Light Transport Analysis

Introduction to Computational Photography

EECS 395/495

Northwestern University

Today

- Light Transport: Overview
- Image Relighting & Dual Photography
- Direct & Global Illumination Analysis

What is Light Transport?

object

What is Light Transport?

- 4D incident light field

$R_i(u_i , v_i , \theta_i , \phi_i)$

incident light field

What is Light Transport?

- 4D exitant light field

$$R_r(u_r, v_r, \theta_r, \phi_r)$$

exitant light field

What is Light Transport?

- 8D reflectant field

$$R(u_i, v_i, \theta_i, \phi_i ; u_r, v_r, \theta_r, \phi_r)$$

Since it is linear, we can represent as a matrix

Reflectance Field Storage Requirements

$$R(u_i, v_i, \theta_i, \phi_i ; u_r, v_r, \theta_r, \phi_r)$$

- 360 x 180 x 180 x 180 x 360 x 180 x 180 x 180
- = 4.4e18 measurements
- x 6 bytes/pixel (in RGB 16-bit)
- = 26 exabytes (billion GB)
- = 82 million 300GB hard drives
- (41 million if we exploit Helmholz Reciprocity)

What is Light Transport

- Light transport matrix is very sparse

- Usually focus on subsets of the 8-D light transport
  - image relighting (4D)
  - dual photography (4D)

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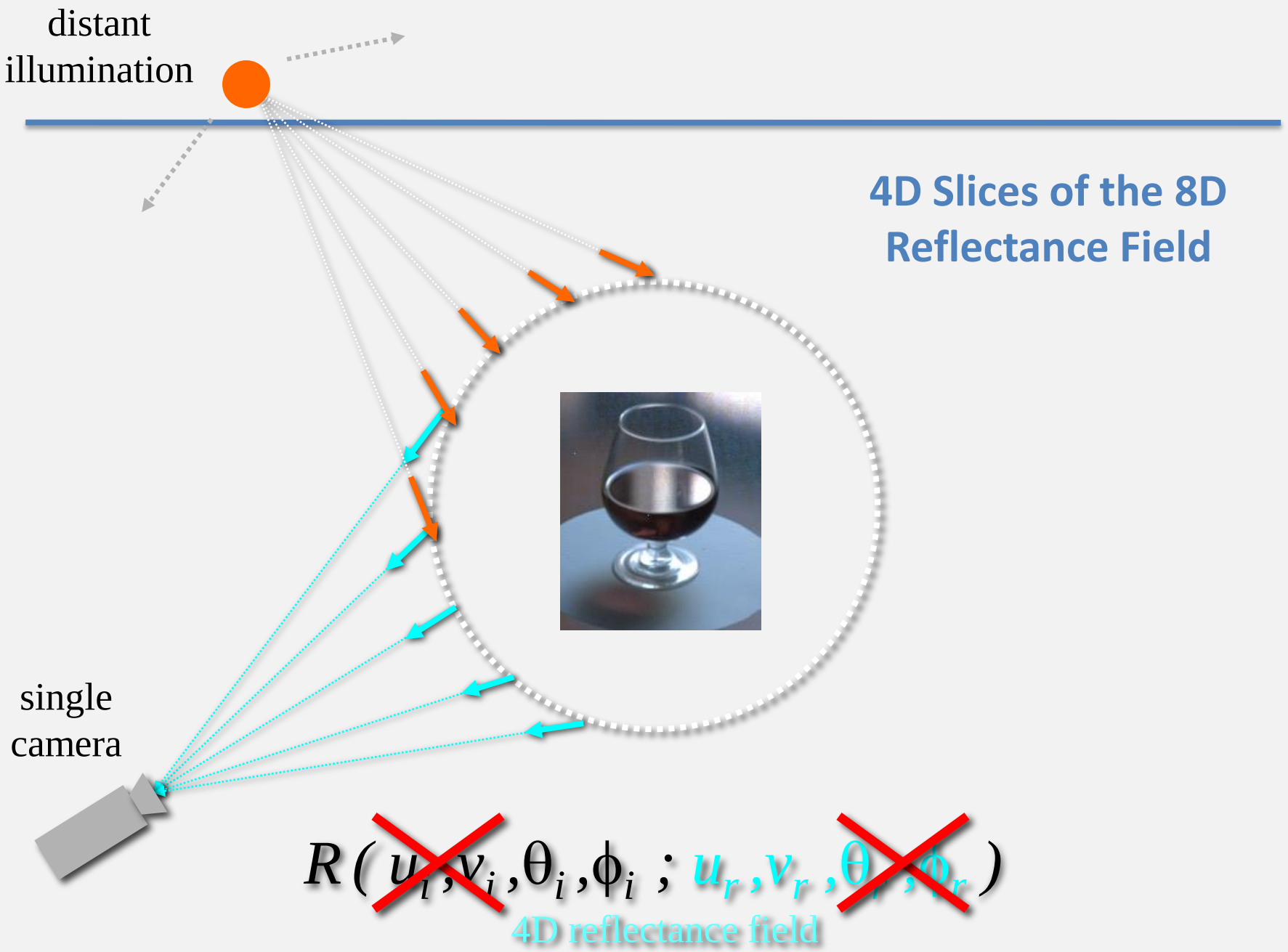

distant
illumination
single
camera
4D Slices of the 8D
Reflectance Field
$R(u_i, v_i, \theta_i, \phi_i ; u_r, v_r, \theta_r, \phi_r)$
4D reflectance field

Relighting – Linear Combination

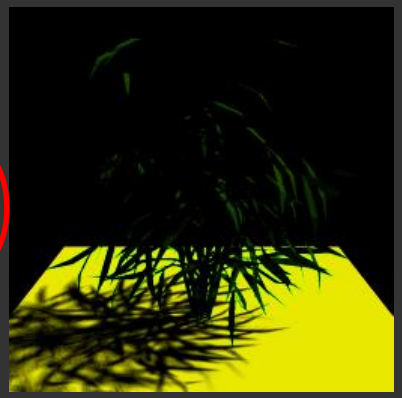
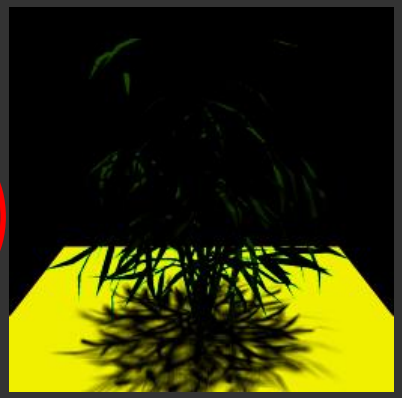
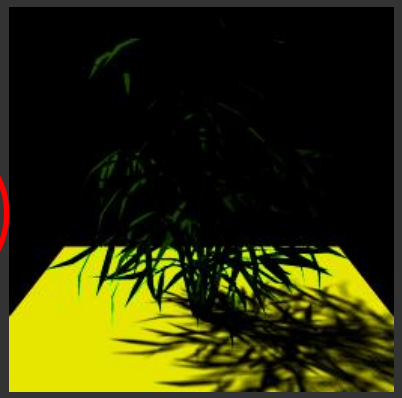
Nimeroff et al 94

Hallinan 94

Dorsey 95

=

Lighting Intensities

l_1  + l_2  + ... + l_N 

Images lit by directional light sources

Relighting – Matrix Vector Multiply

$$\begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_M \end{bmatrix} = \begin{bmatrix} & & & \\ & & & \\ & T & & \\ & & & \end{bmatrix} \begin{bmatrix} L_1 \\ \vdots \end{bmatrix}$$

Output Image Vector

$T_1 \quad T_2 \quad \cdots \quad T_N$

Transport Matrix

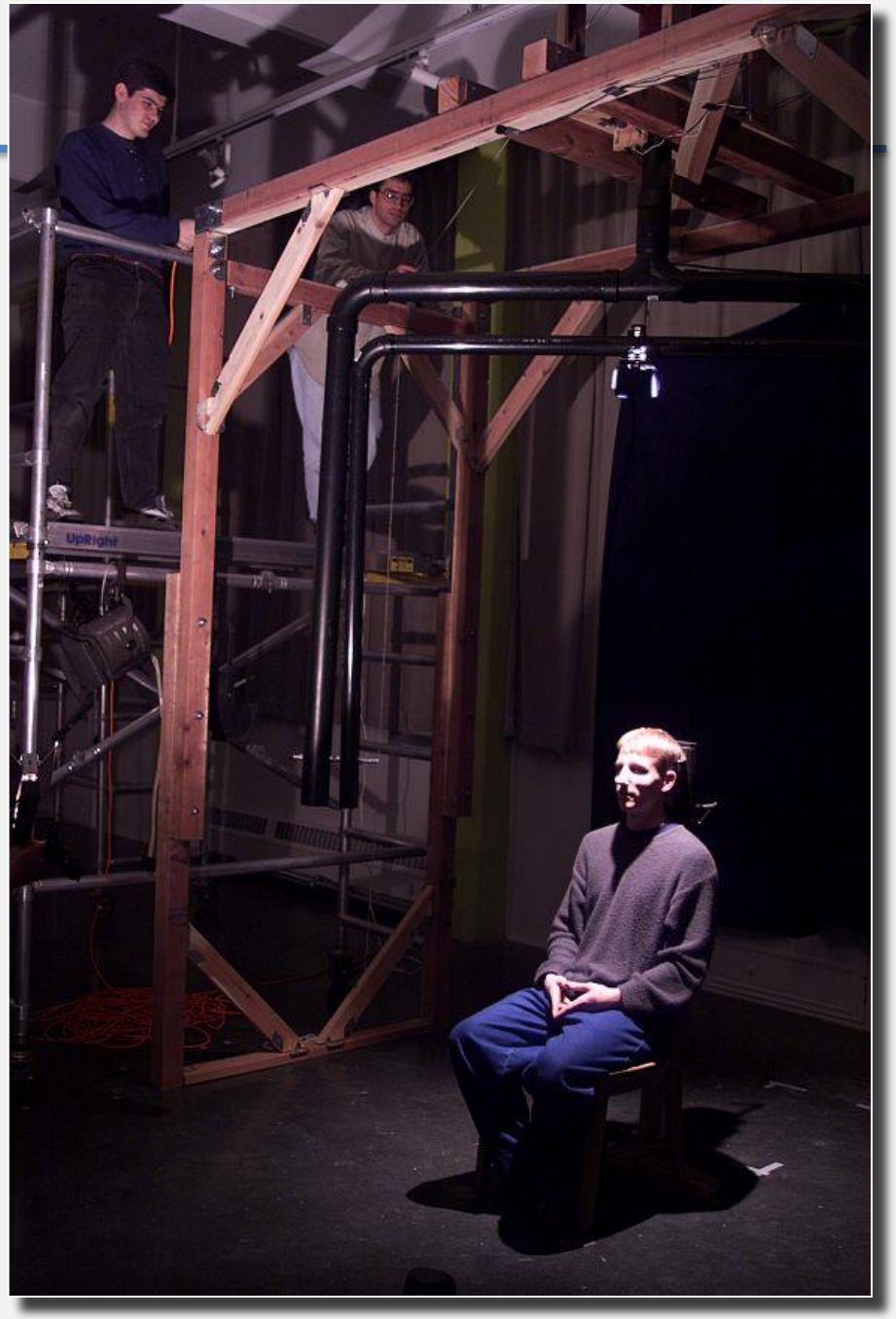
L

Input Lighting (Unfolded Cubemap)

