SIGGRAPH2005

Course 10
Realistic Materials in Computer Graphics

Homogeneous Isotropic BRDFs

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Outline

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- Image-based BRDF measurement
- Efficient measurement
- Validation of analytic BRDF models
- Data-driven BRDF model

Reflectance

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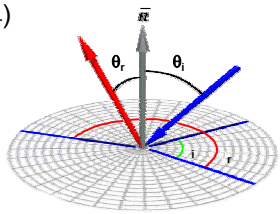
- Bidirectional Reflectance Distribution Function (BRDF)
- $f_r(\theta_i,\phi_i,\theta_r,\phi_r)$



Reflectance

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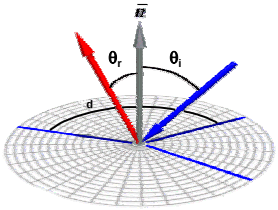
- Isotropic BRDF
- $f_r(\theta_i,\theta_r,\phi_d)$



Measurement

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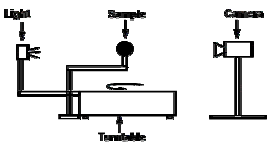
- Inspired by Marshner [1998]



Measurement

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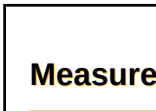
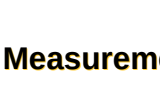
- Camera
  - QImaging Retiga
    - Firewire Connection
    - High-Res (1300x1030)
    - 10 bits, Bayer pattern
    - Exposure 40μs - 16 min
  - HDR imaging
    - 17 images: 40 μs - 30 s
    - Linear Response Curve

Measurement



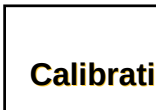
- Light Source
  - Hamamatsu SQ Xenon lamp
    - Stable emission output
    - Continuous and relatively constant radiation spectrum

Measurement



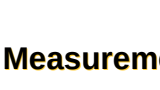
- Turntable
  - Kaidan MD-19
  - Computer-controlled
- Dark Room
  - Walls painted with flat black paint
- Spherical Samples

Calibration



- Geometric calibration
  - Contact digitizer
    - Faro Arm
  - Intrinsic & extrinsic camera parameters
  - Sphere center & radius
  - Light Position
    - parameterized on a circle in 3D

Measurement



- 20-80 million reflectance measurements per material
- Each tabulated BRDF entails 90x90x180x3=4,374,000 measurement bins

Rendering from Tabulated BRDFs

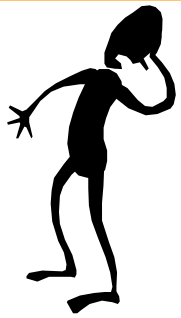
- These BRDFs are immediately useful
- Direct renderings from measurements

Nickel Hematite Gold Paint Pink Felt

Outline

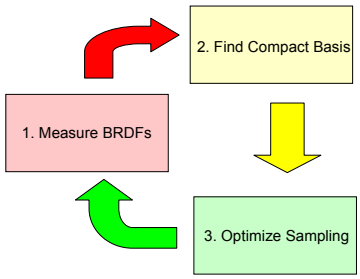
- Image-based BRDF measurement
- Efficient measurement
- Validation of analytic BRDF models
- Data-driven BRDF model

IT WAS PAINFUL!!!



- Each ball took over 4 hours
- In 2 years we measured slightly more than 100 balls
- We repeated the whole process two times, using different light sources, and photometric calibrations
- **Can we apply what we've learned thus far to speed up the process in the future?**

Measurement Process

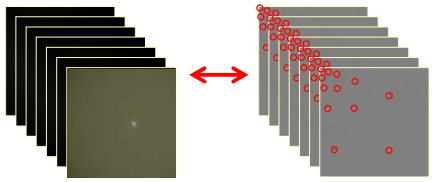


Wavelet Analysis of BRDFs

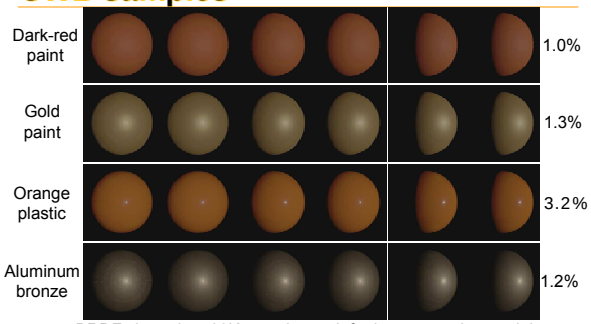
- Wavelets are a very compact representation for BRDFs
  - Schröder [95], Lalonde [97]
  - BRDFs exhibit high frequencies in very specific regions of their parameter space
  - Wavelets perform localized analysis of a larger signal

