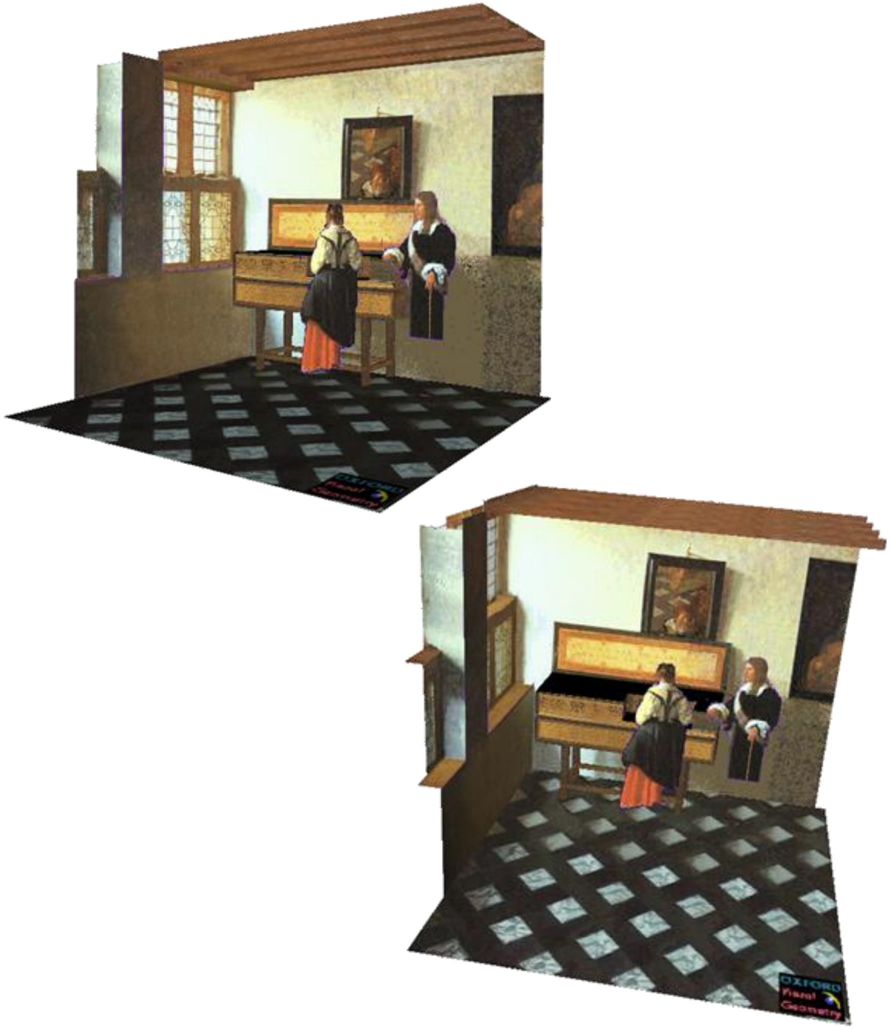
Last Lecture

- Single View Modeling

Vermeer's *Music Lesson*



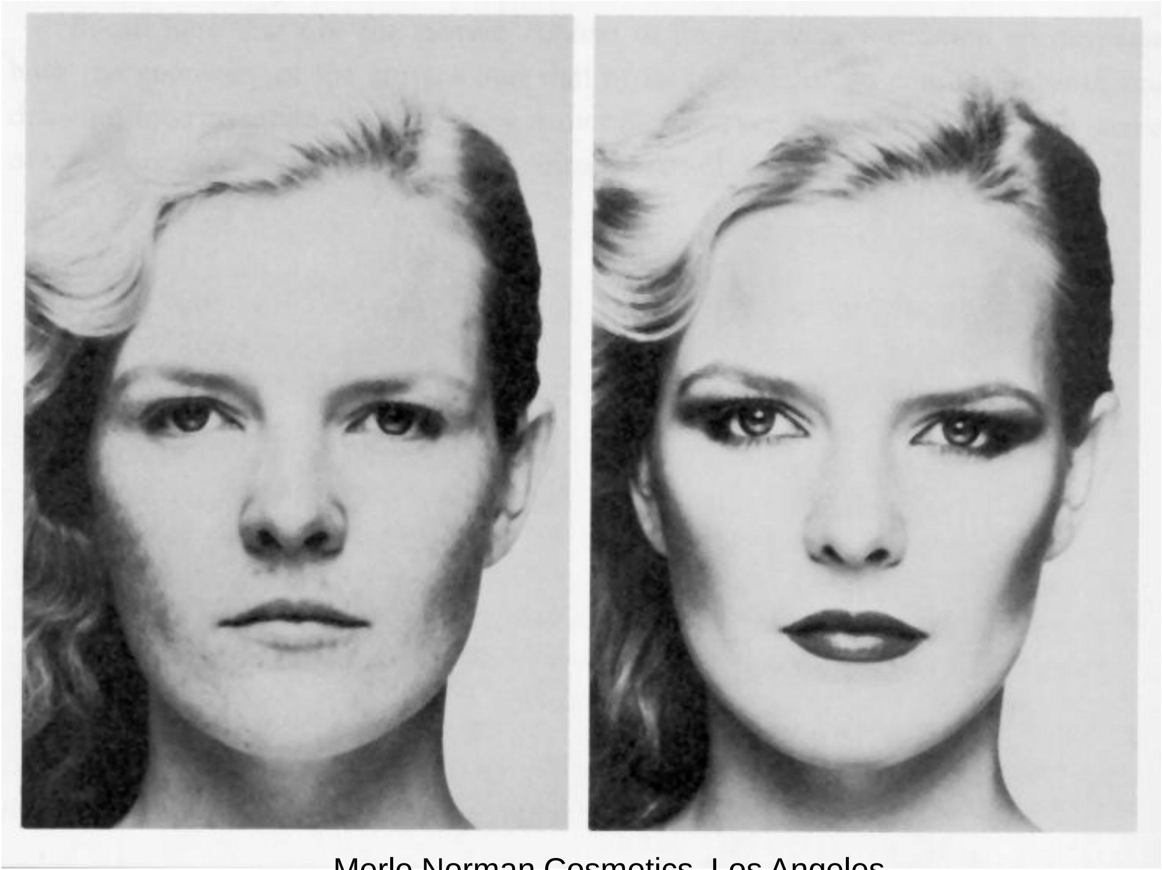
Reconstructions by Criminisi et al.

Today

- Photometric Stereo
- Separate Global and Direct Illumination

Photometric Stereo

Photometric Stereo

