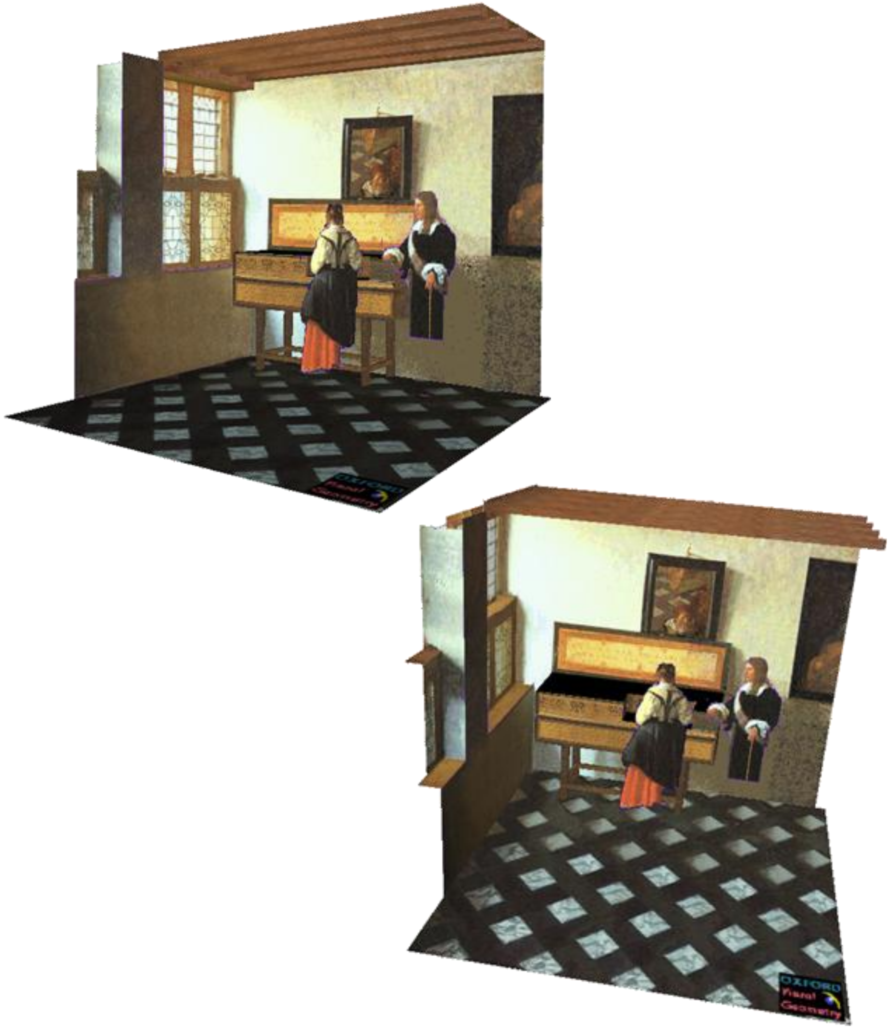
Last Lecture

- Single View Modeling

Vermeer's *Music Lesson*



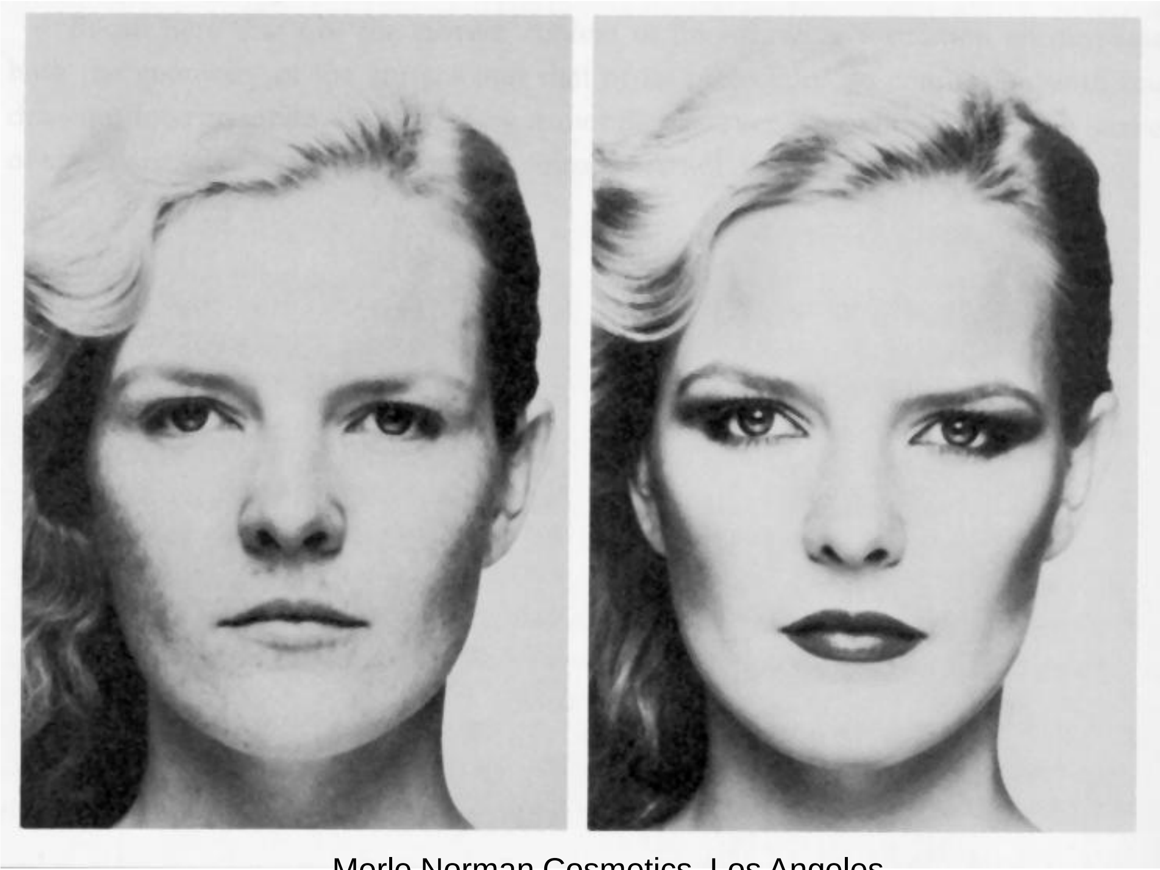
Reconstructions by Criminisi et al.

Today

- Photometric Stereo
- Separate Global and Direct Illumination

Photometric Stereo

Photometric Stereo

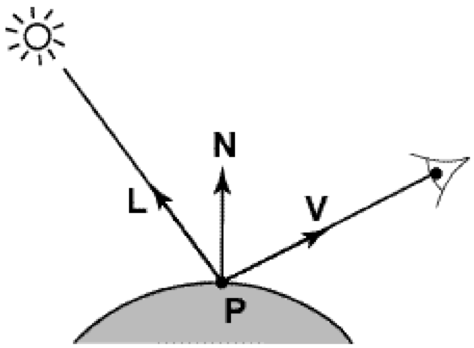


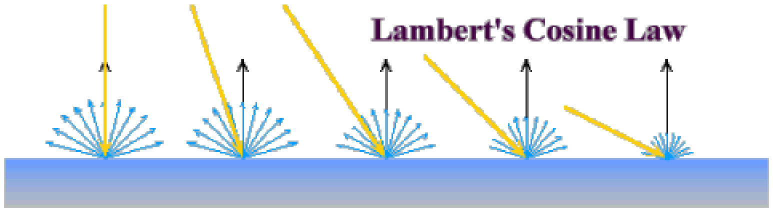
Merle Norman Cosmetics, Los Angeles

Readings

- R. Woodham, *Photometric Method for Determining Surface Orientation from Multiple Images*. Optical Engineering 19(1)139-144 (1980). (PDF)

Diffuse reflection





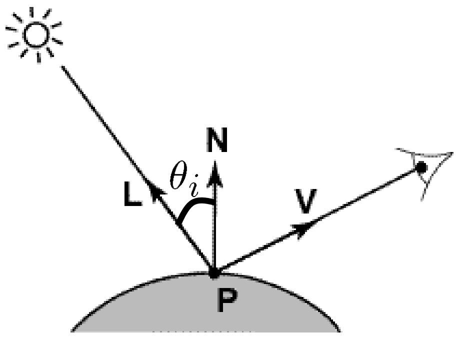
$$R_e = k_d \mathbf{N} \cdot \mathbf{L} R_i$$

image intensity of **P** → $$I = k_d \mathbf{N} \cdot \mathbf{L}$$

Simplifying assumptions

- $I = R_e$: camera response function f is the identity function:
  - can always achieve this in practice by solving for f and applying f^{-1} to each pixel in the image
- $R_i = 1$: light source intensity is 1
  - can achieve this by dividing each pixel in the image by R_i

Shape from shading



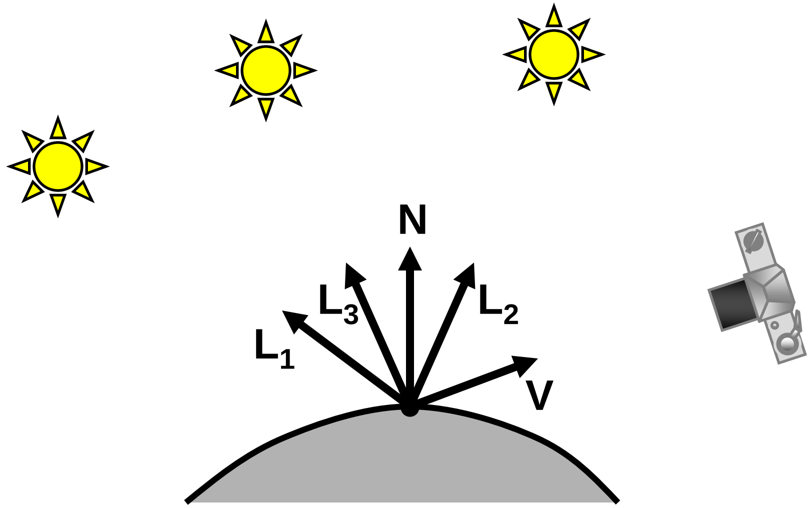
Suppose $k_d = 1$

$$
\begin{aligned}
I &= k_d \mathbf{N} \cdot \mathbf{L} \\
&= \mathbf{N} \cdot \mathbf{L} \\
&= cos\ \theta_i
\end{aligned}
$$

You can directly measure angle between normal and light source

- Not quite enough information to compute surface shape
- But can be if you add some additional info, for example
  - assume a few of the normals are known (e.g., along silhouette)
  - constraints on neighboring normals—“integrability”
  - smoothness
- Hard to get it to work well in practice
  - plus, how many real objects have constant albedo?

Photometric stereo



$$
\begin{aligned}
I_1 &= k_d \mathbf{N} \cdot \mathbf{L_1} \\
I_2 &= k_d \mathbf{N} \cdot \mathbf{L_2} \\
I_3 &= k_d \mathbf{N} \cdot \mathbf{L_3}
\end{aligned}
$$

Can write this as a matrix equation:

$$
\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = k_d \begin{bmatrix} \mathbf{L_1}^T \\ \mathbf{L_2}^T \\ \mathbf{L_3}^T \end{bmatrix} \mathrm{N}
$$

Solving the equations

$$\underbrace{\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}}_{\substack{\mathbf{I} \\ 3 \times 1}} = \underbrace{\begin{bmatrix} \mathbf{L_1}^T \\ \mathbf{L_2}^T \\ \mathbf{L_3}^T \end{bmatrix}}_{\substack{\mathbf{L} \\ 3 \times 3}} \underbrace{k_d \mathbf{N}}_{\substack{\mathbf{G} \\ 3 \times 1}}$$

$$\mathbf{G} = \mathbf{L}^{-1}\mathbf{I}$$

$$k_d = \|\mathbf{G}\|$$

$$\mathbf{N} = \frac{1}{k_d}\mathbf{G}$$

More than three lights

Get better results by using more lights

$$\begin{bmatrix} I_1 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} \mathbf{L_1} \\ \vdots \\ \mathbf{L_n} \end{bmatrix} k_d \mathbf{N}$$

Least squares solution:

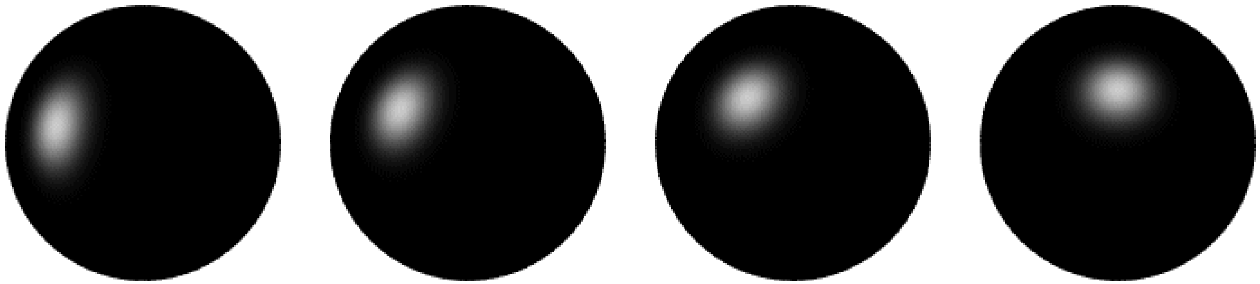
$$\begin{aligned} \mathbf{I} &= \mathbf{LG} \\ \mathbf{L^T I} &= \mathbf{L^T L G} \\ \mathbf{G} &= (\mathbf{L^T L})^{-1}(\mathbf{L^T I}) \end{aligned}$$

Solve for N, k_d as before

What's the size of $\mathbf{L^T L}$?

