Appearance Capture and Modeling

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University of Bonn, Germany
Motivation

- Cultural Heritage
- Visual Prototyping
- Advertisement
- Entertainment
- ...
Motivation

Product advertisement

Cultural Heritage

Food "photography"

Paleontology
Motivation

Product advertisement

Accurate reproduction of characteristic „look“ and „feel“

Cultural Heritage

Food „photography“

Paleontology
Example “Moulages”

Moulage collection at the Department of Dermatology of the University of Bonn
Photographs by Beatrice Bieber
Example “Moulages”

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Moulage “Psoriasis of the nails and the hand”
Example “Moulages”

Dermatology of the University of Bonn
Photographs by Beatrice Bieber

Moulage “Psoriasis of the nails and the hand”
Motivation

- Acquisition and faithful reproduction of appearance of 3D objects
Motivation

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Motivation

- Acquisition and faithful reproduction of appearance of 3D objects
Complexity of Visual Material Appearance

- Material appearance reveals details!
Complexity of Visual Material Appearance

- Material appearance reveals details!
Motivation

- Pipeline

Acquisition -> Modeling -> Transmission and Rendering
Course Outline

1) Introduction
2) Preliminaries of Material Appearance
3) Advances in Appearance Capture
4) Advances in Appearance Modeling
5) Advances in Transmission and Rendering
6) Applications, Novel Trends and Conclusions
Preliminaries of Material Appearance
What is Material Appearance?

- The visual impression of a material on a human observer
- Material appearance reveals details!
Complexity of Visual Material Appearance

- Material appearance reveals details!
Appearance Depends on …

- **Shape**
  - Pose
  - Scale
- **Optical material properties**
  - Color
  - Texture
  - Reflectance behavior
- **Illumination**
  - Different spectral composition (daylight, different house lamps, etc.)
- **Observer**
  - Focus
  - Adaption to brightness
  - Color constancy (discount chromatic bias of illumination)
  - …
Appearance Depends on …

- **Shape**
  - Pose
  - Scale

- **Optical material properties**
  - Color
  - Texture
  - Reflectance behavior

- **Illumination**
  - Different spectral composition (daylight, different house lamps, etc.)

- **Observer**
  - Focus
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Geometry on different scales

Different light direction reveals different details

https://www.wikipedia.org/

Object dependend!

https://www.wired.com/

Object independend!
Complexity of Visual Material Appearance

- Main aspect: surface appearance
  - Different light/view → different look

Ganesha figurine made from labradorite
Why is it so difficult to model material appearance?

- Complex meso-geometry (rough textures)
- Subsurface scattering
- Varying microscopic reflection parameters
- View- and light dependent shadows
- Occlusions
- Local/global illumination effects
How to measure faithfulness?

- Image comparison

Material + Shape + varying poses

Reconstruction

\[ d(\text{orig}, \text{copy}) := \arg \max_{\text{poses}, \text{illum.}} d_{\text{image}}(\text{image}_{\text{orig}}, \text{image}_{\text{copy}}) \]
Complexity of Visual Material Appearance
Properties of Light

\[ \mathbf{r}: \mathbb{R}^+ \rightarrow \mathbb{R}^3 \]

\[ \mathbf{s} \mapsto \mathbf{o} + s \mathbf{d}, \quad \mathbf{s} \in \mathbb{R} \]

http://www.exo.net/~pauld/summer_institute/summer_day8polarization/day8_polarization.html
Properties of Light

- Monochromatic light vs. polychromatic light

\[ r: \mathbb{R}^+ \rightarrow \mathbb{R}^3 \]

\[ s \mapsto o + s \, d, \quad s \in \mathbb{R} \]
Properties of Light

- Monochromatic light vs. polychromatic light
- Polarized light vs. non-polarized light

**Ray Direction and Origin**

\[ \mathbf{r} : \mathbb{R}^+ \to \mathbb{R}^3 \]

\[ s \mapsto \mathbf{o} + s \mathbf{d}, \quad s \in \mathbb{R} \]

http://www.exo.net/~pauld/summer_institute/summer_day8polarization/day8_pol
arization.html
Light Interaction at Surfaces

\[ \lambda_i, t_i \]

\[ \xi_i \]

\[ \phi_i \]

\[ \theta_i \]

\[ \lambda_r, t_r \]

\[ \xi_r \]

\[ \phi_r \]

\[ \theta_r \]
Object Appearance

- Impression of reflection of incident light
- Influenced by features on different scales
Object Appearance

- Impression of reflection of incident light
- Influenced by features on different scales
  - Macroscopic
Object Appearance

- Impression of reflection of incident light
- Influenced by features on different scales
  - Macroscopic
  - Mesoscopic
Object Appearance

- Impression of reflection of incident light
- Influenced by features on different scales
  - Macroscopic
  - Mesoscopic
  - Microscopic
Object Appearance

- Impression of reflection of incident light
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Object Appearance

- Impression of reflection of incident light
- Influenced by features on different scales
  - Macroscopic
  - Mesoscopic
  - Microscopic
- Viewpoint and illumination dependent
Mesoscopic Effects

Self-Occlusion
Mesoscopic Effects

Self-Occlusion
Mesoscopic Effects

Self-Occlusion  Self-Masking
Mesoscopic Effects

Self-Occlusion

Self-Masking
Mesoscopic Effects

- Self-Occlusion
- Self-Masking
- Interreflection
Mesoscopic Effects

Self-Occlusion

Self-Masking

Interreflection

Local Subsurface Scattering
Mesoscopic Effects

- Self-Occlusion
- Self-Masking
- Interreflection
- Local Subsurface Scattering
# A Taxonomy of Surface Classes

<table>
<thead>
<tr>
<th>object type</th>
<th>surface / volume type</th>
<th>class</th>
<th>image formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>opaque</td>
<td>surface, rough</td>
<td>1</td>
<td>diffuse or near diffuse reflectance</td>
</tr>
<tr>
<td></td>
<td>surface, glossy</td>
<td>2</td>
<td>mixed diffuse and specular reflectance</td>
</tr>
<tr>
<td>translucent</td>
<td>surface, smooth</td>
<td>3</td>
<td>ideal or near ideal specular reflectance</td>
</tr>
<tr>
<td>transparent</td>
<td>surface, sub-surface scattering</td>
<td>4</td>
<td>multiple scattering underneath surface</td>
</tr>
<tr>
<td>inhomogeneous</td>
<td>surface, smooth</td>
<td>5</td>
<td>ideal or near ideal specular refraction</td>
</tr>
<tr>
<td></td>
<td>volume, emission / absorption</td>
<td>6</td>
<td>integration along viewing ray</td>
</tr>
<tr>
<td></td>
<td>volume, single scattering</td>
<td>7</td>
<td>integration along viewing ray</td>
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<td></td>
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<td>8</td>
<td>full global light transport without occluders</td>
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<td>mixed scenes, containing many / all of the above</td>
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[Ihrke et al. 2008]
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[Ihrke et al. 2008]
Surface Classes

Diffuse Reflectance

\[ L_{\text{diffuse}} = L_i \ k_{\text{diffuse}} \cos \theta \]

\[ = L_i \ k_{\text{diffuse}} n \ d_i \]

Glossy Reflectance

\[ L_{\text{diffuse}} = L_{\text{diffuse}} + L_{\text{specular}} \]

Specular Reflectance

\[ d_{o,\text{ideal}} = 2 \ n \ (n \ d_i) - d_i \]
Surface Classes

Surfaces with Subsurface Scattering

Refractive Surfaces

\[ \eta_1 \sin \theta_1 = \eta_2 \sin \theta_2 \]
Consider \textit{reflectance field} \\
\[ R(x_i, \omega_i; x_o, \omega_o) \]
parametrized on the sphere that transfers \\
- incident light field \( L_i(x_i, \omega_i) \) \\
to corresponding \\
- outgoing light field \( L_o(x_o, \omega_o) \)

- Note that the scene might be arbitrarily complex
Reflectance Fields

- Light transport is linear:

\[ L_{o,L_i1+L_i2}(x_o, \omega_o) = L_{o,L_i1}(x_o, \omega_o) + L_{o,L_i2}(x_o, \omega_o) \]

- Image-based relighting equation

\[ L_o(x_o, \omega_o) = \int_S \int_{\Omega_i(x_i)} R(x_i, \omega_i; x_o, \omega_o) L_i(x_i, \omega_i) \, d\omega_i \, dx_i \]

eight dimensional reflectance field
Commonly Used Reflectance Models

- **general function (12D)**
  \[ \rho(x_i, y_i, \theta_i, \varphi_i, \lambda_i, t_i, x_r, y_r, \theta_r, \varphi_r, \lambda_r, t_r) \]

- **RF / BSSRDF (8D)**
  \[ \rho_{RF/BSSRDF}(x_i, y_i, \theta_i, \varphi_i, x_r, y_r, \theta_r, \varphi_r) \]

- **SVBRDF (6D)**
  \[ \rho_{SVBRDF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

- **BSSDF (6D)**
  \[ \rho_{BSSDF}(x_r - x_i, y_r - y_i, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

- **SLF (4D)**
  \[ \rho_{SLF}(x, y, \theta_r, \varphi_r) \]

- **SRF (4D)**
  \[ \rho_{SRF}(x, y, \theta_i, \varphi_i) \]

- **BRDF (4D)**
  \[ \rho_{BRDF}(\theta_i, \varphi_i, \theta_r, \varphi_r) \]

- **Texture Maps / Bump Maps (2D)**
  \[ \rho_{Texture \ Map \ / \ Bump \ Map}(x, y) \]
Calibration
Calibration

- Determine relationships between components
Calibration

- Determine relationships between components
  - Geometric relations
Calibration

- Determine relationships between components
  - Geometric relations
Calibration
- Determine relationships between components
  - Geometric relations
Calibration

- Determine relationships between components
  - Geometric relations
Calibration

- Determine relationships between components
  - Geometric relations
  - Radiometric relations
Geometric Calibration
Camera Calibration

- Measurement geometry (of each image)
Camera Calibration

- Measurement geometry (of each image)
- Position & orientation
Camera Calibration

- Measurement geometry (of each image)
- Position & orientation
  - Measured sample
Camera Calibration

- Measurement geometry (of each image)
- Position & orientation
  - Measured sample

} Turntable
Camera Calibration

- Measurement geometry (of each image)
- Position & orientation
  - Measured sample
  - Camera

{Turntable}
Camera Calibration

- Measurement geometry (of each image)
- Position & orientation
  - Measured sample
  - Camera
  - Light source
  } Turntable
Camera Calibration

- Measurement geometry (of each image)
- Position & orientation
  - Measured sample  \{ Turntable \\
  - Camera  \} Center of projection, sensor, view frustum, ...
  - Light source
Camera Calibration

- Measurement geometry (of each image)
- Position & orientation
  - Measured sample
  - Camera
  - Light source

Turntable
Center of projection, sensor, view frustum, ...

Required for 3 tasks:
Camera Calibration

- Measurement geometry (of each image)
- Position & orientation
  - Measured sample
  - Camera
  - Light source

Turntable

Center of projection, sensor, view frustum, ...

Required for 3 tasks:
1. Reconstructing surface geometry
Camera Calibration

- Measurement geometry (of each image)
- Position & orientation
  - Measured sample
  - Camera
  - Light source

Required for 3 tasks:
1. Reconstructing surface geometry
2. Mapping: camera pixels $\mapsto$ surface
Camera Calibration

- Measurement geometry (of each image)
- Position & orientation
  - Measured sample
  - Camera
  - Light source

Required for 3 tasks:
1. Reconstructing surface geometry
2. Mapping: camera pixels $\mapsto$ surface
3. Sampled directions?