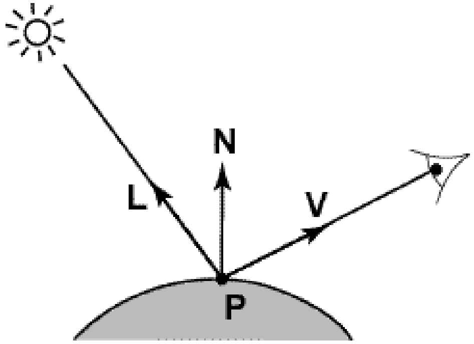


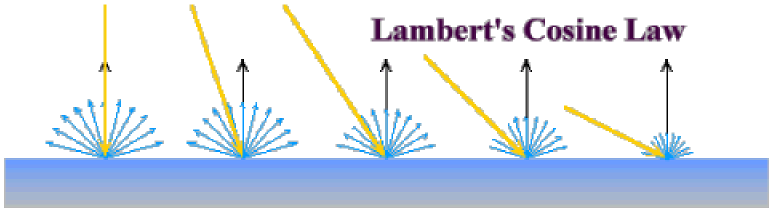
Merle Norman Cosmetics, Los Angeles

Readings

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

Diffuse reflection





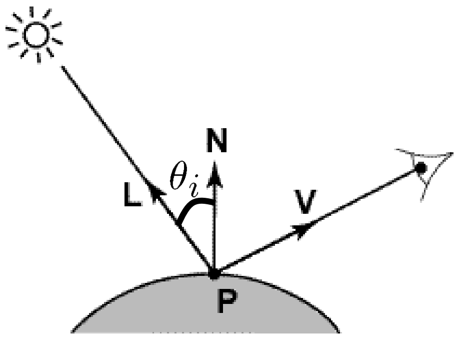
$$R_e = k_d \mathbf{N} \cdot \mathbf{L} R_i$$