Computing light source directions

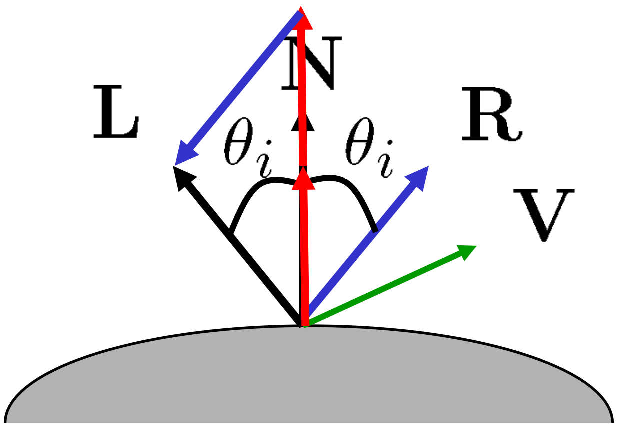
Trick: place a chrome sphere in the scene



- the location of the highlight tells you where the light source is

Recall the rule for specular reflection

For a perfect mirror, light is reflected about **N**



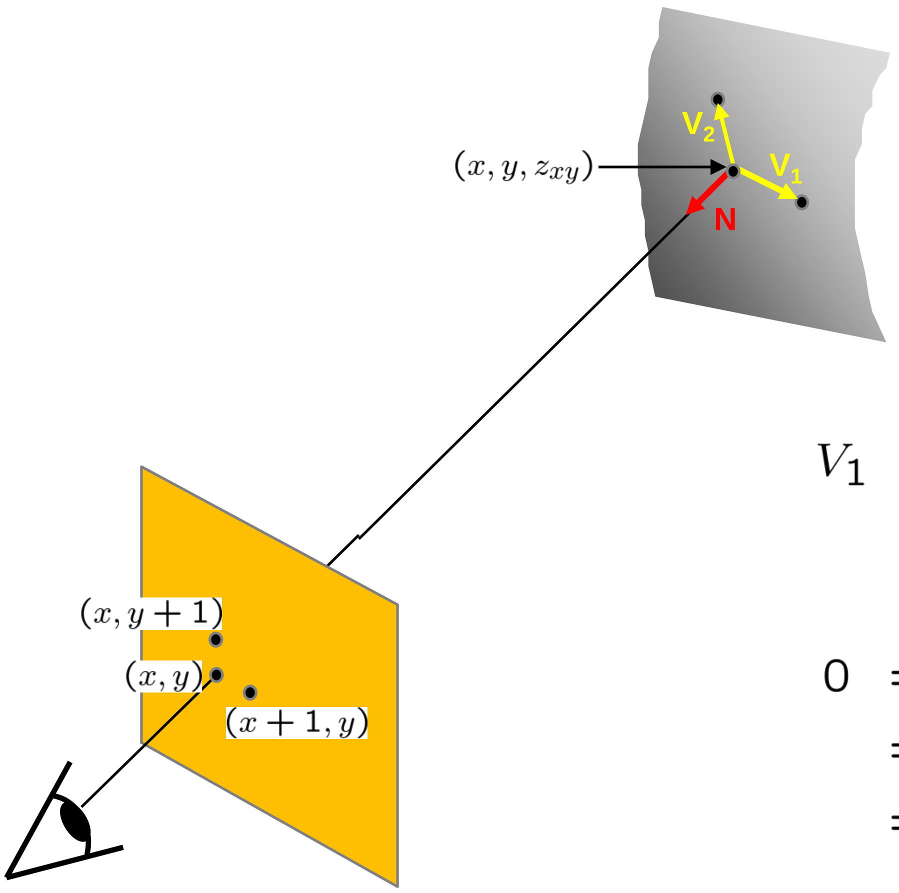
$$R_e = \begin{cases} R_i & \text{if } \mathbf{V} = \mathbf{R} \\ 0 & \text{otherwise} \end{cases}$$

We see a highlight when **V** = **R**

- then L is given as follows:

$$\mathbf{L} = 2(\mathbf{N} \cdot \mathbf{R})\mathbf{N} - \mathbf{R}$$

Depth from normals



$$
\begin{aligned}
V_1 &= (x+1, y, z_{x+1,y}) - (x, y, z_{xy}) \\
&= (1, 0, z_{x+1,y} - z_{xy})
\end{aligned}
$$

$$
\begin{aligned}
0 &= N \cdot V_1 \\
&= (n_x, n_y, n_z) \cdot (1, 0, z_{x+1,y} - z_{xy}) \\
&= n_x + n_z(z_{x+1,y} - z_{xy})
\end{aligned}
$$

Get a similar equation for $\mathbf{V_2}$

- Each normal gives us two linear constraints on z
- compute z values by solving a matrix equation

Example

What if we don’t have mirror ball?

- Hayakawa, Journal of the Optical Society of America, 1994, Photometric stereo under a light source with arbitrary motion.

Limitations

Big problems

- doesn't work for shiny things, semi-translucent things
- shadows, inter-reflections

Smaller problems

- camera and lights have to be distant
- calibration requirements
  - measure light source directions, intensities
  - camera response function

Newer work addresses some of these issues

Some pointers for further reading:

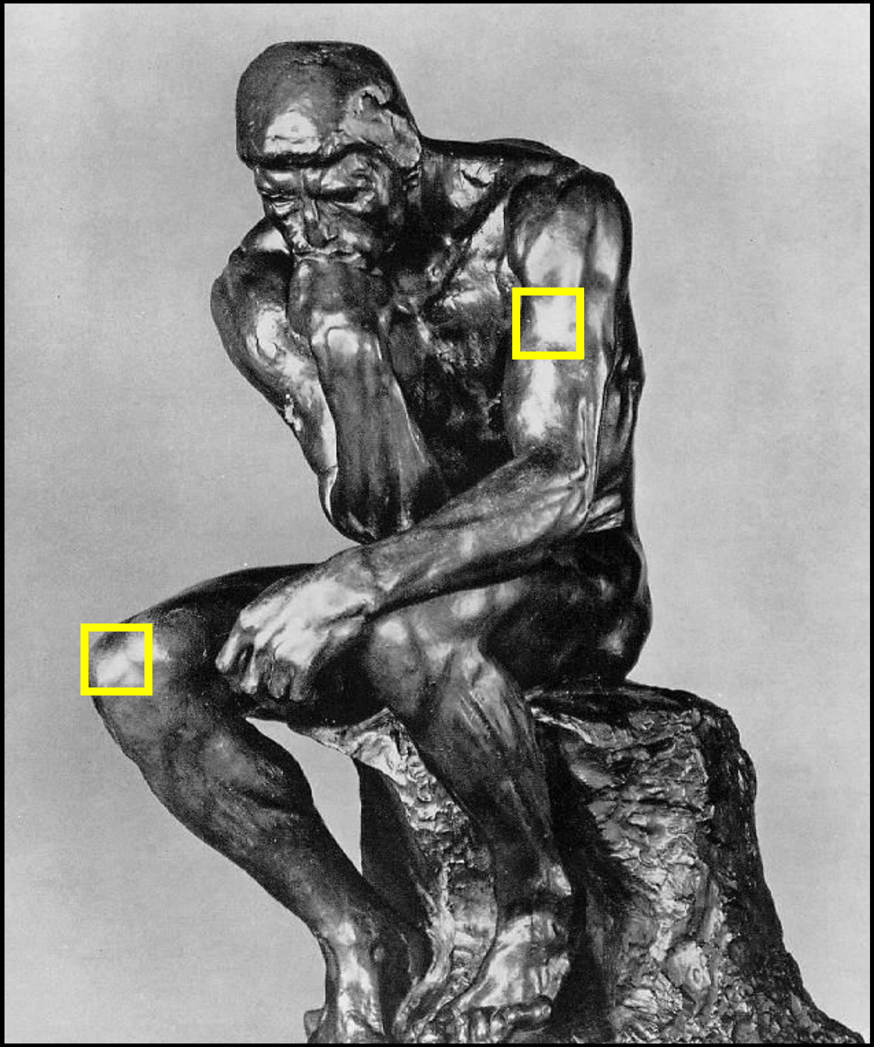
- Zickler, Belhumeur, and Kriegman, *"Helmholtz Stereopsis: Exploiting Reciprocity for Surface Reconstruction."* IJCV, Vol. 49 No. 2/3, pp 215-227.
- Hertzmann & Seitz, "*Example-Based Photometric Stereo: Shape Reconstruction with General, Varying BRDFs*." IEEE Trans. PAMI 2005

Example-based Photometric Stereo

Aaron Hertzmann
University of Toronto

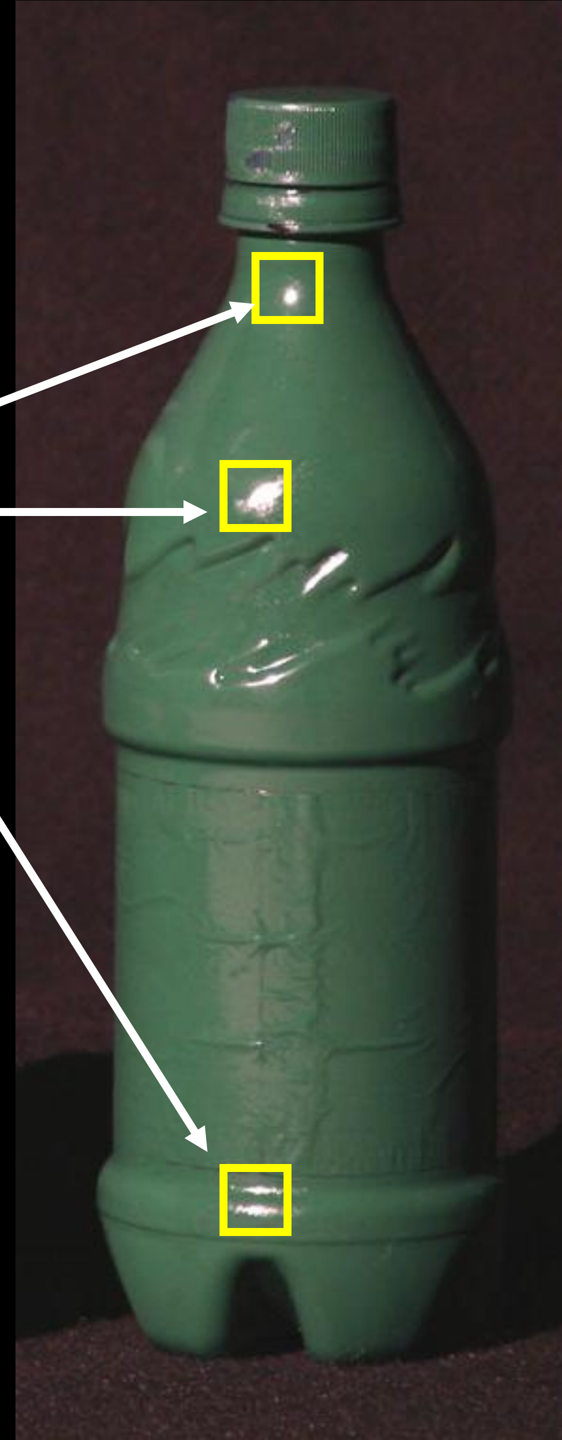
Steven M. Seitz
University of Washington

