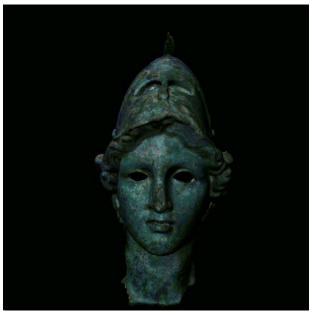
Reflectance Fields and Transport Matrices

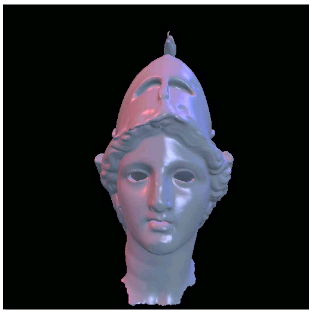
Digitizing Real World Objects

images – no interaction



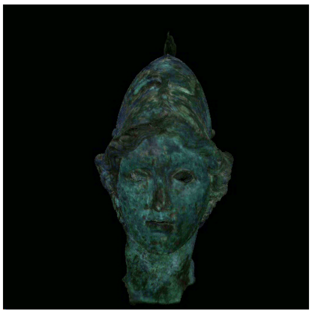
Digitizing Real World Objects

3D geometry – no color

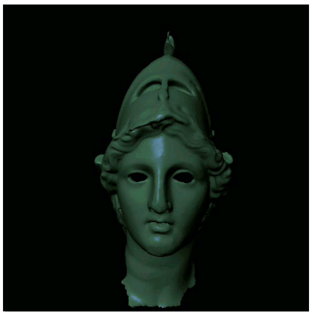


Digitizing Real World Objects

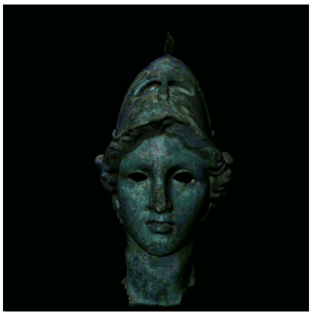
3D geometry plus texture – no relighting



Single Material - BRDF

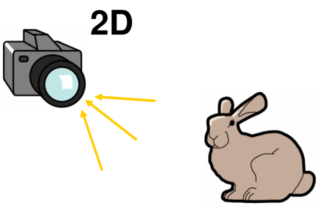


Spatially Varying Material - SVBRDF



Digitizing Real-World Objects

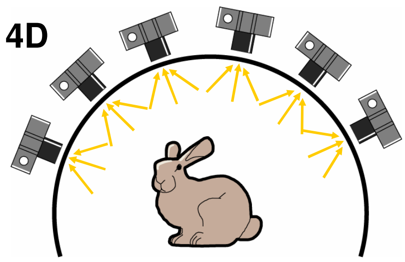
taking a picture



scene

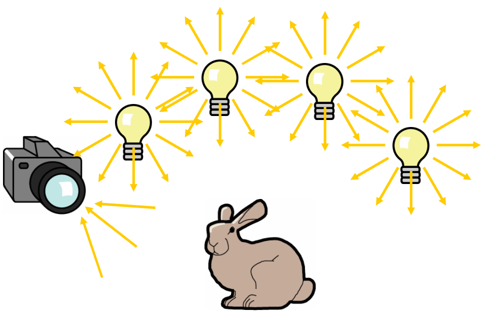
Light Field

[Gortler96], [Levoy96]



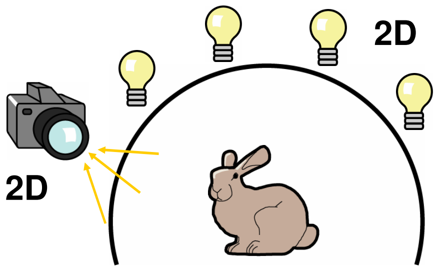
captures the distribution of all outgoing light rays

Relighting



4D Reflectance Field

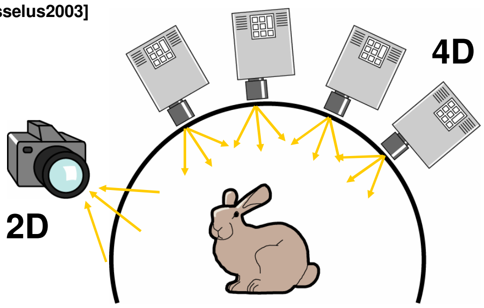
[Debevec2000]



captures the scene for every light direction

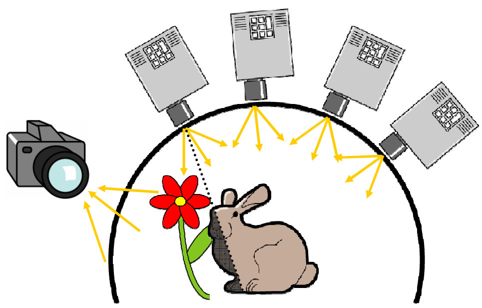
6D Reflectance Field

[Masselus2003]