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



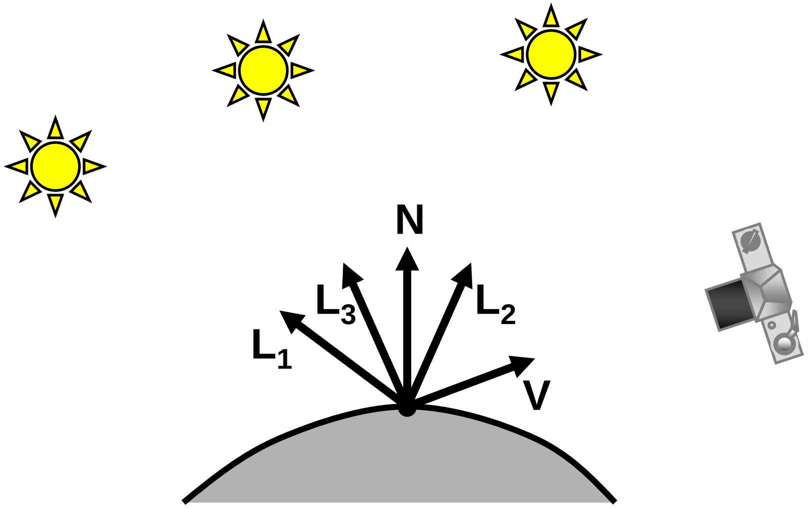
Suppose $k_d = 1$

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

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



$$I_1 = k_d \mathbf{N} \cdot \mathbf{L_1}$$
$$I_2 = k_d \mathbf{N} \cdot \mathbf{L_2}$$
$$I_3 = k_d \mathbf{N} \cdot \mathbf{L_3}$$

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:

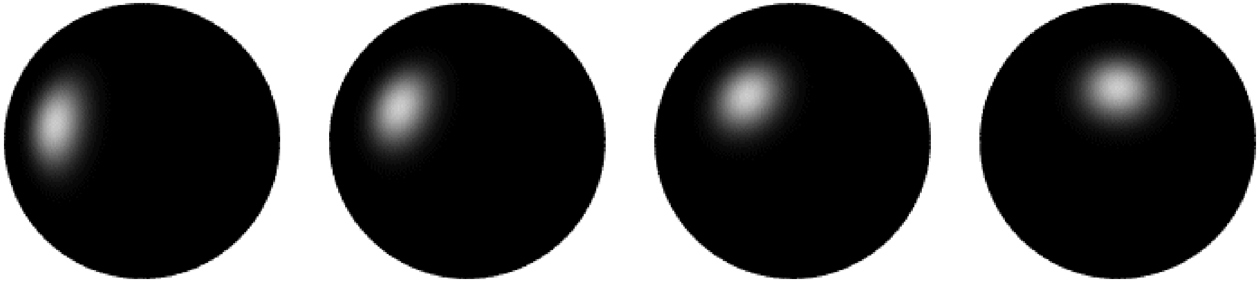
$$\begin{aligned} \mathbf{I} &= \mathbf{LG} \\ \mathbf{L^T I} &= \mathbf{L^T L G} \\ \mathbf{G} &= (\mathbf{L^T L})^{-1} (\mathbf{L^T I}) \end{aligned}$$

Solve for N, k_d as before

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

Computing light source directions

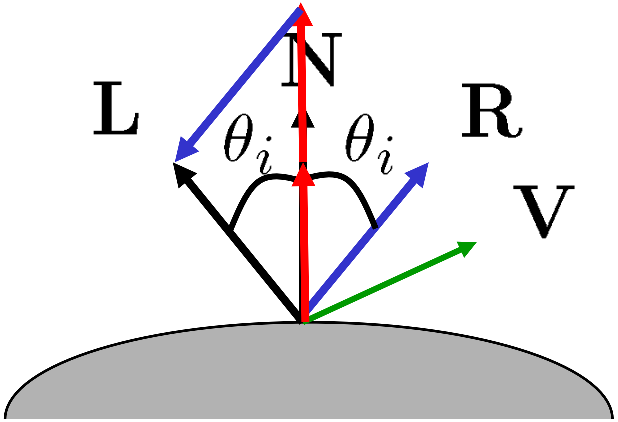
Trick: place a chrome sphere in the scene