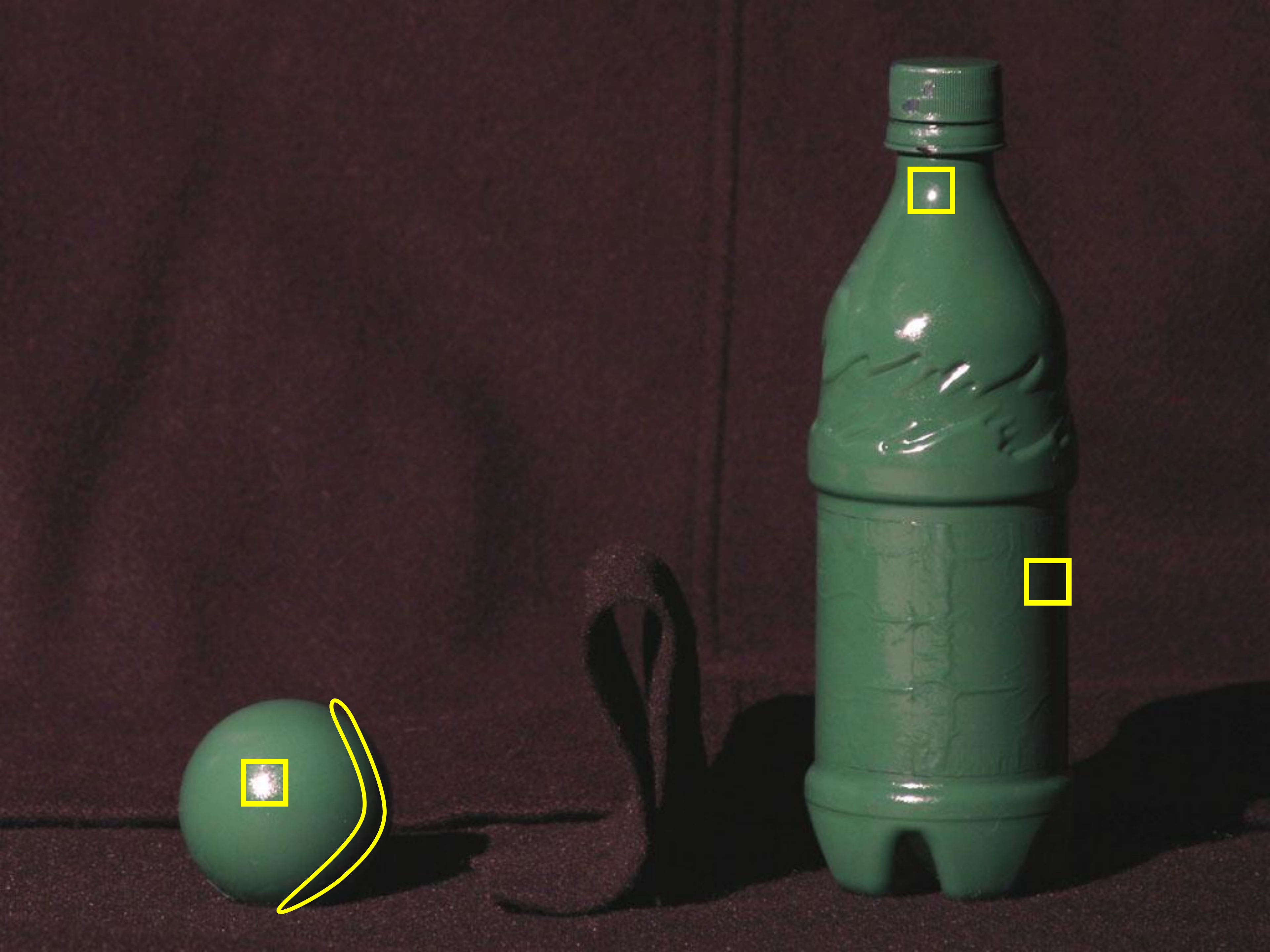
Shiny things

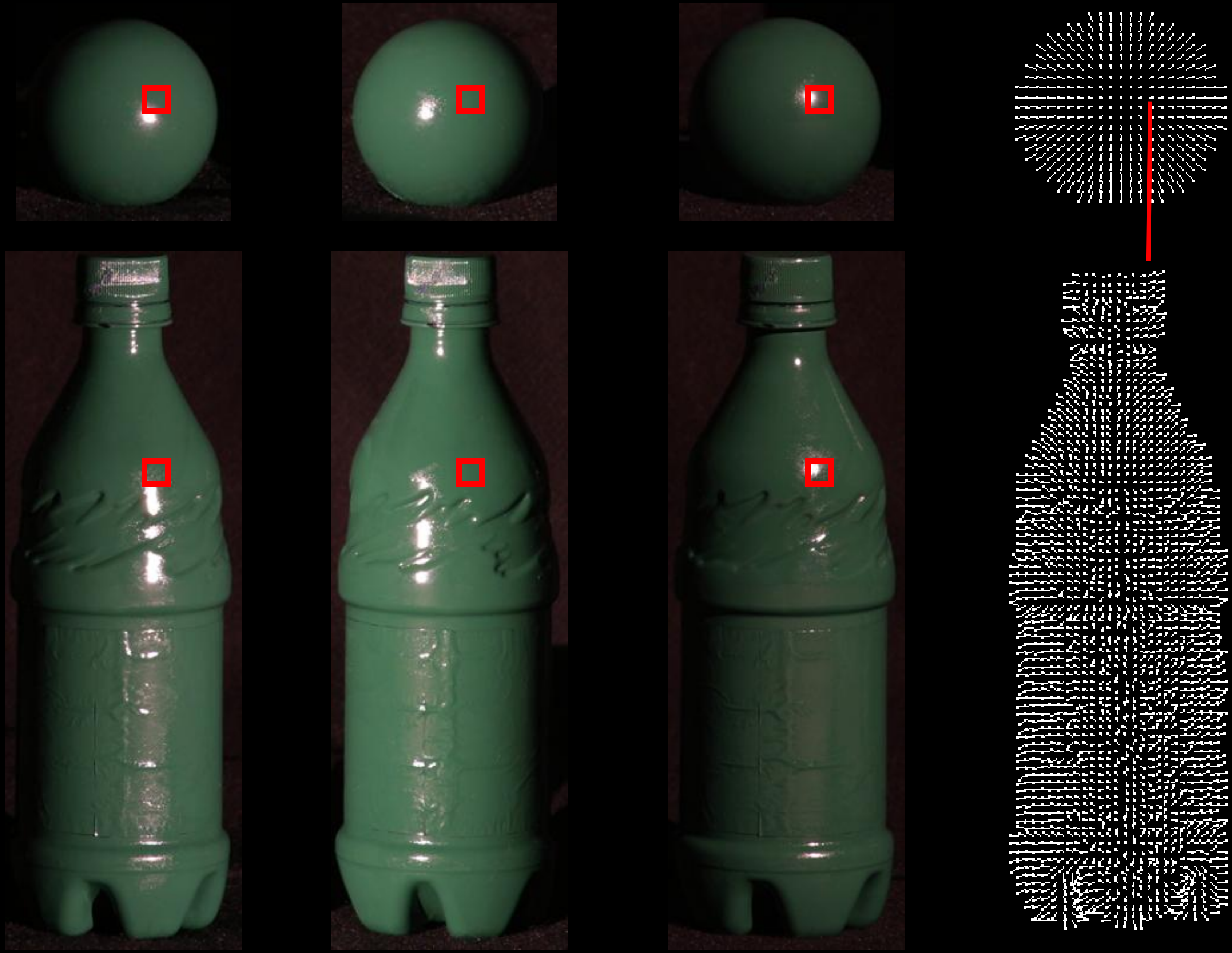


“Orientation consistency”