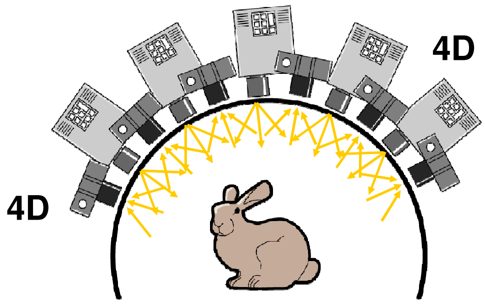
rendering with 4D incident light fields

6D Reflectance Field



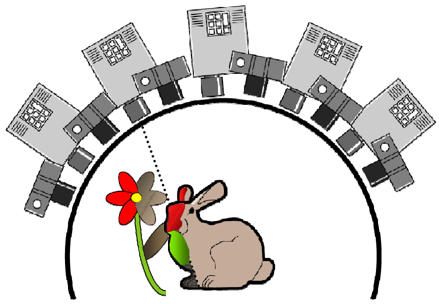
allows for projected light patterns, e.g. shadows

8D Reflectance Field



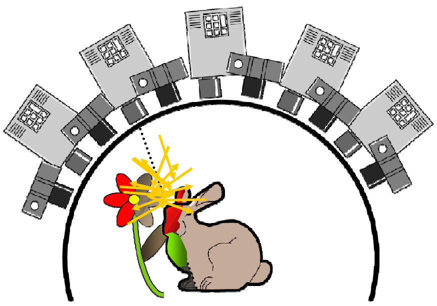
arbitrary viewing and lighting

8D Reflectance Field



8D necessary to synthesize interreflections

8D Reflectance Field

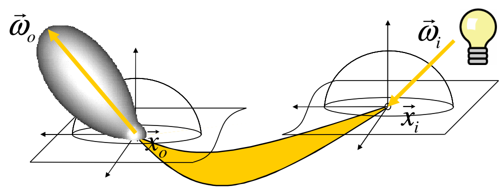


8D necessary to synthesize interreflections

Definition – Reflectance Field

8D function

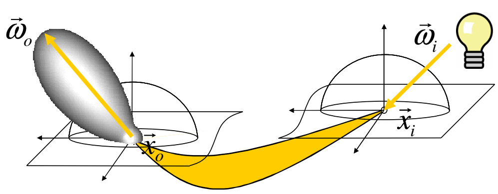
$$f_r((\vec{x}_i, \vec{\omega}_i) \rightarrow (\vec{x}_o, \vec{\omega}_o))$$



Definition – Reflectance Field

ratio of reflected radiance to incident flux

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



Reflectance Field

Radiant light field from A under every possible incident field of illumination.

8 dimensional reflectance field function:

R = R(Ri ; Rr) = R(ui, vi, θi, ϕi ; ur, vr, θr, ϕr)

R(ui, vi, θi, ϕi) → incident light field arriving at A

R(ur, vr, θr, ϕr) → radiant light field leaving A

The Rendering Equation

[Kajiya et al. 1986]

$$L_o(\vec{x}_o,\vec{\omega}_o) = L_e(\vec{x}_o,\vec{\omega}_o)$$
$$+\int_{A_i}\int_{\Omega_i} f_r\big((\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o)\big)L_i(\vec{x}_i,\vec{\omega}_i)\cos\theta_i d\omega_i dx_i$$

How can we measure a reflectance field?

PROBLEM

data in… an *8D function*

- **using** only **100 samples in each dimension**
  - **→ 10^{16} samples (12bytes/sample) = 109,139 TB**
- **largest scanned 3D geometry: 10^8 points**

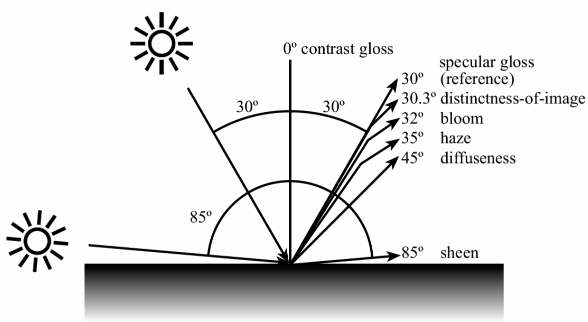
no solution for the full problem (yet)

Approaches

data is coherent in large parts
correlation

explore lower actual dimensionality of the data
restrict reflectance model
restrict viewing or illumination capabilities
adaptive parallel acquisition

