3DV 2018 Tutorial

Material appearance measurement

Jiri Filip

Institute of Information Theory and Automation
of the AS CR

September 8, 2018

ÚTIA

Motivation for appearance measurement

- Materials in real world

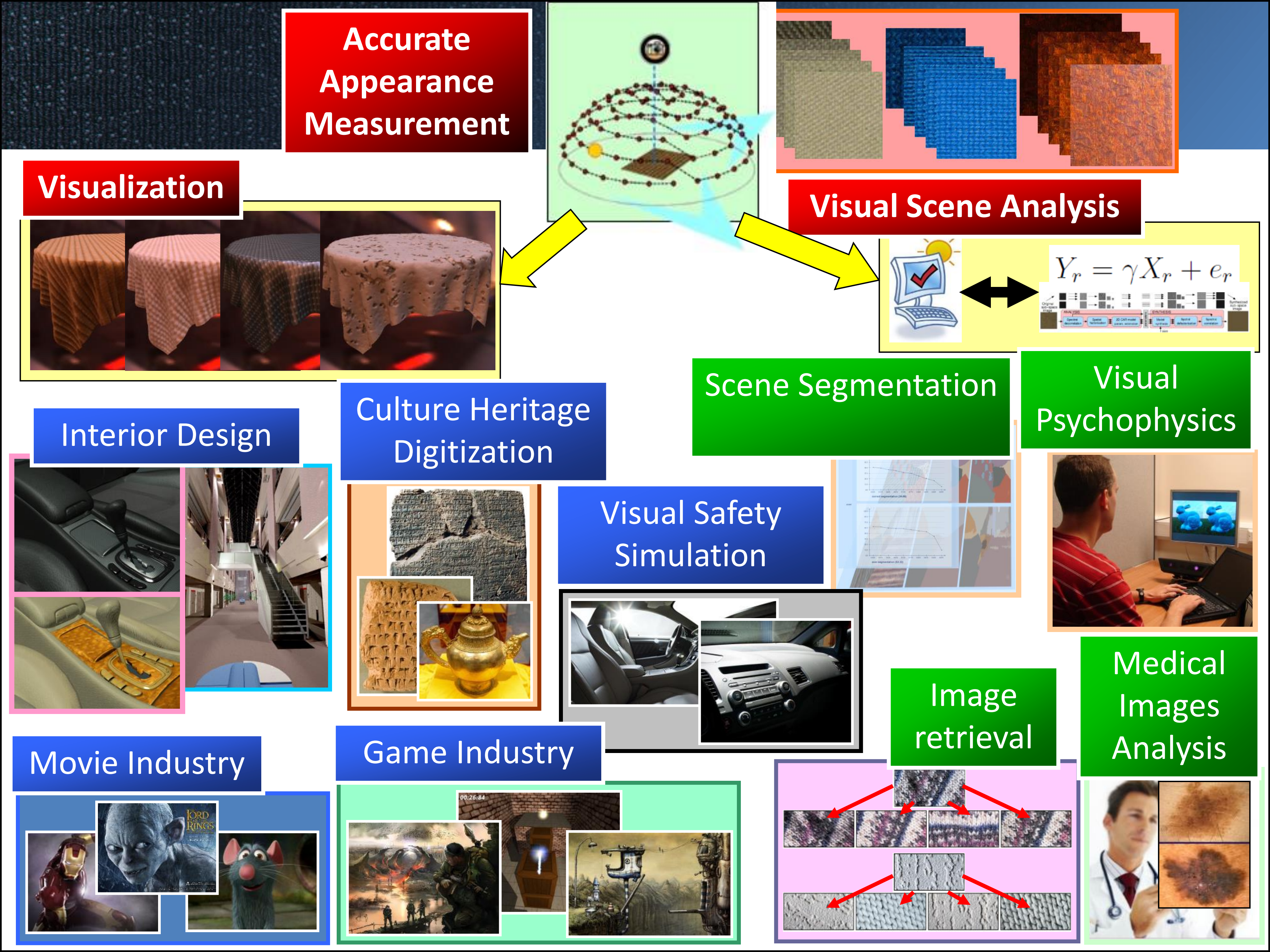
Our mission

- Digital reproduction of material appearance

real world

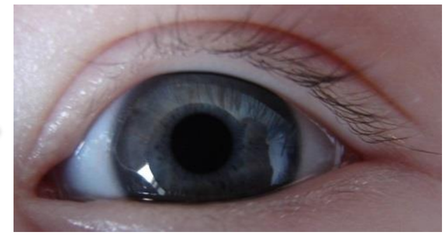
Measurement

digital world


Accurate Appearance Measurement
Visualization
Visual Scene Analysis
$Y_r = \gamma X_r + e_r$
Scene Segmentation
Visual Psychophysics
Interior Design
Culture Heritage Digitization
Visual Safety Simulation
Medical Images Analysis
Image retrieval
Movie Industry
Game Industry
LORD OF THE RINGS

Digital Material Appearance

Virtual Environment



Shapes
3D Geometry

Illumination conditions

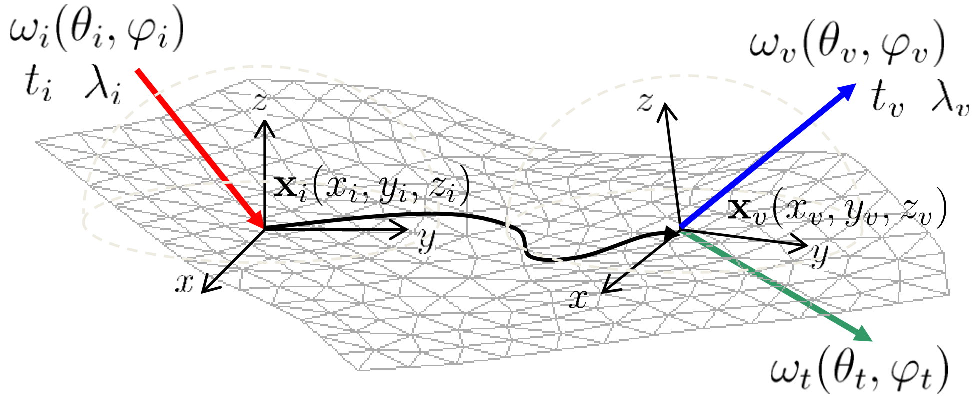
Material Appearance

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



Reflectance

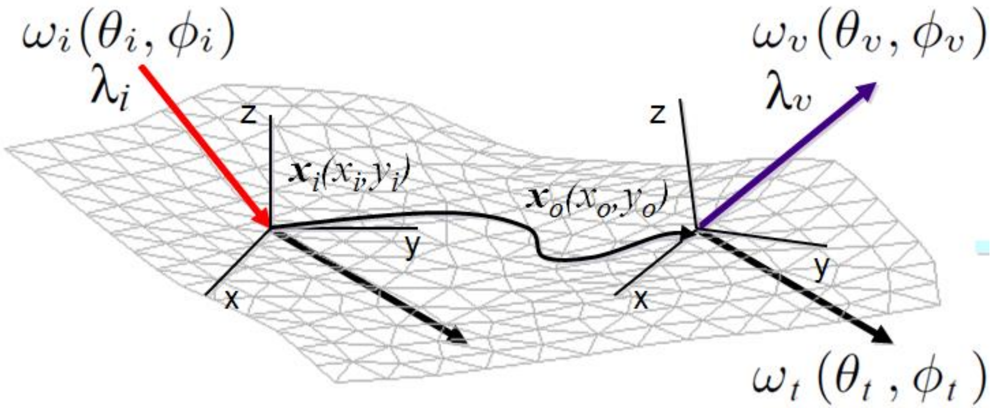
Transmittance

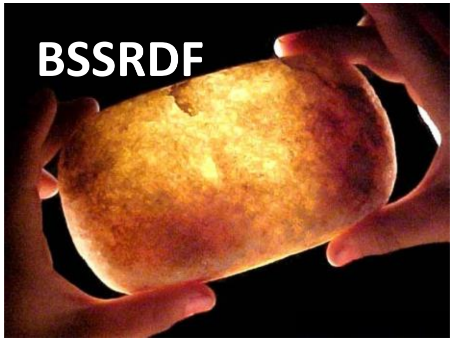
$$Y_r = GRF(\lambda_i, x_i, y_i, z_i, t_i, \theta_i, \varphi_i, \lambda_v, x_v, y_v, z_v, t_v, \theta_v, \varphi_v, \theta_t, \varphi_t)$$

16 dimensions

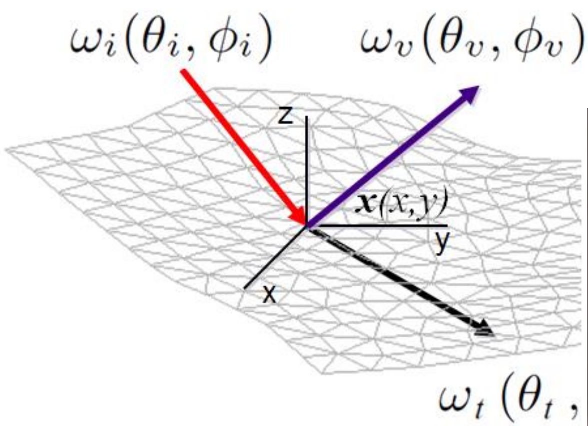
Light-Material Interaction

General model of light-material interaction

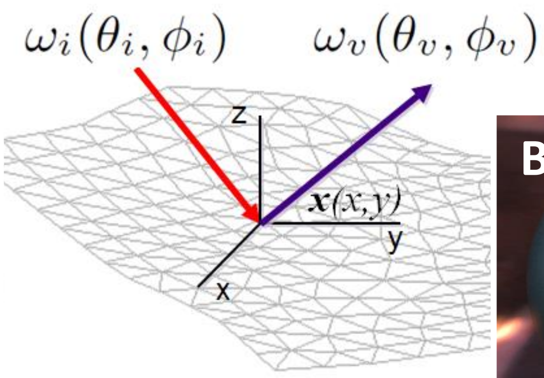


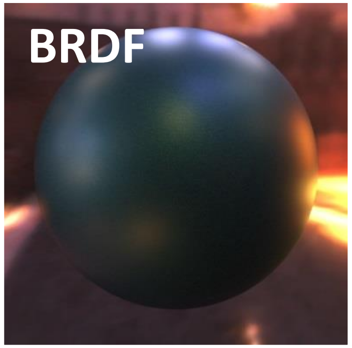


Local scattering effects only

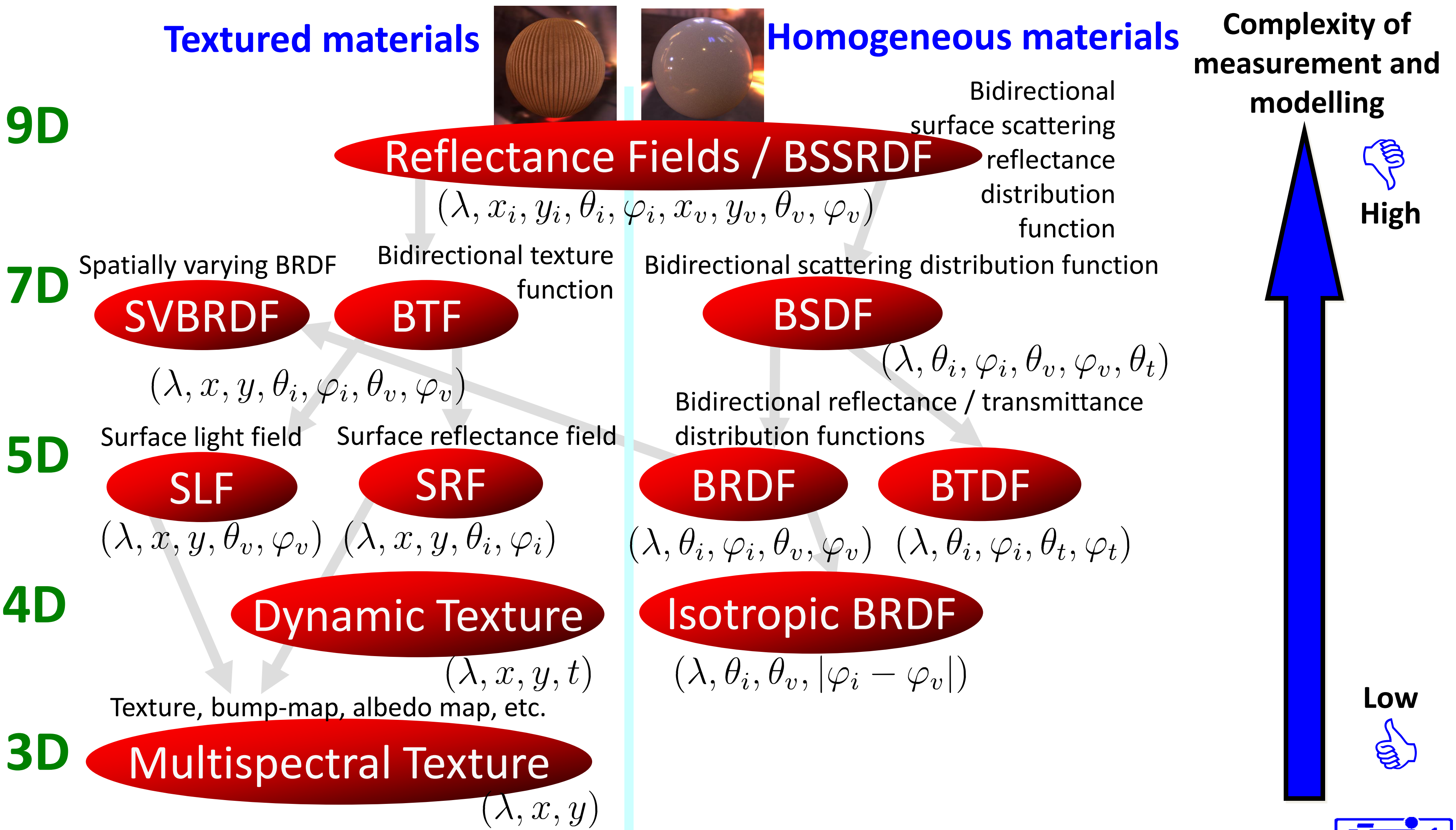


Opaque flat materials





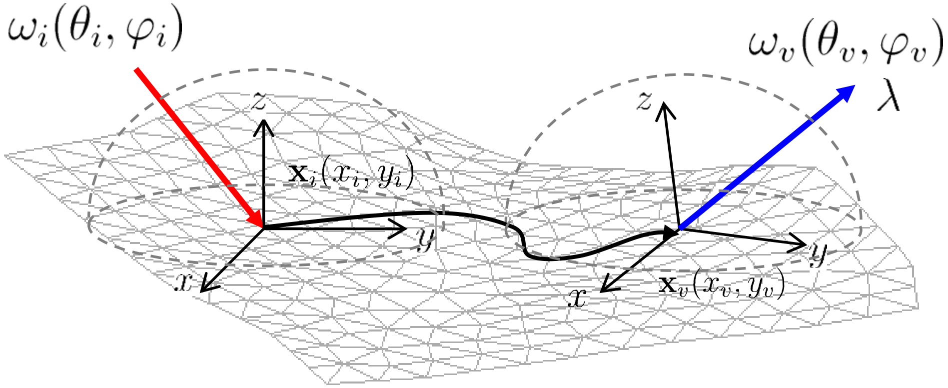
Taxonomy of Material Appearance Representations



ÚTIA

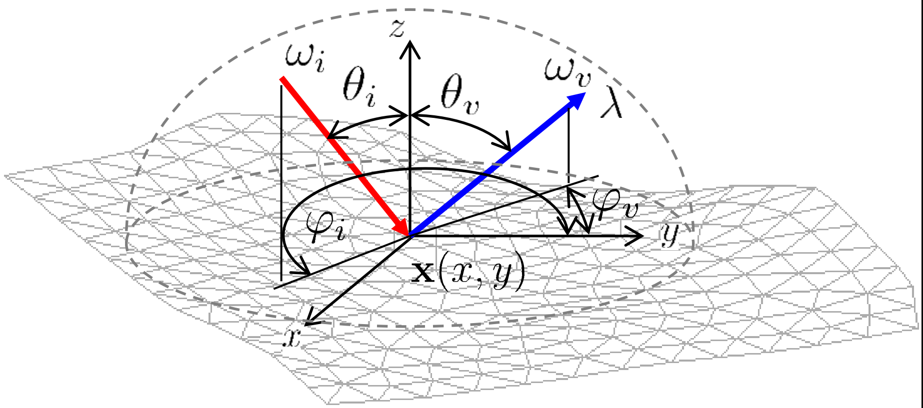
Textured Materials Representations

BSSRDF 9D



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

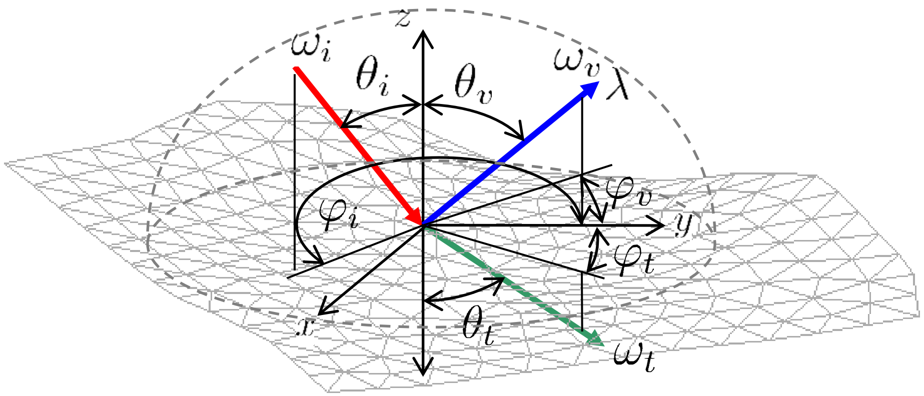
BTF / SVBRDF 7D



$$Y_r = BTF(\lambda, x_i, y_i, \theta_i, \varphi_i, \theta_v, \varphi_v)$$

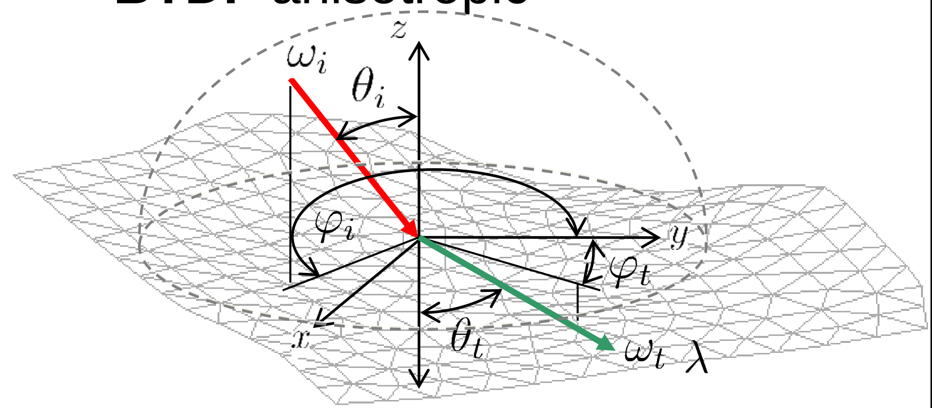
Homogeneous Materials Representations

BSDF 7D



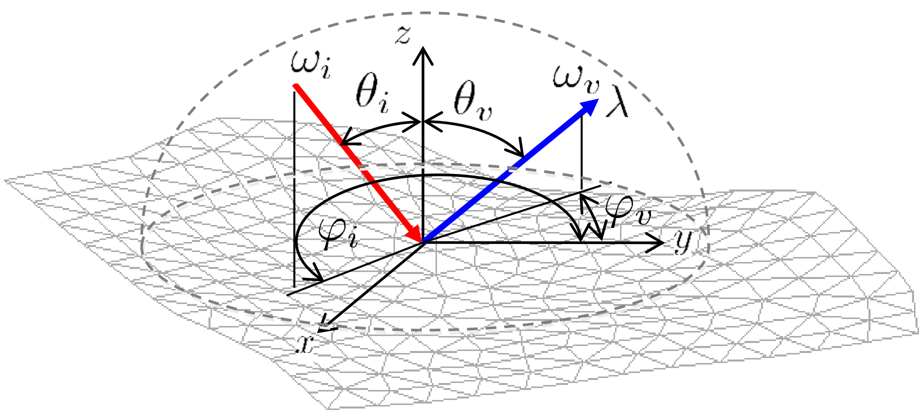
$$Y_r = BSDF(\lambda, \theta_i, \varphi_i, \theta_v, \varphi_v, \theta_t, \varphi_t)$$

BTDF anisotropic 5D



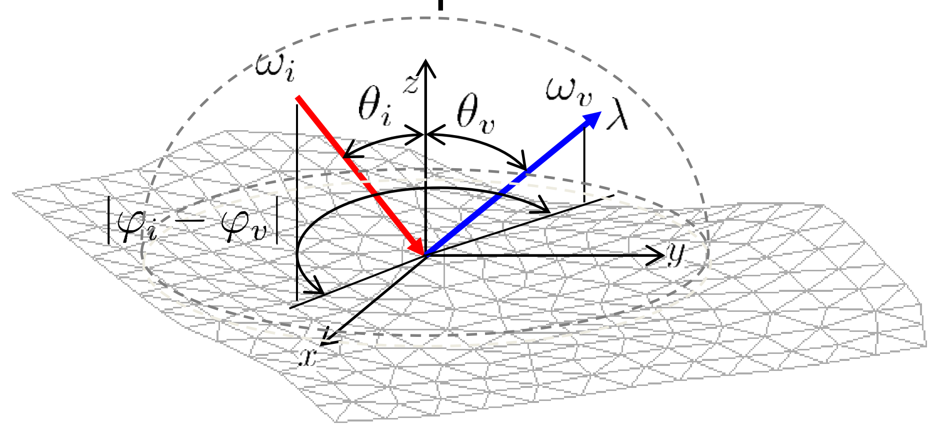
$$Y_r = BTDF(\lambda, \theta_i, \varphi_i, \theta_t, \varphi_t)$$

BRDF anisotropic 5D



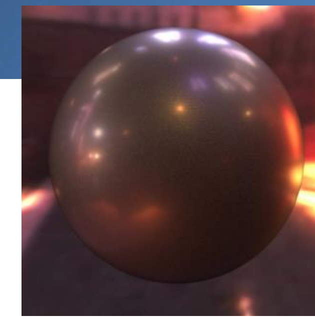
$$Y_r = BRDF(\lambda, \theta_i, \varphi_i, \theta_v, \varphi_v)$$

BRDF isotropic 4D



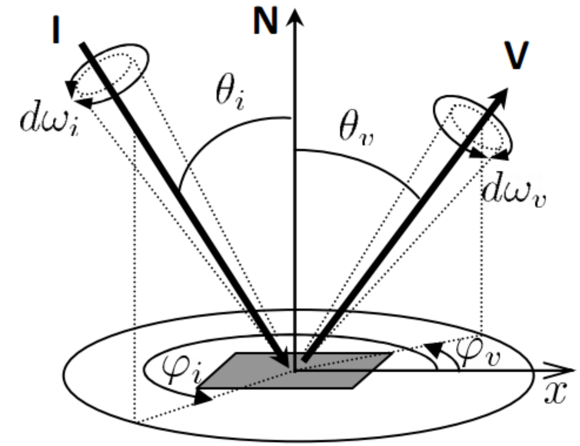
$$Y_r = IBRDF(\lambda, \theta_i, \theta_v, |\varphi_i - \varphi_v|)$$

Bidirectional Reflectance Distribution Function



- Distribution of radiance reflected (L)

$$BRDF(\lambda,\theta_i,\phi_i,\theta_v,\phi_v) = \underbrace{\frac{dL_r(\lambda,\theta_v,\phi_v)}{L_i(\lambda,\theta_i,\phi_i)\cos\theta_i d\omega_i}}_{\text{irradiance } E_i}$$

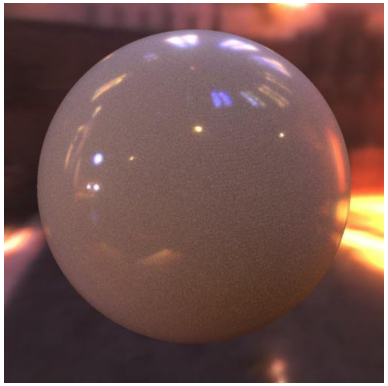


- **Properties**
  - Illum./view directions reciprocity
    - swapping source and sensor does not effect BRDF value
  - Energy conservation
    - portion of energy reflected to all directions has to be between 0 and 1

$$\int_\Omega BRDF(\lambda,\theta_i,\varphi_i,\theta_v,\varphi_v)\cos\theta_v d\omega_v \leq 1$$

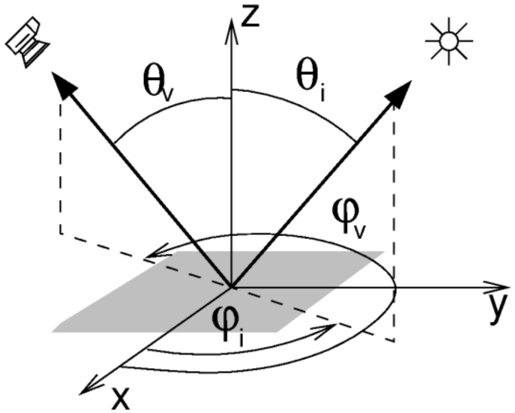
  - Non-negativity

BRDF Measurement Setups Taxonomy



$$BRDF(\lambda, \theta_i, \varphi_i, \theta_v, \varphi_v)$$

5 dimensional data ⇨ 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	compromise accuracy measurements

Isotropic BRDF (4 dimensional): $BRDF(\lambda, \theta_i, \theta_v, \varphi_i - \varphi_v)$