Turntable
Center of projection, sensor, view frustum, ...
Camera Calibration
Camera Calibration

- Model of projection
  15 parameters/camera
Camera Calibration

- Model of projection
  15 parameters/camera

- Feature in captured image
Camera Calibration

- **Model of projection**
  15 parameters/camera

- Feature in captured image
- Prediction of camera model
Camera Calibration

- Model of projection
  15 parameters/camera

- Feature in captured image
- Prediction of camera model
- Minimize reprojection error
Camera Calibration

- Model of projection
  15 parameters/camera

- Feature in captured image

- Prediction of camera model

- Minimize *reprojection error*

- Utilize standard solutions:
  - Zhang’s algorithm [Zha00]
  - Bundle Adjustment [LA09]
Camera Calibration
Camera Calibration

1. Identify markers [MS13]
Camera Calibration

1. Identify markers [MS13]
2. Zhang’s algorithm
1. Identify markers [MS13]
2. Zhang’s algorithm
   “single camera sees target from different angles”
Camera Calibration

1. Identify markers [MS13]
2. Zhang’s algorithm
   “single camera sees target from different angles”
   ➔ board is rotated in front of camera
1. Identify markers [MS13]
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   “single camera sees target from different angles”
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3. Bundle Adjustment
1. Identify markers [MS13]
2. Zhang’s algorithm
   “single camera sees target from different angles”
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3. Bundle Adjustment
   “many cameras see a common static scene”
Camera Calibration

1. Identify markers [MS13]
2. Zhang’s algorithm
   “single camera sees target from different angles”
   → board is rotated in front of camera
3. Bundle Adjustment
   “many cameras see a common static scene”
Camera Calibration

1. Identify markers [MS13]
2. Zhang’s algorithm
   “single camera sees target from different angles”
   ➔ board is rotated in front of camera
3. Bundle Adjustment
   “many cameras see a common static scene”
   ➔ no rotations
   ➔ forget relation between rotated markers
- Model of turntable
- **Model of turntable**
  - Axis of rotation
  - Center of rotation
Turntable Calibration

- Model of turntable
  - Axis of rotation
  - Center of rotation
- Some 3D point

![Model of turntable with axis of rotation, center of rotation, and a 30° rotation angle. A 3D point is also shown on a flat surface.](image)
Turntable Calibration

- Model of turntable
  - Axis of rotation
  - Center of rotation
- Some 3D point
- Different rotations
Turntable Calibration

- **Model of turntable**
  - Axis of rotation
  - Center of rotation
- Some 3D point
- Different rotations
- Prediction of 0° pose
Turntable Calibration

- **Model of turntable**
  - Axis of rotation
  - Center of rotation
- Some 3D point
- Different rotations
- Prediction of $0^\circ$ pose
- Minimize deviation
Turntable Calibration
Turntable Calibration

- 300°
- 310°
- 320°
- 330°
- 340°
- 350°
- 0°
- 10°
- 20°
- 30°
- 40°
- 50°
- 60°
Turntable Calibration
Turntable Calibration
Fit plane to all points (PCA)
Turntable Calibration

Fit plane to all points (PCA) → normal
Turntable Calibration

Fit plane to all points (PCA) → normal

Axis of rotation
Turntable Calibration

Fit plane to all points (PCA) → normal

Center of rotation

Axis of rotation
Turntable Calibration

Fit plane to all points (PCA) → normal

Axis of rotation

Center of rotation

Linear Least Squares; closed form solution
Turntable Calibration

Fit plane to all points (PCA)
→ normal
Light Source Calibration
Light Source Calibration

Cam1
0°

Cam6
15°

Cam11
60°
Light Source Calibration

1. Identify LED reflections
Light Source Calibration

1. Identify LED reflections
2. Raytracing
Light Source Calibration

1. Identify LED reflections
2. Raytracing
Light Source Calibration

1. Identify LED reflections
2. Raytracing
Light Source Calibration

1. Identify LED reflections
2. Raytracing
3. Triangulation [HZ04]
Light Source Calibration

1. Identify LED reflections
2. Raytracing
3. Triangulation [HZ04]
4. Nonlinear optimization [Lev44]
Light Source Calibration

1. Identify LED reflections
2. Raytracing
3. Triangulation [HZ04]
4. Nonlinear optimization [Lev44]
   - LED- & ball-positions
Calibration Results
Calibration Results

- Camera accuracy:
Calibration Results

- Camera accuracy:
  - 0.16 pixels reprojection error
Calibration Results

- Camera accuracy:
  - 0.16 pixels reprojection error
Calibration Results

- Camera accuracy:
  - 0.16 pixels reprojection error
  → 0.001° direction error
Calibration Results

- Camera accuracy:
  - 0.16 pixels reprojection error
    $\rightarrow$ 0.001° direction error
- Turntable accuracy:
  - 0.003° pose deviation
Calibration Results

- Camera accuracy:
  - 0.16 pixels reprojection error
    → 0.001° direction error

- Turntable accuracy:
  - 0.003° pose deviation

- LED accuracy:
  - 0.4 pixels reprojection error
Calibration Results

- Camera accuracy:
  - 0.16 pixels reprojection error
  \[ \rightarrow 0.001^\circ \text{ direction error} \]
- Turntable accuracy:
  - 0.003° pose deviation
- LED accuracy:
  - 0.4 pixels reprojection error
  \[ \rightarrow 0.08^\circ \text{ direction error} \]
Radiometric Calibration
Radiometric Calibration

- Determine the relation between scene and image brightness
  - **before** light arrives at the image plane:
    - **Scene** ➔ **Scenen-radiance** \( L \) ➔ **Lens** ➔ **Image-irradiance** \( E \)

  **Linear relationship!**

- **after**:
  - **Image-irradiance** \( E \) ➔ **Camera electronics** ➔ **measure pixel values** \( I \)

  **Nonlinear Relationship!**
Radiometric Calibration

- Determine the relation between scene and image brightness
  - **before** light arrives at the image plane:
    - Scene \( \rightarrow \) Scenen-radiance \( L \) \( \rightarrow \) Lens \( \rightarrow \) Image-irradiance \( E \)
    - Linear relationship!

- **after**:
  - Image-irradiance \( E \) \( \rightarrow \) Camera electronics \( \rightarrow \) measure pixel values \( I \)
    - Nonlinear Relationship!

**photometric calibration**
Radiometric Calibration

- Camera Response Curve (OECF):
  - Describes relationship between RGB-values and corresponding luminance and is a-priori unknown (and often non-linear)
    - Gamma correction
    - Image (color) optimizations
  - Direct measurement via test chart
    - Patches with known gray levels
    - Uniform illumination
  - Inversion using OECF leads to pixel values linearly related to luminance values

What do these RGB values mean?

© xritephoto.com
Radiometric Correction

\[ \text{et} = 50\text{ms} \]
Radiometric Correction

1. Removal of the effect of hot pixels or sensor bias (dark frame subtraction)

\[
\begin{align*}
\text{et} = 50\text{ms} & \quad \begin{array}{c}
\text{image} \\
\text{frame}
\end{array}
\end{align*}
\]
1. Removal of the effect of hot pixels or sensor bias (dark frame subtraction)

2. Inversion of camera response to obtain energy values from the observed pixel values

\[
\begin{align*}
\text{et} = 50\text{ms} \\
\end{align*}
\]
Radiometric Correction

1. Removal of the effect of hot pixels or sensor bias (dark frame subtraction)
2. Inversion of camera response to obtain energy values from the observed pixel values
Radiometric Correction

1. Removal of the effect of hot pixels or sensor bias (dark frame subtraction)

2. Inversion of camera response to obtain energy values from the observed pixel values
Radiometric Correction

1. Removal of the effect of hot pixels or sensor bias (dark frame subtraction)

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\begin{align*}
\text{et} &= 50 \text{ms} \\
\text{et} &= 500 \text{ms}
\end{align*}
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\[
\begin{array}{c}
\begin{pmatrix}
\text{et = 50ms} \\
\text{et = 500ms}
\end{pmatrix}
\end{array}
\begin{pmatrix}
\text{[sr}^{-1}]
\end{pmatrix}
\]
Advances in Reflectance Acquisition
Motivation

- Both geometry and reflectance have to be acquired
Motivation

- Both geometry and reflectance have to be acquired
Motivation

- Both geometry and reflectance have to be acquired
Geometry Acquisition

- Shape-from-Silhouette
Geometry Acquisition

- Shape-from-Silhouette
Geometry Acquisition

- Shape-from-Silhouette
Geometry Acquisition

- Shape-from-Silhouette
Geometry Acquisition

- Shape-from-Silhouette
Geometry Acquisition

- Shape-from-Silhouette
  - Coarse geometry reconstruction
    - Misleading shape (blur due to misalignment)

Visual Hull
[Mueller et al. 2005]
Geometry Acquisition

- Shape-from-Silhouette
  - Coarse geometry reconstruction
    - Misleading shape (blur due to misalignment)

- Active Triangulation
  - Laser scanning
  - Structured light

[Diagram of Active Triangulation with Camera, Projector, and Distorted Patterns on Surface]

[Visual Hull][Mueller et al. 2005]

[Structured Light][Weinmann et al. 2011]
Geometry Acquisition

- Shape-from-Silhouette
  - Coarse geometry reconstruction
    - Misleading shape (blur due to misalignment)

- Active Triangulation
  - Laser scanning
  - Structured light
    - Highly accurate

Visual Hull [Mueller et al. 2005]
Laser Scan
Structured Light [Weinmann et al. 2011]
Geometry Acquisition
Geometry Acquisition
Geometry Acquisition

triangulation [HZ04]
Geometry Acquisition

triangulation [HZ04]

5% less accurate
Geometry Acquisition
Geometry Acquisition
Geometry Acquisition

0°  45°  90°
Geometry Acquisition
Geometry Acquisition

uncalibrated turntable
Geometry Acquisition

calibrated turntable

uncalibrated turntable
Geometry Acquisition

calibrated turntable

uncalibrated turntable
Geometry Acquisition

- Also possible for flat material samples ...
A short reminder ...

- Complexity of material appearance
A short reminder ...

- Complexity of material appearance
- Multitude of reflectance models

- Textures
- Bump maps

- General function (12D)
  \[ \rho(x_i, y_i, \theta_i, \varphi_i, \lambda_i, t_i, x_r, y_r, \theta_r, \varphi_r, \lambda_r, t_r) \]

- Fixed wavelength and time

- Spatially inhomogeneous materials
- Spatially homogeneous materials

- Reflectance function / BSSRDF (8D)
  \[ \rho_{\text{RF/BSSRDF}}(x_i, y_i, \theta_i, \varphi_i, x_r, y_r, \theta_r, \varphi_r) \]

- BTF (6D)
  \[ \rho_{\text{BTF}}(x, y, \theta_i, \varphi_i) \]

- SVBRDF (6D)
  \[ \rho_{\text{SVBRDF}}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

- BSSDF (6D)
  \[ \rho_{\text{BSSDF}}(x_r - x_i, y_r - y_i, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

- SLF (4D)
  \[ \rho_{\text{SLF}}(x, y, \theta_r) \]

- SRF (4D)
  \[ \rho_{\text{SRF}}(x, y, \theta_i, \varphi_i) \]

- BRDF (4D)
  \[ \rho_{\text{BRDF}}(\theta_i, \varphi_i, \theta_r, \varphi_r) \]

- Texture Maps / Bump Maps (2D)
  \( \rho_{\text{Texture Map / Bump Map}}(x, y) \)
Reflectance Representation

- Often: minimalistic model that allows to represent material appearance characteristics

Photo  Texture  Polynomial Texture Map  BTF
Reflectance Representation

- Often: minimalistic model that allows to represent material appearance characteristics

- Photo
- Texture
- Polynomial Texture Map
- BTF
Reflectance Representation

- Often: minimalistic model that allows to represent material appearance characteristics

Photo  Texture  Polynomial Texture Map  BTF
Reflectance Representation

- Starting point: (known) object geometry, registered images
- Store reflectance parameterized over the surface
Reflectance Representation

- Starting point: (known) object geometry, registered images
- Store reflectance parameterized over the surface
Reflectance Representation

- Starting point: (known) object geometry, registered images
- Store reflectance parameterized over the surface

intersection of viewing ray with 3D geometry + texture mapping
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Reflectance Representation

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- Store reflectance parameterized over the surface

Intersection of viewing ray with 3D geometry + texture mapping
Reflectance Representation

- Assumption:
  - Known geometry
  - Registered camera images

[Lensch et al. 2001/2003]
Reflectance Representation

- Assumption:
  - Known geometry
  - Registered camera images

[Lensch et al. 2001/2003]
Reflectance Representation

- Assumption:
  - Known geometry
  - Registered camera images
- For every point:
Reflectance Representation

- Assumption:
  - Known geometry
  - Registered camera images
- For every point:
  - Measurement
    - Tabulated
Reflectance Representation

