Modeling Anisotropic Surface Reflectance with Example-Based Microfacet Synthesis

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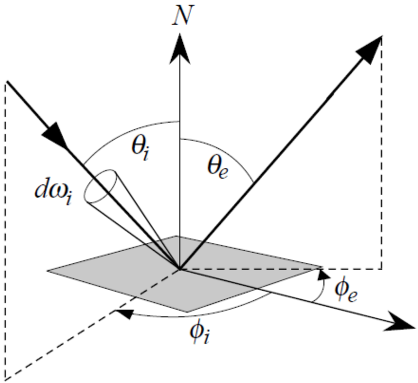
Motivation

- Quest for ultimate realism.
- Reflectance models based on real physical data.
- Capture reduces work of the artist.

To rephrase our desires in graphics

- We want it **simple**.
- We want it **realistic**.
- We want it **fast**.

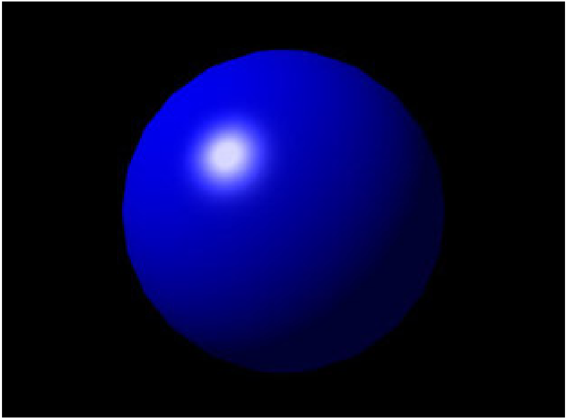
The BRDF



$$\rho(\mathbf{x},\mathbf{i},\mathbf{o}) = \frac{dL(\mathbf{x},\mathbf{o})}{dE(\mathbf{x},\mathbf{i})} = \frac{dL(\mathbf{x},\mathbf{o})}{L(\mathbf{x},\mathbf{i})\cos\theta_i d\mathbf{i}}$$

BRDF Models

Phong (1975): isotropic specular



$$\rho(\mathbf{i}, \mathbf{o}) = k_s \frac{(\mathbf{o} \cdot \mathbf{r})^\alpha}{\mathbf{n} \cdot \mathbf{i}}$$

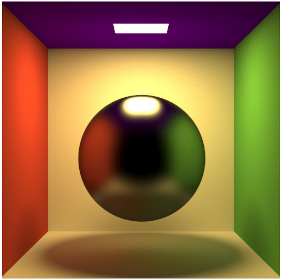
BRDF Models

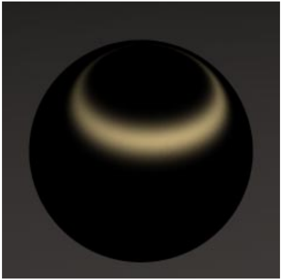
> Why is the oldest specular model, the one introduced by Phong in 1975 [Phong75], still the most widely used to this day? This model is neither theoretically plausible nor empirically correct. Any renderings that use the straight Phong model are most likely wrong because the model is not physical, and more light may be emitted than is received (for example). The sole virtue of the Phong model is its mathematical simplicity.

Measuring and modeling anisotropic reflection, Ward, 1992

BRDF Models

Ward (1992): anisotropic specular

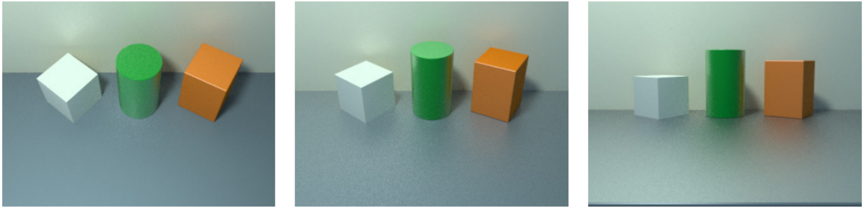




$$\rho(\mathbf{i}, \mathbf{o}) = \frac{k_s}{4\pi\alpha_x\alpha_y\sqrt{\cos\theta_i \cos\theta_o}} e^{-\tan^2\theta_h\left(\frac{\cos^2\phi_h}{\alpha_x^2} + \frac{\sin^2\phi_h}{\alpha_y^2}\right)}$$

BRDF Models

Lafortune (1997): anisotropic specular



$$\rho(\mathbf{i}, \mathbf{o}) = k_s \left(C_x \mathbf{i}_x \mathbf{o}_x + C_y \mathbf{i}_y \mathbf{o}_y + C_z \mathbf{i}_z \mathbf{o}_z \right)^n$$

BRDF Models

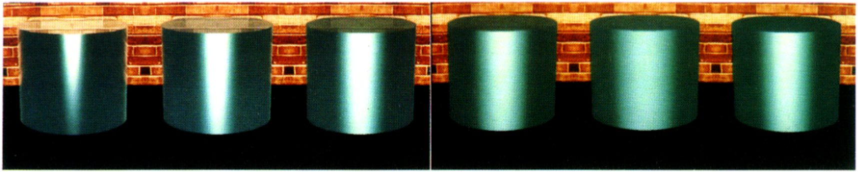
Microfacet: general anisotropic

Cook & Torrance (1982), Ashikhmin and Shirley (2000):

$$\rho_s(\mathbf{x}, \mathbf{i}, s\mathbf{o}) = k_s \frac{D(\mathbf{h})S(\mathbf{i})S(\mathbf{o})F(\mathbf{i}, \mathbf{o})}{4(\mathbf{i} \cdot \mathbf{n})(\mathbf{o} \cdot \mathbf{n})}$$