Gloss Model

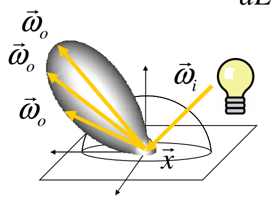


BRDF – 6D

(bidirectional reflectance distribution function)

ratio of reflected radiance to incident irradiance

$$f_r(\vec{x}; \vec{\omega}_i \rightarrow \vec{\omega}_o) = \frac{dL(\vec{x}, \vec{\omega}_o)}{dE(\vec{x}, \vec{\omega}_i)}$$



BRDF Models

- tabulated
- analytic
- factorized
- spherical harmonics
- data-driven

4D-BRDF Measurement

Gonioreflectometer

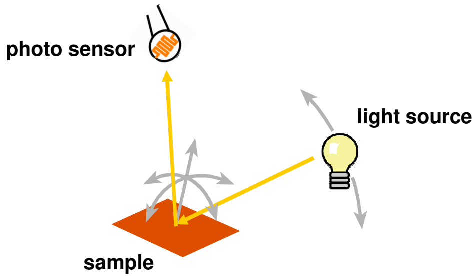


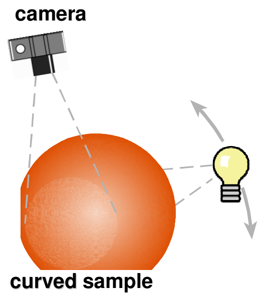
Image-Based BRDF Measurement

[Ward92], [Marschner99], [Lu&Koenderink99]

capture lots of BRDF samples at one shot by a sensor array/camera

homogeneous materials only!

How to get spatially varying materials ?



Clustering of Materials

Spatially Varying Materials

Projection – good Title

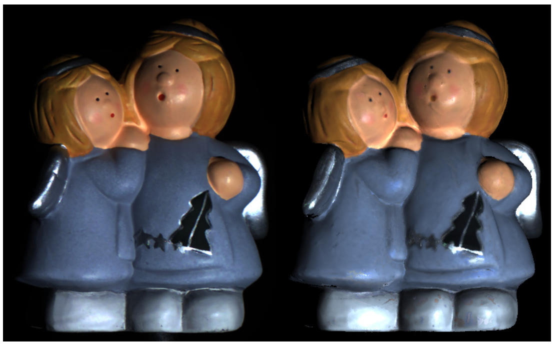
goal: assign separate BRDF to each surface point

- **too few reflectance samples for reliable fit**
- **represent the BRDF of each point by a weighted sum of basis BRDFs:**

$$f_r(\vec{x}) = t_1 f_1 + t_2 f_2 + \ldots + t_m f_m$$

- **this is a *linear* problem**

SBRDF - Results

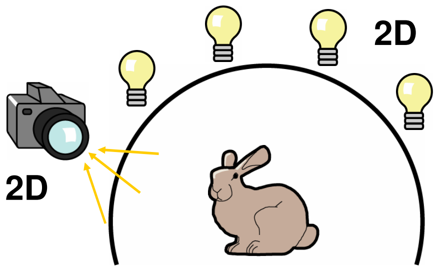


SBRDF - Results

33 images, 2 hours → 120MB model

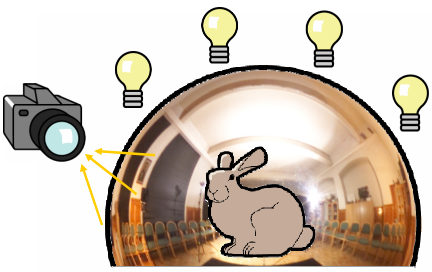
4D Reflectance Field

[Debevec2000]



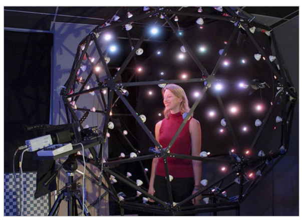
captures the scene for every light direction

4D Reflectance Field



allows for distant lights only

Light Stage



[Debevec2000]

single view point

assumes distant light sources

cannot relight with cast shadows

Performance Relighting

[Peers – SIGGRAPH 07]

video

Environment Matting

[Zongker et al. 1999]

Extension of Alpha Matting capable of capturing transparent and specular objects for one view.

Allows for reproduction with arbitrary backdrops.

A high-resolution 4D reflectance field.


Traditional Alpha Matte

$$C = F + (1-\alpha)B$$

Composite color C

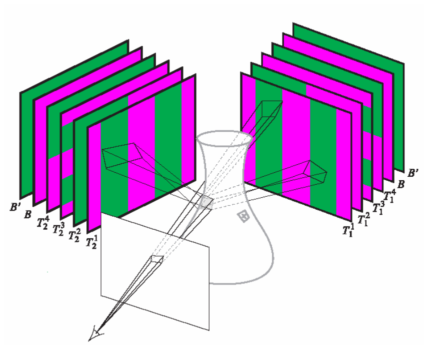
Foreground color F

Background color B

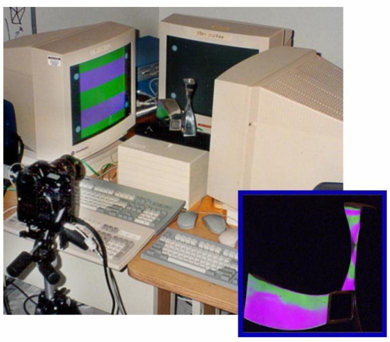
Pixel coverage α

Acquired by blue/green screening

Environment Matte Acquisition



Environment Matting Acquisition



Environment Matting Definition

Add reflected and refracted rays (sum over backdrops)