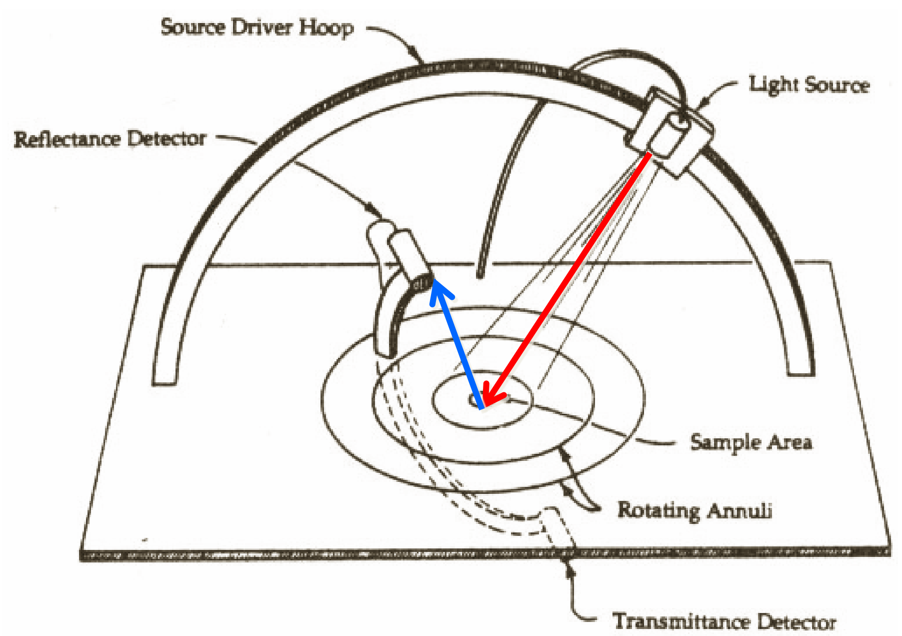
ÚTIA

BRDF Sample Acquisition

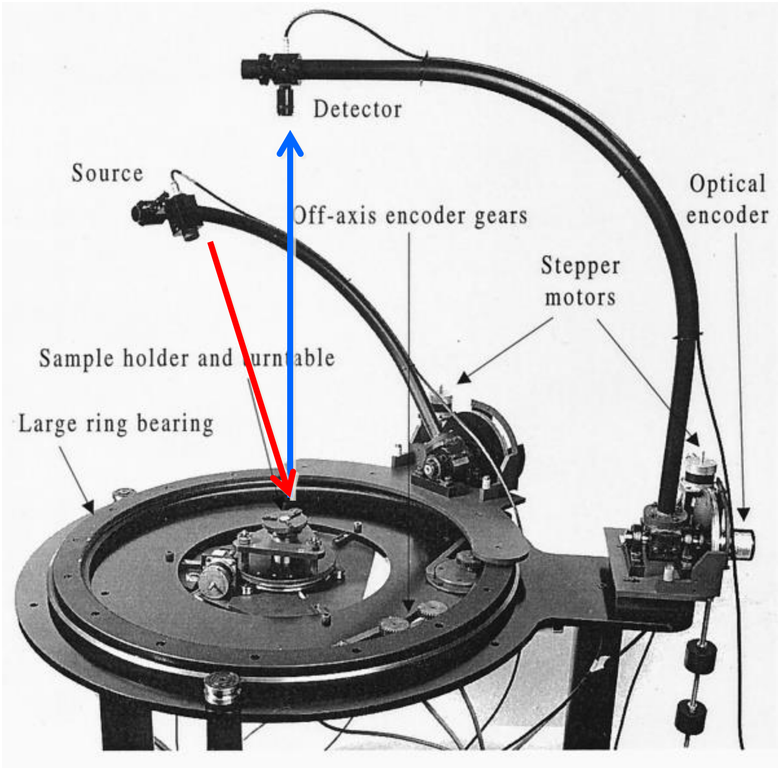
Gonio-reflectometers

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

[Murray & Smith JIES 90]



[White et al. JAO 98]

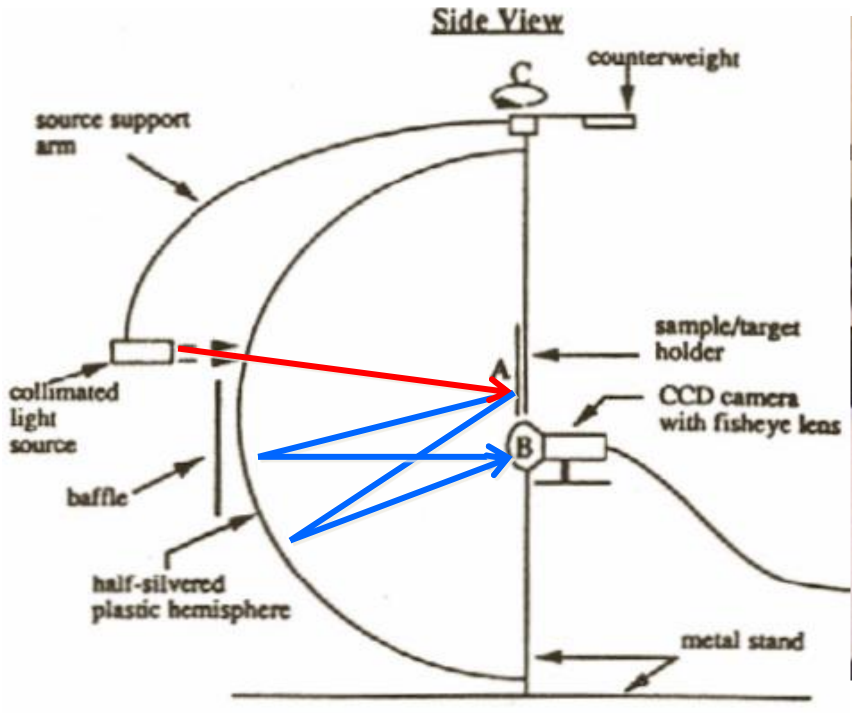


BRDF Sample Acquisition

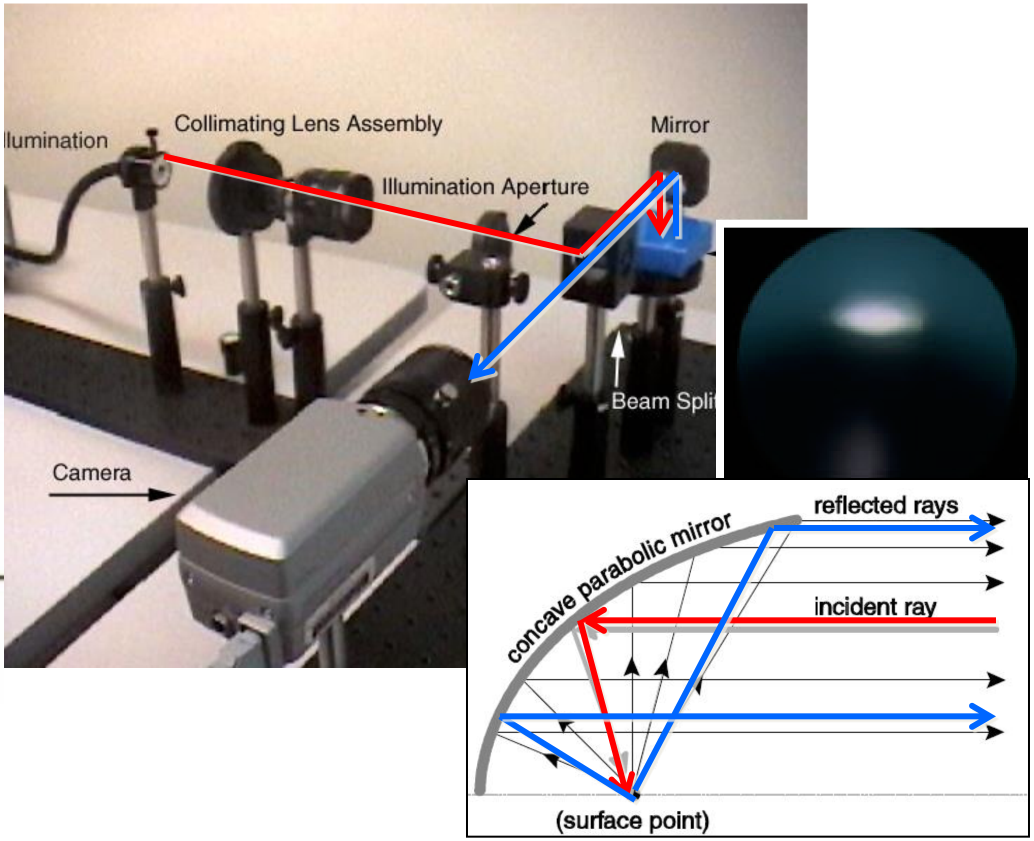
Mirror-based setups

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

[Ward CG 92]



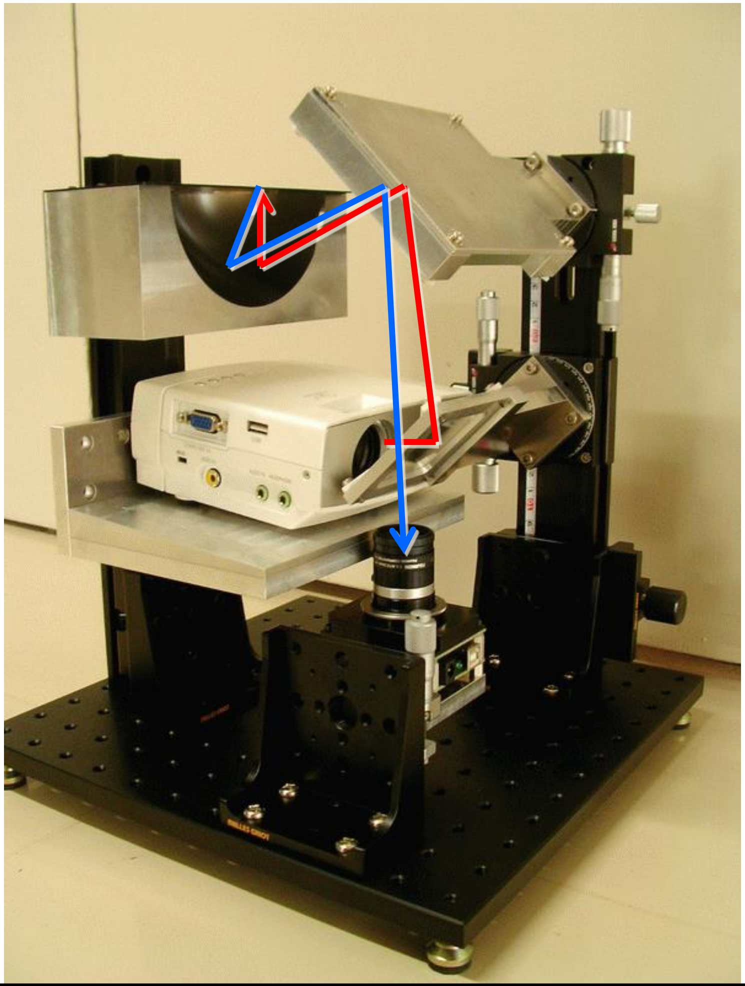
[Dana et al. ICCV 01]



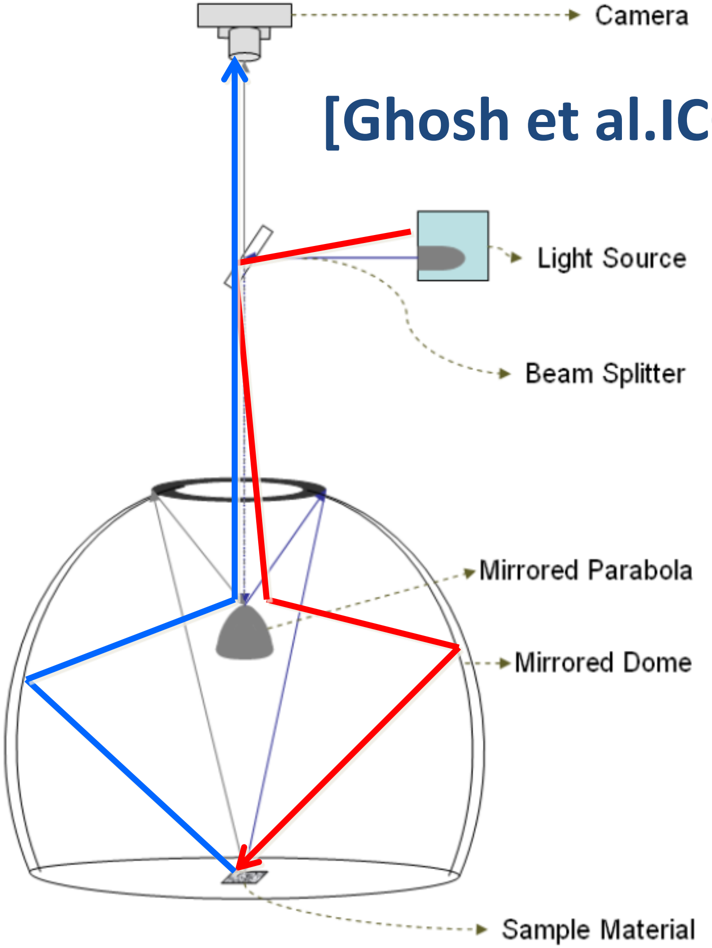
BRDF Sample Acquisition

Mirror-based setups

[Mukaigawa et al. ACCV 07]



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



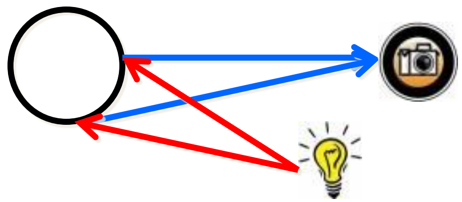
[Ghosh et al.ICCV 07]

BRDF Sample Acquisition

Image-based setups

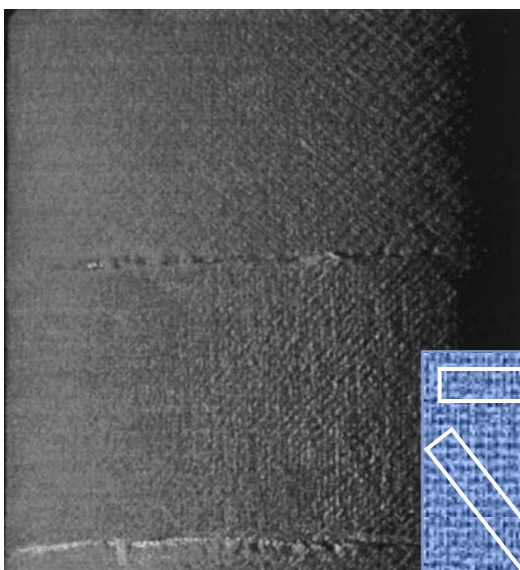
Varying incoming /outgoing directions over **cylinder** image

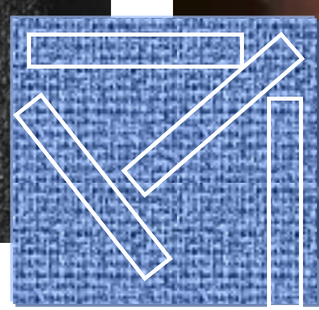
Mechanical DOF reduced by defined sample shape (orientation)



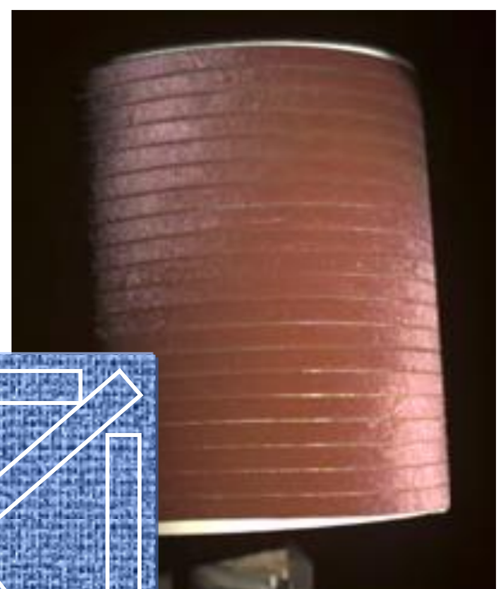
[Marschner et al. JAO 00]
object of estimated geometry

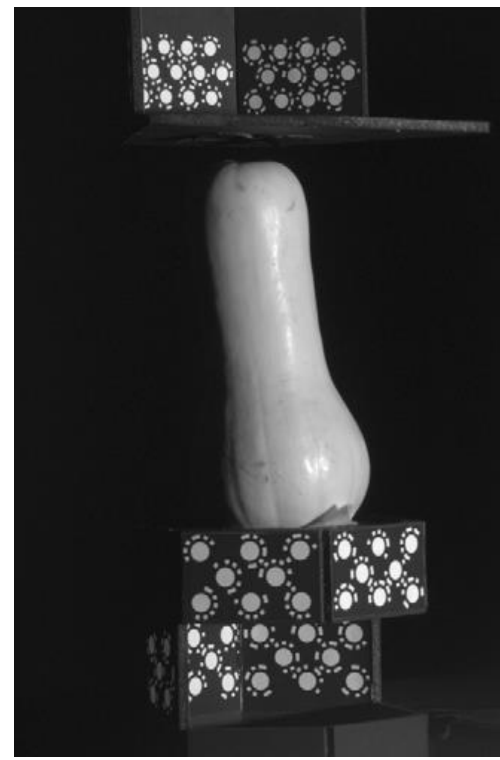
[Lu et al. JAO 98]





[Ngan et al. EGSR 05]

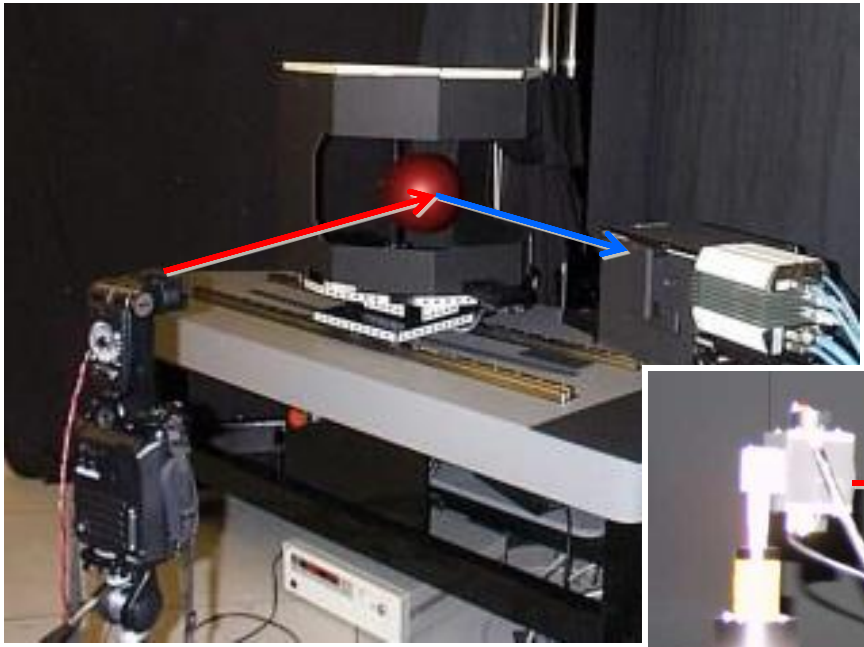




BRDF Sample Acquisition

Image-based setups

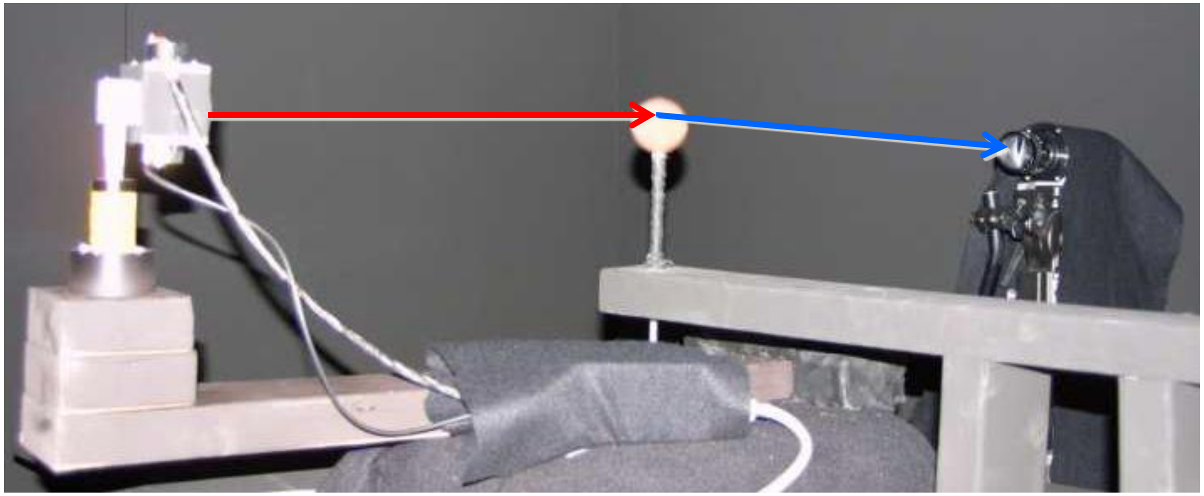
[Marschner PhD 98]



Mechanical DOF reduced by defined sample shape (orientation)

Spherical homogeneous samples

[Matusik et al. EWR 03]



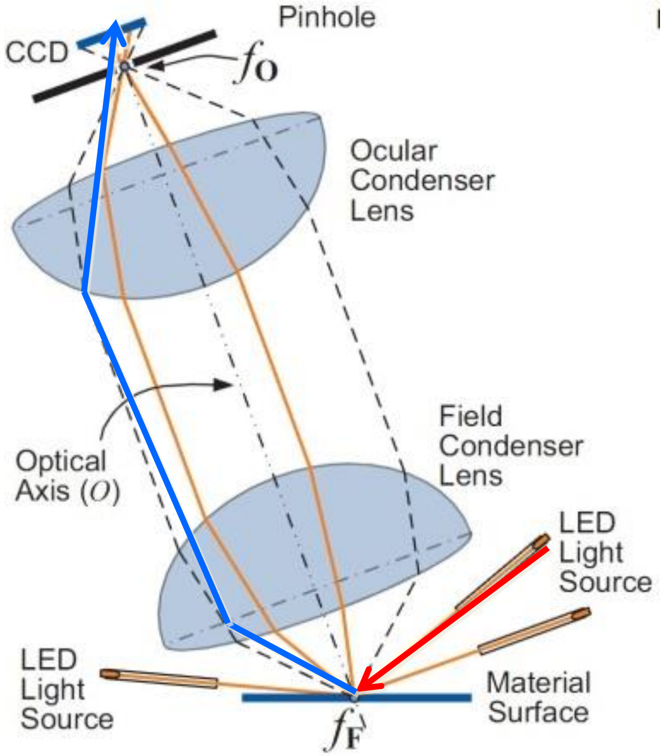
BRDF Sample Acquisition

Portable setups

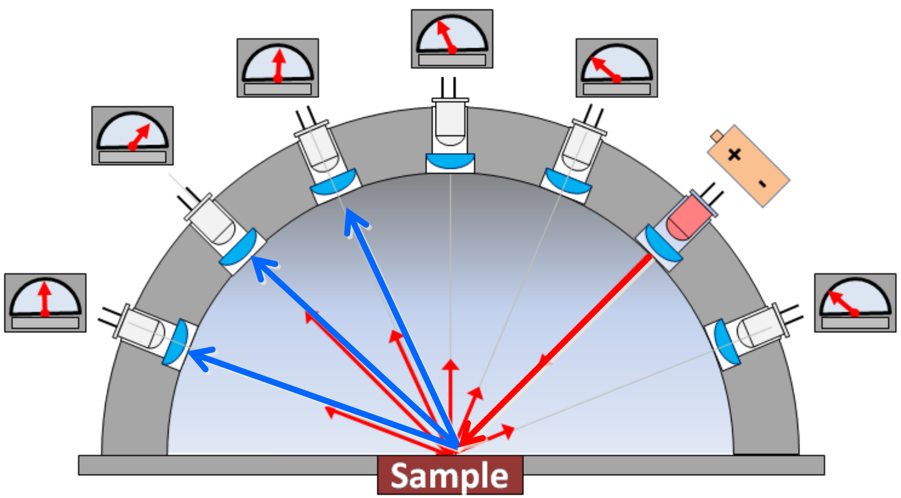
Fast measurement, compromise accuracy, limited:

- number of illumination/sensing elements
- viewing/illumination angles range

[Lan et al. CGF 10]

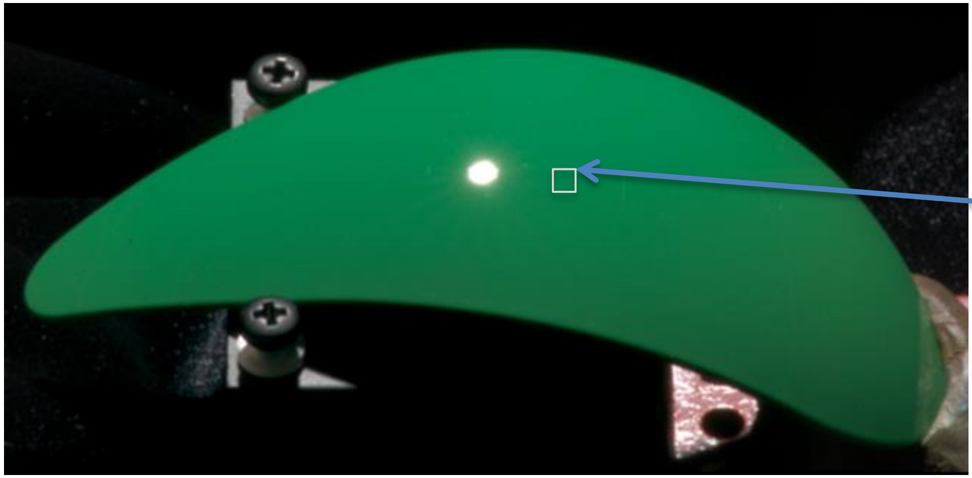


[Ben-azra et al. CVPR 08]