BRDF Models

He et al (1991): general anisotropic



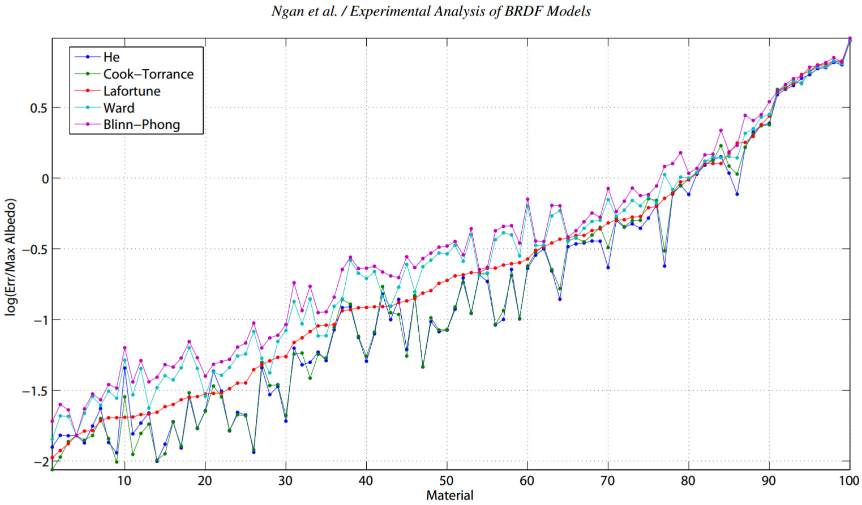
(a) $\sigma_0 = 0.18$ (b) $\sigma_0 = 0.28$ (c) $\sigma_0 = 0.38$ (d) $\sigma_0 = 0.48$ (e) $\sigma_0 = 0.58$ (f) $\sigma_0 = 2.50$

$$\rho_{bd,sp} = \frac{\rho_s}{\cos\theta_i d\omega_i} \cdot \Delta = \frac{|F|^2 \cdot e^{-g} \cdot S}{\cos\theta_i d\omega_i} \cdot \Delta \quad (6)$$

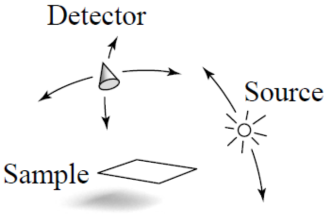
$$\rho_{bd,dd} = \frac{\mathcal{F}(\hat{n}_b, \hat{n}_b, \mathbf{p}) \cdot S}{\cos\theta_i \cdot \cos\theta_r} \cdot \frac{\tau^2}{16\pi} \cdot \sum_{m=1}^{\infty} \frac{g^m e^{-g}}{m! \cdot m} \cdot \exp\left(-\frac{v_{xy}^2 \tau^2}{4m}\right) \quad (7)$$

$$\rho_{bd,ud} = a(\lambda) \quad (8)$$

BRDF Models: Comparison (2005)

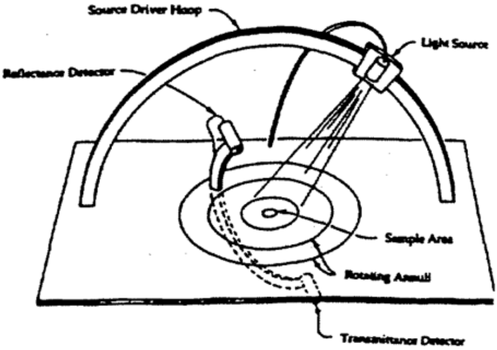


A (sparse) sample of BRDF capture technologies: 1992



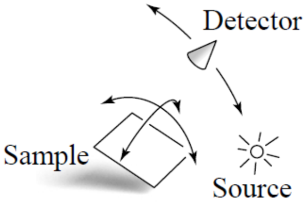
Flat object; photodetector and light source moveable.
Ward, 1992.

A (sparse) sample of BRDF capture technologies: 1992



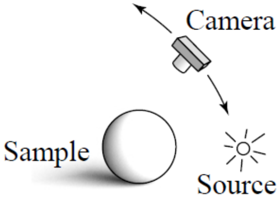
Gonioreflectometer.

A (sparse) sample of BRDF capture technologies



Flat object; object rotatable, photodetector moveable.

A (sparse) sample of BRDF capture technologies: 1999

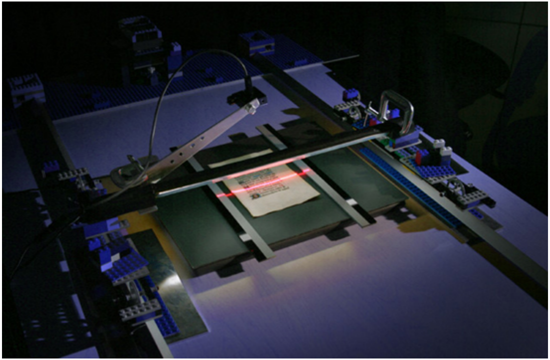


Curved object; camera moveable.
Marschner et al., 1999.

A (sparse) sample of BRDF capture technologies: 2003

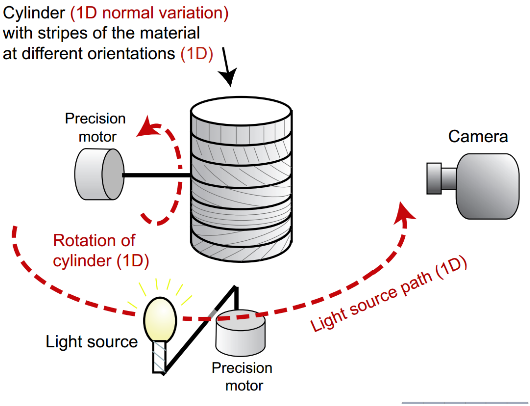
Image-based reconstruction of spatial appearance and geometric detail.
Lensch et al, 2003.

