Radiometry and Appearance Models

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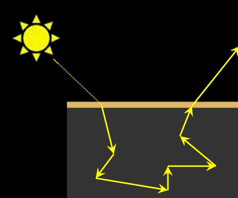
The Visual World

Rich variety of materials: characterized by surface reflectance, scattering

Understanding Reflectance

for each position:
  for each direction of incident light:
    for each reflected direction:
      how much light is reflected?

Understanding Scattering



for each incident position:
  for each exitant position:
    how much light is scattered?

Motivation

- Understanding appearance models aids in:
  - Photorealistic image synthesis
  - Image-based view and lighting interpolation
  - 3D reconstruction from images
  - Image interpretation
  - Understanding human material perception

Overview

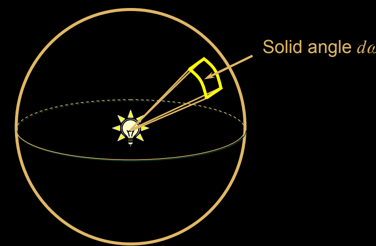
- Radiometry and Radiometric Units
- BRDF properties and common BRDFs
- Subsurface scattering
- Taxonomy of reflection and scattering functions

Radiometric Units

- Light is a form of energy - measured in Joules (J)
- Power: energy per unit time
  - Measured in Joules/sec = Watts (W)
  - Also called Radiant Flux (Φ)

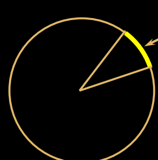
Point Light in a Direction

- Total radiant flux in Watts
- How to define angular dependence?
  - Solid angle

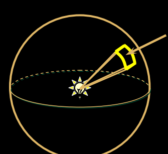


Digression – Solid Angle

- Angle in radians

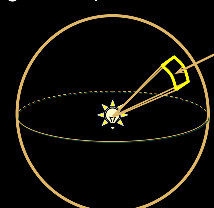


- Solid angle in steradians



Point Light in a Direction

- Total radiant flux in Watts
- How to define angular dependence?
  - Solid angle



- Radiant flux per unit solid angle
  - Measured in Watts per steradian (W/sr)

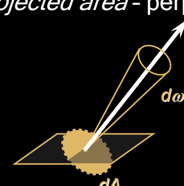
Light Falling on a Surface

- Power per unit area - Irradiance (E)
  - Measured in W/m^2
- Move surface away from light
  - Inverse square law: E ~ 1/r^2

- Tilt surface away from light
  - Cosine law: E ~ $\mathbf{n} \cdot \mathbf{l}$

Light Emitted from a Surface in a Direction

- Power per unit area per unit solid angle - Radiance (L)
  - Measured in W/m^2/sr
  - *Projected area* - perpendicular to given direction



$$L = \frac{d\Phi}{dA\, d\omega}$$

  - Cameras (and our eyes) “see” radiance

Surface Reflectance – BRDF

- Bidirectional Reflectance Distribution Function

$$f_r(\omega_i \to \omega_o) = \frac{dL_o(\omega_o)}{dE_i(\omega_i)}$$

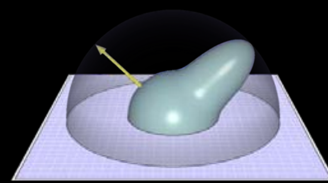
- 4-dimensional function: also written as

$$f_r(\theta_i, \phi_i, \theta_o, \phi_o) = \frac{dL_o(\omega_o)}{dE_i(\omega_i)}$$

F. E. Nicodemus, J. C. Richmond, J. J. Hsia, and I. W. Ginsberg,
Geometrical Considerations and Nomenclature for Reflectance,
Boulder CO: National Bureau of Standards, 1977.

BRDF

- Radiance/irradiance ratio
  - Directional exitant radiance distribution
  - For each direction of incident irradiance



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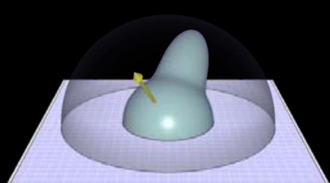

BRDF

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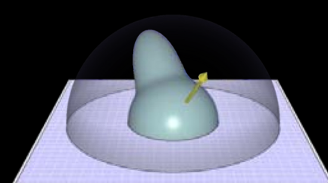


Properties of the BRDF

- Energy conservation:

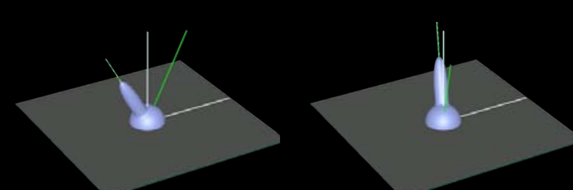
$$\int_\Omega f_r \cos\theta_o \, d\omega_o \le 1$$

- Helmholtz reciprocity:

$$f_r(\omega_i \to \omega_o) = f_r(\omega_o \to \omega_i)$$

Isotropy

- A BRDF is isotropic if it stays the same when surface is rotated around normal

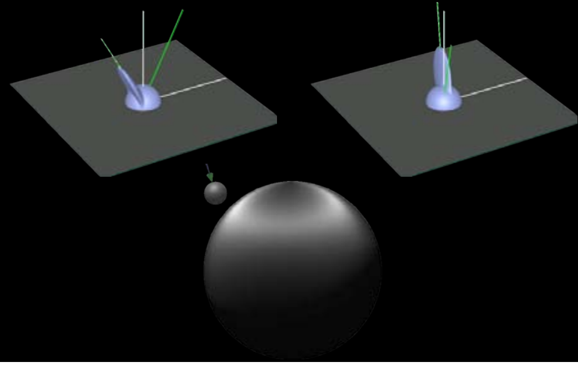


- Isotropic BRDFs are 3-dimesional functions:

$$f_r(\theta_i, \theta_o, \phi_i - \phi_o)$$

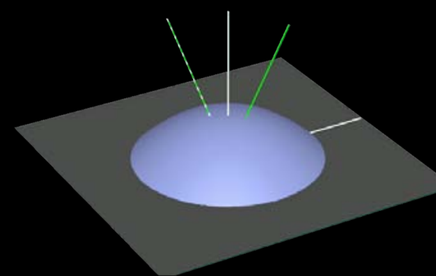
Anisotropy

- Anisotropic BRDFs do depend on surface rotation



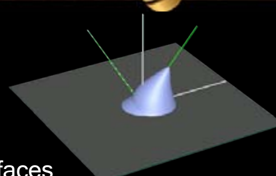
Other BRDF Features

- BRDFs for dusty surfaces scatter light towards grazing angles

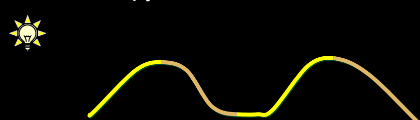


Other BRDF Features

- Retroreflection: strong reflection back towards the light source



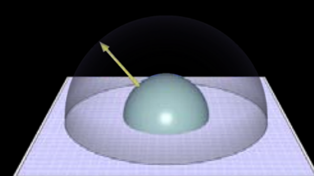
- Can arise from bumpy diffuse surfaces



- … or from corner reflectors

Lambertian BRDF

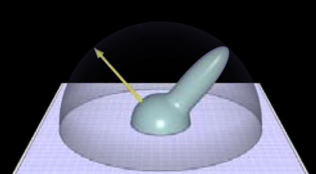
- Constant BRDF: ideal diffuse reflectance



$$f_r = const. = \frac{\rho}{\pi}$$

Blinn-Phong BRDF

- Simple BRDF describing specular reflection



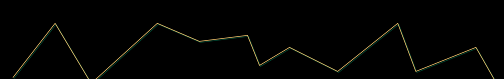
$$f_r = \frac{\rho}{\pi} + k_s (n \cdot h)^{\alpha}$$

Torrance-Sparrow BRDF

- Physically-based BRDF model
  - Originally used in the physics community

$$f_r = \frac{D\,G\,F}{\pi \cos\theta_i \cos\theta_o}$$

- Assume surface consists of tiny “microfacets” with mirror reflection off each

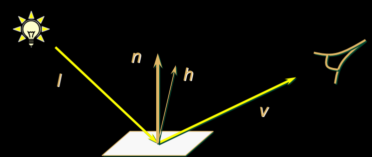


Torrance-Sparrow BRDF

- D term is distribution of microfacets (i.e., how many are pointing in each direction)
- Beckmann distribution

$$D = \frac{e^{-[(\tan\beta)/m]^2}}{4m^2\cos^4\beta}$$

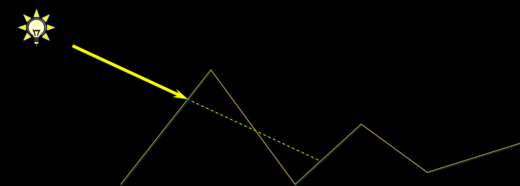
β is angle between n and h
h is halfway between l and v
m is "roughness" parameter



Torrance-Sparrow BRDF

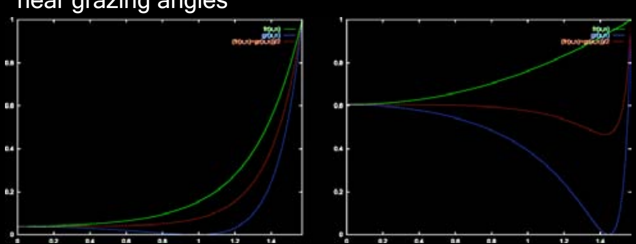
- G term accounts for self-shadowing

$$G = \min\left\{1, \frac{2(n\cdot h)(n\cdot v)}{(v\cdot h)}, \frac{2(n\cdot h)(n\cdot l)}{(v\cdot h)}\right\}$$



Torrance-Sparrow BRDF

- F is Fresnel term - reflection from an ideal smooth surface (solution of Maxwell's equations)
- Consequence: most surfaces reflect (much) more strongly near grazing angles



Dielectric

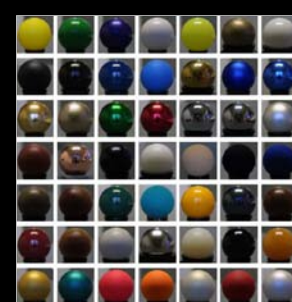
Metal
(note behavior at Brewster's angle)

Complex BRDF Models

Analytic

[COOK & TORRANCE 1982]

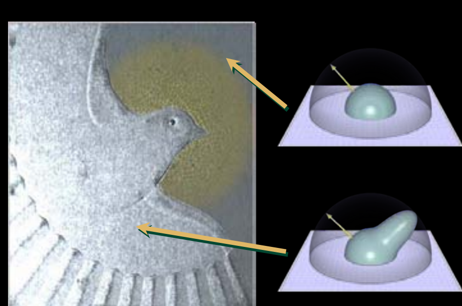
Measured



[MATUSIK ET AL. 2003]

The SVBRDF: 6D

Spatially-
Varying
Bi-Directional
Reflectance
Distribution
Function



Bidirectional Texture Functions

- For non-flat samples, datasets include effects due to occlusion, shadowing
  - Often called *Bidirectional Texture Functions* - BTFs

[DANA ET AL. 1999

Translucent Materials

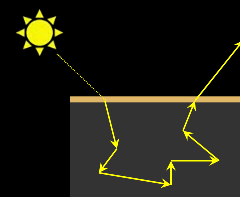
Surface reflection only

With subsurface scattering

[PEERS ET AL. 2006

Subsurface Scattering

- Translucency: light no longer leaves surface at point of incidence
  - Not a BRDF!



The BSSRDF

- The Bidirectional Scattering-Surface Reflection Distribution Function

$$S(x_i, y_i, \theta_i, \phi_i, x_o, y_o, \theta_o, \phi_o)$$

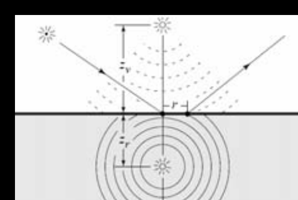
  - Generalization of spatially-varying BRDF

BSSRDF Simplification

- BSSRDF often dominated by multiple scattering
- Accurately modeled by diffusion approximation

$$S = F(\theta_i) R(\| x_i - x_o \|) F'(\theta_o)$$

  - Angular behavior described by Fresnel equations
  - Spatial behavior equivalent to a dipole



BSSRDF Dipole Model

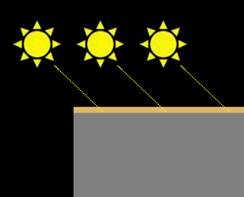
Surface reflection only

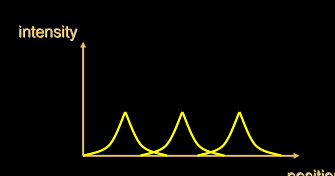
With subsurface scattering

[WANN JENSEN ET AL. 20

BSSRDF: Homogeneous

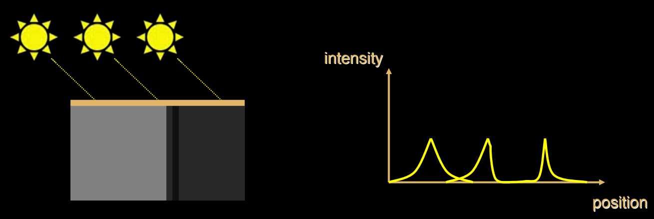
- Homogeneous: uniform material



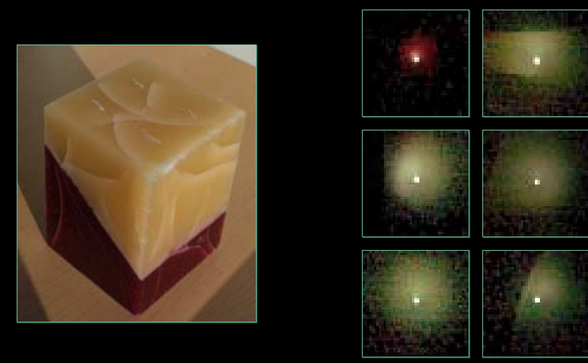


BSSRDF: Heterogeneous

- Homogeneous: uniform material
- Heterogeneous: spatially-varying materials



Heterogeneous Scattering

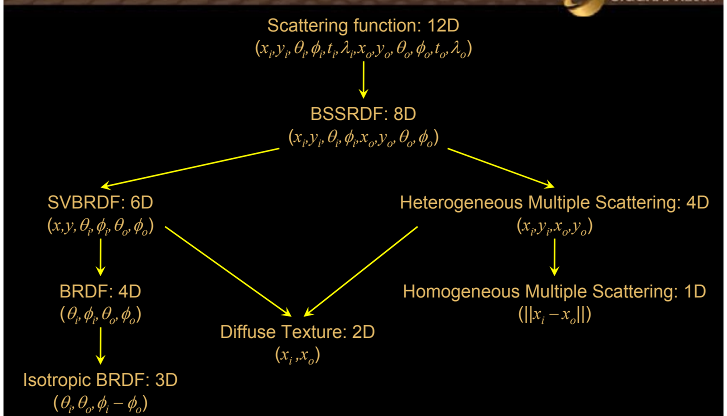


[PEERS ET AL. 2006]

Generalizing Further

- Many additional effects could be incorporated into appearance functions: add 1 dimension for each
  - Wavelength
  - Fluorescence
  - Time dependence
  - Phosphorescence

Appearance Taxonomy



Rest of This Tutorial

- A Review of Radiometry & Physical Models – *Rusinkiewicz*
- Principles of Acquisition – *Zickler*
- (Spatially Varying) BRDF Models – *Lawrence*
- From BSSRDFs to 8D Reflectance Fields – *Lensch*
- The Human Face Scanner Project – *Weyrich*
- Future Directions / Q&A

Principles of Acquisition

Todd Zickler
Harvard University

Outline

1. 5D: Homogeneous Reflectance (BRDF)
2. 7D: Spatially-varying Reflectance (SV-BRDF)
3. 9D: Subsurface Scattering (BSSRDF)
4. Calibration
5. Open problems

Balancing Needs

1. (Per-object) Acquisition Time
2. Accuracy and Precision
3. Cost
4. Generality: how broad is the class of surfaces being considered?

Homogeneous Reflectance

- BRDF: Five dimensional domain

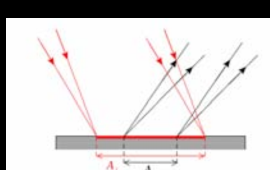
$$f(\lambda, \vec{\omega}_i, \vec{\omega}_o) = f(\lambda, \theta_i, \phi_i, \theta_o, \phi_o)$$

- Isotropic BRDF: Four dimensional domain

$$f(\lambda, \theta_i, \theta_o, |\phi_i - \phi_o|)$$

BRDF: Measurement Scale

- One measures *averages* of the BRDF over finite intervals of surface area and solid angle.
- The measurement scale must be appropriate for the BRDF model to be valid (more on this later).



The Gonioreflectometer

Four-axis gonioreflectometer

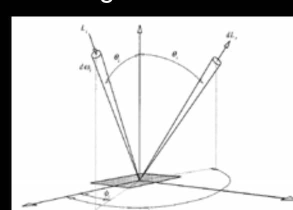
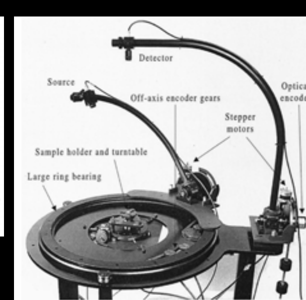


Fig. 1. Coordinate system for defining the BRDF.