- Assumption:
  - Known geometry
  - Registered camera images

- For every point:
  - Measurement
    - Tabulated
  - In local orientation
Reflectance Representation

- Assumption:
  - Known geometry
  - Registered camera images

- For every point:
  - Measurement
    - Tabulated
    - In local orientation
    - Local hemispheres
Reflectance Representation

- Assumption:
  - Known geometry
  - Registered camera images

- For every point:
  - Measurement
    - Tabulated
    - Camera hemispheres
    - In local orientation
    - Local hemispheres
Appearance Representation

• Gather samples
Appearance Representation

• Gather samples
Appearance Representation

- Gather samples
Appearance Representation

- Gather samples
- Not measured
Appearance Representation

• Gather samples
  • Not measured
  • Irregular
Appearance Representation

- Gather samples
- Not measured
- Irregular
- Occlusion
Appearance Representation

- Gather samples
- Not measured
- Irregular
- Occlusion
general function (12D)
\[ \rho(x_i, y_i, \theta_i, \varphi_i, \lambda_i, t_i, x_r, y_r, \theta_r, \varphi_r, \lambda_r, t_r) \]
fixed wavelength and time
RF / BSSRDF (8D)
\[ \rho_{RF/BSSRDF}(x_i, y_i, \theta_i, \varphi_i, x_r, y_r, \theta_r, \varphi_r) \]
spatially inhomogeneous materials
BTF (6D)
\[ \rho_{BTF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \]
fixed lighting
SLF (4D)
\[ \rho_{SLF}(x, y, \theta_r, \varphi_r) \]
diffuse (nearly) flat
Texture Maps / Bump Maps (2D)
\[ \rho_{Texture Map / Bump Map}(x, y) \]
fixed position
Fixed lighting
Spatially inhomogeneous materials
SVBRDF (6D)
\[ \rho_{SVBRDF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \]
fixed view
SRF (4D)
\[ \rho_{SRF}(x, y, \theta_i, \varphi_i) \]
Spatially homogeneous materials
BSSDF (6D)
\[ \rho_{BSSDF}(x_r - x_i, y_r - y_i, \theta_i, \varphi_i, \theta_r, \varphi_r) \]
opaque materials
fixed position
general function (12D)
\[ \rho(x_i, y_i, \theta_i, \varphi_i, \lambda_i, t_i, x_r, y_r, \theta_r, \varphi_r, \lambda_r, t_r) \]

fixed wavelength and time

RF / BSSRDF (8D)
\[ \rho_{RF/BSSRDF}(x_i, y_i, \theta_i, \varphi_i, x_r, y_r, \theta_r, \varphi_r) \]

spatially inhomogeneous materials

BTF (6D)
\[ \rho_{BTF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

spatially homogeneous materials

SVBRDF (6D)
\[ \rho_{SVBRDF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

spatially inhomogeneous materials

BSSDF (6D)
\[ \rho_{BSSDF}(x_r - x_i, y_r - y_i, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

fixed lighting

fixed position

SLF (4D)
\[ \rho_{SLF}(x, y, \theta_r, \varphi_r) \]

fixed view

fixed position

SRF (4D)
\[ \rho_{SRF}(x, y, \theta_i, \varphi_i) \]

fixed view

BRDF (4D)
\[ \rho_{BRDF}(\theta_i, \varphi_i, \theta_r, \varphi_r) \]

diffuse (nearly) flat

Texture Maps / Bump Maps (2D)
\[ \rho_{Texture\ Map/\ Bump\ Map}(x, y) \]
Texture Representation

- Texture Map: $\rho_{\text{Texture Map}}(x)$
  no view-/light dependency
- Texture Map: $\rho_{\text{Texture Map}}(x)$
  no view-/light dependency
Texture Representation

- Texture Map: $\rho_{\text{Texture Map}}(x)$
  no view-/light dependency
Texture Representation

- Texture Map: $\rho_{\text{Texture Map}}(x)$
  no view-/light dependency
- Dense sampling required!
  - Only per-vertex information might be too coarse
- Texture Map: $\rho_{\text{Texture Map}}(x)$
  no view-/light dependency
- Dense sampling required!
  - Only per-vertex information might be too coarse
- Which colors should be stored?
Texture Acquisition

- View selection
Texture Acquisition

- View selection
Texture Acquisition

- View selection

- Single view:
  - Projection of images onto surface geometry
  - Selection of best view based on MRF
Texture Acquisition

- View selection
  - Single view:
    - Projection of images onto surface geometry
    - Selection of best view based on MRF

\[ E = E_{\text{Data}} + E_{\text{Reg}} \]

Quality of images:
- footprint size of faces in image domain
- resolution
- gradient magnitudes over footprint
- photo-consistency

Penalizes seams between patches
Texture Acquisition

- View selection

  - Single view:
    - Projection of images onto surface geometry
    - Selection of best view based on MRF

  \[ E = E_{\text{Data}} + E_{\text{Reg}} \]

  - Multiple views:
    - Per-face blending
    - Smoothness of neighboring patches
    - Consideration of discontinuities
    - Inclusion of scale-dependency

Quality of images:
- footprint size of faces in image domain
- resolution
- gradient magnitudes over footprint
- photo-consistency

Penalizes seams between patches
Texture Acquisition

- Color adjustment:
  - Trivial for single view acquisition
Texture Acquisition

- Color adjustment:
  - Trivial for single view acquisition
  - Multi-view scenarios:
    - Determine single color value per surface point from multiple observations
    - Requires photometric adjustments
BRDF Representation

- **BRDF:** $\rho_{\text{BRDF}}(\omega_i, \omega_r)$
  
  - Suitable for flat, homogeneous materials
  
  - Various different models:
    - Parametric models
    - Non-parametric models
  
  - Measurements under varying $\omega_i, \omega_r$
Setup Designs (1/4)

- Gonioreflectometer-like setups:
  - Typically 1 camera, 1 light source
  - Sequential for $\omega_i, \omega_o$

[Hünerhoff et al. 2006]
Setup Designs (1/4)

- Gonioreflectometer-like setups:
  - Typically 1 camera, 1 light source
  - Sequential for $\omega_i, \omega_o$
  - Various flavors:
    - Different number of DOFs
    - Robot rotates sample
      - Fixed light, moving camera
      - Fixed camera, robot moves light
    - Robots move camera and light
Setup Designs (1/4)

- Gonioreflectometer-like setups:
  - Typically 1 camera, 1 light source
  - Sequential for $\omega_i, \omega_o$
  - Various flavors:
    - Different number of DOFs
    - Robot rotates sample
      - Fixed light, moving camera
      - Fixed camera, robot moves light
    - Robots move camera and light
  - Parallel measurements
Setup Designs (2/4)

- Mirror-based setups:
  - 1 camera
  - 1 light source (projector)
- Mirror-based setups:
  - 1 camera
  - 1 light source (projector)
  - Clever arrangement of components
Setup Designs (2/4)

- Mirror-based setups:
  - 1 camera
  - 1 light source (projector)
  - Clever arrangement of components
Setup Designs (2/4)

- Mirror-based setups:
  - 1 camera
  - 1 light source (projector)
  - Clever arrangement of components

[Mukaigawa et al. 2007/2009]
- Exploitation of geometric configurations:
  [Lu and Little, Marschner, Ngan and Durand, etc.]
Setup Designs (3/4)

- Exploitation of geometric configurations:
  [Lu and Little, Marschner, Ngan and Durand, etc.]
  - Spherical samples
Setup Designs (3/4)

- Exploitation of geometric configurations:
  [Lu and Little, Marschner, Ngan and Durand, etc.]

  - Spherical samples
  - Cylindrical samples
Setup Designs (3/4)

- Exploitation of geometric configurations:
  [Lu and Little, Marschner, Ngan and Durand, etc.]

- Spherical samples

- Cylindrical samples

- Samples with measured geometry
- Arrays of detectors / light sources
Representation

- SVBRDF: $\rho_{\text{SVBRDF}}(x, \omega_i, \omega_r)$
Representation

- SVBRDF: $\rho_{SVBRDF}(x, \omega_i, \omega_r)$
Representation

- $\rho_{SVBRDF}(x, \omega_i, \omega_r)$
- **SVBRDF:** $\rho_{SVBRDF}(x, \omega_i, \omega_r)$

- *Spatial distribution of mutually independent BRDFs*
- **SVBRDF**: $\rho_{SVBRDF}(x, \omega_i, \omega_r)$

- *Spatial distribution of mutually independent BRDFs*

- *Need to be stored on the true geometry*
Representation

- **SVBRDF:** $\rho_{SVBRDF}(x, \omega_i, \omega_r)$

- **Spatial distribution of mutually independent BRDFs**

- **Need to be stored on the true geometry**

- Various approaches:
  - Sparse sampling approaches (parametric)
  - Dense sampling approaches (parametric or data-driven)

[Lensch et al. 2005]
SVBRDF Acquisition

- Sparse sampling approaches:
SVBRDF Acquisition

- Sparse sampling approaches:
  - Camera at fixed/various viewpoints, moveable light source [Lensch et al. 2001/2003, Goldman et al.]
SVBRDF Acquisition

- Sparse sampling approaches:
  - Camera at fixed/various viewpoints, moveable light source [Lensch et al. 2001/2003, Goldman et al.]
  - Gonioreflectometer-like setups [McAllister 2002]
SVBRDF Acquisition

- Sparse sampling approaches:
  - Camera at fixed/various viewpoints, moveable light source [Lensch et al. 2001/2003, Goldman et al.]
  - Gonioreflectometer-like setups [McAllister 2002]
  - Condenser lens based setups [Dong et al. 2010]
SVBRDF Acquisition

- Sparse sampling approaches:
  - Camera at fixed/Various viewpoints, moveable light source [Lensch et al. 2001/2003, Goldman et al.]
  - Gonioreflectometer-like setups [McAllister 2002]
  - Condenser lens based setups [Dong et al. 2010]
  - Arrays of cameras/light sources [Weyrich et al. 2006]
SVBRDF Acquisition

- Sparse sampling approaches:
  - Camera at fixed/various viewpoints, moveable light source [Lensch et al. 2001/2003, Goldman et al.]
  - Gonioreflectometer-like setups [McAllister 2002]
  - Condenser lens based setups [Dong et al. 2010]
  - Arrays of cameras/light sources [Weyrich et al. 2006]
- Setups for light-weight setups / uncontrolled conditions:
SVBRDF Acquisition

- Setups for light-weight setups / uncontrolled conditions:
  - Collections of internet images [Haber et al. 2009]
SVBRDF Acquisition

- Setups for light-weight setups / uncontrolled conditions:
  - Collections of internet images [Haber et al. 2009]
  - Hand-held video cameras [Palma et al. 2012]
SVBRDF Acquisition

- Setups for light-weight setups / uncontrolled conditions:
  - Collections of internet images [Haber et al. 2009]
  - Hand-held video cameras [Palma et al. 2012]
  - Mobile hardware [Riviere et al. 2014, Aittala et al. 2015]
    - Illumination with flash light (extended light source / tablet for specular materials)
**SVBRDF Acquisition**

- Setups for light-weight setups / uncontrolled conditions:
  - Collections of internet images [Haber et al. 2009]
  - Hand-held video cameras [Palma et al. 2012]
  - Mobile hardware [Riviere et al. 2014, Aittala et al. 2015]
    - Illumination with flash light (extended light source / tablet for specular materials)
    - Exploitation of self-similarities in reflectance behavior
SVBRDF Acquisition

- Dense sampling approaches:
SVBRDF Acquisition

- Dense sampling approaches:
- Mirror-based approaches
  [Dana and Wang 2004]
SVBRDF Acquisition

- Dense sampling approaches:
  - Mirror-based approaches
    [Dana and Wang 2004]
  - Gonioreflectometers
SVBRDF Acquisition

- Dense sampling approaches:
  - Mirror-based approaches
    [Dana and Wang 2004]
  - Gonioreflectometers
  - Camera arrays / light source arrays
    [Köhler et al. 2013, Nöll et al. 2013, Nöll et al. 2015]
SVBRDF Acquisition

- Dense sampling approaches:
  - Mirror-based approaches
    [Dana and Wang 2004]
  - Gonioreflectometers
  - Camera arrays / light source arrays
    [Köhler et al. 2013, Nöll et al. 2013, Nöll et al. 2015]
  - Continuous spherical harmonic gradient illumination (LED arc)
    [Tunwattanapong et al. 2013]
SVBRDF Acquisition