- 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**



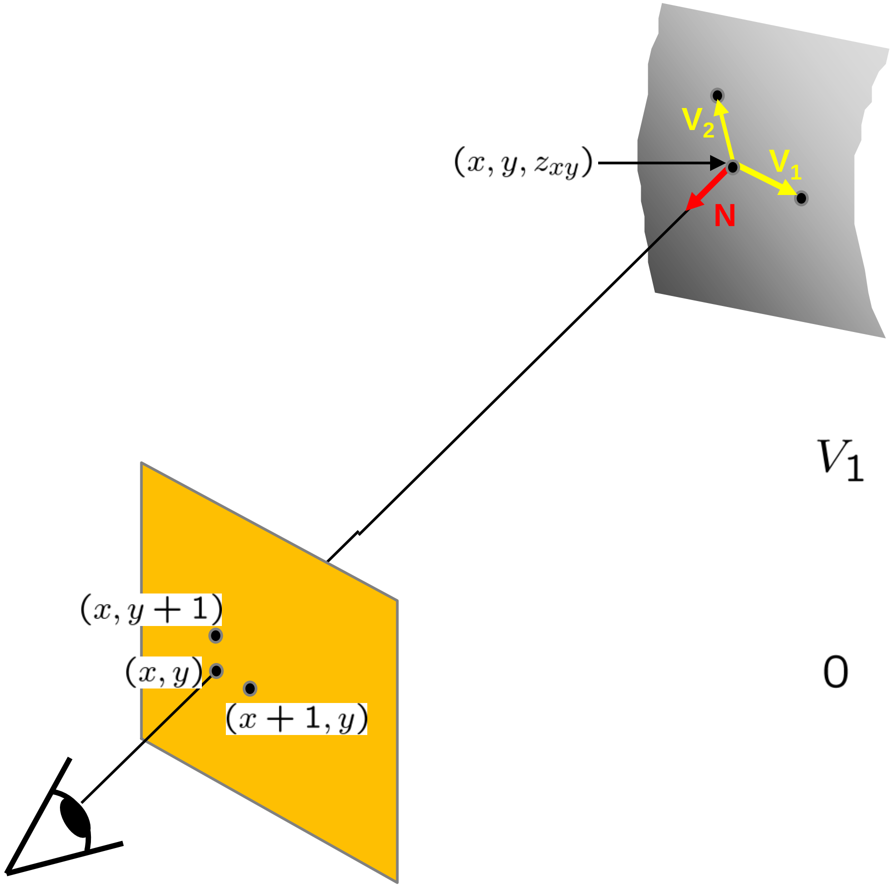
$$R_e = \begin{cases} R_i & \text{if } \mathbf{V} = \mathbf{R} \\ 0 & \text{otherwise} \end{cases}$$

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

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:

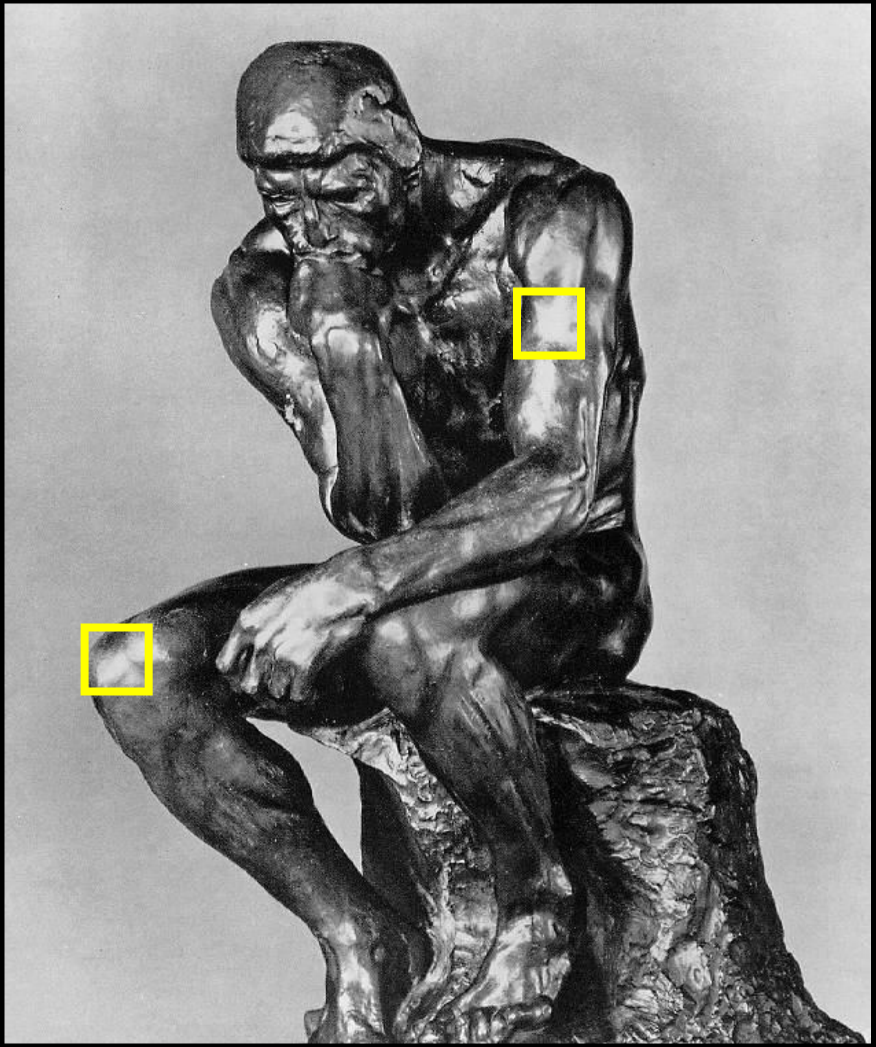
- Zickler, Belhumeur, and Kriegman, *"Helmholtz Stereopsis: Exploiting Reciprocity for Surface Reconstruction."* IJCV, Vol. 49 No. 2/3, pp 215-227.
- Hertzmann & Seitz, "*Example-Based Photometric Stereo: Shape Reconstruction with General, Varying BRDFs*." IEEE Trans. PAMI 2005