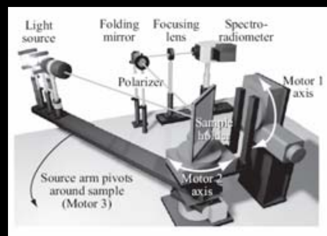


[White et al., 1998]

The Gonioreflectometer

Three-axis gonioreflectometer

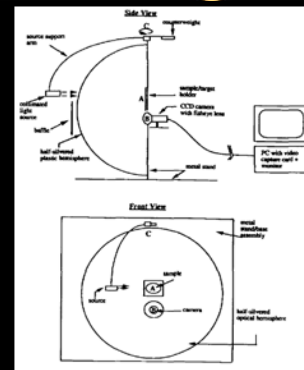
- Isotropic BRDF
- 1000 angular samples
- 31 spectral samples
- ~10 hours per BRDF



[Li et al., 2005]

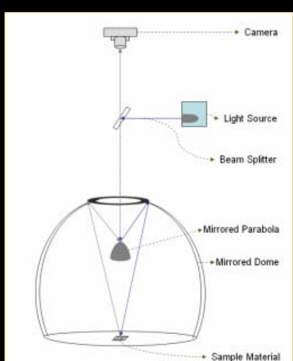
Image-based measurement: planar

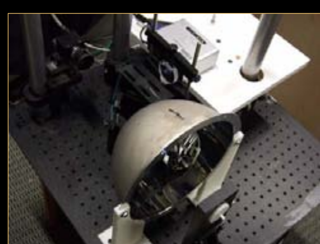
- Camera: Observe multiple output angles simultaneously
- Trade precision (and accuracy?) for efficiency



[Ward, 1992]

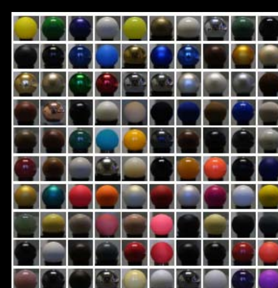
Image-based measurement: planar



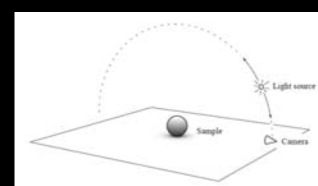


[Ghosh et al., 2007]

Image-based measurement: curved

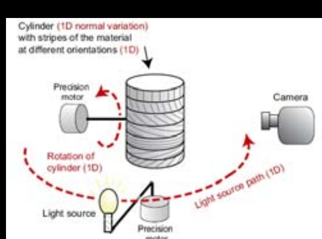


[Matusik et al., 2003]
[http://www.merl.com/brdf/]



[Marschner, 1998; Lu et al., 1998]

Image-based measurement: curved



[Ngan et al., 2005]

Image-based measurement: general

[Marschner et al., 1999]

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Spatially-varying Reflectance

- SV-BRDF: Seven dimensional domain

$$f(\lambda, \vec{x}, \vec{\omega_i}, \vec{\omega}_o) = f(\lambda, x, y, \theta_i, \phi_i, \theta_o, \phi_o)$$

- Isotropic SV-BRDF: Six dimensional domain

$$f(\lambda, x, y, \theta_i, \theta_o, |\phi_i - \phi_o|)$$

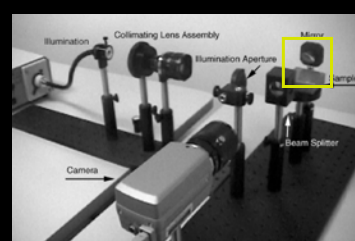
Planar Surfaces: The Spatial Gonioreflectometer

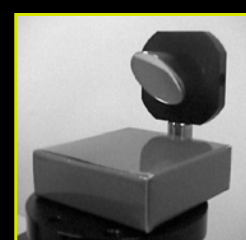
Three-axis spatial gonioreflectometer

[Dana et al., 1997; McAllister, 2002]

Planar Surfaces: Another Spatial Gonioreflectometer

- Can use catadioptrics to re-sort light rays and exchange spatial and angular resolution.





[Dana et al., 2004]

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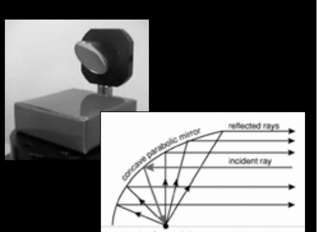
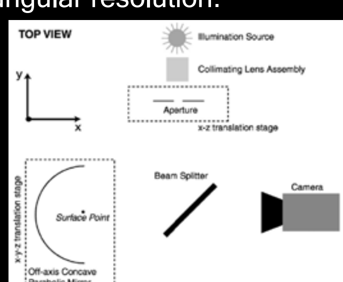
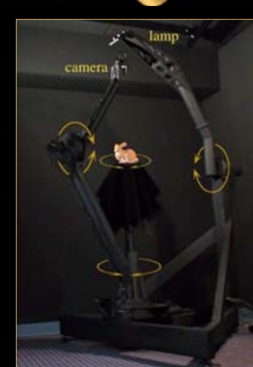




[Dana et al., 2004]

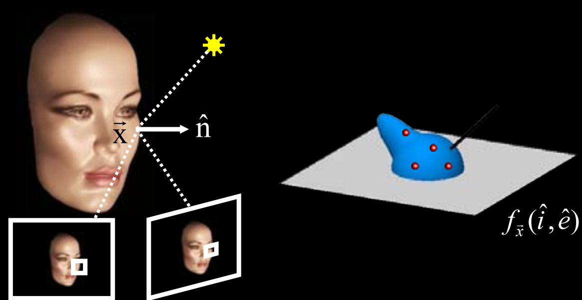
Curved Surfaces

- Many interesting surfaces are not planar.
- Non-planar shapes can be used, provided the shape is known.



[Stanford Spherical Gantry]
(also Cornell, UVA, UCSD,...)

Counting Images



5° sampling:	1,000,000 images	$>10^6$ MB
1° sampling:	625,000,000 images	$>10^9$ MB

Counting Images

Reduce acquisition time by:

1. Designing efficient acquisition systems
2. Using parametric BRDF models
3. Exploiting common reflectance phenomena

5° sampling:	1,000,000 images	$>10^6$ MB
1° sampling:	625,000,000 images	$>10^9$ MB

Acquisition Systems

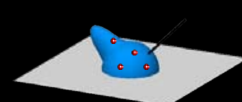
[Stanford Graphics]


[USC-ICT]


[MERL]

Parametric Approaches

- Pro: requires estimating only a handful of parameters at each surface point.
- Con: requires choice of specific parametric family (Oren-Nayar, Cook-Torrance, Phong,...)



$$f_{\vec{x}}(\hat{i},\hat{e}) \leftarrow f_{\vec{x}}(\vec{\alpha}_{\vec{x}};\hat{i},\hat{e})$$

Parametric Approaches

- Some parametric approaches:
  - [Sato, Wheeler, Ikeuchi, 1997]
  - [Yu et al., 1999]
  - [Boivin, Gagalowicz, 2001]
  - [Lensch, et al., 2001]
  - [McAllister, Lastra, Heidrich, 2002]
  - [Georghiades, 2003]
  - [Goldman et al., 2005]
  - ...

General Reflectance Properties

- Isotropy: from a 6D domain to 5D
- Reciprocity: cuts the angular domain in half
- Compressibility: BRDF is slowly varying over much of its angular domain
- Separability: distinct diffuse and specular components
- Spatial smoothness: slow variation from point to point
- Spatial regularity: a common per-object BRDF basis

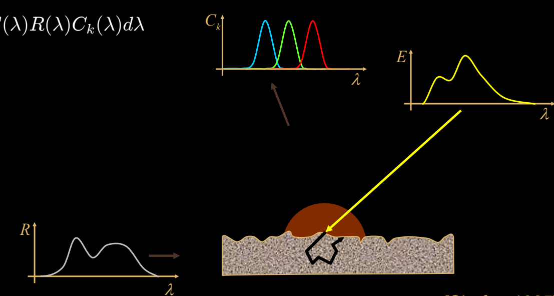
General Reflectance Properties

- Isotropy, reciprocity, separability are commonly exploited
- Compressibility
  - Implicit in parametric approaches; used in non-parametric approaches as well
- Spatial smoothness
  - Exploited in parametric (e.g., [Sato, Wheeler, Ikeuchi, 1997]) and non-parametric (e.g., [Zickler et al., 2006]) approaches
- Spatial regularity
  - Exploited in parametric (e.g., [Lensch et al., 2001], [Goldman et al. 2005]) and non-parametric (e.g., [Lawrence et al., 2006]) approaches

Separability (Dichromatic Model)

$$\mathbf{I}_{RGB} = (\hat{\mathbf{n}} \cdot \hat{\mathbf{i}})\mathbf{D}$$

$$D_k = \int E(\lambda)R(\lambda)C_k(\lambda)d\lambda$$



[Shafer, 1985]

Separability (Dichromatic Model)

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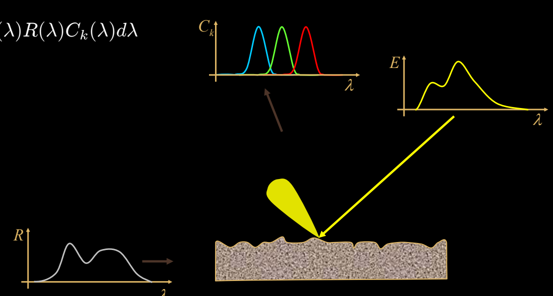


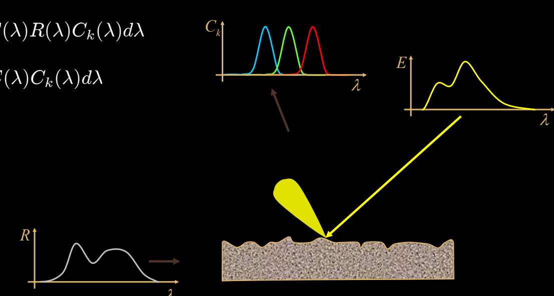
[Shafer, 1985]

Separability (Dichromatic Model)

$$\mathbf{I}_{RGB} = (\hat{\mathbf{n}} \cdot \hat{\mathbf{i}})\mathbf{D} + f(\hat{\mathbf{n}}, \hat{\mathbf{i}}, \hat{\mathbf{v}})\mathbf{S}$$

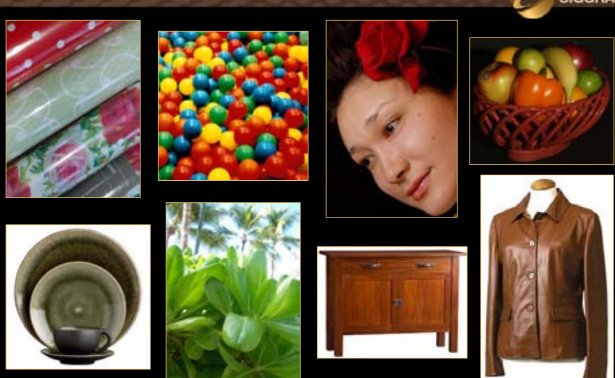
$$D_k = \int E(\lambda)R(\lambda)C_k(\lambda)d\lambda$$

$$S_k = \int E(\lambda)C_k(\lambda)d\lambda$$



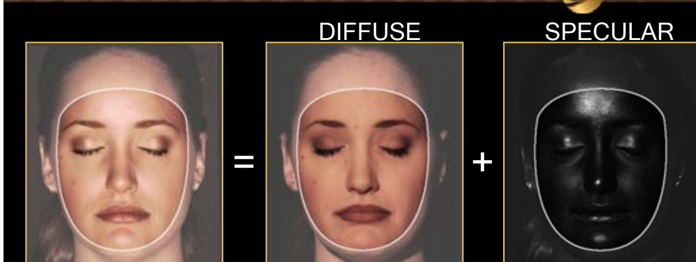
[Shafer, 1985]

"Separable" Materials



[Tominga and Wandell, 1989; Healey, 1989; Lee et al., 1990]

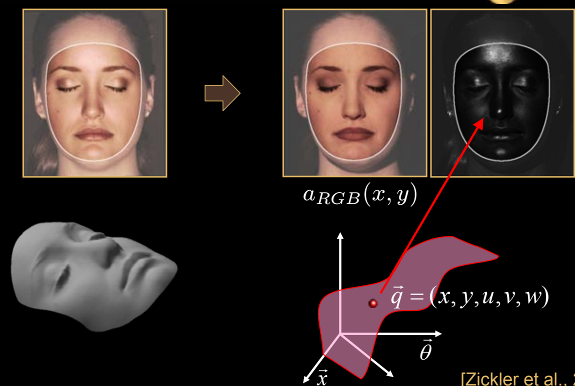
Implications for Acquisition



DIFFUSE:
- Approx. Lambertian
- Rapid spatial variation
- Randomly polarized

SPECULAR:
- Non-Lambertian
- Slow spatial variation
- Monochromatic
- Partially polarized

Example: Reflectance Sharing

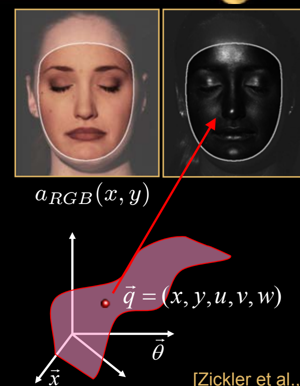


[Zickler et al., 2006]

Example: Reflectance Sharing

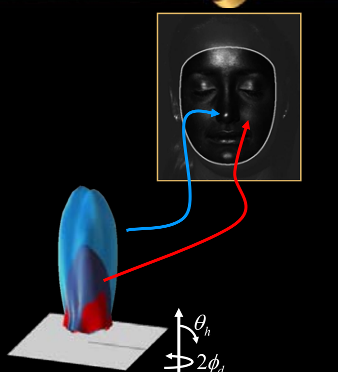
Exploits:

- Separability
- Isotropy/Reciprocity
- Compressibility
- Slow spatial variation



[Zickler et al., 2006]

Example: Reflectance Sharing



[Zickler et al., 2006]

Outline

1. 5D: Homogeneous Reflectance (BRDF)
2. 7D: Spatially-varying Reflectance (SV-BRDF)
3. 9D: Subsurface Scattering (BSSRDF)
4. Calibration
5. Open problems

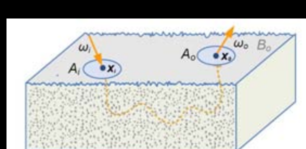
Subsurface Scattering

- BSSRDF:

$$S(\lambda, \vec{x}_i, \vec{\omega}_i, \vec{x}_o, \vec{\omega}_o)$$

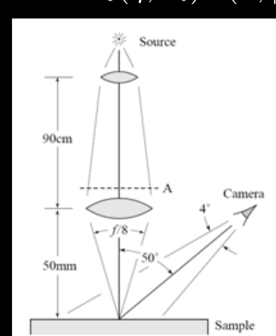
- Homogeneous, multiple scattering:

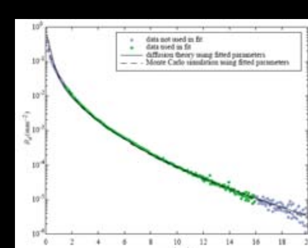
$$F_t(\eta, \vec{\omega}_i) R(\lambda, ||\vec{x}_i - \vec{x}_o||) F_t(\eta, \vec{\omega}_o)$$



BSSRDF

$$F_t(\eta, \vec{\omega}_i) R(\lambda, ||\vec{x}_i - \vec{x}_o||) F_t(\eta, \vec{\omega}_o)$$

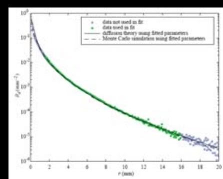




[Jensen et al., 2001]

BSSRDF

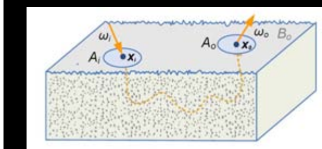
Material	σ'_s [mm^{-1}]			σ_a [mm^{-1}]			Diffuse Reflectance			η
	R	G	B	R	G	B	R	G	B	
Apple	2.29	2.39	1.97	0.0030	0.0034	0.046	0.85	0.84	0.53	1.3
Chicken1	0.15	0.21	0.38	0.015	0.077	0.19	0.31	0.15	0.10	1.3
Chicken2	0.19	0.25	0.32	0.018	0.088	0.20	0.32	0.16	0.10	1.3
Cream	7.38	5.47	3.15	0.0002	0.0028	0.0163	0.98	0.90	0.73	1.3
Ketchup	0.18	0.07	0.03	0.061	0.97	1.45	0.16	0.01	0.00	1.3
Marble	2.19	2.62	3.00	0.0021	0.0041	0.0071	0.83	0.79	0.75	1.5
Potato	0.68	0.70	0.55	0.0024	0.0090	0.12	0.77	0.62	0.21	1.3
Skimmilk	0.70	1.22	1.90	0.0014	0.0025	0.0142	0.81	0.81	0.69	1.3
Skin1	0.74	0.88	1.01	0.032	0.17	0.48	0.44	0.22	0.13	1.3
Skin2	1.09	1.59	1.79	0.013	0.070	0.145	0.63	0.44	0.34	1.3
Spectralon	11.6	20.4	14.9	0.00	0.00	0.00	1.00	1.00	1.00	1.3
Wholemilk	2.55	3.21	3.77	0.0011	0.0024	0.014	0.91	0.88	0.76	1.3

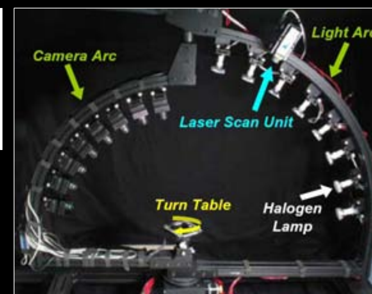


[Jensen et al., 2001]

BSSRDF

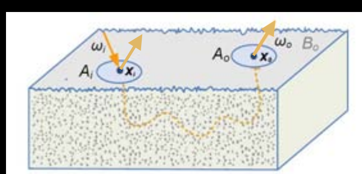
$$S(\lambda, \vec{x}_i, \vec{\omega}_i, \vec{x}_o, \vec{\omega}_o) = f_i(\vec{\omega}_i) R_d(\vec{x}_i, \vec{x}_o) f_o(\vec{x}_o, \vec{\omega}_o)$$