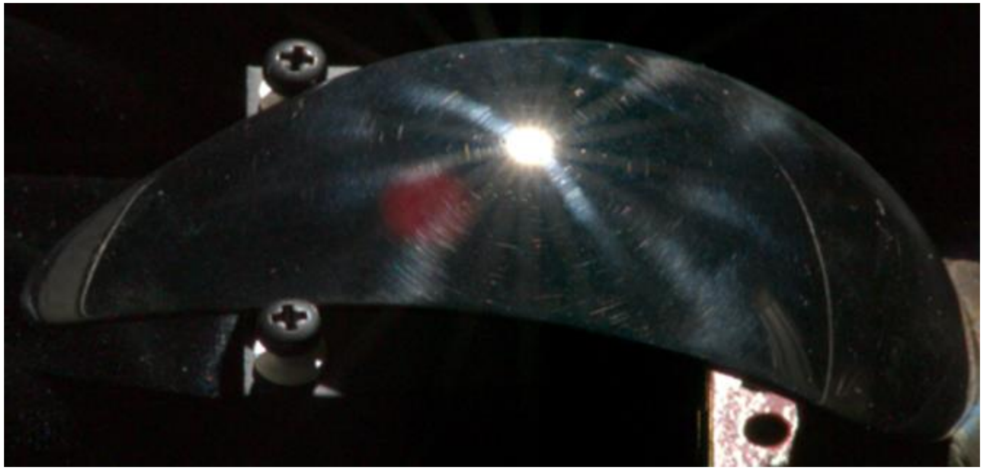
Measurement of Specular BRDFs

Green paint with thick acrylic coating



Measured area 3x3 mm

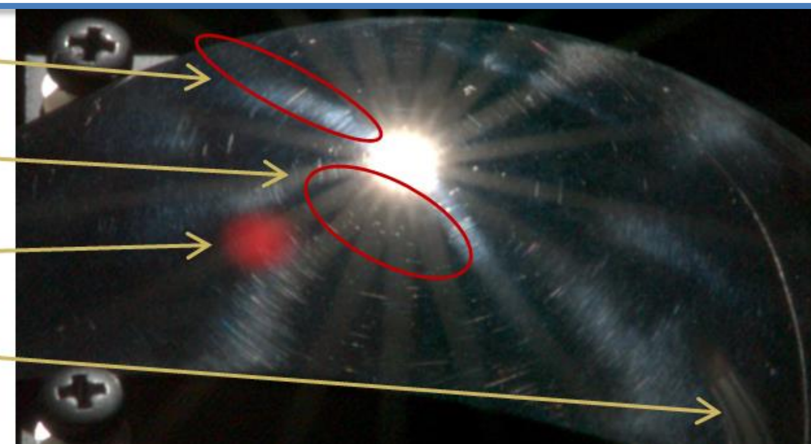
Silver 925 (silver 92.5%, copper 7.5%)



Shape courtesy of Lechler S.p.a. Como, Italy

Measurement-related issues

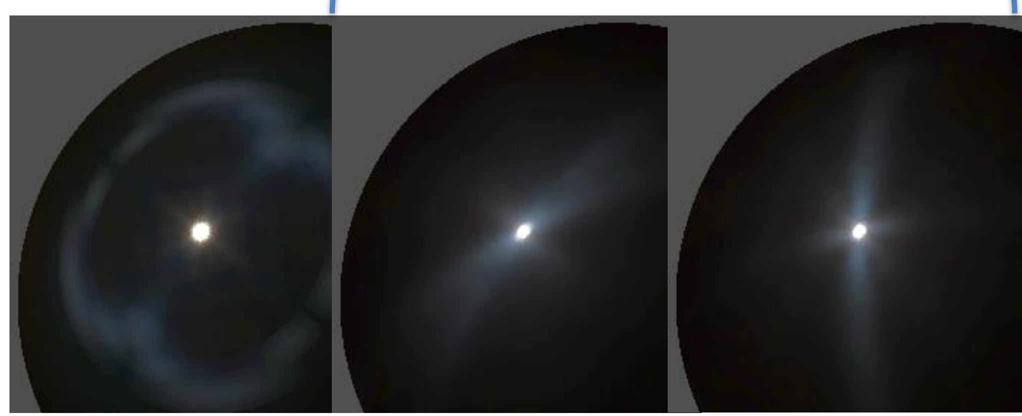
- anisotropy due to polishing
- light refraction on aperture
- lens flare artifact
- reflections of environment



Anisotropic artifacts

- due to insufficient polishing
- highlight perpendicular to scratches
- can be avoided by selecting appropriate

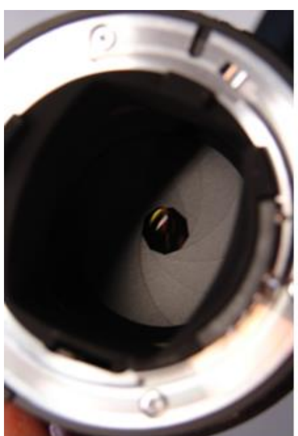
BRDFs from MERL database cannot be safely used as a reference

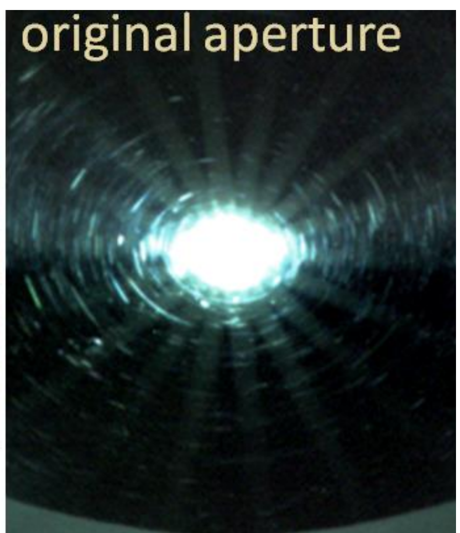


Measurement-related issues

Diffraction on aperture

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

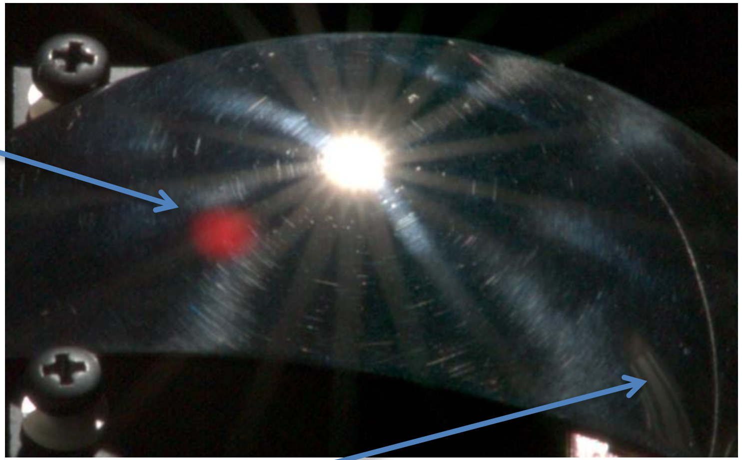




Measurement-related issues

Lens flare

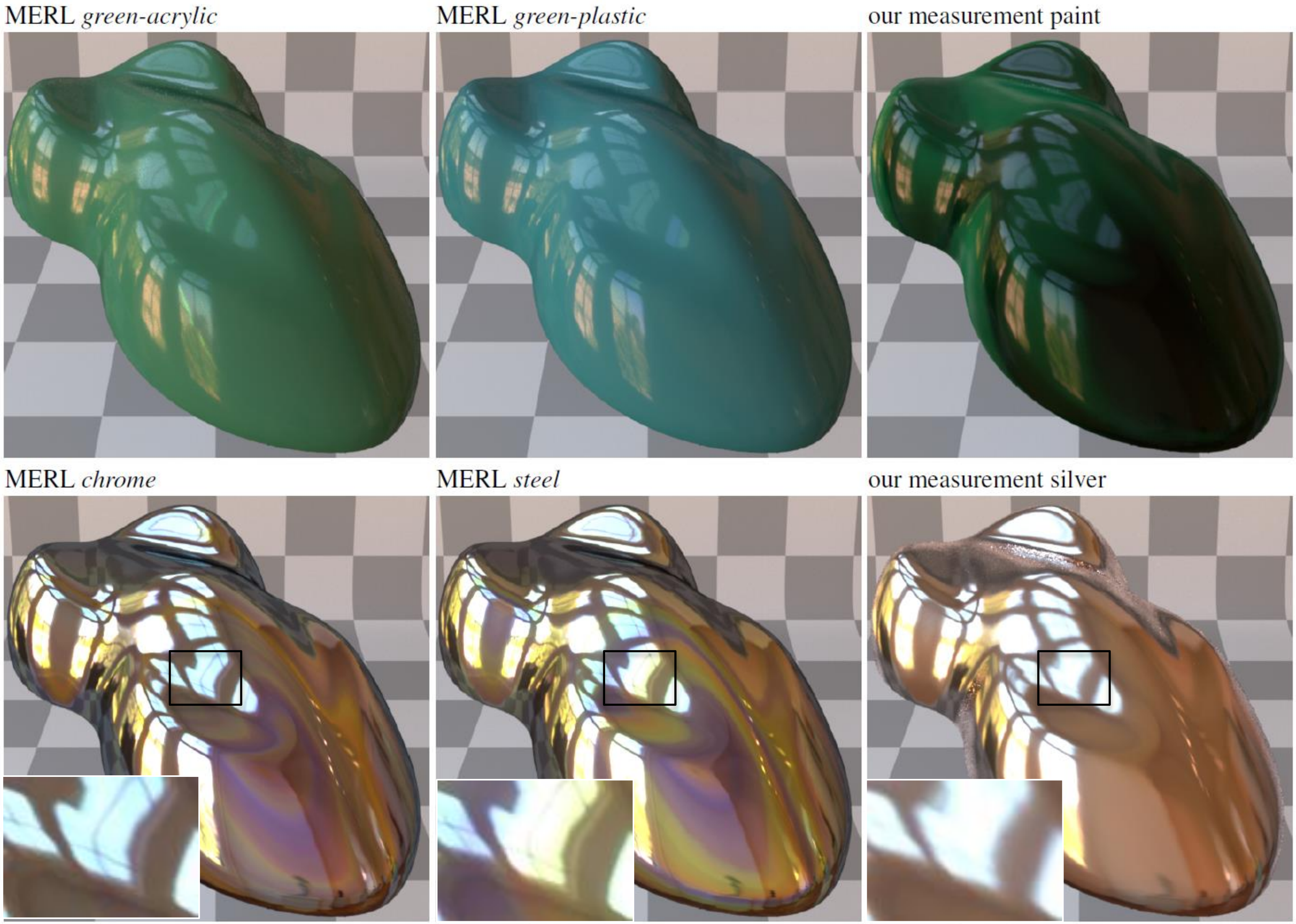
- usually red spot due to inter-reflection in lens body
- the more elements the more pronounced
- Suppressed by a long lens hood



Reflection from environment

- mirror-like finishes reflect environment – diffuse black covering

Results – specular BRDFs



Spatially-Varying BRDF Measurement

[McAllister 02]

$$SVBRDF(\lambda, \underline{x, y}, \theta_i, \varphi_i, \theta_v, \varphi_v)$$

- **7 dimensional data** ⇨ 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

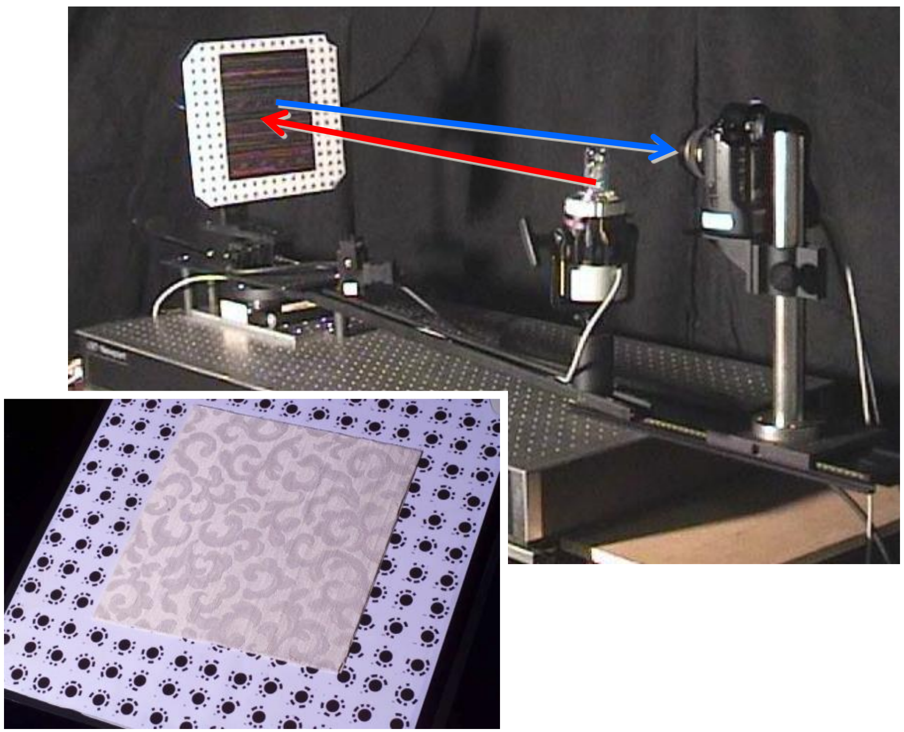
ÚTIA

SV-BRDF Sample Acquisition

Gonio-reflectometers

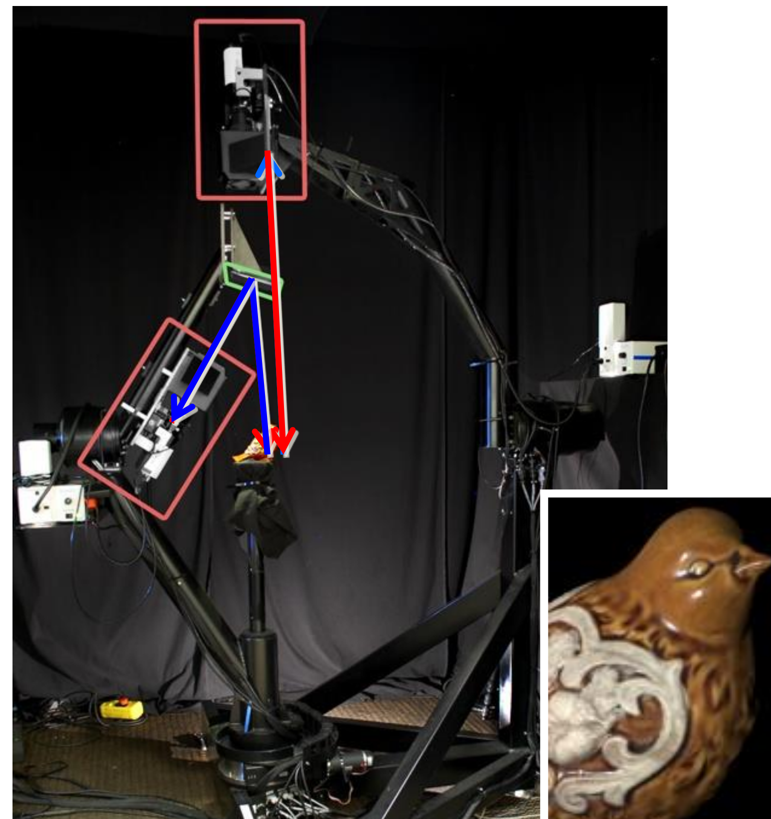
[McAllister GH 02]

- moving light, tilting sample



[Holroyd et al. TOG 10]

Simultaneous measurement of geometry and SVBRDF



SV-BRDF Sample Acquisition

Light stages

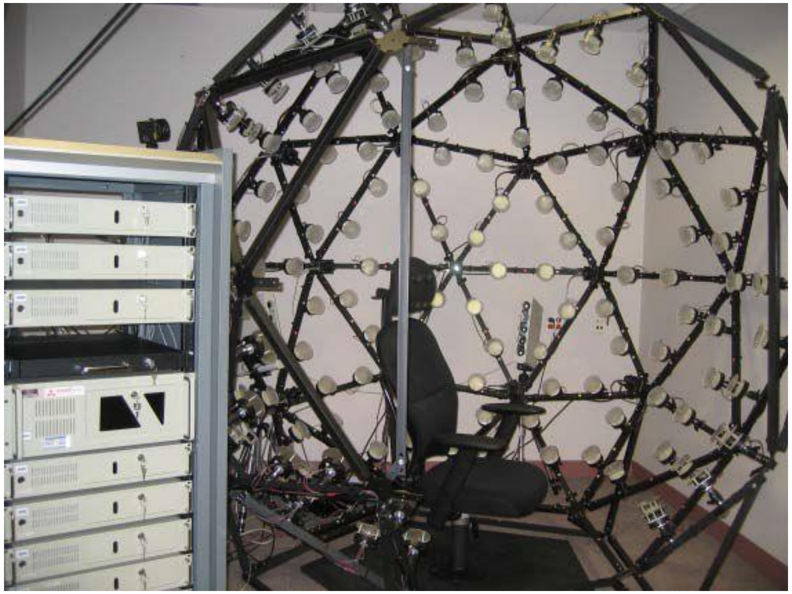
Facial SVBRDF measurement

- 156 lights, high-speed camera

[Debevec et al. SIG 00]

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

[Weyrich et al. SIG 06]



SV-BRDF Sample Acquisition

Portable setups

Fast measurement, compromise accuracy:

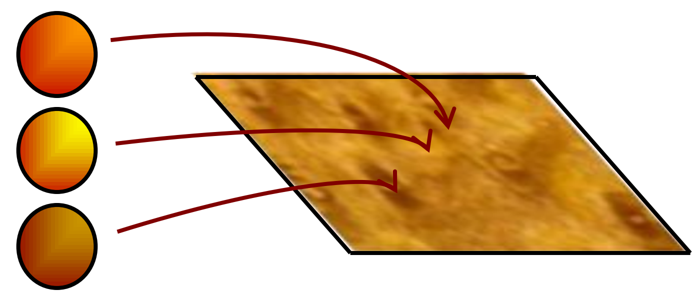
- Sparsely measured BRDF registered to measured object reflectance map (single view, many lights)
- Anisotropic BRDFs

BRDF 1

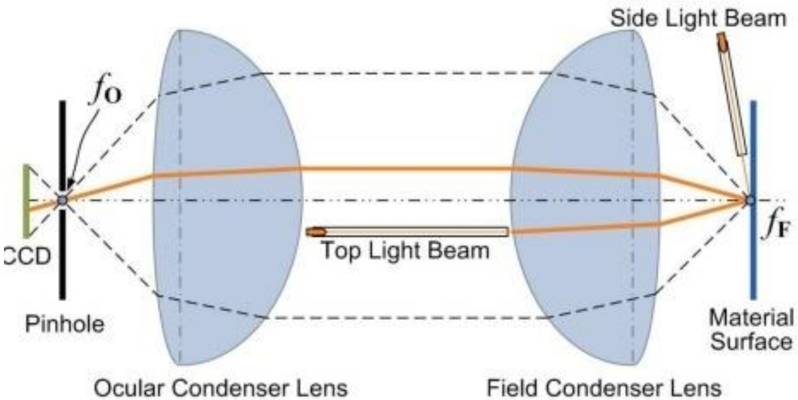
BRDF 2

....

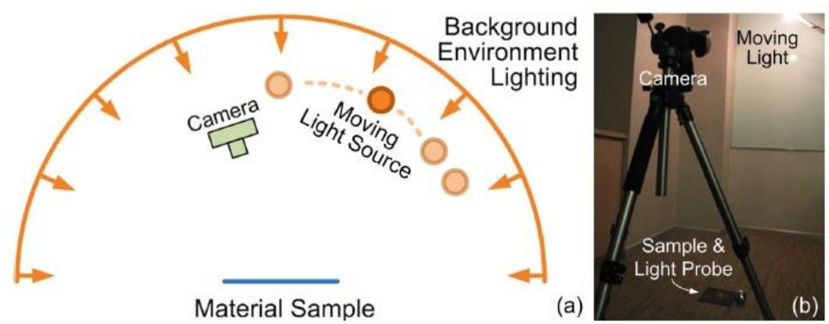
BRDF n



[Dong et al. SIG 10]



BRDF measurement

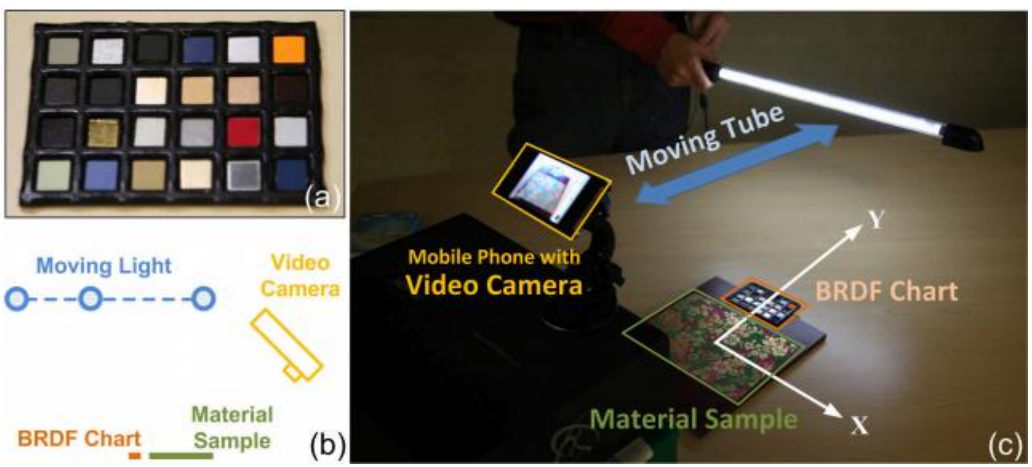


Reflectance-map measurement

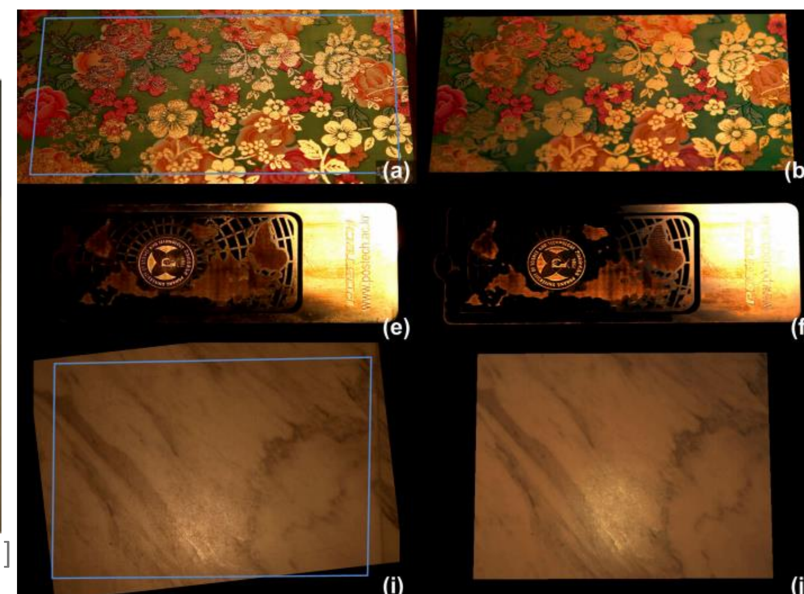
SVBRDF Capture & Modeling

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



[Ren et al. 11 ACM]



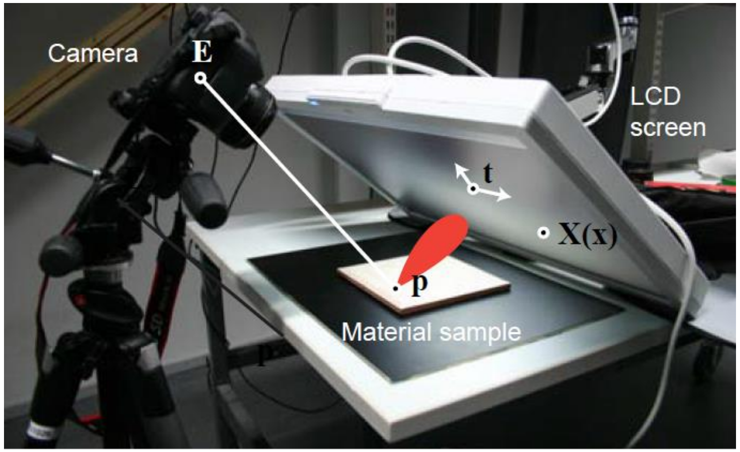
SV-BRDF Sample Acquisition

Portable setups

[Aittala et al. SIGGRAPH 13]

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



SV-BRDF Sample Acquisition

Portable setups

[Aittala et al. SIGGRAPH 15]

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 od stationary texture in the material ⇨ repeatable structure

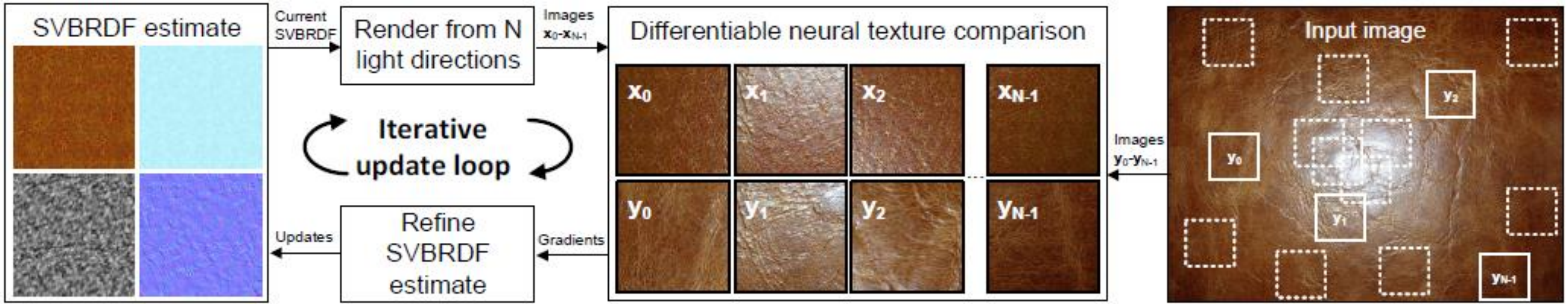
SV-BRDF Sample Acquisition

Portable setups

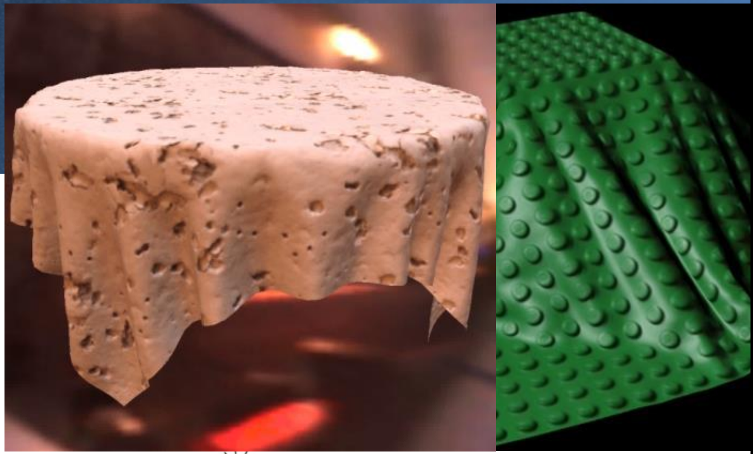
[Aittala et al. SIGGRAPH 16]

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 ⇨ fitting diffuse and specular coefficients maps