Wavelet Analysis of BRDFs

- For a given BRDF, most (+97%) of the information is in only a few wavelet coefficients
- Repeat for all BRDFs, and compute their union Common Wavelet Basis (CWB) = ~69,000 coefficients
- This gives 69K specific places to measure each BRDF



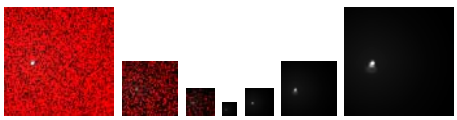
BRDFs Reconstructed from CWB samples



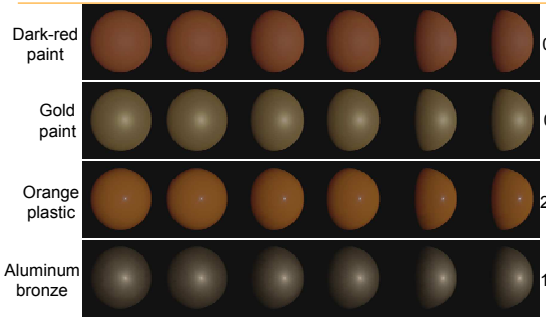
BRDFs based on 69K samples on left, dense samples on right

Pull-Push Reconstruction of BRDFs

- Alternatively, use Pull-Push to reconstruct (Gortler, et al. 96)
- Treat as scattered data interpolation problem



Push-Pull Reconstructions

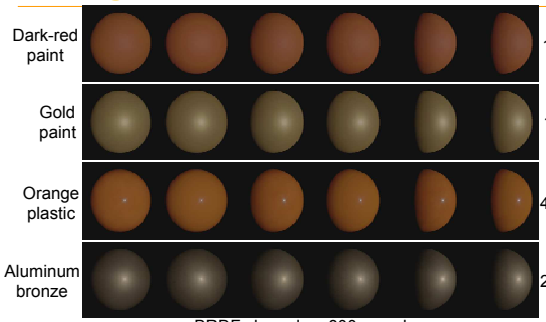


Linear Combinations of BRDFs (LCB)

- Can we find a linear combination of our existing BRDFs that match any new one?
- Requires only estimating 100 coefficients for source BRDFs
- Compute a set of 800 constraints that allow estimating these 100 coefficients robustly

α_1 + α_2 + α_3 + α_4 + ...=

Linear Combinations of BRDFs



BRDFs based on 800 samples

Sampling Methods Discussion

- CWB and Push-Pull
  - require 69,000 measurements
  - BRDF database not required
- Linear Combination of BRDFs
  - requires fewer measurements (800)
  - requires BRDF database

Outline

- Image-based BRDF measurement
- Efficient measurement
- Validation of analytic BRDF models
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BRDF Models

- Phenomenological
  - Phong [75]
    - Blinn-Phong [77]
  - Ward [92]
  - Lafortune et al. [97]
  - Ashikhmin et al. [00]
- Physical
  - Cook-Torrance [81]
  - He et al. [91]

Roughly increasing computation time

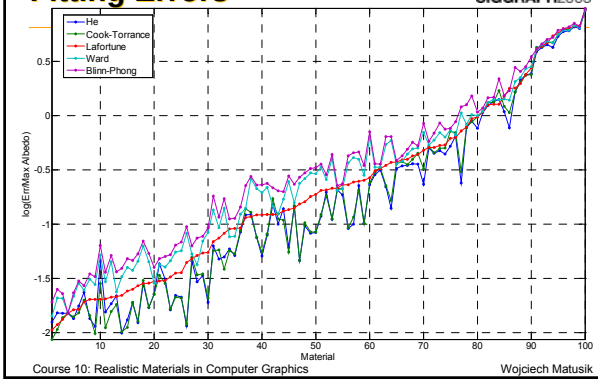
BRDF Fitting

- Target models: Blinn-Phong, Cook-Torrance, He et al., Lafortune et al. , Ward, Ashikhmin-Shirley
- Assumption
  - Lambertian diffuse
  - Model parameters color independent