[Tong et al., 2005]

Direct/Sub-surface Separation



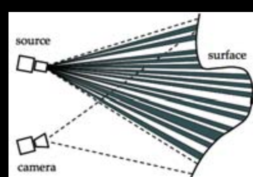


Image Direct Sub-surface

[Nayar et al., 2006]

Outline

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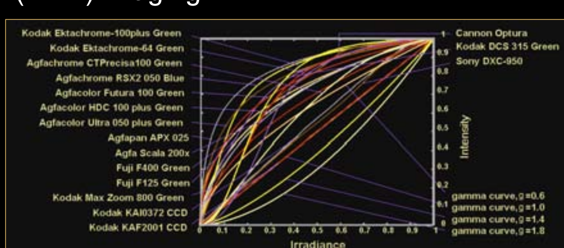
Radiometric Calibration

- Camera:
  - Response function and high dynamic range (HDR) imaging



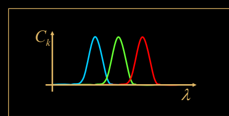
[Grossberg and Nayar, 2003]

Radiometric Calibration

- Camera:
  - Response function and high dynamic range (HDR)
  - Optical fall-off

Radiometric Calibration

- Camera:
  - Response function and high dynamic range (HDR)
  - Optical fall-off
  - Spectral filters



Radiometric Calibration

- Camera:
  - Response function and high dynamic range (HDR)
  - Optical fall-off
  - Spectral filters
  - Thermal noise (at least)

Radiometric Calibration

- Light source(s):
  - Temporal variation
  - Angular non-uniformity
  - Spectral power distribution
- Projector(s):
  - Optical fall-off
  - Spectral filters

Geometric Calibration

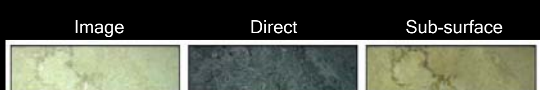
- Camera/projector parameters (intrinsic/extrinsic)

- Source direction
- Surface Shape. Ideally:
  - Surface normals (Photometric stereo; Helmholtz stereo)
  - Independent of reflectance
  - Same images used for shape and reflectance

[Debevec et al., 2007]

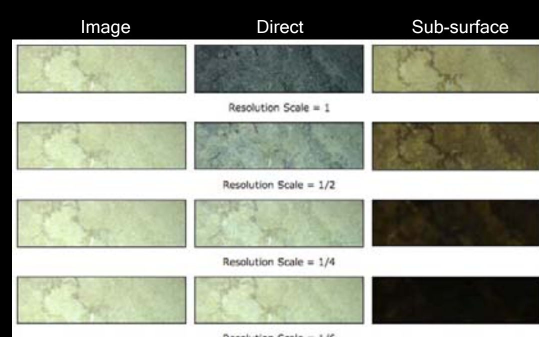
Some Open Problems

- Automatic scale selection



Some Open Problems

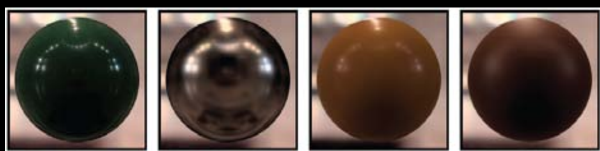
- Automatic scale selection



[Nayar et al., 2006]

Some Open Problems

- Automatic scale selection
- Acquisition (inference) in complex lighting environments. [Dror 2001, Ramamoorthi and Hanrahan 2001]



Some Open Problems

- Automatic scale selection
- Acquisition (inference) in complex lighting environments. [Dror 2001, Ramamoorthi and Hanrahan 2001]
- SV-BRDF acquisition as an inference problem. What are the priors?
- Increased spectral resolution
- Combined shape and reflectance acquisition

Spatially-Varying BRDF Models

Jason Lawrence
University of Virginia

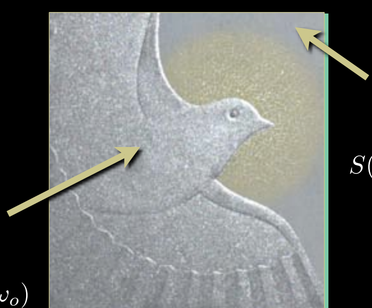
SIGGRAPH2008

A Spatially-Varying BRDF

$S(u, v, \omega_i, \omega_o)$

A Spatially-Varying BRDF

$S(u_0, v_0, \omega_i, \omega_o)$



$S(u_1, v_1, \omega_i, \omega_o)$

Talk Outline

- acquisition
- representations
- future directions

Acquisition

Acquisition

. . .

Outline

- acquisition
- **representations**
- future directions

Representation

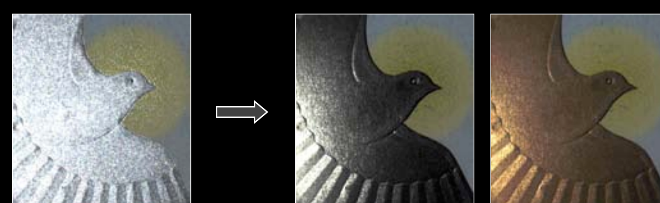
- goals
  - compact
  - editable
  - sampling
- challenges
  - scattered data
  - dimensionality
  - massive datasets

Representation

- goals
  - compact
  - editable
  - sampling
- challenges
  - scattered data
  - dimensionality
  - massive datasets

Goal

- input: large set of reflectance measurements
- representation that is compact and editable



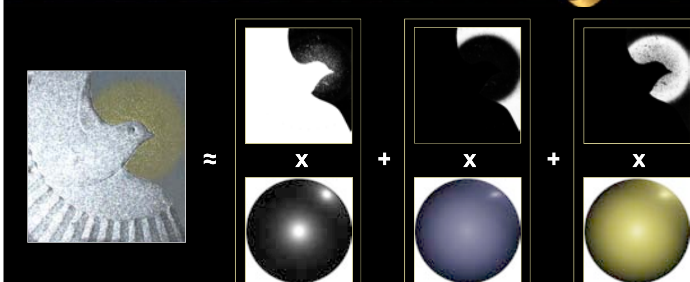
input measurements (1000s of images)

result of editing material properties

Strategy: Basis Decomposition

$$S(u, v, \omega_i, \omega_o, \lambda) \approx \sum_{k=1}^{K} T_k(u, v)\rho_k(\omega_i, \omega_o, \lambda)$$

Strategy: Basis Decomposition



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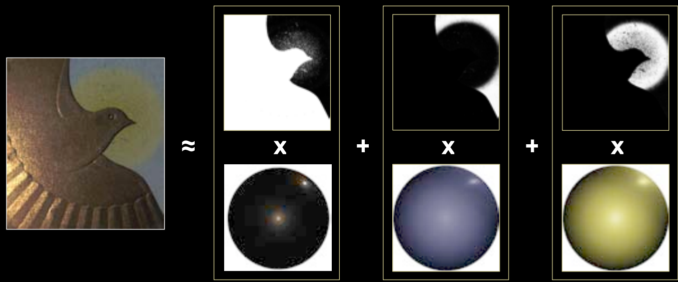
Strategy: Basis Decomposition



$$S(u,v,\omega_i,\omega_o,\lambda) \approx \sum_{k=1}^{K} T_k(u,v)\rho_k(\omega_i,\omega_o,\lambda)$$

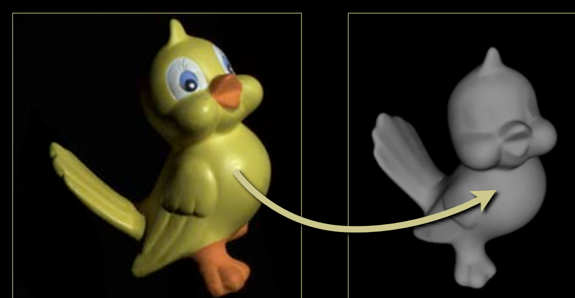
General Strategy

- parametric
  - fit parametric BRDF model
  - cluster
  - reproject onto basis
- non-parametric
  - tabulate the reflectance data
  - cast as matrix factorization
  - place constraints on factors

Acquisition

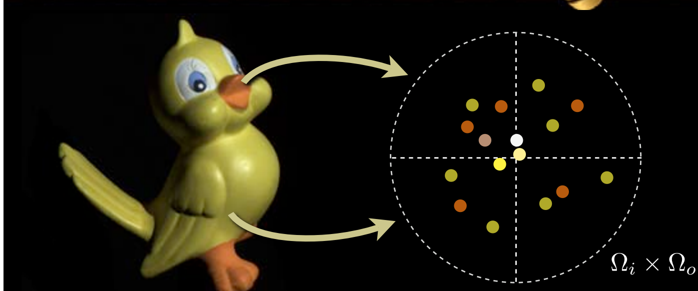
Lensch, H., Kautz, J., Goesele, M., Heidrich, W., Seidel, H.-P.
Image-Based Reconstruction Spatial Appearance
ACM Transactions on Graphics 22(3), 2003

Registration



silhouette-based alignment procedure

Fitting Lafortune Parameters

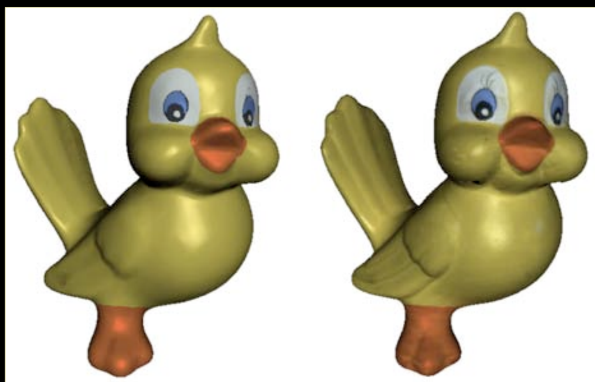


$$\rho(\vec{l},\vec{v}) = k_d + \sum_i \left[C_{x,i}(l_x v_x + l_y v_y) + C_{z,i} l_z v_z\right]^{N_i}$$

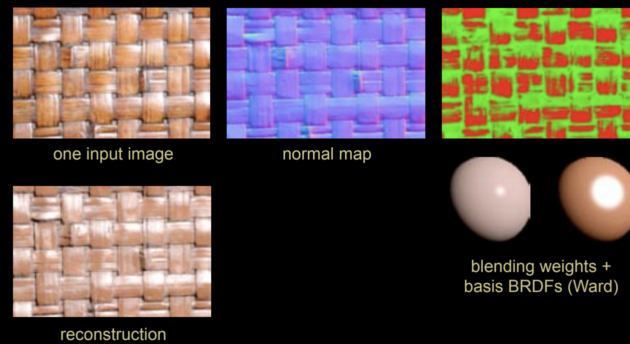
Clustering

split / refine

Reprojection



Goldman et al. 2005

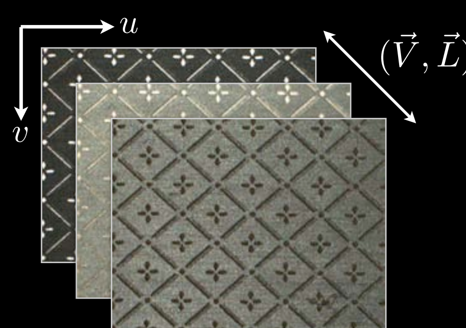


Goldman, D., Curless, B., Hertzmann, A., Seitz, S.
Shape and Spatially Varying BRDFs from Photometric Stereo
Proceedings of ICCV 2005.

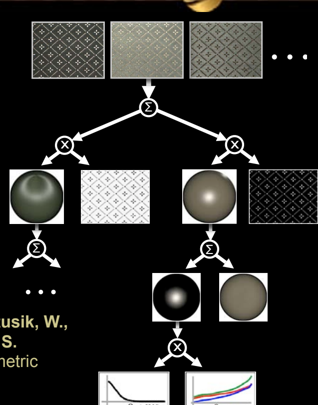
General Strategy

- parametric
  - fit parametric BRDF model
  - cluster
  - reproject onto basis
- **non-parametric**
  - **tabulate the reflectance data**
  - **cast as matrix factorization**
  - **place constraints on factors**

Wallpaper Dataset

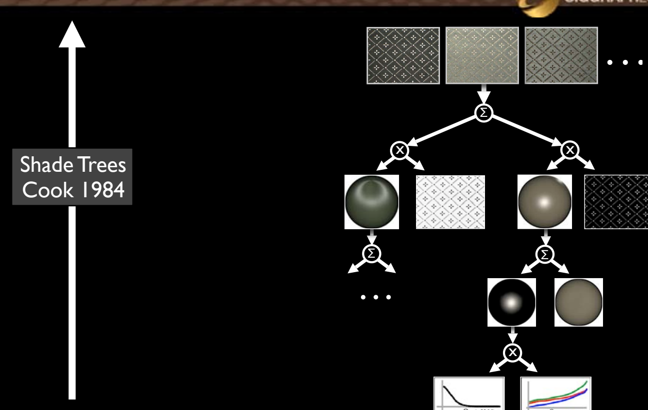


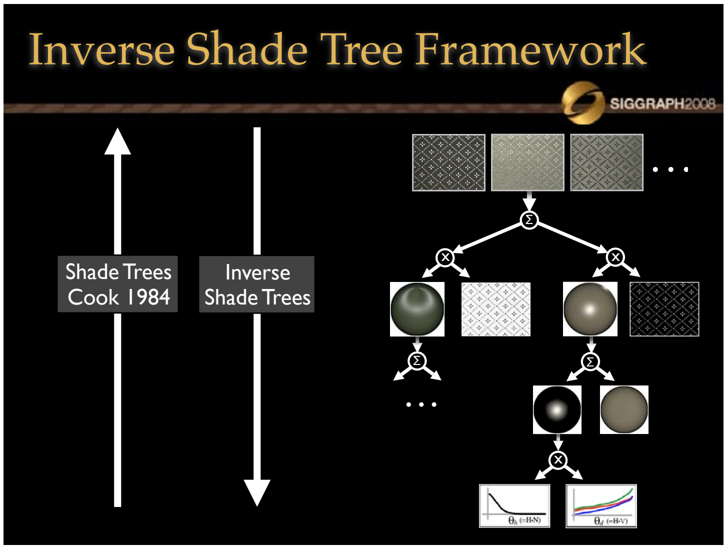
Inverse Shade Trees

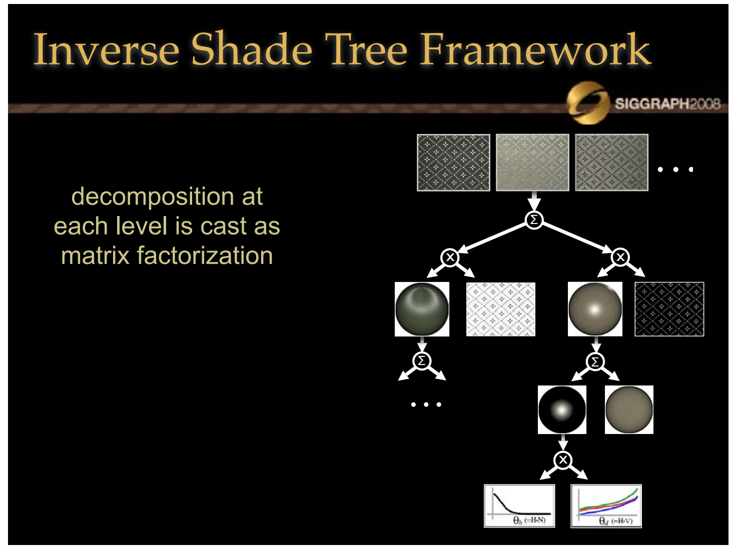


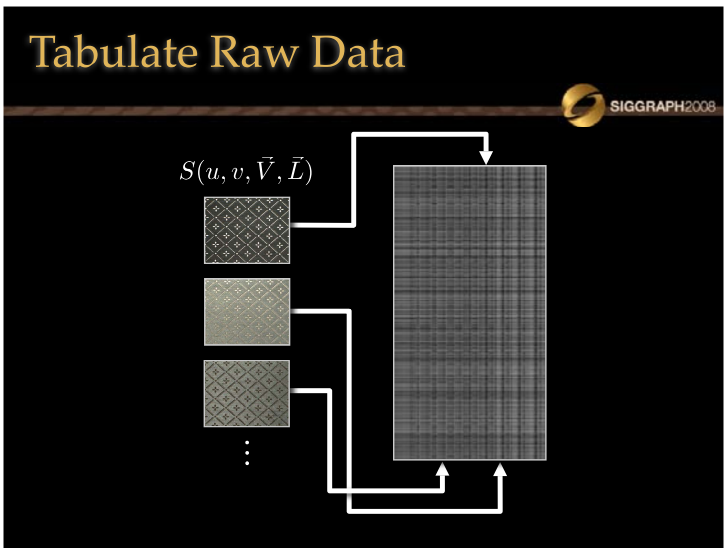
Lawrence, J., Ben-Artzi, A., DeCoro, C., Matusik, W., Pfister, H., Ramamoorthi, R., Rusinkiewicz, S.
Inverse Shade Tree Framework for Non-Parametric Material Representation and Editing
Proceedings of SIGGRAPH 2006.