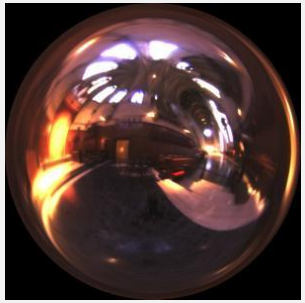
l_1 $+ l_2$ $+ \cdots\cdots + l_N$

Light Stage 1

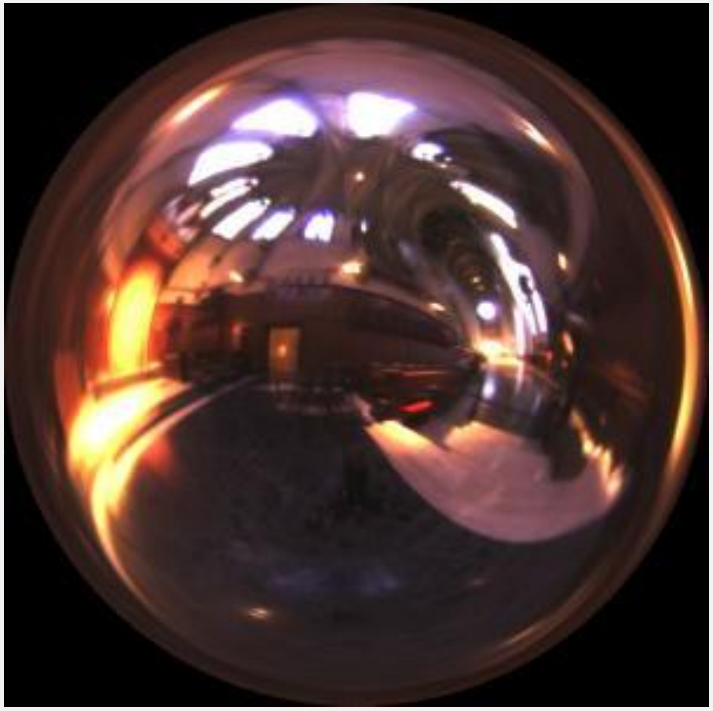
Debevec, Hawkins, Tchou, Duiker, Sarokin, and Sagar. *Acquiring the Reflectance Field of a Human Face*. SIGGRAPH 2000.

