3DV 2018 Tutorial

Material appearance measurement

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Motivation for appearance measurement

• Materials in real world
Our mission

• Digital reproduction of material appearance
Digital Material Appearance

Virtual Environment

Shapes 3D Geometry

Illumination conditions

Material Appearance
Outline

1. Taxonomy of material appearance representations
2. Measurement approaches
   • BRDF
   • SVBRDF
   • BTF
3. Angular parameterizations
4. Anisotropic vs. isotropic BRDF
5. Uniform vs. adaptive measurement strategies
6. Publicly available datasets
Light-Material Interaction

General Reflectance Function

\[ Y_r = GRF(\lambda_i, x_i, y_i, z_i, t_i, \theta_i, \varphi_i, \lambda_v, x_v, y_v, z_v, t_v, \theta_v, \varphi_v, \theta_t, \varphi_t) \]

16 dimensions
Light-Material Interaction

General model of light-material interaction

Local scattering effects only

Opaque flat materials

BSSRDF

BRDF
Taxonomy of Material Appearance Representations

Textured materials

- 9D Reflectance Fields / BSSRDF
  \((\lambda, x_i, y_i, \theta_i, \varphi_i, x_v, y_v, \theta_v, \varphi_v)\)
- 7D Spatially varying BRDF
- 7D BTF
  \((\lambda, x, y, \theta_i, \varphi_i, \theta_v, \varphi_v)\)
- 5D Surface light field
- 5D SRF
  \((\lambda, x, y, \theta_v, \varphi_v)\)
- 4D Dynamic Texture
  \((\lambda, x, y, t)\)
- 3D Multispectral Texture
  \((\lambda, x, y)\)

Homogeneous materials

- 9D Bidirectional surface scattering reflectance distribution function
- 7D Bidirectional texture function
- 6D BSDF
  \((\lambda, \theta_i, \varphi_i, \theta_v, \varphi_v, \theta_t)\)
- 5D BRDF
  \((\lambda, \theta_i, \varphi_i, \theta_v, \varphi_v)\)
- 4D BTDF
  \((\lambda, \theta_i, \varphi_i, \theta_t, \varphi_t)\)
- 3D Isotropic BRDF
  \((\lambda, \theta_i, \theta_v, |\varphi_i - \varphi_v|)\)

Complexity of measurement and modelling

- High
- Low
Textured Materials Representations

**BSSRDF**

\[ Y_r = BSSRDF(\lambda, x_i, y_i, \theta_i, \varphi_i, x_v, y_v, \theta_v, \varphi_v) \]

**9D**

\[ \omega_i(\theta_i, \varphi_i) \]
\[ \omega_v(\theta_v, \varphi_v) \]

**BTF / SVBRDF**

\[ Y_r = BTF(\lambda, x_i, y_i, \theta_i, \varphi_i, \theta_v, \varphi_v) \]
Homogeneous Materials Representations

**BSDF**

\[ Y_r = BSDF(\lambda, \theta_i, \varphi_i, \theta_v, \varphi_v, \theta_t, \varphi_t) \]

**BTDF anisotropic**

\[ Y_r = BTDF(\lambda, \theta_i, \varphi_i, \theta_t, \varphi_t) \]

**BRDF anisotropic**

\[ Y_r = BRDF(\lambda, \theta_i, \varphi_i, \theta_v, \varphi_v) \]

**BRDF isotropic**

\[ Y_r = IBRDF(\lambda, \theta_i, \theta_v, |\varphi_i - \varphi_v|) \]
Bidirectional Reflectance Distribution Function

- Distribution of radiance reflected (L)

\[
BRDF(\lambda, \theta_i, \phi_i, \theta_v, \phi_v) = \frac{dL_r(\lambda, \theta_v, \phi_v)}{L_i(\lambda, \theta_i, \phi_i) \cos \theta_i d\omega_i}
\]

irradiance \( E_i \)

- Properties
  - Illum./view directions reciprocity
    - swapping source and sensor does not effect BRDF value
  - Energy conservation
    - portion of energy reflected to all directions has to be between 0 and 1
      \[
      \int_\Omega BRDF(\lambda, \theta_i, \phi_i, \theta_v, \phi_v) \cos \theta_v d\omega_v \leq 1
      \]
  - Non-negativity
BRDF Measurement Setups Taxonomy

\[ BRDF(\lambda, \theta_i, \varphi_i, \theta_v, \varphi_v) \]