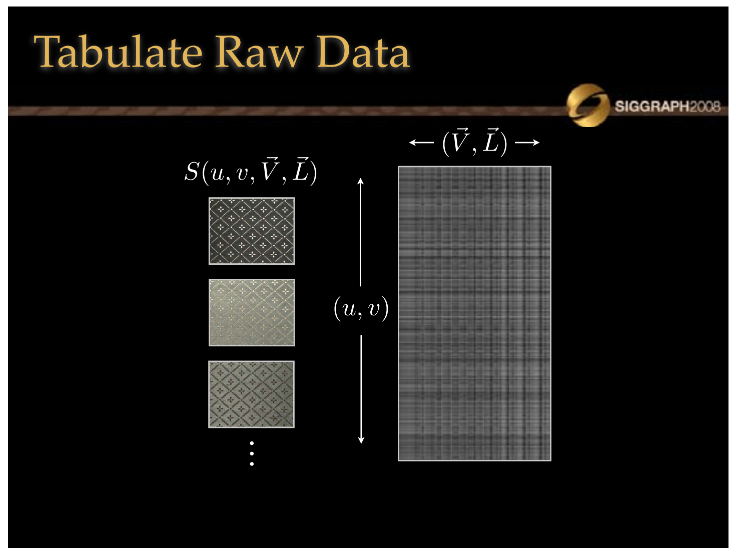
Inverse Shade Tree Framework

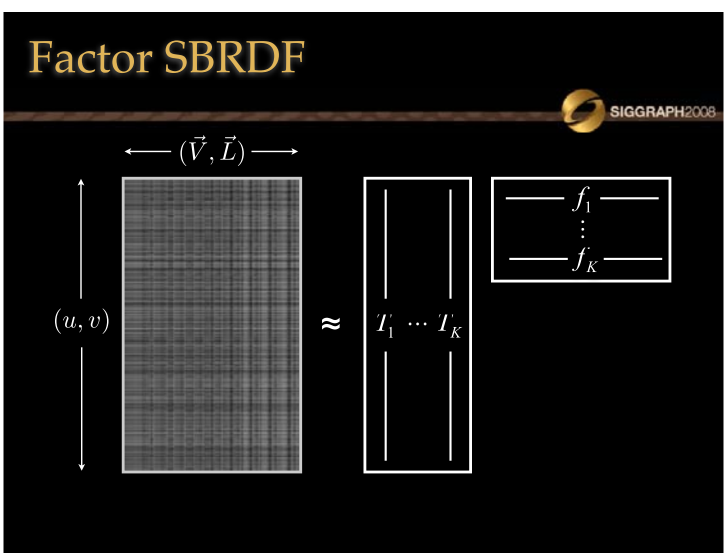


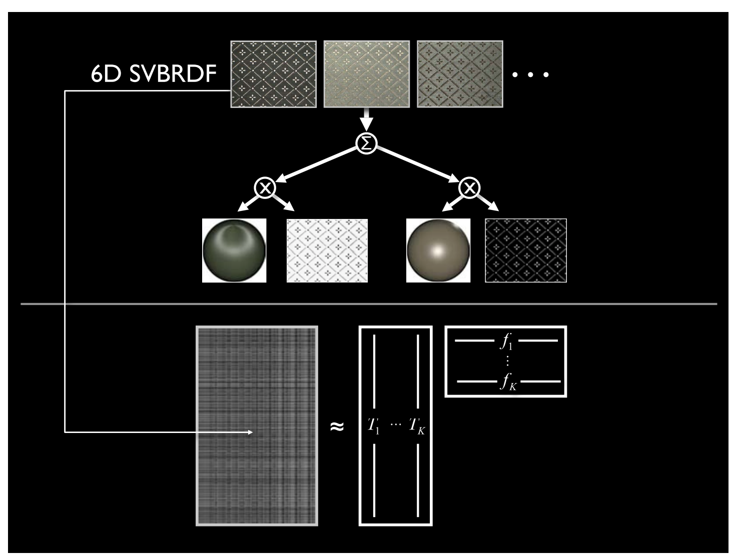

Inverse Shade Tree Framework
SIGGRAPH2008
Shade Trees
Cook 1984
Inverse
Shade Trees

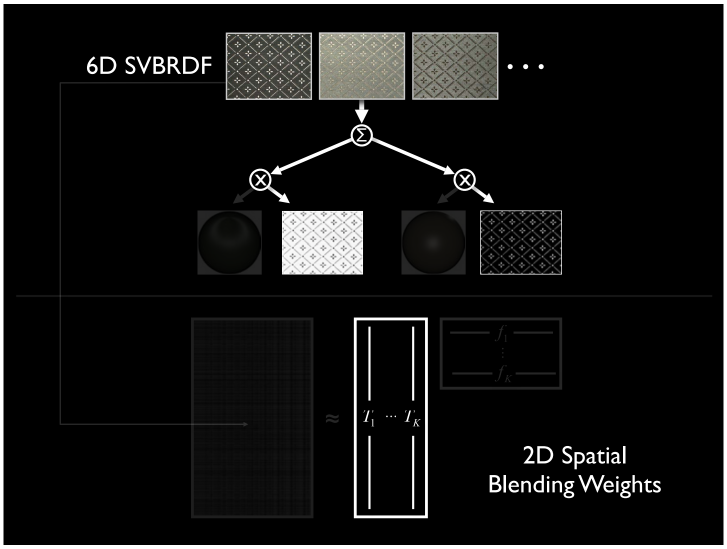

Inverse Shade Tree Framework
SIGGRAPH2008
decomposition at
each level is cast as
matrix factorization

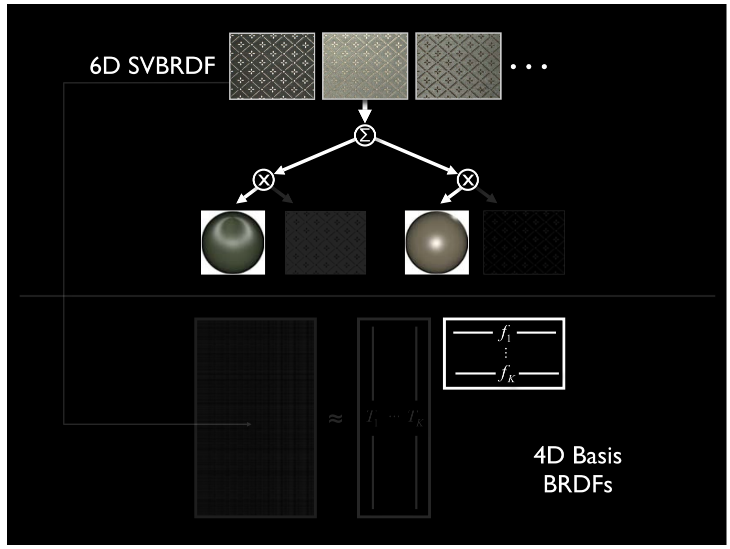

Tabulate Raw Data
SIGGRAPH2008
$S(u, v, \vec{V}, \vec{L})$


Tabulate Raw Data
SIGGRAPH2008
$S(u, v, \vec{V}, \vec{L})$
$(\vec{V}, \vec{L})$
(u, v)


Factor SBRDF
SIGGRAPH2008
$(\vec{V}, \vec{L})$
(u, v)
$\approx$
$T_1 \cdots T_K$
f_1
f_K


6D SVBRDF
$\approx$
$T_1 \cdots T_K$
f_1
f_K





Research Challenge

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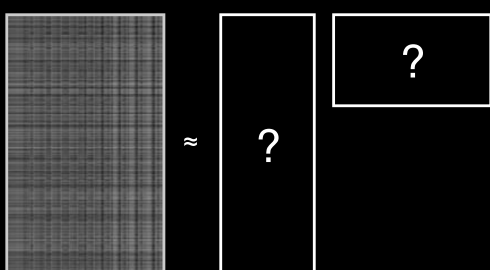
providing an intuitive factorization:



Key Idea

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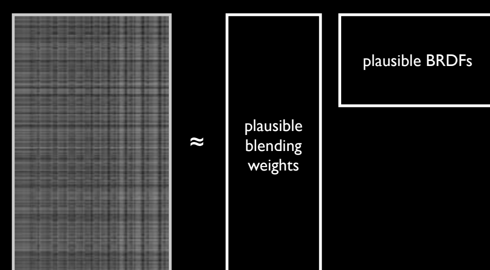
incorporate domain-specific knowledge as constraints of factorization:



Factorization Constraints

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- **non-negativity: reflectance functions are non-negative**
- **sparsity: few BRDFs at each position**
- **domain-specific:**
  - **energy conservation, monotonicity, etc.**

Factorization Algorithms

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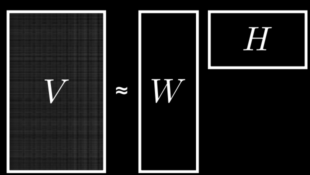
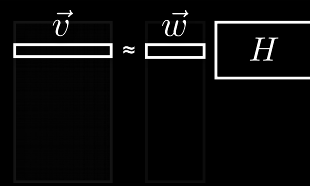
algorithm	properties			
	linear	positive	sparse	domain
PCA	✓	✗	✗	✗
clustering	✗	✓	✓	✗
NMF	✓	✓	✓	✗
ACLS	✓	✓	✓	✓

Alternating Constrained LS



1. Initialize W and H
2. Update W
3. Update H
4. Iterate until convergence

Alternating Constrained LS



1. Initialize W and H
2. Update W
3. Update H
4. Iterate until convergence

convex QP problem

$$\min_{\vec{w}} \|\vec{v} - \vec{w}H\|^2$$

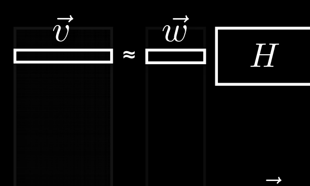
$$\vec{l} \leq \left\{ \begin{array}{c} \vec{w}^T \\ A\vec{w}^T \end{array} \right\} \leq \vec{u}$$

Reflectance Constraints

- **non-negativity**
  - **constraint on value**
- **energy conservation**
  - **constraint on sum**
- **monotonicity**
  - **constraint on derivative**

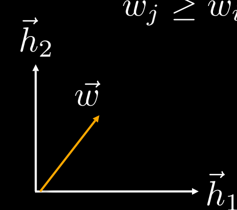
$$\vec{l} \leq \left\{ \begin{array}{c} \vec{w}^T \\ A\vec{w}^T \end{array} \right\} \leq \vec{u}$$

Measure of Sparsity

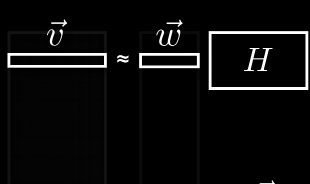


$$E_{sparse} = \sum_{i \neq j} w_i$$

$$w_j \geq w_i, i = 1...K$$



Measure of Sparsity



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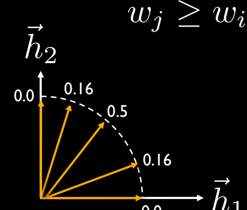
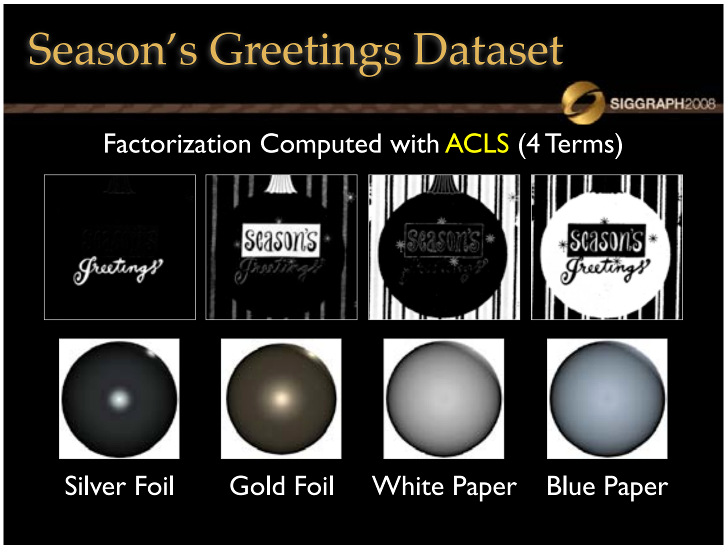
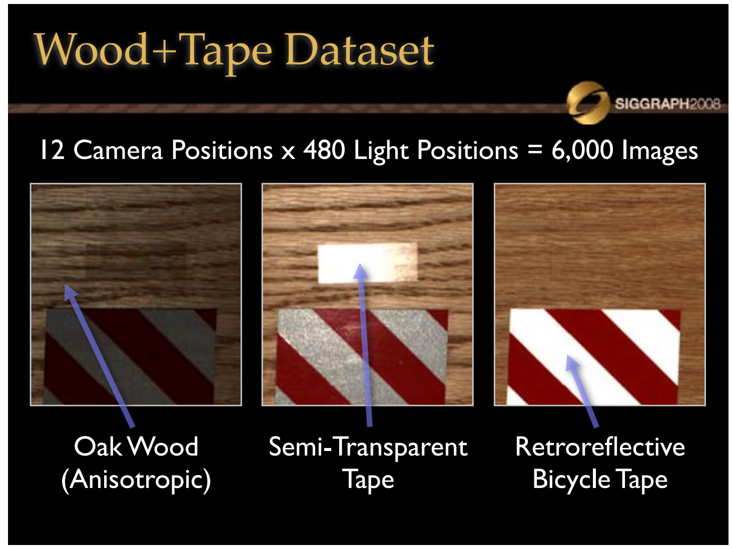


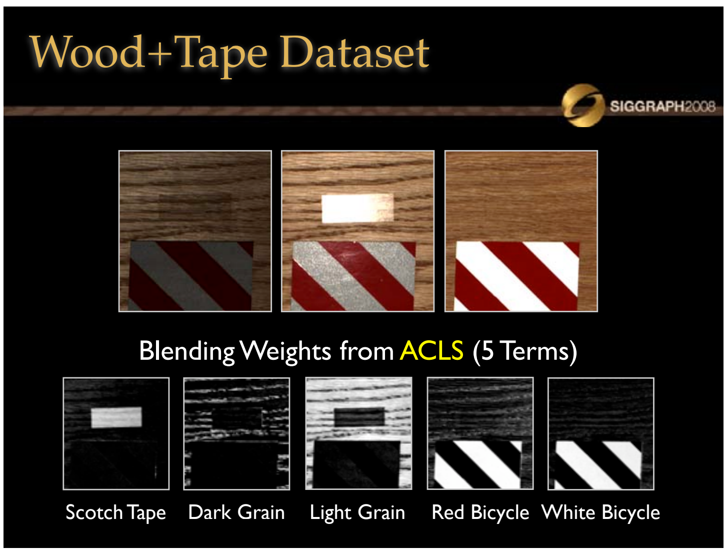
Season's Greetings Dataset

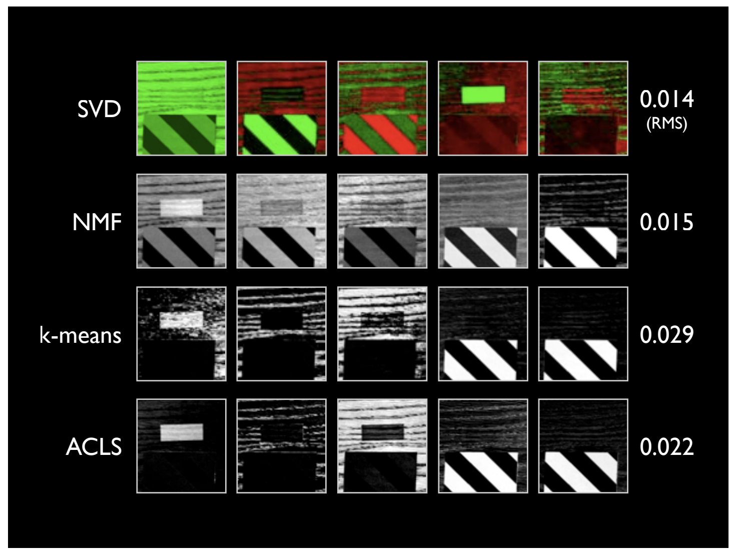
5 Camera Positions ... tions ~ 1,750 Images

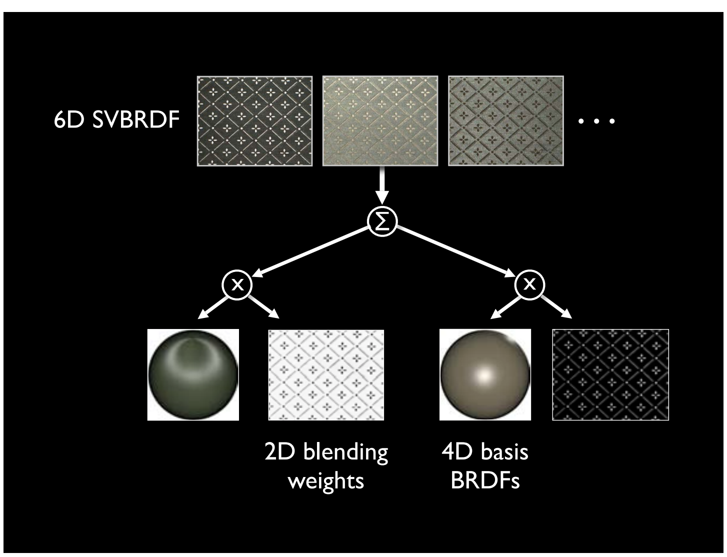
Gold Foil Silver Foil White Paper Blue Paper

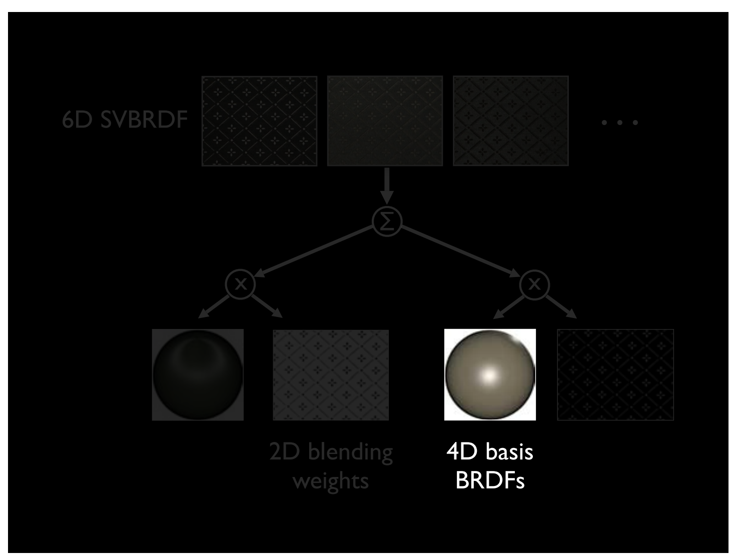

Season's Greetings Dataset
SIGGRAPH2008
Factorization Computed with ACLS (4 Terms)
Silver Foil
Gold Foil
White Paper
Blue Paper