BRDF Fitting

- Given model M, find optimal parameters **p** that best approximate the measurements
- Metric:
  - RMS of $(\rho_{measured} - M(\mathbf{p}))\ (\cos\theta_i)$ over non-empty bins in the tabulated data
  - Lafortune [97]:
    - $(\rho_{measured} - M(\mathbf{p}))\ (\cos\theta_i)\ (\cos\theta_o)$

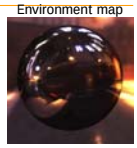
Fitting Errors



Dark blue paint

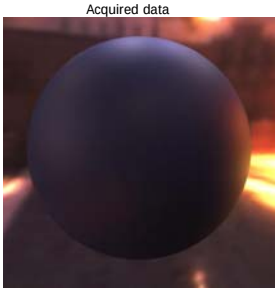
Acquired data

Environment map

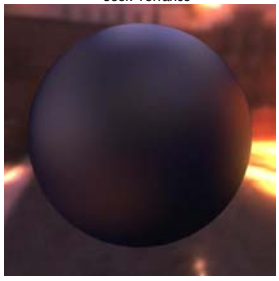


Dark blue paint

Acquired data

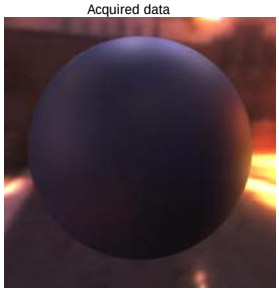


Cook-Torrance



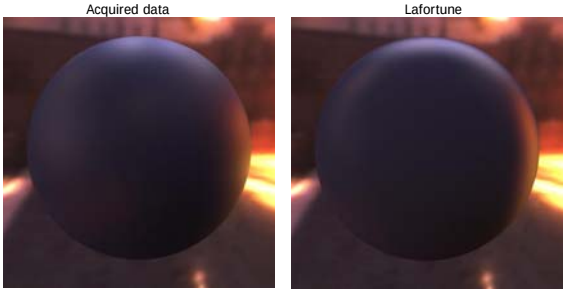
Dark blue paint

Acquired data

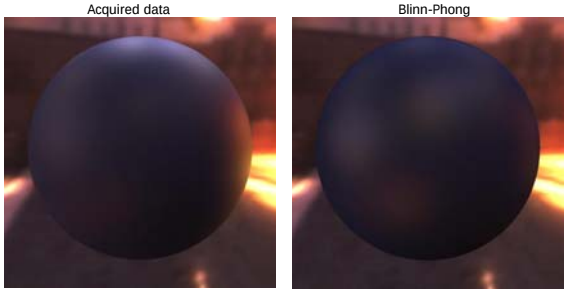


Ashikhmin

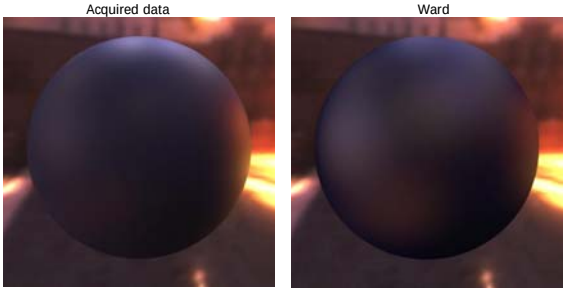
Dark blue paint



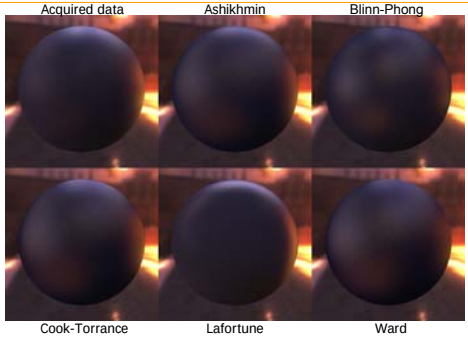
Dark blue paint



Dark blue paint

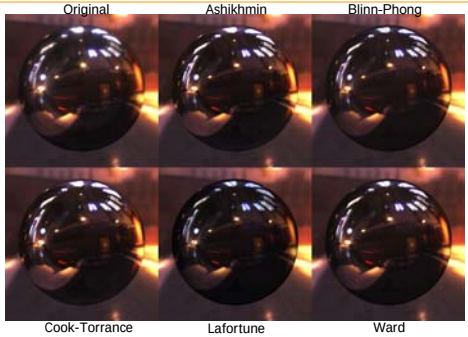


Dark blue paint



Chrome

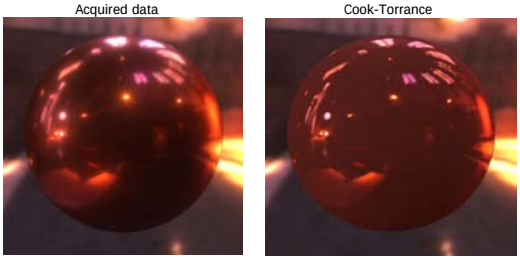
Chrome



Observations

- Some materials impossible to represent with a single lobe

Acquired data | Cook-Torrance

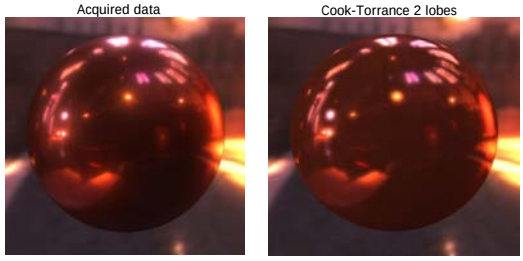


Material – Red Christmas Ball

Adding a second lobe

- Some materials impossible to represent with a single lobe