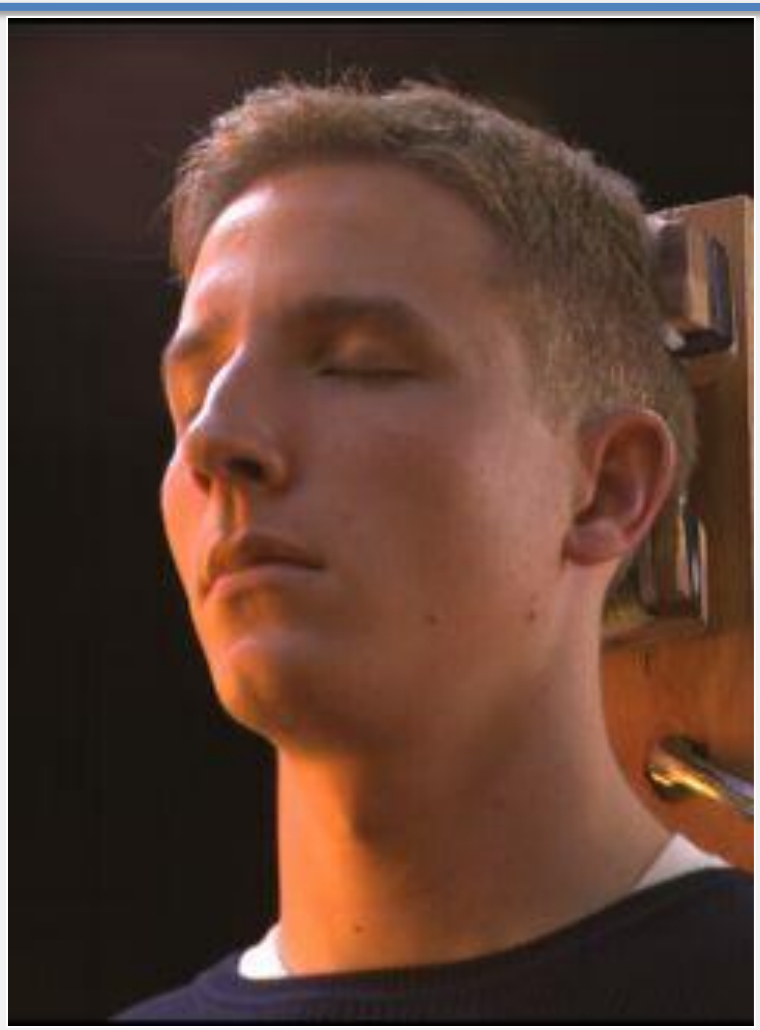


Light Stage 4D Reflectance Field

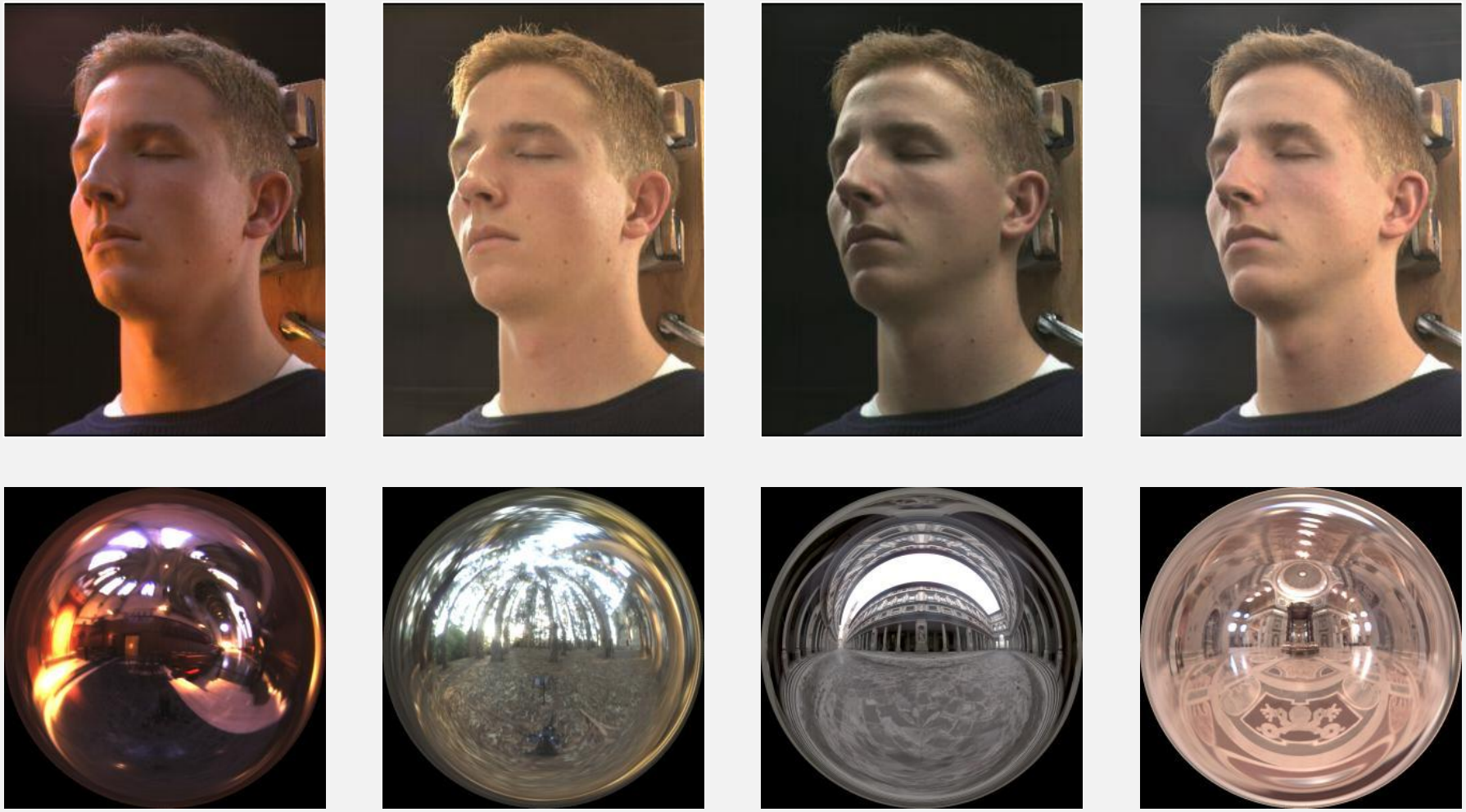


Light Stage 4D Reflectance Field

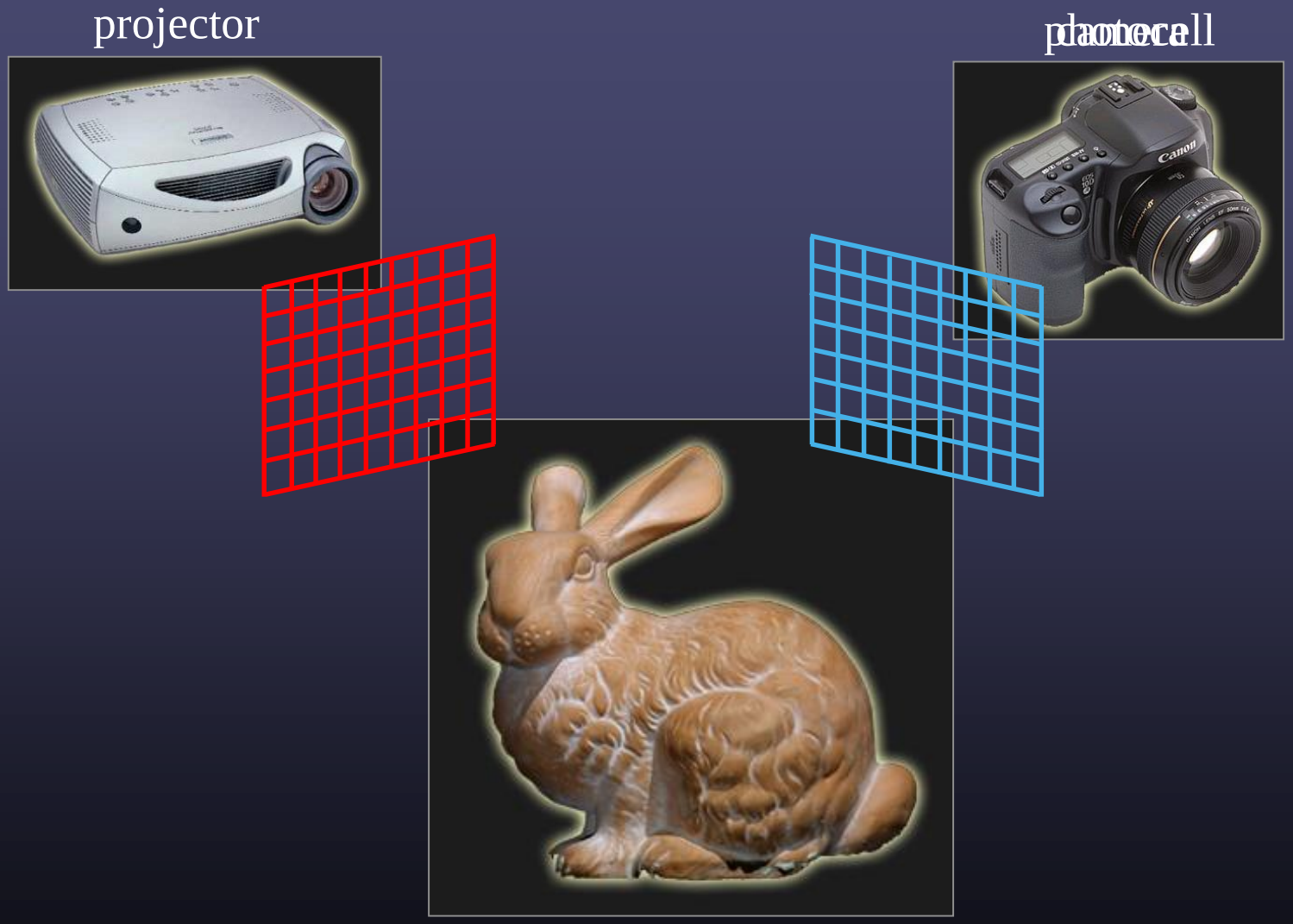




Relighting Results

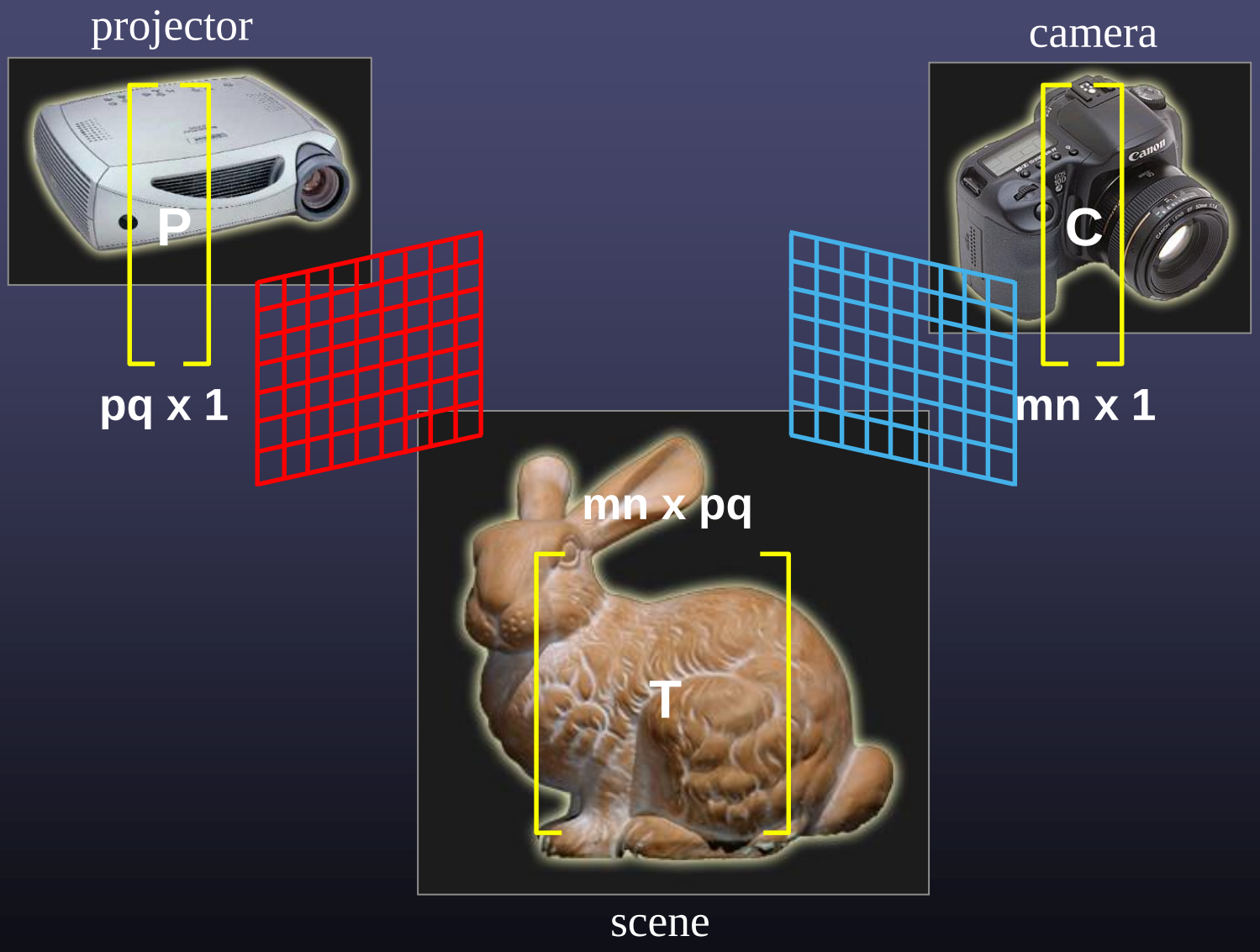


Dual Photography: The 4D transport matrix

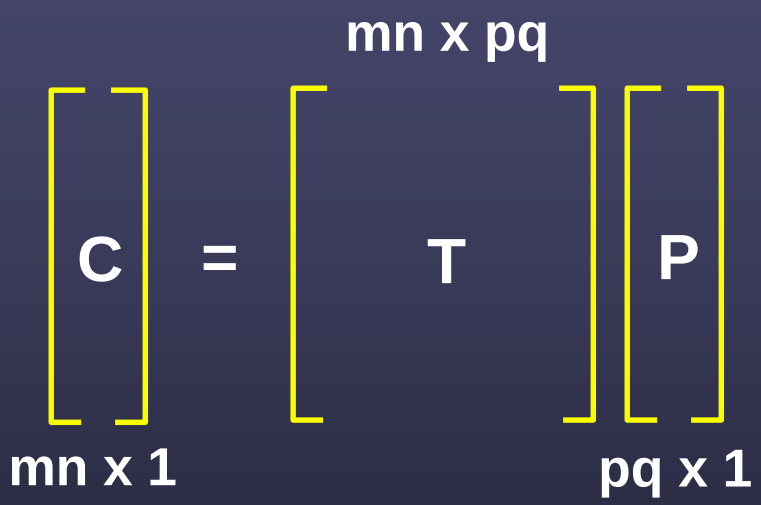


[Sen, et al., 2007]