Example-based Photometric Stereo

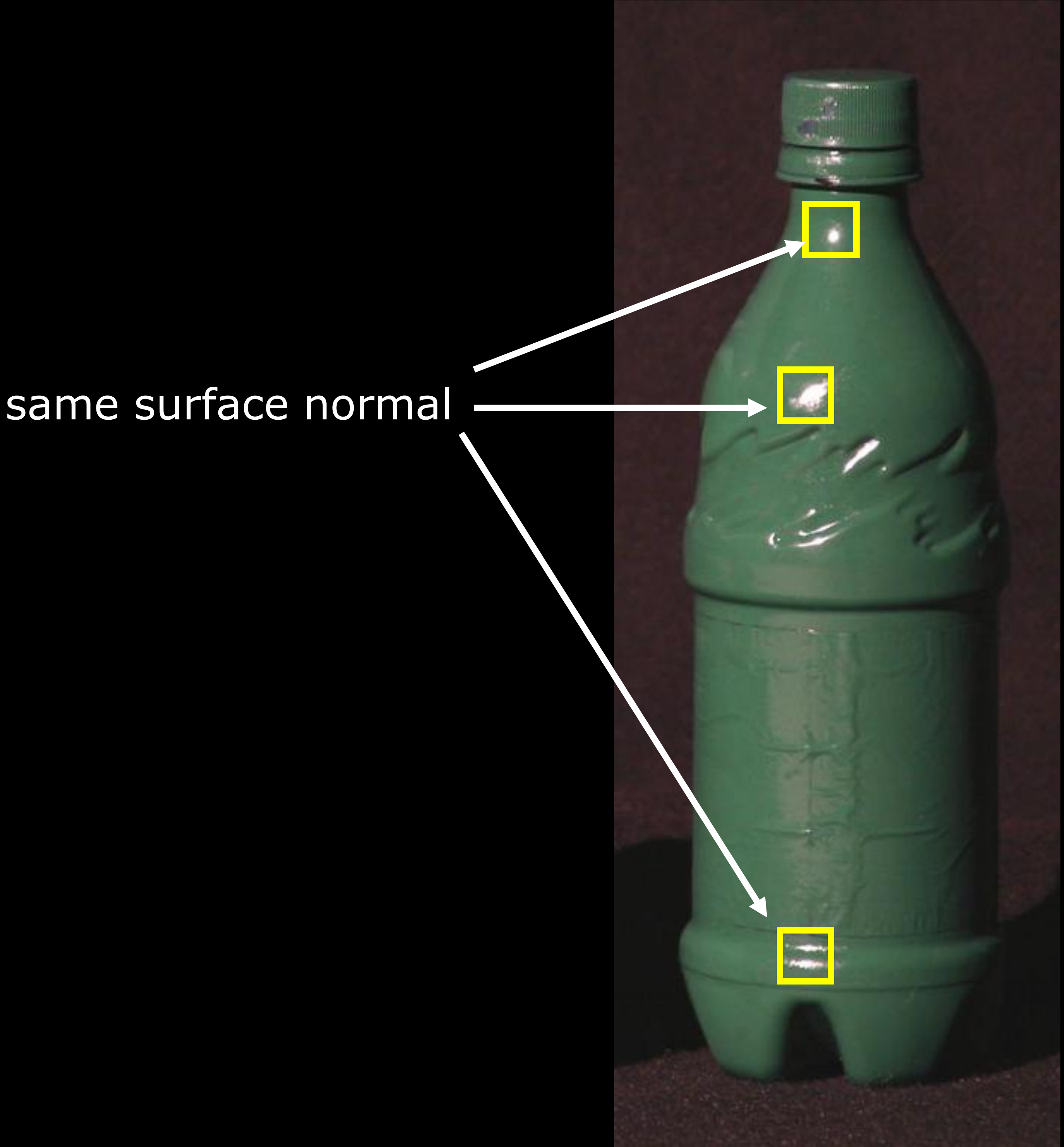
Aaron Hertzmann