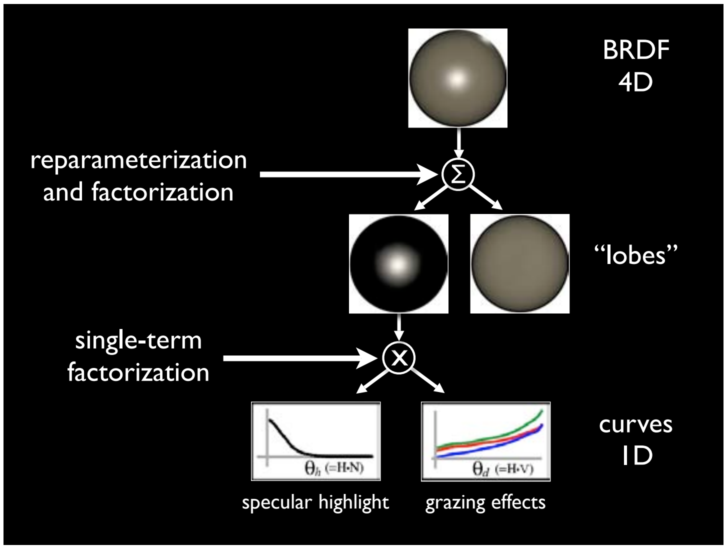

Wood+Tape Dataset
SIGGRAPH2008
12 Camera Positions x 480 Light Positions = 6,000 Images
Oak Wood (Anisotropic)
Semi-Transparent Tape
Retroreflective Bicycle Tape

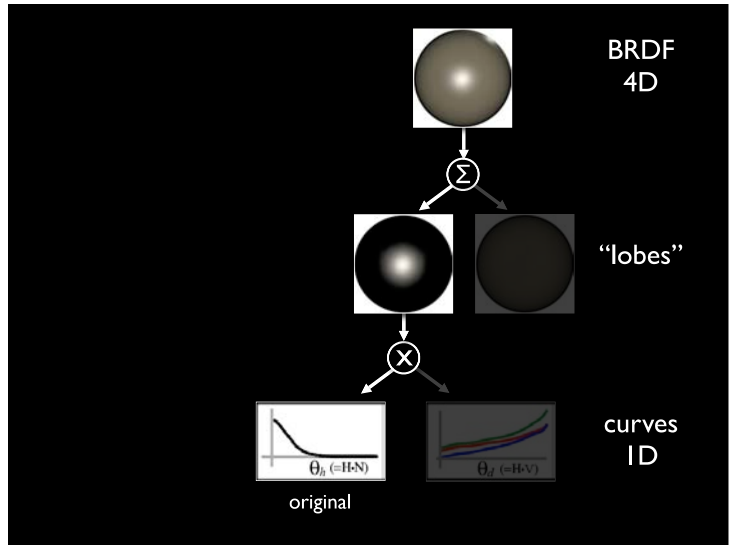

Wood+Tape Dataset
SIGGRAPH2008
Blending Weights from ACLS (5 Terms)
Scotch Tape
Dark Grain
Light Grain
Red Bicycle
White Bicycle

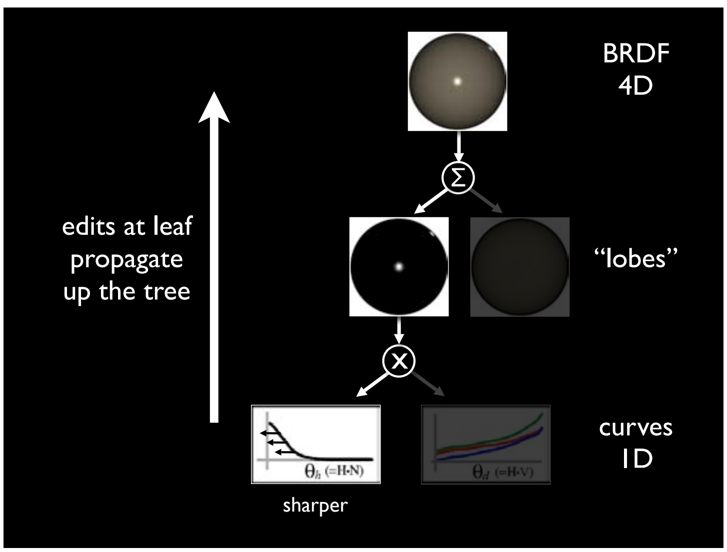

SVD
0.014
(RMS)
NMF
0.015
k-means
0.029
ACLS
0.022

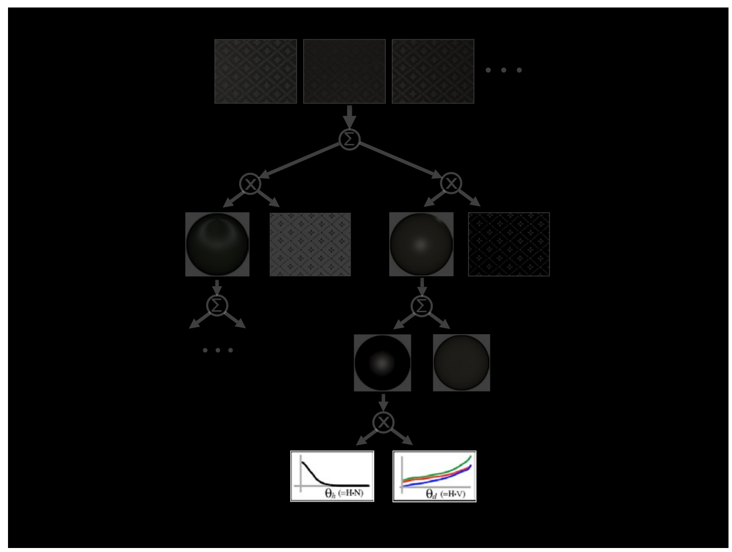

6D SVBRDF
. . .
Σ
2D blending weights
4D basis BRDFs

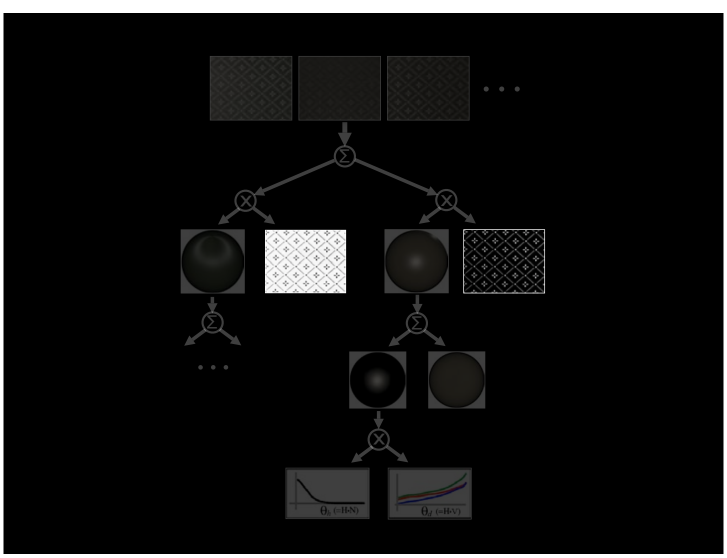

6D SVBRDF
2D blending weights
4D basis BRDFs











Summary

SIGGRAPH2008

- representation goals:
  - compact
  - editable
  - supports rendering
- basis decomposition
  - parametric
  - non-parametric

Summary

- sparse/scattered data
- interpolation
- flexibility
- local minima

Summary

- sparse/scattered data
- interpolation
- flexibility
- local minima

Summary

- sparse/scattered data
- interpolation
- flexibility/accuracy
- local minima

Summary

- sparse/scattered data
- interpolation
- flexibility
- local minima

Future Directions

- higher-dimensional datasets
  - subsurface scattering / reflectance field
  - time-varying properties
  - etc.
- rigorous probabilistic framework
- measurement
  - synchronous shape + appearance
  - lowering calibration burden

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SIGGRAPH2008

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Future Directions

SIGGRAPH2008

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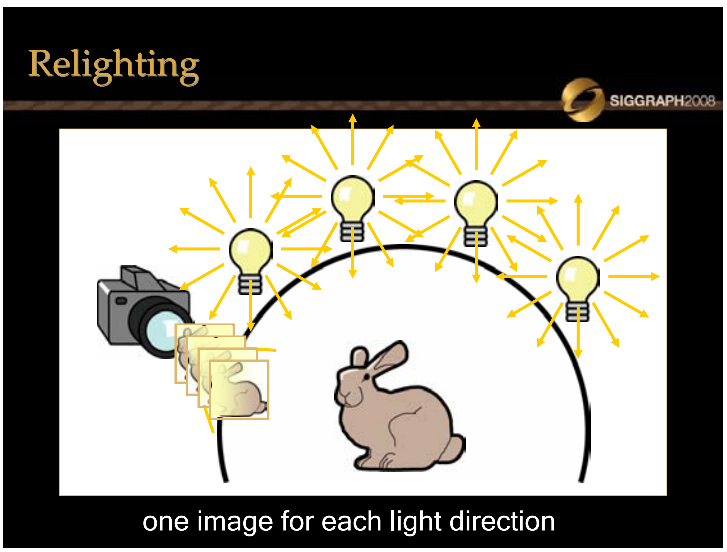
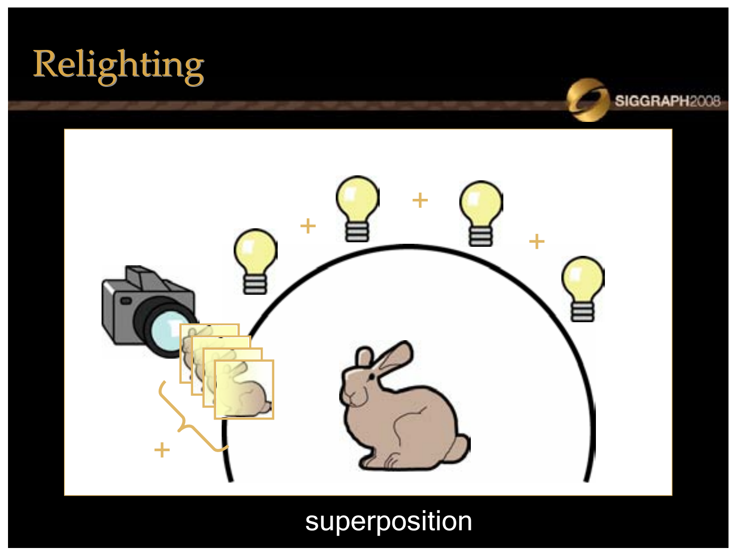
SIGGRAPH2008
From BSSRDFs
to 8D Reflectance Fields
Hendrik P. A. Lensch
MPI Informatik
SIGGRAPH 2008 Class
Los Angeles, August, 2008

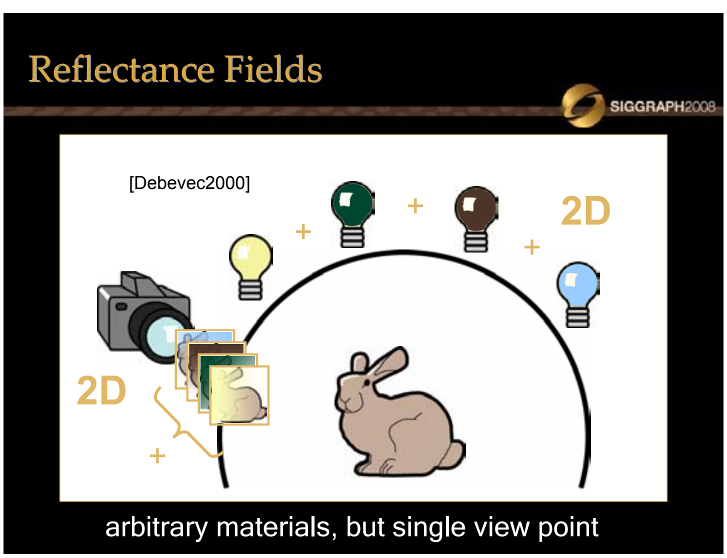
Digitizing Real World Objects
SIGGRAPH2008
relighting with arbitrary illumination patterns



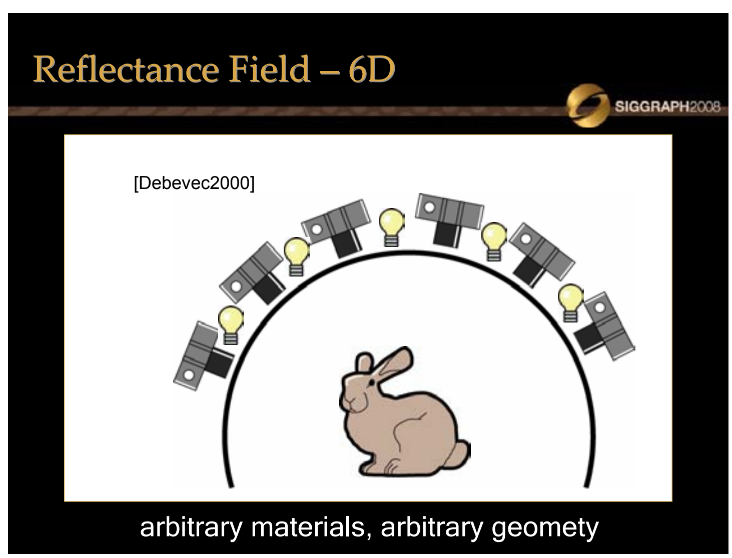
Relighting
SIGGRAPH2008
one image for each light direction



Relighting
SIGGRAPH2008
superposition

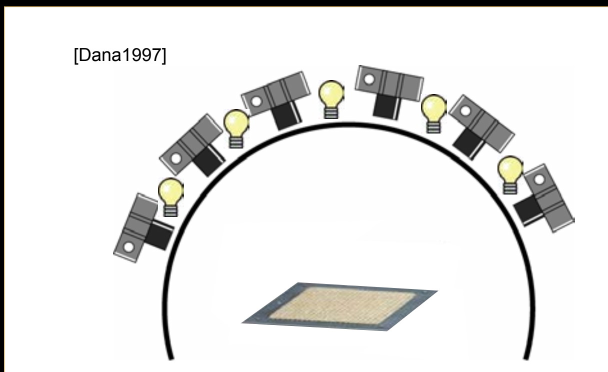


Reflectance Fields
SIGGRAPH2008
[Debevec2000]
2D
2D
arbitrary materials, but single view point



Reflectance Field – 6D
SIGGRAPH2008
[Debevec2000]
arbitrary materials, arbitrary geomety

Bidirectional Texture Functions



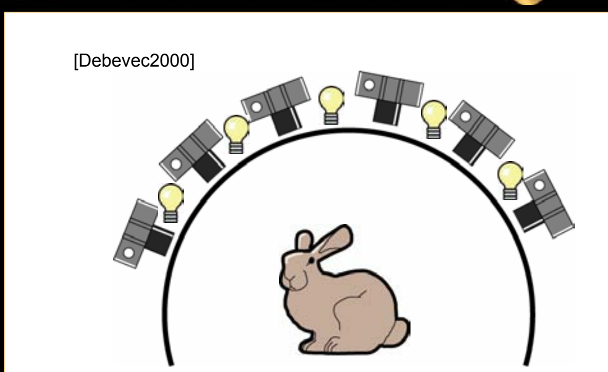
arbitrary materials, surface patch

BTF Acquisition Devices

[Sattler2003]

[Mueller2005]

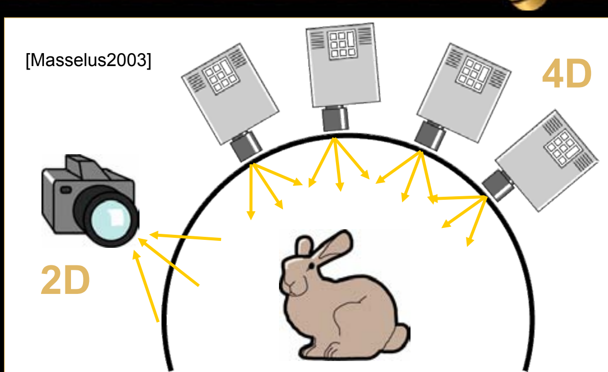
Far-Field Reflectance Fields



arbitrary materials, but distant light sources only

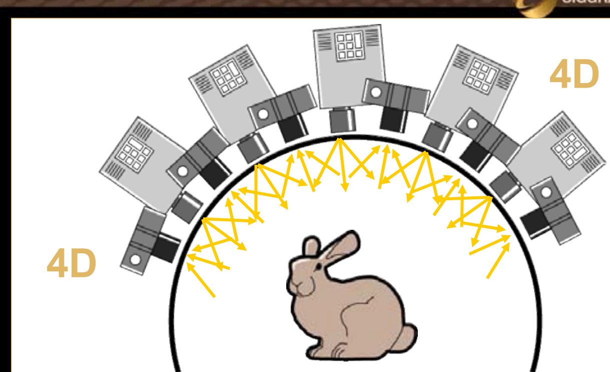
Far- vs. Near-Field Illumination

6D Reflectance Fields



relighting with 4D incident light fields

8D Reflectance Fields



arbitrary materials +
arbitrary view point + arbitrary illumination

Definition – Reflectance Field

8D function = BSSRDF

$$f_r((\vec{x}_i,\vec{\omega}_i) \to (\vec{x}_o,\vec{\omega}_o))$$

Definition – Reflectance Field

ratio of reflected radiance to incident flux

$$f_r((\vec{x}_i,\vec{\omega}_i) \to (\vec{x}_o,\vec{\omega}_o)) = \frac{dL_o(\vec{x}_o,\vec{\omega}_o)}{d\phi_i(\vec{x}_i,\vec{\omega}_i)}$$