A (sparse) sample of BRDF capture technologies: 2003



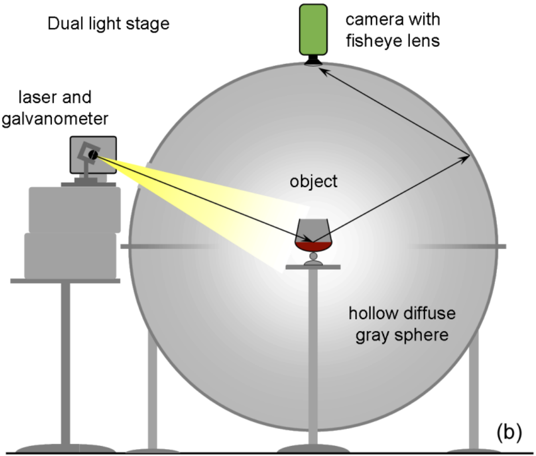
Linear light source reflectometry.
Gardner et al, 2003.

A (sparse) sample of BRDF capture technologies: 2005



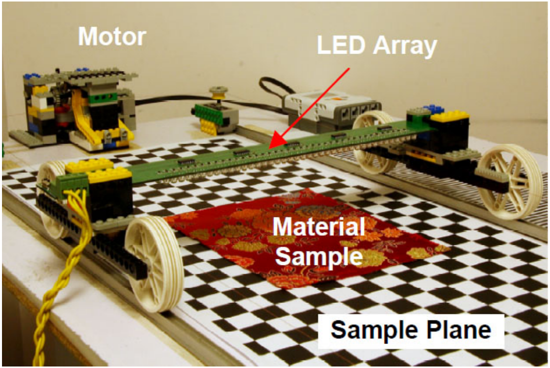
Ngan et al, 2005.

A (sparse) sample of BRDF capture technologies: 2005



Hawkins et al, 2005.

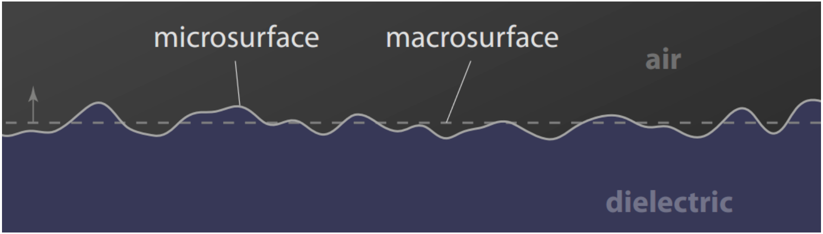
A (sparse) sample of BRDF capture technologies: 2008



Wang et al, 2008.

A review of the microfacet model

- Assume surface is composed of many small, flat micro mirrors (facets).
- Each surface reflects light according to its microfacet normal (**h**).
- A microfacet's contribution only counts if it is visible to both **i** and **o**.



Microfacet BRDF

- The BRDF for the microfacet model is:

$$\rho(\mathbf{x}, \mathbf{i}, \mathbf{o}) = \underbrace{\rho_d(\mathbf{x}, \mathbf{i}, \mathbf{o})}_{\text{diffuse}} + \underbrace{k_s(\mathbf{x})\rho_s(\mathbf{x}, \mathbf{i}, \mathbf{o})}_{\text{specular}}$$

- Diffuse term $\rho_d(\mathbf{x}, \mathbf{i}, \mathbf{o})$: constant and accounts for light that bounces multiple times
- Specular term $\rho_s(\mathbf{x}, \mathbf{i}, \mathbf{o})$: view-dependent

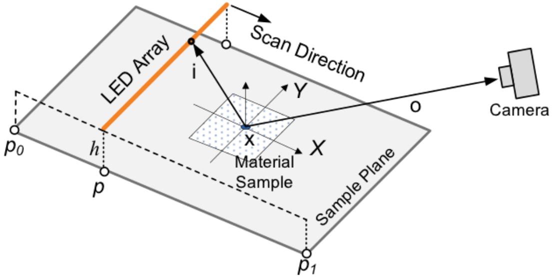
Microfacet specular term

- The specular includes anisotropy:

$$\rho_s(\mathbf{x}, \mathbf{i}, \mathbf{o}) = \frac{1}{4(\mathbf{i} \cdot \mathbf{n})(\mathbf{o} \cdot \mathbf{n})} \underbrace{D(\mathbf{x}, \mathbf{h})}_{\text{NDF}} \underbrace{G(\mathbf{x}, \mathbf{o}, \mathbf{i})}_{\text{shadow term}} \underbrace{F(\mathbf{x}, \mathbf{o}, \mathbf{i})}_{\text{Fresnel term}}$$

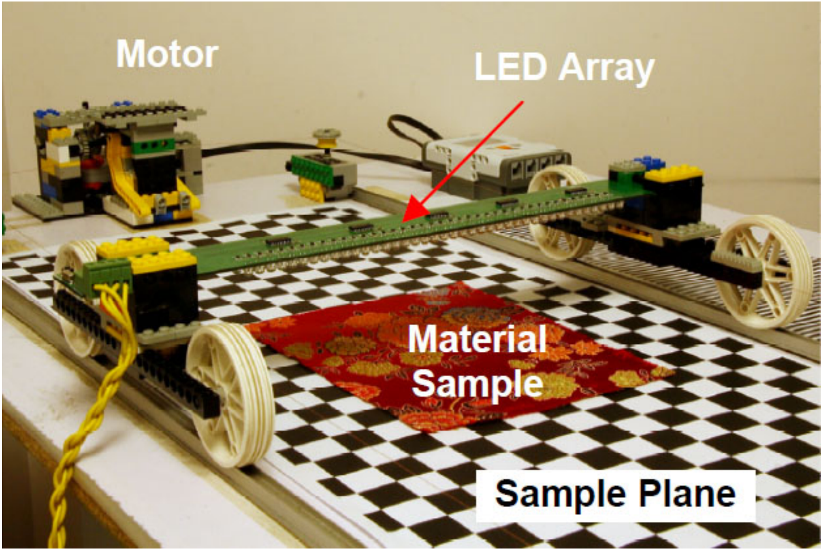
- D: distribution of the microsurface normals ("NDF")
- G: Smith shadowing term, which describes the visibility of the microsurface normal.
- F: Fresnel term, which describes reflection from each specular microsurface.