5 dimensional data \( \rightarrow \) 4 dimensions depend on camera, light & sample positioning

Measurement setup with 4 mechanical degrees of freedom:

- Gonio-reflectometers
  - sample/light/camera 1/2/1

- Mirror-based setups
  - sample/light 2/2 + many views at once

- Image-based setups
  - light/camera 1/1 + defined shape

- Portable setups

Isotropic BRDF (4 dimensional): \[ BRDF(\lambda, \theta_i, \theta_v, \varphi_i - \varphi_v) \]
BRDF Sample Acquisition

Gonio-reflectometers

Sequential sampling of 4D space ➔
moving sample, light & camera

[Murray & Smith JIES 90]

[White et al. JAO 98]
Mirror-based setups

Mechanical DOF reduced by multiple-views in mirror image (directional illumination)

[Ward CG 92]

[Dana et al. ICCV 01]
Mirror-based setups

[Mukaigawa et al. ACCV 07]

Mechanical DOF reduced by multiple-views in mirror image (projected illumination pattern)

[Ghosh et al. ICCV 07]
BRDF Sample Acquisition

Image-based setups

Varying incoming /outgoing directions over cylinder image

Mechanical DOF reduced by defined sample shape (orientation)

[Marschner et al. JAO 00]
object of estimated geometry

[Lu et al. JAO 98]  [Ngan et al. EGSR 05]
BRDF Sample Acquisition

**Image-based setups**

Mechanical DOF reduced by defined sample shape (orientation)

[Spherical homogeneous samples]

[Marschner PhD 98]

[Matusik et al. EWR 03]
BRDF Sample Acquisition

Portable setups

Fast measurement, compromise accuracy, limited:
• number of illumination/sensing elements
• viewing/illumination angles range

[Ben-azra et al. CVPR 08]

[Lan et al. CGF 10]
Measurement of Specular BRDFs

Green paint with thick acrylic coating

Silver 925 (silver 92.5%, copper 7.5%)

Shape courtesy of Lechler S.p.a. Como, Italy
Measurement-related issues

- anisotropy due to polishing
- light refraction on aperture
- lens flare artifact
- reflections of environment

Anisotropic artifacts
- due to insufficient polishing
- highlight perpendicular to scratches
- can be avoided by selecting appropriate BRDFs from MERL database cannot be safely used as a reference
Measurement-related issues

Diffraction on aperture

- wave effect of light $\Rightarrow$ light passing narrow slit
- bright streak perpendicular to aperture blades
- streaks in both directions $\Rightarrow$ odd number of blades $\Rightarrow$ twice so many streaks
- pronounced for narrow aperture and bright point-light
- solved by circular aperture
Measurement-related issues

Lens flare
- usually red spot due to inter-reflection in lens body
- the more elements the more pronounced
- Suppressed by a long lens hood

Reflection from environment
- mirror-like finishes reflect environment – diffuse black covering
Results – specular BRDFs

MERL green-acrylic  MERL green-plastic  our measurement paint

MERL chrome  MERL steel  our measurement silver
Spatially-Varying BRDF Measurement

$SV BRDF(\lambda, x, y, \theta_i, \varphi_i, \theta_v, \varphi_v)$

- 7 dimensional data $\Rightarrow$ 4 dimensions depend on camera, light & sample positioning
- Restricted to opaque, flat surfaces where BRDF reciprocity holds

Measurement setup with 4 mechanical degrees of freedom:

- Gonio-reflectometers
  - sample/light/camera 1/2/1
- Image-based setups
  - sparse view/light sampling 2/2 + known geometry
- Light-stages
  - many lights/cameras 2/2
- Portable setups
  - registration of BRDF measurement to sparse object images

[McAllister 02]
SV-BRDF Sample Acquisition

Gonio-reflectometers

[McAllister GH 02]
- moving light, tilting sample

[Holroyd et al. TOG 10]
Simultaneous measurement of geometry and SVBRDF
Light stages

Facial SVBRDF measurement
- 156 lights, high-speed camera

[Debevec et al. SIG 00]