Main Problem

- sampling an *8D function*
  - spending 100 samples/dimension
    → 10^{16} samples
  - hi-res 3D geometry: 10^8 vertices
- coherence in reflectance fields
  → reduced data complexity
- no complete solution yet

Approaches

- limited reflectance model
- limited reproduction
  - viewer position
  - incident illuminaton
- adaptive parallel acquisition
- advanced interpolation

Relighting with 4D Incident Light Fields

- goal: relighting with spatially varying illumination, e.g. spot lights

Acquisition with Large Blocks

- fixed camera perspective
- rotating illumination

Relighting Results

SIGGRAPH2008

Translucent Objects

SIGGRAPH2008

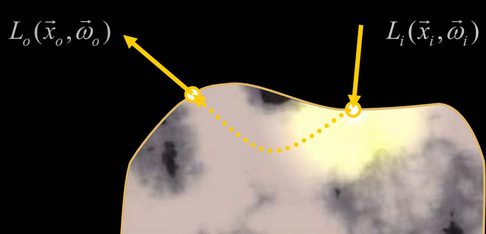
- light transport through the object
- scattering dampens high frequencies

BSSRDF – 8D

SIGGRAPH2008

bidirectional scattering-surface reflectance distribution function [Nicodemus77]

$$f_r\left((\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o)\right)$$

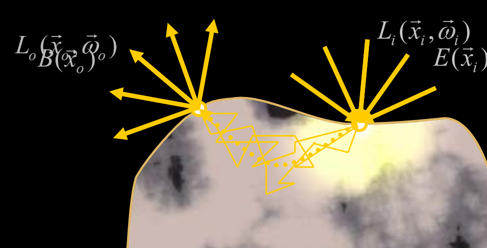


Diffuse Approximation

SIGGRAPH2008

neglect directional dependency [Jensen 2001]

- multiple scattering leads to diffuse light transport



4D - Diffuse Approximation

SIGGRAPH2008

⇒ diffuse reflectance function $R_d(\vec{x}_i,\vec{x}_0)$

- four dimensions only
- dense sampling is possible

Diffuse Reflectance Fucntion R_d

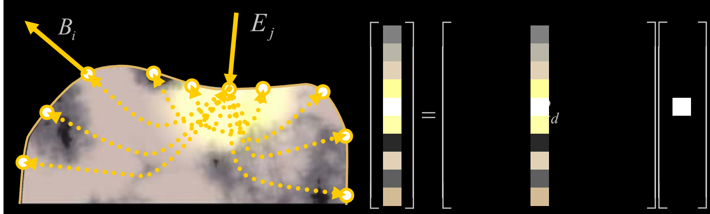
SIGGRAPH2008

- discretize the surface
  - enumerate all surface points
  - vectors for irradiance E and radiosity B
- matrix R_d
  - linear point-to-point transport

$$\begin{bmatrix} B_i \end{bmatrix} = \begin{bmatrix} & R_d & \end{bmatrix} \begin{bmatrix} E_j \end{bmatrix}$$

Basic Idea

- direct measurement of R_d
  - illuminate individual surface points
  - capture impulse response function



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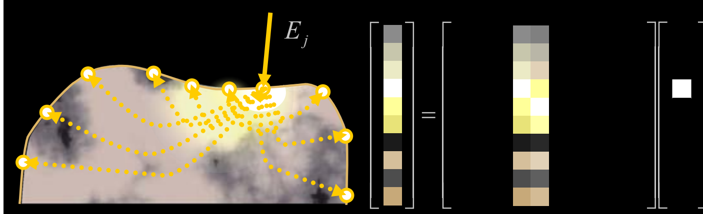

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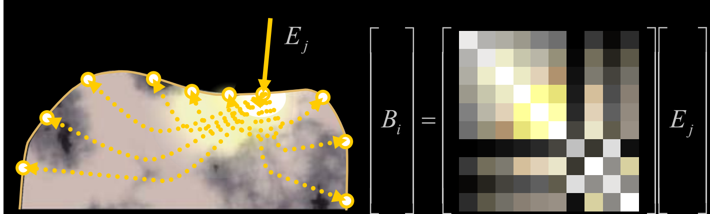
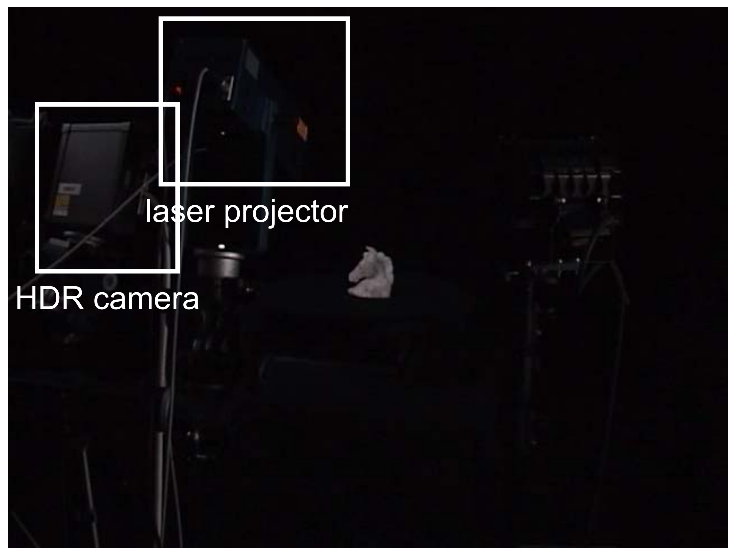




Matrix Representation

- 500.000 - 1.000.000 input images
  - $\Rightarrow$ ~100.000^2 entries
- fill up holes (inpainting)
- hierarchical representation
- hardware assisted rendering
  - analysis
  - real-time rendering

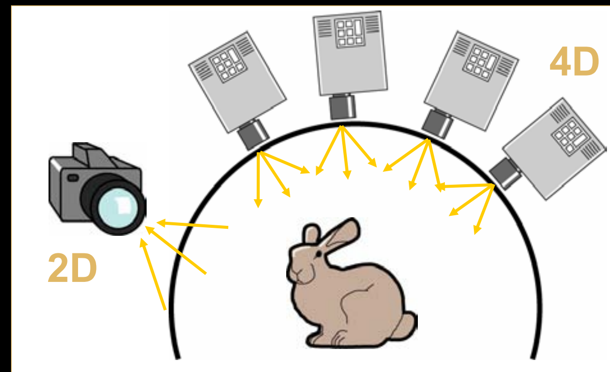
[Lensch, Goesele, Bekaert, Magnor, Lang, Seidel – PG2003]

Video

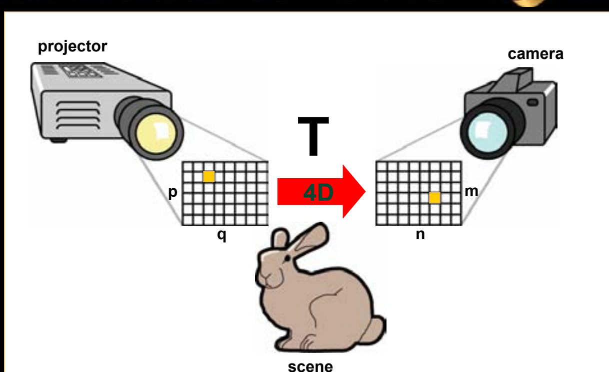
1.000.000 images, 22 hours → model - 800MB

[Goesele, Lensch, Lang, Fuchs, Seidel - SIGGRAPH 2004]

Fixed Perspective + Arbitrary Illumination

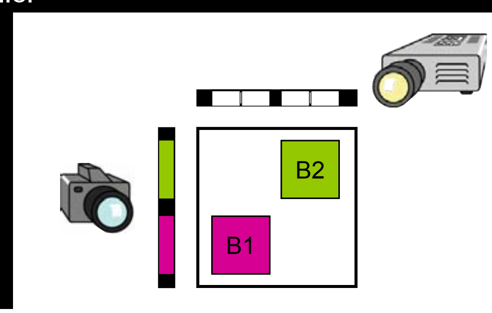


Pixel-to-Pixel Transport



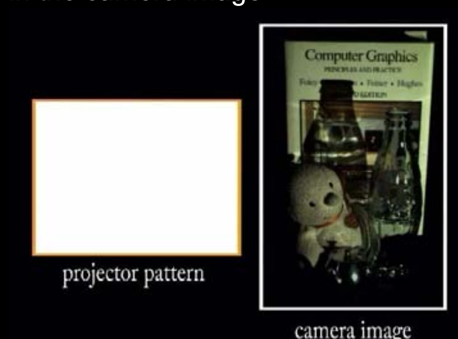
Adaptive Parallel Acquisition

- assumption: sparse matrix
- radiometrically independent blocks can be sensed in parallel



Adaptive Parallel Acquisition

parallelized acquisition of regions which do not overlap in the camera image



Adaptive Parallel Acquisition

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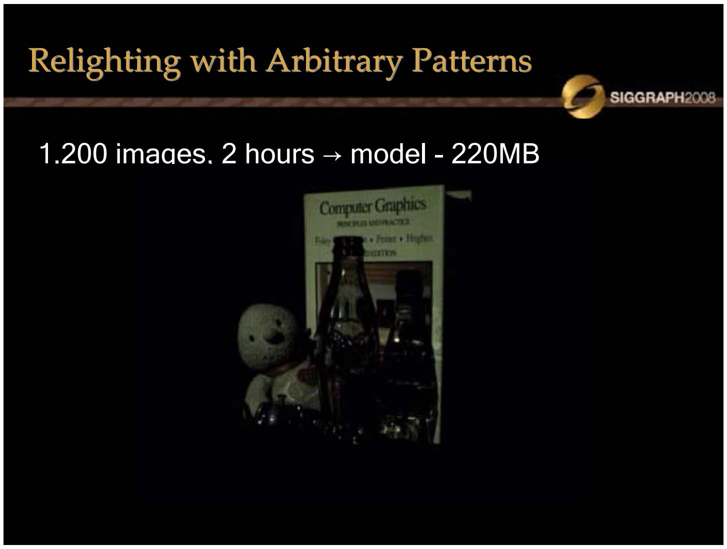
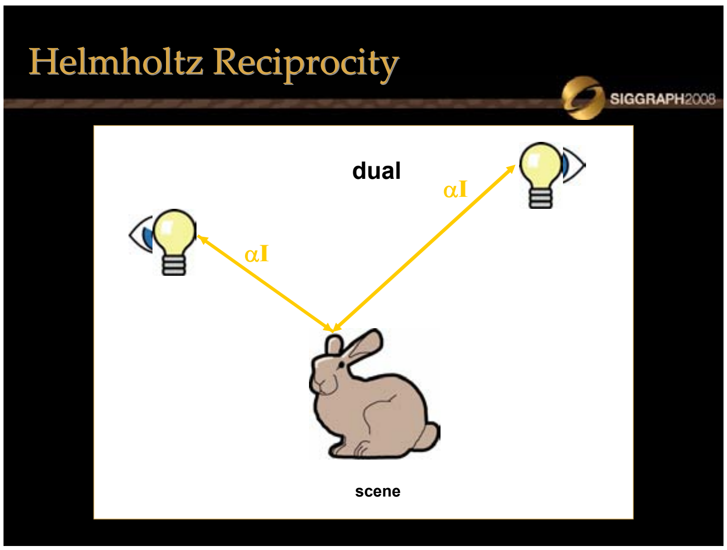

Relighting with Arbitrary Patterns
SIGGRAPH2008
1.200 images, 2 hours → model - 220MB
Computer Graphics


Captured Global Light Transport
SIGGRAPH2008


Helmholtz Reciprocity
SIGGRAPH2008
dual
αI
αI
scene

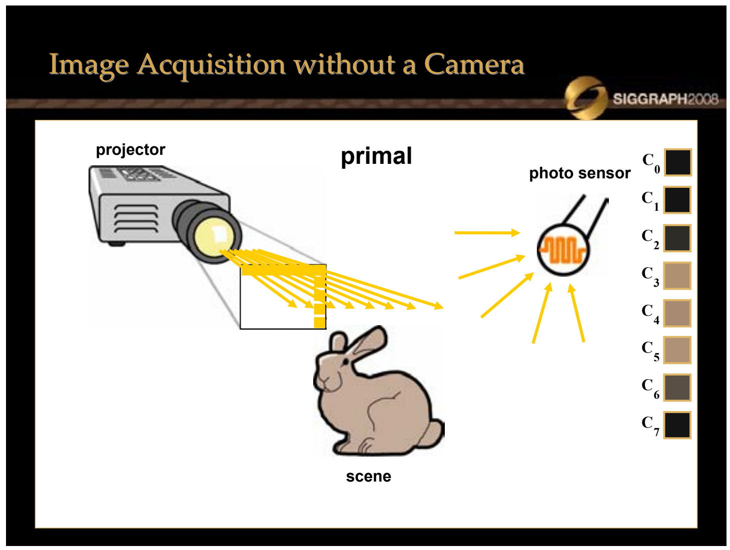


Image Acquisition without a Camera
SIGGRAPH2008
projector
primal
photo sensor
C0
C1
C2
C3
C4
C5
C6
C7
scene

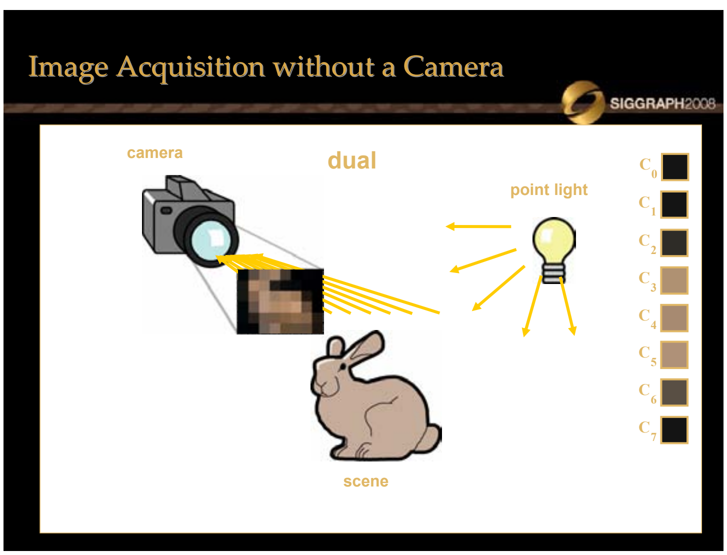
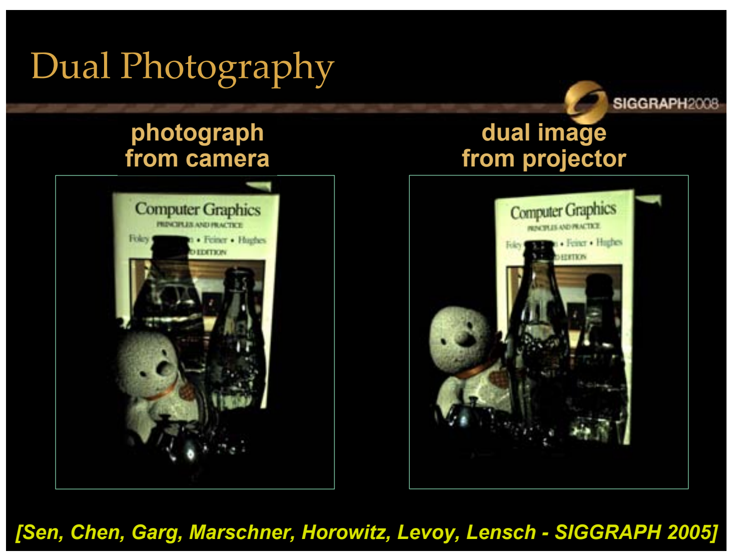
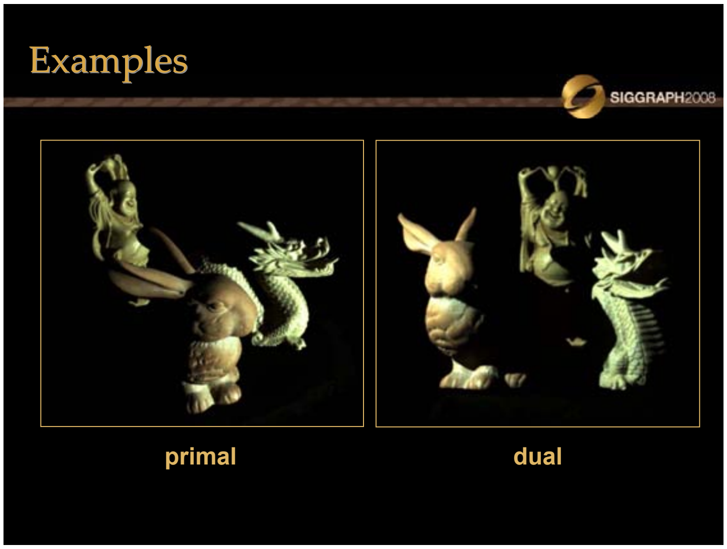
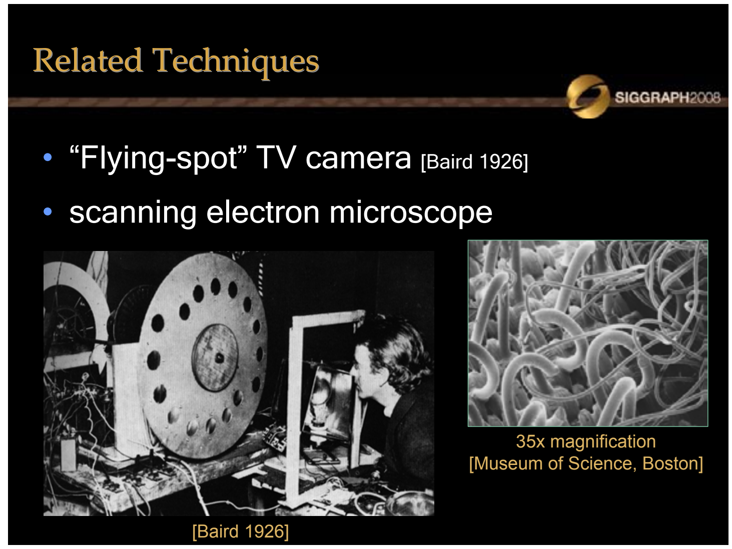
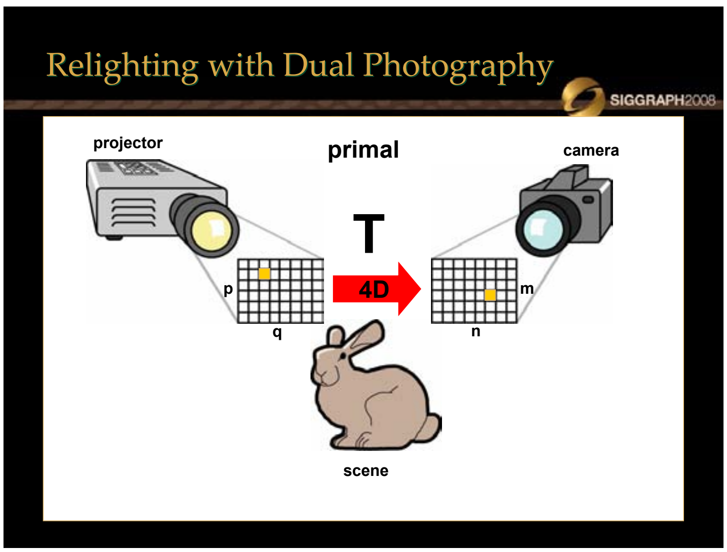