Experimental setup

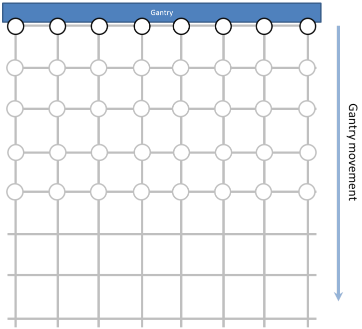


- Linear light source is placed on a gantry, about 4cm above the sample.
- Idea: we know the position of the gantry and the camera, so we can get **i** and **o**.
- Move the light source to vary **i**, then sample the intensity at each point on the material.

Experimental setup

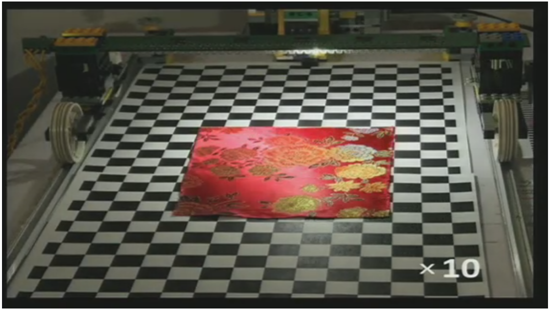


More specifically...



- Linear light source is an array of 40 point LED light sources.
- Switch on the LEDs one by one and sample the material.
  - **This ensures that the luminaire is a point source.**
- Move the gantry in each step and repeat, to create a grid of point lights over the entire sample.

Data capture



- At the end of the run, each point on the material has been lit by LEDs from many angles (**i**).
- These are the raw image data samples $I_q(\mathbf{x})$.

Pre-processing

Our experimental setup directly provides us with the BRDF:

$$\rho(\mathbf{x}, \mathbf{i}, \mathbf{o}) = \frac{dL(\mathbf{x}, \mathbf{o})}{dE(\mathbf{x}, \mathbf{i})}$$

Pre-processing

Our experimental setup directly provides us with the BRDF:

$$\rho(\mathbf{x}, \mathbf{i}, \mathbf{o}) = \frac{dL(\mathbf{x}, \mathbf{o})}{dE(\mathbf{x}, \mathbf{i})}$$
$$= \frac{dL(\mathbf{x}, \mathbf{o})}{(\mathbf{n} \cdot \mathbf{i}_q(\mathbf{x}))\, L(\mathbf{x}, \mathbf{i}) d\mathbf{i}}$$

Pre-processing

Our experimental setup directly provides us with the BRDF:

$$\rho(\mathbf{x}, \mathbf{i}, \mathbf{o}) = \frac{dL(\mathbf{x}, \mathbf{o})}{dE(\mathbf{x}, \mathbf{i})}$$
$$= \frac{dL(\mathbf{x}, \mathbf{o})}{(\mathbf{n} \cdot \mathbf{i}_q(\mathbf{x}))\, L(\mathbf{x}, \mathbf{i}) d\mathbf{i}}$$
$$= \frac{I_q(\mathbf{x})}{(\mathbf{n} \cdot \mathbf{i}_q(\mathbf{x}))\, L_q ||P_q - \mathbf{x}||^2}$$

Approximate the LED as a point source

Pre-processing

Our experimental setup directly provides us with the BRDF:

$$\begin{aligned}\rho(\mathbf{x}, \mathbf{i}, \mathbf{o}) &= \frac{dL(\mathbf{x}, \mathbf{o})}{dE(\mathbf{x}, \mathbf{i})} \\ &= \frac{dL(\mathbf{x}, \mathbf{o})}{(\mathbf{n} \cdot \mathbf{i}_q(\mathbf{x}))\, L(\mathbf{x}, \mathbf{i}) d\mathbf{i}} \\ &= \frac{I_q(\mathbf{x})}{(\mathbf{n} \cdot \mathbf{i}_q(\mathbf{x}))\, L_q ||P_q - \mathbf{x}||^2}\end{aligned}$$

We could tabulate $\rho(\mathbf{x}, \mathbf{i}, \mathbf{o})$ at this point

Pre-processing

Our experimental setup directly provides us with the BRDF:

$$\rho(\mathbf{x}, \mathbf{i}, \mathbf{o}) = \frac{dL(\mathbf{x}, \mathbf{o})}{dE(\mathbf{x}, \mathbf{i})}$$

$$= \frac{dL(\mathbf{x}, \mathbf{o})}{(\mathbf{n} \cdot \mathbf{i}_q(\mathbf{x}))\, L(\mathbf{x}, \mathbf{i}) d\mathbf{i}}$$

$$= \frac{I_q(\mathbf{x})}{(\mathbf{n} \cdot \mathbf{i}_q(\mathbf{x}))\, L_q ||P_q - \mathbf{x}||^2}$$

We could tabulate $\rho(\mathbf{x}, \mathbf{i}, \mathbf{o})$ at this point

- Large storage requirements
- Difficult to edit
- Gaps in the $(\mathbf{i}, \mathbf{o})$ domain

Pre-processing

Dichromatic BRDF model

$$\rho(\mathbf{x},\mathbf{i},\mathbf{o}) = \underbrace{\rho_d(\mathbf{x},\mathbf{i},\mathbf{o})}_{\text{diffuse}} + \underbrace{k_s(\mathbf{x})\rho_s(\mathbf{x},\mathbf{i},\mathbf{o})}_{\text{specular}}$$

Pre-processing

Dichromatic BRDF model

$$\rho(\mathbf{x},\mathbf{i},\mathbf{o}) = \underbrace{\rho_d(\mathbf{x},\mathbf{i},\mathbf{o})}_{\text{diffuse}} + \underbrace{k_s(\mathbf{x})\rho_s(\mathbf{x},\mathbf{i},\mathbf{o})}_{\text{specular}}$$