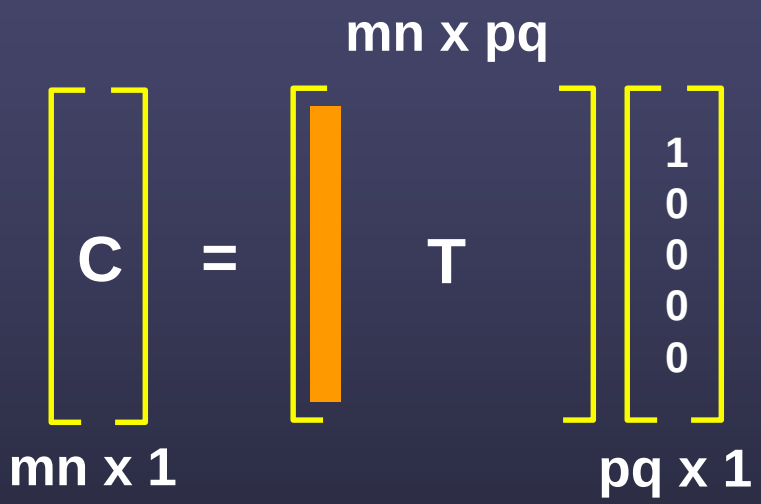
The 4D transport matrix



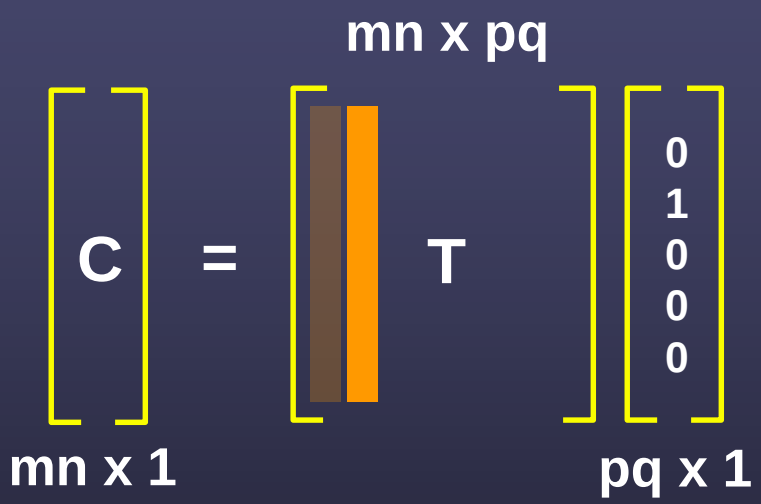
The 4D transport matrix



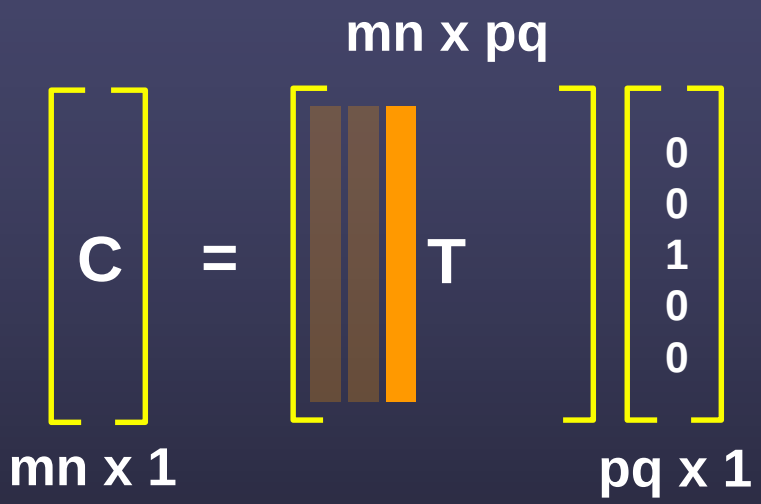
The 4D transport matrix



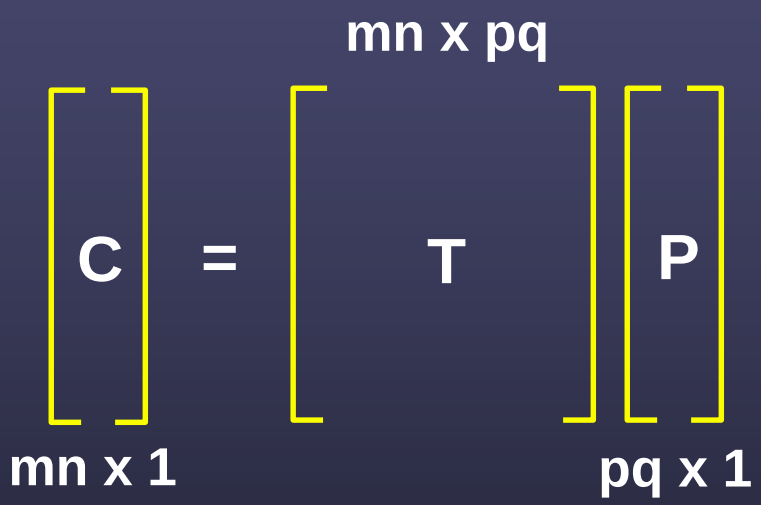
The 4D transport matrix



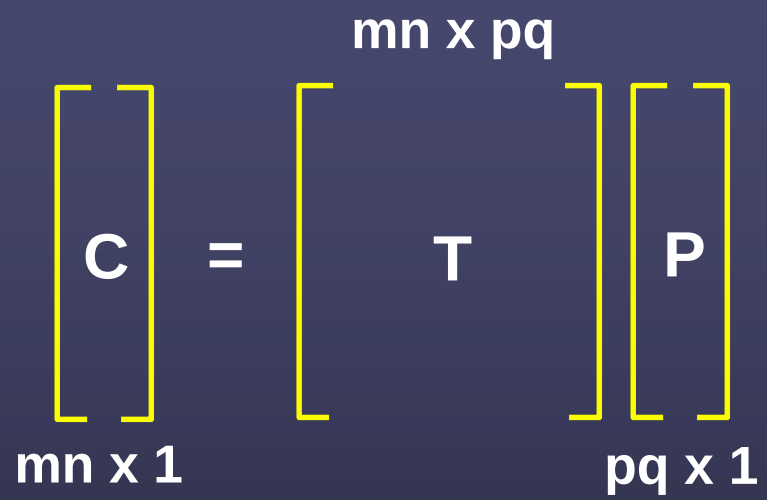
The 4D transport matrix



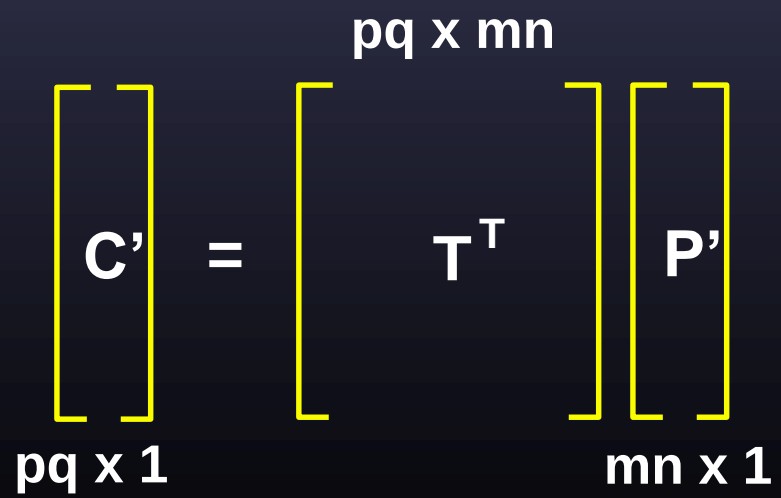
The 4D transport matrix



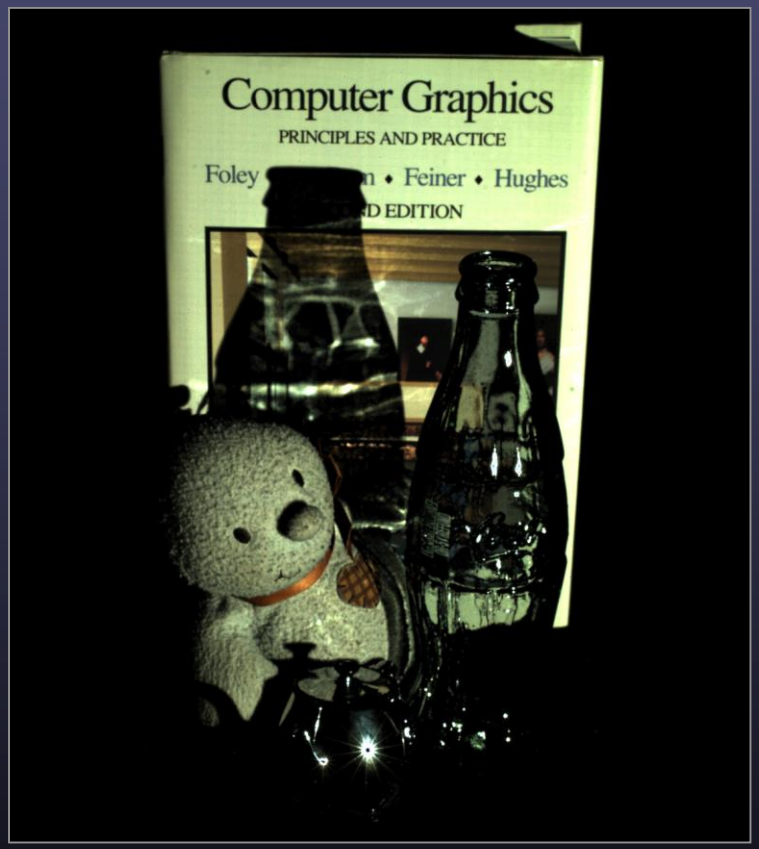
The 4D transport matrix



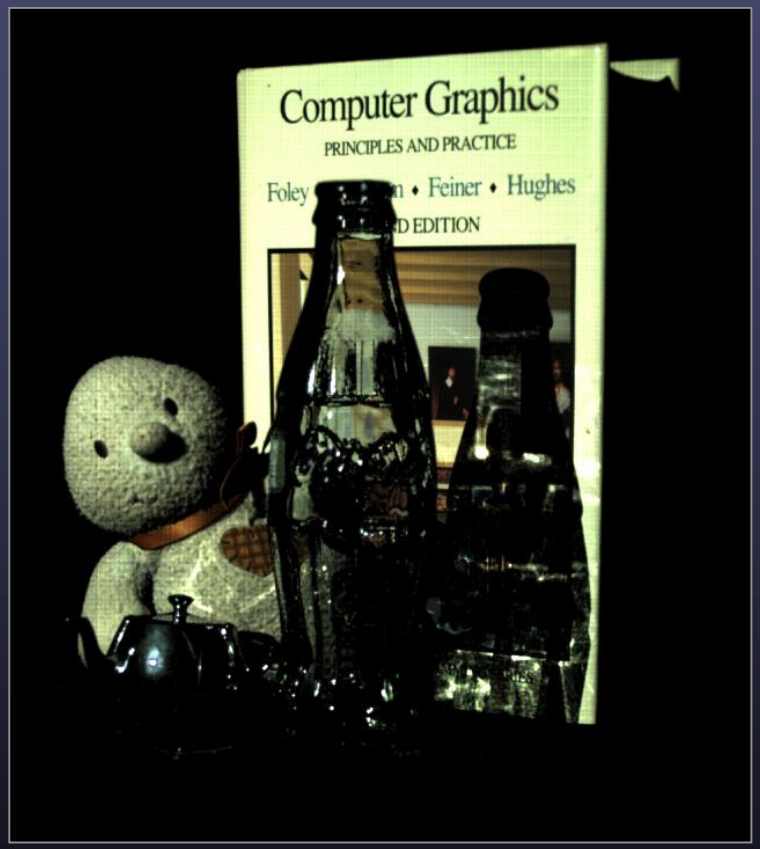
applying Helmholtz reciprocity...



Example



conventional photograph
with light coming from right



dual photograph
as seen from projector's position

© 2005 Marc Levoy

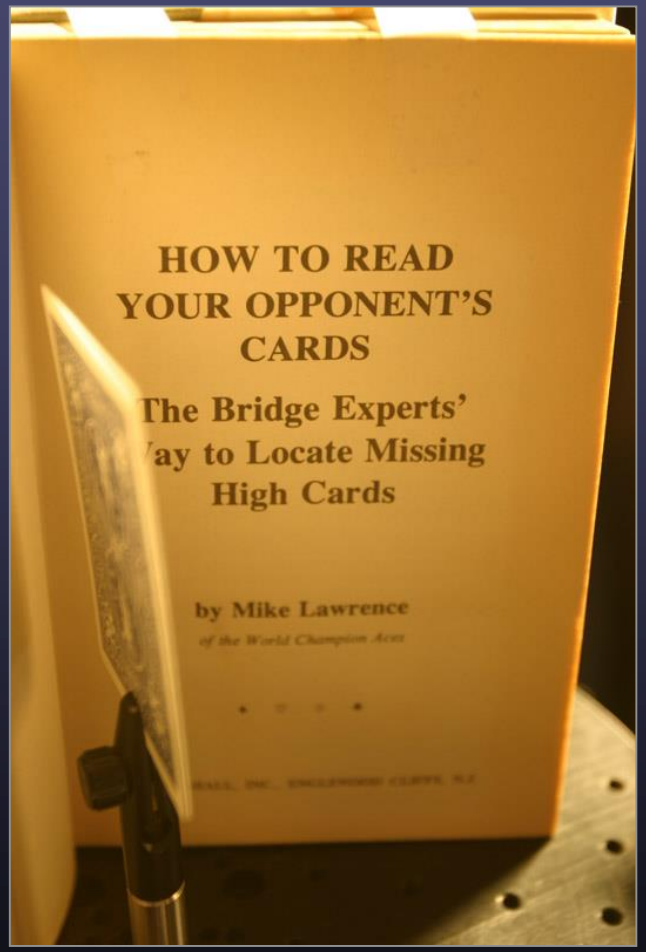
Properties of the transport matrix

- little interreflection → sparse matrix
- many interreflections → dense matrix
- convex object → diagonal matrix
- concave object → full matrix

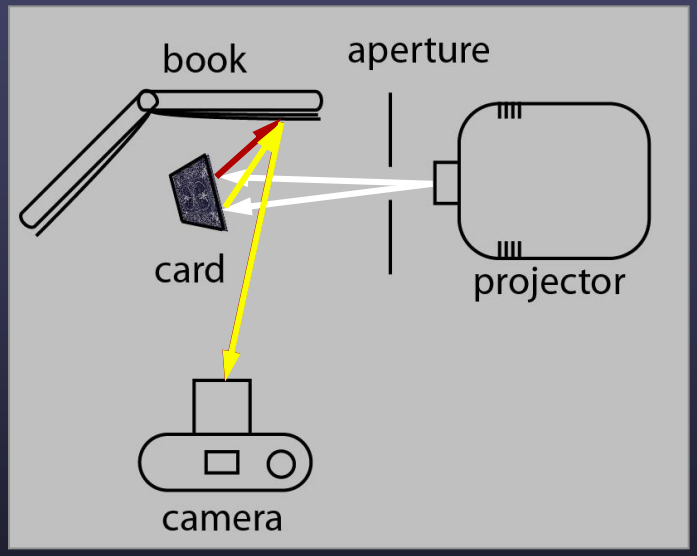
Can we create a dual photograph entirely from diffuse reflections?