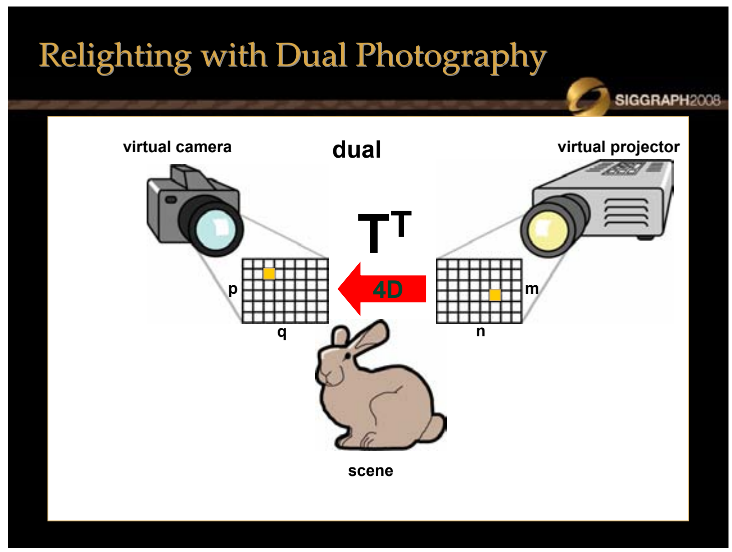
Image Acquisition without a Camera
SIGGRAPH2008
camera
dual
point light
C0
C1
C2
C3
C4
C5
C6
C7
scene

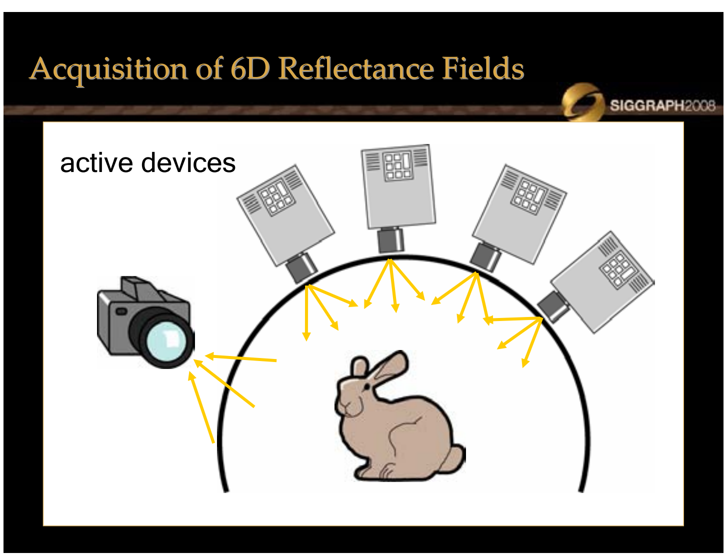

Dual Photography
SIGGRAPH2008
photograph
from camera
dual image
from projector
Computer Graphics
Computer Graphics
[Sen, Chen, Garg, Marschner, Horowitz, Levoy, Lensch - SIGGRAPH 2005]

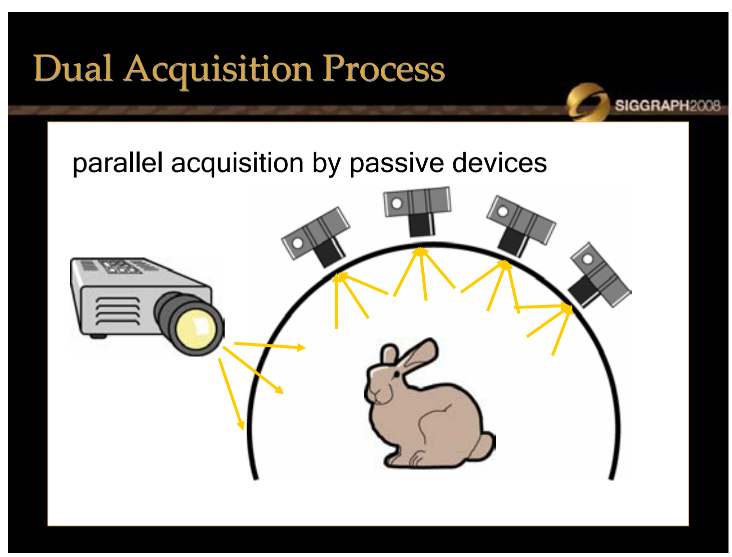

Examples
SIGGRAPH2008
primal
dual


Related Techniques
SIGGRAPH2008
• "Flying-spot" TV camera [Baird 1926]
• scanning electron microscope
35x magnification
[Museum of Science, Boston]
[Baird 1926]


Relighting with Dual Photography
SIGGRAPH2008
projector
primal
camera
T
4D
p
q
n
m
scene


Relighting with Dual Photography
SIGGRAPH2008
virtual camera
dual
virtual projector
T^T
4D
p
q
n
m
scene


Acquisition of 6D Reflectance Fields
SIGGRAPH2008
active devices

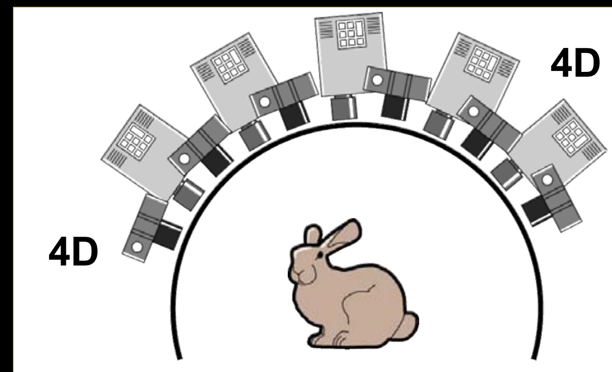

Dual Acquisition Process
SIGGRAPH2008
parallel acquisition by passive devices

Smooth Interpolation

100.000 images, 26 hours → model - 4.5GB

[Chen, Lensch - VMV2005]

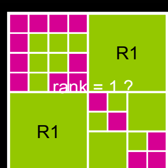
8D Reflectance Fields



arbitrary view point + arbitrary illumination

ℋ-Matrices

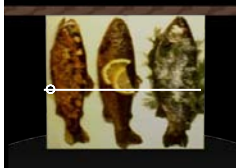
[Hackbusch2000]



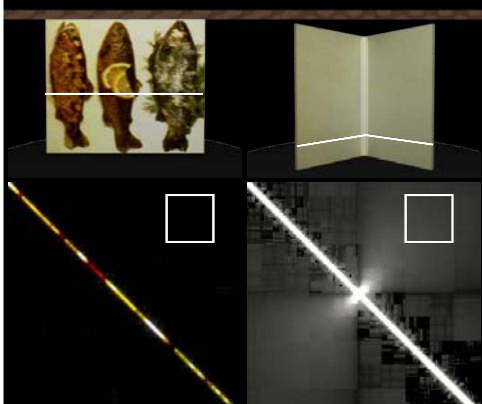
efficient representation of dense but *data-sparse* matrices

- subdivision hierarchy
- local low-rank approximation
- efficient evaluation

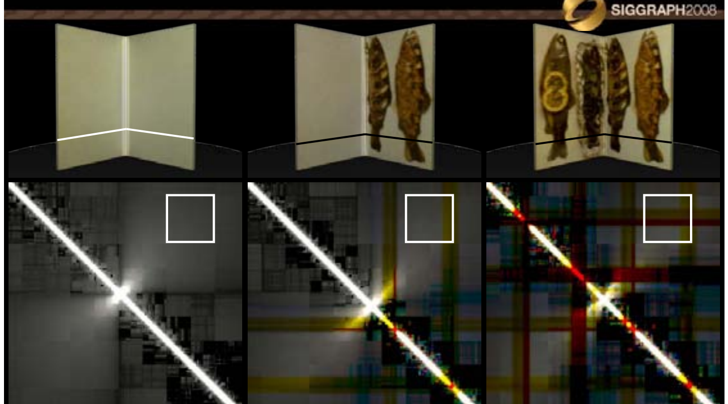
Direct vs. Indirect Reflections



Direct vs. Indirect Reflections

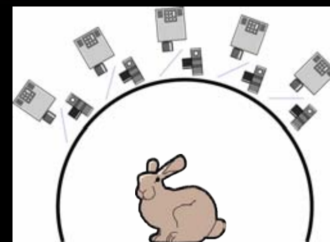


Direct vs. Indirect Reflections



2D Slices through a Reflectance Field

Symmetric Acquisition



- symmetric 8th order tensor
- rank-1 approximation from two images only
- parallel acquisition of dense matrices

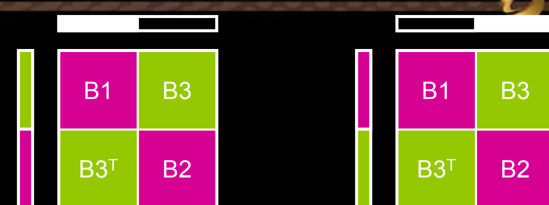
[Garg, Talvala, Levoy, Lensch – EGSR06]

Symmetric Exploration

B3 – row sums
B2 – rows+columns

B3 – column sums
B1 – rows+columns

Symmetric Exploration



B3 – row sums
B2 – rows+columns

B3 – column sums
B1 – rows+columns

rank-1 approximation?

Hierarchical Rank-1Decomposition

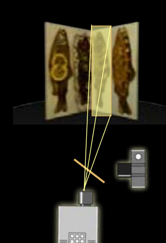
already determined

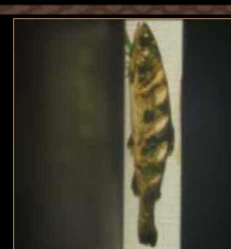
radiometrically independent

B1 and B2 are investigated in parallel.

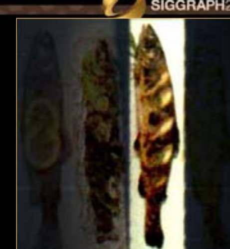
parallel acquisition even for dense matrices

Dual vs. Symmetric Photography





Dual Photography



Symmetric Photography

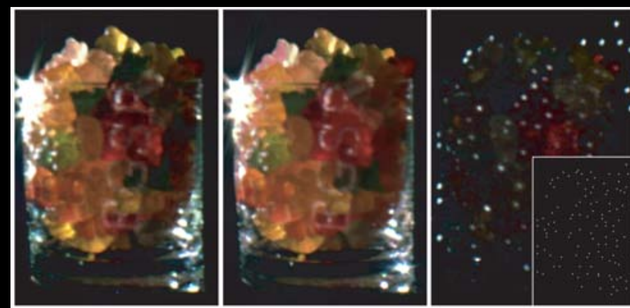
- increased SNR because regions are determined at large block sizes

An 8D Reflectance Field

3.300 images, 6 hours → model - 1.4 GB

Virtual Photography

- reflectance fields of arbitrarily complex scenes

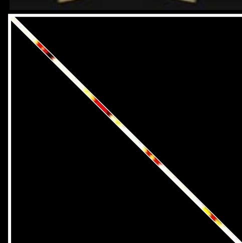


novel illumination | original | acquisiton pattern

[Garg, Talvala, Levoy, Lensch – EGSR 2006]

Application of Near-field Reflectance Fields

- getting rid of global effects



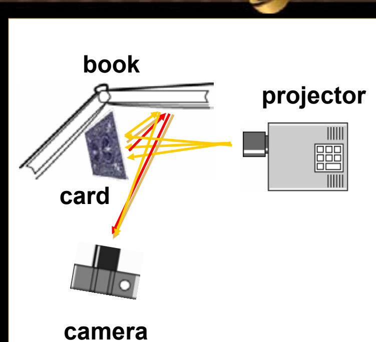
compare [Nayar2006]

Application to 3D Scanning

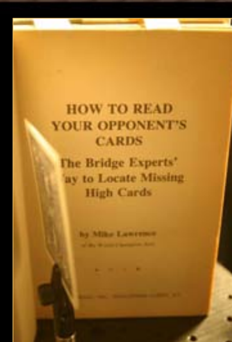
[Chen, Fuchs, Lensch, Seidel – CVPR 2007]

Card Experiment

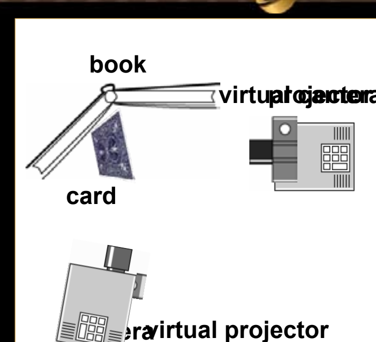
primal



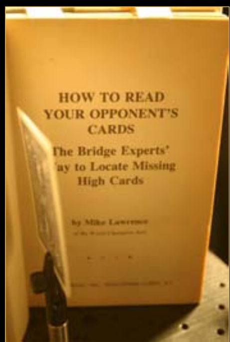
Card Experiment



primal



Card Experiment



primal

dual

Near-Field Reflectance Fields

- Sequential Sampling
- Dual Photography
- Symmetric Photography based on $\mathcal{H}$-matrices

- first methods for acquiring the global light transport in arbitrary scenes

Challenges

- densely sampled 8D reflectance fields
- upsampling / interpolation
- dynamic near-field reflectance fields
- interactive relighting
- global illumination with reflectance fields
- theory on the complexity of reflectance fields

Thanks

- BMBF (FKC01IMC01)
- DFG - Emmy Noether Program

Max Planck Center

mpii max planck institut informatik

http://mpi-inf.mpg.de/~lensch

The Human Face Scanner Project

Tim Weyrich
Princeton University

ICCV 2007 Tutorial — Rio de Janeiro, Oct 15, 2007

Facial Appearance Acquisition

"Grand challenge" in appearance acquisition:

- Complex reflectance and scattering properties
- *In vivo* measurements required
- High expectation by the observer
- Appearance editing desirable

Analysis of Human Faces

Analysis of Human Faces Using a Measurement-Based Skin Reflectance Model
[Weyrich et al. 2006]

joint work at ETH Zurich, Switzerland, and Mitsubishi Electric Research Laboratories, Cambridge, MA

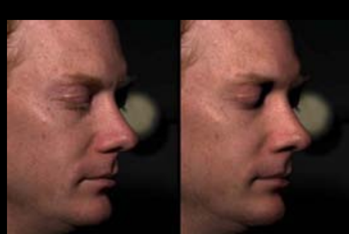
Photograph — Rendered

Objectives

- Capture facial appearance

Objectives

- Capture facial appearance
- Reconstruct realistic face models



Photograph — Rendered

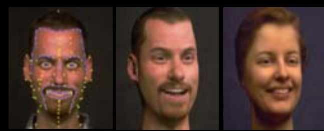
Objectives

- Capture facial appearance
- Reconstruct realistic face models
- High-level controls to alter appearance

Target Skin — Altered Appearance

Capturing Face Appearance

- Explicit Modeling
  - Geometry + texture
    [PIGHIN ET AL. 1998]

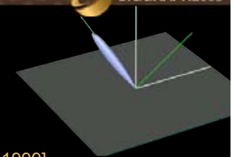


[PIGHIN ET AL. 1998]

- Image-based Methods
  - Reflectance fields
    [DEBEVEC ET AL. 2000],
    [HAWKINS ET AL. 2004]

[HAWKINS ET AL. 2004]