Assumption: There is some $(\mathbf{i},\mathbf{o})$ for which $\rho_s(\mathbf{x},\mathbf{i},\mathbf{o}) \approx 0$

$$\implies \rho_d(\mathbf{x}) = \min_q \; \rho(\mathbf{x},\mathbf{i}_q,\mathbf{o})$$

$$= \min_q \; \frac{I_q(\mathbf{x})}{(\mathbf{n}\cdot\mathbf{i}_q(\mathbf{x}))\, L_q ||P_q - \mathbf{x}||^2}$$

Pre-processing

- Subtracting away the diffuse component leaves the specular component:

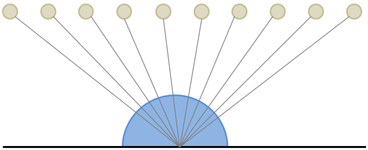
$$\rho_s(\mathbf{x}, \mathbf{i}_q(\mathbf{x}), \mathbf{o}) = \underbrace{\rho(\mathbf{x}, \mathbf{i}_q(\mathbf{x}), \mathbf{o})}_{\text{raw data}} - \rho_d(\mathbf{x})$$

Pre-processing

- Subtracting away the diffuse component leaves the specular component:

$$\rho_s(\mathbf{x}, \mathbf{i}_q(\mathbf{x}), \mathbf{o}) = \underbrace{\rho(\mathbf{x}, \mathbf{i}_q(\mathbf{x}), \mathbf{o})}_{\text{raw data}} - \rho_d(\mathbf{x})$$

- But there's another problem:



- Use push-pull (Gortler, 1996) to interpolate measurements.

Analysis of the data

Microfacet Model

$$\rho_s(\mathbf{x}, \mathbf{i}, \mathbf{o}) = k_s(\mathbf{x}) \frac{D(\mathbf{x}, \mathbf{h}) S(\mathbf{x}, \mathbf{i}) S(\mathbf{x}, \mathbf{o}) F(\mathbf{x}, \mathbf{i}, \mathbf{o})}{4(\mathbf{i} \cdot \mathbf{n})(\mathbf{o} \cdot \mathbf{n})}$$

Analysis of the data

Microfacet Model

$$\rho_s(\mathbf{x}, \mathbf{i}, \mathbf{o}) = k_s(\mathbf{x}) \frac{D(\mathbf{x}, \mathbf{h}) S(\mathbf{x}, \mathbf{i}) S(\mathbf{x}, \mathbf{o}) F(\mathbf{x}, \mathbf{i}, \mathbf{o})}{4(\mathbf{i} \cdot \mathbf{n})(\mathbf{o} \cdot \mathbf{n})}$$

We know S in terms of D from [Ashikmin et al 2000]:

$$S(\mathbf{x}, \mathbf{k}) = \frac{(\mathbf{k} \cdot \mathbf{n})}{\int (\mathbf{h} \cdot \mathbf{k}) D(\mathbf{x}, \mathbf{h}) d\omega}$$

Analysis of the data

Microfacet Model

$$\rho_s(\mathbf{x},\mathbf{i},\mathbf{o}) = k_s(\mathbf{x})\frac{D(\mathbf{x},\mathbf{h})S(\mathbf{x},\mathbf{i})S(\mathbf{x},\mathbf{o})F(\mathbf{x},\mathbf{i},\mathbf{o})}{4(\mathbf{i}\cdot\mathbf{n})(\mathbf{o}\cdot\mathbf{n})}$$

We know S in terms of D from [Ashikmin et al 2000]:

$$S(\mathbf{x},\mathbf{k}) = \frac{(\mathbf{k}\cdot\mathbf{n})}{\int(\mathbf{h}\cdot\mathbf{k})D(\mathbf{x},\mathbf{h})d\omega}$$

We don't know D and F

Analysis of the data

Microfacet Model

$$\rho_s(\mathbf{x}, \mathbf{i}, \mathbf{o}) = k_s(\mathbf{x}) \frac{D(\mathbf{x}, \mathbf{h}) S(\mathbf{x}, \mathbf{i}) S(\mathbf{x}, \mathbf{o}) F(\mathbf{x}, \mathbf{i}, \mathbf{o})}{4(\mathbf{i} \cdot \mathbf{n})(\mathbf{o} \cdot \mathbf{n})}$$

Since F and S are smooth, assume $F(\mathbf{x}, \mathbf{i}, \mathbf{o}) = 1$, $S(\mathbf{x}, \mathbf{k}) = 1$, and $k_s = \frac{1}{\pi}$

Analysis of the data

Microfacet Model

$$\rho_s(\mathbf{x}, \mathbf{i}, \mathbf{o}) = k_s(\mathbf{x}) \frac{D(\mathbf{x}, \mathbf{h}) S(\mathbf{x}, \mathbf{i}) S(\mathbf{x}, \mathbf{o}) F(\mathbf{x}, \mathbf{i}, \mathbf{o})}{4(\mathbf{i} \cdot \mathbf{n})(\mathbf{o} \cdot \mathbf{n})}$$

Since F and S are smooth, assume $F(\mathbf{x}, \mathbf{i}, \mathbf{o}) = 1$, $S(\mathbf{x}, \mathbf{k}) = 1$, and $k_s = \frac{1}{\pi}$

Now we can solve for D:

$$D(\mathbf{x}, \mathbf{h}) = \begin{cases} \frac{4\pi \rho_s(\mathbf{x}, \mathbf{o}, \mathbf{i}(\mathbf{h}))(\mathbf{i}(\mathbf{h}) \cdot \mathbf{n})(\mathbf{o} \cdot \mathbf{n})}{S(\mathbf{x}, \mathbf{i}(\mathbf{h})) S(\mathbf{x}, \mathbf{o})} & \mathbf{h} \in \Omega \\ 0 & \mathbf{h} \notin \Omega \end{cases}$$

Analysis of the data

Microfacet Model

$$\rho_s(\mathbf{x},\mathbf{i},\mathbf{o}) = k_s(\mathbf{x})\frac{D(\mathbf{x},\mathbf{h})S(\mathbf{x},\mathbf{i})S(\mathbf{x},\mathbf{o})F(\mathbf{x},\mathbf{i},\mathbf{o})}{4(\mathbf{i}\cdot\mathbf{n})(\mathbf{o}\cdot\mathbf{n})}$$