• 150 lights, 16 cameras
• structured light for geometry capture

[Weyrich et al. SIG 06]
Portable setups

Fast measurement, compromise accuracy:

- Sparsely measured BRDF registered to measured object reflectance map (single view, many lights)
- Anisotropic BRDFs

[ Dong et al. SIG 10 ]

BRDF measurement

Reflectance-map measurement
SVBRDF Capture & Modeling

Portable setups

- [Ren et al. TOG 11] - “pocket reflectometry”: SVBRDF from movie of static object lit by linear light source captured by a static mobile phone camera
  - Use set of BRDF reflectance targets (selection is important)
  - Measured reflectance fitted as a mixture of target’s BRDFs

![Portable setups diagram](image)
SV-BRDF Sample Acquisition

Portable setups

SVBRDF Capture In The Frequency Domain

- reflection of Fourier basis patterns emitted from the screen ➔ fitting reflectance by Gaussian mixture models
- different sampling frequencies ➔ 131 images
- viewing rays reflecting into the screen as reflectance lobe
- each captured pixel ➔ integral of the product of this projected lobe and the illumination pattern

[Aittala et al. SIGGRAPH 13]
SV-BRDF Sample Acquisition

Portable setups

Two-Shot SVBRDF Capture for Stationary Materials

- smartphone a capturing device
- acquisition limited to retroreflective BRDF slice ⇔ camera close to illumination
- fitting micro-facet BRDF model
- assumption of stationary texture in the material ⇔ repeatable structure

[Aittala et al. SIGGRAPH 15]
SV-BRDF Sample Acquisition

Portable setups [Aittala et al. SIGGRAPH 16]

Reflectance Modeling by Neural Texture Synthesis
- spatially varying parametric reflectance models from a single image taken with flash illumination
- materials with stationary texture
- decomposition of image into local tiles
- deep convolutional neural network \( \Rightarrow \) fitting diffuse and specular coefficients maps
Bidirectional Texture Function

- BTF – Bidirectional Texture Function
- Illumination/view directions dependent texture
  \[ BTF(\lambda, x, y, \theta_i, \phi_i, \theta_v, \phi_v) \]
- Includes: inter-reflections, sub-surface scattering, local masking and shadowing
- One of the best practical representations of textured materials appearance
- Massive data \( \Rightarrow \) thousands of images per material (GBs)
- Compression and modelling is inevitable
BRDF vs. BTF

polyester fabric

BTF – additional texture information

BRDF

1071 DPI
Measured BTF Data

- Plastic weave
- Wood
- Leather
- Burlap
BTF Measurement Setups Taxonomy

**Sample Measurement**

**Measurement setup with 4 mechanical degrees of freedom:**

- **Moving Sample & Camera**
  - sample/camera $3/1$ ($1/1 +$ many lights)

- **Moving Sample & Light**
  - sample/light $2/2$

- **Moving Sample, Light & Camera**
  - sample/light/camera $1/2/1$

- **Moving Sample**

- **Static Measurement Setups**
  - many lights & cameras
  - (real/virtual)

**Gonio-reflectometers**

**Mirrors, domes**

**Portable setups**

$BTF(\lambda, x, y, \theta_i, \varphi_i, \theta_v, \varphi_v)$

7 dimensional data $\Rightarrow$ 4 dimensions depend on camera, light & sample positioning
BTF Sample Acquisition

Gonioreflectometer – Moving Sample & Camera

CURET-Columbia&Utrecht University

[Dana et al. ACM TOG99]

Database: 61 samples

Illu./View directions:
55/max.205 = 215 img.

Max. illu./view elev.:

85°/85°

Rectified images:

400 x 300 pixels

Measurement time:
n/a

http://www1.cs.columbia.edu/CAVE/software/curet
BTF Sample Acquisition

Goniorelectrometer – Moving Sample & Camera

Bonn University
[Sattler et al. EGSR 03]

Database:

10 samples (4 HDR)

Illu./View directions:
81/81 = 6 561 img.

Max. illu./view elev.:
75°/75°

Rectified images:
800 x 800 pixels

Measurement time:
~ 14 hours

http://btf.cs.uni-bonn.de/
BTF Sample Acquisition

Yale University [Koudelka et al., TEXTURE 03]

Database: 17 samples

Illu./View directions:

120/90 = 10 800 img.