Skin Reflectance Models



- BRDF *(bi-directional reflectance distribution function)*
  - BRDF approximation of scattering
    [HANRAHAN AND KRUEGER 1993], [STAM 2001]
  - Image-based BRDF [MARSCHNER ET AL. 1999]
- BSSRDF *(bi-directional surface scattering reflectance distribution function)*
  - Single-layered skin model [JENSEN ET AL. 2001]
  - Multi-layered skin model [DONNER AND JENSEN 2005/2006]
- BTF *(bi-directional texture function)*
  - Spatially varying reflectance of skin patches
    [CULA AND DANA 2002]

Appearance Editing

- Image-based editing
  - Manual editing by skilled artists
  - Melanin/hemoglobin model
    [TSUMURA ET AL. 2003]

[TSUMURA ET AL. 2003]

- Morphable face model
  [BLANZ AND VETTER 1999],
  [FUCHS ET AL. 2005]

[BLANZ AND VETTER 1999]

Production Environment

- Gemini Man
  [WILLIAMS ET AL. 2005]
- Hulk, Harry Potter II
  [HERY 2003/2005]
- Matrix
  [BORSHUKOV 2003]
- Spider Man II
  [SAGAR ET AL. 2004]

© ILM [HERY 2003]

[BORSHUKOV 2003]

Project Contributions

- Acquisition hardware for the facial BSSRDF
  - Translucency measurements
  - Facial reflectance fields
- Practical skin model to be fitted
  - Simple, but realistic
  - Suited for production environments
- Analysis of physiological parameters
- Intuitive appearance editing framework

Outline

- Skin appearance acquisition
- Face data processing
- Reflectance Model Fit
- Reflectance Analysis
- Appearance Transfer

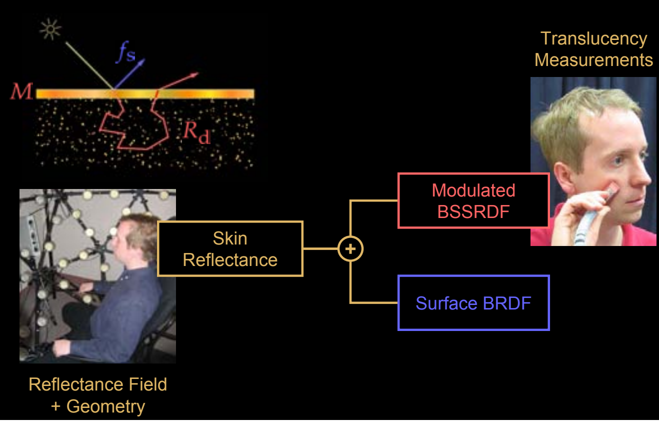
Skin Appearance

- Skin most important for facial appearance
- Main effects due to skin's translucent layers

Skin Appearance

- Skin most important for facial appearance
- Main effects due to skin's translucent layers
- Light transport affected by
  - Air/skin interface (reflectance/refraction)
  - Epidermis, Dermis (scattering/absorption)

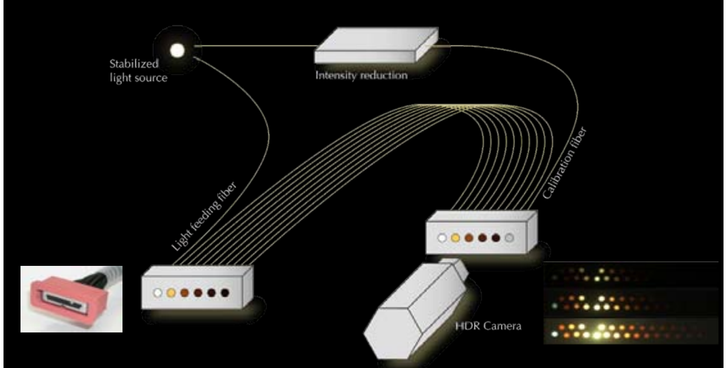
Reflectance Acquisition



"BSSRDF Gun"

- Subcutaneous light transport measurements
- Measures translucency (mean free path ℓ)
  - Contact measurements
  - Light transport through optical fibers
- Suction pump ensures contact

"BSSRDF Gun"



Reflectance Field Acquisition

- Spherical acquisition dome
  - 16 cameras @ 1300 x 1030
  - 150 LED light sources
  - Commercial 3D scanner

Reflectance Field Acquisition

- Spherical acquisition dome
  - 16 cameras @ 1300 x 1030
  - 150 LED light sources
  - Commercial 3D scanner
- Dual-exposure HDR

Reflectance Field Acquisition

SIGGRAPH2008

- Spherical acquisition dome
  - 16 cameras @ 1300 x 1030
  - 150 LED light sources
  - Commercial 3D scanner
- Dual-exposure HDR
- 25 seconds

Sample Reflectance Field

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(images before radiometric correction)

Outline

SIGGRAPH2008

- Skin appearance acquisition
- Face data processing
- Reflectance Model Fit
- Reflectance Analysis
- Appearance Transfer

Overview

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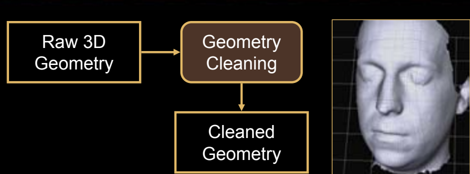
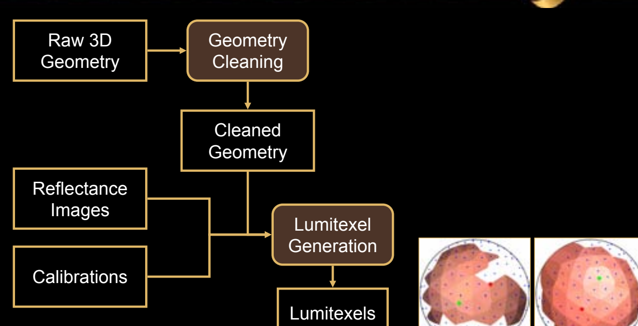
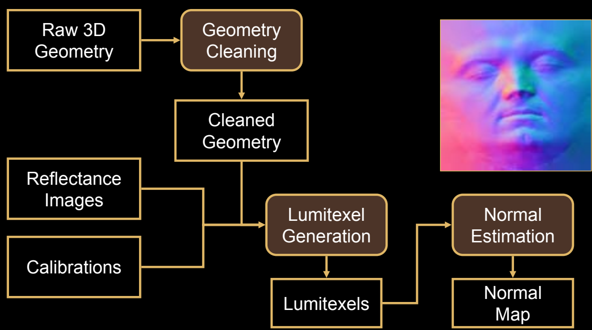


Overview

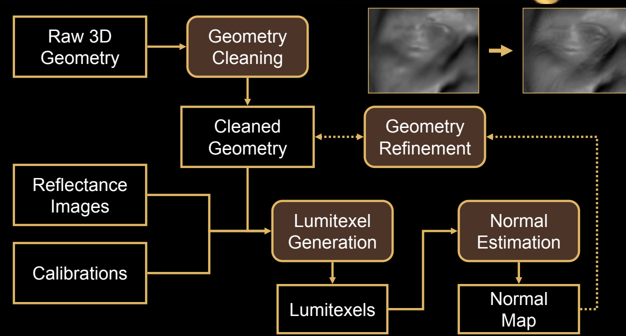
SIGGRAPH2008



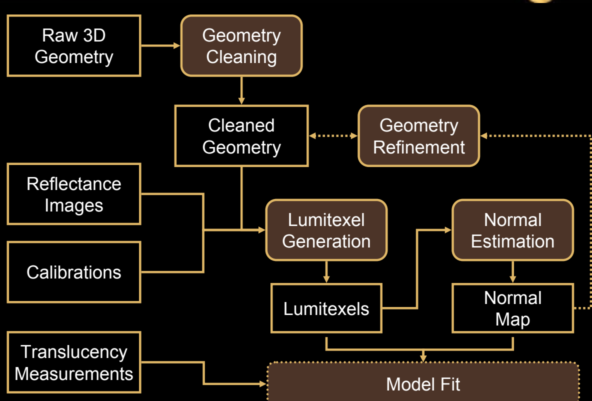
Overview



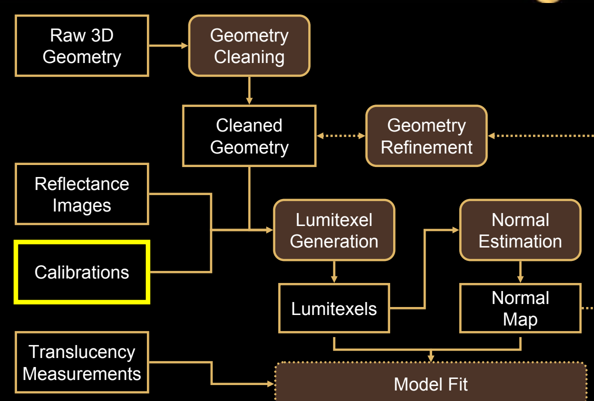
Overview



Overview



Overview



Camera Calibration

- Intrinsics
  - Using Intel OpenCV library
  - Based on checker-board images
- Extrinsics
  - n-camera calibration (n = 16)
  - Euclidian bundle optimization
  - Correspondences from LED swept through volume

Camera Calibration

- Vignetting & color calibration
  - Radial image intensity fall-off
  - Relative sensor calibration of all cameras
  - Affine color correction model [FUNT 2000]
  - Equalizes images taken under identical conditions
- Radiometric calibration
  - Implicitly through light source calibration

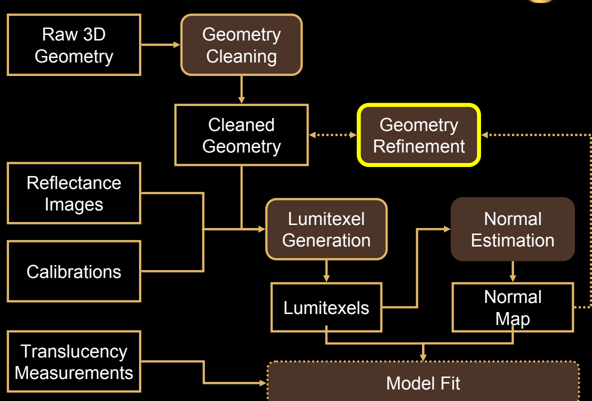
Light Source Calibration

- Desired parameters
  - Light source color
  - Light cone fall-off
- Fluorilon™ reflectance target
  - Perfect diffuse reflector
  - Reflects 99.9% of incident radiance
- Reflectance fields of different orientations
- Fitting 2nd-order polynomial to spot cross-section

"BSSRDF Gun" Calibration

- Relative fiber transmittance
  - Light table with opal glass diffuser
- Black image calibration
- Irradiance calibration
  - Skim milk as secondary standard
  - Values as measured by [JENSEN ET AL. 2001]

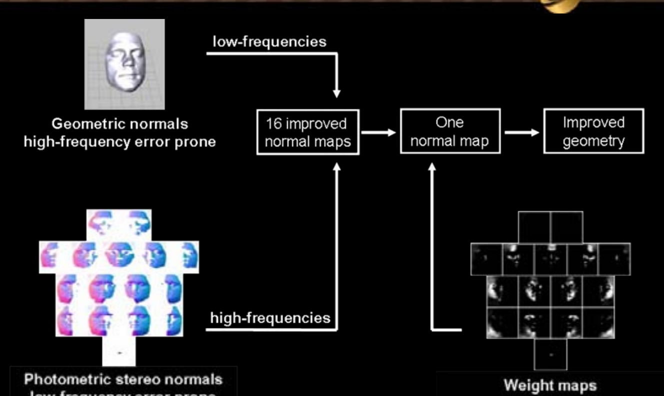
Overview



Geometry Refinement

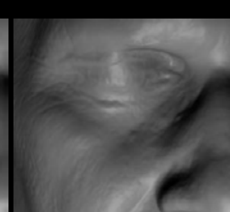
- Geometry and normal information crucial
- Normal estimation
  - Photometric stereo
  - Lambertian assumption
  - Problem: bias, discontinuities
- Normal and geometry improvement adapting [NEHAB ET AL. 2005]

Geometry Refinement



Geometry Refinement

3D Scanner



Improved geometry

Photograph

Outline

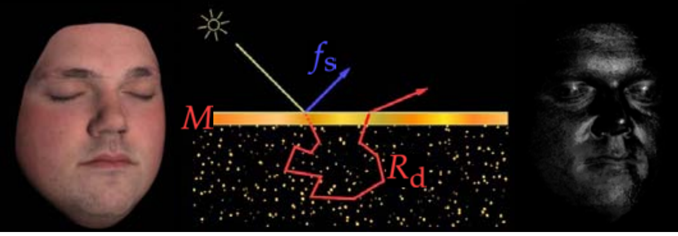
- Skin appearance acquisition
- Face data processing
- Reflectance Model Fit
- Reflectance Analysis
- Appearance Transfer

Skin Reflectance Model

Skin Reflectance

Diffuse Subsurface Scattering (BSSRDF)

Specular Reflection (BRDF)



Skin Reflectance Model

Skin Reflectance

Diffuse Subsurface Scattering (BSSRDF)

Specular Reflection (BRDF)

Dipole Approximation
[JENSEN ET AL. 2001]

- Analytic model
- Isotropic scattering in homogeneous materials
- Modulation texture M
[GOESELE ET AL. 2004]

Torrance-Sparrow BRDF

- Physically based
- Micro-facets

Model Fit

Skin Reflectance

Diffuse Subsurface Scattering (BSSRDF)

Specular Reflection (BRDF)

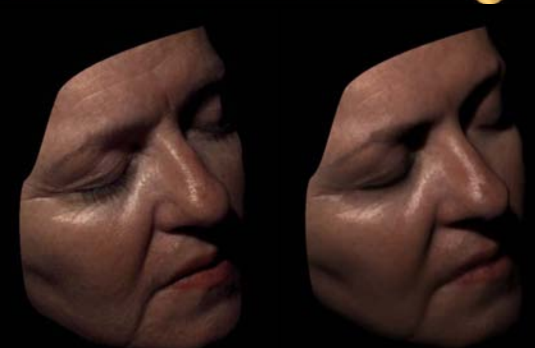
+

Translucency measurements

Face Reconstruction

Photograph Reconstruction

Reconstruction



Photograph Reconstruction

Reconstruction

Face Reconstruction

Face Reconstruction

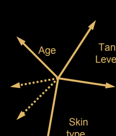
Outline

- Skin appearance acquisition
- Face data processing
- Reflectance Model Fit
- Reflectance Analysis
- Appearance Transfer

The Face Database

- Scanned 149 subjects

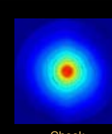
- Classification by
  - Skin type, gender, age, …
  - Facial region

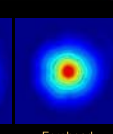


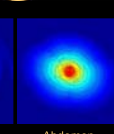
- Analysis of variation in model parameters

Translucency Variance

- Model validation
  - Facial scattering is isotropic





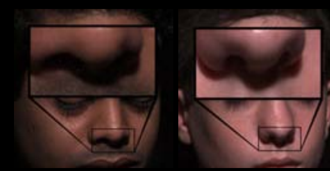


Translucency Variance

- Model validation
  - Facial scattering is isotropic
- Spatial translucency variance minute

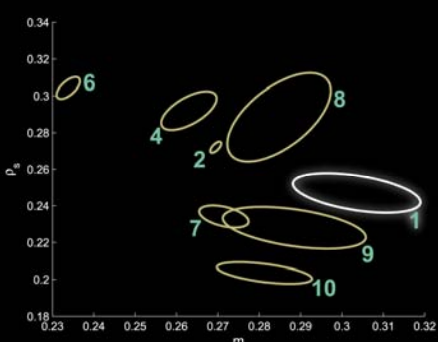
Translucency Variance

- Model validation
  - Facial scattering is isotropic
- Spatial translucency variance minute
- Inter-subject variance negligible
  - Small variance between males and females

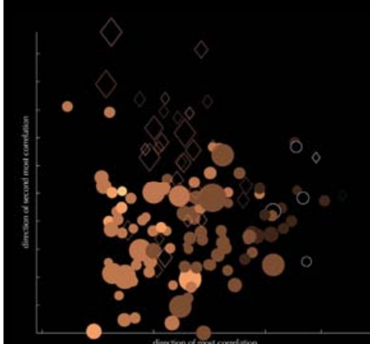


Min Translucency   Max Translucency

Spatial BRDF Variance



Skin Trait Variations



(o/◊) = (m/f), size = age, color = skin type

- Canonical Correlation Analysis (CCA)
  - Directions of maximal correlation in BRDF parameter space
- BRDF: correlates with *skin type* and *gender*
- Albedo: highly correlated with *skin type*

Outline

- Skin appearance acquisition
- Face data processing
- Reflectance Model Fit
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- Appearance Transfer

Appearance Editing

- From parameter observations derive intuitive user controls
  - Main tool: texture synthesis [HEEGER AND BERGEN 1995], [MATUSIK ET AL. 2005]
  - Applicable to all model parameter types
  - Add freckles, moles, gloss variations, …
- General appearance editing framework

Results Appearance Transfer

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Target face   Freckles applied

Results Appearance Transfer

SIGGRAPH2008

Target face   Changed skin type

Results Appearance Transfer

SIGGRAPH2008

Target face   Lotion applied, Stubbles reduced

Contributions

SIGGRAPH2008

- Acquisition hardware for the facial BSSRDF
  - Translucency measurements
  - Facial reflectance fields
- Practical skin model to be fitted
  - Simple, but realistic
  - Suited for production environments
- Analysis of physiological parameters
- Intuitive data-driven appearance editing framework
- Published appearance database of human faces

Potential Extensions

SIGGRAPH2008

- Facial hair
  - Eye-brows, eye-lashes
  - Beard, stubbles
  - Velvety hair

- Spectral measurements
- Multi-layered model using additional model assumptions (e.g. [Donner and Jensen 2006])
- *Will increasing measurement accuracy increase the perceived degree of realism?*

Q & A

Appearance database online at:

http://www.merl.com/facescanning/