- Dense sampling approaches:
  - Mirror-based approaches
    [Dana and Wang 2004]
  - Gonioreflectometers
  - Camera arrays / light source arrays [Köhler et al. 2013, Nöll et al. 2013, Nöll et al. 2015]
  - Continuous spherical harmonic gradient illumination (LED arc)
    [Tunwattanapong et al. 2013]
  - Generalized linear light source reflectometry [Chen et al. 2014]
general function (12D)
\[ \rho(x_i, y_i, \theta_i, \varphi_i, \lambda_i, t_i, x_r, y_r, \theta_r, \varphi_r, \lambda_r, t_r) \]

fixed wavelength and time

RF / BSSRDF (8D)
\[ \rho_{RF/BSSRDF}(x_i, y_i, \theta_i, \varphi_i, x_r, y_r, \theta_r, \varphi_r) \]

spatially inhomogeneous materials

spatially homogeneous materials

BTF (6D)
\[ \rho_{BTF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

SVBRDF (6D)
\[ \rho_{SVBRDF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

BSSDF (6D)
\[ \rho_{BSSDF}(x_r - x_i, y_r - y_i, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

diffuse (nearly) flat

Texture Maps / Bump Maps (2D)
\[ \rho_{Texture Map / Bump Map}(x, y) \]
Representation

- Reminder:
  Reflectance field: \( R_V(\vec{x}_i, \omega_i; \vec{x}_o, \omega_o) \)

- BTF: \( B_V(\omega_i; \vec{x}_o, \omega_o) \) [Dana1997]

  special reflectance field that transfers
  
  - incident \textbf{directional} light field \( L_{i,V}^d(\omega_i) \)
  
  to corresponding
  
  - outgoing light field \( L_{o,V}(\vec{x}_o, \omega_o) \)

  parametrized on an approx. flat surface \( V \)

- Sample resulting light field \( L_{o,V} \) via photographs
Setup Designs (1/3)

- Gonioreflectometer
  - 1 camera
  - 1 light source
  - Parallel for $x_o$
  - Sequential for $\omega_i, \omega_o$
  - Various flavors:
Setup Designs (1/3)

- **Gonioreflectometer**
  - 1 camera
  - 1 light source
  - Parallel for $\mathbf{x}_o$
  - Sequential for $\omega_i, \omega_o$
  - Various flavors:
    - Robot rotates sample
      - Fixed light, moving camera
        [Dana1997], [Sattler2003], [Kimachi2006]
Setup Designs (1/3)

- Gonioreflectometer
  - 1 camera
  - 1 light source
  - Parallel for $x_o$
  - Sequential for $\omega_i, \omega_o$
  - Various flavors:
    - Robot rotates sample
      - Fixed light, moving camera
        [Dana1997], [Sattler2003], [Kimachi2006]
      - Fixed camera, robot moves light
        [McAllister2000], [Koudelka2003], [Tsuchida2005]
Setup Designs (1/3)

- **Gonioreflectometer**
  - 1 camera
  - 1 light source
  - Parallel for $x_o$
  - Sequential for $\omega_i, \omega_o$
  - Various flavors:
    - Robot rotates sample
      - Fixed light, moving camera
        [Dana1997], [Sattler2003], [Kimachi2006]
      - Fixed camera, robot moves light
        [McAllister2000], [Koudelka2003], [Tsuchida2005]
    - Robots move camera **and** light
      [Holroyd2010], [Filip2013]
Setup Designs (2/3)

Mirrors / Kaleidoscope

- 1 camera
- 1 light source (projector)
Setup Designs (2/3)

Mirrors / Kaleidoscope
- 1 camera
- 1 light source (projector)
- Curved mirror
  [Wang2006]
    - Parallel for $\omega_o$
    - Sequential for $\overrightarrow{x_o}$, $\omega_i$
Mirrors / Kaleidoscope

- 1 camera
- 1 light source (projector)
- Curved mirror  
  [Wang2006]
  - Parallel for $\omega_o$
  - Sequential for $\vec{x}_o$, $\omega_i$
- Piecewise planar
  - Parabolic arrangement  
  [Tagawa2012]
Setup Designs (2/3)

Mirrors / Kaleidoscope
- 1 camera
- 1 light source (projector)
- Curved mirror
  - Parallel for $\omega_o$
  - Sequential for $x_o$, $\omega_i$
- Piecewise planar
  - Parabolic arrangement
    [Tagawa2012]
  - Kaleidoscope
    [Han2003], [Ihrke2012]
Setup Designs (2/3)

Mirrors / Kaleidoscope
- 1 camera
- 1 light source (projector)
- Curved mirror
  - Parallel for $\omega_o$
  - Sequential for $\bar{x}_o$, $\omega_i$
- Piecewise planar
  - Parabolic arrangement
    - Parallel for $\omega_o$
    - Sequential for $\bar{x}_o$, $\omega_i$
- No moving parts
  - Parallel for $\bar{x}_o$ and $\omega_o$
  - Sequential for $\omega_i$
Camera arrays
- Multiple cameras
- Multiple lights
- (Semi-)parallel for $\overrightarrow{x_0}$ and $\omega_0$
- Sequential sampling of $\omega_i$
Setup Designs (3/3)

- Camera arrays
  - Multiple cameras
  - Multiple lights
  - (Semi-)parallel for $\vec{x}_o$ and $\omega_o$
  - Sequential sampling of $\omega_i$
  - Turntable rotates sample

[Furukawa2002], [Matusik2002], [Tong2005], [Köhler2013], [Schwartz2013]
- **Camera arrays**
  - Multiple cameras
  - Multiple lights
  - (Semi-)parallel for $\mathbf{x}_o$ and $\omega_o$
  - Sequential sampling of $\omega_i$
  - Turntable rotates sample
    - [Furukawa2002], [Matusik2002], [Tong2005], [Köhler2013], [Schwartz2013]
  - No moving parts
    - [Müller2004], [Weyrich2005], [Hu2010], [Wu2011]
Comparison (1/3): Direction Sampling

Gonioreflectometers

- **\( \omega_i \)**
  - ![Image](image1)
  - ![Image](image2)
  - ![Image](image3)
  - ![Image](image4)
  - ![Image](image5)
  - ![Image](image6)

- **\( \omega_o \)**
  - ![Image](image7)
  - ![Image](image8)
  - ![Image](image9)
  - ![Image](image10)
  - ![Image](image11)
  - ![Image](image12)

**204**
- [DVGNK97]

**311 / 7,650**
- [McA02]

**6,561**
- [FVH*13],[SSK03]

**10,800**
- [KMBK03]

**568**
- [KTT06]

Mirrors

- **\( \omega_i \)**
  - ![Image](image13)
  - ![Image](image14)
  - ![Image](image15)

- **\( \omega_o \)**
  - ![Image](image16)
  - ![Image](image17)
  - ![Image](image18)

**484**
- [HP03]

**1.9 \times 10^8**
- [WD06]

**2,500**
- [MTK*10]

Camera arrays

- **\( \omega_i \)**
  - ![Image](image19)
  - ![Image](image20)
  - ![Image](image21)
  - ![Image](image22)

- **\( \omega_o \)**
  - ![Image](image23)
  - ![Image](image24)
  - ![Image](image25)
  - ![Image](image26)

**4,320**
- [FKIS02]

**12,960**
- [MPZ*02]

**22,801**
- [MMS*04]

**52,272**
- [SSWK13]
Comparison (1/3): Direction Sampling

### Gonioreflectometers

- \( \omega_i \)
  - [DVGNK97]: 204
  - [McA02]: 311 / 7,650

- \( \omega_o \)
  - [FVH*13], [SSK03]: 6,561
  - [KMBK03]: 10,800
  - [KTT06]: 568

### Mirrors

- \( \omega_i \)
  - [HP03]: 484
  - [WD06]: 1.9 \times 10^8
  - [MTK*10]: 2,500

- \( \omega_o \)
  - [FKIS02]: 4,320
  - [MPZ*02]: 12,960
  - [MMS*04]: 22,801
  - [SSWK13]: 52,272

### Camera arrays

- \( \omega_i \)
  - [MV06]: 2,500
- \( \omega_o \)
  - [MPZ*02]: 12,960
  - [MMS*04]: 22,801
  - [SSWK13]: 52,272
Comparison (1/3): Direction Sampling

Gonioreflectometers

\[ \omega_i \]
204
[DVGNK97]

\[ \omega_o \]
311 / 7,650
[McA02]

\[ \omega_i \]
6,561
[FVH*13], [SSK03]

\[ \omega_o \]
10,800
[KMBK03]

\[ \omega_i \]
568
[KTT06]

Mirrors

\[ \omega_i \]
484
[HP03]

\[ \omega_o \]
1.9 \times 10^8
[WD06]

\[ \omega_i \]
2,500
[MTK*10]

\[ \omega_o \]

Camera arrays

\[ \omega_i \]
4,320
[FKIS02]

\[ \omega_o \]
12,960
[MPZ*02]

\[ \omega_i \]
22,801
[MMS*04]

\[ \omega_o \]
52,272
[SSWK13]
Comparison (1/3): Direction Sampling

Gonioreflectometers

ωᵢ

204
[DVGNK97]

ωₒ

311 / 7,650
[McA02]

6,561
[FVH*13],[SSK03]

10,800
[KMBK03]

568
[KTT06]

Mirrors

ωᵢ

484
[HP03]

1.9×10⁸
[WD06]

2,500
[MTK*10]

12,960
[MPZ*02]

22,801
[MMS*04]

52,272
[SSWK13]

Camera arrays

ωᵢ

ωₒ

ωᵢ

ωₒ
Comparison (1/3): Direction Sampling

**Gonioreflectometers**

- \( \omega_i \) (Direction Sampling): 204 [DVGNK97]
- \( \omega_o \) (Wavelength Distribution): 311/7,650 [McA02]

**Mirrors**

- \( \omega_i \): 484 [HP03], 1.9×10^8 [WD06], 2,500 [MTK*10]
- \( \omega_o \): 6,561 [FVH*13], [SSK03], 10,800 [KMBK03], 568 [KTT06]

**Camera arrays**

- \( \omega_i \): 4,320 [FKIS02], 12,960 [MPZ*02], 22,801 [MMS*04], 52,272 [SSWK13]
Comparison (2/3): Spatial Sampling

Gonioreflectometers

- McA02
- SSK03
- RSK10
- DVGNK97
- KMBK03

Camera arrays

- KNRS13
- SSWK13
- MMS*04
- SWRK11

Mirrors

- HP03
- MTK*10
- IRM*12
- WD06
Comparison (2/3): Spatial Sampling

Gonioreflectometers

- McA02
- SSK03
- HLZ10
- FVH*13
- RSK10
- DVGNK97
- KMBK03

Camera arrays

- KNRS13
- SSWK13
- MMS*04
- SWRK11

Mirrors

- IRM*12
- HP03
- WD06
- MMS*10

0.6 x 0.6 cm²
Comparison (2/3): Spatial Sampling

Gonioreflectometers

- McA02
- SSK03
- RSK10
- DVGNK97
- KMBK03

Camera arrays

- KNRS13
- SSWK13
- MMS*04
- SWRK11

Mirrors

- IRM*12
- HP03
- WD06
- IRM*12

\[0.6 \times 0.6 \text{ cm}^2\]
Comparison (2/3): Spatial Sampling

Gonioreflectometers

- McA02
- SSK03
- HLZ10
- FVH*13
- RSK10
- DVGNK97
- KMBK03

Camera arrays

- KNRS13
- SSWK13
- MMS*04
- SWRK11

Mirrors

- IRM*12
- HP03
- WD06

0.6 x 0.6 cm²
Comparison (2/3): Spatial Sampling

Gonioreflectometers

- McA02
- SSK03
- FVH*13
- RSK10
- DVGNK97
- KMBK03

Camera arrays

- KNRS13
- SSWK13
- MMS*04
- SWRK11

Mirrors

- IRM*12
- HP03
- WD06

---

0.6 x 0.6 cm²

46 x 46 cm²

1000 DPI
Comparison (3/3): Speed

Gonioreflectometers | Mirrors | Camera arrays

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Comparison (3/3): Speed

Gonioreflectometers

- Dana1997: 1 hour
- McAllister2001: 0.75 hours
- Sattler2003: 36 hours
- Koudelka2003: 14 hours
- Tsichaid2005: 10 hours
- Rump2010: 13 hours
- Holroyd2010: 60 hours
- Filip2013: 5 hours
- Han2003: 1 hour
- Wang2006: 2.3 years
- Ihrke2012: 93.5 hours