$$C = F + (1-\alpha)B + \sum_{i=1}^{m} R_i M(T_i, A_i)$$

Reflectance R

Texture T

Axis-aligned area A

Averaging operator $M(T, A)$

Environment Matte Extensions

Gaussian Filter kernel [Chuang et al. 2000]

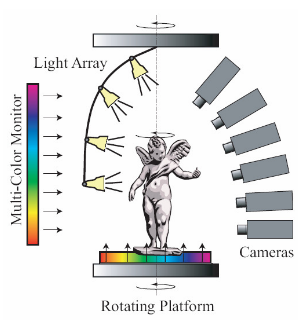
Real-time acquisition [Chuang et al. 2000]

Wavelets in acquisition [Peers et al. 2003]

Multiple View Points (Opacity hulls)
[Matusik 2002]

Opacity Hulls [Matusik 2002]

combines Debevec's reflectance fields with environment mattes (~ 60,000 images).



Opacity Hulls [Matusik 2003]

combines Debevec's reflectance fields with environment mattes.

Bidirectional Texture Functions (BTFs)

[Dana et al. 1999]

Reflectance field of a planar texture

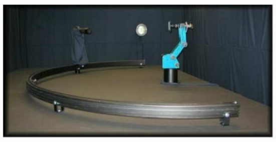
Replicated over a synthetic surface

Captures shadowing and masking effects due to macro structure.

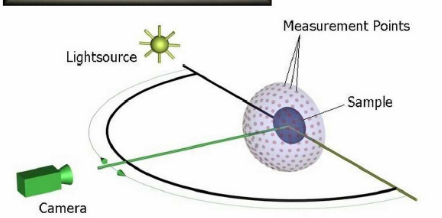
(Tabulated Spatially Varying BRDF)

No geometry at silhouettes

BTF Acquisition

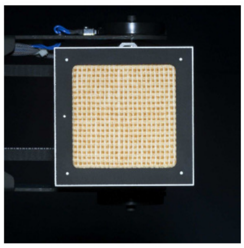


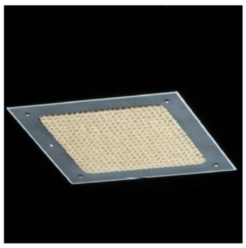
[Sattler et al. 2003]



BTF Acquisition

Material sample

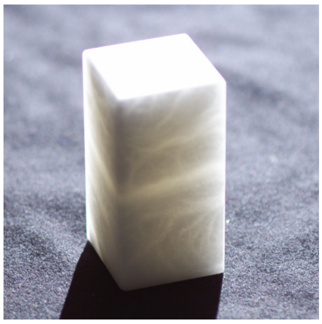




BTF - Rendering

virtual prototyping [Gero Müller2005]

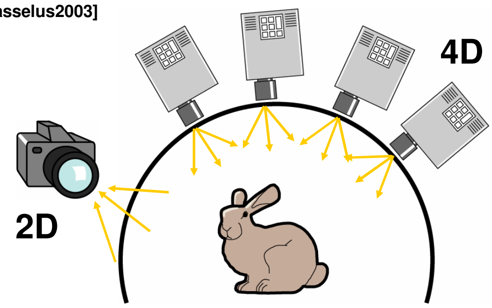
What about this?



... requires per-ray measurements

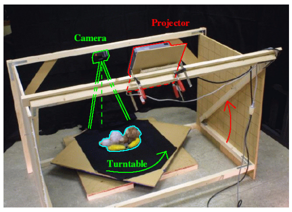
6D Reflectance Field

[Masselus2003]



rendering with 4D incident light fields

Relighting with 4D Incident Light Fields



[Masselus2003]

6D reflectance field

spatially varying illumination

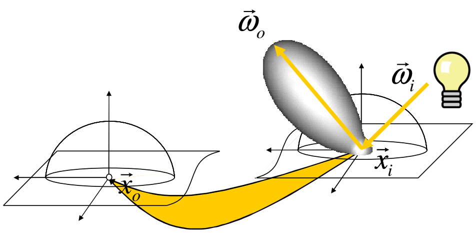
low resolution 16x16

~20 hours/acquisition

Subsurface Scattering

light penetrates the surface

light scatters inside the object

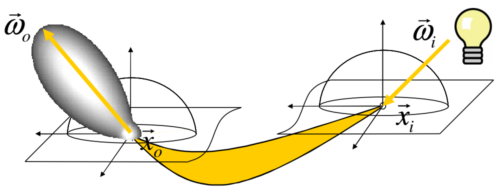


BSSRDF – 8D

bidirectional scattering-surface reflectance distribution function [Nicodemus77]