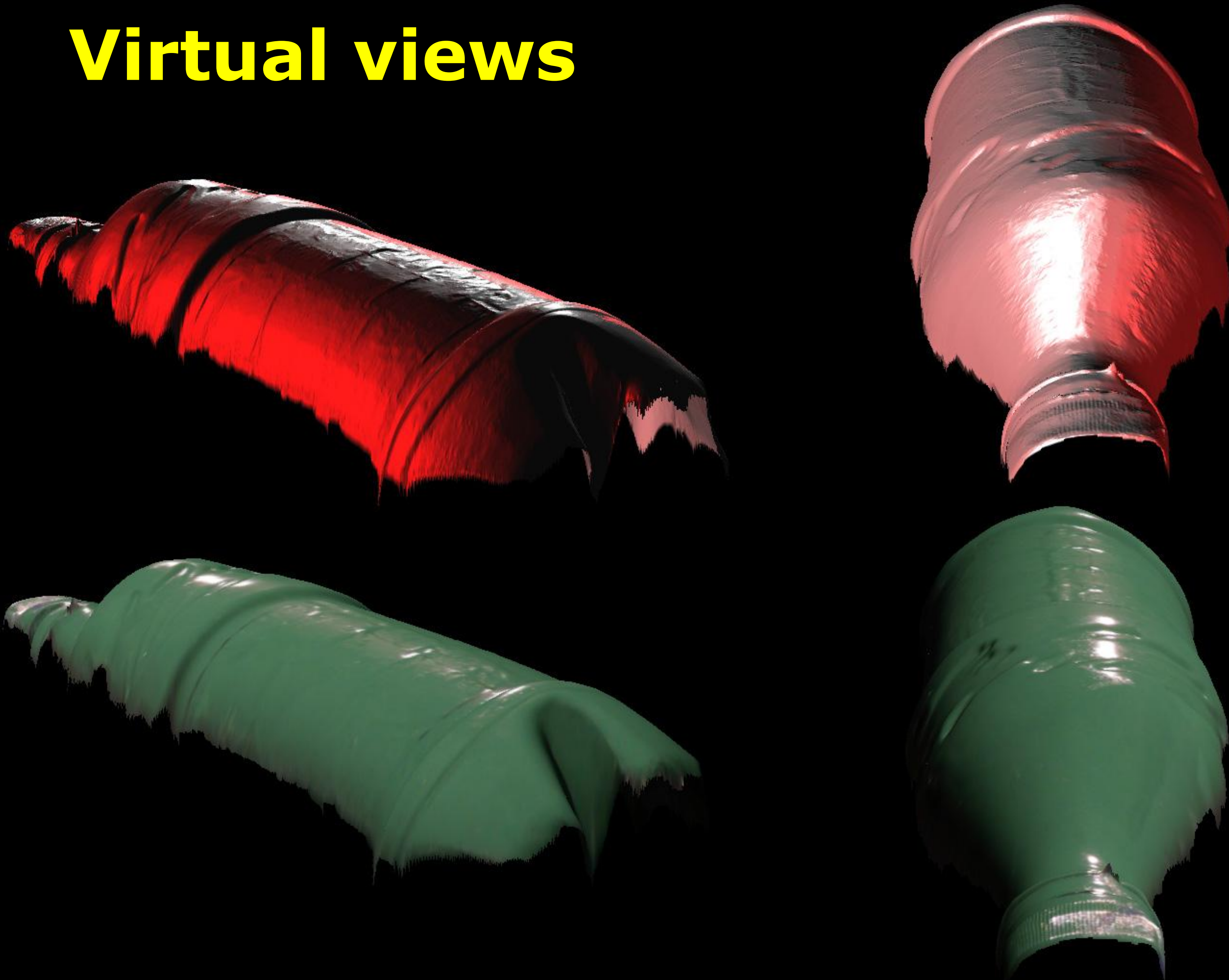
same surface normal







Virtual views

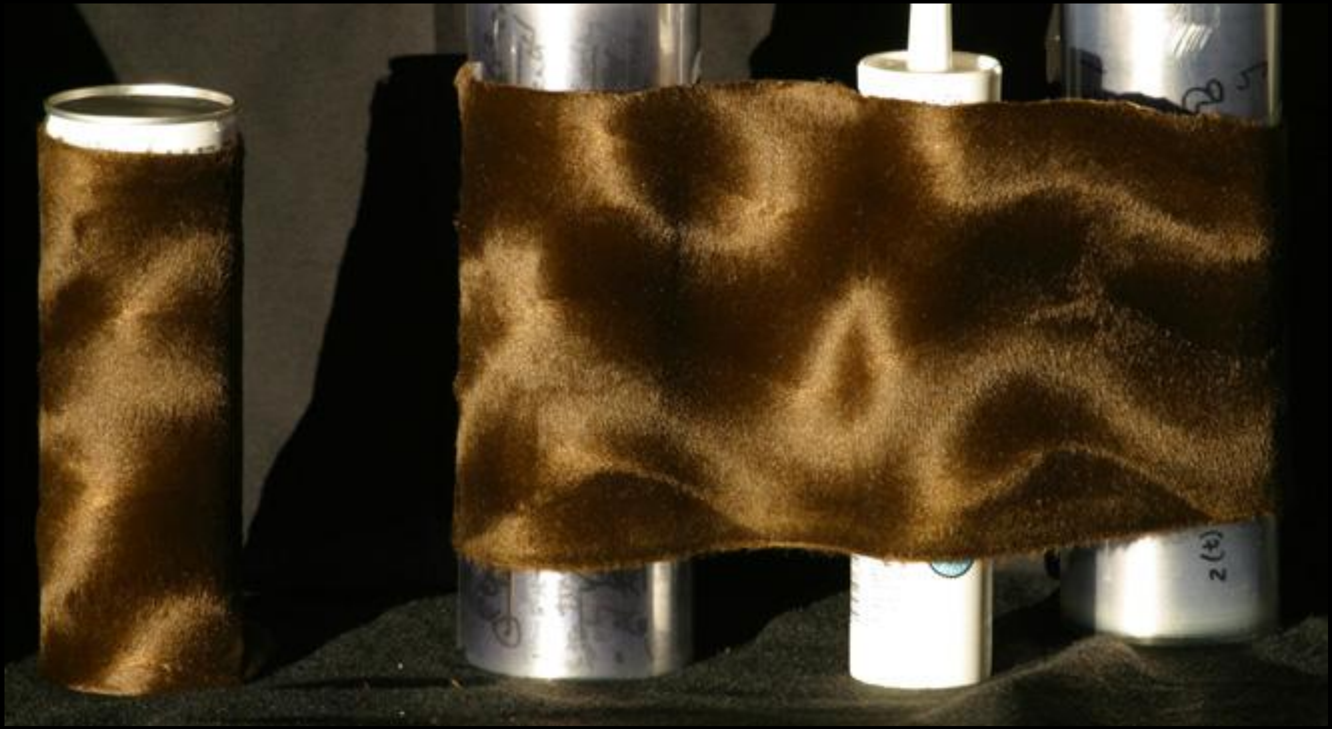


Velvet

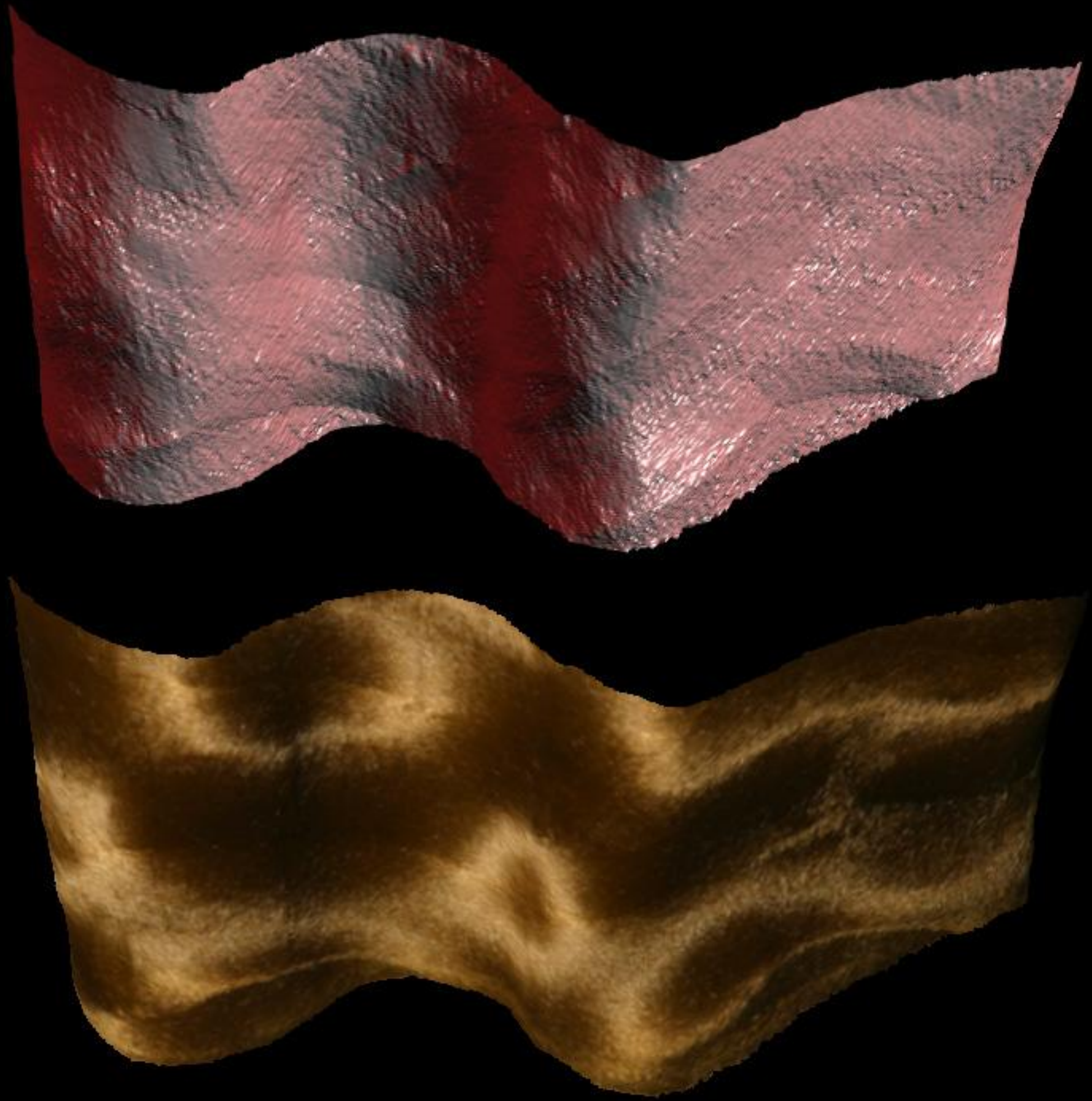
Virtual Views

Brushed Fur

Brushed Fur



Virtual Views



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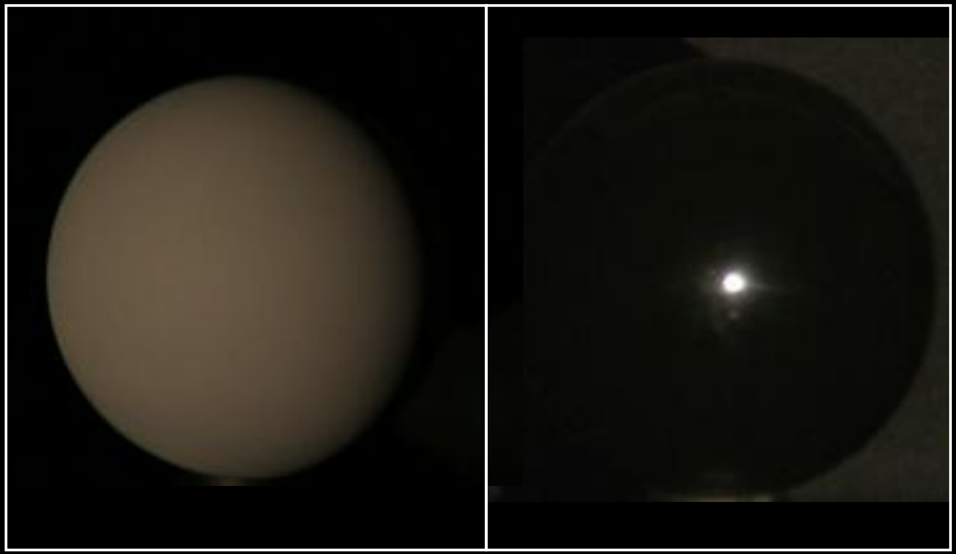
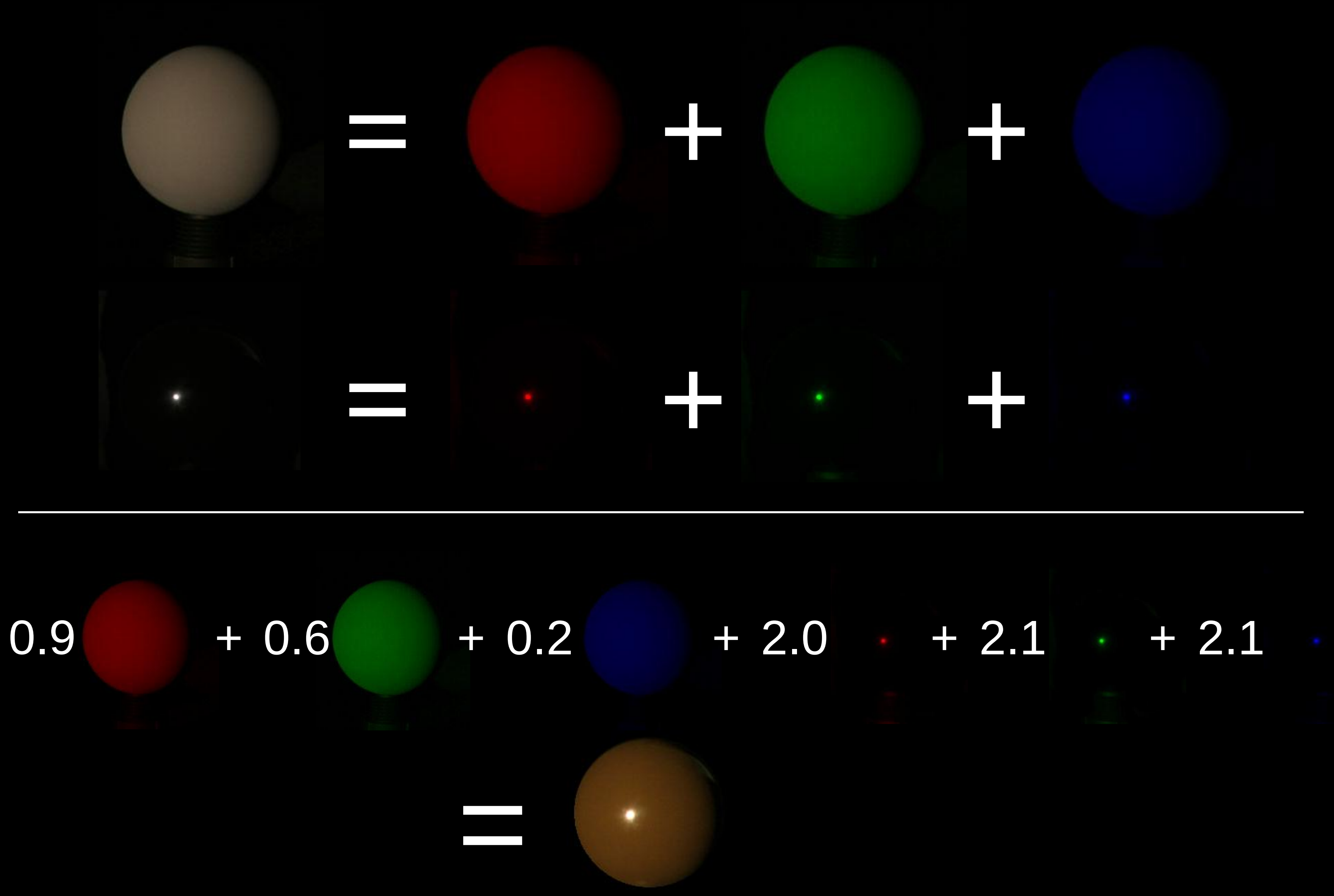
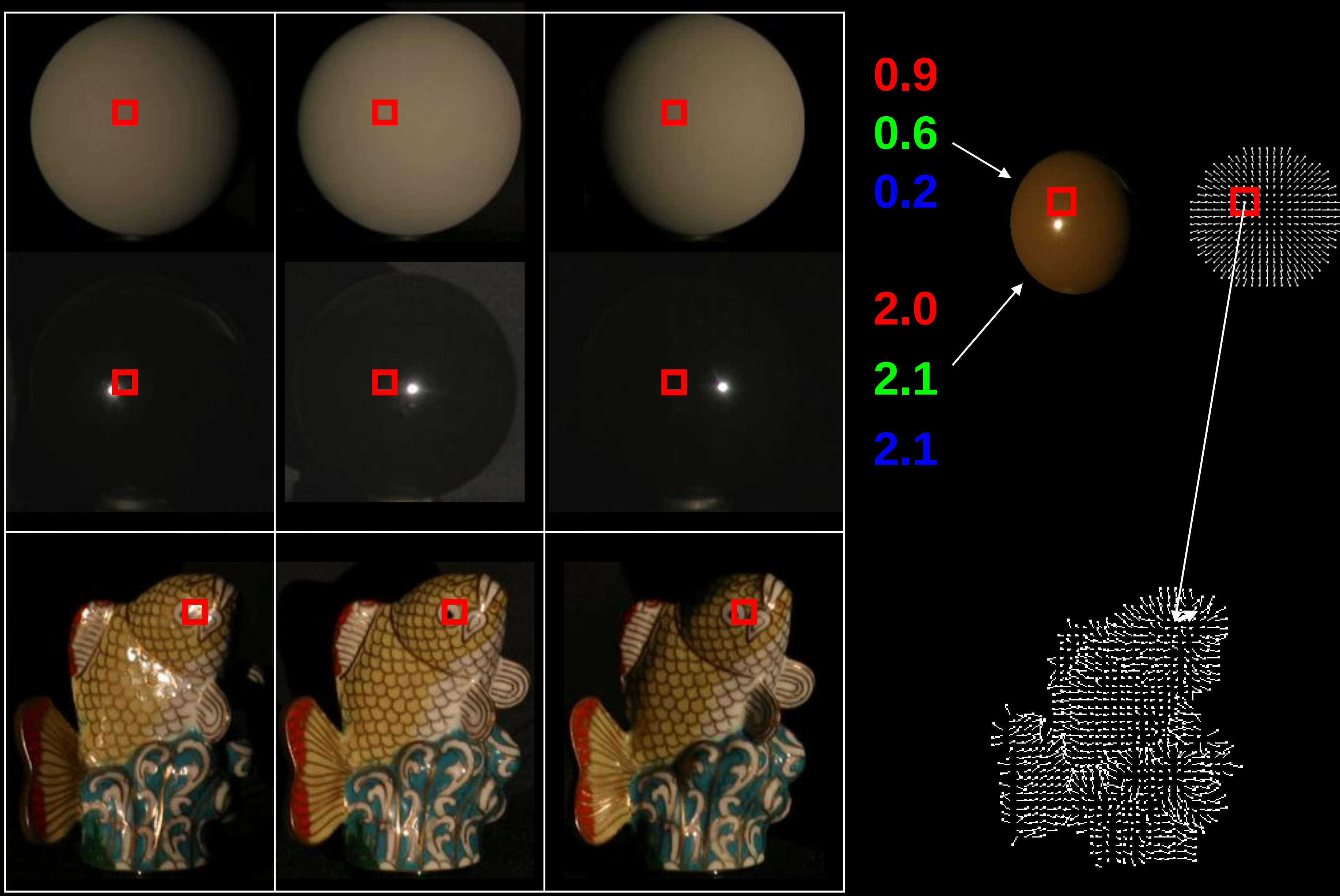
Located in the beautiful northwest corner of Connecticut, Canton has been our company's home for the last three years and we have been in complete operation for over ten years. Proud of our reputation, Salem Specialty Ball Company has over fifty years of combined experience allowing us to provide top-notch quality technical support and expert engineering consultation



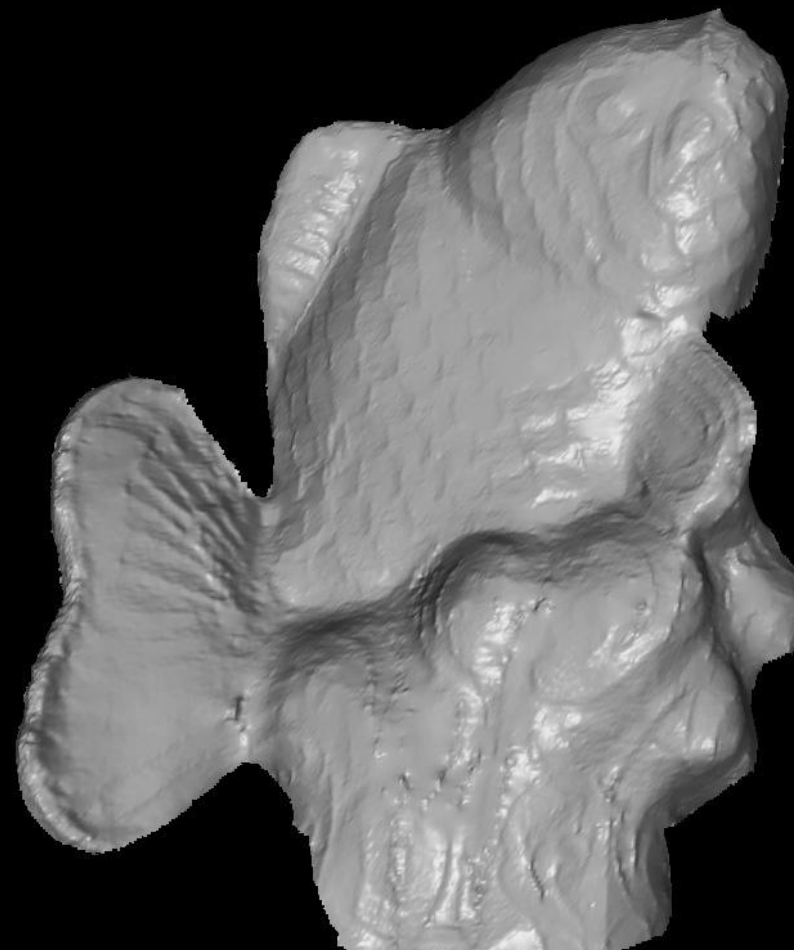
Linear combinations of materials




0.9
0.6
0.2
2.0
2.1
2.1

Virtual views

laser scan



photometric stereo

Problem definition

Estimate 3D shape by varying illumination, fixed camera

Operating conditions

- any opaque material
- distant camera, lighting
- reference object available
- no shadows, interreflections, transparency

Fast Separation of Direct and Global Images Using High Frequency Illumination

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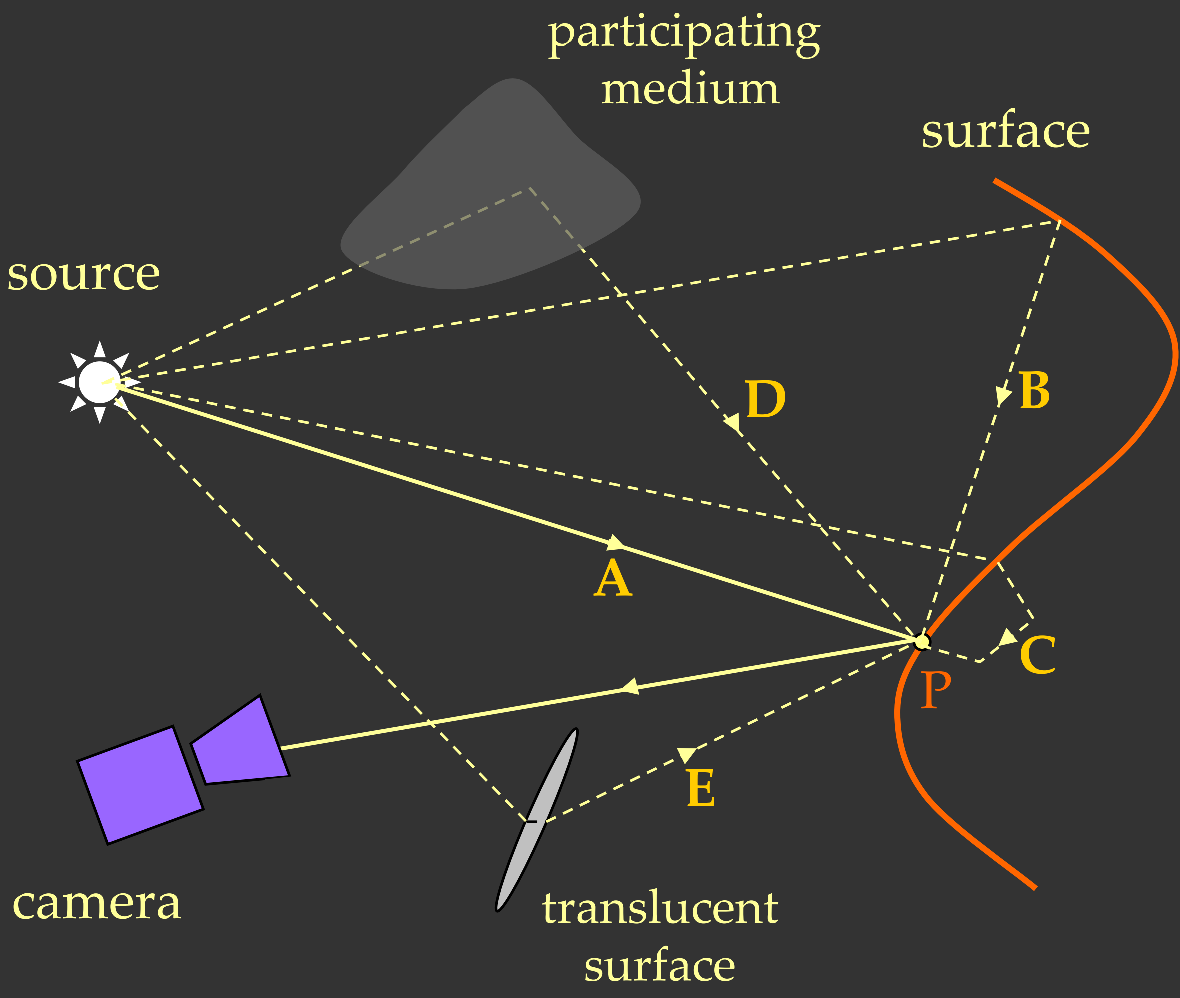
Columbia University
Michael D. Grossberg
City College of New York
Ramesh Raskar
MERL