Mirrors

- Matusik2002: 14 hours
- Muller2004: 1.80 hours
- Weyrich2005: 0.007 hours
- Tone2005: 2 hours
- Nol2010: 0.5 hours
- Schwartz2013: 7 hours
- Kohler2013: 0.95 hours

Camera arrays

- 25 seconds
- BSSRDF: $\rho_{\text{BSSRDF}}(x_i, \omega_i, x_r, \omega_r)$
- Generalization of spatially varying BRDF
- 8-dimensional
  - makes acquisition expensive!
- Models subsurface scattering
BSSRDF Acquisition

- Separation of diffuse and specular components:
BSSRDF Acquisition

- Separation of diffuse and specular components:
  - Diffuse/global component:
    - Describes non-local reflection
    - Determined by scattering of light within the material
BSSRDF Acquisition

- Separation of diffuse and specular components:
  - Diffuse/global component:
    - Describes non-local reflection
    - Determined by scattering of light within the material
  - Specular/direct component
    - Describes local reflection, i.e. direct reflection

Global Component

Direct Component
- Separation of diffuse and specular components:
  - Diffuse/global component:
    - Describes non-local reflection
    - Determined by scattering of light within the material
  - Specular/direct component
    - Describes local reflection, i.e. direct reflection
  - Approaches based on
    - Dichromatic reflectance models
    - Polarization (e.g. [Wolff and Boult 1991])
    - High-frequency illumination patterns [Nayar et al. 2006]
BSSRDF Acquisition

- Acquisition of subsurface scattering characteristics:
  - Homogeneous materials:
    - Simple analytical models (single scattering characteristics) + additional dipole models for multiple scattering [Jensen et al. 2001]
    - Similar model used in [Weyrich et al. 2006]

[Lensch et al. 2005]
BSSRDF Acquisition

- Acquisition of subsurface scattering characteristics:
  - Homogeneous materials:
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      [Jensen et al. 2001]
    - Similar model used in
      [Weyrich et al. 2006]
  - Inhomogeneous materials:
    - Use of exponential functions (instead of dipole model) and geometry
      [Fuchs et al. 2005]
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      [Fuchs et al. 2005]
BSSRDF Acquisition

- Acquisition of subsurface scattering characteristics:
  - Inhomogeneous materials:
    - Neglection of influence of $\omega_i$ on $\omega_r$
      
      \[ [\text{Goesele et al. 2004}] \rightarrow \rho(x_i, x_r) \]
Inhomogeneous materials: Neglection of influence of $\kappa_i$ on $\kappa_r$ [Goesele et al. 2004]

$L_o(\bar{x}_o, \bar{\omega}_o)$ $L_i(\bar{x}_i, \bar{\omega}_i)$

[Turntable with Object] [Goesele et al. 2004]
BSSRDF Acquisition

Acquisition of subsurface scattering characteristics:

Inhomogeneous materials:

Neglection of influence of $\kappa_i$ on $\kappa_r$ [Goesele et al. 2004]

Turntable with Object [Goesele et al. 2004]
BSSRDF Acquisition

- Acquisition of subsurface scattering characteristics: Inhomogeneous materials
- Neglection of influence of $\delta_i$ on $\delta_r$ (Goesele et al. 2004) $\rightarrow \rho x_i, x_r$ (Goesele et al. 2004)
BSSRDF Acquisition

- Acquisition of subsurface scattering characteristics

Inhomogeneous materials:
Neglection of influence of $\delta_i$ on $\delta_r$ [Goesele et al. 2004] → $\rho \cdot x_i$ [Goesele et al. 2004]
BSSRDF Acquisition

Acquisition of subsurface scattering characteristics:

- Inhomogeneous materials:
  - Neglection of influence of $\kappa_i$ on $\kappa_r$ [Goesele et al. 2004]

$$B(\vec{x}_o) = E(\vec{x}_i)$$

$$B_i = [\text{matrix}] = E_j$$
BSSRDF Acquisition

- Acquisition of subsurface scattering characteristics:
  - Inhomogeneous materials:
    - Neglection of influence of $\omega_i$ on $\omega_r$
      [Goesele et al. 2004] $\Rightarrow \rho(x_i, x_r)$
    - Grid of projected points
      [Peers et al. 2006]
BSSRDF Acquisition

- Acquisition of subsurface scattering characteristics:
  - Inhomogeneous materials:
    - Neglection of influence of $\omega_i$ on $\omega_r$ [Goesele et al. 2004] $\Rightarrow \rho(x_i, x_r)$
  - Grid of projected points [Peers et al. 2006]
  - Multi-layer models [Donner and Jensen 2005], [Donner et al. 2008], [Ghosh et al. 2008], [Dong et al. 2010]
BSSRDF Acquisition

- Acquiring BSSRDF characteristics

  - Inhomogeneous materials:
    Neglection of influence of scattering coefficients $\kappa_i$ on $\kappa_r$:
    [Goesele et al. 2004] $\rho_{x_i}, \rho_{x_r}$

  - Grid of projected points:
    [Peers et al. 2006]

  - Multi-layer models:
    [Donner and Jensen 2005], [Donner et al. 2008], [Ghosh et al. 2008], [Dong et al. 2010]

  - Separate acquisition of global and local scattering:
    [Tong et al. 2005]
general function (12D)
\[ \rho(x_i, y_i, \theta_i, \varphi_i, \lambda_i, t_i, x_r, y_r, \theta_r, \varphi_r, \lambda_r, t_r) \]

fixed wavelength and time

RF / BSSRDF (8D)
\[ \rho_{RF/BSSRDF}(x_i, y_i, \theta_i, \varphi_i, x_r, y_r, \theta_r, \varphi_r) \]

spatially inhomogeneous materials

BTF (6D)
\[ \rho_{BTF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

spatially inhomogeneous materials

SVBRDF (6D)
\[ \rho_{SVBRDF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

spatially homogeneous materials

BSSDF (6D)
\[ \rho_{BSSDF}(x_r - x_i, y_r - y_i, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

general lighting

fixed position

fixed lighting

fixed view

diffuse (nearly) flat

Texture Maps / Bump Maps (2D)
\[ \rho_{Texture Map/Bump Map}(x, y) \]
Representation

- Reflectance field:  \( R_V(\vec{x}_i, \omega_i; \vec{x}_o, \omega_o) \) [Debevec2000]

- Appearance of „stuff“ inside \( V \) (as a light field \( L_{o,V}(\vec{x}_o, \omega_o) \))
  given light from outside \( V \) (as a light field \( L_{i,V}(\vec{x}_i, \omega_i) \))

- 8-dimensional
- Reflectance field:  \( R_V(\vec{x}_i, \omega_i; \vec{x}_o, \omega_o) \) [Debevec2000]

- Appearance of „stuff“ inside \( V \) (as a light field \( L_{o,V}(\vec{x}_o, \omega_o) \)) given light from outside \( V \) (as a light field \( L_{i,V}(\vec{x}_i, \omega_i) \))

- 8-dimensional

- Related to BSSRDF [Nicodemus1977]
general function (12D)\
\( \rho(x_i, y_i, \theta_i, \varphi_i, \lambda_i, t_i, x_r, y_r, \theta_r, \varphi_r, \lambda_r, t_r) \)

fixed wavelength and time

RF / BSSRDF (8D)\
\( \rho_{RF/BSSRDF}(x_i, y_i, \theta_i, \varphi_i, x_r, y_r, \theta_r, \varphi_r) \)

spatially inhomogeneous materials

spatially inhomogeneous materials

spatially homogeneous materials

BTF (6D)\
\( \rho_{BTF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \)

SVBRDF (6D)\
\( \rho_{SVBRDF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \)

BSSDF (6D)\
\( \rho_{BSSDF}(x_r - x_i, y_r - y_i, \theta_i, \varphi_i, \theta_r, \varphi_r) \)

fixed lighting

fixed position

fixed view

fixed lighting

fixed view

fixed position

opaque materials

diffuse (nearly) flat

SLF (4D)\
\( \rho_{SLF}(x, y, \theta_r, \varphi_r) \)

SRF (4D)\
\( \rho_{SRF}(x, y, \theta_i, \varphi_i) \)

BRDF (4D)\
\( \rho_{BRDF}(\theta_i, \varphi_i, \theta_r, \varphi_r) \)

Texture Maps / Bump Maps (2D)\
\( \rho_{Texture Map / Bump Map}(x, y) \)
Surface Light Field Acquisition

- Surface light field:

\[ \rho_{\text{SLF}}(x, \omega_r) \]

[Wood et al. 2000]
- Surface light field:

\[ \rho_{SLF}(x, \omega_r) \]
Surface Light Field Acquisition

- Surface light field:
  \[ \rho_{\text{SLF}}(x, \omega_r) \]

- Setup designs:
  - Single camera at different viewpoints
Surface Light Field Acquisition

- Surface light field:
  \( \rho_{SLF}(x, \omega_r) \)

- Setup designs:
  - Single camera at different viewpoints
  - Camera arrays
    [Wilburn et al. 2005]
Surface Light Field Acquisition

- Surface light field:
  \[ \rho_{SLF}(x, \omega_r) \]

- Setup designs:
  - Single camera at different viewpoints
  - Camera arrays
    [Wilburn et al. 2005]
Surface Light Field Acquisition

- Surface light field:
  \[ \rho_{\text{SLF}}(x, \omega_r) \]

- Setup designs:
  - Single camera at different viewpoints
  - Camera arrays
    [Wilburn et al. 2005]
  - Compressive sensing
    [Kamal et al. 2012], [Marwah et al. 2013]
general function (12D)
\[ \rho(x_i, y_i, \theta_i, \varphi_i, \lambda_i, t_i, x_r, y_r, \theta_r, \varphi_r, \lambda_r, t_r) \]

fixed wavelength and time

RF / BSSRDF (8D)
\[ \rho_{RF / BSSRDF}(x_i, y_i, \theta_i, \varphi_i, x_r, y_r, \theta_r, \varphi_r) \]

spatially inhomogeneous materials

BTF (6D)
\[ \rho_{BTF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

spatially inhomogeneous materials

SVBRDF (6D)
\[ \rho_{SVBRDF}(x, y, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

spatially homogeneous materials

BSSDF (6D)
\[ \rho_{BSSDF}(x_r - x_i, y_r - y_i, \theta_i, \varphi_i, \theta_r, \varphi_r) \]

fixed lighting

fixed position

SLF (4D)
\[ \rho_{SLF}(x, y, \theta_r, \varphi_r) \]

fixed view

diffuse (nearly) flat

Texture Maps / Bump Maps (2D)
\[ \rho_{Texture Map / Bump Map}(x, y) \]

SRF (4D)
\[ \rho_{SRF}(x, y, \theta_i, \varphi_i) \]

BRDF (4D)
\[ \rho_{BRDF}(\theta_i, \varphi_i, \theta_r, \varphi_r) \]

fixed lighting

fixed view

opaque materials

fixed position
Reflectance Field Representation

- Surface reflectance field:
  \[ \rho_{SRF}(x, \omega_i) \]
- Often image-based
- Does not rely on knowledge about surface geometry
- Representations:
  - Model-driven
  - Data-driven
Reflectance Field Representation

- Surface reflectance field:
  \[ \rho_{SRF}(x, \omega_i) \]
- Often image-based
- Does not rely on knowledge about surface geometry
- Representations:
  - Model-driven
  - Data-driven
Surface Reflectance Field Acquisition

- Single viewpoint  
  (1 camera)
- Multiple light directions
  - Different variants:
Surface Reflectance Field Acquisition

- Single viewpoint
  (1 camera)
- Multiple light directions
  - Different variants:
    - Moving light source
Surface Reflectance Field Acquisition

- Single viewpoint (1 camera)
- Multiple light directions
  - Different variants:
    - Moving light source
    - Light source arrays
The respective report and a list of references can be found in:

Advances in Geometry and Reflectance Acquisition
Michael Weinmann und Reinhard Klein
SIGGRAPH Asia 2015 Courses, ACM, 2015
http://dl.acm.org/citation.cfm?id=2818165
Advances in Appearance Modeling
Appearance Compression
Motivation

- Compression mostly solved for 2D textures
  - Good codecs exists
  - Level-of-Detail

- But for e.g. BTFs…
  - GBs or TBs *per material / object*
  - Should be consistent in the angular domain
Motivation

- Compression facilitates...
  - Rendering
    - Offline (data should fit RAM)
    - Online (data must fit GPU RAM)
  - Editing / synthesis
  - Transmission
Motivation

- Do we need that many samples?