© 2005 Marc Levoy

Dual photography from diffuse reflections



the camera's view



VIDEO

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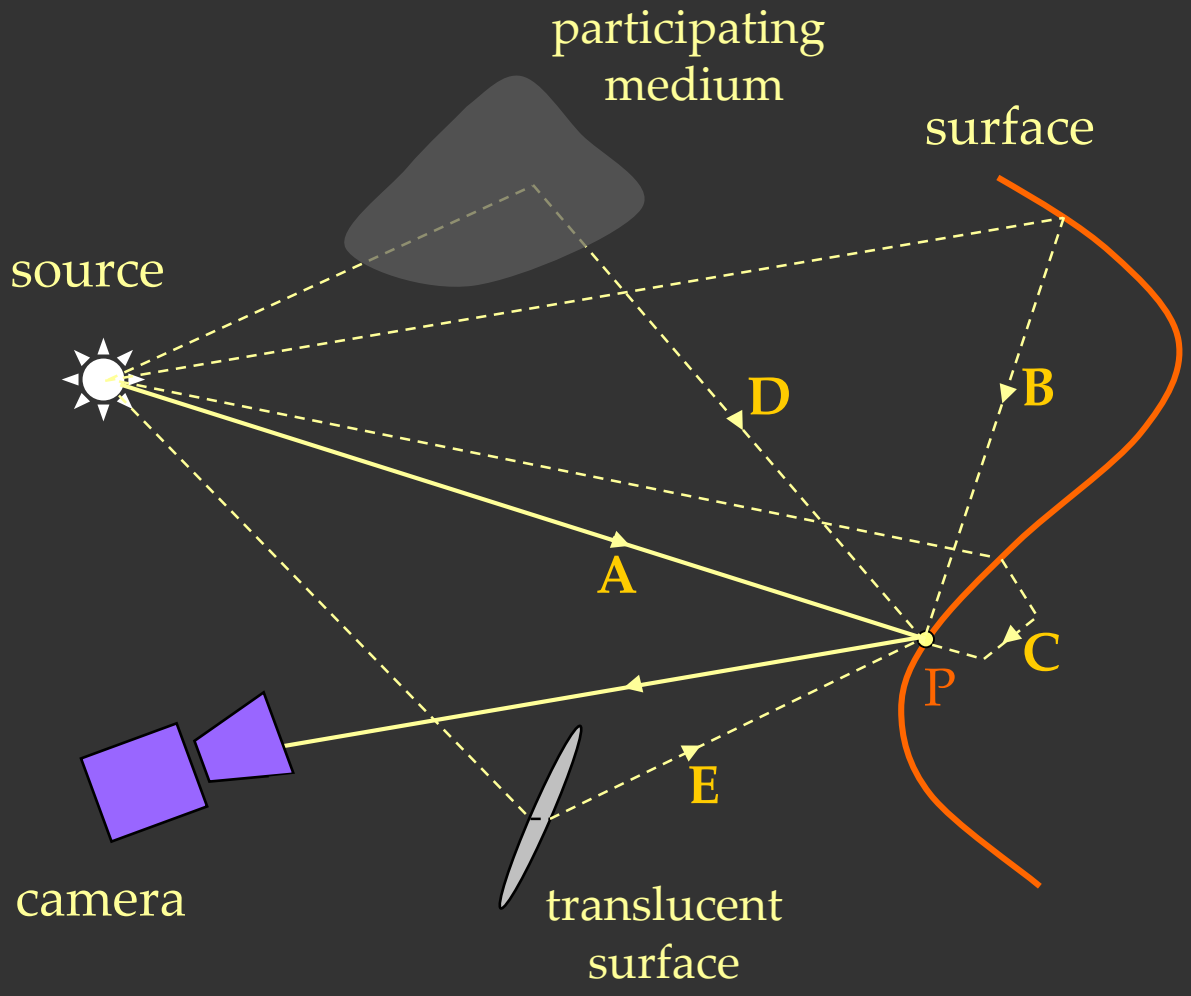
Direct and Global Illumination