SIGGRAPH Conference
Boston, July 2006

Support: ONR, NSF, MERL

Direct and Global Illumination



A : Direct

B : Interrelection

C : Subsurface

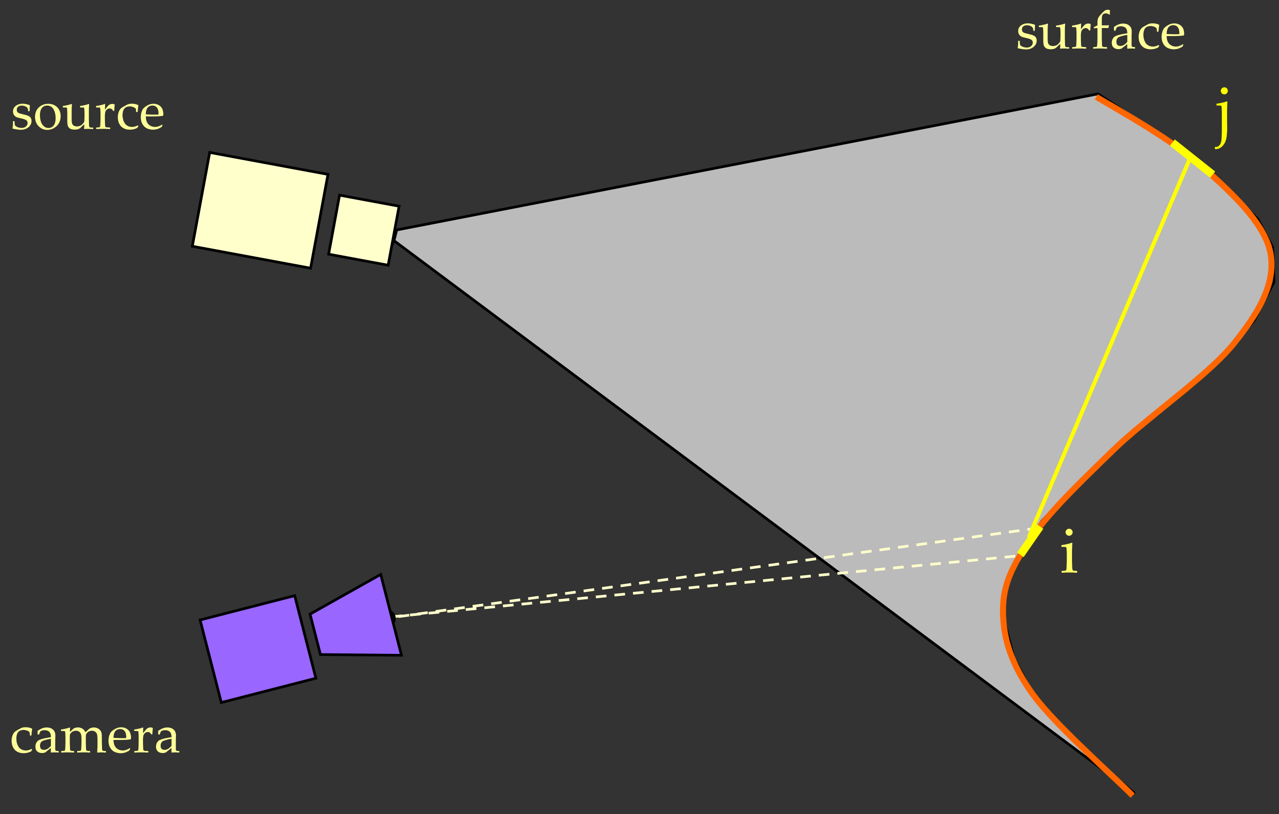
D : Volumetric

E : Diffusion

Fast Separation of Direct and Global Images

- Create Novel Images of the Scene
- Enhance Brightness Based Vision Methods
- New Insights into Material Properties