Since F and S are smooth, assume $F(\mathbf{x},\mathbf{i},\mathbf{o}) = 1$, $S(\mathbf{x},\mathbf{k}) = 1$, and $k_s = \frac{1}{\pi}$

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which gives us a new estimate of S:

$$S(\mathbf{x},\mathbf{k}) = \frac{(\mathbf{k}\cdot\mathbf{n})}{\int(\mathbf{h}\cdot\mathbf{k})D(\mathbf{x},\mathbf{h})d\omega}$$

Analysis of the data

Microfacet Model

$$\rho_s(\mathbf{x},\mathbf{i},\mathbf{o}) = k_s(\mathbf{x})\frac{D(\mathbf{x},\mathbf{h})S(\mathbf{x},\mathbf{i})S(\mathbf{x},\mathbf{o})F(\mathbf{x},\mathbf{i},\mathbf{o})}{4(\mathbf{i}\cdot\mathbf{n})(\mathbf{o}\cdot\mathbf{n})}$$

Since F and S are smooth, assume $F(\mathbf{x},\mathbf{i},\mathbf{o}) = 1$, $S(\mathbf{x},\mathbf{k}) = 1$, and $k_s = \frac{1}{\pi}$

Now we can solve for D:

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which gives us a new estimate of S:

$$S(\mathbf{x},\mathbf{k}) = \frac{(\mathbf{k}\cdot\mathbf{n})}{\int(\mathbf{h}\cdot\mathbf{k})D(\mathbf{x},\mathbf{h})d\omega}$$

repeat!

Analysis of the data

Microfacet Model

$$\rho_s(\mathbf{x}, \mathbf{i}, \mathbf{o}) = k_s(\mathbf{x}) \frac{D(\mathbf{x}, \mathbf{h}) S(\mathbf{x}, \mathbf{i}) S(\mathbf{x}, \mathbf{o}) F(\mathbf{x}, \mathbf{i}, \mathbf{o})}{4(\mathbf{i} \cdot \mathbf{n})(\mathbf{o} \cdot \mathbf{n})}$$

The specular coefficient $k_s(\mathbf{x})$ **is**:

$$k_s(\mathbf{x}) = \int (\mathbf{n} \cdot \mathbf{h}) D(\mathbf{x}, \mathbf{h}) d\omega$$

which lets us normalize D:

$$D(\mathbf{x}, \mathbf{h}) \leftarrow \frac{D(\mathbf{x}, \mathbf{h})}{k_s}$$

Analysis of the data

Microfacet Model

$$\rho_s(\mathbf{x}, \mathbf{i}, \mathbf{o}) = k_s(\mathbf{x}) \frac{D(\mathbf{x}, \mathbf{h}) S(\mathbf{x}, \mathbf{i}) S(\mathbf{x}, \mathbf{o}) F(\mathbf{x}, \mathbf{i}, \mathbf{o})}{4(\mathbf{i} \cdot \mathbf{n})(\mathbf{o} \cdot \mathbf{n})}$$

The only remaining piece is F

Analysis of the data

Microfacet Model

$$\rho_s(\mathbf{x}, \mathbf{i}, \mathbf{o}) = k_s(\mathbf{x}) \frac{D(\mathbf{x}, \mathbf{h}) S(\mathbf{x}, \mathbf{i}) S(\mathbf{x}, \mathbf{o}) F(\mathbf{x}, \mathbf{i}, \mathbf{o})}{4(\mathbf{i} \cdot \mathbf{n})(\mathbf{o} \cdot \mathbf{n})}$$

The only remaining piece is F

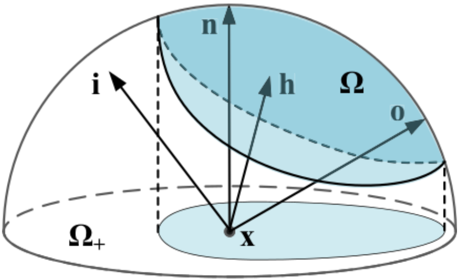
$$F_m(\mathbf{x}, \mathbf{i}, \mathbf{o}) = \frac{4\pi \rho_s(\mathbf{x}, \mathbf{o}, \mathbf{i})(\mathbf{i} \cdot \mathbf{n})(\mathbf{o} \cdot \mathbf{n})}{S(\mathbf{x}, \mathbf{i}) S(\mathbf{x}, \mathbf{o}) k_s(\mathbf{x}) D(\mathbf{x}, \mathbf{h})}$$

Use F_m to find the closest η, then use the standard form for F

Problem

Problem

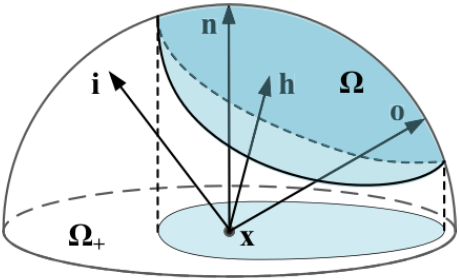
We only have $D(\mathbf{x}, \mathbf{h})$ for a subset of the hemisphere