= Reflectance Field

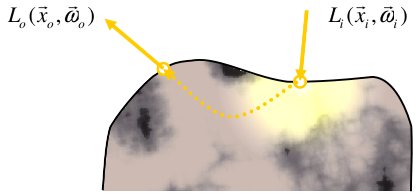
$$f_r((\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o))=\frac{dL_o(\vec{x}_o,\vec{\omega}_o)}{d\phi_i(\vec{x}_i,\vec{\omega}_i)}$$



Modeling Translucent Objects

BSSRDF – 8D

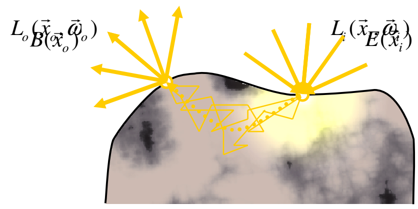
$$f_r\left((\vec{x}_i, \vec{\omega}_i) \rightarrow (\vec{x}_o, \vec{\omega}_o)\right)$$



Diffuse Approximation

neglect directional dependence [Jensen 2001]

- **frequent scattering events in optically dense media lead to diffuse scattering inside the media**

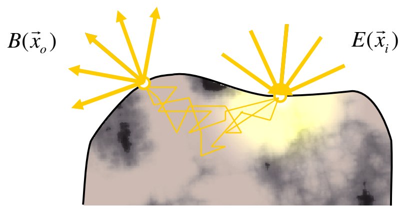


Diffuse Approximation

diffuse reflectance function

$$R_d(\vec{x}_i, \vec{x}_0)$$

- **only 4 dimensions**
- **possible to acquire**



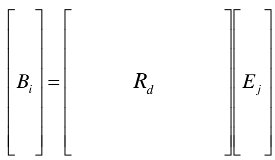
Diffuse Reflectance Function R_d

discretize the surface

- **enumerate all points on the surface**
- **vectors of irradiance E and radiosity B**

represent R_d as matrix

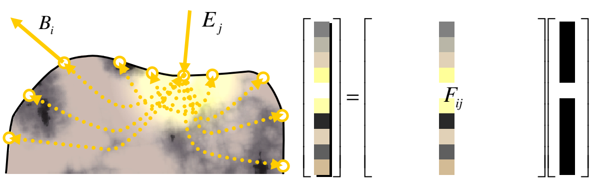
- **light transport** or each pair of points
- **linear transport**



Key Idea

directly record F_{ij} for real objects

- **illuminate individual surface points of an object**
- **record impulse response function**
- **results in a point-to-point throughput factor matrix**



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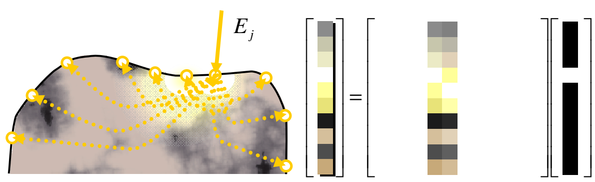

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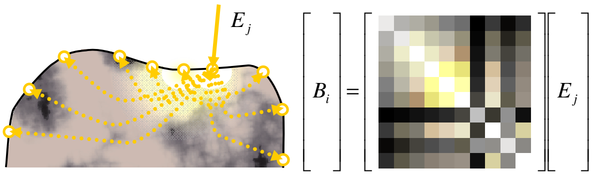


Results

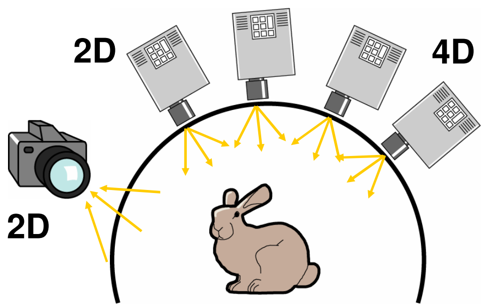

photograph


rendering

Results [SIGGRAPH 2004]

1,000,000 images, 22hours → 800MB model

Fixed View + Arbitrary Lighting



Approach

goals:

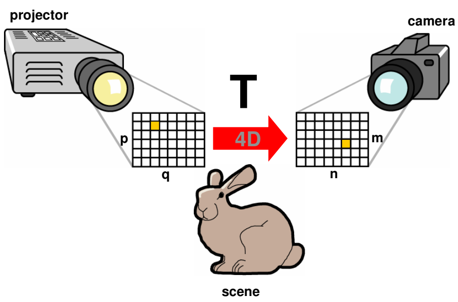
- no constraint on the type of scene
- high resolution