University of Toronto

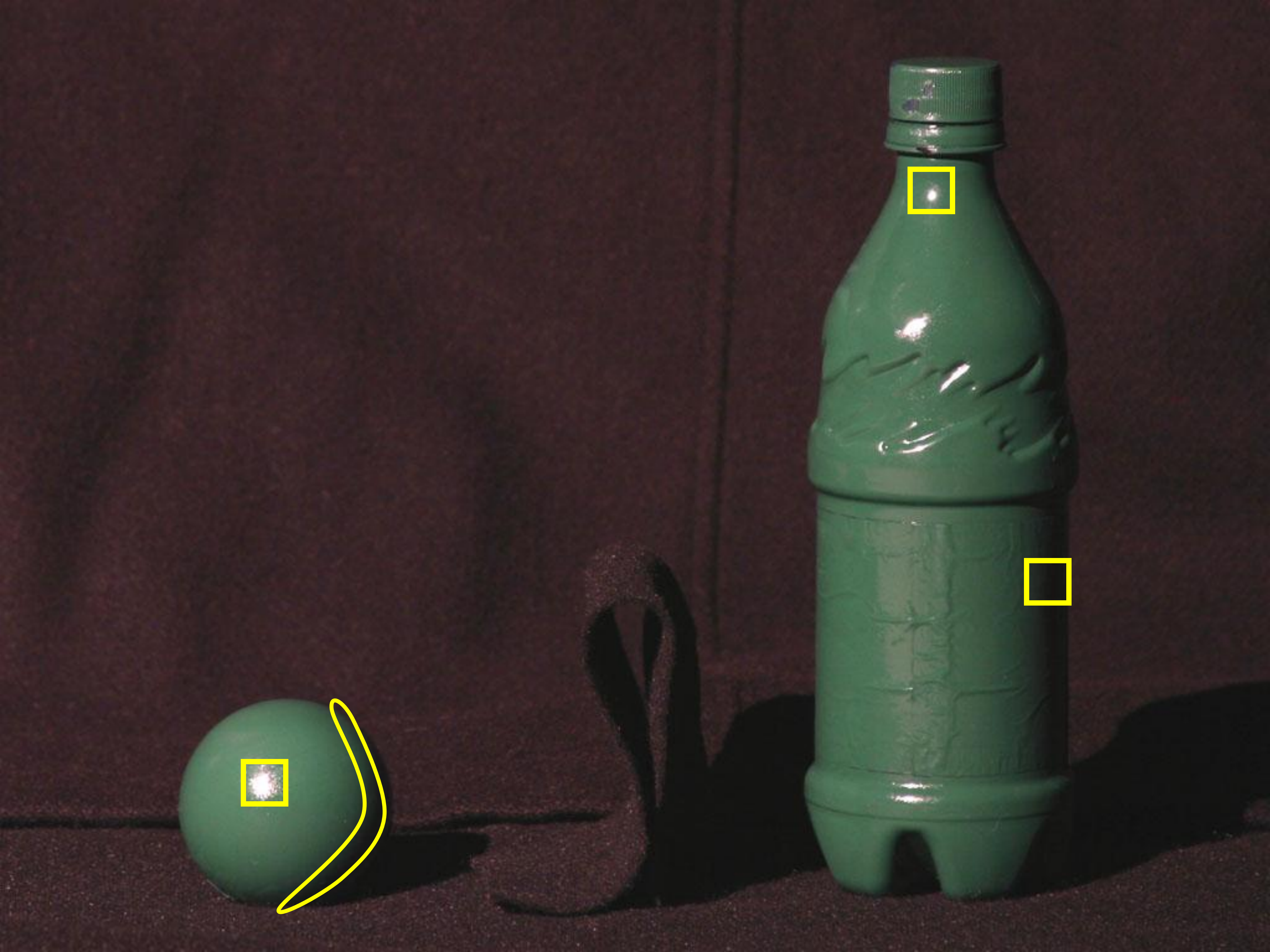
Steven M. Seitz
University of Washington