A : Direct

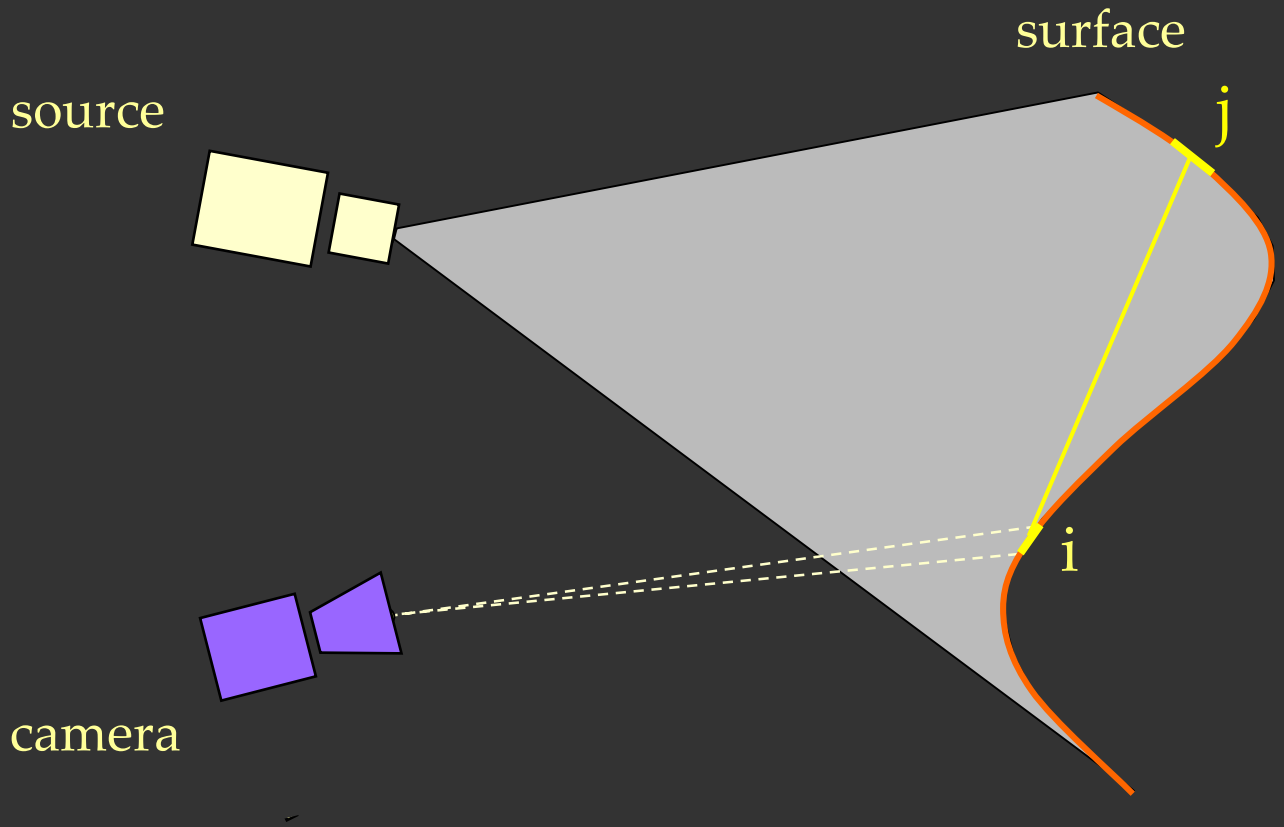
B : Interrelection

C : Subsurface

D : Volumetric

E : Diffusion

Direct and Global Components: Interreflections



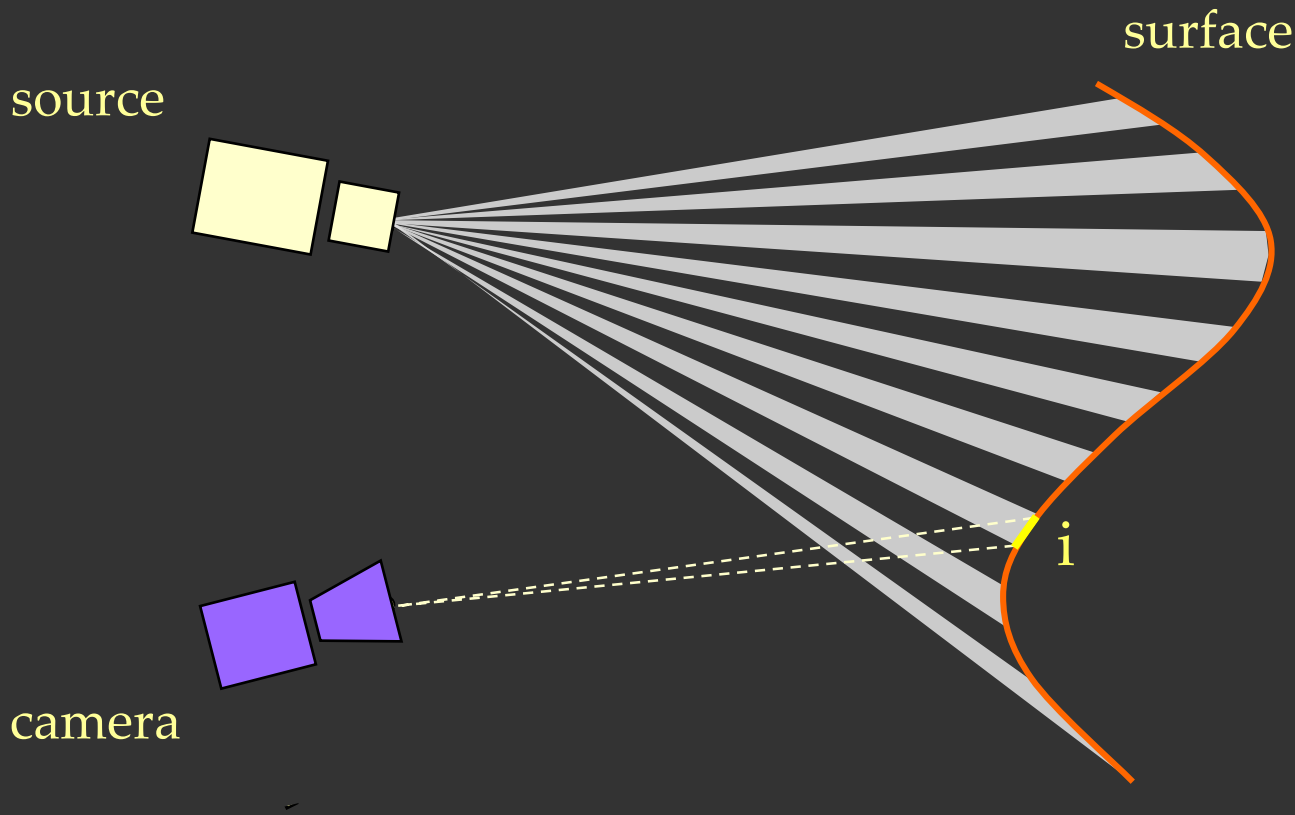
$$L[c,i] = L_d[c,i] + L_g[c,i]$$

radiance direct global

$$L_g[c,i] = \sum_P A[i,j]\, L[i,j]$$

BRDF and geometry

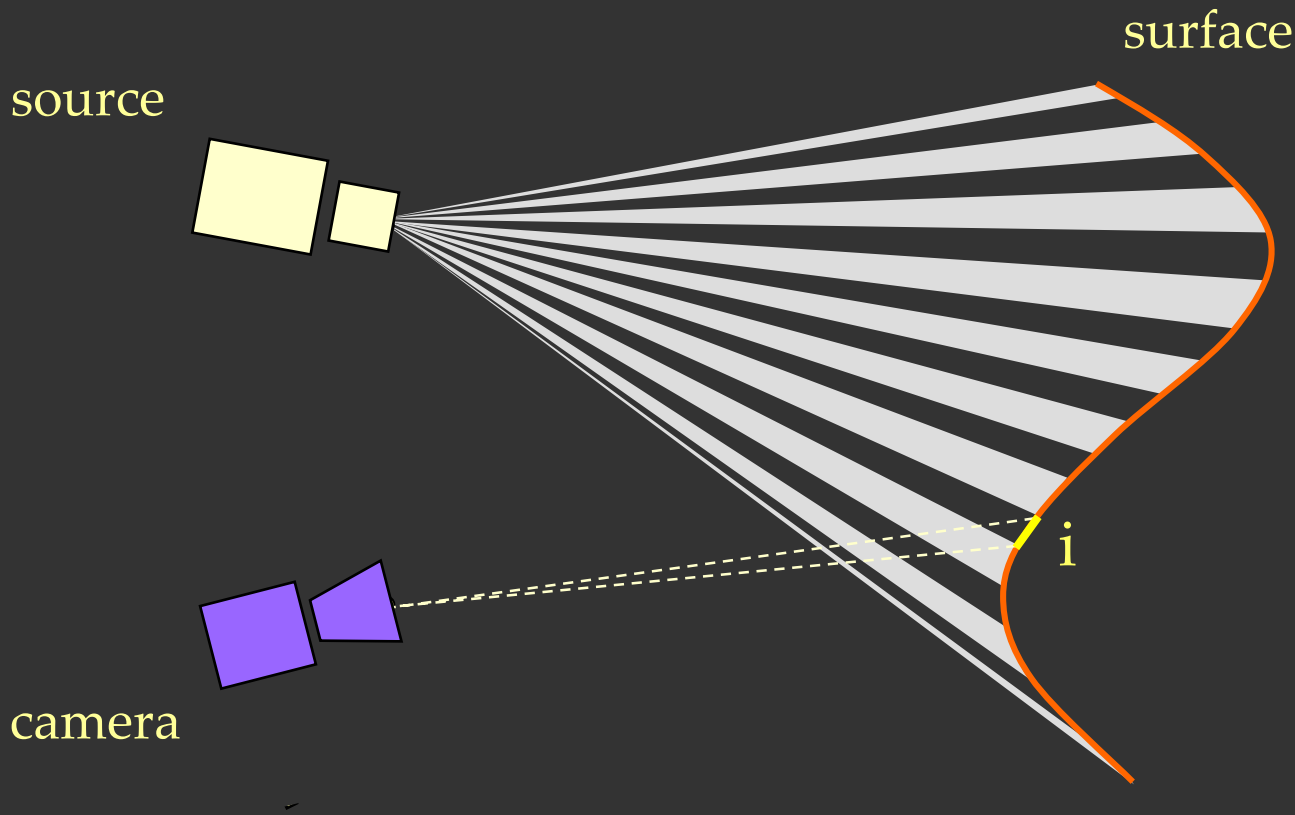
High Frequency Illumination Pattern



$$L^{+}[c,i] = L_d[c,i] + \alpha L_g[c,i]$$

fraction of activated source elements

High Frequency Illumination Pattern



$$L^{+}[c,i] = L_d[c,i] + \alpha\, L_g[c,i]$$

$$L^{-}[c,i] = (1-\alpha)\, L_g[c,i]$$

fraction of activated source elements

Separation from Two Images

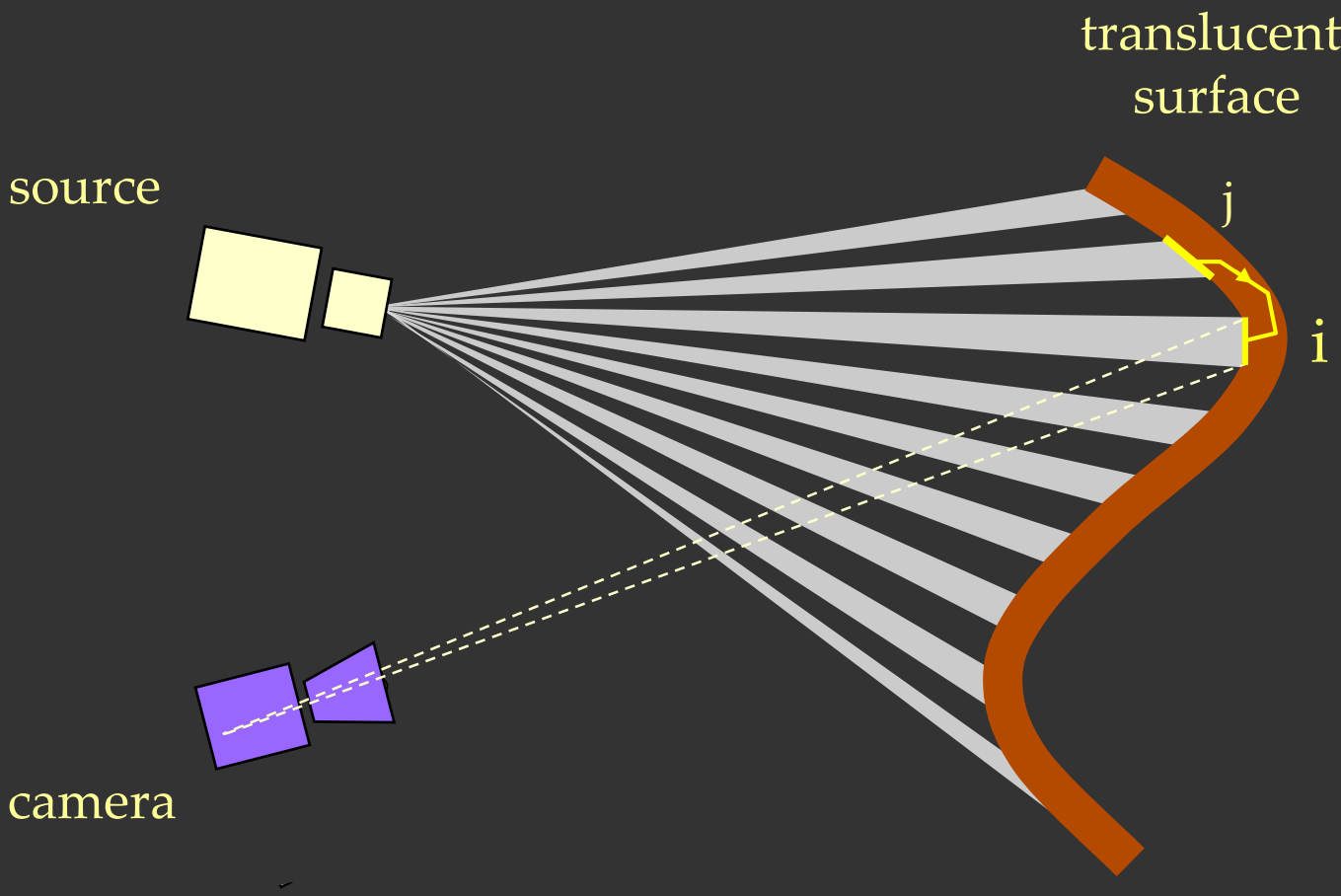
$\alpha = \frac{1}{2}$:

$$L_d = L_{\max} - L_{\min}, \quad L_g = 2L_{\min}$$

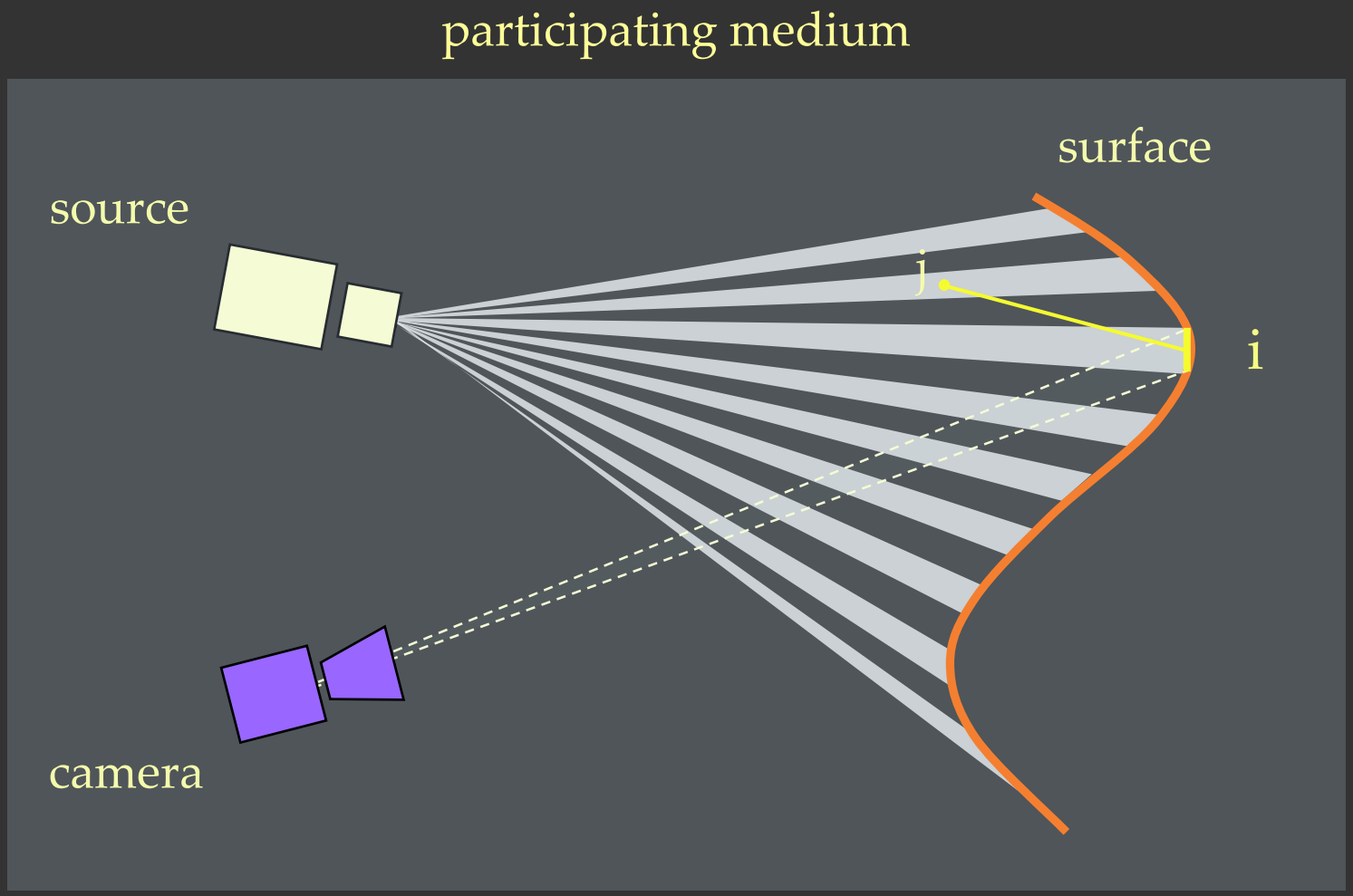
direct

global

Other Global Effects: Subsurface Scattering



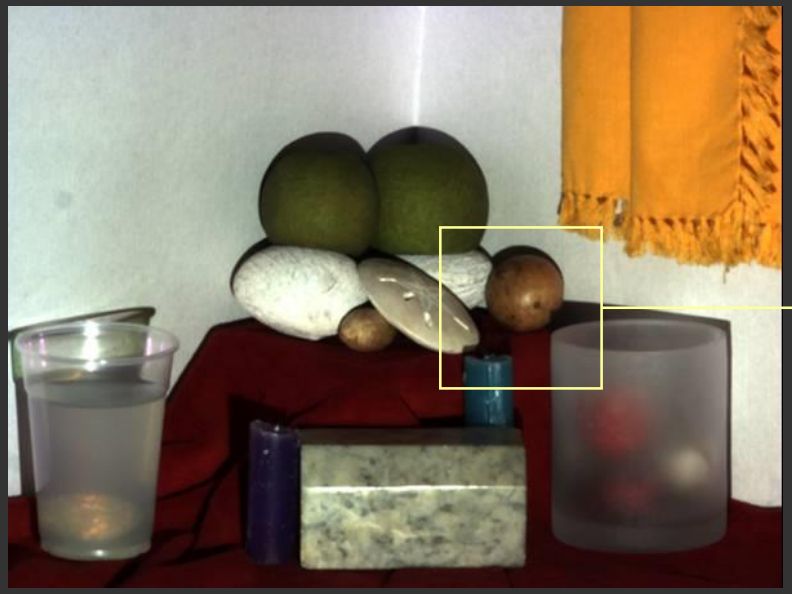
Other Global Effects: Volumetric Scattering