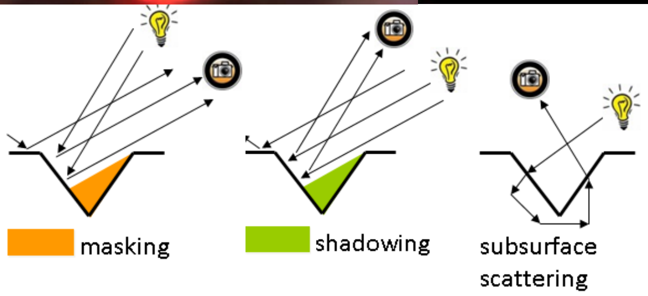


Bidirectional Texture Function



- BTF – Bidirectional Texture Function
- Illumination/view directions dependent texture

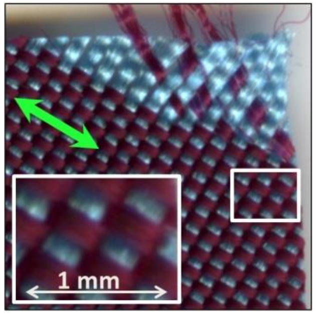
$$BTF(\lambda, x, y, \theta_i, \phi_i, \theta_v, \phi_v)$$



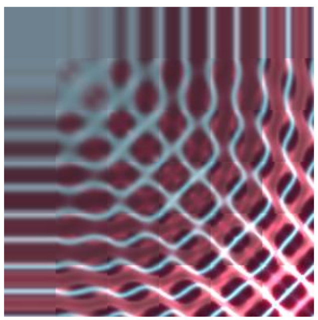
- Includes: inter-reflections, sub-surface scattering, local masking and shadowing
- One of the best practical representations of textured materials appearance
- Massive data ⇨ thousands of images per material (GBs)
- Compression and modelling is inevitable

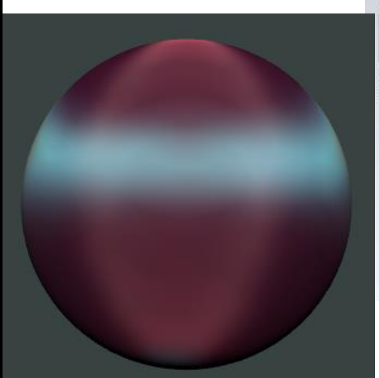
BRDF vs. BTF

polyester fabric

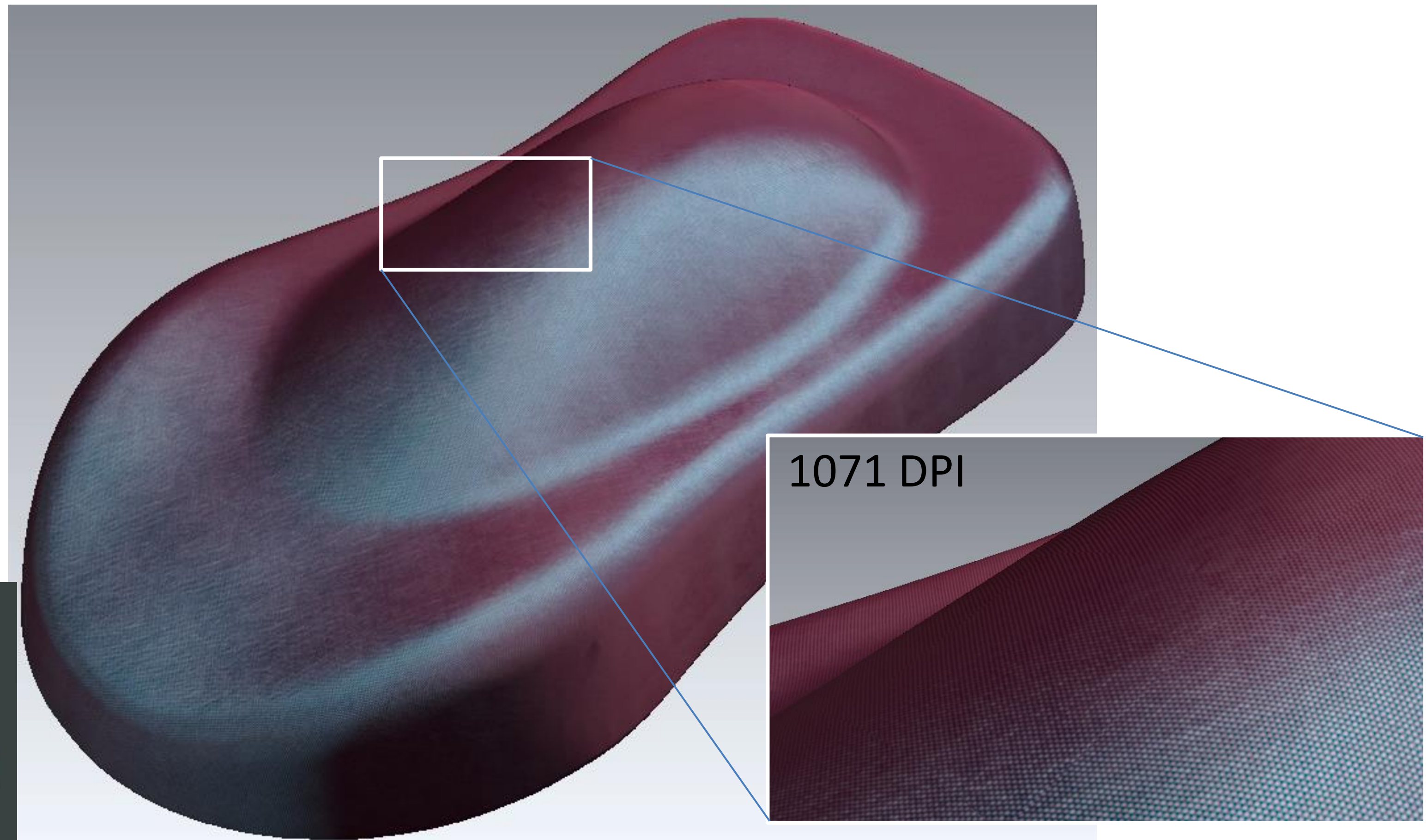


BRDF

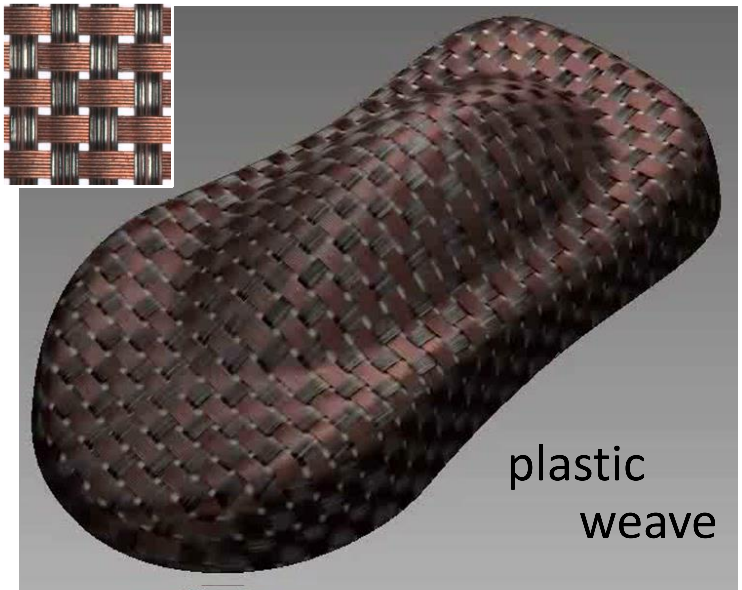


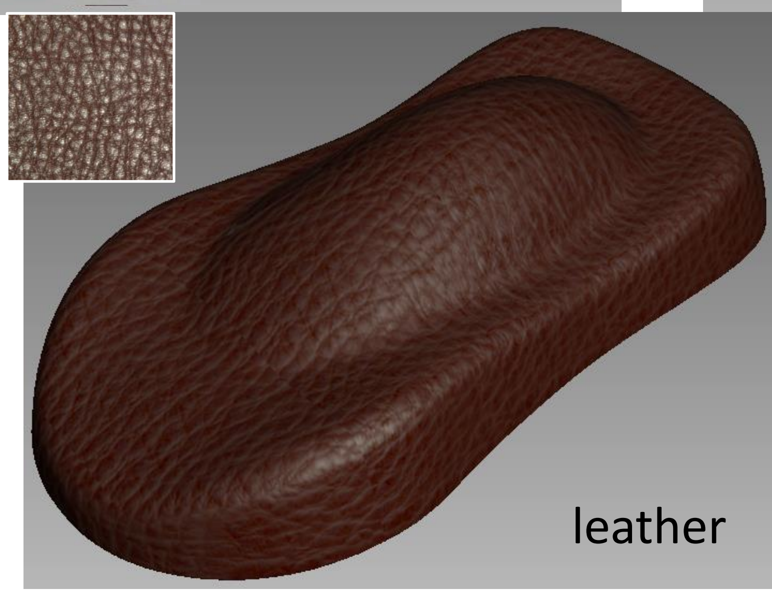


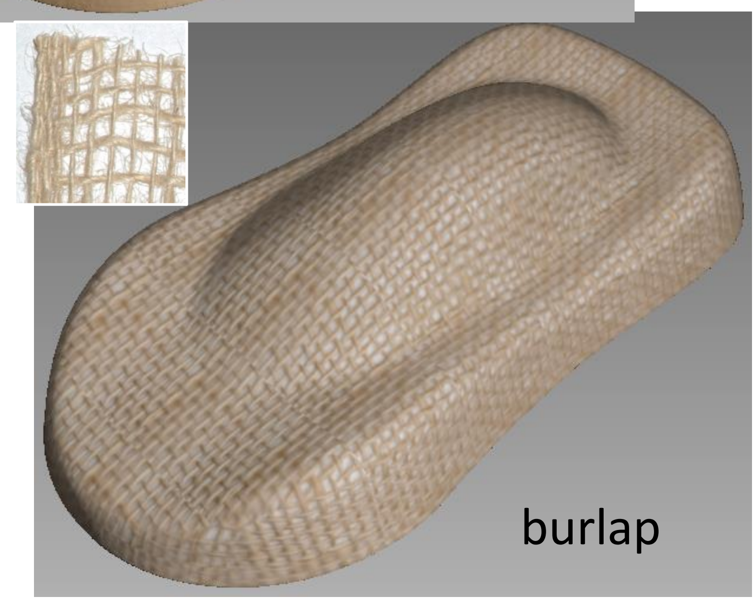
BTF – additional texture information



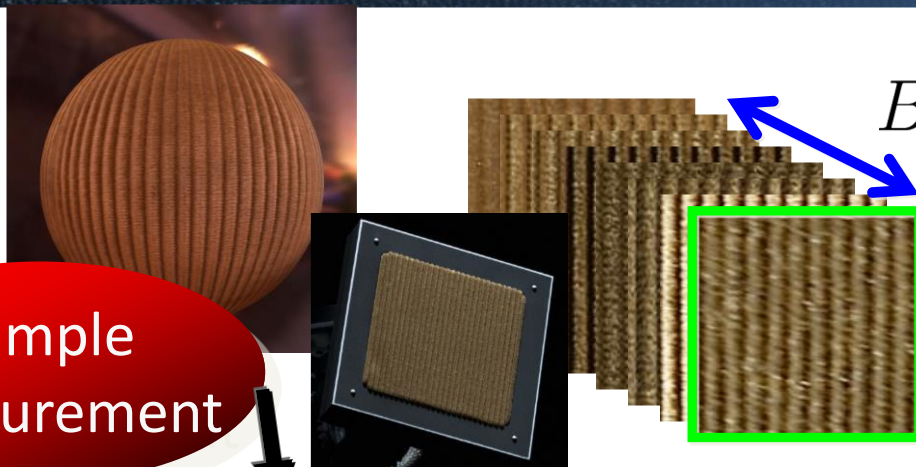
Measured BTF Data







BTF Measurement Setups Taxonomy



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

7 dimensional data ⇨

4 dimensions depend on camera, light & sample positioning

Sample Measurement

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

- **Gonio-reflectometers**
  - 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**
- **Mirrors, domes**
  - Moving Sample — sample **1** + many lights & cameras
  - Static Measurement Setups — many lights & cameras (real/virtual)
- **Portable setups**

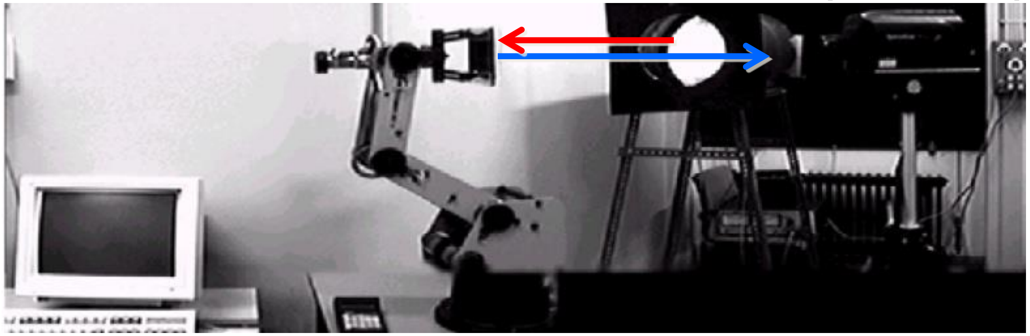
BTF Sample Acquisition

1999

Gonioreflectometer – Moving Sample & Camera

[Dana et al. 99]

CURET-Columbia&Utrecht University
[Dana et al. ACM TOG99]



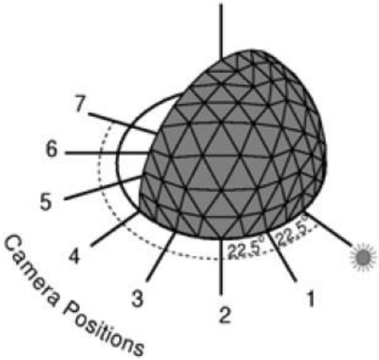
Database: 61 samples

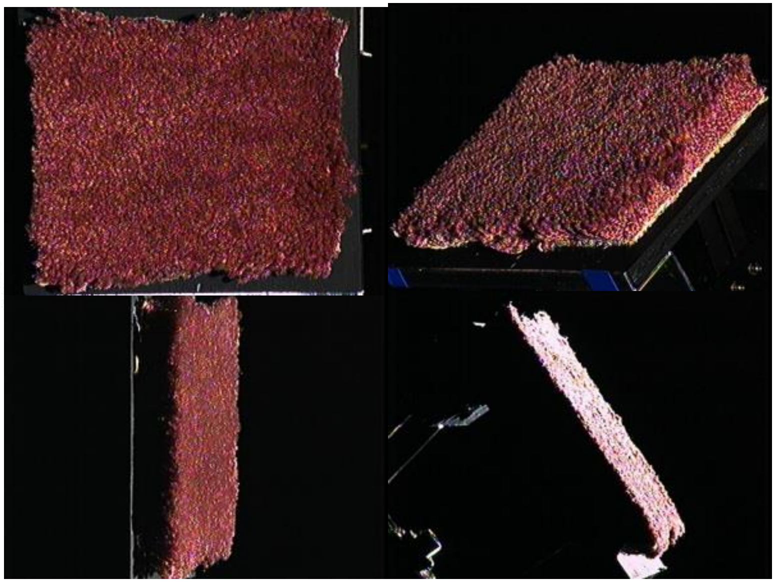
Illu./View directions:

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

2003

Gonioreflectometer – Moving Sample & Camera

Bonn University
[Sattler et al. EGSR 03]

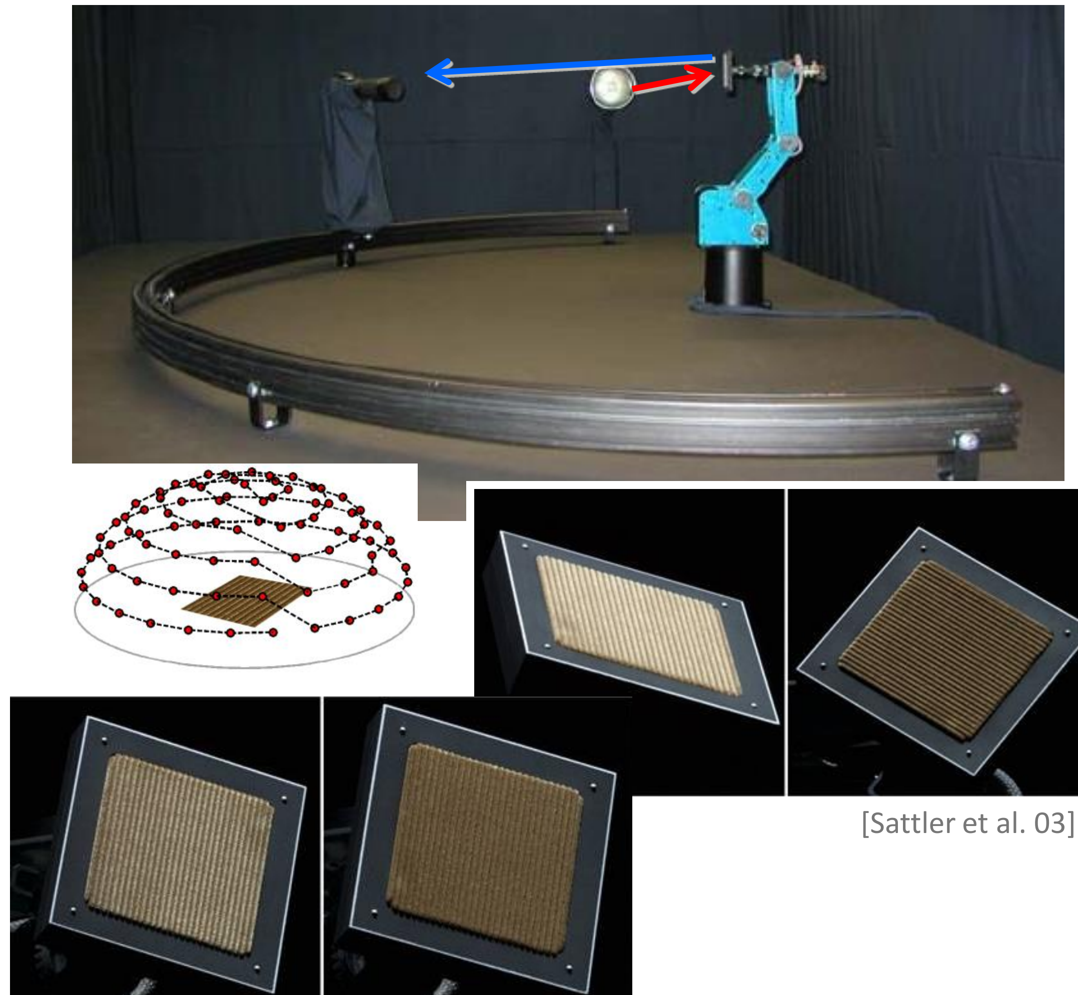
Database:
10 samples (4 HDR)

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

Max. illu./view elev.:
75°/75°

Rectified images:
800 x 800 pixels

Measurement time:
~ 14 hours



[Sattler et al. 03]

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

BTF Sample Acquisition

2003

Gonioreflectometer – Moving Sample & Light

Yale University [Koudelka et al., TEXTURE 03]

Database: 17 samples

Illu./View directions:

120/90 = 10 800 img.

Max. illu./view elev.:

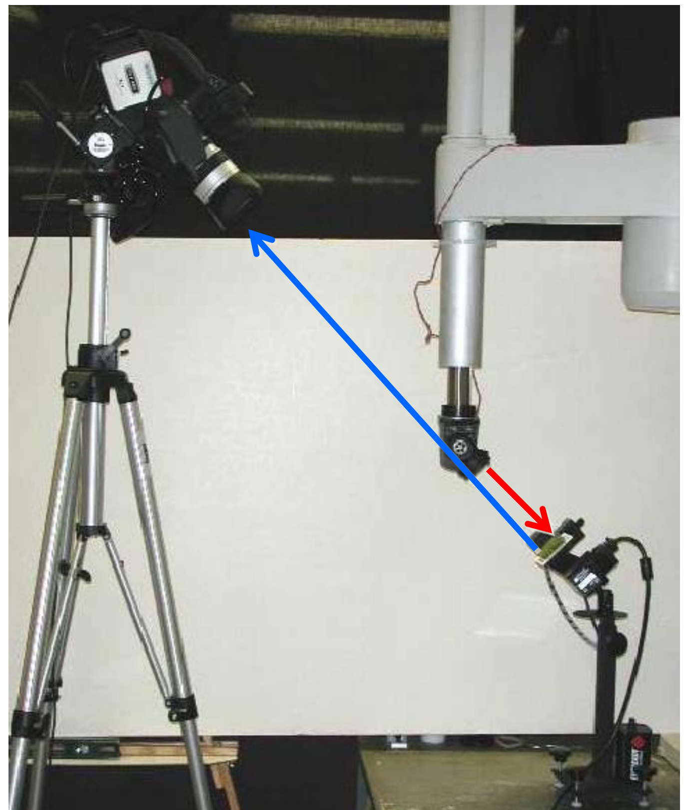
80º/75º

Rectified images:

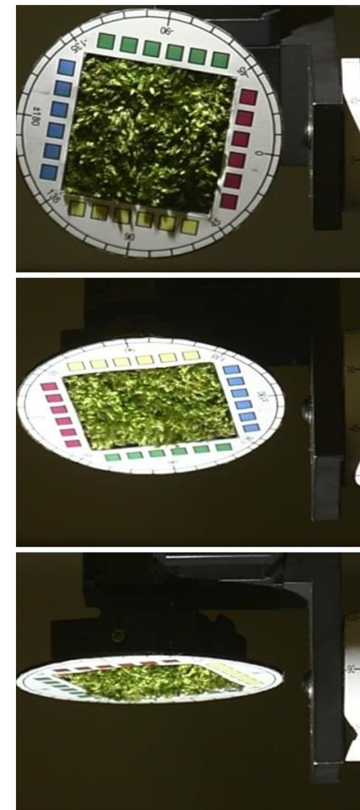
192 x 192 pixels

Measurement time:

~ 10 hours



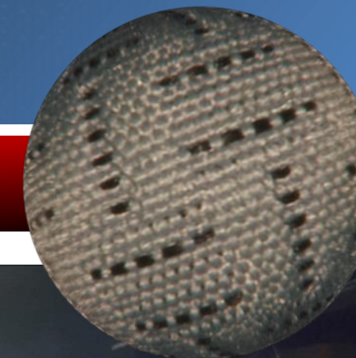
[Koudelka et al. 03]



`http://vision.ucsd.edu/kriegman-grp/research/vst`

BTF Sample Acquisition

2011



Gonioreflectometer – Moving Sample, Light & Camera

UTIA AS CR

[Haindl&Filip CVPR13]

Illu./View directions:
arbitrary/arbitrary (81/81)

Max. illu./view elev.:
$90^o/90^o$

Rectified images:
2000 x 2000 pixels

Database: publicly available

Measurement time: ~10 hours

`http://btf.utia.cas.cz`

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

ÚTIA

BTF Sample Acquisition

2004

Mirrors – Moving Sample & Light

Rutgers University
[Dana & Wang, JOSA 04]

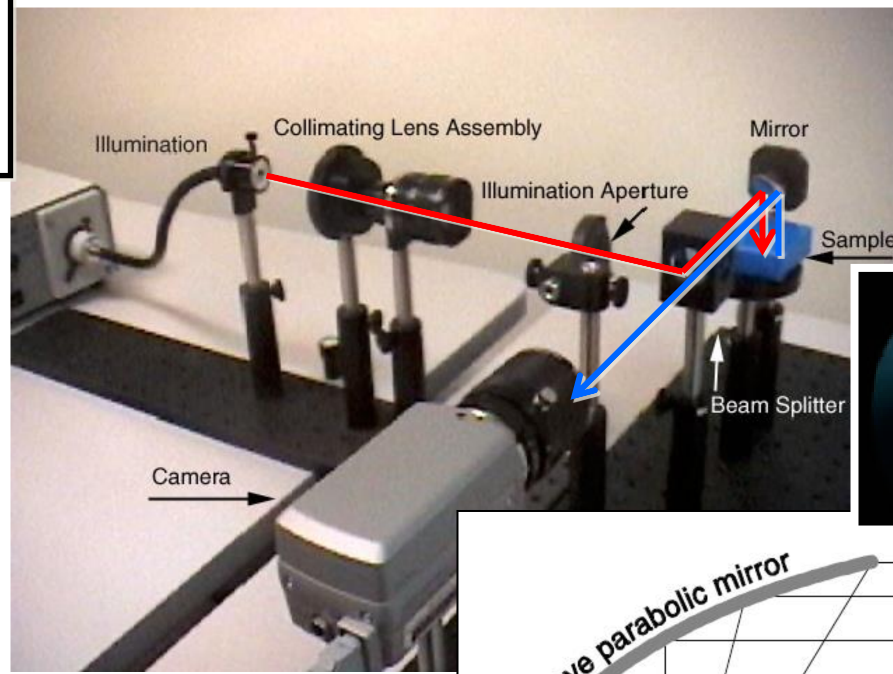
Database: n/a

Illu./View directions:
continuous

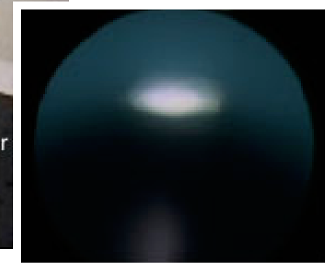
Max. illu./view elev.:
23-37°/23-37°

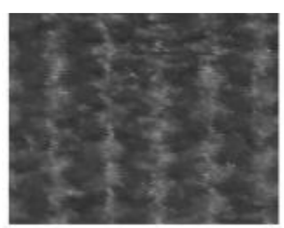
Rectified images:
~ 200 x 200 pixels

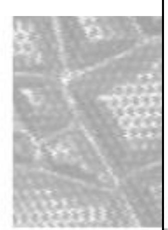
Measurement time:
~1 hour

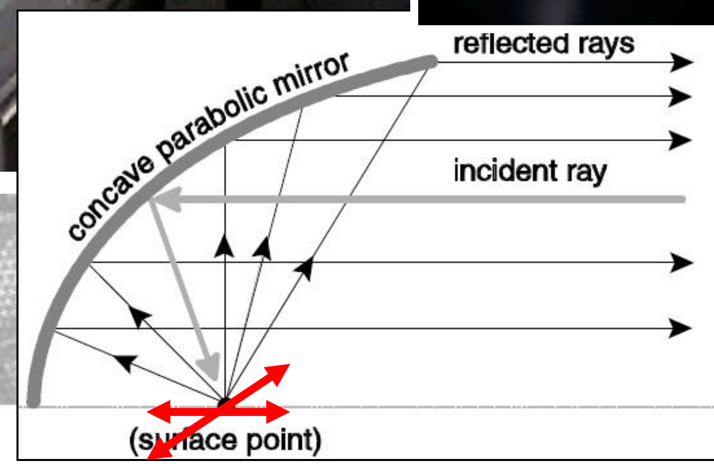


[Dana & Wang 03]