1,200,000 pictures for each projector

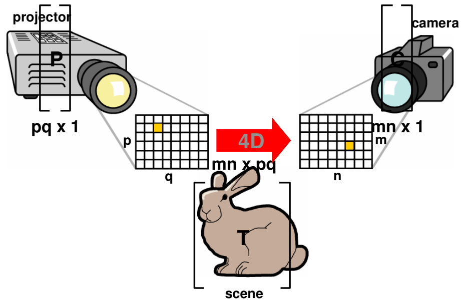
explore sparseness through adaptive multiplexed acquistion

exploit Helmholtz reciprocity

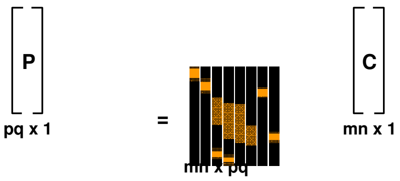
Pixel-to-Pixel Transport



Mathematical Notation



Mathematical Notation



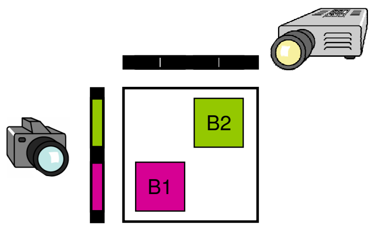
matrix properties

- little interreflection ↔ T rather sparse
- many interreflections ↔T rather dense

Adaptive Parallel Acquisition

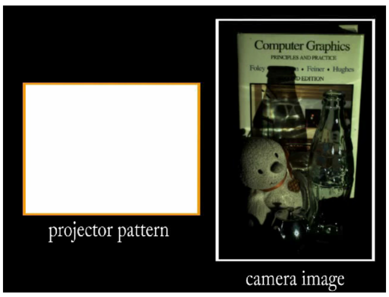
assumption: sparse matrix

radiometrically independent blocks can be sensed in parallel



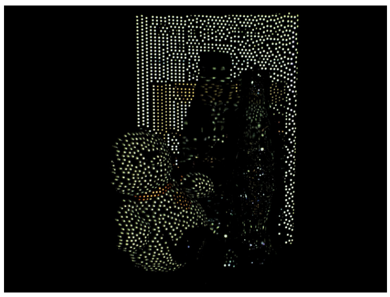
Adaptive Multiplexed Acquisition

parallel investigation if regions do not overlap in camera image



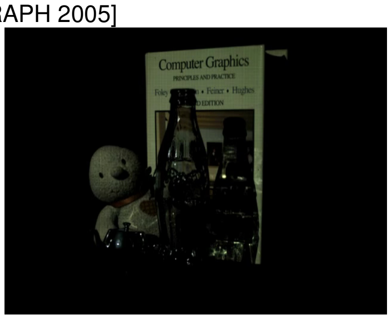
Adaptive Acquisition

parallel investigation if regions do not overlap in camera image

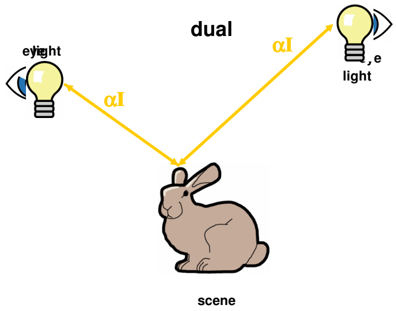


Relighting with 2D Patterns

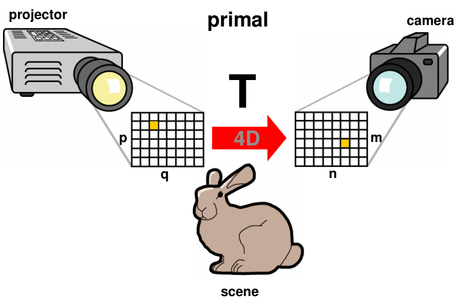
[SIGGRAPH 2005]