Direct and Global Components: Interreflections



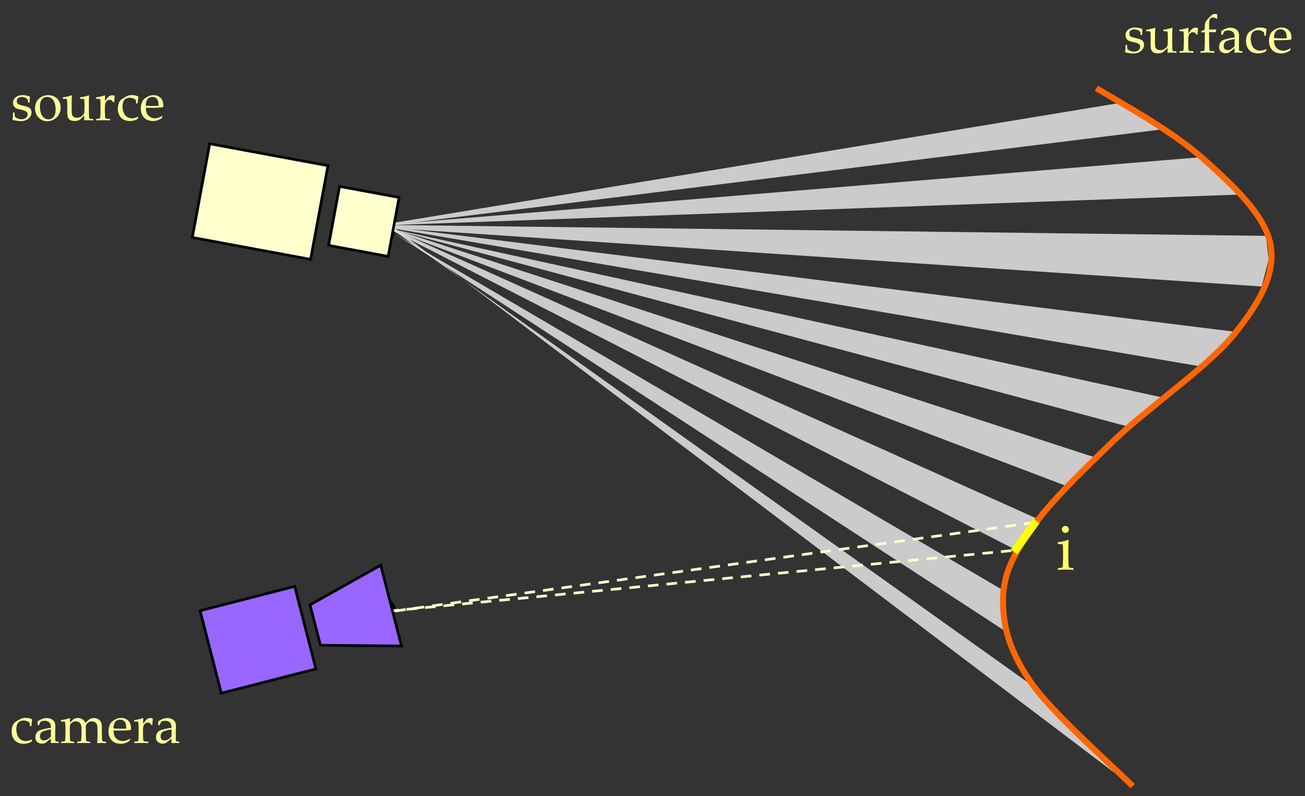
$$L[c,i] = L_d[c,i] + L_g[c,i]$$

radiance direct global

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

BRDF and geometry

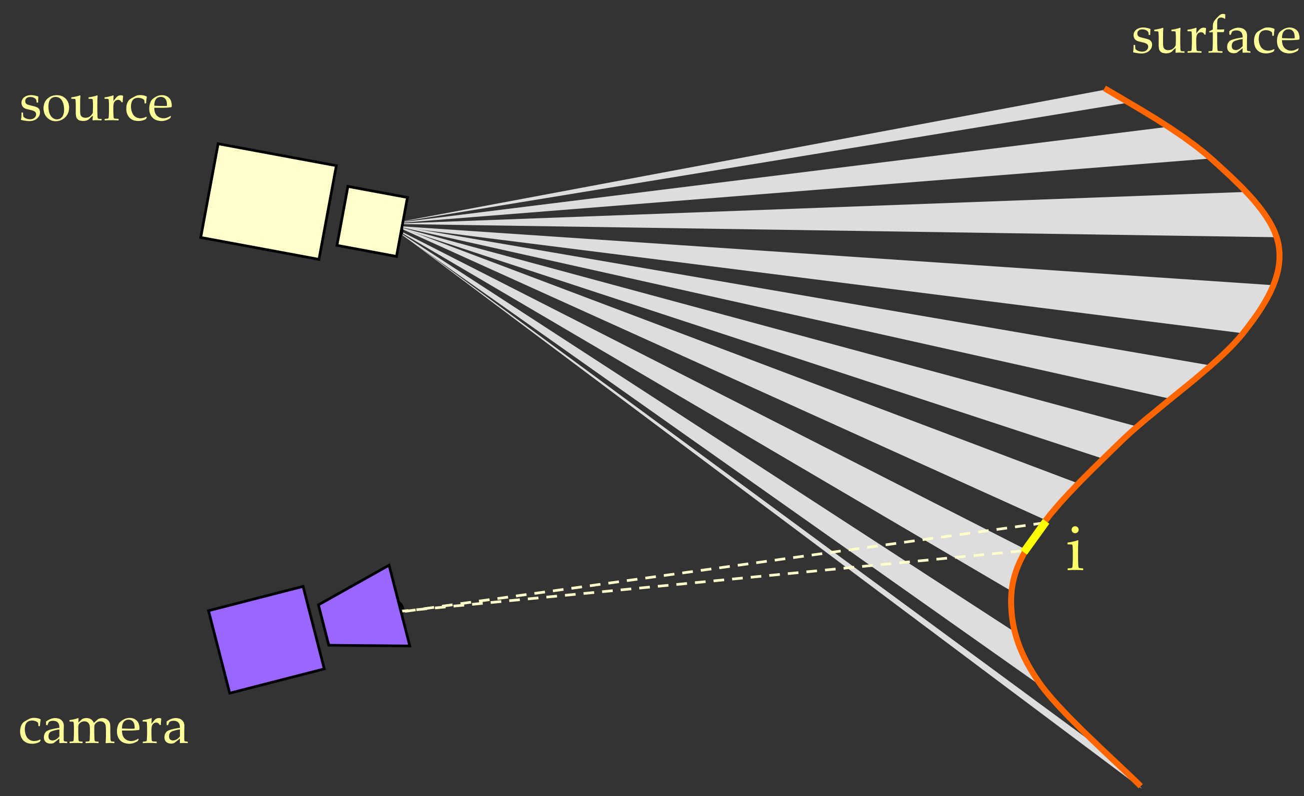
High Frequency Illumination Pattern



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

fraction of activated source elements

High Frequency Illumination Pattern



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

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

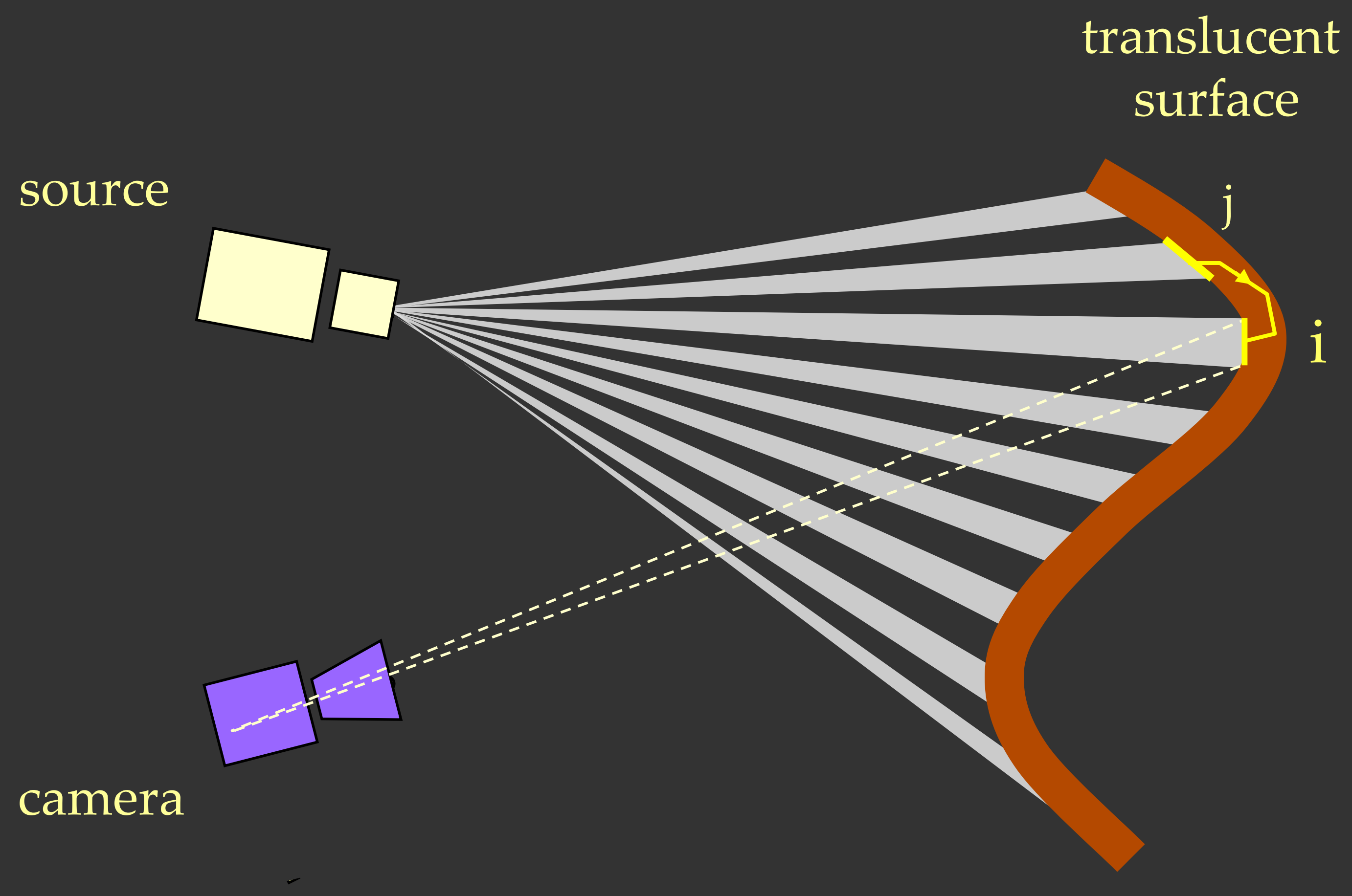
fraction of activated source elements

Separation from Two Images

$\alpha = \frac{1}{2}$: $\boxed{L_d = L_{max} - L_{min} \,,\; L_g = 2L_{min}}$

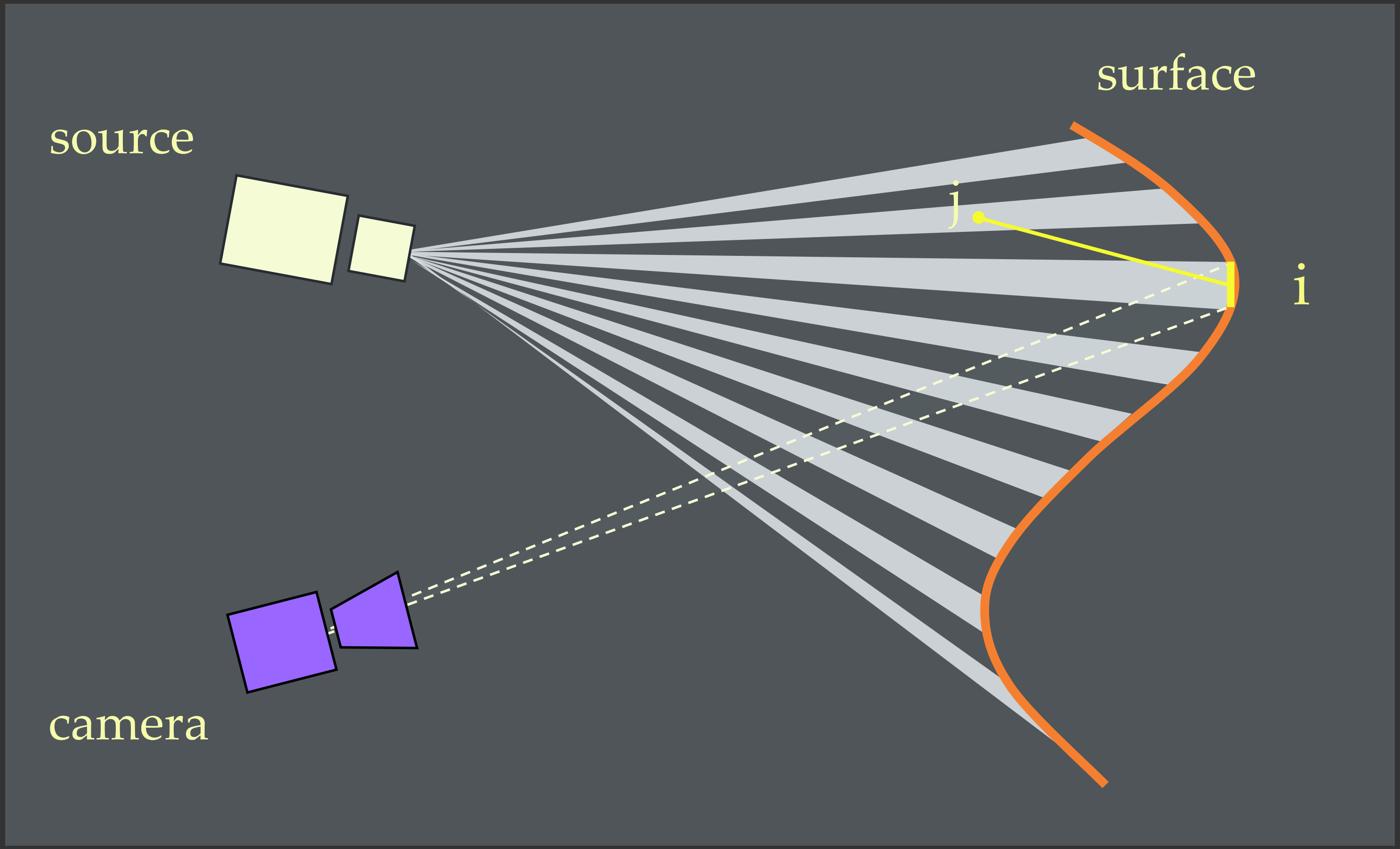
direct global

Other Global Effects: Subsurface Scattering



Other Global Effects: Volumetric Scattering

participating medium



Diffuse Interreflections

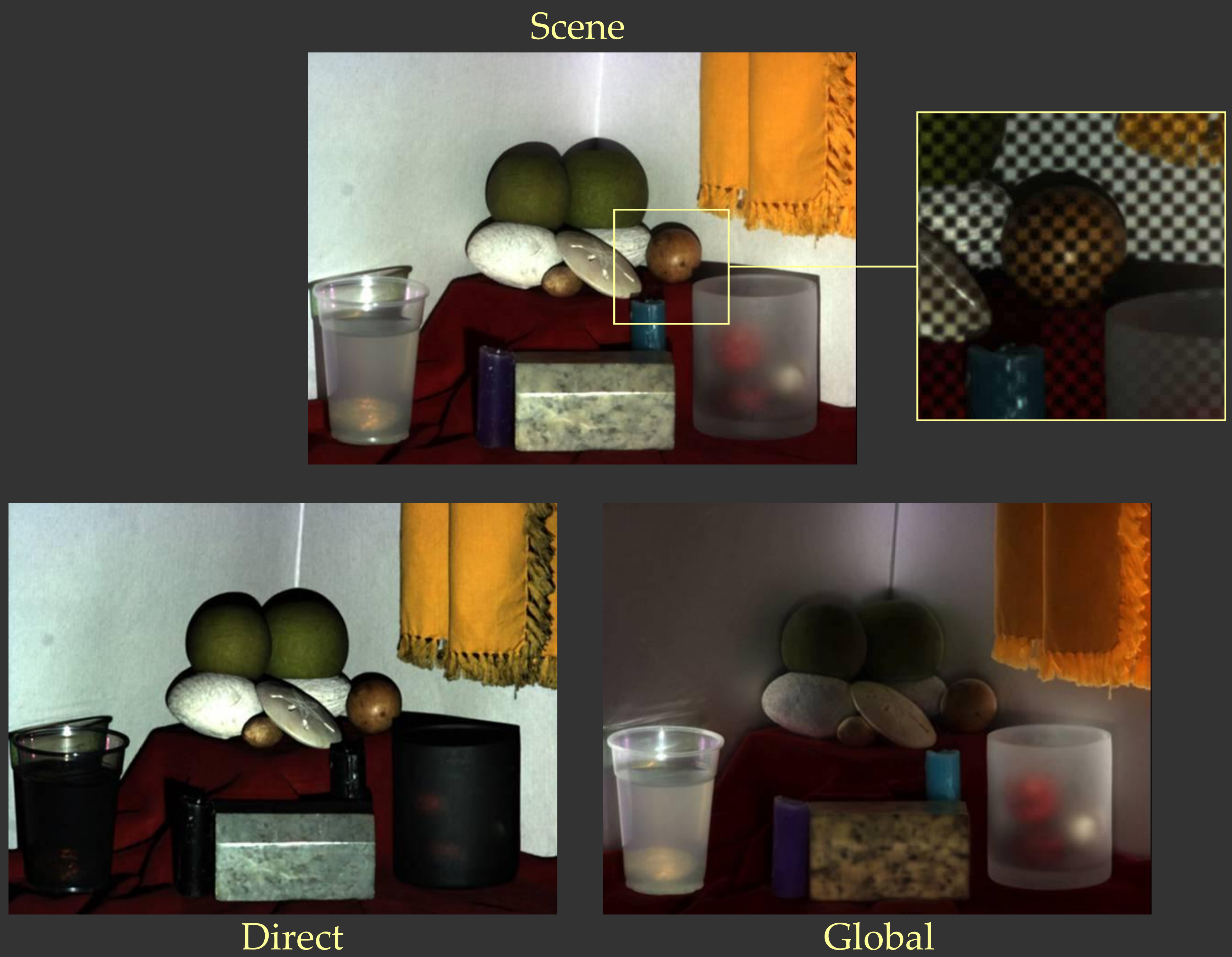
Specular Interreflections

Diffusion

Volumetric Scattering

Subsurface Scattering

Scene


Scene
Direct
Global

Real World Examples:

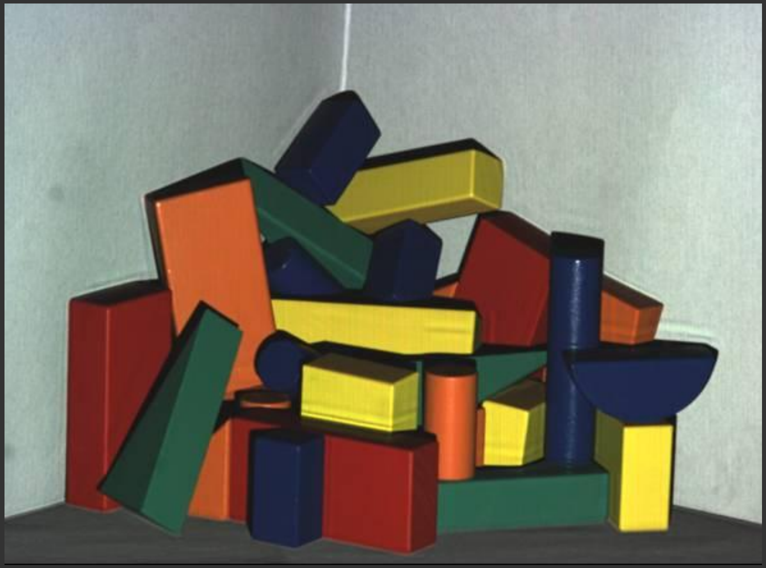
Can You Guess the Images?

Eggs: Diffuse Interreflections

Direct

Global

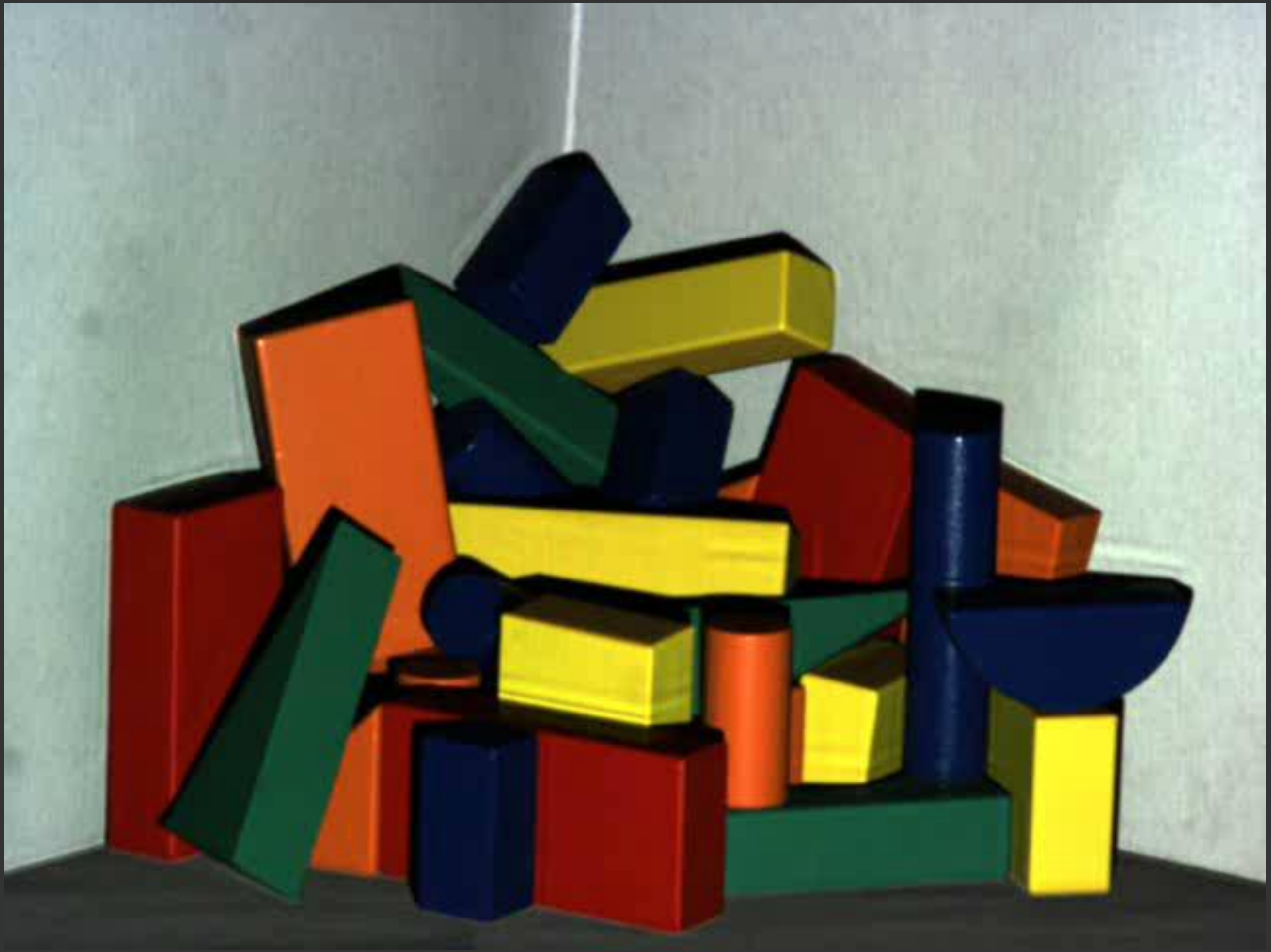
Wooden Blocks: Specular Interreflections