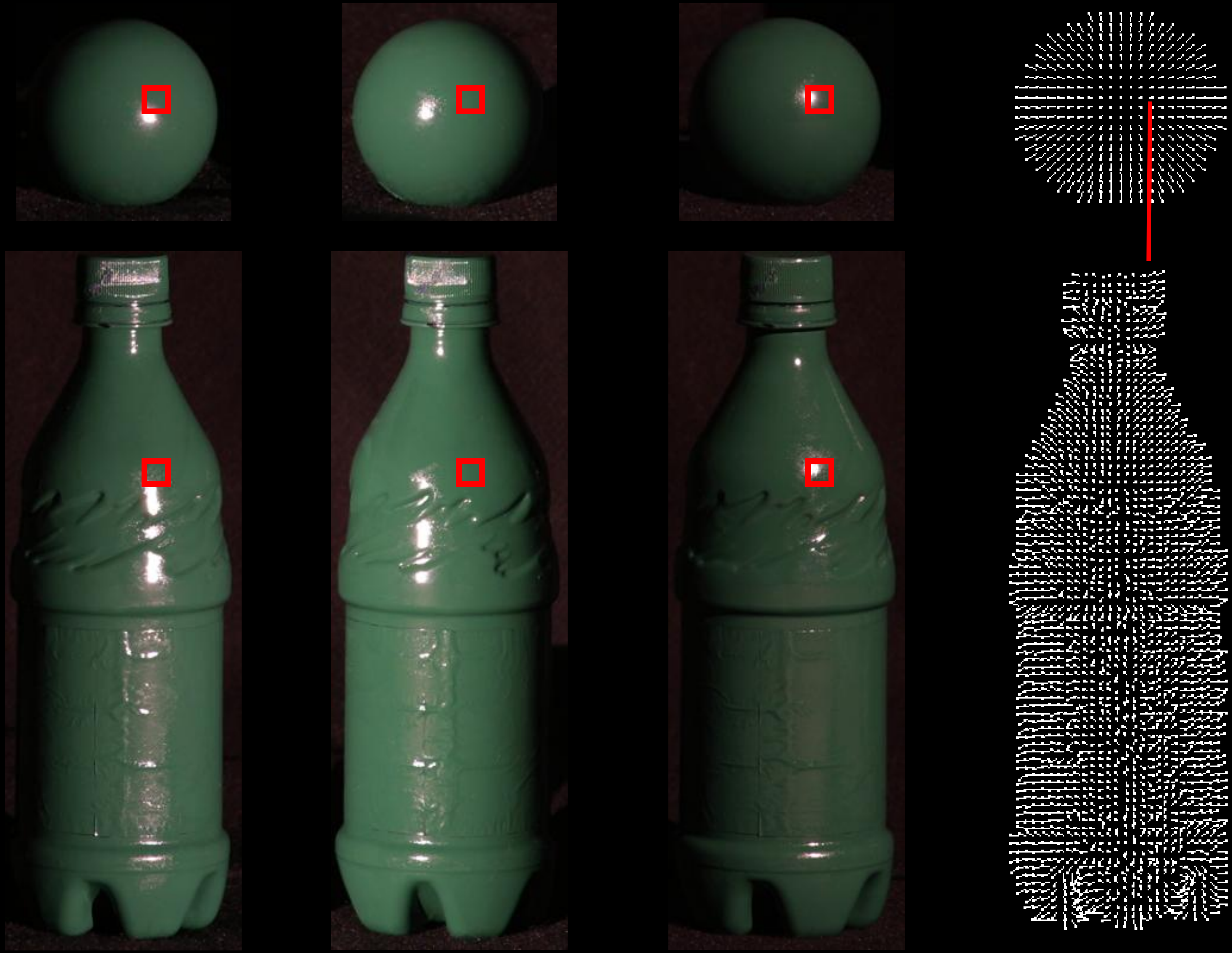
Shiny things



"Orientation consistency"


