surface reflectometry

- Specular albedo: **MC integration**

dBRDF [M. Ashikmin and S. Premoze 2007]

\[
f_T(\omega_i, \omega_r) = \frac{c}{2 \cos \theta_i - \cos^2 \theta_i}
\]

Measured radiance

Specular albedo map
• Roughness: Microfacet BRDF fit

GGX [Walter et al. 2007]
Mobile surface reflectometry

Rendering – frontal view

[Equation: $\omega_i = \omega_r$]
Mobile surface reflectometry

Rendering – novel view

[Riviere et al. 16]
Mobile surface reflectometry

Rendering – novel view

[Riviere et al. 16]
Material appearance recap ...
Thank You!