Diffuse
Interreflections
Specular
Interreflections
Diffusion
Volumetric
Scattering
Subsurface
Scattering

Scene

Scene



Direct

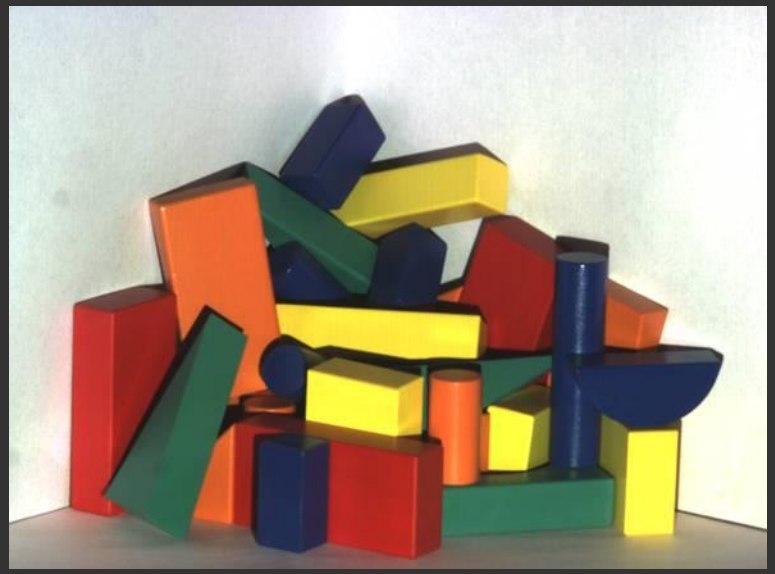
Global

Eggs: Diffuse Interreflections

Direct

Global

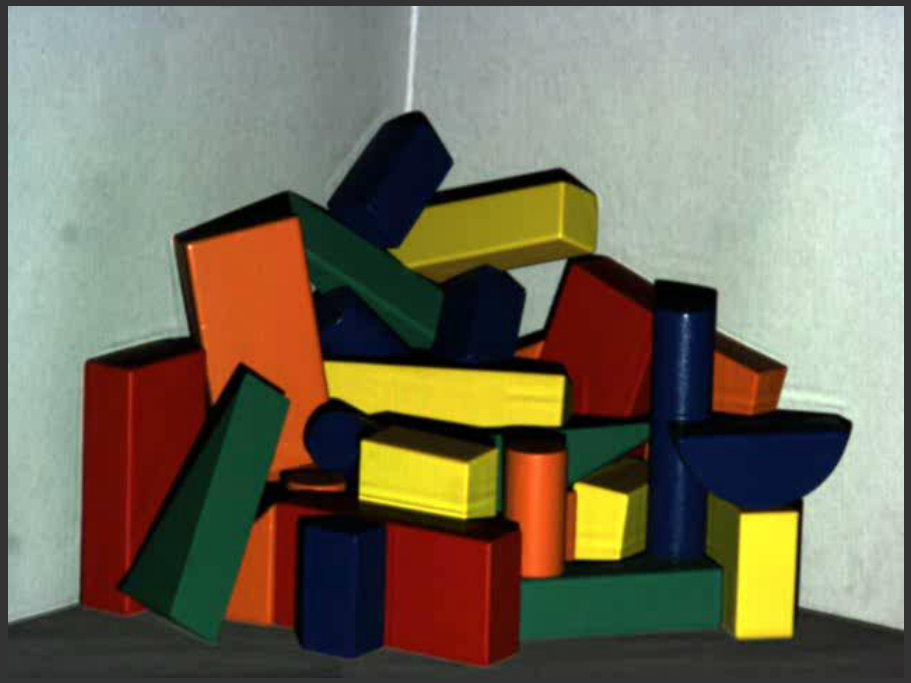
Wooden Blocks: Specular Interreflections



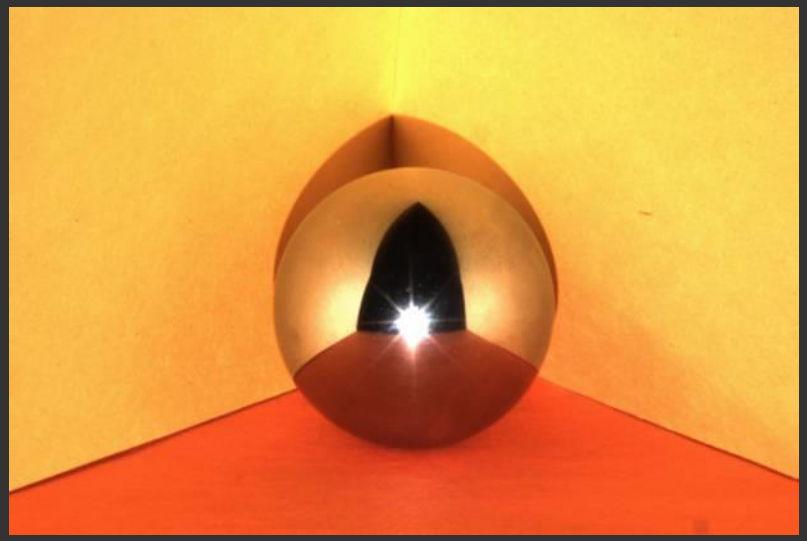
Direct

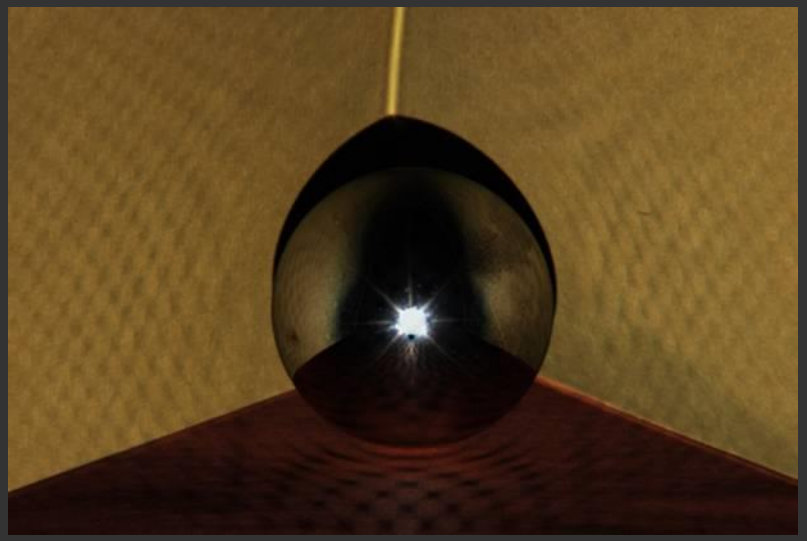
Global

Novel Images

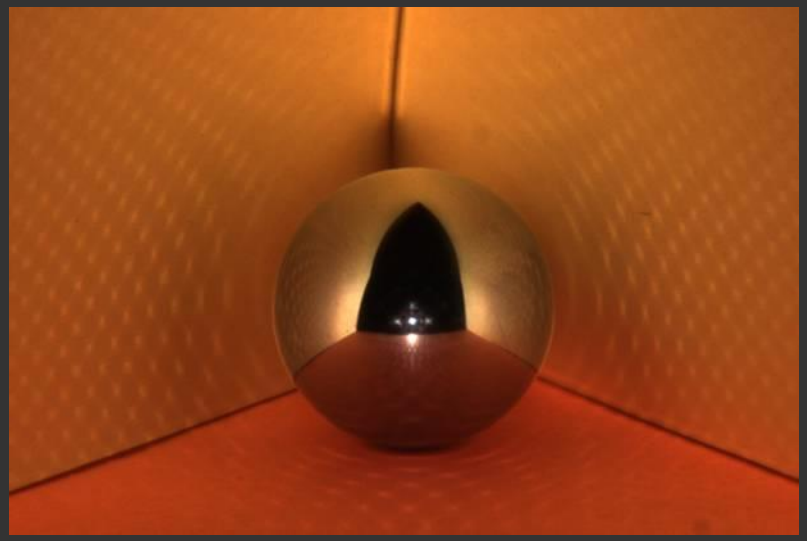


Mirror Ball: Failure Case





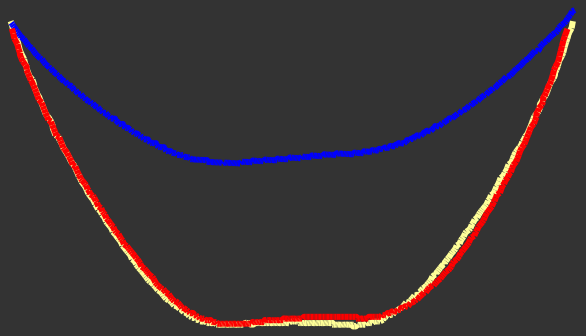
Direct



Global

Photometric Stereo using Direct Images

Shape



Nayar et al., 1991

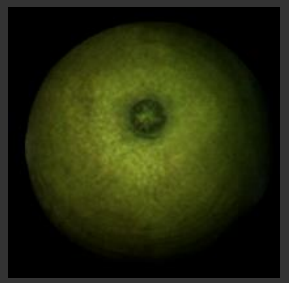
Kitchen Sink: Volumetric Scattering

Volumetric Scattering:
Chandrasekar 50, Ishimaru 78

Direct

Global

Novel Image



Peppers: Subsurface Scattering

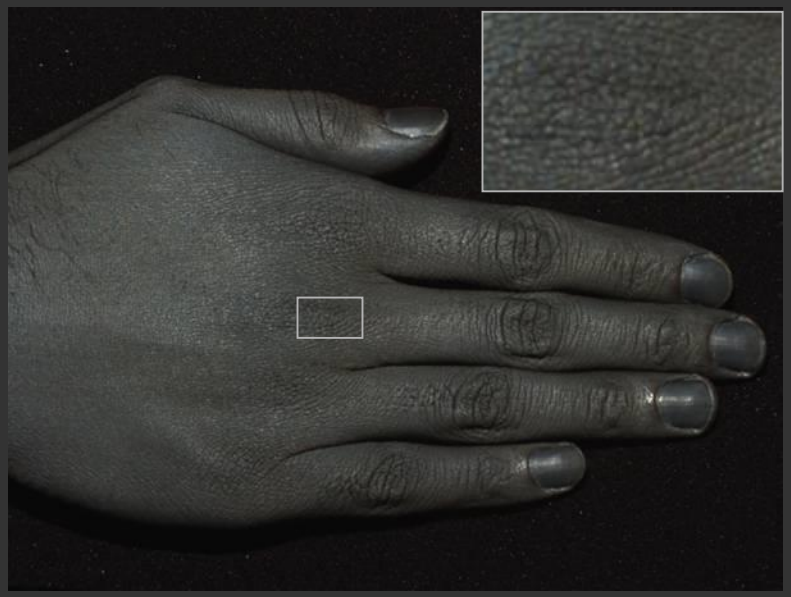
Direct

Global

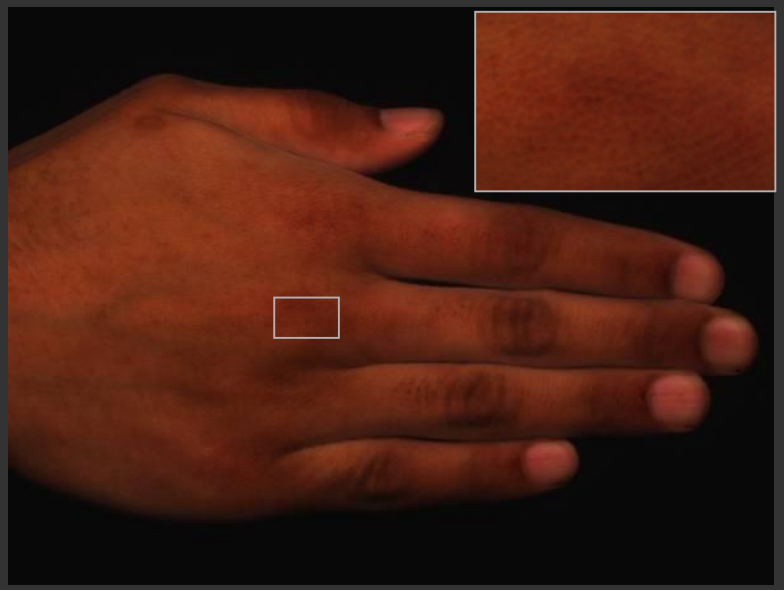
Novel Images

Hand

Skin: Hanrahan and Krueger 93, Uchida 96, Haro 01, Jensen et al. 01, Cula and Dana 02, Igarashi et al. 05, Weyrich et al. 05