Material moves below mirror

BTF Sample Acquisition

2003

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.:

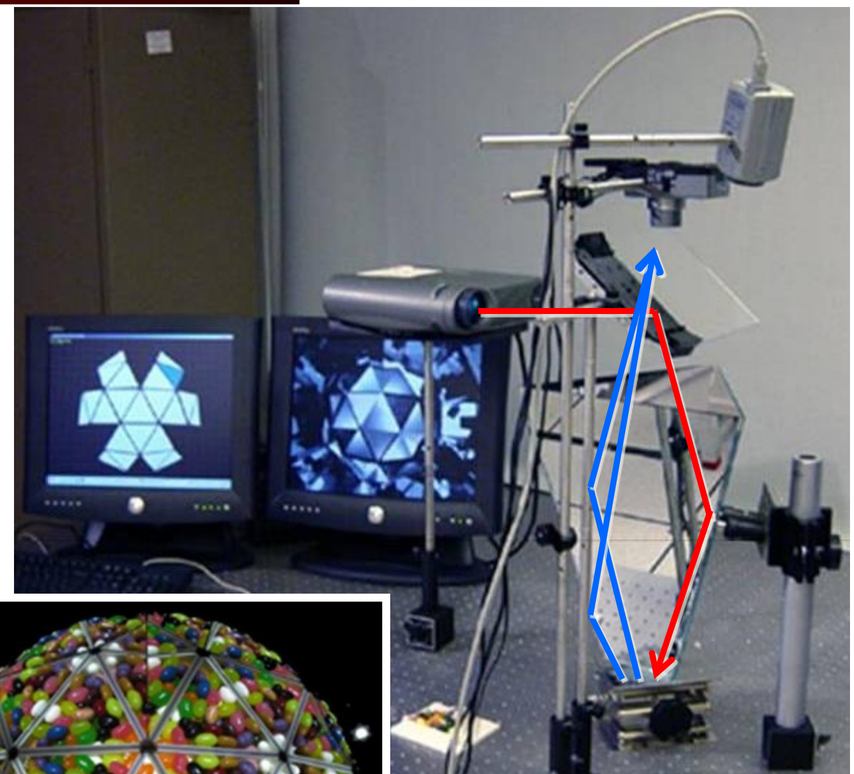
76°/76°

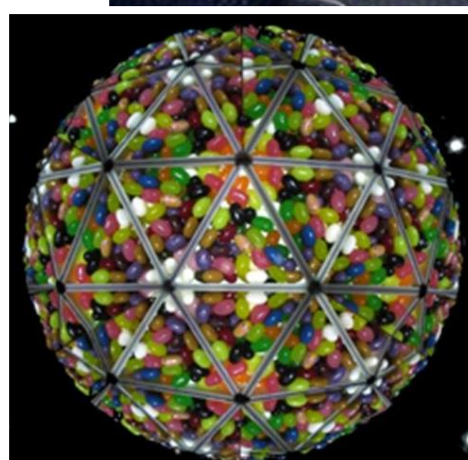
Rectified images:

~ 200 x 200 pixels

Measurement time:

~1 hour





[Han et al. 03]

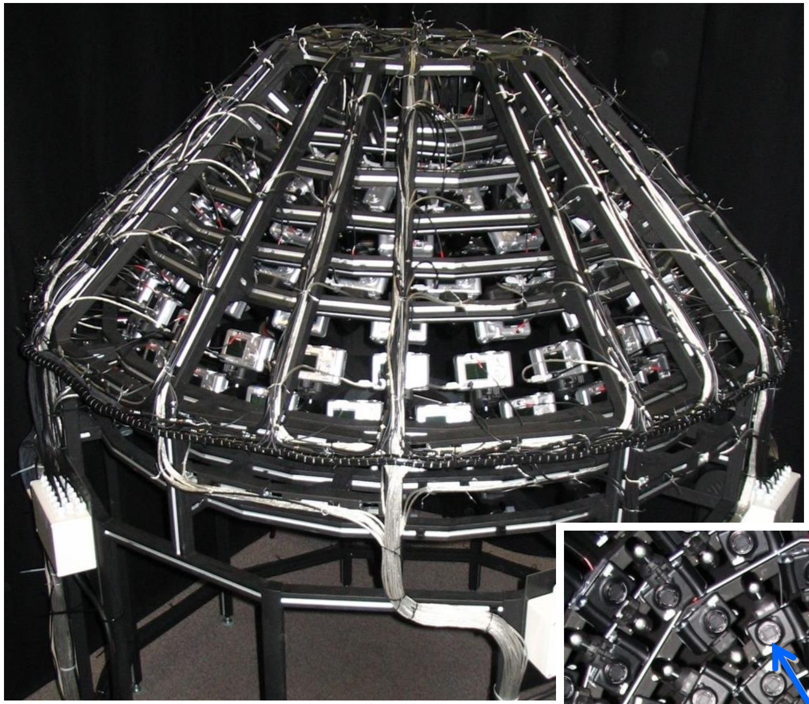
BTF Sample Acquisition

2005

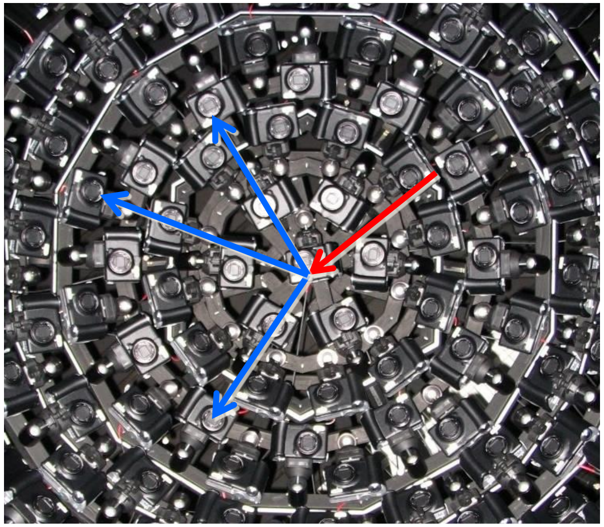
Dome – Static Measurement Setups

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



[Muller et al. 03]



BTF Sample Acquisition

2014

Dome – Moving Sample, portable

Bonn University
[Schwartz et al. 14]

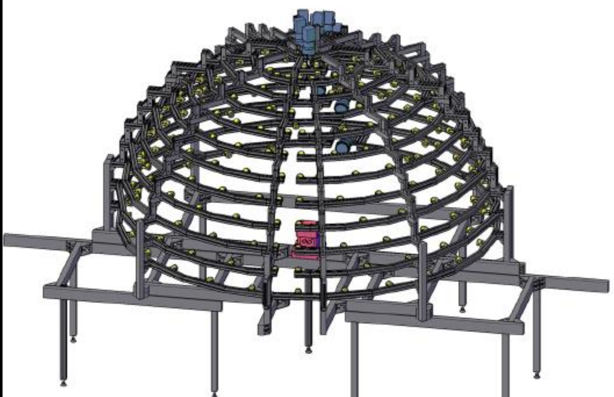
- Dome setup used in industry

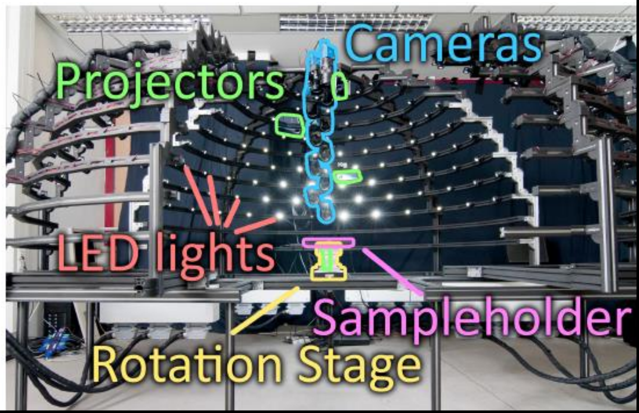
Illu./View directions: 198/264 = 52 272 images

Max. illu./view elev.: 75 degrees

Rectified images: 1024 x 1024 pixels

Measurement time: 4-10 hours

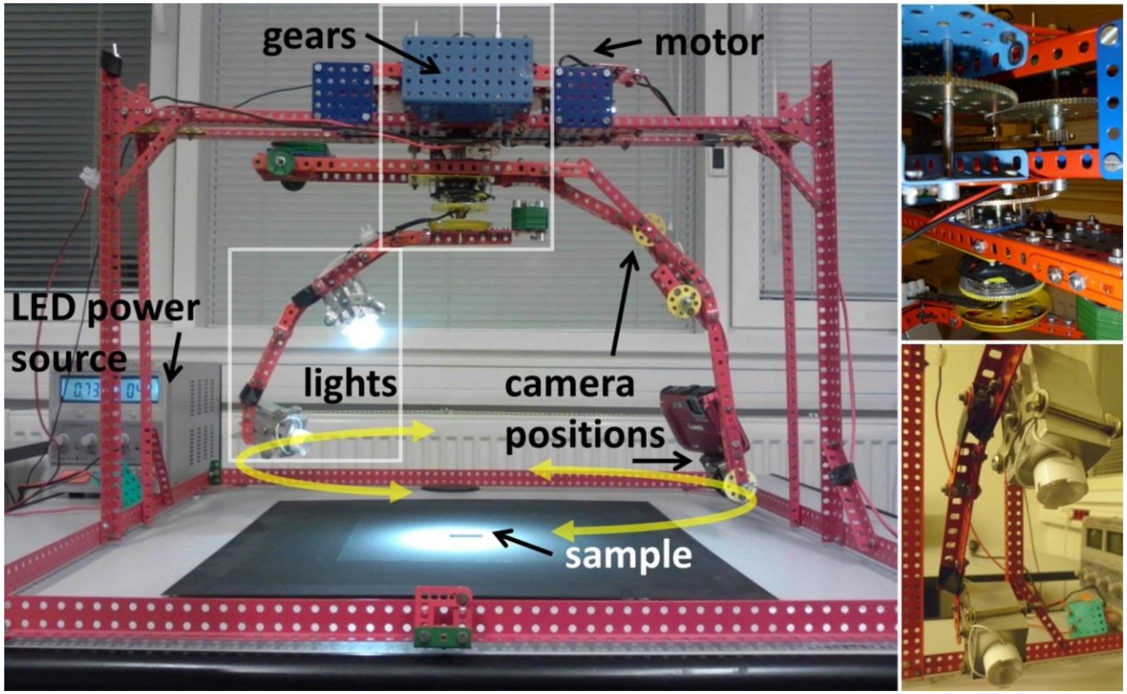




Rapid Measurement Approach

Portable Setups

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

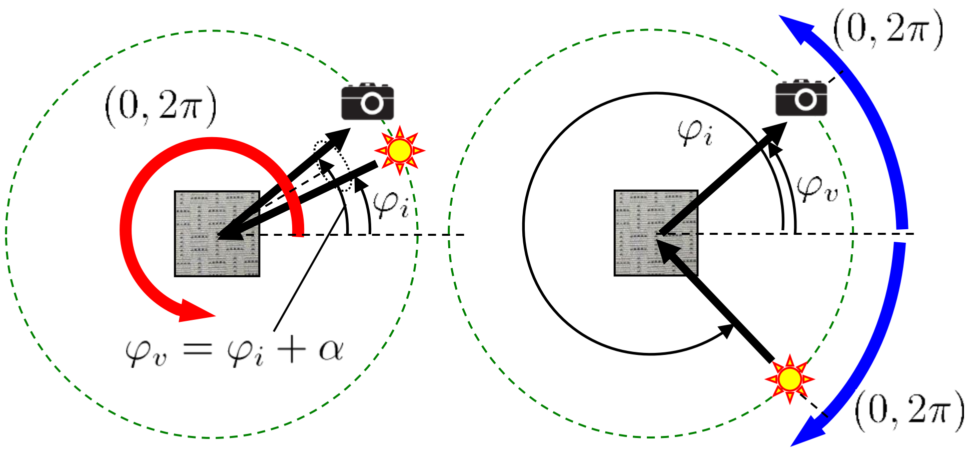


- 2 LEDs
- compact camera
- approximate BTF ⇨ capturing time 4 minutes

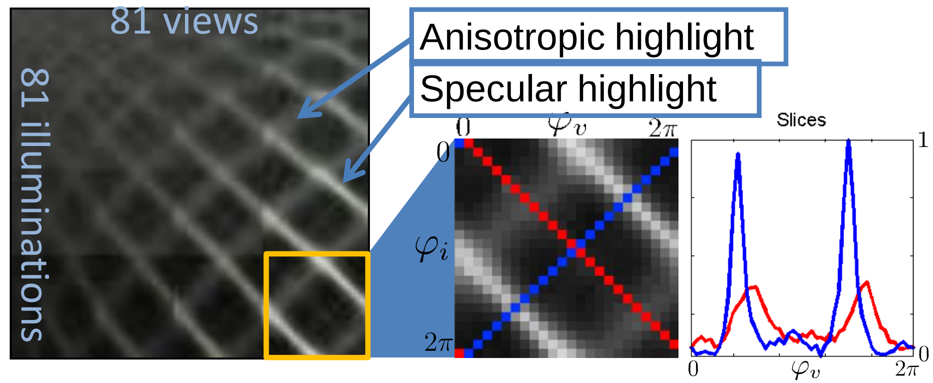
ÚTIA

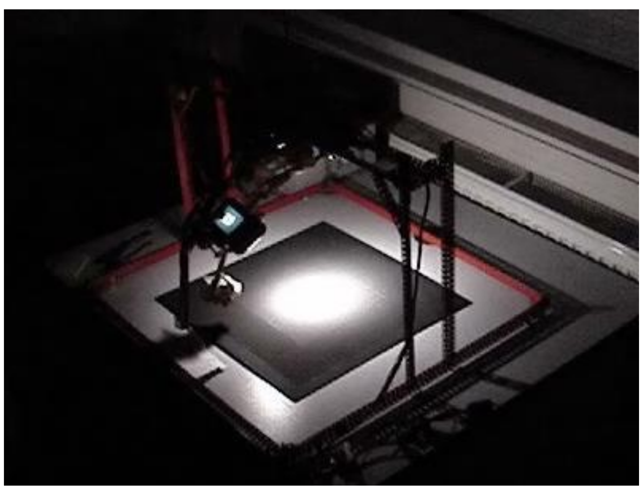
Rapid Measurement Approach

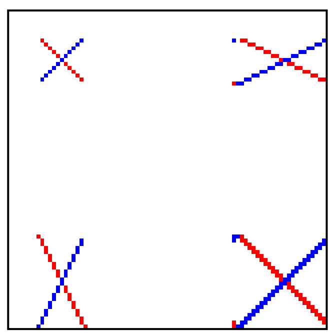
measurement procedure



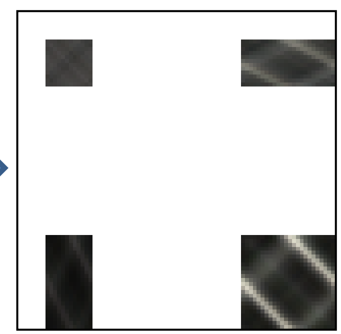
Reference 6561 images



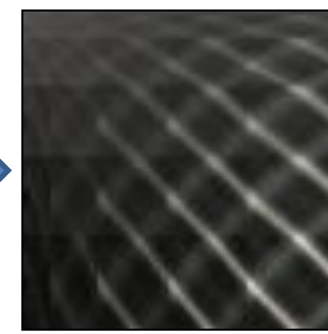




8 slices 169 images



subspaces reconstruction

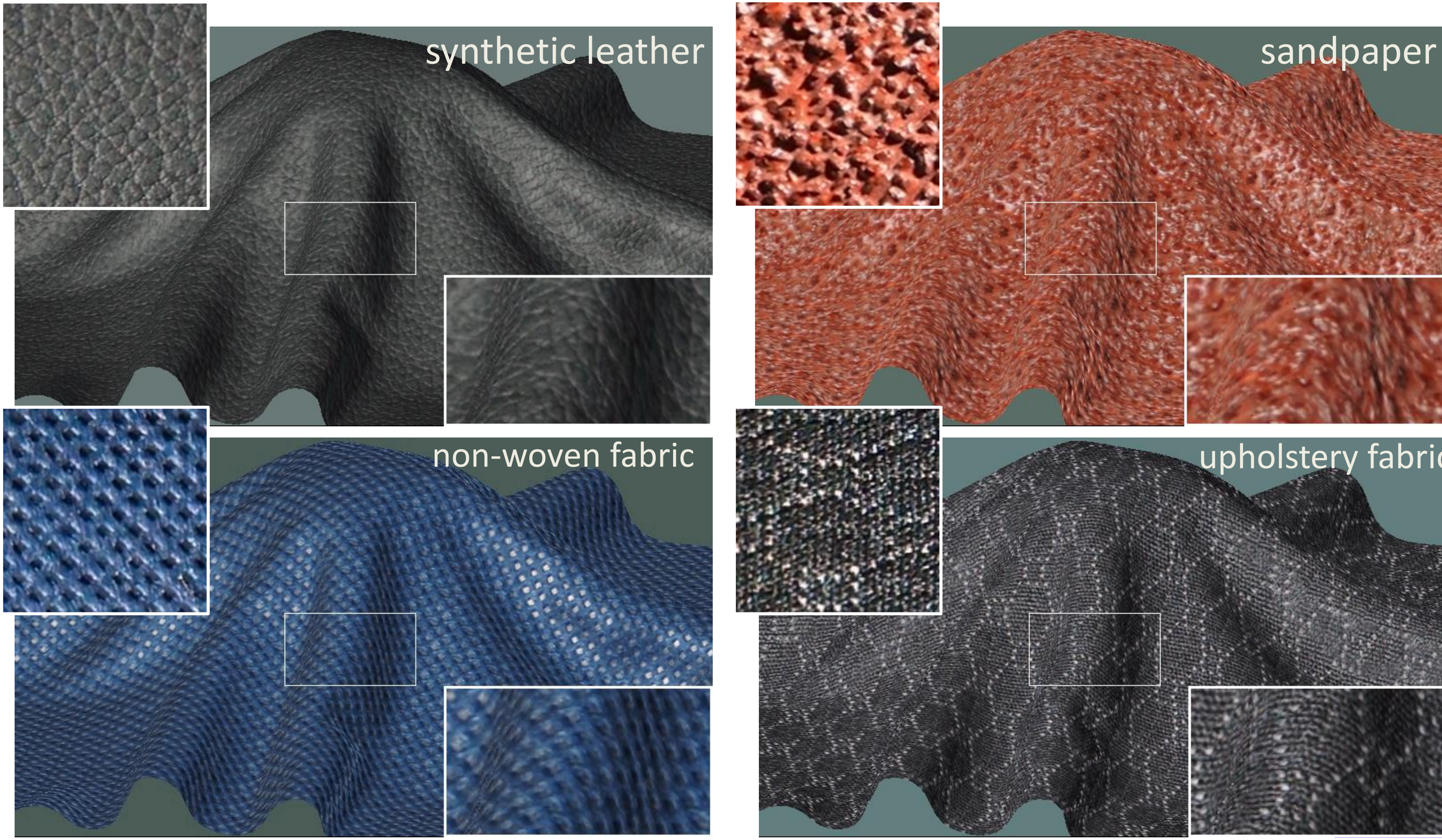


missing images interpolation

ÚTIA

Results of Portable Setup

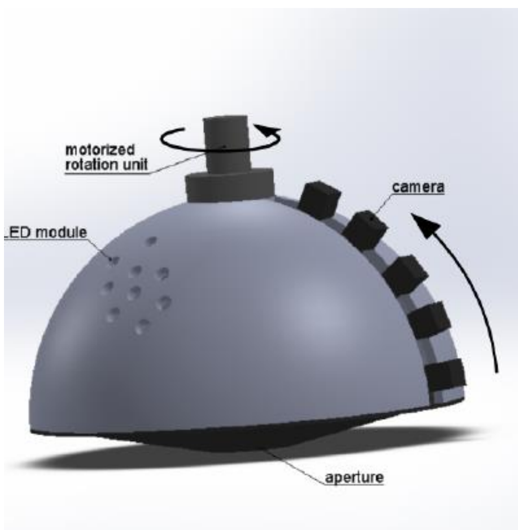
materials photo & measured appearance (169 images)

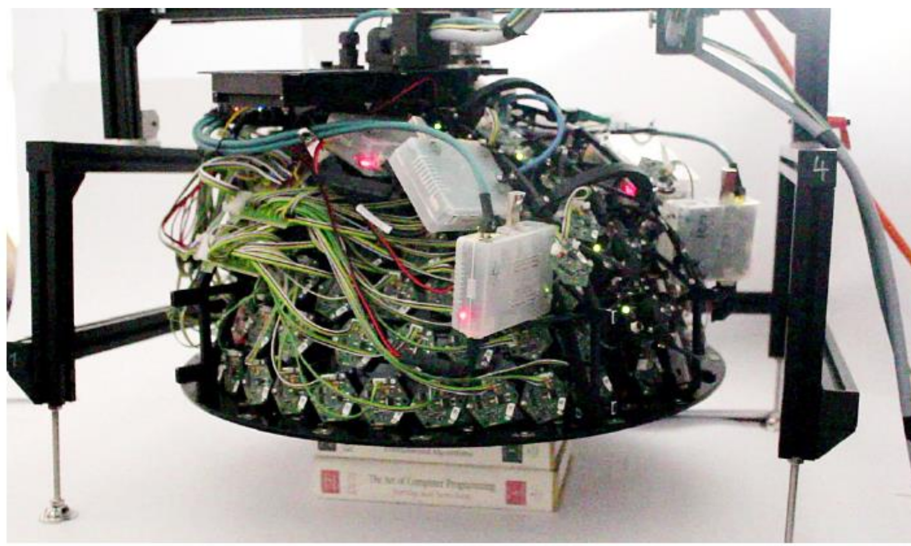


Rapid Measurement Approach

Portable Setups

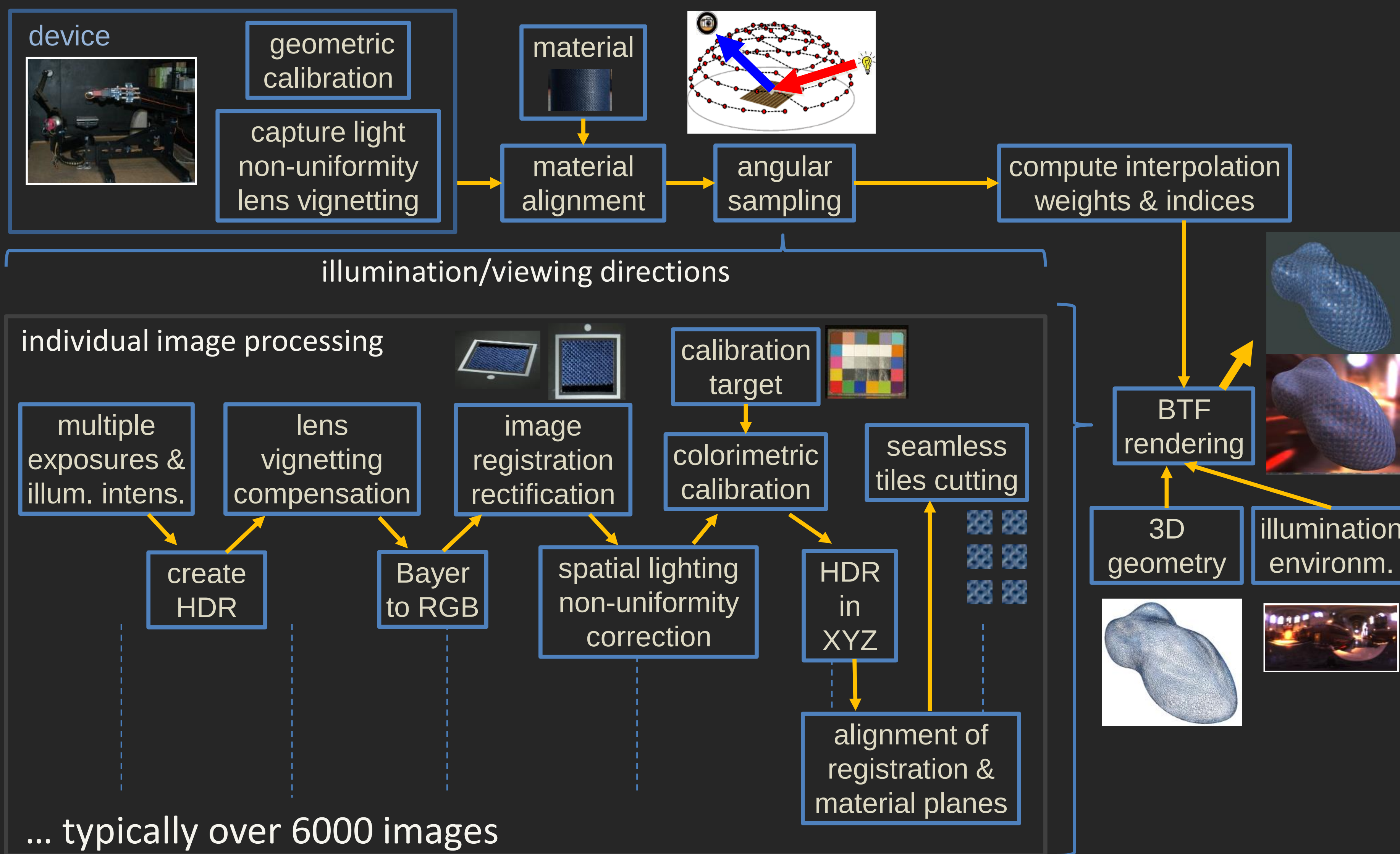
- **LightDrum** [Havran et al. Sensors 2016]
- Portable solution for fast on-site BTF measurement
- Body with lights and cameras rotates above the measured material





ÚTIA

BTF Capturing & Visualization Pipeline



BTF – HDR and Spectral Measurement

- 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 ⇨ need for full spectral measurements.
- [Lyssi 09] – full spectral BTF measurement and calibration on [Sattler et al. 03] setup.
  - Spectral Filter ⇨ 30 wavelength bands (430 – 720 nm)
  - 30 x 81 x 81 images ⇨ enormous measurement times (3 days)
  - sample in OpenEXR = **1 TeraByte**
- [Rump et al. 10] – GT data for multispectral BTF