Standard solution: rotate the sample and repeat the process

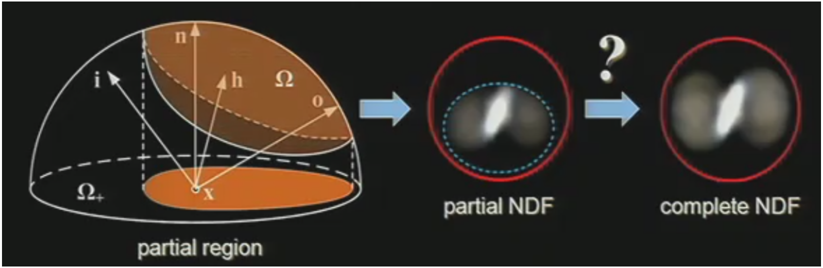
Problem

We only have $D(\mathbf{x}, \mathbf{h})$ for a subset of the hemisphere

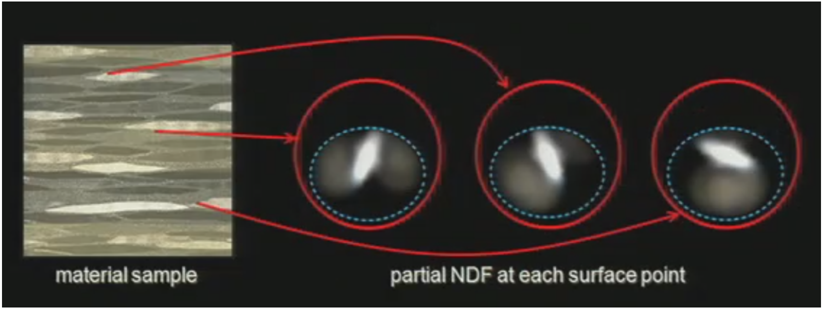


Standard solution: rotate the sample and repeat the process
This paper: use $D(\mathbf{x}, \mathbf{h})$ from other points

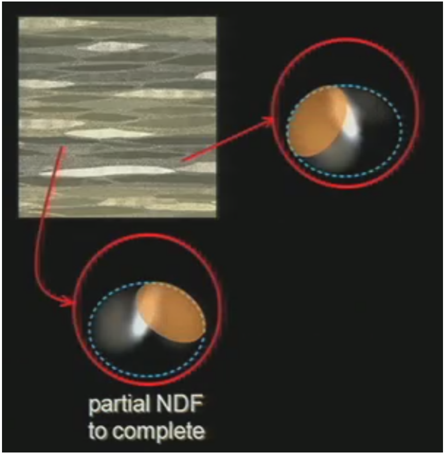
Analysis of the data



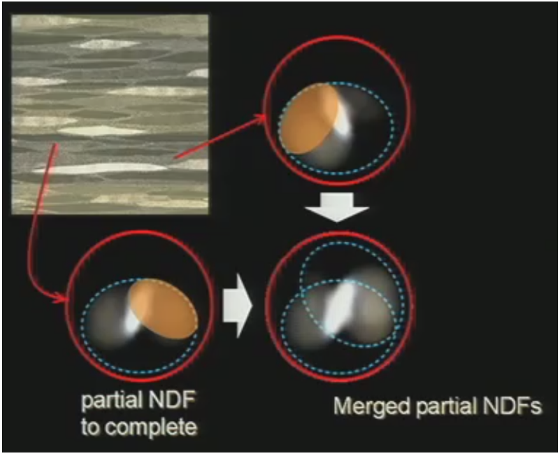
Analysis of the data



Analysis of the data



Analysis of the data



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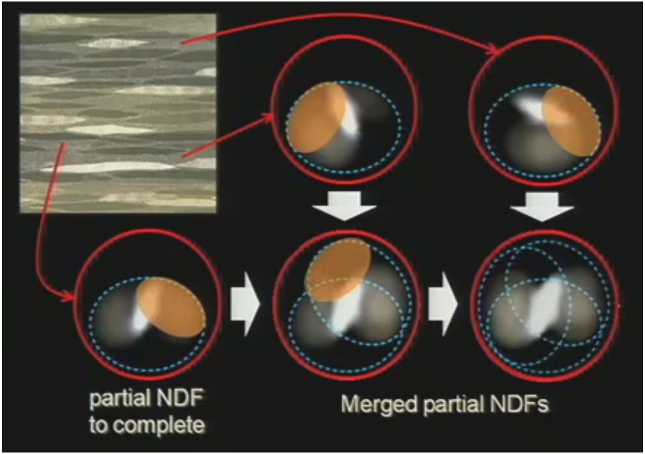

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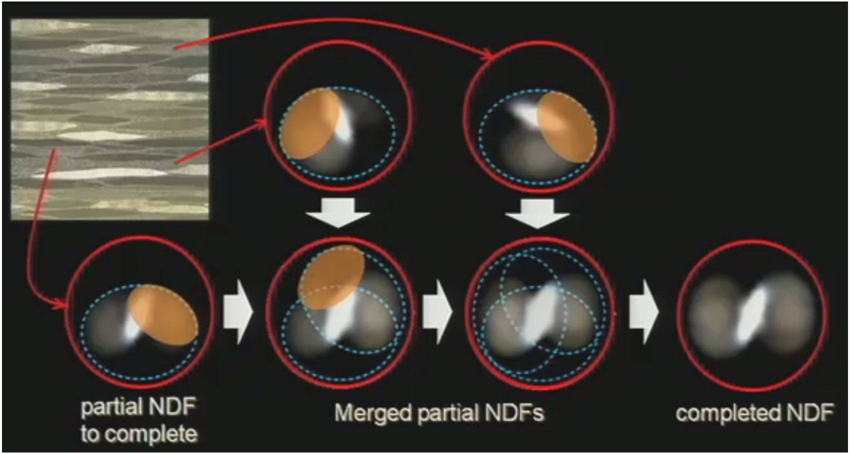

Speed Optimizations

Brute-force search is extremely slow

$$N = 640,000 \text{ surface points}$$
$$M = 1000 \text{ rotation angles}$$

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Brute-force search is extremely slow

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$$N^2 M \approx 5 \times 10^{11} \text{ rotation/compare operations}$$

Speed Optimizations

Optimizations

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1. NDF Clustering
   - *k*-means clustering: reduce search space by 100x
   - Reduce search time by $\sim 100^2$