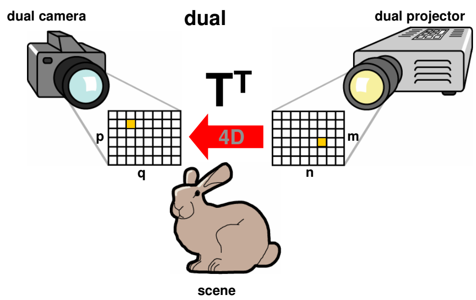
Helmholtz Reciprocity



Dual Photography for Relighting

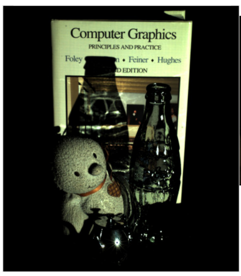


Dual Photography for Relighting

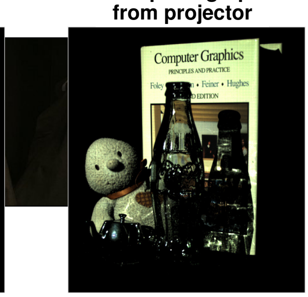


Using the Transposed T Matrix

standard photograph from camera



dual photograph from projector



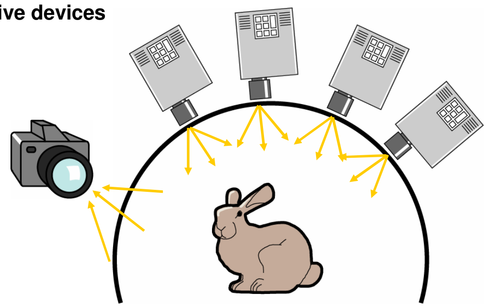
Sample Results

primal

dual

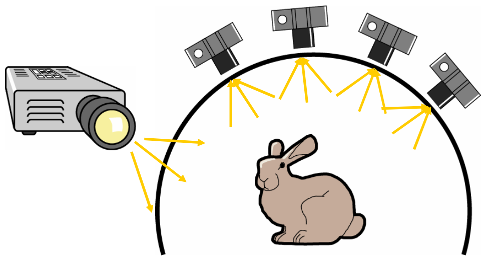
Capturing 6D Reflectance Fields

active devices

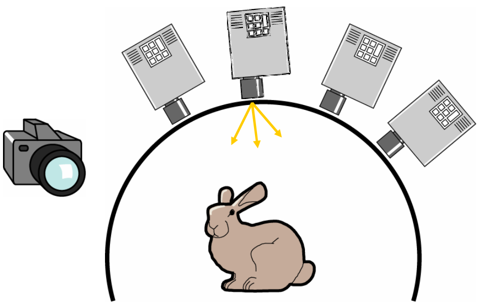


Dual Capture Process

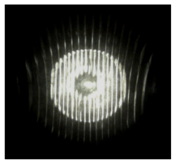
parallelization using passive devices



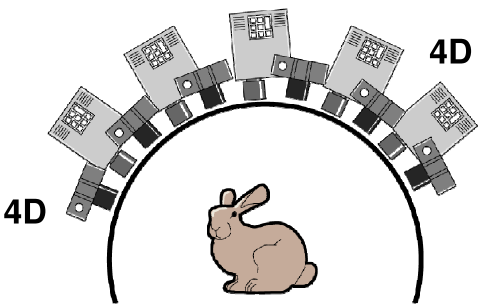
Light Source Interpolation [VMV2005]



Relighting with 4D Incident Light Fields



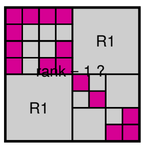
8D Reflectance Fields



arbitrary view point + arbitrary illumination

$\mathcal{H}$-Matrices

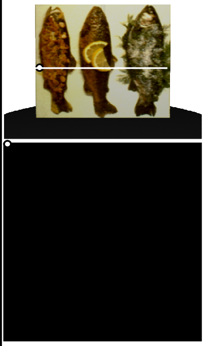
[Hackbusch2000]



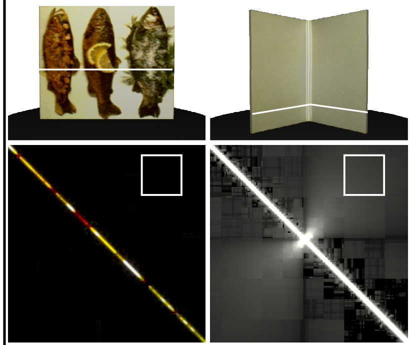
efficient representation of dense but *data-sparse* matrices

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

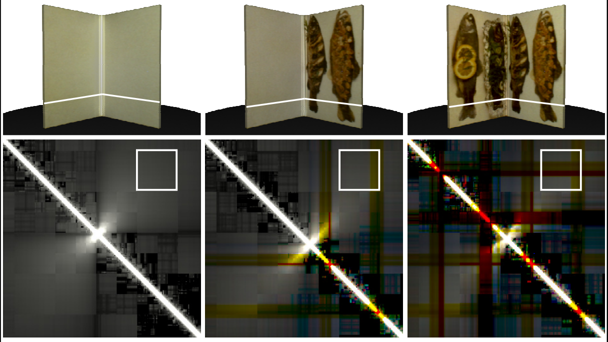
Direct vs. Indirect Reflexions



Direct vs. Indirect Reflexions

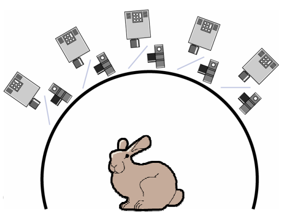


Direct vs. Indirect Reflexions



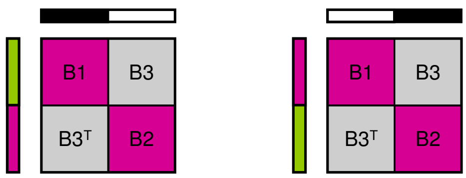
2D Slices through a Reflectance Field

Symmetric Acquisition



symmetric 8^{th}
rank-1 approximation from two images only
parallel acquisition of dense matrices