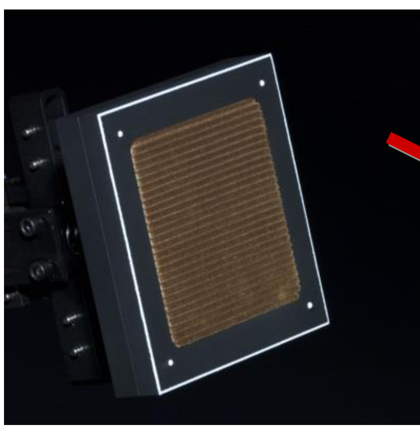
[Sattler et al. 03]

Spatial Reflectance Data Rectification

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

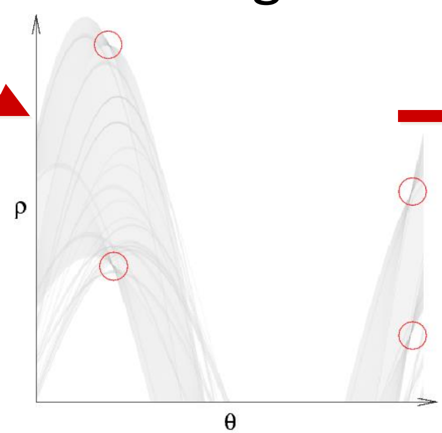
Using:

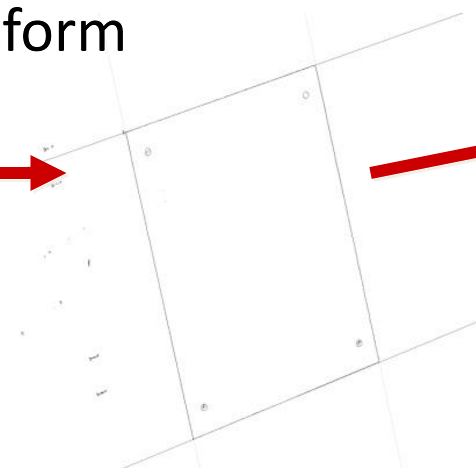
- Registration marks
- Intersection of sample borders
- Predefined geometric transformation (static setups)

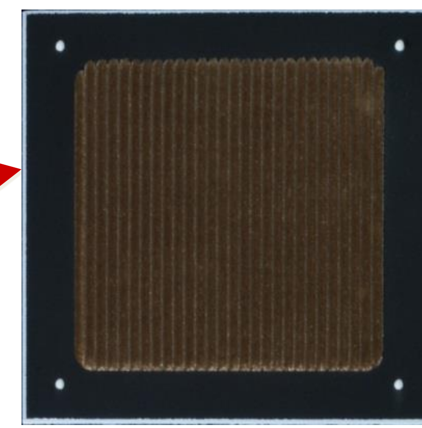


Lines detection

Hough transform



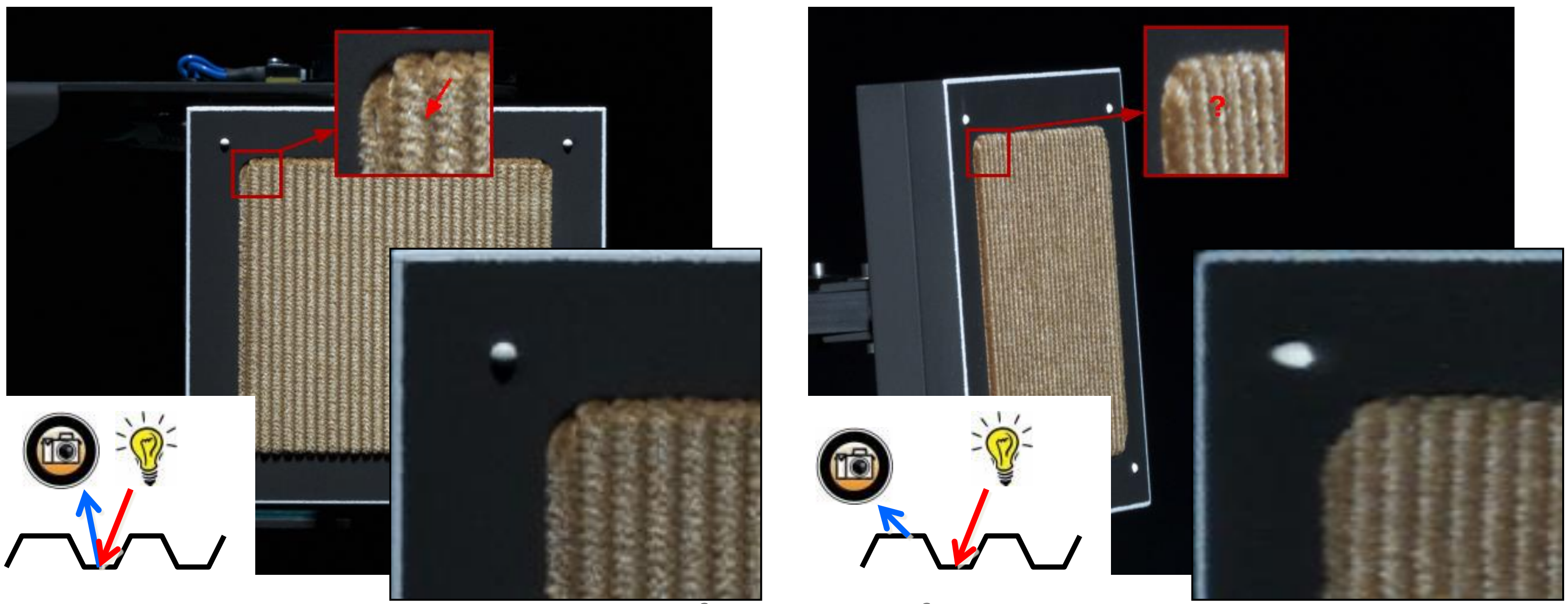




BTF vs. SV-BRDF

Contrary to SVBRDF, BTF face problem with rough structure samples

- Different views ⇨ **Pixel-wise misalignment**, due to occlusion
- Solution ⇨ process individual views separately

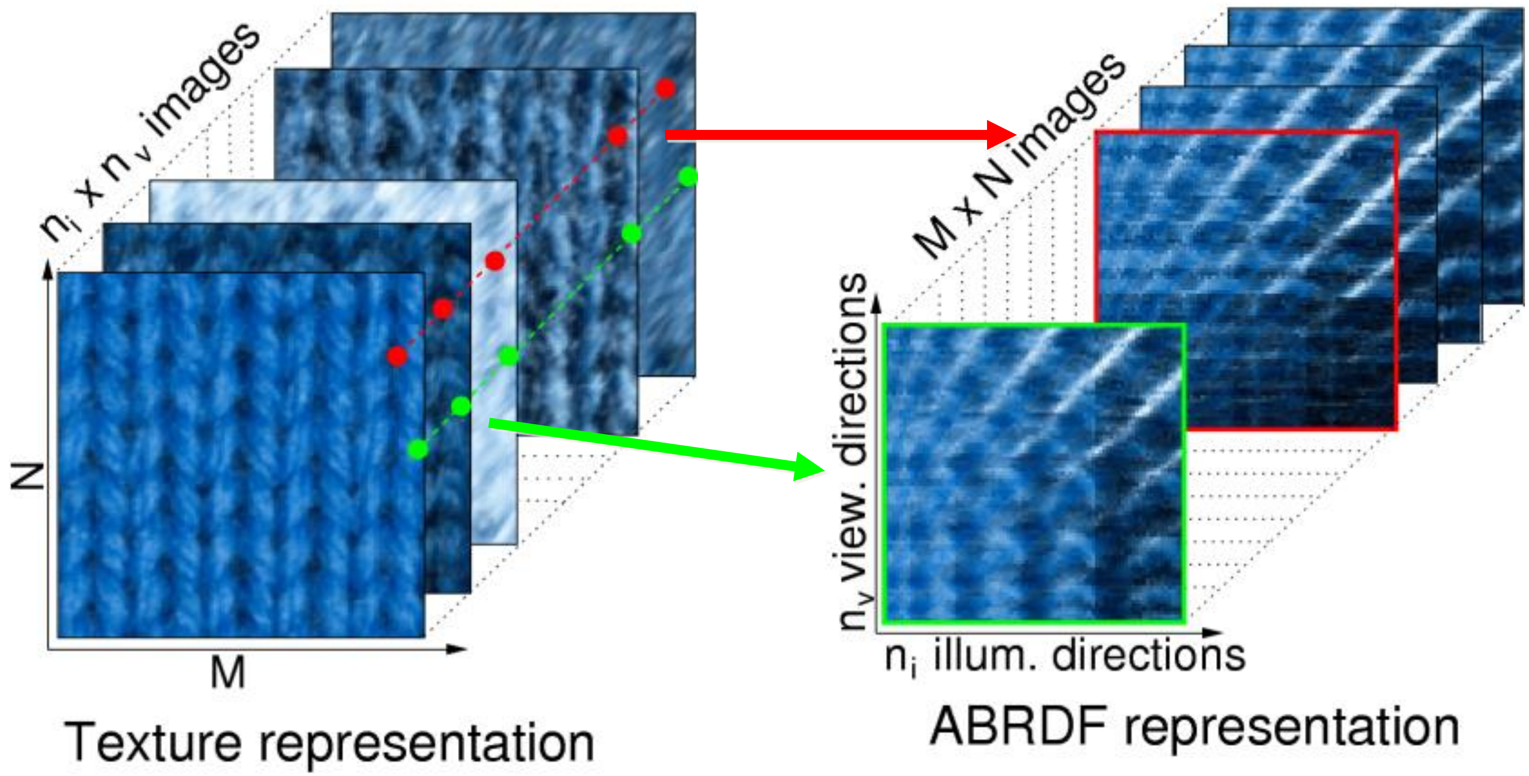


Courtesy of University of Bonn

BTF - no geometrical information ⇨ no material profile at object edges

ÚTIA

Measured Data Representation



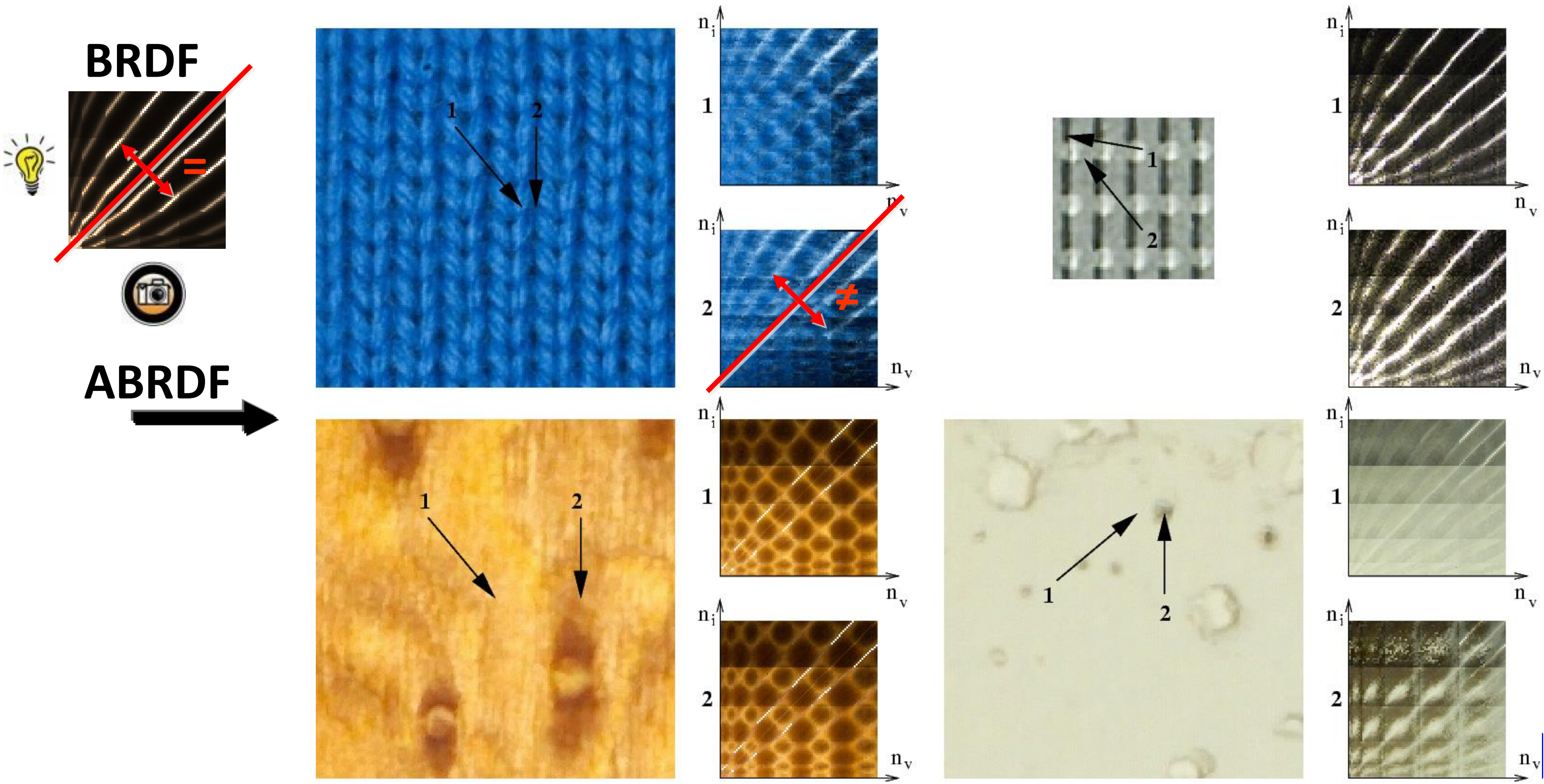
- Only images for the same view are correctly registered
- Shadows/occlusion compensation required prior to processing

- Illuminations/views aligned
- Highlights positions fixed
- Easier pixel-wise comparison.

Apparent BRDFs

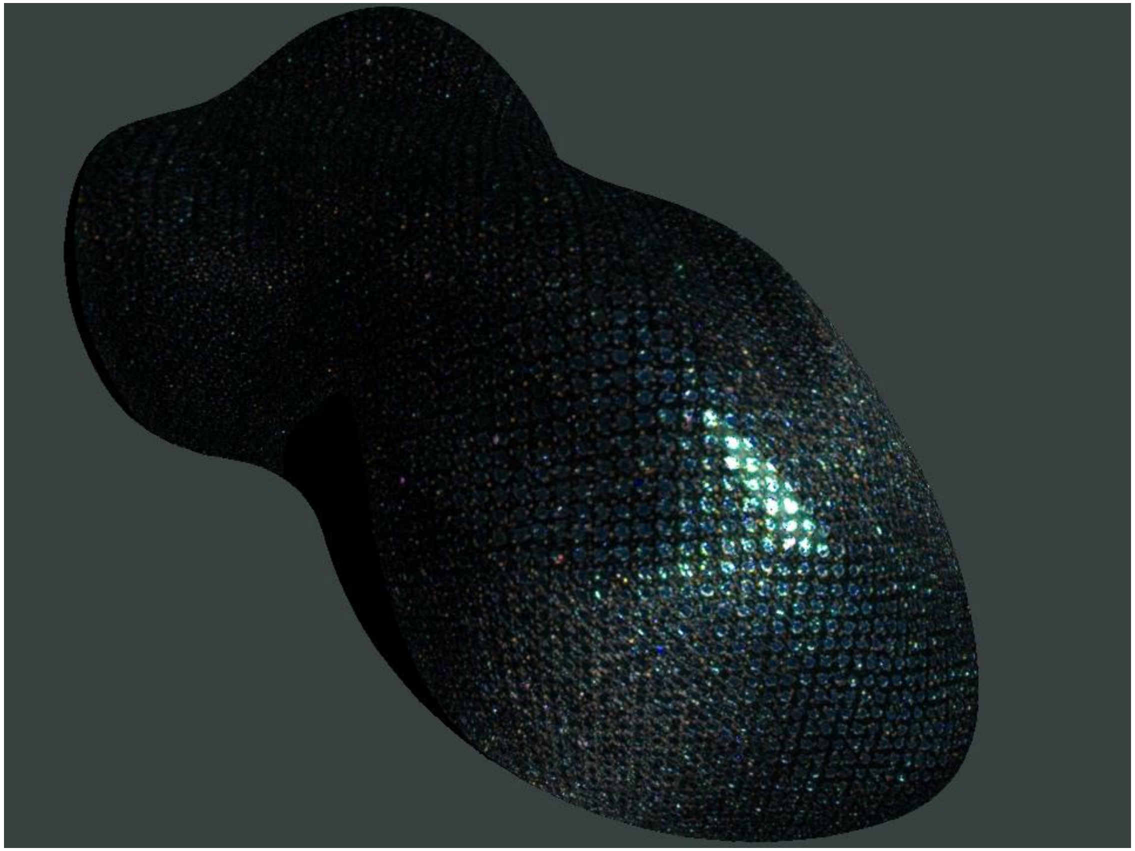
Apparent BRDF ≠ BRDF (masking, occlusions, shadowing, etc..)

possible violation of: Helmholtz reciprocity & energy conservation

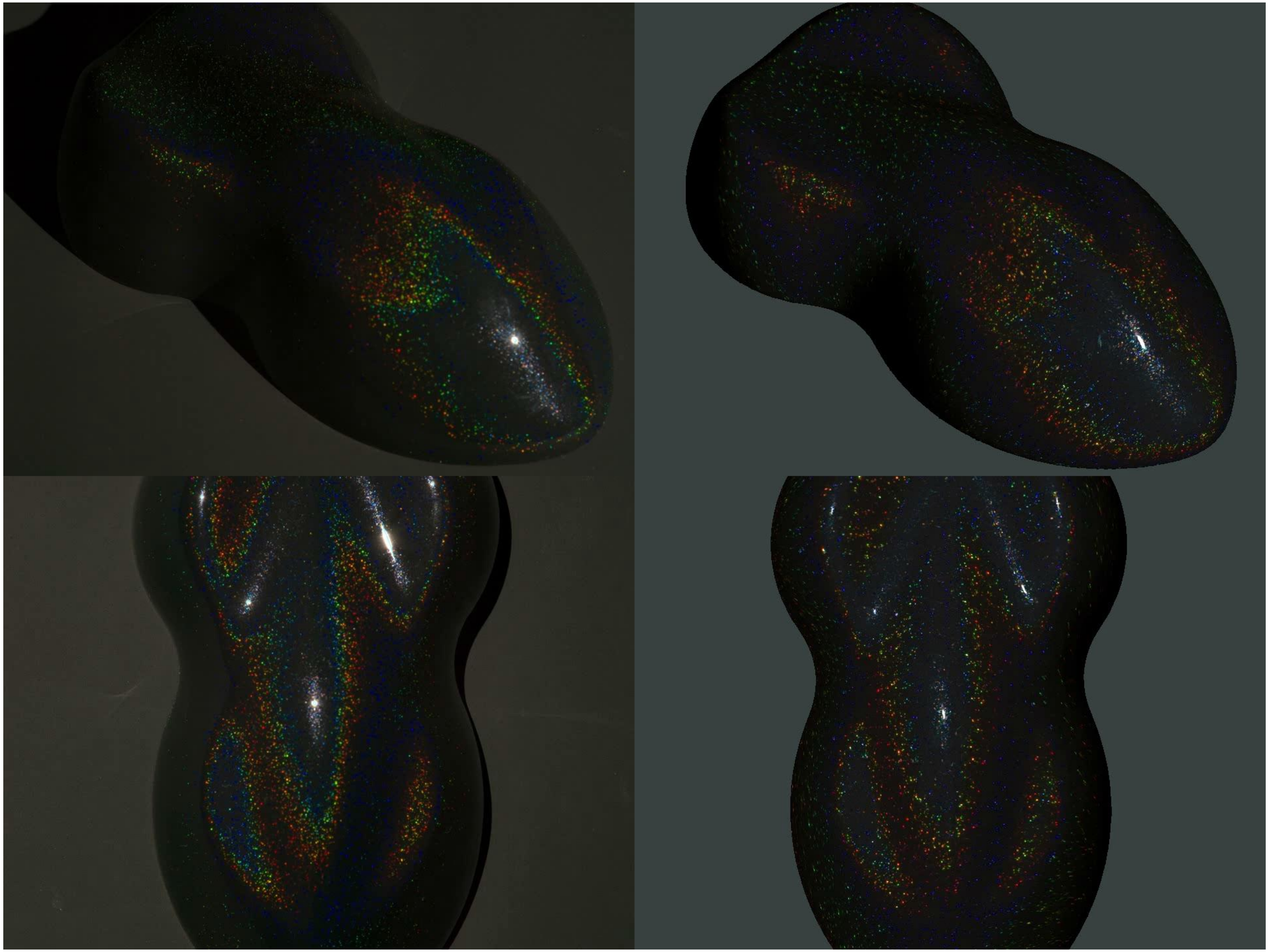


Challenging materials

- Combination of specular, diffuse and anisotropic features

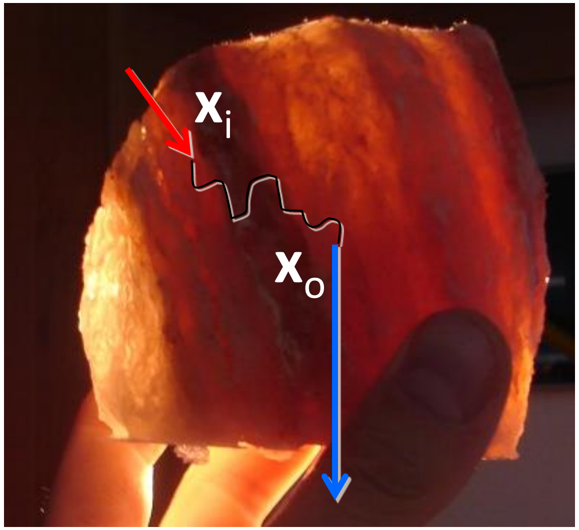


Challenging materials



BSSRDF Measurement

Bidirectional subsurface-scattering reflectance distribution function



$$BSSRDF(\lambda, \underline{x_i, y_i}, \underline{x_o, y_o}, \underline{\theta_i, \varphi_i}, \underline{\theta_v, \varphi_v})$$

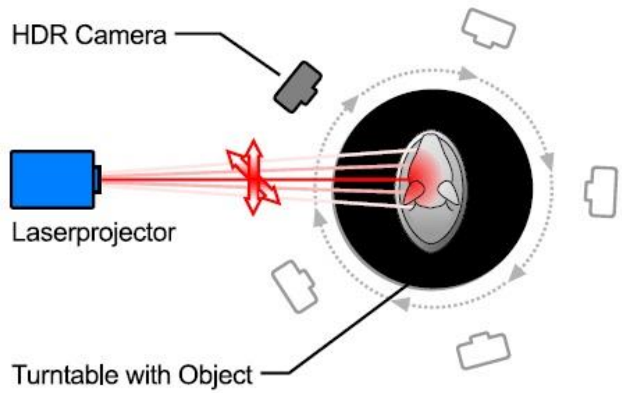
[Nicodemus et al. 77]

BTF includes scattering information, but difficult to separate

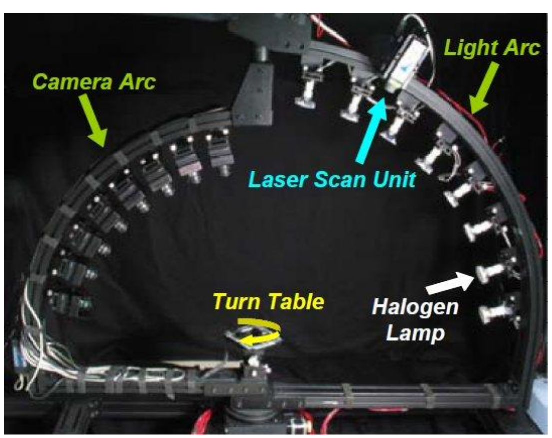
- **General 9 dimensional data** ⇨ often called as **reflectance fields**
- Describes light transport (scattering) in material structure between any pairs of incoming and outgoing rays
- Translucent materials
- Direct measurement very sparse due to high data dimensionality

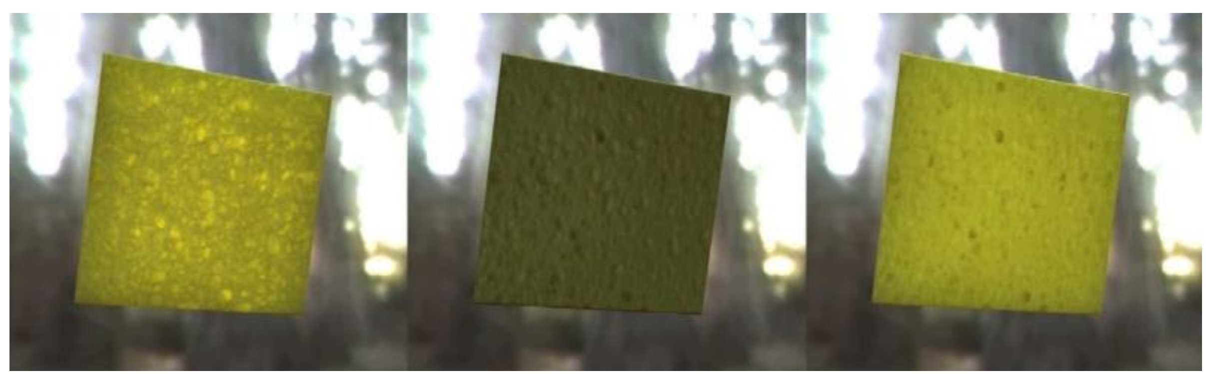
BSSRDF Measurement

[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





BTF+local scat. BTF BTF+global scat.