Acquired data | Cook-Torrance 2 lobes



Material – Red Christmas Ball

Observations

- Cook-Torrance, Ashikhmin
  - Consistently outperform the other models
- Lafortune
  - High discrepancy near grazing angle
  - Shape of lobe very different
- Ward, Blinn-Phong
  - unable to reproduce Fresnel effect

Outline

- Image-based BRDF measurement
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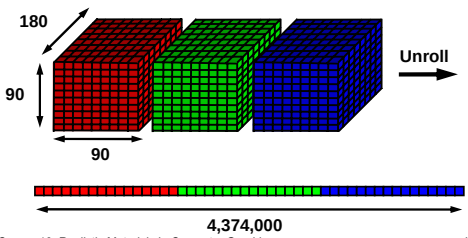
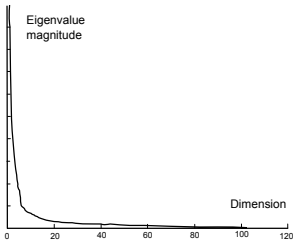
BRDFs as Vectors in High Dimensional Space

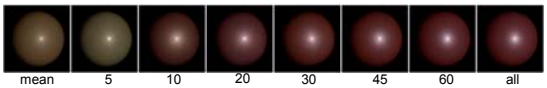
- Each tabulated BRDF is a vector in 90x90x180x3 =4,374,000 dimensional space



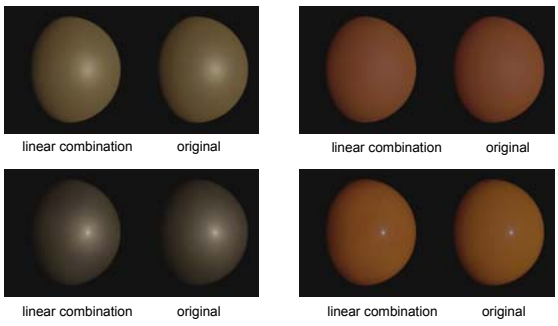
Linear Analysis (PCA)

- Find optimal linear basis for our data set
- 45 components needed to reduce residue to under measurement error





Cross-Validation of Linear Model

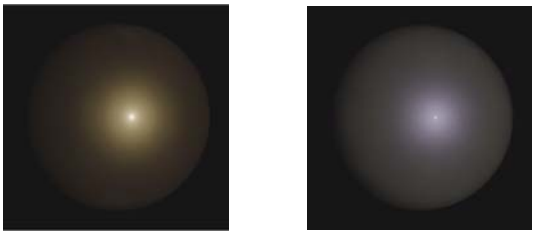


BRDF Modeling using Linear Subspace

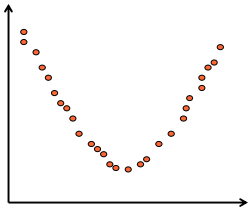
- Navigation in linear subspace
  - interpolation
  - extrapolation
- All results are linear combinations of the source BRDFs

Problems with Linear Subspace Modeling

- Large number of basis vectors (45)
- Some linear combinations yield invalid or unlikely BRDFs



Why does linear modeling fail?