Speed Optimizations

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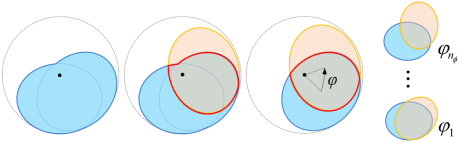
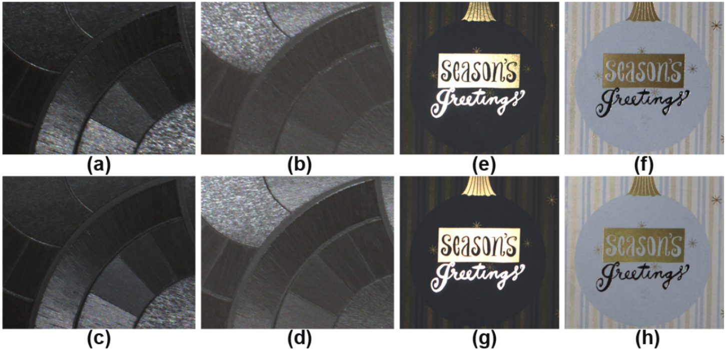
1. NDF Clustering
   - *k*-means clustering: reduce search space by 100x
   - Reduce search time by $\sim 100^2$
2. Search Pruning
   - Intersection approximation



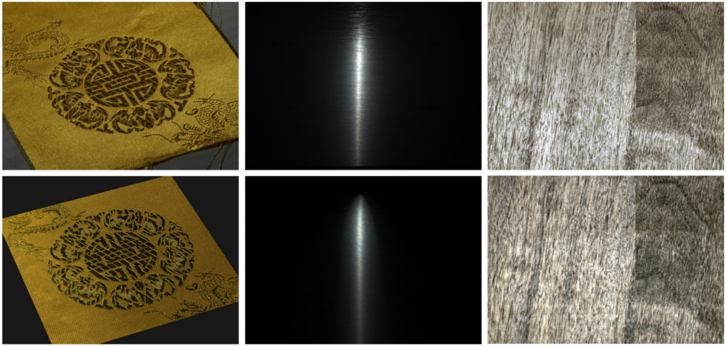
   - Approximate nearest neighbour (ANN) search after subsampling $D(\mathbf{x}, \mathbf{h})$ (from 3072 to 32)

Results



- Top row: original measurements.
- Bottom row: synthesis results.

Results



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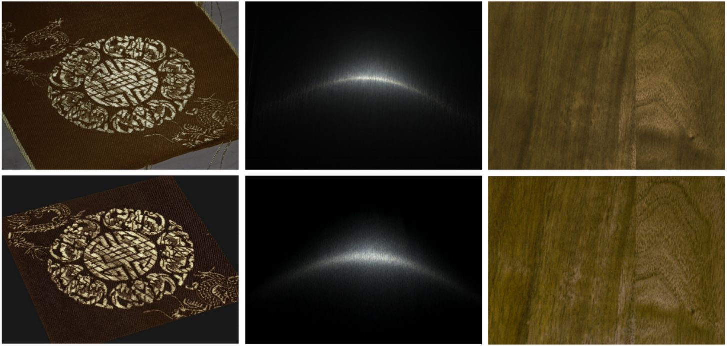
Results



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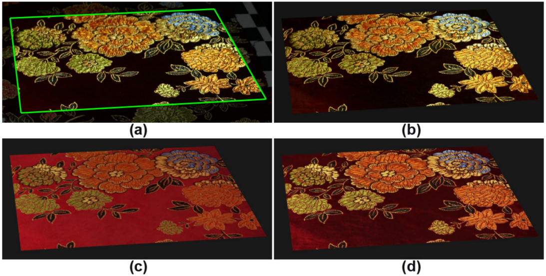
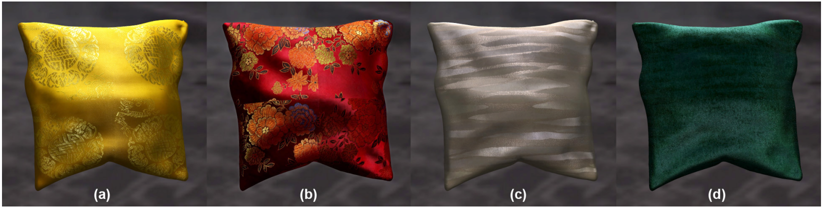
Results



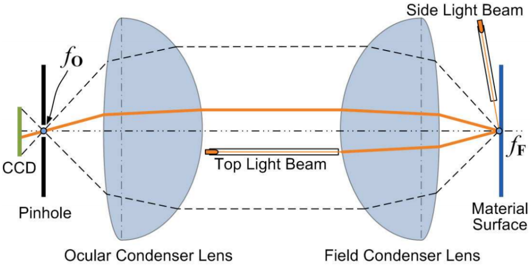
- (a) real appearance.
- (b) rendered using Microfacet synthesis method.
- (c) rendered using isotropic Ward.
- (d) rendered using anisotropic Ward.

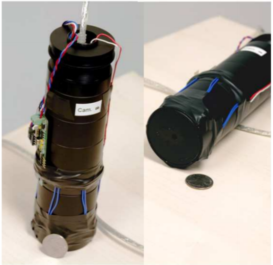
Results



Rendering: (a) yellow satin, (b) red satin, (c) wallpaper, (d) velvet

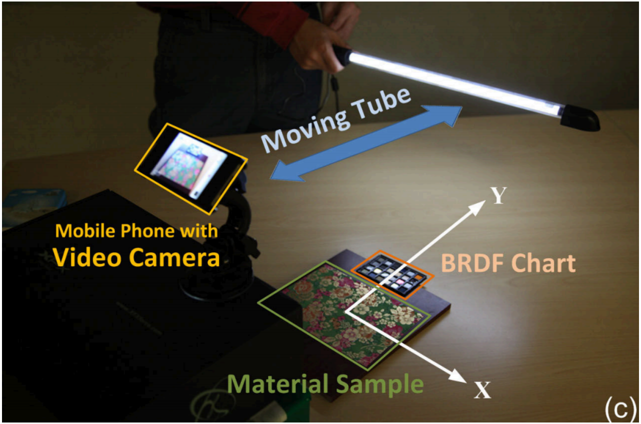
Subsequent devices: 2010





Dong et al, 2010.

Subsequent devices: 2011



Ren et al, 2011.

Questions?