Direct



Global

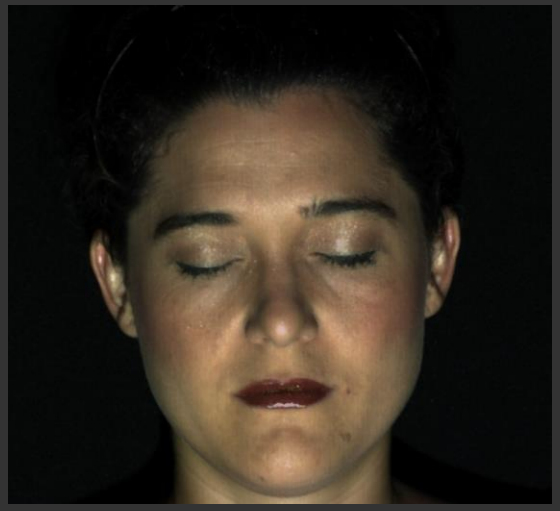
Face: Without and With Makeup

Without Makeup

Direct

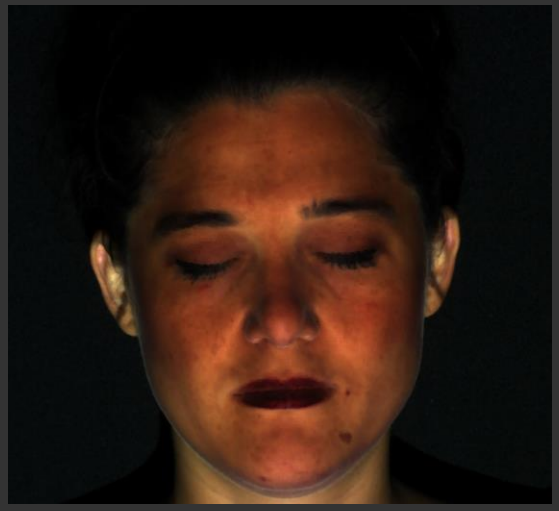
Global

With Makeup



Direct

Global



Blonde Hair

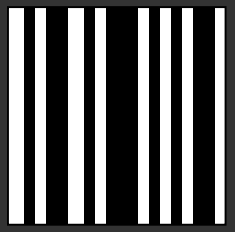
Hair Scattering: Stamm et al. 77, Bustard and Smith 91, Lu et al. 00 Marschner et al. 03

Direct

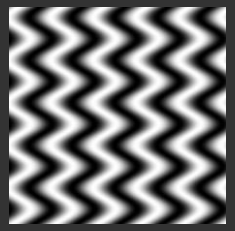
Global

Variants of Separation Method

- Coded Structured Light

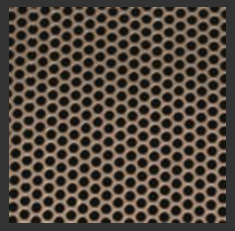


- Shifted Sinusoids



- Shadow of Line Occluder

- Shadow of Mesh Occluders



Building Corner

Stick

Shadow

3D from Shadows:
Bouguet and Perona 99

$$L_d = L_{\max} - L_{\min}, \quad L_g = L_{\min}$$

direct

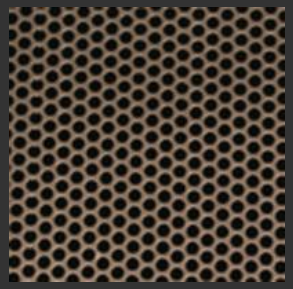
global

Building Corner

Direct

Global

Shower Curtain: Diffuser



Mesh

Shadow

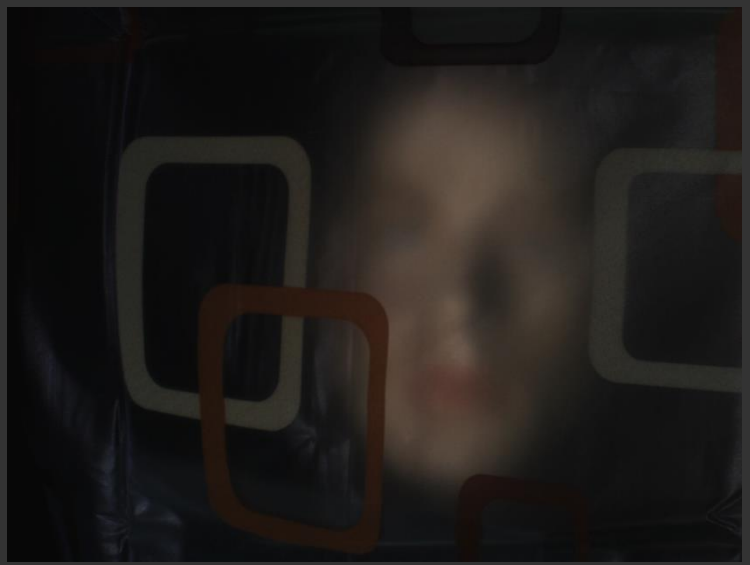
$$L_d = L_{\max} - \beta\, L_{\min}\,, \quad L_g = \beta\, L_{\min}$$

direct

global

Shower Curtain: Diffuser

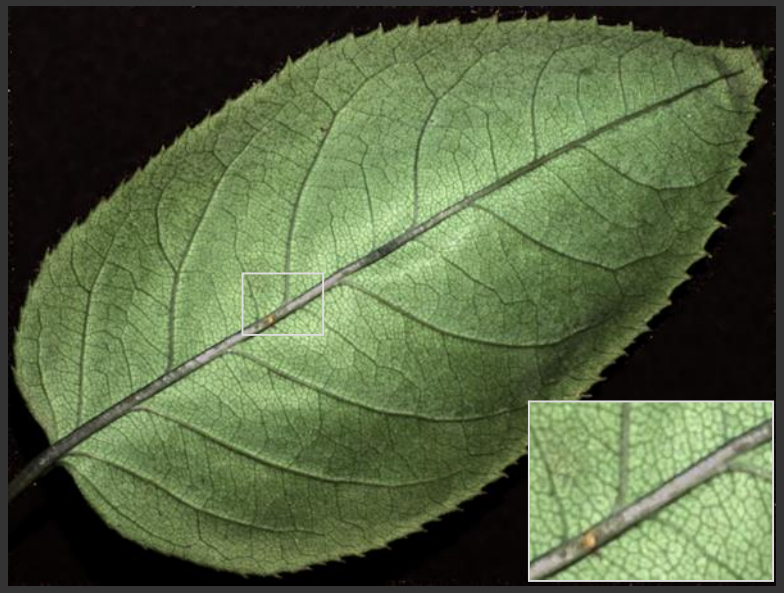
Direct



Global

Tea Rose Leaf

Leaf Anatomy: Purves et al. 03

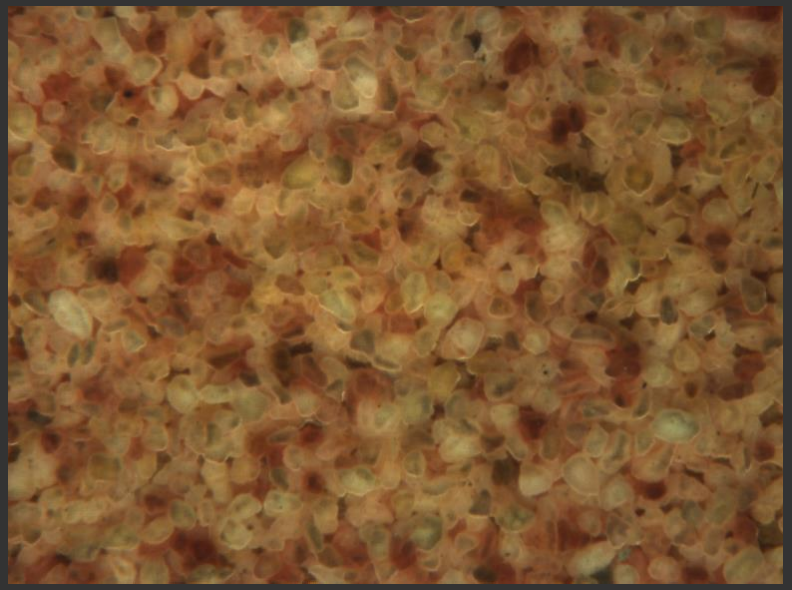


Direct

Global

Pebbles: 3D Texture

Direct

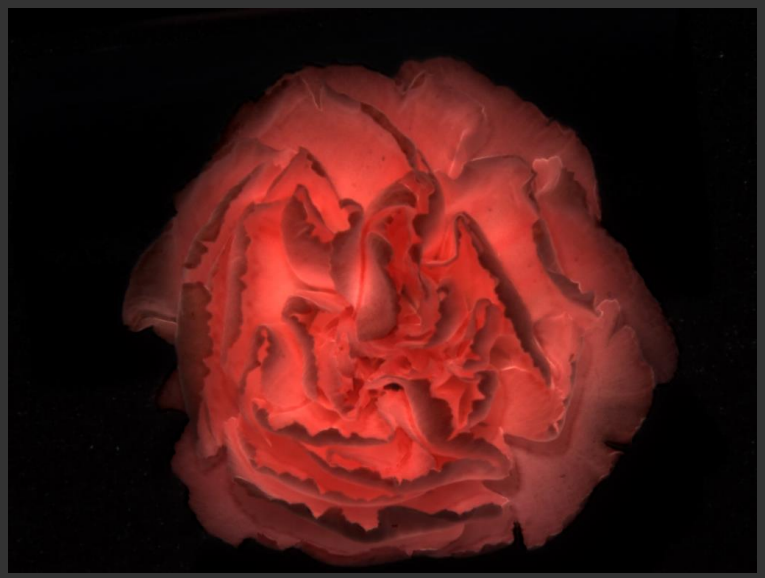


Global

Pink Carnation

Spectral Bleeding: Funt et al. 91

Direct



Global

Summary

- Fast and Simple Separation Method
- No Prior Knowledge of Material Properties
- Wide Variety of Global Effects
- Implications:
    - Generation of Novel Images
    - Enhance Computer Vision Methods
    - Insights into Properties of Materials

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