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

With scattering model

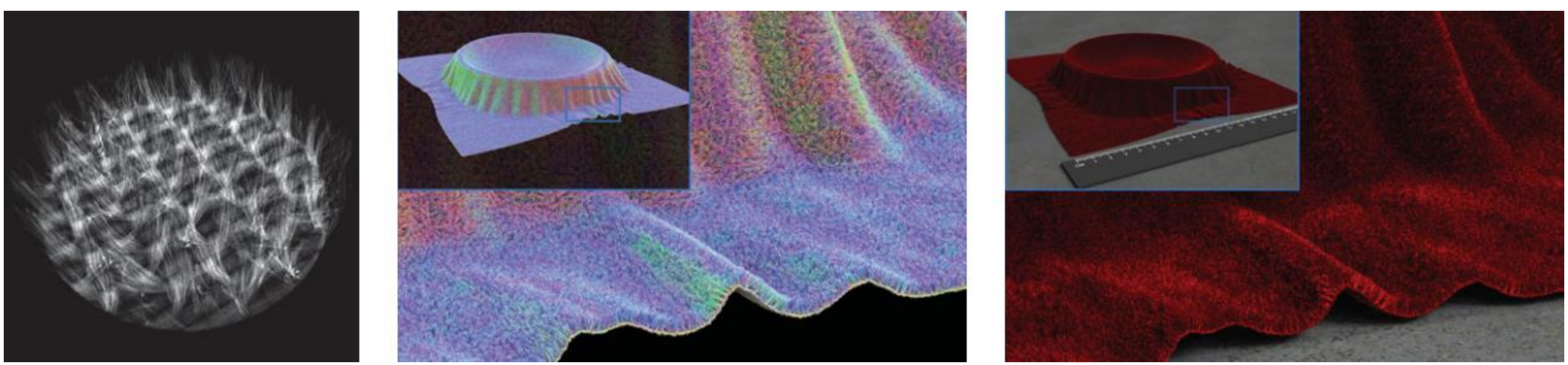
- Diffuse/specular reflectance components separation (polarization/color/illum. patterns) **[Shaffer 85]**, **[Nayar et al. JCV 97]**, **[Nayar et al. TOG 06]** ⇨ diffuse component represents light refraction inside material structure ⇨ fitting scattering models parameters to diffuse component.

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

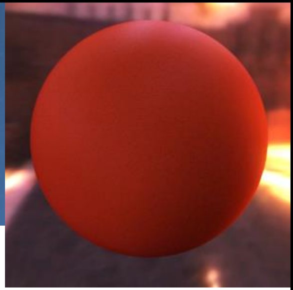
☒ assumes single material, lengthy rendering, limited dynamic range of the scanner



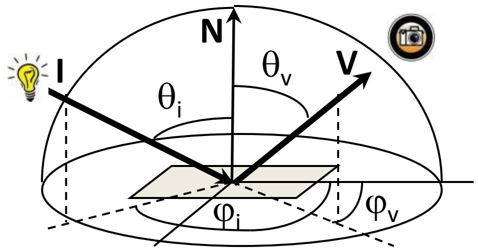
[Zhao et al. 11, ACM]

ÚTIA

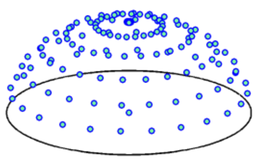
Angular Parameterizations

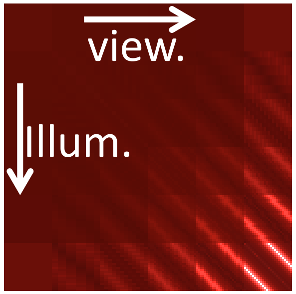


- Illumination-view

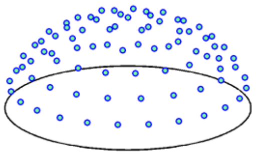


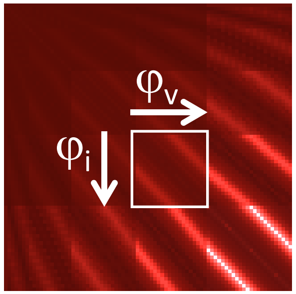
Angularly uniform



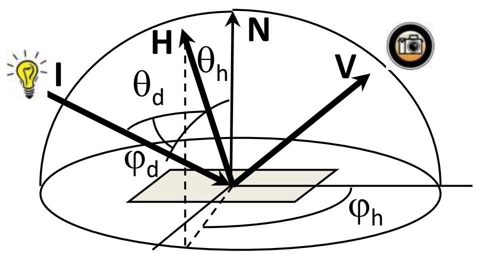


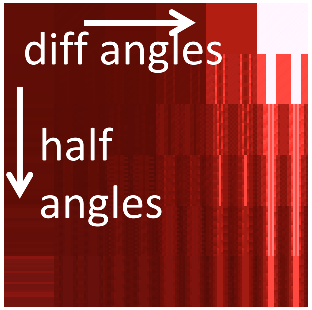
Spatially uniform



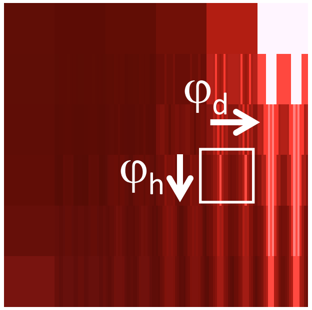


- Half-difference angles [Rusinkiewicz 98]

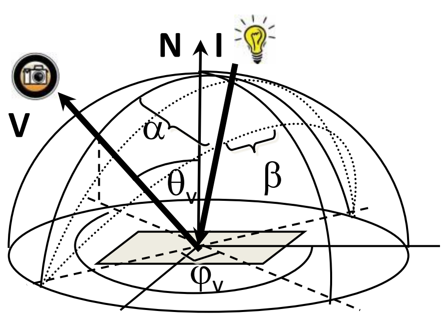


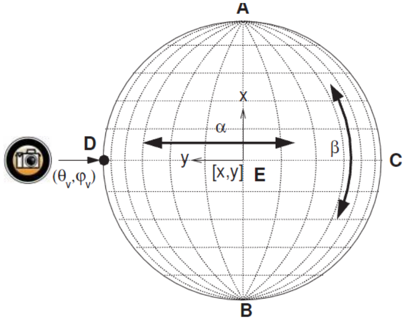


Isotropy enforced

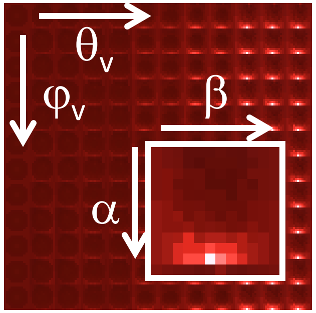


- Onion slices model [Havran et al. CGF 09]

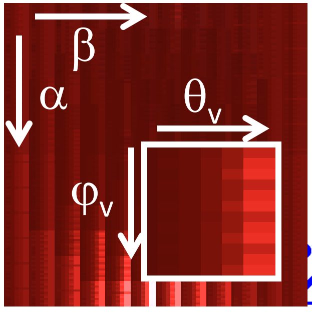




Illu. blobs

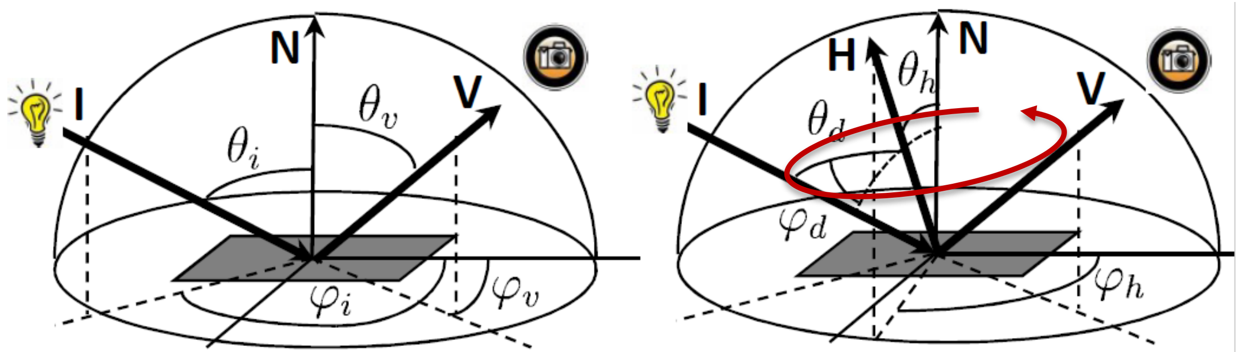


View blobs

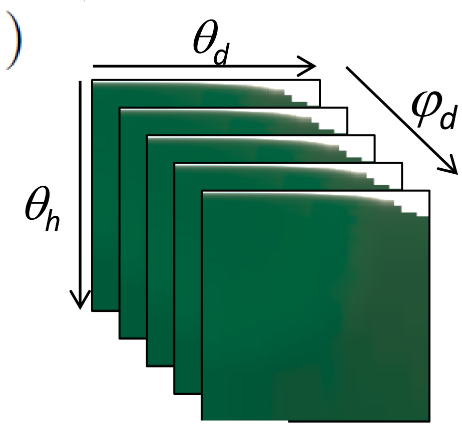


Half-Difference Parameterization

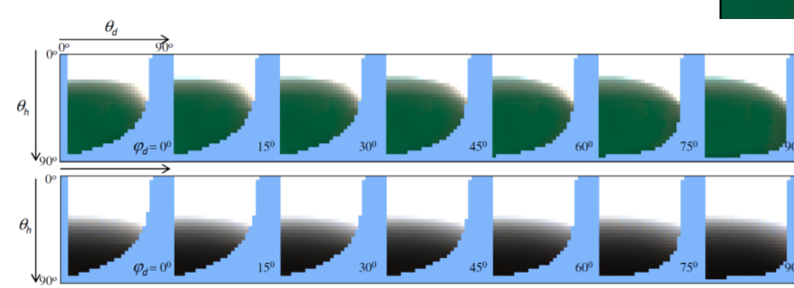
BRDF in half-difference parameterization [Rusinkiewicz 98]



$$f_r(\theta_i, \varphi_i, \theta_v, \varphi_v) \rightarrow f_r(\theta_h, \varphi_h, \theta_d, \varphi_d)$$



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



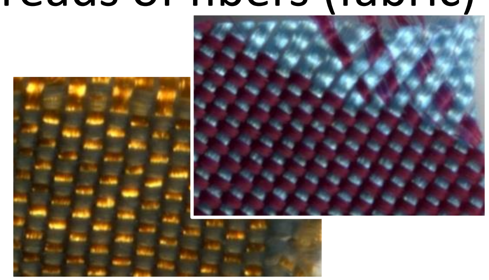
Anisotropic Material Appearance

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

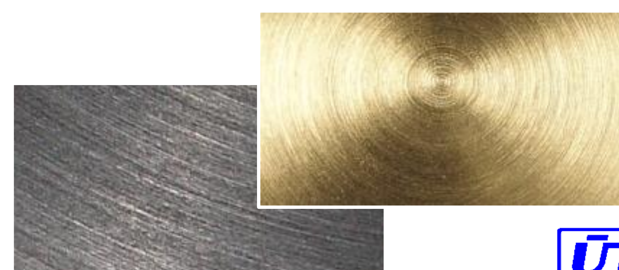
Present in many materials:

directional fibers
(fabric, wood, hair)

weaving pattern/height profile
of threads of fibers (fabric)



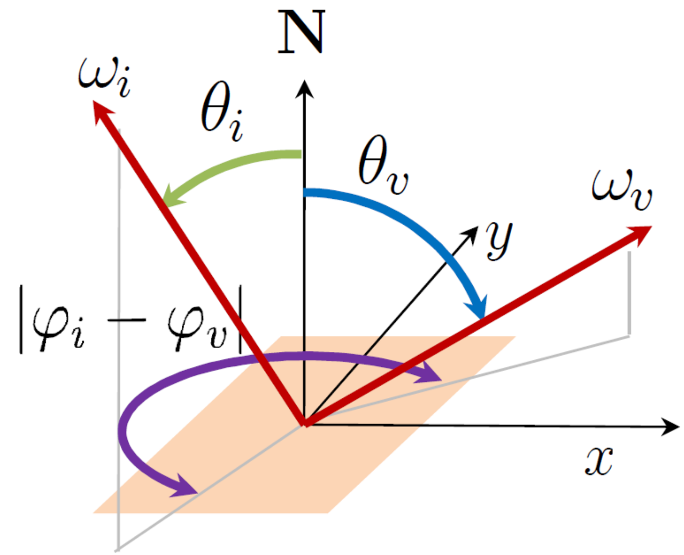
surface machining/finishing
(metal, plastic, wood, …)



Anisotropic vs. Isotropic Appearance

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

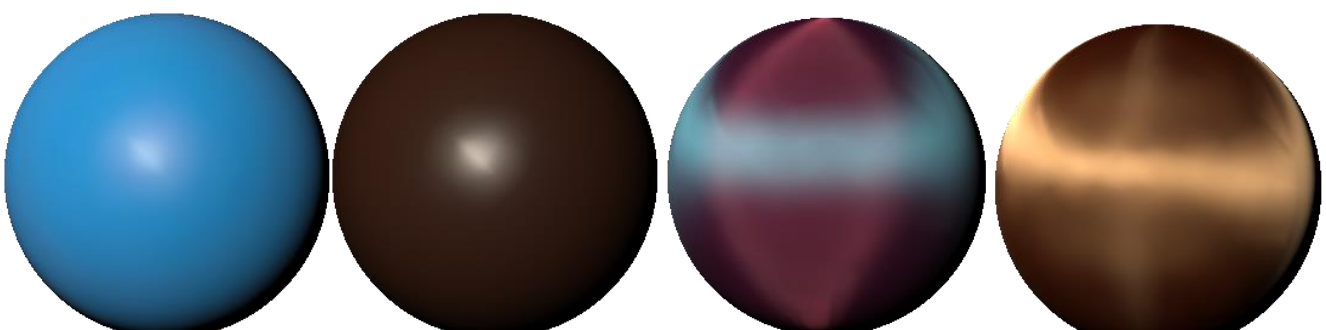
$$BRDF(\lambda, \theta_i, \phi_i, \theta_v, \phi_v)$$



- Isotropic vs. anisotropic BRDF

$$B(\theta_i, \theta_v, |\varphi_i - \varphi_v|)$$

$$B(\theta_i, \varphi_i, \theta_v, \varphi_v)$$



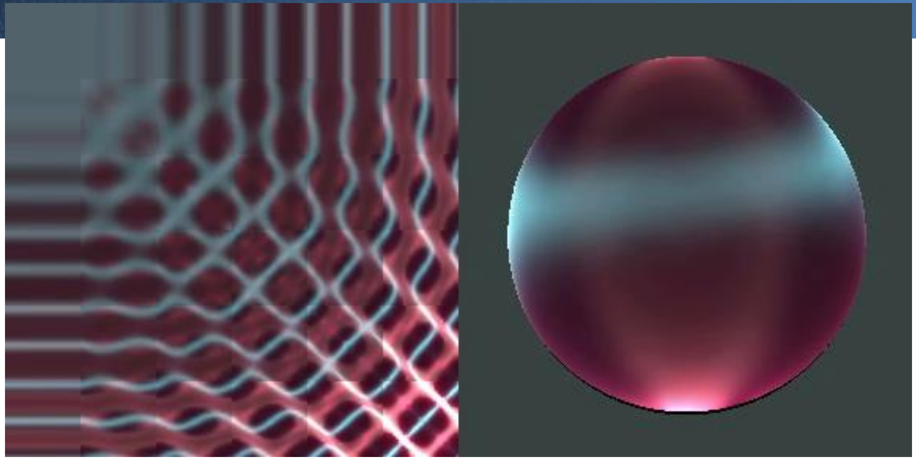
Anisotropic Material Appearance

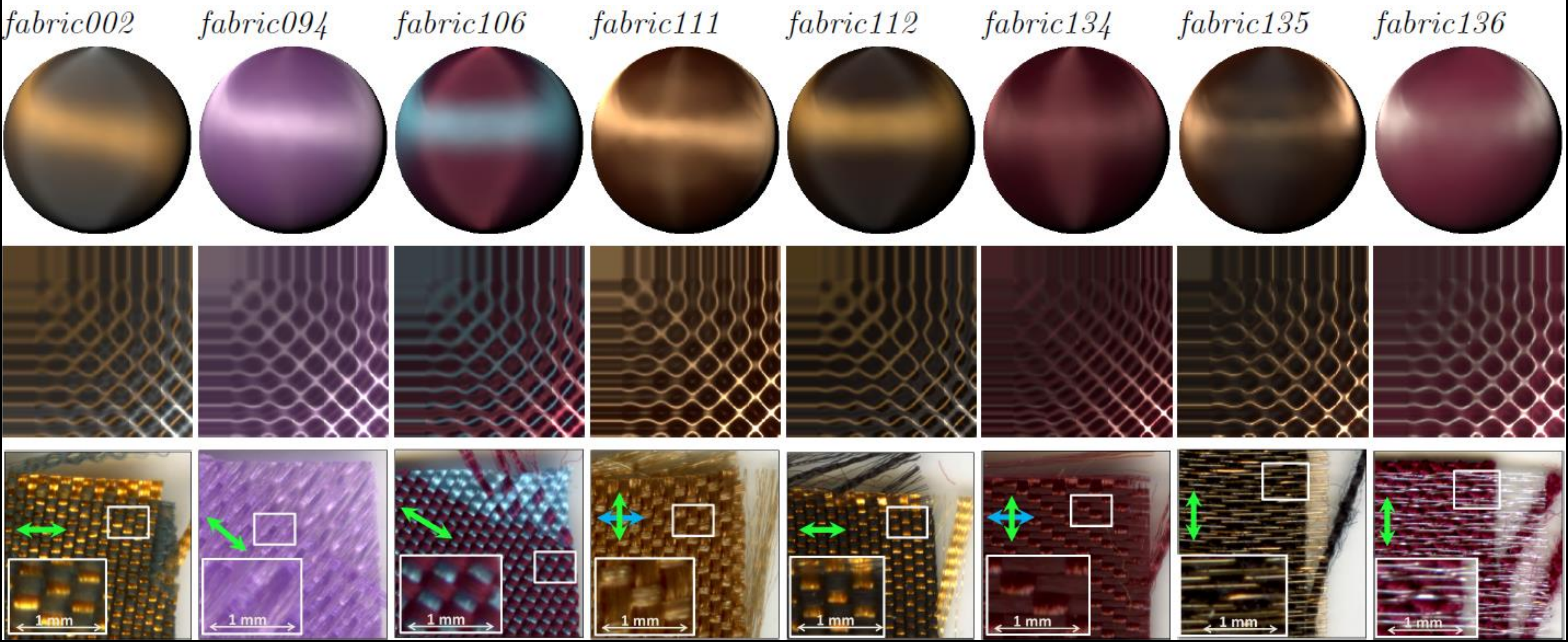
Capturing of anisotropy increases complexity of the appearance acquisition process

ŪTIA

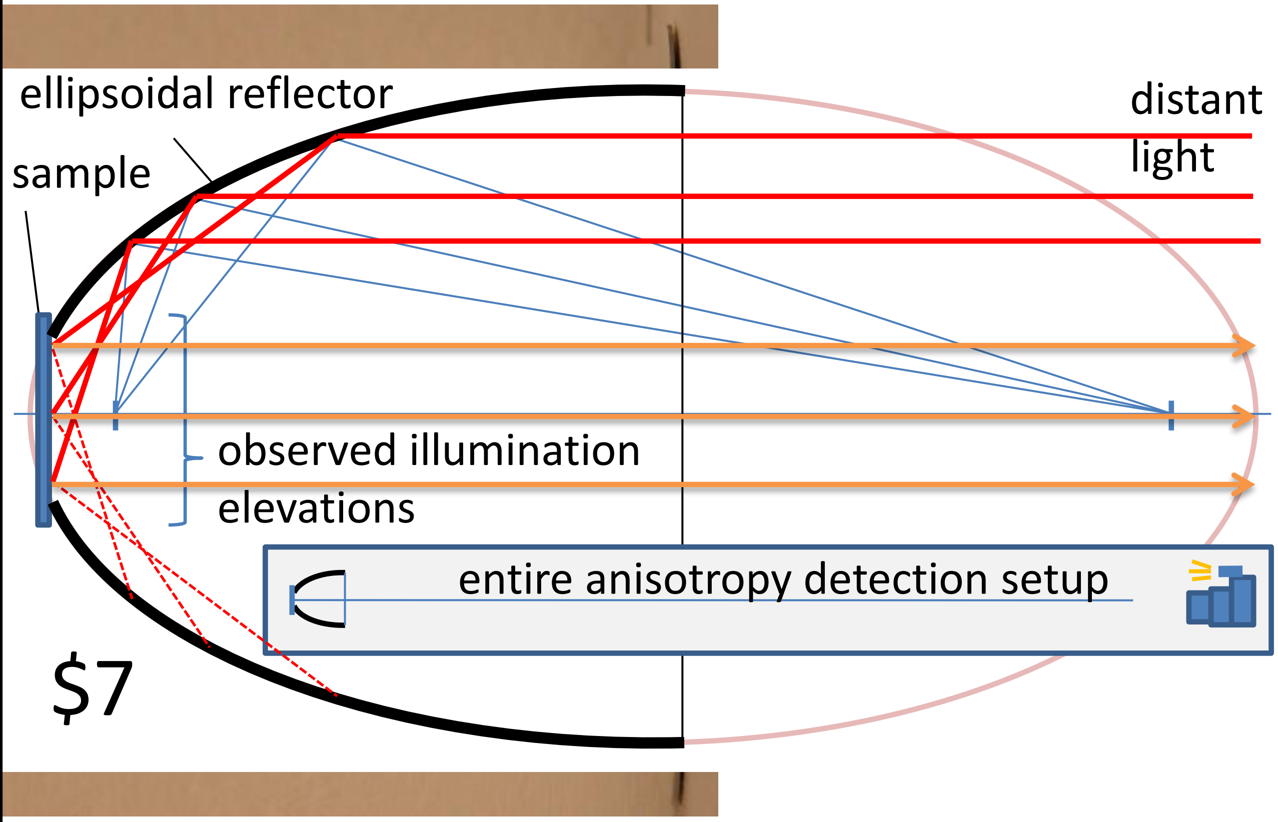
Anisotropic Material Appearance

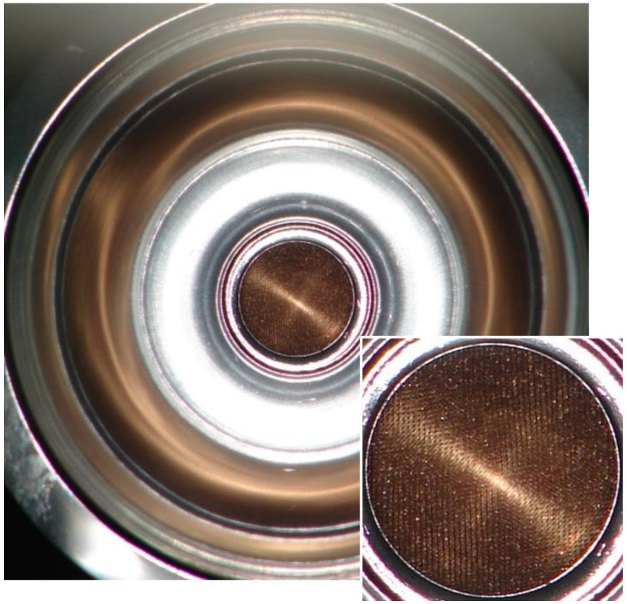
- Highlights dependent on initial position of material within appearance acquisition





Fast Anisotropy Detection

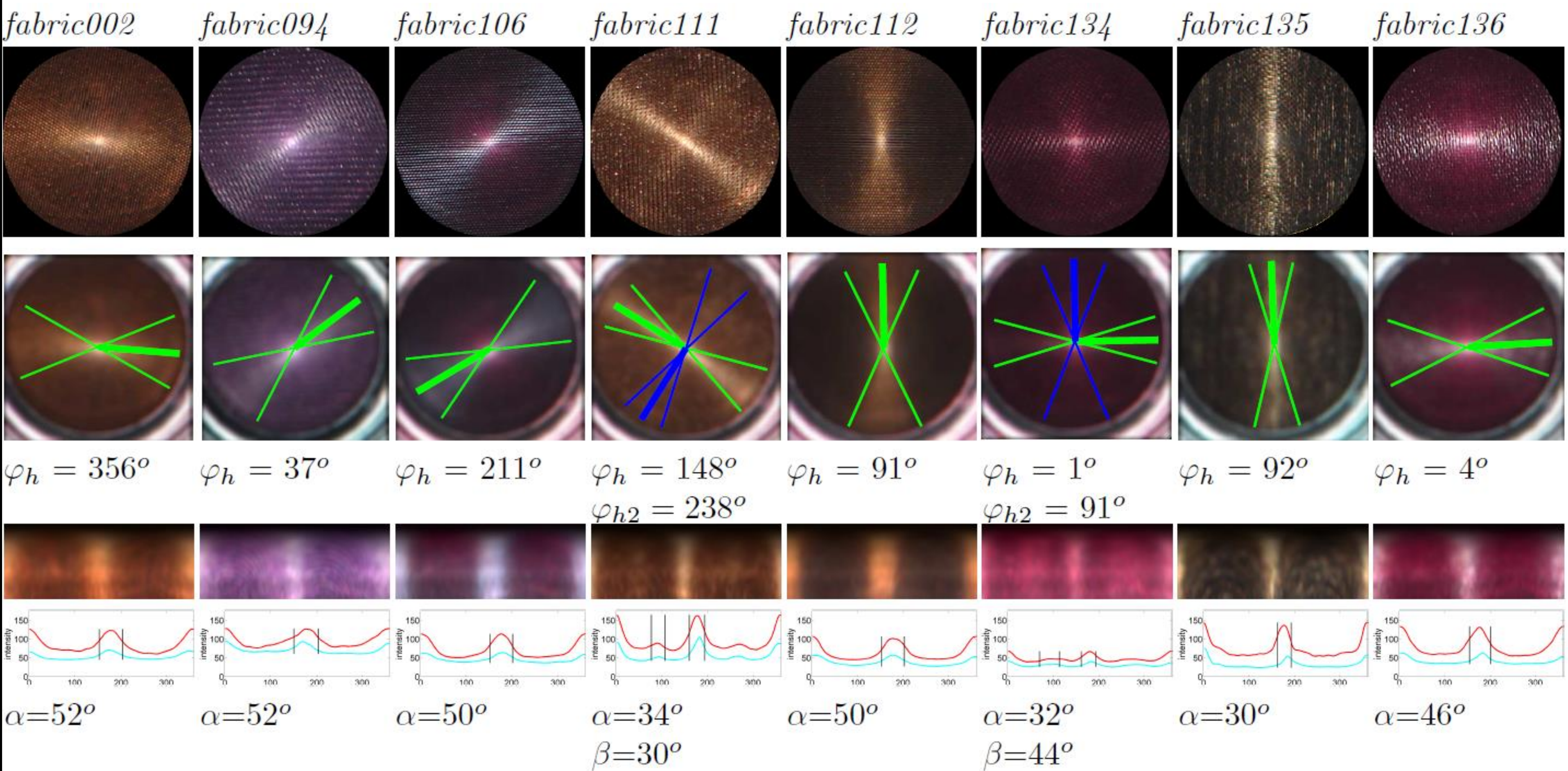




Properties

- Simple setup of reflector and camera 1.5 m apart, no calibration
- Aggregated illumination using flashlight
- All illumination azimuths recorded

Fast Anisotropy Detection

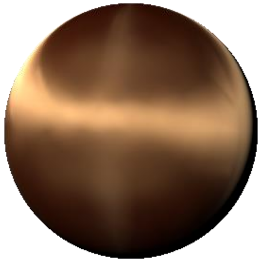


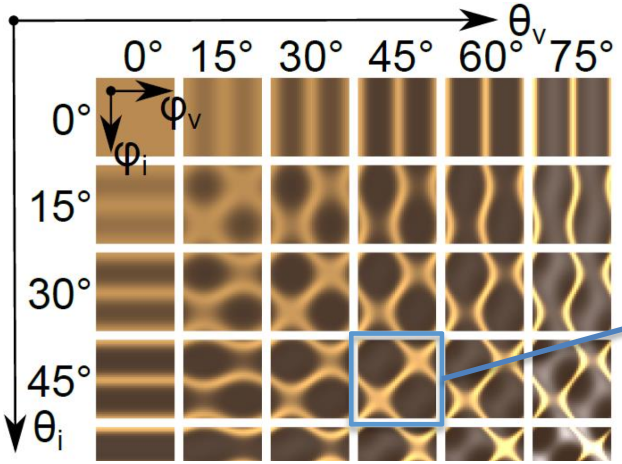
estimated reflectance

reference BRDF

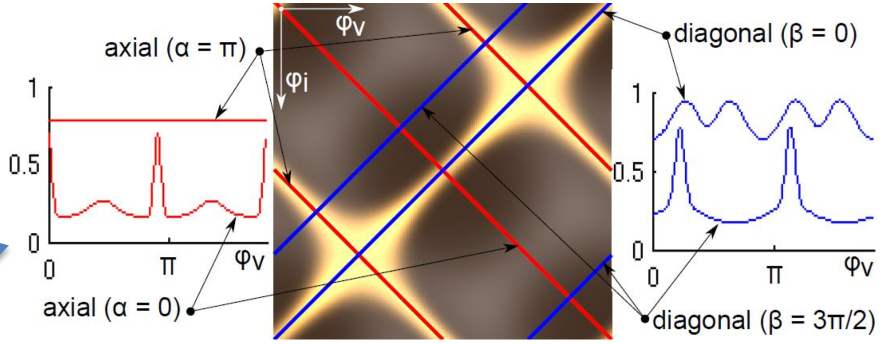
Uniform vs. adaptive sampling approaches

- **BRDF slices**



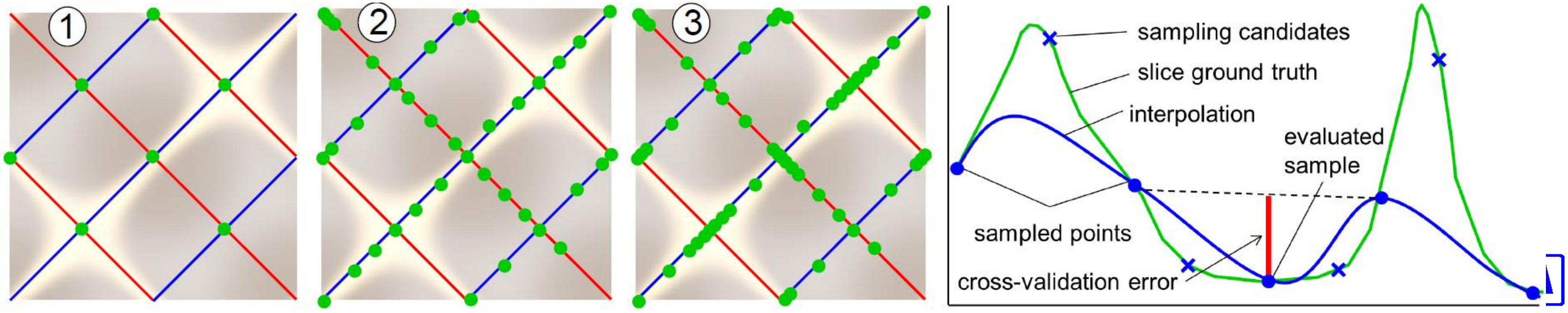


Axial and diagonal slices (azimuths)[CVPR 13]



- **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.