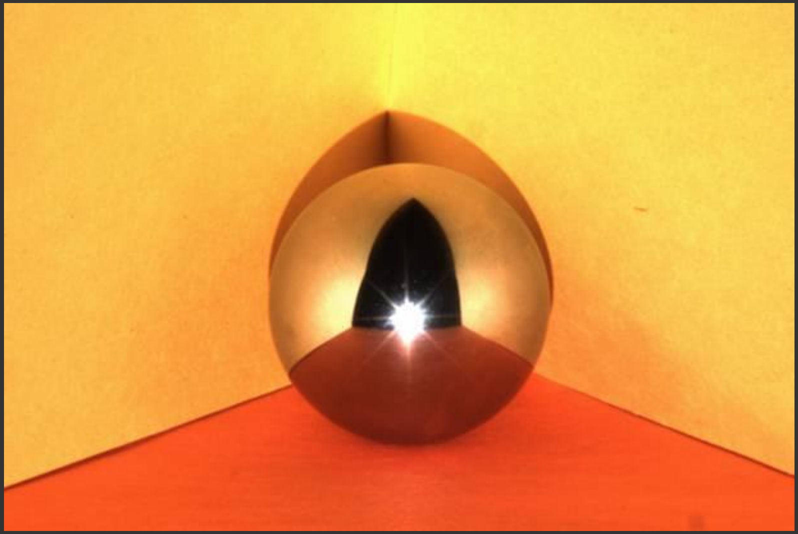
Direct

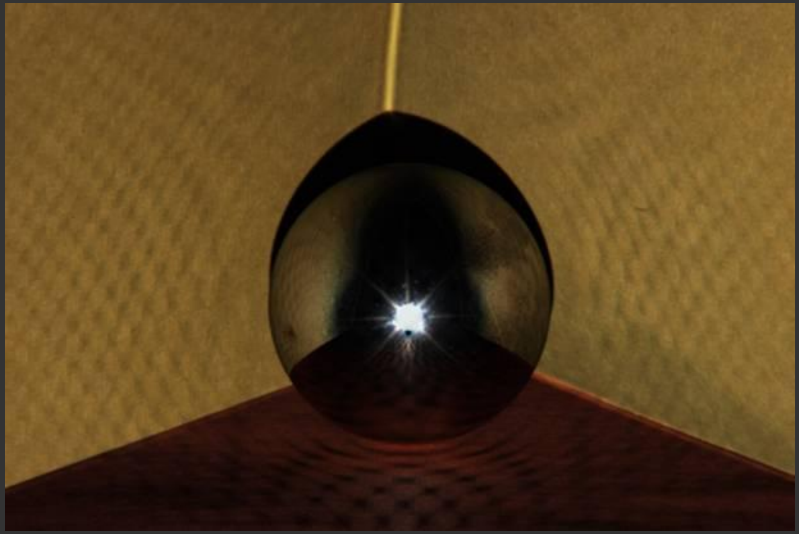
Global

Novel Images

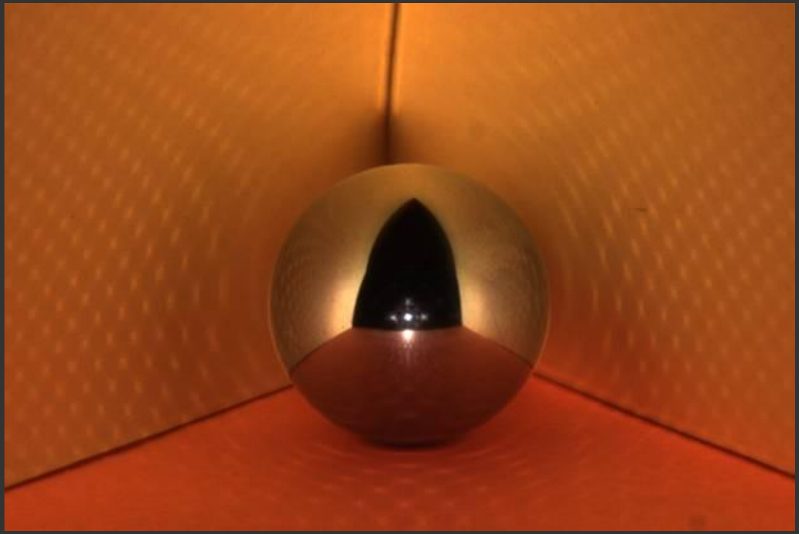


Mirror Ball: Failure Case





Direct



Global

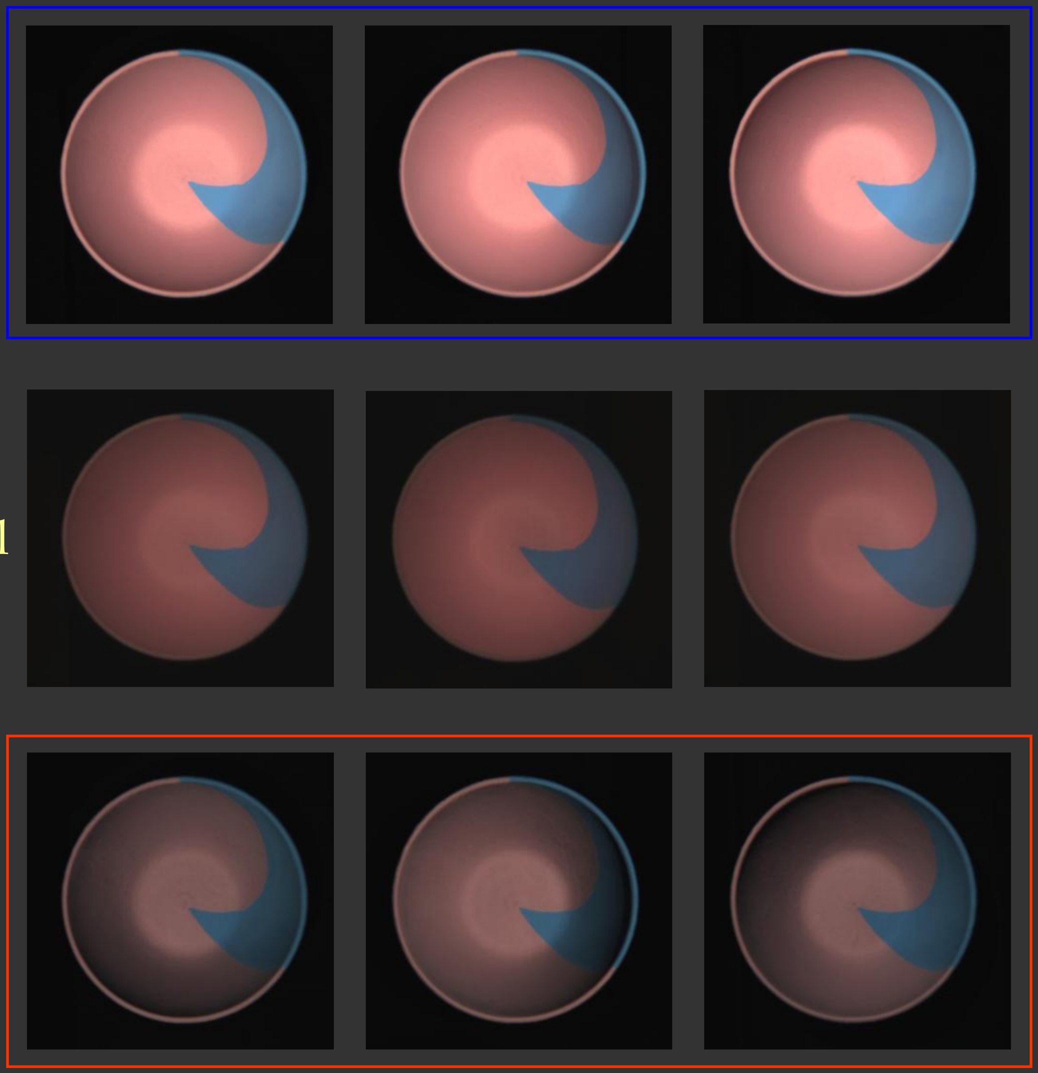
Photometric Stereo using Direct Images

Source 1 Source 2 Source 3

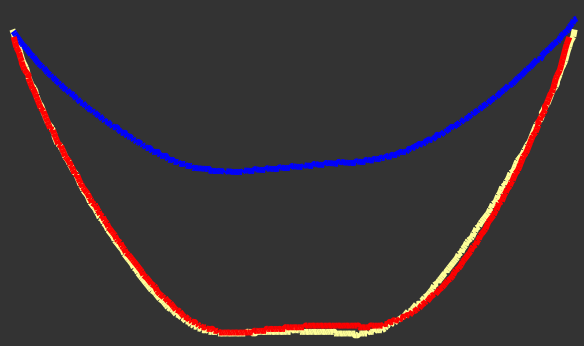
Bowl

Global

Direct



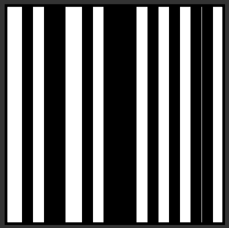
Shape



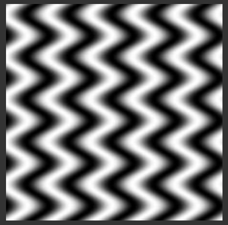
Nayar et al., 1991

Variants of Separation Method

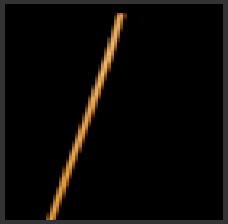
- Coded Structured Light



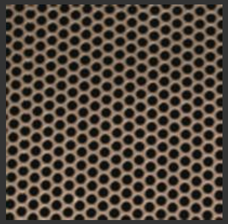
- Shifted Sinusoids



- Shadow of Line Occluder



- Shadow of Mesh Occluders



Building Corner

Stick

Shadow

3D from Shadows:
Bouguet and Perona 99

$$\underbrace{L_d}_{\text{direct}} = L_{\max} - L_{\min} \,, \quad \underbrace{L_g}_{\text{global}} = L_{\min}$$