Max. illu./view elev.:

80°/75°

Rectified images:

192 x 192 pixels

Measurement time:

~ 10 hours

http://vision.ucsd.edu/kriegman-grp/research/vst
BTF Sample Acquisition

UTIA AS CR
[Haindl&Filip CVPR13]

Illu./View directions:
arbitrary/arbitrary (81/81)
Max. illu./view elev.:
90°/90°

Rectified images:
2000 x 2000 pixels

Database: publicly available

Measurement time: ~10 hours

- Spectral & HDRI measurements
- Arms angular accuracy: 0.03°
- Resolution: over 1000 DPI

http://btf.utia.cas.cz
Rutgers University
[Dana & Wang, JOSA 04]

Database: n/a
Illu./View directions: continuous
Max. illu./view elev.: 23-37°/23-37°
Rectified images: ~200 x 200 pixels
Measurement time: ~1 hour

Material moves below mirror
BTF Sample Acquisition

Mirrors – Static Measurement Setups

New York University
[Han et al., ACM TOG 03]

Database: n/a
Illu./View directions:
22-79/22-79 =
484 – 6241 img.
Max. illu./view elev.:
76°/76°
Rectified images:
~ 200 x 200 pixels
Measurement time:
~1 hour
BTF Sample Acquisition

Dome – Static Measurement Setups

Bonn University
[Müller et al. 05]

Illu./View directions: 151/151 = 22 801 img.
Max. illu./view elev.: n/a
Rectified images: 1024 x 1024 pixels
Database: n/a
Measurement time: ~1 hour
BTF Sample Acquisition

Dome – Moving Sample, portable

Bonn University
[Schwartz et al. 14]

- Dome setup used in industry
  Illu./View directions: 198/264 = 52 272 images
  Max. illu./view elev.: 75 degrees
  Rectified images: 1024 x 1024 pixels
  Measurement time: 4-10 hours
Rapid Measurement Approach

- Measurement of BTF 6561 images ➔ 20 hours
- Faster solutions needed for practical usage
- Proof-of-concept prototype ➔ construction set

- 2 LEDs
- compact camera
- approximate BTF ➔ capturing time 4 minutes
Rapid Measurement Approach

measurement procedure

\( \varphi_v = \varphi_i + \alpha \)

(0, 2\( \pi \))

Reference 6561 images

81 views

81 illuminations

Specular highlight

Anisotropic highlight

8 slices 169 images

subspaces reconstruction

missing images interpolation
Results of Portable Setup

materials photo & measured appearance (169 images)

- synthetic leather
- sandpaper
- non-woven fabric
- upholstery fabric
Rapid Measurement Approach

Portable Setups

- **LightDrum** [Havran et al. Sensors 2016]
- Portable solution for fast on-site BTF measurement
- Body with lights and cameras rotates above the measured material
BTF Capturing & Visualization Pipeline

- **device**
  - geometric calibration
  - capture light non-uniformity
  - lens vignetting

- **material**
  - material alignment
  - angular sampling

- **illumination/viewing directions**

- **individual image processing**
  - multiple exposures & illum. intens.
  - lens vignetting compensation
  - image registration rectification
  - spatial lighting non-uniformity correction
  - calibration target
  - colorimetric calibration
  - create HDR
  - Bayer to RGB

- **compute interpolation weights & indices**
  - seamless tiles cutting

- **alignment of registration & material planes**

- **BTF rendering**
  - HDR in XYZ

- **3D geometry**

- **illumination environm.**

... typically over 6000 images
Most system measure RGB data in 8-bit/colour channel.

University Bonn Database (UBO) – 4 HDR architectural samples.

Materials appearance depends on light’s spectrum \(\Rightarrow\) need for full spectral measurements.