- That, or a good model for interpolation
Model-Driven BRDF Compression
Lambert

- \( f_{\text{Lambert}} = \text{const} \)
- Simple analytical model for mostly diffuse surfaces
Blinn-Phong [Blinn 1977]

- \( f_{\text{Blinn-Phong}} = k_s \cdot \langle \hat{h}, \hat{n} \rangle^n \)
- \( k_s \) - specular color & intensity
- \( n \) - specularity
Ward [Ward 1992]

\[ f_{\text{Ward}} = \frac{k_s}{4\pi\alpha_x\alpha_y\sqrt{\cos \theta_i \cos \theta_o}} \cdot e^{\tan^2 \theta_h \left( \frac{\cos^2 \phi_h}{\alpha_x^2} + \frac{\sin^2 \phi_h}{\alpha_y^2} \right)} \]

- \( k_s \) - specular color & intensity
- \( \alpha_x \) - lobe width in tangential direction
- \( \alpha_y \) - lobe width in bi-tangential direction
- $f_{Lafortune} = k_s \cdot (\hat{l}^t \cdot M \cdot \hat{v})^m$
- $k_s$ - specularity
- $M$ - symmetric 3x3 matrix
Torrance-Sparrow
[Torrance et al. 1967]

\[ f_{\text{Torrance-Sparrow}} = \frac{k_s}{4} \cdot \frac{D(m) \cdot F(\eta) \cdot G}{\langle \vec{n}, \vec{l} \rangle \cdot \langle \vec{n}, \vec{v} \rangle} \]

- D - distribution of normal directions
- \( m \) - RMS slope of micro-facets
- \( G \) - geometric attenuation factor
- \( F \) - Fresnel term
- \( \eta \) - Complex refractive index
Model Fitting

- BRDF models highly non-linear
  - Non-linear optimization necessary
  - E.g. Levenberg-Marquardt (least-squares) or similar

- Error term? [Löw et al. 2012]
  - $\sum (\log(1 + \cos \theta_i \cdot f_{brdf}) - \log(1 + \cos \theta_i \cdot f_{measured}))^2$
  - Logarithm reduces dynamic range

![Images showing linear, ground truth, and logarithmic results]
MERL BRDF Database [Matusik 2003]

- 100 isotropic materials
- 90x90x180x3 = 4,374,000 samples / material
- Ruzinkiewicz parameterization
Example: Dark Blue Paint

Acquired data

Blinn-Phong  Ward  Lafortune  Torrance
Evaluation [Ngan et al. 2006]

- Observed order of quality (roughly):
  - Torrance
  - Lafortune
  - Ward
  - Blinn-Phong
Composite Models

- Some materials impossible to represent by single lobe
  - Layering e.g. can produce multiple lobes

Acquired data  Torrance, 1 lobe  Torrance, 2 lobes
- Novel analytical BRDF models from measured data via genetic algorithm
- User-specified amount of free parameters
Spherical Harmonics

- Orthonormal basis for $L^2(S^2)$
- Fitting: simple basis projection per fixed viewing direction:

$$c_i^\vec{v} = \int f_{brdf}(\vec{l}, \vec{v}) \cdot y_i(\vec{l}) d\vec{l}$$

- Enable real-time environmental lighting
- Useful for SVBRDFs and BTFs, too
## BRDF Models - Overview

<table>
<thead>
<tr>
<th>Model</th>
<th># parameters</th>
</tr>
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<tr>
<td>Lambert</td>
<td>1 (RGB)</td>
</tr>
<tr>
<td>Blinn-Phong</td>
<td>2 (RGB) + 1</td>
</tr>
<tr>
<td>Ward</td>
<td>2 (RGB) + 3</td>
</tr>
<tr>
<td>Lafortune</td>
<td>2 (RGB) + 4</td>
</tr>
<tr>
<td>Torrence-Sparrow</td>
<td>2 (RGB) + 2</td>
</tr>
<tr>
<td>genBRDF</td>
<td>User-defined, &lt; 5 typical, possibly RGB</td>
</tr>
<tr>
<td>Spherical harmonics</td>
<td>&lt; 100 per view, typical</td>
</tr>
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</table>

→ Excellent compression, even with multiple lobes, quality often satisfactory
SVBRDFs

- Extension of BRDFs to spatial domain
  - *Per-texel* BRDFs

- Appropriate for materials with little non-local effects
  - Smooth, connected meso-scale geometry
  - Little subsurface scattering

[Lensch et al.]
SVBRDF Fitting

- Much more involved
- Needs to deal with:
  - Typically much lower #samples (not homogeneous); [Aittala et al. 2015] combine sparse BRDFs from similar texels for robust fitting from two images

Figure 1: Given a flash-no-flash image pair of a “textured” material sample, our system produces a set of spatially varying BRDF parameters (an SVBRDF, right) that can be used for relighting the surface. The capture (left) happens in-situ using a mobile phone.
SVBRDF Fitting

- Possibly meso-scale surface structure (rotated normals, occlusion, parallax, interreflections)

- Can be accounted for to some extent ([Ruiters et al. 2009])

→ One set of BRDF parameters / texel
→ Very good compression, but…

Mean relative BRDF error

Original
Our Technique (with light exchange)

0.030 / 0.007 mm
8.9%
2.7%
Limitations

- Meso-structure: BRDF \(\rightarrow\) A(pparent)BRDF

- Expensive to re-create from SVBRDF
Limitations

- Meso-structure: BRDF $\rightarrow$ A(pparent)BRDF

- Expensive to re-create from SVBRDF
Limitations

- Meso-structure: BRDF $\rightarrow$ A(pparent)BRDF

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- Meso-structure: BRDF $\rightarrow$ A(pparent)BRDF

- Expensive to re-create from SVBRDF
Limitations

- Meso-structure: BRDF $\rightarrow$ A(pparent)BRDF

- Expensive to re-create from SVBRDF

Influence from neighborhood

Impossible to describe with analytical model

Retro-reflection

Specular reflection
Model-Driven BTF Compression
BTF Sparse Parametric Mixture Models [Wu et al. 2011]

- Represent ABRDFs as mixture of analytical models + residual
- Clustering on ABRDFs
- 1 residual / cluster

→ Compression ratios of 1:70 – 1:300
Spherical Harmonics

- ABRDFs also representable in SH basis
- Enables real-time rendering of environmentally-lit BTFs
- More SHs necessary to represent high-frequency effects
  - Coarse sampling of view hemisphere → not much compression, but:
  - Can be applied after certain other compression methods
Data-Driven BRDF Compression
- **Idea:** Instead of pre-designed models, …
- … use models derived from data

\[
\text{reconstructed ABRDF} = h_0 + g_1 + h_1 + g_2 + h_2 + g_3 + \ldots
\]
Linear Models For BRDFs
[Matusik et al. 2003a]

- Principal Component Analysis (PCA) on MERL database:
  - $D = \text{mean} + \text{EVs} \cdot \text{Coeffs}$
  - Performed in log(RGB) color space
    - Less dynamic range (highlights!)
    - HVS more sensitive to ratios
Linear Models For BRDFs

- Result: 45 eigen-BRDFs suffice (error <1%)

→ Linear model with 45 parameters (45 eigen-BRDFs must be kept)
Linear Models For BRDFs
[Matusik 2003b]

- MERL database as linear model generalizes to new BRDFs:

\[ B_{\text{new}} \approx D \cdot (D^\dagger \cdot B_{\text{new}}) \]

- 800 samples sufficient for robust fitting

→ “Any” isotropic BRDF representable by 100 parameters or 800 samples
Data-Driven SVBRDF/BTF compression
Linear Models For SVBRDFs/BTFs
[Koudelka et al. 2003]

- Truncated singular value decomposition (SVD) on BTFs
- Eckart-Young theorem: best $L^2$ rank-k approximation

Eigen-textures compressed with JPEG

[Steinhausen et al. 2015]
Linear Models For SVBRDFs/BTFs

- Result: 150 – 200 eigen-ABRDFs suffice

Original
700 MB

50 EVs
500 KB

150 EVs
1.6 MB
Linear Models For SVBRDFs/BTFs

- Many variants have been proposed, e.g.
  - Per-view factorization [Sattler et al. 2003]
  - Per-cluster factorization ("local PCA") [Müller et al. 2003]

- Important factors:
  - Error metric
  - Color space
  - Parameterization

L2 error
Reference
Logarithmic

[Menzel et al. 2007]
Parameterization [Mueller et al. 2006]

- Align ABRDFs for maximum correlation before PCA using spherical correlation (based on SHs)

- Changes per-texel local coordinate system

2 EVs, unaligned, 200 KB  
Original, 900 MB  
2 EVs, aligned, 200 KB

Original BTF  
Aligned BTF
Common Linear Models
[den Brok et al. 2015]

- Problem so far: factorized BTFs completely unrelated
  - E.g. no blending, interpolation, distance metric, …

- linear models derived from BTF database
  - Generalize to non-database BTFs
  - 200-1000 eigen-ABRDFs sufficient (vs. 100 per material)
  - Also useful in acquisition [den Brok et al. 2014, 2015]
  - Rendering slow, but quick to recompute per-material SVD
Multilinear Models

- Represent BTF not as a matrix, but as a higher-order tensor
- Apply generalization of matrix factorization
  - PARAFAC
  - Tucker decomposition

<table>
<thead>
<tr>
<th>Reference</th>
<th>Decomposition</th>
<th>Tensor Layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Furukawa-2002]</td>
<td>CANDECOMP/PARAFAC</td>
<td>View × Light × Position</td>
</tr>
<tr>
<td>[Vasilescu-2004]</td>
<td>Tucker</td>
<td>View × Light × Position</td>
</tr>
<tr>
<td>[Wang-2005]</td>
<td>Tucker</td>
<td>View × Light × X × Y</td>
</tr>
<tr>
<td>[Wu-2008]</td>
<td>Hierarchical Tucker</td>
<td>View × Light × X × Y</td>
</tr>
<tr>
<td>[Ruiters-2009]</td>
<td>Sparse Tensor Decomposition</td>
<td>View × (Color*Light) × Position</td>
</tr>
<tr>
<td>[Ruiters-2012]</td>
<td>CANDECOMP/PARAFAC</td>
<td>$\theta_h \times \theta_d \times \varphi_a \times$ Position× Color</td>
</tr>
<tr>
<td>[Tsai-2012]</td>
<td>K-CTA</td>
<td>View × Light × X × Y</td>
</tr>
</tbody>
</table>
Sparse Tensor Decomposition
[Ruiters et al. 2009]

- Sparse coding of a matrix via K-SVD:

\[ Y \approx D \cdot X \]

- Faster evaluation
- More compact
Sparse Tensor Decomposition

Decomposition is calculated by unfolding tensor and applying K-SVD on unfolded tensor.
Sparse Tensor Decomposition

- Only uses correlations in one mode
- Can be repeated along different modes:

\[ T \approx D_{i_1 j_1} x_{j_1 i_2 j_2}^{(1)} x_{j_2 i_3 j_3}^{(2)} \ldots x_{j_N i_N}^{(N)} \]

- BTF represented as a mode-3 tensor
  - (Color*Light) \times Views \times Position

\[ D \]
\[ x^{(1)} \ldots x^{(N-1)} \]
\[ x^{(N)} \]

Mode-2 dictionary tensor
Sparse mode-3 tensors
Sparse mode-2 tensor
Sparse Tensor Decomposition

Drawback: slow GPU rendering

Original 14.77 GB

Sparse Tensor Decomposition
3.9 MB, RMS: 0.0058

PCA 4.0 MB, RMS: 0.0074
(Multi-)Linear Models - Comparison

![Graph 1: Size vs. RHS Error](image1)

![Graph 2: Render Time vs. RHS Error](image2)
Vector Quantization [Filip et al. 2008]

- Vector quantization for BTFs
  - Replace individual textures with indices to similar ones

- Degradation metric: mean texture variance
  - Determined through psychophysical experiment, along with thresholds

- Can be combined with PCA for further compression
Conclusion - Compression

- Large repertoire of methods for appearance compression
- Impressive compression ratios possible
- There is still demand:
  - Ever-growing sample rates, both
    - Angular (blur, ghosting, …)
    - and spatial (HD, {4,8}K, …)
  - Synthesis / interactive editing on compressed data
Appearance Synthesis
Motivation

- Acquisition process often very expensive, or...
- ...difficult for large material samples

- Designers may wish to change properties of existing materials, or...
- ...to quickly create novel materials from scratch
Model-Driven Synthesis
Model-Driven (SV)BRDF Synthesis

- Synthesis of (SV)BRDFs easy in principle:
- Just change the model parameters and/or height-field!

