Experimental Validation of Analytical BRDF Models

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Goal

- Evaluate and analyze the performance of analytical reflectance models
BRDF

- Bidirectional Reflectance Distribution Function
BRDF

- Bidirectional Reflectance Distribution Function
  \[ R(\theta_i, \phi_i ; \theta_o, \phi_o) \]
BRDF

• Bidirectional Reflectance Distribution Function
  \[ R(\theta_i, \phi_i; \theta_o, \phi_o) \]

• Our study: isotropic material
  – Invariant when material is rotated
  – BRDF is 3D
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]
BRDF Models

- Phenomenological
  - Phong [75]
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- Physical
  - Cook-Torrance [81]
  - He et al. [91]

Roughly increasing computation time
Differences in BRDF Models

- Specular lobe definition
  - Mirror direction
  - Half vector
- Specular lobe falloff
  - $\cos^n$ (cosine lobe)
  - Gaussian
Differences in BRDF Models

- Specular lobe definition
  - Mirror direction
  - Half vector
- Specular lobe falloff
  - $\cos^n$ (cosine lobe)
  - Gaussian
- Fresnel effect
  - surface becomes more reflective near grazing angle

[Lafortune 97]
Available Measurements

- Columbia-Utrecht Reflectance and Texture Database –
  - ~60 materials, 205 measurements per BRDF
- Cornell’s measurements
  - ~10 materials, 1439 measurements per BRDF
- Matusik’s image-based measurements
  - ~100 materials, ~4 million measurements per BRDF
  - Include metals, plastic, paints, fabric, etc.
Matusik’s measurements

- Basis of our validation and analysis
- Part of the dataset is available on the web!
Validation Method

- **BRDF Models**
  - Phong, Blinn-Phong, Ward, Lafortune, Ashikhmin, Cook-Torrance

- **Data fitting**
  - Each material is fitted to each of the models
  - Minimize
    - \( L^2 \) error of the BRDF multiplied by the cosine of incident angle
Dark blue paint

Acquired data

Environment map

Material – Dark blue paint
Dark blue paint

Material – Dark blue paint
Dark blue paint

Material – Dark blue paint

Acquired data

Ashikhmin
Dark blue paint

Material – Dark blue paint
Dark blue paint

Acquired data

Blinn-Phong

Material – Dark blue paint
Dark blue paint

Acquired data

Ward

Material – Dark blue paint
Dark blue paint

Acquired data
Ashikhmin
Blinn-Phong

Cook-Torrance
Lafortune
Ward

Material – Dark blue paint
Chrome

Acquired data
Material – Chrome
Observations

- Some materials impossible to represent with a single lobe

Material – Red Christmas Ball

Acquired data

Cook-Torrance
Adding a second lobe

- Some materials impossible to represent with a single lobe

**Material – Red Christmas Ball**

- Acquired data
- Cook-Torrance 2 lobes
Fitting Errors

Cook-Torrance

log(Error)

Material (Sorted in the error of the Cook-Torrance model)
Fitting Errors

Ashikhmin

Material (Sorted in the error of the Ashikhmin model)
Fitting Errors

Ward

log(Error)

Material (Sorted in the error of the Ward model)
Fitting Errors

Blinn-Phong

log(Error)

Material (Sorted in the error of the Blinn-Phong model)


Fitting Errors

Material (Sorted in the error of the Lafortune model)
Dark blue paint

Acquired data

Material – Dark blue paint
Dark blue paint

- Cook-Torrance fit, incidence plane, 4 different incident angles
Material – Dark blue paint

Cook-Torrance

Fitted model
Data
Dark blue paint

Cook-Torrance

Blinn-Phong

Material – Dark blue paint
Dark blue paint

Cook-Torrance

Ward

Blinn-Phong

Material – Dark blue paint
Dark blue paint

Cook-Torrance

Blinn-Phong

Ward

Lafortune

Material – Dark blue paint
Dark blue paint

- Hemispherical plot for a fixed incoming angle
  - False color correspond to value of the BRDF

Acquired data
Dark blue paint

Acquired data

Cook-Torrance
Dark blue paint

Acquired data

Ashikhmin
Dark blue paint

Acquired data

Lafortune
Dark blue paint

Original

Cook-Torrance

Lafortune

Ashikhmin

Material – Dark blue paint
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
Analysis

• Lafortune model
  – Very popular
    • Simple, inexpensive to evaluate
    • Handle phenomena like off-specular reflection, retroreflection
    • importance sampling friendly
Analysis

• Lafortune model
  – High discrepancy near grazing angle

Acquired data – gold paint
Lafortune fit
Analysis

- Lafortune model
  - High discrepancy near grazing angle
Lobe definition

- Peak at mirror direction
Lobe definition

• Peak at mirror direction
  – Mirror-vector, View-vector
    • Phong, Lafortune*
Lobe definition

• Peak at mirror direction
  – Mirror-vector, View-vector
    • Phong, Lafortune*
  – Half-vector, Normal
    • All other models
Lobe definition

• In the incidence plane, the angle is different by a factor of 2.

• Outside the incidence plane, the relation is not as simple
Mirror lobe \((V,R)\)

- Red circle: set of directions \(V_i\) with constant angle from \(R\) (mirror vector)
Half vector lobe (H,N)

- Blue circle: set of half vectors $H_i$ with constant angle from N (normal)
Half vector lobe (H,N)

- Remapping half-vector $H_1$ to the corresponding outgoing direction $V_{H_1}$
Lobe Comparison

- Green contour: set of half-vectors remapped to outgoing directions

NOT A CIRCLE!
Lobe Comparison

- Shape of green contour is dependent on L
Lobe Comparison

- Full lobe

Half vector lobe

Mirror lobe
Dark blue paint

Original

Cook-Torrance

Lafortune

Ashikhmin

Material – Dark blue paint
Half vector lobe

- Consistent with what we observe in the dataset.

Example: Plot of “PVC” BRDF at 55° incidence
Microfacet theory

- [Torrance & Sparrow 1967]
  - Surface modeled by tiny perfect mirrors
  - Value of BRDF at (L, V)
    - # of mirrors oriented halfway between L and V
  - BRDF naturally represented by function of H

[Shirley 97]
Microfacet theory

• [Torrance & Sparrow 1967]
  – Surface modeled by tiny perfect mirrors
  – Value of BRDF at \((L,V)\)
    • \# of mirrors oriented halfway between \(L\) and \(V\)
  – BRDF naturally represented by function of \(H\)

• Shape of the mirror lobe cannot be explained with any microfacet distribution
Phong vs Blinn-Phong

- Blinn uses half vector lobe instead of mirror lobe in the original model [1977]
Phong vs Blinn-Phong

- Blinn uses half vector lobe instead of mirror lobe in the original model [1977]
- Lower numerical error in nearly all cases!
Conclusion

• Half vector lobe better than mirror lobe
• Fresnel effect is important
• Cook-Torrance and Ashikhmin models match real data quite well

Future Work

• Anisotropic materials
• Gain insight by grouping materials into classes
Questions?