[Lyssi 09] – full spectral BTF measurement and calibration on [Sattler et al. 03] setup.
- Spectral Filter \(\Rightarrow\) 30 wavelength bands (430 – 720 nm)
- 30 x 81 x 81 images \(\Rightarrow\) enormous measurement times (3 days)
- Sample in OpenEXR = 1 TeraByte

[Rump et al. 10] – GT data for multispectral BTF.
Spatial Reflectance Data Rectification

- **Registration and resampling** images of different views $\rightarrow$ same size images, surface normal aligned with viewing direction

Using:
- Registration marks
- Intersection of sample borders
- Predefined geometric transformation (static setups)

**Lines detection**

**Hough transform**
Contrary to SVBRDF, BTF face problem with rough structure samples

- Different views $\Rightarrow$ **Pixel-wise misalignment**, due to occlusion
- Solution $\Rightarrow$ process individual views separately

BTF - no geometrical information $\Rightarrow$ no material profile at object edges
Measured Data Representation

Texture representation
- Only images for the same view are correctly registered
- Shadows/occlusion compensation required prior to processing

ABRDF representation
- Illuminations/views aligned
- Highlights positions fixed
- Easier pixel-wise comparison.
Apparent BRDFs

Apparent BRDF ≠ BRDF (masking, occlusions, shadowing, etc.)
possible violation of: Helmholtz reciprocity & energy conservation
Challenging materials

- Combination of specular, diffuse and anisotropic features
Challenging materials
BSSRDF Measurement

Bidirectional subsurface-scattering reflectance distribution function

\[ BSSRDF(\lambda, x_i, y_i, x_o, y_o, \theta_i, \varphi_i, \theta_v, \varphi_v) \]

[Bicodemus et al. 77]

BTF includes scattering information, but difficult to separate

- **General 9 dimensional data** \( \Leftrightarrow \) often called as *reflectance fields*
- Describes light transport (scattering) in material structure between any pairs of incoming and outgoing rays
- Translucent materials
- Direct measurement very sparse due to high data dimensionality
BSSRDF Measurement

[Goesele et al. TOG 04 ] – laser-based sparse spatially varying subsurface scattering measurement

[ Tong et al. TOG 05 ] – BTF combined with local laser-based subsurface scattering measurement
BSSRDF Measurement

• Models of subsurface scattering in homogeneous dielectric materials are available, measurement of models parameters:
  [Jensen et al. SIG 01] – dipole model of dielectrics, validated by scattering measurement of focused beam

![Without scattering model](image1)
![With scattering model](image2)

• Diffuse/specular reflectance components separation (polarization/color/illum. patterns) [Shaffer 85], [Nayar et al. JCV 97], [Nayar et al. TOG 06] → diffuse component represents light refraction inside material structure → fitting scattering models parameters to diffuse component.
Volumetric Models Acquisition

[Zhao et al. 11 TOG] – material geometry scanned by X-Ray Micro CT scanner (resolution $1024^2$). Scattering information transferred to volumetric data by matching of several samples photographs.

✓ realistic appearance

☒ assumes single material, lengthy rendering, limited dynamic range of the scanner

[Zhao et al. 11, ACM]
Angular Parameterizations

- **Illumination-view**
  - Angularly uniform
  - Spatially uniform

- **Half-difference angles** [Rusinkiewicz 98]

- **Onion slices model** [Havran et al. CGF 09]
BRDF in half-difference parameterization [Rusinkiewicz 98]

- reciprocity $\varphi_d = \varphi_d + \pi$
- bilateral symmetry
- function called as characteristic slice of material [Burley 12]
- Bivariate BRDF
Anisotropic Material Appearance

- property of being directionally dependent
- azimuthally-dependent material’s appearance

Present in many materials:

- directional fibers (fabric, wood, hair)
- weaving pattern/height profile of threads of fibers (fabric)
- surface machining/finishing (metal, plastic, wood, …)
Anisotropic vs. Isotropic Appearance

- BRDF – Bidirectional Reflectance Distribution Function
- Illumination and view dependent reflectance

\[ BRDF(\lambda, \theta_i, \phi_i, \theta_v, \phi_v) \]

- Isotropic vs. anisotropic BRDF

\[ B(\theta_i, \theta_v, |\varphi_i - \varphi_v|) \quad B(\theta_i, \varphi_i, \theta_v, \varphi_v) \]
Anisotropic Material Appearance

Capturing of anisotropy increases complexity of the appearance acquisition process
Anisotropic Material Appearance

• Highlights dependent on initial position of material within appearance acquisition
Fast Anisotropy Detection