[Ngan et al. 2006b]

- Can be meaningful physically; however, …
Disney BRDF Model

- …not intuitive: humans think in different categories:
Disney BRDF Model [Burley 2012]

- Composition of (modified) existing BRDF models with intuitive parameters
- New parameters control underlying old parameters
- Parameters normalized $\rightarrow$ robust interpolation
Disney BRDF Model

- Interpolation enables limited spatial variance through masks:
Model-Driven BTF Synthesis [Wu et al. 2011]

- SPMM also useful for BTF editing
- Texture synthesis for spatial domain
- Angular domain: change BRDFs’ weights and parameters
Model-Driven BTF Synthesis
[Schröder et al. 2013]

- Rendering of SVBRDFs with non-local effects too slow
- Rapidly generate BTF (model-agnostic!) from editable cloth material model [Schröder et al. 2011]:

Image                  Pattern                  Synthetic model
                        |                            | Edit
                        |                            |
Pattern               Yarn                  Fiber
Automatic             Manually / From Manufacturer
Non-local Reconstruction

- Render a few HQ BTF textures, the rest with few SPP

- On the high-quality sub-BTFs:
  - Construct k-nearest-neighbor graph
  - Gaussian weights of neighbors

- Reconstruction:
  - Weighted sum of neighbor ABRDFs
  - Artificially increases #SPP
Non-local Reconstruction

<table>
<thead>
<tr>
<th>Raytraced textures</th>
<th>Reconstructions</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="128 spp" /></td>
<td><img src="image2" alt="128 spp" /></td>
</tr>
<tr>
<td><img src="image3" alt="8 spp" /></td>
<td><img src="image4" alt="8 spp" /></td>
</tr>
<tr>
<td><img src="image5" alt="2 spp" /></td>
<td><img src="image6" alt="2 spp" /></td>
</tr>
<tr>
<td><img src="image7" alt="1 spp" /></td>
<td><img src="image8" alt="1 spp" /></td>
</tr>
</tbody>
</table>
Non-local Reconstruction

Our method (8 spp)

Reference (128 spp)
Editing

Rendering

Edit
Data-Driven Synthesis
Data-Driven BRDF Synthesis [Matusik et al. 2003a]

- Fit non-linear manifold to MERL database using “manifold charting”

Charted manifolds of BRDF data

reconstruction error

manifold dimensionality

charts = subspace projections of samples (from unknown manifold)

connection = affine merger of charts
Semantic Editing

- User-specified traits identified in database materials

- Support vector machines → hyperplanes separating classes

- Non-negativity and conservation of energy enforced → physically plausible BRDFs
Semantic Editing

Gradually increasing specularity

Oxidization of polished steel
Data-Driven BTF Synthesis
[Koudelka et al. 2003]

- Apply 2D texture synthesis to BTF eigen-textures
  → Works on compressed data

- Produces consistent BTFs

- Restricted to a single material
“BTF Shop” [Kautz et al. 2007]

- Interactive BTF editing
- Introduces operators for interactive BTF editing:
  - Tone & color
  - Angular blur & sharpen
  - Rotation of local coordinate frame
  - Shadow creation / removal
  - Change of height field

Effect of angular blur / sharpen
- Operators can be applied to user-selected regions
- Multi-threaded, tile-based, on-demand: some level of interactivity (2-10 s)
BTF Interpolation [Ruiters et al. 2013]

- Lift patch-based texture interpolation to BTFs
BTF Interpolation

2D case

For each scale → Patch Extraction → Patch Interpolation → Synthesis → Statistical Synthesis

Texture $T_0$  Feature Map $F_0$  Neighborhoods $\mathcal{N}_0$  Interpolated Neighborhoods $\mathcal{N}'$

Texture $T_1$  Feature Map $F_1$  Neighborhoods $\mathcal{N}_1$  Texture $T'$
BTF Interpolation

- Heightfield
- Feature Map
- Distance Channel
- Eigen-Textures

19 channel Image
### BTF Interpolation

<table>
<thead>
<tr>
<th>Features</th>
<th>0° view</th>
<th>60° view, no heightfield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material 1</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Blended</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
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<tr>
<td>Material 2</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
</tbody>
</table>
BTF Interpolation

- Projection onto heightfield
- Still a BTF!
  - But represented on a different reference geometry
BTF Interpolation

- Projection onto heightfield
- Still a BTF!
  - But represented on a different reference geometry
BTF Interpolation

- 60° view
- 0° view

Reduced parallax

Approximate Heightfield

Material Surface

- Projection onto heightfield
- Still a BTF!
  - But represented on a different reference geometry
# BTF Interpolation

<table>
<thead>
<tr>
<th>Features</th>
<th>0° view</th>
<th>60° view, no heightfield</th>
<th>60° view, with heightfield</th>
</tr>
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<tbody>
<tr>
<td><strong>Material 1</strong></td>
<td><img src="image1" alt="Features" /></td>
<td><img src="image2" alt="60° view" /></td>
<td><img src="image3" alt="60° view" /></td>
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<tr>
<td><strong>Blended</strong></td>
<td><img src="image4" alt="Features" /></td>
<td><img src="image5" alt="60° view" /></td>
<td><img src="image6" alt="60° view" /></td>
</tr>
<tr>
<td><strong>Material 2</strong></td>
<td><img src="image7" alt="Features" /></td>
<td><img src="image8" alt="60° view" /></td>
<td><img src="image9" alt="60° view" /></td>
</tr>
</tbody>
</table>
BTF Interpolation
BTF Extrapolation
[Steinhausen et al. 2015]

- Extract smaller sample
- Measure
- Sample BTF $S$
- Extrapolate
- Full BTF $M$
- Acquire & process images
  - on scans + BTFs
  - pixel-wise texture synthesis
- Full material sample
- Constraint Set $C$
BTF Extrapolation
[Steinhausen et al. 2015]

Extract smaller sample → Measure

Full material sample

Measure → Sample BTF $S$

Extrapolate → Full BTF $M$

Acquire & process images → Constraint Set $\mathcal{C}$

- on scans + BTFs
- pixel-wise texture synthesis

- $\mathcal{S}$
BTF Extrapolation

NN search on constraint images and normal map
30 s

Reference

Texture optimization
[Kwatra et al. 2005]
1 h
Conclusion - Synthesis

- A variety of appearance synthesis and editing methods exists

- Challenges:
  - Interactivity
  - Intuitivity
  - Intuitive material-specific models
  - BTF editing / synthesis relies on height-field / parallax-correction
    - May be difficult / impossible to acquire
    - Purely data-driven approach preferable
### References

|----------------------|--------------------------------------------------------------------------------------------------|
## References

<table>
<thead>
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<th>Reference</th>
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<td>[Steinhausen et al. 2015]</td>
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<td>[Torrance et al. 1967]</td>
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<td>[Ward 1992]</td>
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<tr>
<td>[Wu et al. 2011]</td>
<td></td>
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</tbody>
</table>
Transmission and Rendering
Rendering - Overview

- Model Driven Rendering

- Data Driven Rendering
  - BRDF Rendering
  - SVBRDF Rendering
  - Reflectance Field Rendering

- Image Based Lighting

- BTF Rendering and Transmission
  - Streaming of BTFs
  - LOD on BTFs
Model Driven Rendering
Phenomenological BRDF rendering

- Evaluate BRDF-model in Fragment Shader
  
  - E.g. Lafortune Model: \( f_{brdf} = \sum k_{s,i} \cdot (\hat{l}^t \cdot M_i \cdot \hat{v})^m \)

```cpp
// Lafortune Fragment Shader

// lobe.w = specularity
float lobeFunc(in vec3 L, in vec3 V, in vec lobe) {
    return pow(max(0.0, dot(vec3(lobe)*L, V)), lobe.w);
}

void main() {
    vec3 I = vec3(0,0,0);
    vec3 L = normalize(LightDir);
    if (L.z > 0.0) {
        vec3 V = normalize(ViewDir);
        for (int i = 0; i < numLobes; i++) {
            I += albedo[i]*lobeFunc(L, V, lobes[i]);
        }
        I += diffuse*L.z;
        I = min(vec3(1), I);
    }
    gl_FragColor = vec4(I, 1);
}
```

Diagonalization via change of basis

Diffuse

Lafortune
Physical BRDF rendering

- E.g. Torrance-Sparrow Model [Torrance67]:
  \[ f_{brdf} = \frac{k_s}{4} \cdot \frac{D \cdot F \cdot G}{\langle \hat{n}, \hat{l} \rangle \cdot \langle \hat{n}, \hat{v} \rangle} \]

  - \( D \): statistical distribution of normal directions
  - Modeled as 2D-probability density function

    - Torrance Sparrow: Beckmann distribution
      \[ D = \exp\left(-\frac{\tan^2(\alpha)}{m^2}\right) \cdot \frac{\pi m^2 \cos^4(\alpha)}{\alpha = \arccos(\langle \hat{n}, \hat{h} \rangle)} \]

    - Ashikhmin et. al. (2000): extension for anisotropy

Isotrop  Anisotrop

\( D \) means: % reflected light
Physical BRDF rendering

- Oren-Nayar model [Oren94]:
  - Eliminates dark borders
  - Idea similar to Torrance-Sparrow model
    - Microfacets reflect ideal diffuse
  - Parameter $\sigma$ for surface roughness
Data Driven Rendering
BRDF Rendering

- (Measured) BRDF = 4D data
- E.g. Use Parabolic representation
  - Possibly with Resampling
- Hardware interpolation only possible for light direction
  - Interpolate view direction manual

[Matusik03]
SVBRDF Rendering

- SVBRDF = „Spatial distribution of mutually Independent BRDFs“

Photograph

[MathAllister02]

Fitted analytical SVBRDF
- SVBRDF = BRDF per pixel

Store BRDF parameters in Texture Map
- Mc Allister et al. 2002: Hardware combiners / Multiple renderpasses

- Today: evaluation in Fragment shader [McAllister02]
Wang et al. 2008 [Wang08]: Model spatially varying, anisotropic reflection using data from a single view

- Microfacet Based SVBRDF model
- Measured 2D-slice of BRDF at each point and fitted NDF

2009: SVRBDF Bootstrapping [Wang et al.]
Rendering Reflectance Fields
Reflectance Field Rendering

- Reflectance fields
  - Single point of view, arbitrary light directions
- Polynomial Texture Maps (PTMs) [Malzbender01]
  - Fitt polynomial per pixel and store coefficients

\[ L(u, v, l_u, l_v) = a_0 l_u^2 + a_1 l_u^2 + a_2 l_u l_v + a_3 l_u + a_4 l_v + a_5 \]
PTM Rendering

\[ L(u, v, l_u, l_v) = a_0 l_u^2 + a_1 l_v^2 + a_2 l_u l_v + a_3 l_u + a_4 l_v + a_5 \]

- \( u, v \) - texture coordinates
- \( l_u, l_v \) - projection of light direction into image plane
- \( a_0 - a_5 \) - coefficients stored in texture map
- Evaluate in Fragment Shader

[Malzbender01]
PTM Rendering

- First implementation (2001) [Malzbender01]
  - 8 bit textures with scale $s_i$ and bias $b_i$ (LDR)
    \[ a_i = s_i (a'_i - b_i) \]

- Current implementations
  - Floating point textures (HDR)
  - Run in browser (WebGL)
  - Level Of Detail streaming