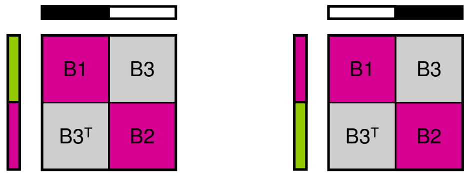
Symmetric Exploration



B3 – row sums
B2 – rows+columns

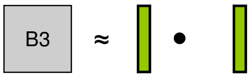
B3 – column sums
B1 – rows+columns

Symmetric Exploration



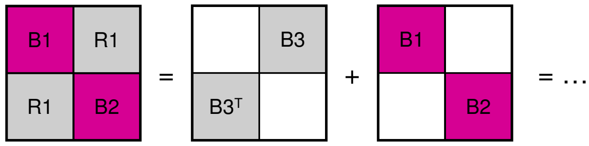
B3 – row sums
B2 – rows+columns

B3 – column sums
B1 – rows+columns

rank-1 approximation? 

Computational Photography   Hendrik Lensch, Summer 2007

Hierarchical Rank-1Decomposition



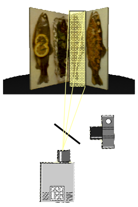
already determined   radiometrically independent

B1 and B2 are investigated in parallel.

parallel acquisition even for dense matrices

Computational Photography   Hendrik Lensch, Summer 2007

Dual vs. Symmetric



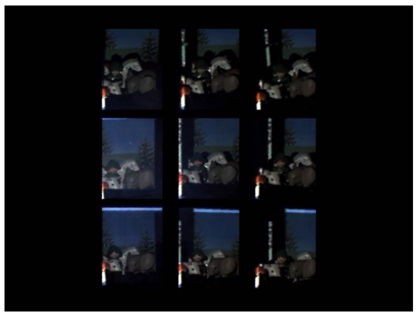
Dual Photography

Symmetric Photography

Computational Photography   Hendrik Lensch, Summer 2007

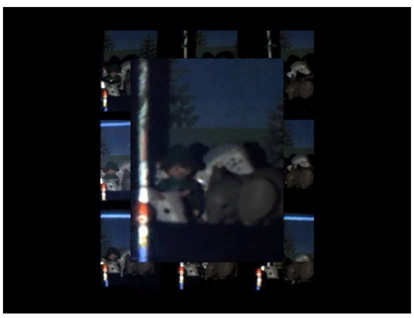
An 8D Reflectance Field

3.300 images, 6 hours → model – 1.4 GB



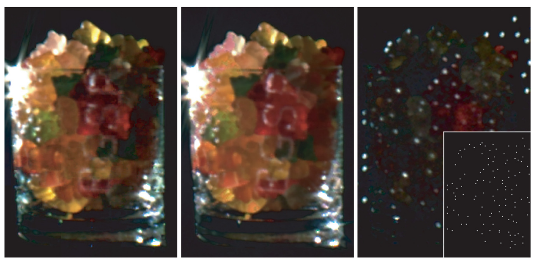
Computational Photography   Hendrik Lensch, Summer 2007

An 8D-Reflectance Field



Computational Photography   Hendrik Lensch, Summer 2007

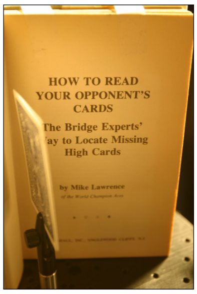
Virtual Photography



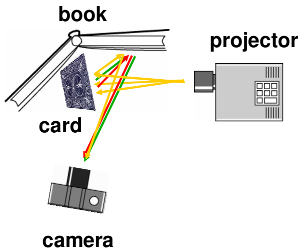
novel illumination   original   acquisiton pattern

Computational Photography   *[Garg, Talvala, Levoy, Lensch – EGSR 2006]*

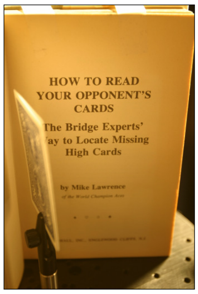
Card Experiment



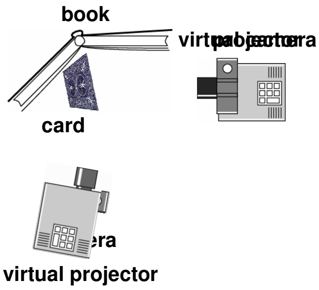
primal



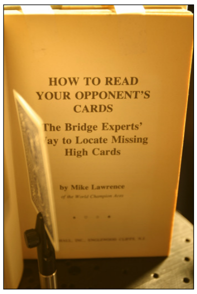
Card Experiment



primal



Card Experiment



primal

dual

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