Properties

• Simple setup of reflector and camera 1.5 m apart, no calibration
• Aggregated illumination using flashlight
• All illumination azimuths recorded
Fast Anisotropy Detection

estimated reflectance
reference BRDF
Uniform vs. adaptive sampling approaches

- **BRDF slices**

- **Problem decomposition**: adaptive measurement of 4D function ↪ adaptive measurement of 1D functions in 4D space

  adaptive sampling based on a cross-validation error in control samples
BRDF Data Compression

• **Splines** [He et al., SIG 92]
  – Used for storing precomputed BRDF model values
  – Do not exploit BRDF symmetry, low compression

• **Spherical harmonics** [Westin et al., SIG 92]
  – Analogy of sin, cos basis functions on sphere in frequency domain
  – Requires many parameters otherwise produces artifacts

• **Spherical wavelets** [Schroder & Sweldens, SIG 95]
  – Basis functions localized in both spatial and frequency domain

• **Zernike polynomials** [Koenderink et al., ECCV 96]
  – Polynomial functions used in optics as a basis functions mapped on hemisphere
BRDF Data Factorization

[Kautz et al. 99] – use SVD to produce two 2D factors instead of 4D BRDF.

\[ BRDF(\omega_i, \omega_v) \approx \sum_{k=1}^{K_j} P_{k, r_1, r_2}(\pi_1(\omega_i, \omega_v))Q_{k, r_1, r_2}(\pi_2(\omega_i, \omega_v)) \]

[McCool et al. 01] – use Homomorphic factorization to generate more than two positive factors.

\[ BRDF(\omega_i, \omega_v) \approx \prod_{j=1}^{J} P_{j, r_1, r_2}(\pi_j(\omega_i, \omega_v)) \]

[Suykens et al. 03] – each pixel = product of three or more two-dimensional positive factors using chained matrix factorisation.

\[ BRDF(\omega_i, \omega_v) \approx \prod_{j=1}^{J} \sum_{k=1}^{K_j} P_{j, k, r_1, r_2}(\pi_{j, 1}(\omega_i, \omega_v))Q_{j, k, r_1, r_2}(\pi_{j, 2}(\omega_i, \omega_v)) \]

\( \checkmark \) factors in form of textures \( \Rightarrow \) interactive rendering

\( \times \) For compression of measured BRDFs only

[Suykens et al. 03]
Empirically Derived BRDF Models

- **Phong shading** [Phong ACM 75]
  - Ambient, diffuse, and specular terms
  
  \[ BRDF(I, V) = k_a i_a + k_d (I \cdot N)i_d + k_s (R \cdot V)\alpha i_s \]
  
  \( k \ldots \) material coeffs., \( i \ldots \) light coeffs. \( R = 2(I \cdot N)N - I \)

  - More computationally efficient modification [Blinn SIG 77] replaced term \( R \cdot V \) by \( N \cdot H \). Used in OpenGL and Direct3D implementations.

  - Improving energy conservation for metallic surfaces using facet-based model [Neumann et al. CGF 99].
Empirically Derived BRDF Models

- **[Schlick EG 94] -** anisotropic, energy conserving, simplified Fresnel refraction

- **[Lafortune et al. EG 97]** generalized phys. plausible cosine lobes, one lobe model as 5 params.

\[ Y_{i,v} = \rho [\omega_i^T D \omega_v]^n = \rho [D_x u_x v_x + D_y u_y v_y + D_z u_z v_z]^n \]

- Extension of Phong model

  **[Ashikhmin & Shirley JGT 00]**
  - non-Lambertian diffuse term, anisotropic, energy conserving, Fresnel refraction
  - intuitive parameters, complex computation
Physically-Derived BRDF Models

- **Micro-facet models** [Torrance & Sparrow JOSA 67]
  - Diffuse (Lambertian lobe) and scattering parts
  - Each facet – long V-cavity $\rightarrow$ perfect reflector
  - Random sizes and Gaussian distribution
  - Improvement [Cook & Torrance SIG 81], reflectance as
    - Fresnel function $F$
    - Facet distribution $D$
    - Shadowing/Masking term $G$

- Complete model [He et al. CG 91]
  - Inter-reflections, occlusions, polarization, interference, diffraction, wave effects of light, ...
  - Isotropic reflections only
Physically-Derived BRDF Models