- Advantages
  - Realtime rendering
  - High resolution in spatial domain
  - Highly compressible
    - Palletization, Image compression
PTM Examples

Top: PTM, Bottom: conventional Texturemap, Source [Malzbender01]

Source [http://vcg.isti.cnr.it]
Image Based Lighting
Environment Maps

- Environment Maps
  - Store incident light for one point
  - Environment map at infinity $\rightarrow$ valid for all points

- Glossy Environment Maps
  - Project using Spherical Harmonics
    - Less coefficients $\rightarrow$ more blurred

$L_{env}(\omega) \approx \sum_{i=1}^{n} l_i y_i(\omega)$

[Kautz et al. 2005]
Spherical Harmonics Reflectance Maps

- Supports arbitrary BRDFs
- No Self-Shadowing and Interreflections

Isotropic  Anisotropic
Precomputed Radiance Transfer
[Sloan 2002]

- Precompute light transport for every point
  - Matrix which transforms incident lighting to transferred radiance
- Includes shadowing, inter-reflections
  - Static BRDF and geometry
  - Illumination and viewing direction can be changed in realtime
- Everything in SH
  - Vector matrix multiplication
- Course at Siggraph 2005 [Kautz et al.]
Precomputed Radiance Transfer

No shadows  Shadows  Interreflected

[Sloan02]
Interactive Relighting

- Interactive Relighting with Dynamic BRDFs [Sun07]
  - Factorized light transport into terms for lighting, viewing and BRDF parameters: *Precomputer Transfer Tensors (PTT)*
  - Illumination, viewing direction and BRDF can be changed in realtime
  - Geometry still static

[Sun07]
BTF Rendering
BTF Overview

- **6D Function:** $f_{btf}(x, y, \omega_i, \phi_i, \omega_o, \phi_o)$
  - Apparent BRDFs (ABRDF) at each $(x, y)$
    - Includes non-local effects at each point $(x, y)$
  - Acquired via measurement
  - Materials and Objects

- **Huge size**
  - Depends on acquisition setup and material/object
  - ~500GB uncompressed [Schwartz11]

**Compression needed for (realtime) rendering**

- Tensor based
- PCA / SVD based: FMF / DFMF-compression

In contrast to SVBRDFs

Costly to decompress: no random access

„Cheap“ to decompress + good compression
FMF / DFMF compression

For each Colorchannel

View x Light

Pixels

= 

B

= 

U

×

Σ

×

V^T

= 

u_1 \sigma_1 v_1^T

+ 

u_2 \sigma_2 v_2^T

+ 

u_3 \sigma_3 v_3^T

+ ...
FMF / DFMF-BTF Rendering

- 2D texture lookups!
FMF vs. DFMF Compression

Ammonite
Uncompressed  FMF  DFMF

Ganesha
Uncompressed  FMF  DFMF
BTF Examples

Photographic picture (tonemapped HDR)

BTF + Geometry [Schwartz2011] (tonemapped HDR)

BRDF mixture (8× Cook-Torrance)
BTF Examples

Photographic picture (tonemapped HDR)

BTF + Geometry
Schwartz et al. 2011 (tonemapped HDR)

Polynomial Texture Map
Malzbender et al. 2001
(*Single view and LDR!*)
Advances in Transmission
WebGL-based Streaming and Presentation Framework for Bidirectional Texture Functions

[Schwartz et al. 2011]
Problem description

- Transmission and rendering of Geometry + BTF
- Geometry
  - File size ~4.3 MB
  - Transmission solutions exist
  - Even low-bandwidth
- BTF
  - 4 Megapixel BTF
    - Uncompressed: ~ 500 GB
    - Compressed: ~ 1GB
- Naïve transmission not feasible
Solution

- Progressive BTF streaming
  - Start rendering ASAP
  - Progressive refinement

- Rendering: WebGL
  - Allows for real-time object-exploration
  - Supported by most modern browsers
  - Cross platform
Progressive Transmission

- Transmit small “chunks” of data using
  - Transmit each color channel separately

```
Angular component #1
Spatial component #1

Angular component #2
Spatial component #2

Angular component #3
Spatial component #3

Angular component #4
Spatial component #4
```

HTTP Request

```
Simple JPEG

Progressive JPEG
```

Quality
First chunk (YUV) required to start rendering

Size of one BTF chunk
- Spatial resolution: 1 Megapixel
- Angular resolution: \( \sim 15° \), Parabolic map: \( 32 \times 32 \)
- 16 bit floats

12 MB required

Chunks still too large
Chunk compression

- Store components as images
  - Spatial components ~
    natural images
  - Angular components ~
    low frequency images

- Use wavelet compression
  and store as png
  - Huffman encoding
    - Supported natively by browsers
- Limit chunksize by limited number of wavelets
- Improve quality later by transmitting differences
  - Also wavelet compressed
- Use WebGL shader for decompression and blending
- Optimal transmission order is the biggest decrease in RMSE

0.4bpp  0.8bpp  1.2bpp  1.6bpp
Qualitative Analysis

0.87 MB
First renderable version

1 MB

7 MB

46.4 MB
Fully transmitted

534 GB
Reference

http://btf.cs.uni-bonn.de/viewer
Demonstration

WebGL BTF-Object Viewer

Digitized objects: Buddha, Donkey, Minotaur, Samurai

Synthetic objects: Quad, Dragon

Material selection: clear Material, Rustica, Red Fabric, Leather

High-quality objects (experimental): Buddha 32 components, Buddha 64 components, Buddha 4M Gigapixels

FPS: 16

Exposure: 4
Components: 32
UV Scale: 1
Rotation Speed: 6
Light Rotation Speed: 0
Light file download: 47MB
Bandwidth: 1MB/s

Component Status
Angular

Spatial

Streaming progress: pause, resume

Use mouse to rotate viewpoint, [SHIFT] + mouse to move viewpoint, [CTRL] + mouse to rotate light and Scrollwheel to change distance.

http://schreckhorn/webglbtfviewer/bifs/buddha_32c_4MP/spatial_components_Y_0_1.png
Level-of-Detail Streaming and Rendering using Bidirectional Sparse Virtual Texture Functions

[Schwartz et al. 2013]
Problem for (realtime) rendering

- Huge data size!
  - 4 x 4 Megapixel BTFs
    2,1 Terabytes

- Compression
  - Decorrelated Full Matrix Factorization
    3.2 GB

GPU memory!
Recap: Level of Detail

- Hierarchical Level of Detail
  - [Clark 1976]
    - „Active Set“ in Memory
    - Different resolutions
  - LOD on Textures:
    - Clipmaps [Tanner 1998]
    - Sparse Virtual Textures [Barret 2008]
    - Megatextures [van Waveren 2009]
Recap: Sparse Virtual Textures

- Divide into tiles

Huge texture

Active Set := Tilecache

LUT
Recap: Sparse Virtual Textures

- Divide into tiles
- Lower resolution versions

**Huge** texture

**Active Set := Tilecache**

**LUT**

```
0 0 - -
0 1 - -
0 2 0 0
0 3 0 0
1 0 0 1
1 1 0 2
1 3 0 0
...
```
LoD on BTFs

- Combine LoD from DFMF with SVT

- LoDs are orthogonal
- Bidirectional Sparse Virtual Texture Functions (BSVTFs)
Challenge: Loading Strategy

- Optimize image quality ... on a budget

B

Full
Costs: 5

Costs: 2
E=0.23

Costs: 1.25
E=0.26

Costs: 2
E=0.11
Challenge: Loading Strategy (2)

- Global problem
- Increase resolution here?
- Or here?
  - For which vi?
- Add vi+1 here?

How to decide?
Solution: Global Optimization

- Minimize error to full BTF solution over all screen pixels:
  \[
  \arg\min_V \sum_S d(S_{full}(x,y), \tilde{S}(x,y))
  \]

- Hard to compute directly
  - Requires full solution \( S_{full} \) ...

- Solution:
  - Approximation for runtime decision
    - Runtime assessment of “gain” and “loss”
    - Precomputed weight per tile

- Loaded tiles and resolutions of \( v_1, \ldots, v_i \)

Rendering with BSVTF

- Full
- E=0.23
  - X
- E=0.26
  - X
- E=0.11
  - ✓
Results: Approximation Quality

- BTF, full rank: 2,650,000 MB
- FMF, rank 100: 3,940 MB
- FMF, rank 6: 238 MB
- BSVTF: 230 MB
Results: Realtime Rendering

- Test on desktop PC
  - GPU: NVIDIA GeForce GTX 780 (4 GB Dedicated RAM)
  - CPU: Intel Core i7 (3.4Ghz)
- Animation sequences

<table>
<thead>
<tr>
<th></th>
<th>Data Size</th>
<th>FPS</th>
<th>Compressed Data</th>
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<tbody>
<tr>
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<td>10.5 GB</td>
<td>33</td>
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<tr>
<td>38.7987 FPS</td>
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<td>181 MB</td>
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<td>45</td>
<td>45 FPS</td>
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- using BSVTF
- only FMF compression
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<tr>
<td>Wang09</td>
<td>Jiaping Wang, Yue Dong, Xin Tong, John Snyder, Moshe Ben-Ezra, Yanxiang Lan, and Baining Guo, <em>SVBRDF Bootstrapping</em>, TechReport, May 2009, Microsoft Research</td>
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<td>McAllister02</td>
<td>McAllister, David K. and Lastra, Anselmo and Heidrich, Wolfgang, <em>Efficient Rendering of Spatial Bi-directional Reflectance Distribution Functions</em>, Eurographics 2002, pages 079-088</td>
</tr>
</tbody>
</table>
Applications, Novel Trends and Conclusions
Applications
Motivation

- Cultural Heritage
- Visual Prototyping
- Advertisement
- Entertainment
- ...

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Motivation

Product advertisement
Motivation

Product advertisement

Food „photography“
Motivation

Product advertisment

Cultural Heritage

Food „photography“
Motivation

Product advertisment

Cultural Heritage

Food „photography“

Paleontology
Example “Moulages”

Moulage collection at the Department of Dermatology of the University of Bonn
Photographs by Beatrice Bieber
Example “Moulages”

Moulage collection at the Department of Dermatology of the University of Bonn
Photographs by Beatrice Bieber
Example “Moulages”

Moulage collection at the Department of Dermatology of the University of Bonn
Photographs by Beatrice Bieber

Moulage “Psoriasis of the nails and the hand”
Example “Moulages”

Moulage “Psoriasis of the nails and the hand”
Object Acquisition
Photorealistic Rendering
Photorealistic Rendering
Interactive Inspection
Further Applications in Industry

Rendered car cockpit [Meseth et al. 2006]

Accurate reproduction of characteristic „look“ and „feel“
Novel Trends
Acquisition

- Light-weight solutions
  - Cheap hardware, ideally mobile hardware
Acquisition

- Light-weight solutions
  - Cheap hardware, ideally mobile hardware

- Solutions for uncontrolled conditions
  - **Beyond** lab conditions
  - Sparsely sampled data

[Aittala et al. 2015]
Acquisition

- Light-weight solutions
  - Cheap hardware, ideally mobile hardware

- Solutions for uncontrolled conditions
  - **Beyond** lab conditions
  - Sparsely sampled data

- Mass digitization
Acquisition

- Light-weight solutions
  - Cheap hardware, ideally mobile hardware

- Solutions for uncontrolled conditions
  - Beyond lab conditions
  - Sparsely sampled data

- Mass digitization
  - Fast acquisition

Moulage collection at the Department of Dermatology of the University of Bonn
Photographs by Beatrice Bieber
Appearance Modeling

- Compact representations
Appearance Modeling

- Compact representations
Appearance Modeling

- Compact representations
- Per-class material models

[Yan et al. 2015]
Appearance Modeling

- Compact representations
- Per-class material models
- Data-driven editing

[Yan et al. 2015]
Appearance Modeling

- Compact representations
- Per-class material models
- Data-driven editing
- Material extrapolation

GOAL: measure and handle appearance of large-scale samples
Conclusions
Conclusions

- Summary:
  - Preliminaries of Material Appearance
  - Calibration
  - Reflectance Acquisition
  - Appearance Modeling
  - Transmission and Rendering
  - Applications
  - Novel Trends

- Future Work:
  - Still much work to do ... 😊
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