Building Corner

Direct

Global

Shower Curtain: Diffuser

Mesh

Shadow

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

direct

global

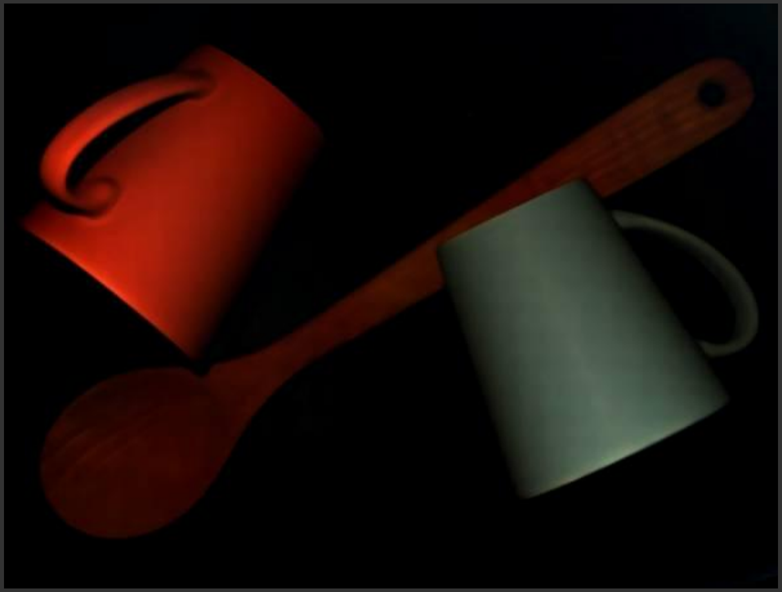
Shower Curtain: Diffuser

Direct

Global

Kitchen Sink: Volumetric Scattering

Volumetric Scattering:
Chandrasekar 50, Ishimaru 78



Direct

Global

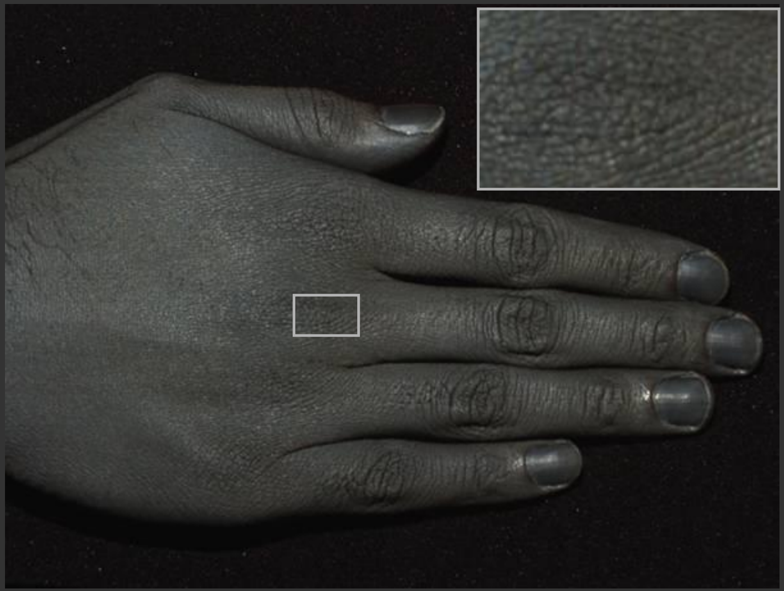
Peppers: Subsurface Scattering

Direct

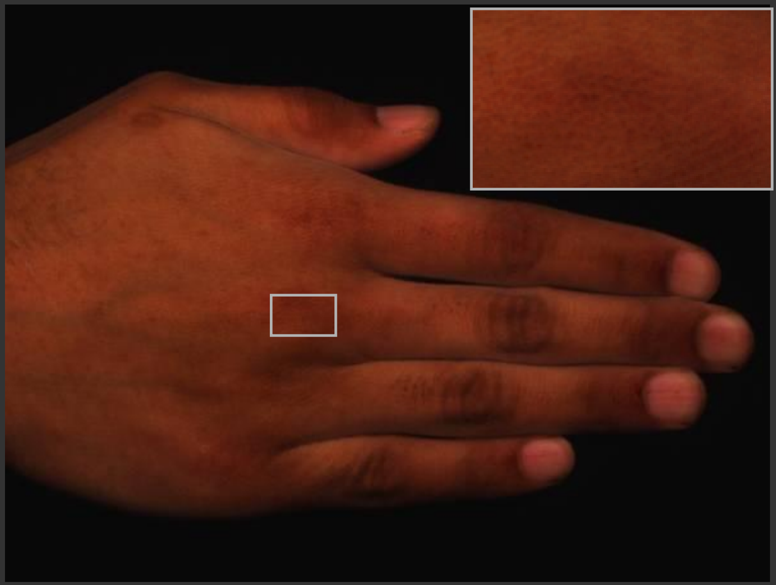
Global

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

Hands

Afric. Amer. Female | Chinese Male | Spanish Male

Afric. Amer. Female | Chinese Male | Spanish Male

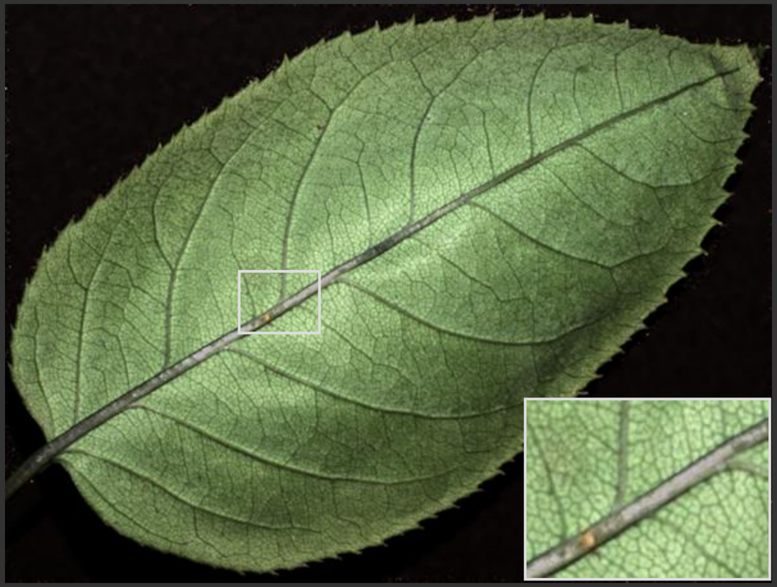
Direct

Afric. Amer. Female | Chinese Male | Spanish Male

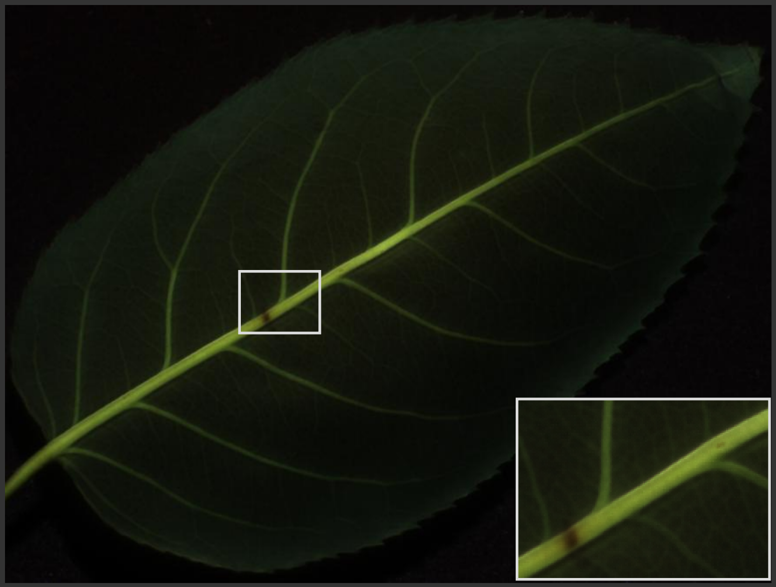
Global

Tea Rose Leaf

Leaf Anatomy: Purves et al. 03

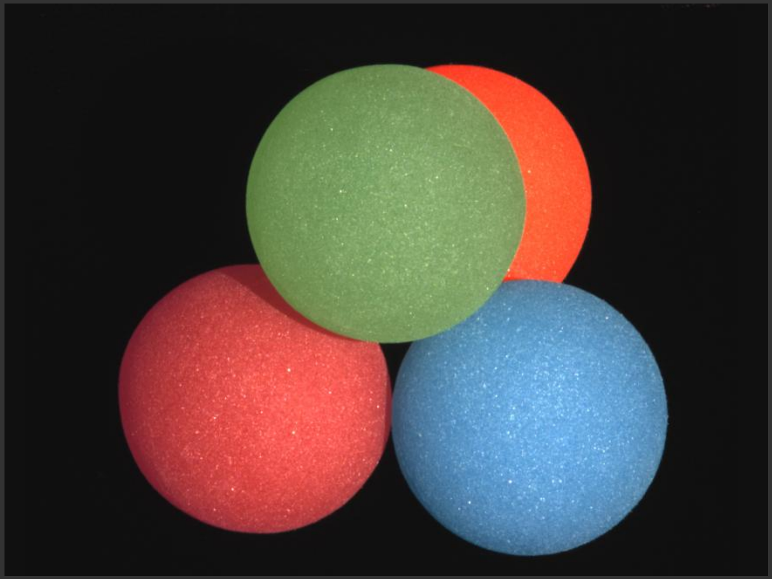


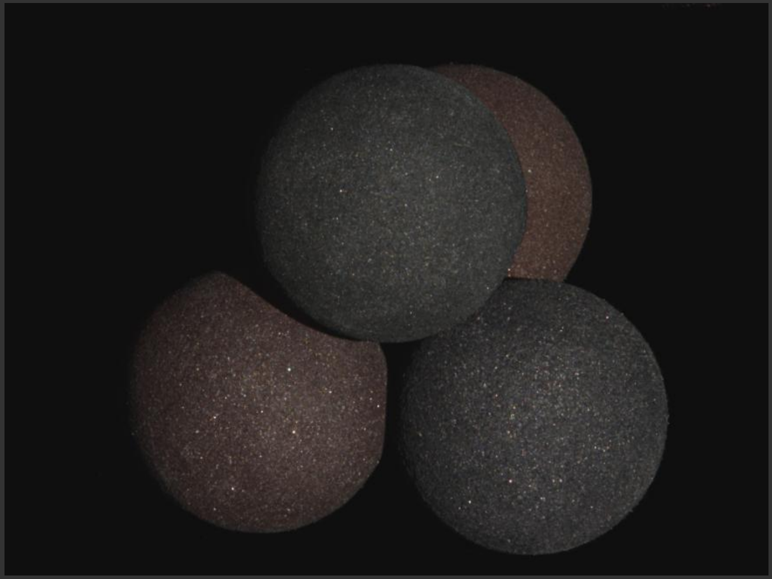
Direct



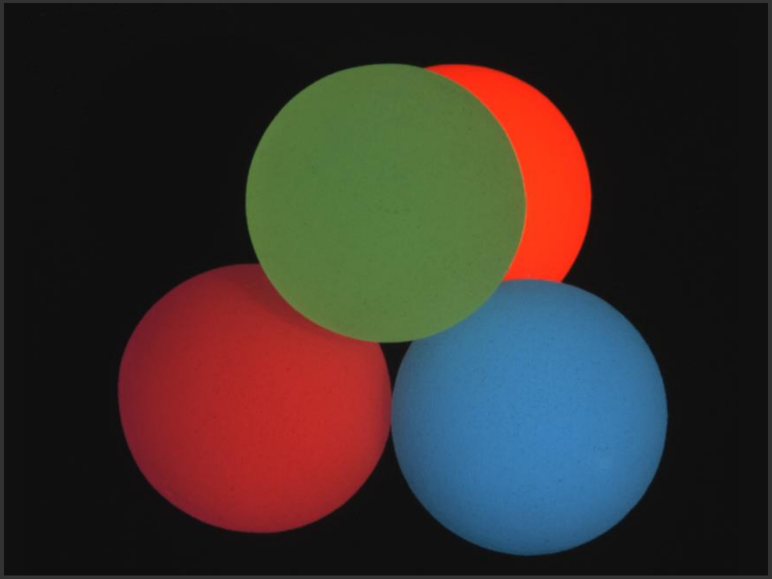
Global

Translucent Rubber Balls





Direct



Global

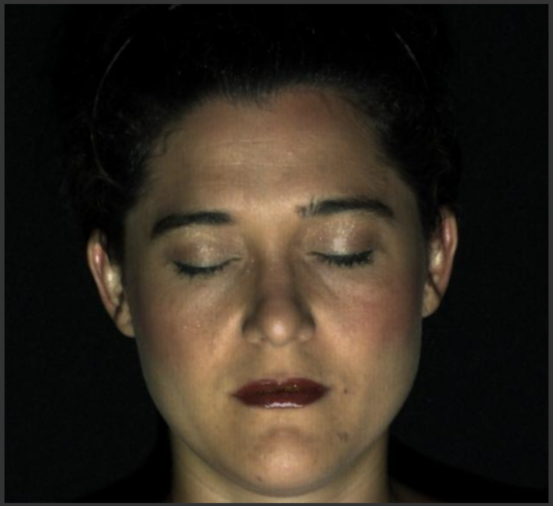
Face: Without and With Makeup

Without Makeup

Direct

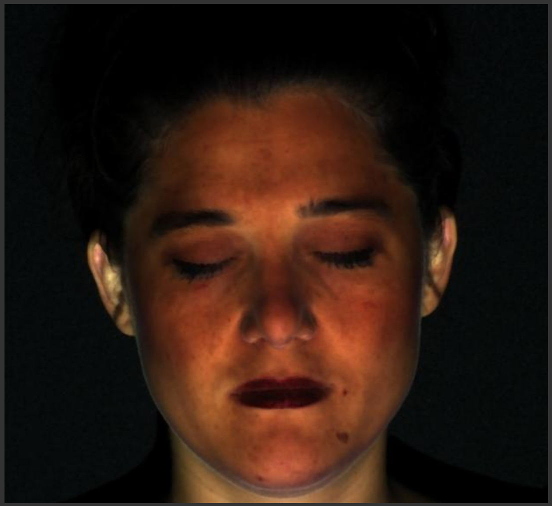
Global

With Makeup



Direct

Global



Blonde Hair

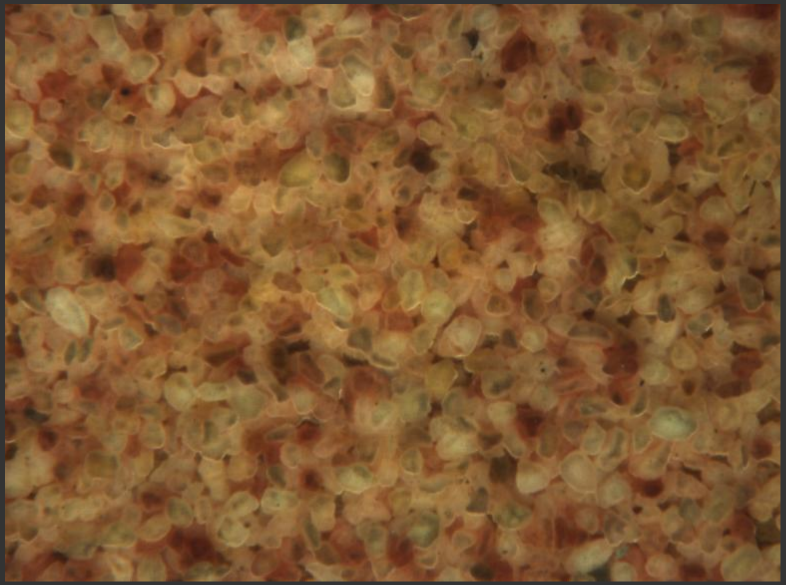
Hair Scattering: Stamm et al. 77, Bustard and Smith 91, Lu et al. 00 Marschner et al. 03

Direct

Global

Pebbles: 3D Texture

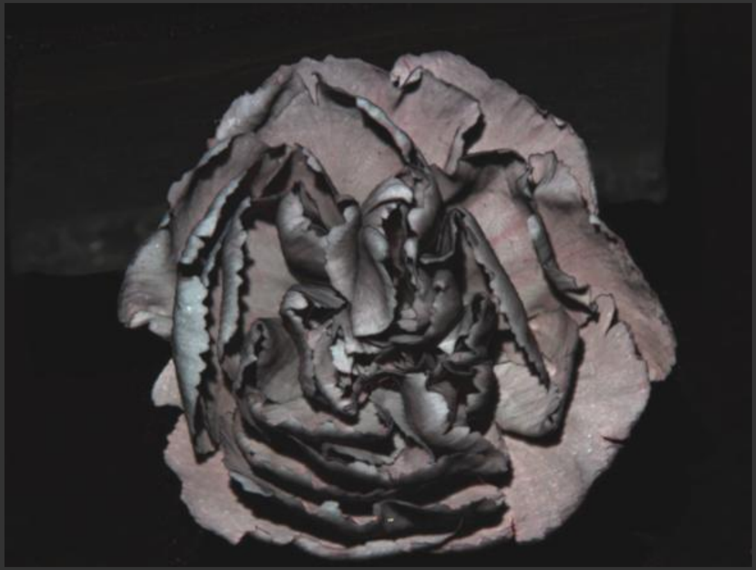
Direct



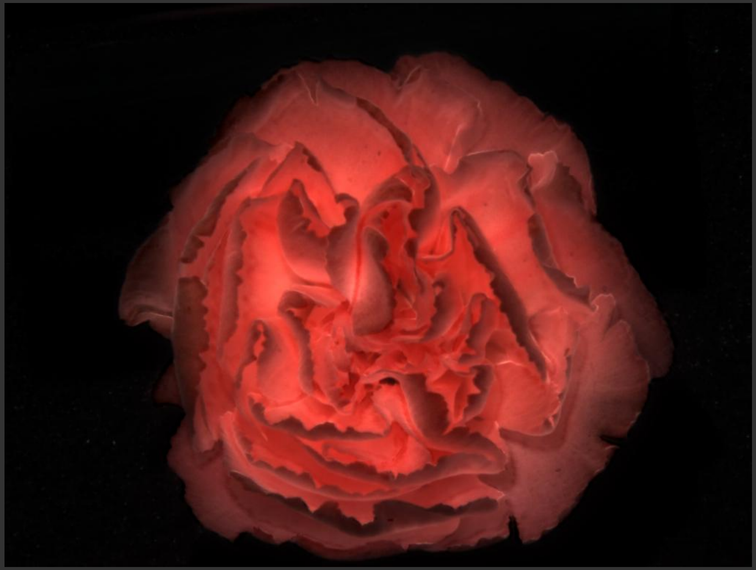
Global

Pink Carnation

Spectral Bleeding: Funt et al. 91



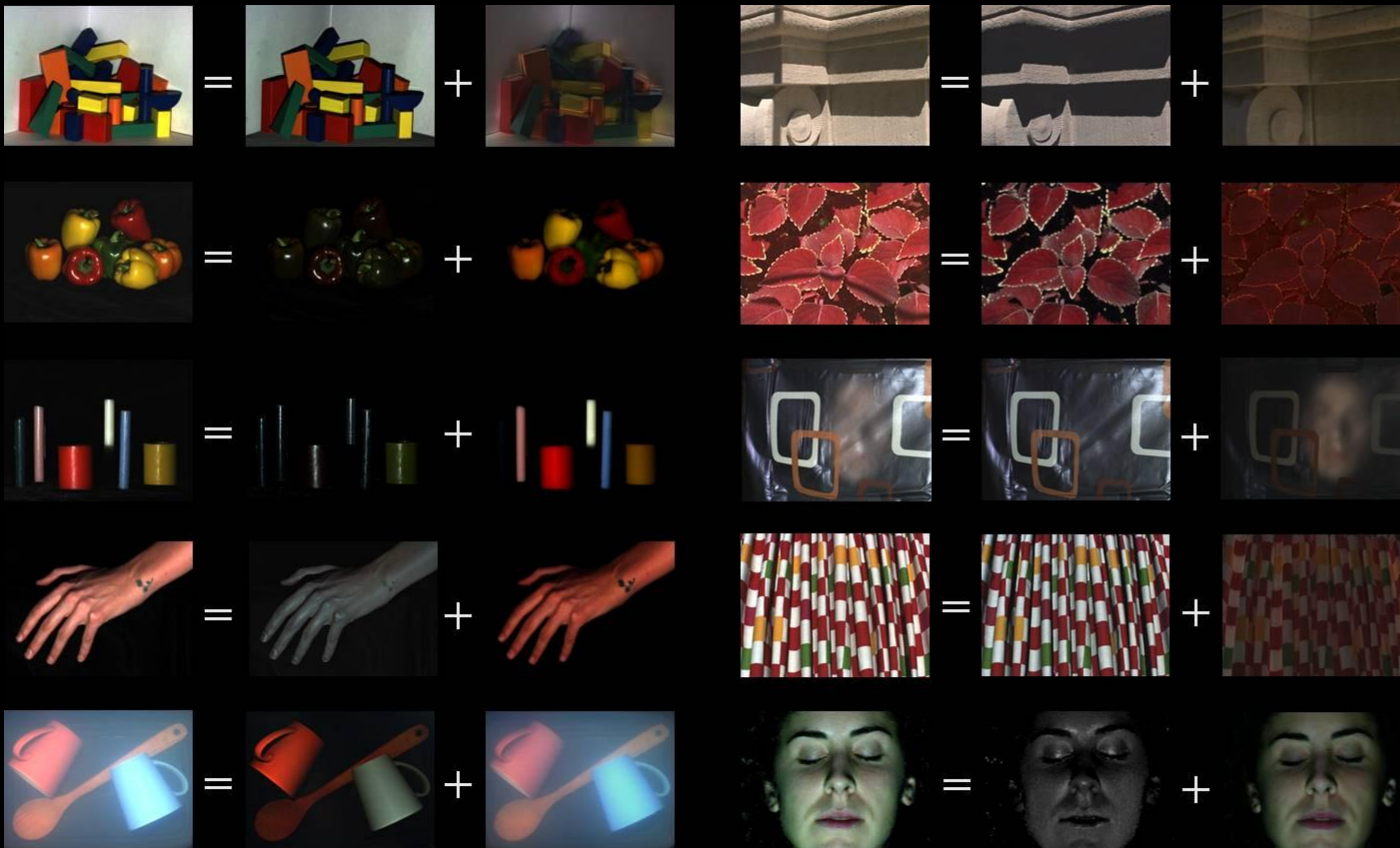
Direct



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



http://www1.cs.columbia.edu/CAVE/projects/separation/separation.php