- Simplified analytical microfacet model [Ward CG 92]
  - Specularity as \( \exp() \) function, four physically meaningful parameters, anisotropy modeling
    \[
    BRDF(\theta_i, \theta_v) = \frac{k_d}{\pi} + k_s \frac{1}{\cos \theta_i \cos \theta_v} \frac{e^{-\tan^2 \theta_n/\alpha^2}}{4\pi \alpha^2}
    \]
  - normalization in [Duer 05]

- Microgeometry model [Westin 92]
  - Geometry based model \( \Rightarrow \) More general
  - Underlying material geometry has to be known, difficult to fit to measured BRDFs
Physically-Derived BRDF Models

• Model of diffuse reflection from rough surfaces
  [Oren & Nayar IJCV 95]
  – Uses [Torrance & Sparrow JOSA 67] micro-facet model,
  – Roughness as probability distribution of facet slopes,
  – Each facet has Lambertian reflectance.

• [Schlick 94 CGF 94]
  – Anisotropic, Sub-surface effects in layered materials, energy conservation
  – Account for difference between homogeneous and heterogeneous materials
  – Variable complexity formulations
Physically-Derived BRDF Models

  - Anisotropic extension of facet distribution, energy conservation, simple fitting, fast rendering

Cook-Torrance:

\[
BRDF(\theta_i, \theta_v) = \frac{k_d}{\pi} + k_s \frac{F(\theta_h)D(\theta_h)G(\theta_i, \theta_v)}{\pi \cos \theta_i \cos \theta_v}
\]

Kurt et al.:

\[
BRDF(\theta_i, \theta_v) = \frac{k_d}{\pi} + k_s \frac{F(VH)D(\theta_h, \phi_h)}{4(VH)(\cos \theta_i \cos \theta_v)^\alpha}
\]
Conclusions on BRDF Modeling

• Wide range of BRDF modeling and compression techniques available
  – Non-linear iterative estimation of parameters, depends on initialization
  – Memory efficient representation of BRDF
• Results of BRDF models \(\Rightarrow\) low-pass filter.
• Higher quality \(\Rightarrow\) more parameters to store
  \(\Rightarrow\) often more complex fitting

[Havran et al. 09 JW]
Appearance data publicly available

BRDF Databases
- MERL BRDF database [Matusik et al. SIG03] – 100 isotropic BRDFs
- UTIA BRDF database [Vavra&Filip PG14] – 150 anisotropic BRDFs
- http://btf.utia.cas.cz

BTF Databases
- CURET-Columbia&Utrecht University [Dana et al. ACM TOG99] – 61 BTFs (limited sampling directions)
  http://www1.cs.columbia.edu/CAVE/software/curet
- Yale University BTF database
  http://vision.ucsd.edu/kriegman-grp/research/vst
- University Bonn BTF database – 100 BTFs
  http://btf.cs.uni-bonn.de/
- UTIA BTF database [Filip et al. VC18] – 22 BTFs
  http://btf.utia.cas.cz
UTIA Anisotropic BRDF Database

http://btf.utia.cas.cz

6 carpet

96 fabric
- upholstery
- apparel
- cushion

16 leather (genuine & imitations)

6 plastic

16 wood (genuine)

10 other materials
plaster, paper, paint, ....
UTIA Anisotropic BRDF Database

http://btf.utia.cas.cz

elevation step = 15°
azimuthal step = 7.5°
UTIA BTF database – 22 materials

BTF database
• 6 BTFs as collection of images
• 16 BTFs in BIG data format

http://btf.utia.cas.cz
Conclusions on Appearance Measurement

- Measurement setup design depend on the required application
- source of errors ⇨ images registration, angular parameterization, angular sampling
- High accuracy ⇨ no moving parts or simple mechanical elements
- Maximum sample size ⇨ influences distance of light & camera (directional light, orthographic projection)
- Maximum sample height ⇨ influences selection of measurement technique (e.g. SVBRDF vs. BTF)
- Special treatment of specular and anisotropic materials
- Data-consistency-critical applications ⇨ non-uniform or adaptive sampling strategies
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**BRDF models (continued)**


**SVBRDF modeling**

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**SVBRDF modeling** (continued)


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