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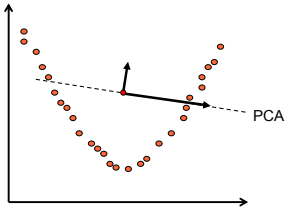
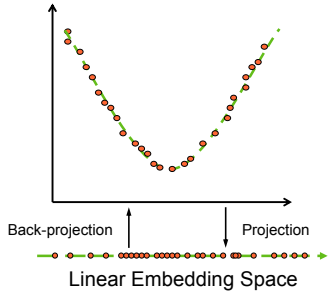
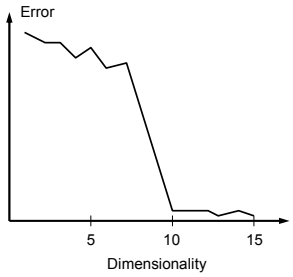


Non-Linear Manifold Learning



Results of Non-Linear Manifold Learning

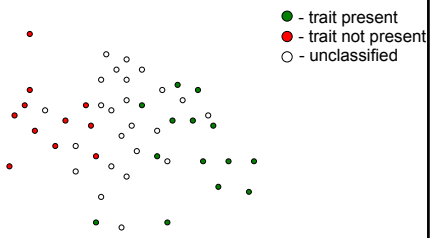
- Charting [Brand03]
- At 15 dimensions reconstruction error is less than 1%
- Parameter count similar to analytical models



Intuitive User Interface for our BRDF Model

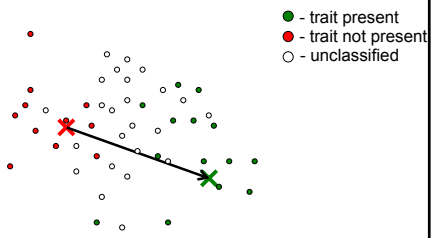
- User classification of BRDFs according to a set of predefined traits
  - e.g.: *red*, *specular*, *diffuse*, *metallic*, *plastic*, *rough*, *silver*, *fabric*, *acrylic*, *greasy*, *dusty*, …
- User starts from a source BRDF and applies trait vectors to create desired model

Trait Vector Determination



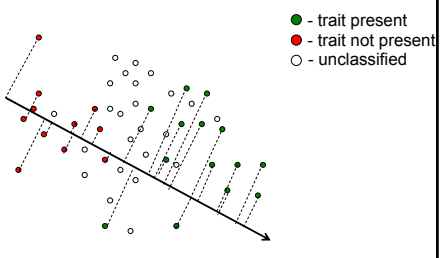
Trait Vector Determination

- **Mean difference**



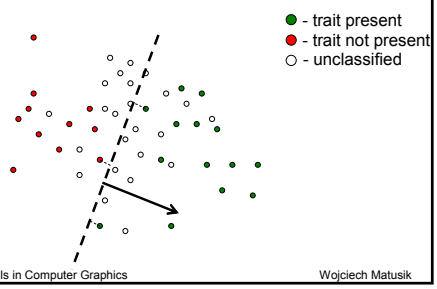
Trait Vector Determination

- **Fisher's linear discriminant**
  - Find the axis such that distribution projected onto it are the most separable



Trait Vector Determination

- **Support Vector Machines**
  - Find optimal partitioning hyperplane, and use its normal



Navigation Results

Adding Silver Trait

Navigation Results

Adding Specular Trait

Navigation Results

Adding Metallic Trait

Navigation Results

Adding Glossy Trait

Representing Physical Processes

Steel Oxidation

Outline

- Image-based BRDF measurement
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- Validation of analytic BRDF models
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Acknowledgements

- Matt Brand
- Fredo Durand
- Leonard McMillan
- Addy Ngan
- Hanspeter Pfister

Questions?