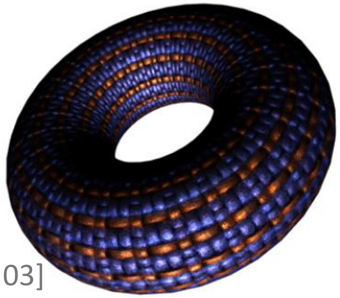
$$BRDF(\omega_i, \omega_v) \approx \prod_{j=1}^{J} P_{j,r_1,r_2}(\pi_j(\omega_i, \omega_v))$$

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

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

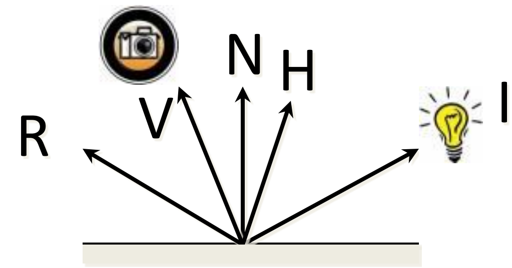
☑ factors in form of textures ⇨ interactive rendering

☒ For compression of measured BRDFs only



[Suykens et al. 03]

Empirically Derived BRDF Models



- **Phong shading** [Phong ACM 75]
  - Ambient, diffuse, and specular terms

$$BRDF(I,V) = k_a i_a + k_d (I \cdot N) i_d + k_s (R \cdot V)^{\alpha} i_s$$

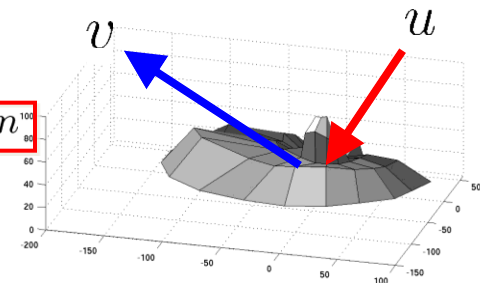
$k \ldots$ material coefs., $i \ldots$ light coefs. $R = 2(I \cdot N)N - I$

  - 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.

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



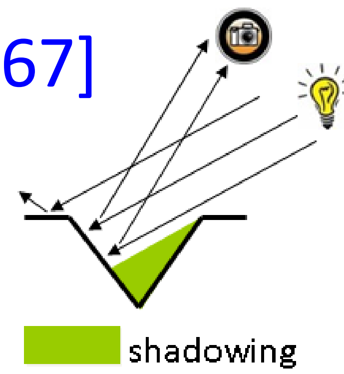
- Extension of Phong model [Ashikhmin & Shirley JGT 00]
  - non-Lambertian diffuse term, anisotropic, energy conserving, Fresnel refraction
  - intuitive parameters, complex computation

Physically-Derived BRDF Models

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

$$BRDF(\theta_i, \theta_v) = \frac{F(\theta_h)D(\theta_h)G(\theta_i, \theta_v)}{\pi \cos\theta_i \cos\theta_v}$$

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



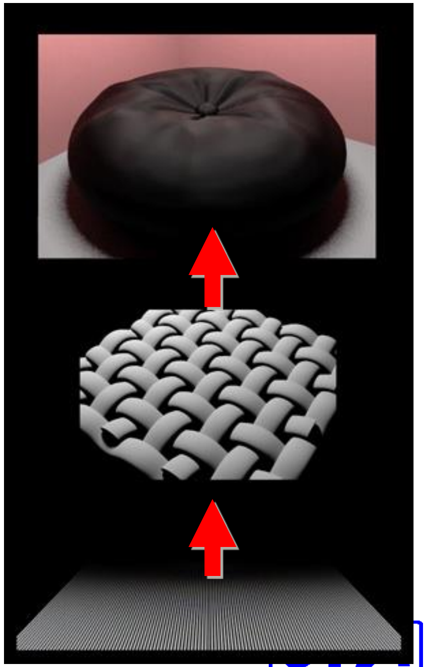
Physically-Derived BRDF Models

- Simplified analytical microfacet model [Ward CG 92]
  - Specularity as exp() function, four physically meaningful parameters, anisotropy modeling

$$BRDF(\theta_i, \theta_v) = \frac{k_d}{\pi} + k_s \frac{1}{\cos\theta_i \cos\theta_v} \frac{e^{-\tan^2\theta_h/\alpha^2}}{4\pi\alpha^2}$$

  - normalization in [Duer 05]
- Microgeometry model [Westin 92]
  – Geometry based model ⇨ More general
  ☒ Underlying material geometry has to be known, difficult to fit to measured BRDFs

[Westin ©ACM 92]



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

- [Kurt et al. CG 10] – modification of Cook-Torrance microfacet model.
  - 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.:

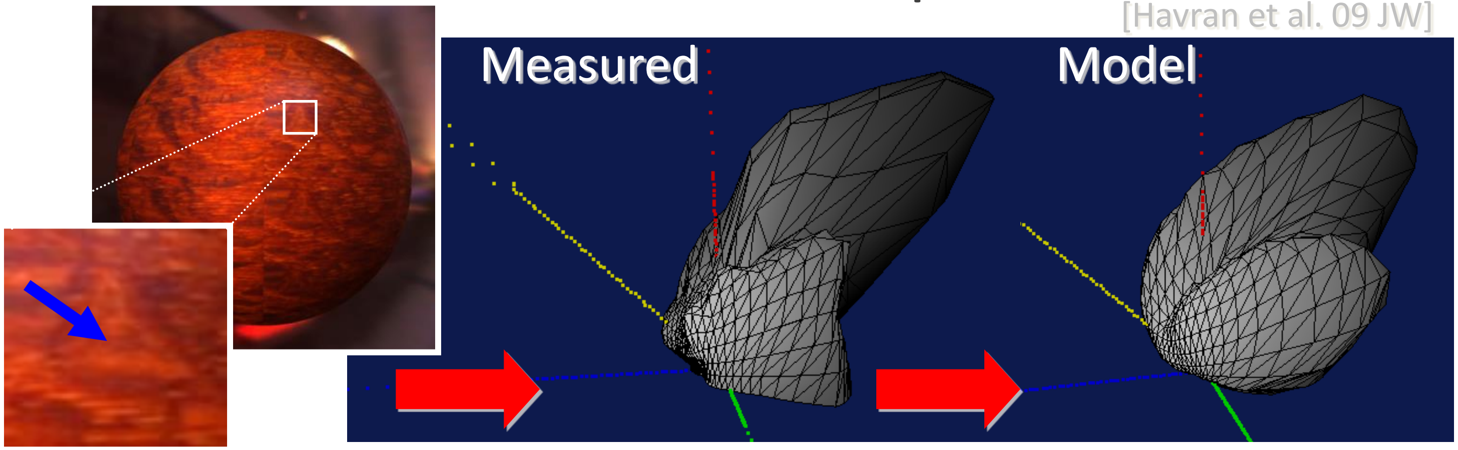
$$BRDF(\theta_i, \theta_v) = \frac{k_d}{\pi} + k_s \frac{F(\mathbf{VH}) D(\theta_h, \varphi_h)}{4(\mathbf{VH})(\cos\theta_i \cos\theta_v)^{\alpha}}$$

ÚTIA

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 ⇨ low-pass filter.

[Havran et al. 09 JW]



- Higher quality ⇨ more parameters to store
  ⇨ often more complex fitting

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

ÚTIA

UTIA Anisotropic BRDF Database

http://btf.utia.cas.cz

10 other materials
plaster,
paper,
paint, ...

UTIA Anisotropic BRDF Database

http://btf.utia.cas.cz

elevation step = 15^0
azimuthal step = 7.5^0

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

Acknowledgement

Contact

Jiří Filip jiri.filip@utia.cz
http://staff.utia.cz/filip

BTF & BRDF Data http://btf.utia.cas.cz

Funding

- Czech Science Foundation grants No. 17-18407S, 14-02652S, 103/11/0335
- EC FP7 Marie Curie ERG 239294 (PASIMA)

ÚTIA

References

BRDF measurement

- Murray-Coleman, J., Smith, A.: *The automated measurement of BRDFs and their application to luminaire modeling*. Journal of the Illuminating Engineering Society pp. 87–99 (1990)
- White, D.R., Saunders, P., Bonsey, S.J., van de Ven, J., Edgar, H.: *Reflectometer for measuring the bidirectional reflectance of rough surfaces*. Journal of Applied Optics 37, 3450–3454 (1998)
- Ward, G.: *Measuring and modeling anisotropic reflection*. Computer Graphics 26(2) (1992)
- Dana, K.: *BRDF/BTF measurement device*. ICCV 2001, vol. 2, pp. 460–466 (2001)
- Mukaigawa, Y., Sumino, K., Yagi, Y.: *Multiplexed illumination for measuring BRDF using an ellipsoidal mirror and a projector*, ACCV'07, pp. 246–257
- Ghosh, A., Achutha, S., Heidrich, W., O'Toole, M.: *BRDF acquisition with basis illumination*. ICCV 2007, 1–8 (2007)

References

BRDF measurement

- Lu, R., Koenderink, J.J., Kappers, A.M.L.: *Optical properties (bidirectional reflectance distribution functions) of velvet*. Applied Optics 37, 5974 5984 (1998)
- Ngan, A., Durand, F., Matusik, W.: *Experimental analysis of BRDF models*. Eurographics Symposium on Rendering 2005 pp. 117–126 (2005)
- Marschner, S.R., Westin, S.H., Lafortune, E.P.F., Torrance, K.E.: *Image-based biderectional reflectance distribution function measurement*. Applied Optics 39 (2000)
- Matusik,W., Pfister H.P. Brand, M., McMillan, L.: *Image-based BRDF measurement including human skin*. In: Proceedings of 10th EurographicsWorkshop on Rendering, pp. 139–152 (2003)
- Ben-Ezra, M., Wang, J., Wilburn, B., Li, X., Ma, L.: *An LED-only BRDF measurement device*. CVPR 2008, 1–8
- Lan, Y., Dong, Y.,Wang, J., Tong, X., Guo, B.: *Condenser-based instant reflectometry*. Computer Graphics Forum 29(7), 2091–2098 (2010)

References

SV-BRDF measurement

- McAllister, D.K., Lastra, A., Heidrich, W.: *Efficient rendering of spatial bi-directional reflectance distribution functions*. Graphics Hardware pp. 77–88 (2002)
- Holroyd, M., Lawrence, J., Zickler, T.: *A coaxial optical scanner for synchronous acquisition of 3D geometry and surface reflectance*. ACM Trans. Graph. 29, 99:1–99:12 (2010)
- Lensch, H.P.A., Goesele, M., Kautz, J., Heidrich, W., Seidel, H.P.: *Image-based reconstruction of spatially varying materials*. 12th Eurographics Workshop on Rendering Techniques, 2001, pp.103–114, (2001)
- Matusik, W., Pfister, H., Ngan, A., Beardsley, P., Ziegler, R., McMillan, L.: *Image-based 3D photography using opacity hulls*. ACM Trans. Graph. 21, 427–437 (2002)
- Debevec, P., Hawkins, T., Tchou, C., Duiker, H.P., Sarokin, W., Sagar, M.: *Acquiring the reflectance field of a human face*. CGIT, SIGGRAPH ’00, pp. 145–156., (2000)

References

SV-BRDF measurement

- Weyrich, T., Matusik, W., Pfister, H., Bickel, B., Donner, C., Tu, C., McAndless, J., Lee, J., Ngan, A., Jensen, H.W., Gross, M.: *Analysis of human faces using a measurement-based skin reflectance model*. SIGGRAPH ’06, pp. 1013–1024. (2006)
- Aittala, M., Weyrich, T., Lehtinen, J. 2013. *Practical SVBRDF capture in the frequency domain*. ACM Transactions on Graphics (Proc. SIGGRAPH) 32, 4 (July), 110:1–110:12.
- Aittala, M., Weyrich, T., Lehtinen, J. 2015. *Two-Shot SVBRDF Capture for Stationary Materials*. ACM Trans. Graph. 34, 4, Article 110 (August 2015), 13 pages.
- Aittala, M., Aila, T., Lehtinen, J. 2016. *Reflectance Modeling by Neural Texture Synthesis*. ACM Trans. Graph. 35, 4, Article 65 (July 2016), 13 pages.

References

BTF measurement

- K. Dana, B. van Ginneken, S. Nayar, and J. Koenderink, *Reflectance and Texture of Real-World Surfaces*, ACM Trans. Graphics, vol. 18, no. 1, pp. 1-34, 1999,
- M. Sattler, R. Sarlette, and R. Klein, *Efficient and Realistic Visualization of Cloth*, Proc. Eurographics Symp. Rendering, pp. 167-178, June 2003,
- A. Neubeck, A. Zalesny, and L. Gool, *3D Texture Reconstruction from Extensive BTF Data*, Texture 2005, pp. 13-18, Oct. 2005.
- M. Koudelka, S. Magda, P. Belhumeur, and D. Kriegman, *Acquisition, Compression, and Synthesis of Bidirectional Texture Functions*, Texture 2003, pp. 47-52, Oct. 2003,
- K. Dana and J. Wang, *Device for Convenient Measurement of Spatially Varying Bidirectional Reflectance*, J. Optical Soc. America, vol. 21, no. 1, pp. 1-12, 2004.
- J.Y. Han and K. Perlin, *Measuring Bidirectional Texture Reflectance with a Kaleidoscope*, ACM Trans. Graphics, vol. 22, no. 3, pp. 741-748, 2003,
- G. Muller, G. Bendels, and R. Klein, *Rapid Synchronous Acquisition of Geometry and BTF for Cultural Heritage Artefacts*, Proc. Sixth Int'l Symp. Virtual Reality, Archaeology and Cultural Heritage, pp. 13-20, 2005.

References

BTF measurement

Spectral BTF Measurement

- D. Lyssi, *A reflectometer setup for spectral BTF measurement, CESCG, Apr. 2009,*
- M. Rump, R. Sarlette, and R. Klein, *Groundtruth Data for Multispectral Bidirectional Texture Functions*, In proceedings of CGIV 2010, to appear, June 2010,
- Martin Rump and Reinhard Klein, *Spectralization: Reconstructing spectra from sparse data*, In proceedings of EGSR 2010, to appear, June 2010.

References

BSSRDF measurements

- Nicodemus, F., J.C., R., Hsia, J., Ginsburg, I., Limperis, T.: *Geometrical considerations and nomenclature for reflectance*. NBS Monograph 160, National Bureau of Standards, U.S. Department of Commerce, Washington, D. C. pp. 1–52 (1977)
- Goesele, M., Lensch, H.P.A., Lang, J., Fuchs, C., Seidel, H.P.: *Disco: acquisition of translucent objects*. ACM Trans. Graph. 23, 835–844 (2004)
- Tong, X., Wang, J., Lin, S., Guo, B., Shum, H.Y.: *Modeling and rendering of quasihomogeneous materials*. In: ACM SIGGRAPH 2005 Papers, SIGGRAPH ’05, pp. 1054–1061. ACM, New York, NY, USA (2005)
- Jensen, H.W., Marschner, S.R., Levoy, M., Hanrahan, P.: *A practical model for subsurface light transport*. In: Proceedings of the 28th annual conference on Computer graphics and interactive techniques, SIGGRAPH ’01, pp. 511–518. ACM, New York, NY, USA (2001)

References

BSSRDF - diffuse/specular components separation

- Shafer, S.A.: *Using color to separate reflection components*. Color Research & Application 10(4), 210–218 (1985)
- Nayar, S.K., Fang, X.S., Boult, T.: *Separation of reflection components using color and polarization*. International Journal of Computer Vision 21, 163–186 (1997).
- Nayar, S.K., Krishnan, G., Grossberg, M.D., Raskar, R.: *Fast separation of direct and global components of a scene using high frequency illumination*. ACM Trans. Graph. 25, 935–944 (2006)

Volumetric Model Acquisition

- S. Zhao,W. Jakob, S. Marschner, K. Bala, *Building volumetric appearance models of fabric using micro CT imaging*, ACM Trans. Graph., 30(4), 2011

ÚTIA

References

BRDF representation

- Rusinkiewicz, S.M., *A new change of variables for efficient BRDF representation*, Rendering techniques' 98, 1998, pp. 11,
- Havran V., Filip J., Myzskowski K., *Bidirectional Texture Function Compression based on Multi-Level Vector Quantization*. Computer Graphics Forum, vol. 29, no. 1, pp. 175-190, March 2010

BRDF factorization

- J. Kautz and M.D. McCool. *Interactive rendering with arbitrary BRDFs using separable approximations*. In Proceedings of the 10th Eurographics Workshop on Rendering, pages 281-292, 1999.
- M.D. McCool, J. Ang, and A. Ahmad. *Homomorphic factorization of BRDFs for high-performance rendering*. In E. Fiume, editor, ACM SIGGRAPH 2001, ACM Press, pages 185-194, 2001.
- F. Suykens, K. Berge, A. Lagae, and P. Dutre, *Interactive rendering with bidirectional texture functions*. In Computer Graphics Forum, pages 463-472, 2003.)

ŪTIA

References

BRDF compression

- He X. D., Heynen P. O., Phillips R. L., Torrance K. E., Salesin D. H., Greenberg D. P., *A fast and accurate light reflection model*, SIGGRAPH Comput. Graph. 26(2), 1992, pp. 253-254,
- Westin S. H., Arvo J. R., Torrance K. E., *Predicting reflectance functions from complex surfaces*, SIGGRAPH '92, 1992, pp. 255-264,
- Schroder P., Sweldens W., *Spherical wavelets: efficiently representing functions on the sphere*, SIGGRAPH '95, 1995, pp. 161-172,
- Koenderink J. J., van Doorn A. J., Stavridi M., *Bidirectional Reflection Distribution Function Expressed in Terms of Surface Scattering Modes*, ECCV '96, 1996, pp. 28-39,

BRDF models

- Phong B.T., *Illumination for Computer Generated Images*, Communications of the ACM, 18(6), pp. 31-317, 1975,

References

BRDF models (continued)

- Blinn J.F., *Models of Light Reflection for Computer Synthesized Pictures*, Computer Graphics Proceedings, pp.192-198, 1977,
- Neumann L., Neumann A., Szirmay-Kalos L., *Compact metallic reflectance models*, Computer Graphics Forum, 18(13), 1999,
- Ashikhmin M., Shirley, P., *An Anisotropic Phong Light Reflection Model*, Journal of Graphics Tools, 5(2), pp. 25-32, 2000,
- Torrance K. and Sparrow E., *Theory for Off-Specular Reflection from Rough Surfaces*, Journal of the Optical Society of America, 57(9), pp. 1105-1114, 1967,
- Cook R. L., Torrance K. E., *A reflectance model for computer graphics*, ACM SIGGRAPH 1981, 15(3), pp. 307-316, 1981,
- He X., Torrance K. E.m, Sillion F.X., Greenberg D.P., *A Comprehensive Physical Model for Light Reflection*, Computer Graphics, 25(4), 1991,

ÚTIA

References

BRDF models (continued)

- Blinn J.F., *Models of Light Reflection for Computer Synthesized Pictures*, Computer Graphics Proceedings, pp.192-198, 1977,
- Neumann L., Neumann A., Szirmay-Kalos L., *Compact metallic reflectance models*, Computer Graphics Forum, 18(13), 1999,
- Ashikhmin M., Shirley, P., *An Anisotropic Phong Light Reflection Model*, Journal of Graphics Tools, 5(2), pp. 25-32, 2000,
- Torrance K. and Sparrow E., *Theory for Off-Specular Reflection from Rough Surfaces*, Journal of the Optical Society of America, 57(9), pp. 1105-1114, 1967,
- Cook R. L., Torrance K. E., *A reflectance model for computer graphics*, ACM SIGGRAPH 1981, 15(3), pp. 307-316, 1981,
- He X., Torrance K. E.m, Sillion F.X., Greenberg D.P., *A Comprehensive Physical Model for Light Reflection*, Computer Graphics, 25(4), 1991,

References

BRDF models (continued)

- Nayar S. K., Oren M., *Generalization of the Lambertian Model and Implications for Machine Vision*, International Journal of Computer Vision, 14(-), pp. 227-251, 1995,
- Schlick, C., *An Inexpensive BRDF Model for Physically-based Rendering*, Computer Graphics Forum, 13(3), pp. 149-162, 1994,
- Lafortune E. P., Foo S. Ch., Torrance K. E., Greenberg, D. P., *Non-Linear Approximation of Reflectance Functions*, Computer Graphics, 31, pp. 117-126, 1997,

SVBRDF modeling

- McAllister D. K., Lastra A., Heidrich W., *Efficient Rendering of Spatial Bi-directional Reflectance Distribution Functions*, Graphics Hardware, pp. 77-88, 2002,
- Gardner A., Tchou C., Hawkins T., Debevec, P., *Linear light source reflectometry*, ACM SIGGRAPH, pp. 749-758, 2003,

References

SVBRDF modeling (continued)

- Lensch H. P. A., Kautz J., Goesele M., Heidrich W., Seidel H.-P., *Image-based reconstruction of spatial appearance and geometric detail*, ACM Trans. Graph., 22(2), pp. 234-257, 2003,
- Marschner S. R., Westin S. H., Arbree A., Moon J. T., *Measuring and modeling the appearance of finished wood*, ACM Trans. Graph., 24(3), 2005, pp. 727-734,
- Wang J., Zhao S., Tong X., Snyder J., Guo B., *Modeling anisotropic surface reflectance with example-based microfacet synthesis*, ACM SIGGRAPH 2008 papers, pp. 41:1-41:9
- Kautz J., Sattler M., Sarlette R., Klein R., Seidel H.-P., *Decoupling BRDFs from surface mesostructures*, Proceedings of Graphics Interface 2004, pp 177-182,
- Dong Y., Wang J., Tong X., Snyder J., Lan Y., Ben-Ezra M., Guo B., *Manifold bootstrapping for SVBRDF capture*, ACM SIGGRAPH 2010 papers, pp. 98:1-98:10,

References

SVBRDF modeling (continued)

- P. Ren, J. Wang, J. Snyder, X. Tong, B. Guo, *Pocket reflectometry*, ACM SIGGRAPH 2011 papers, pp.45:1--45:10, 2011

SVBRDF editing

- Lawrence J., Ben-Artzi A., DeCoro C., Matusik W., Pfister H., Ramamoorthi R., Rusinkiewicz S., *Inverse shade trees for non-parametric material representation and editing*, ACM SIGGRAPH 2006 Papers, pp. 735-745,
- Pellacini F., Lawrence J., *AppWand: editing measured materials using appearance-driven optimization*, ACM Trans. Graph., 26(3), 2007,
- Matusik W., Ajdin B., Gu J., Lawrence J., Lensch H.P. A., Pellacini F., Rusinkiewicz S., *Printing spatially-varying reflectance*, ACM SIGGRAPH Asia 2009 papers, pp. 128:1-128:9.