same surface normal

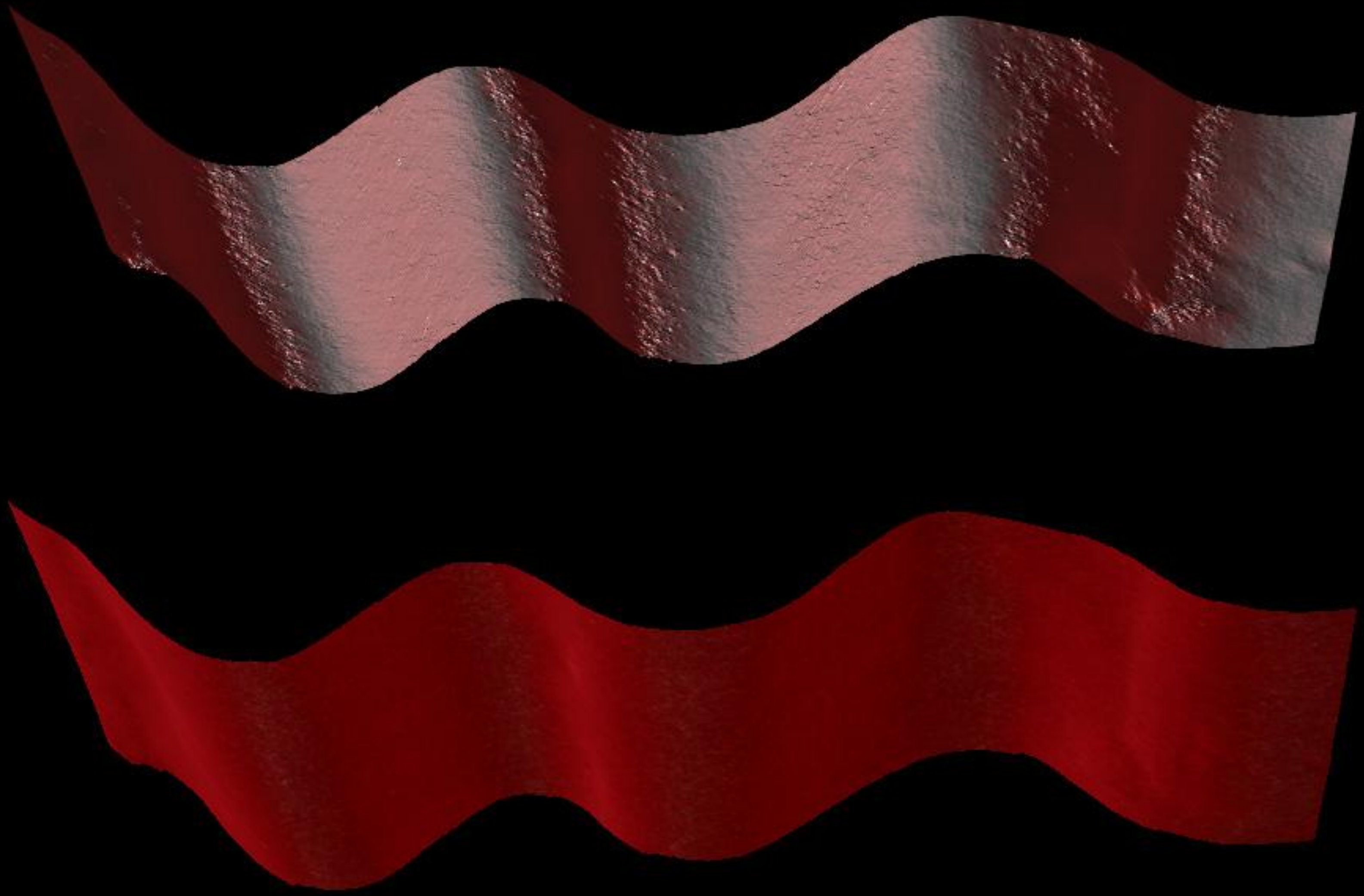




Virtual views

Velvet

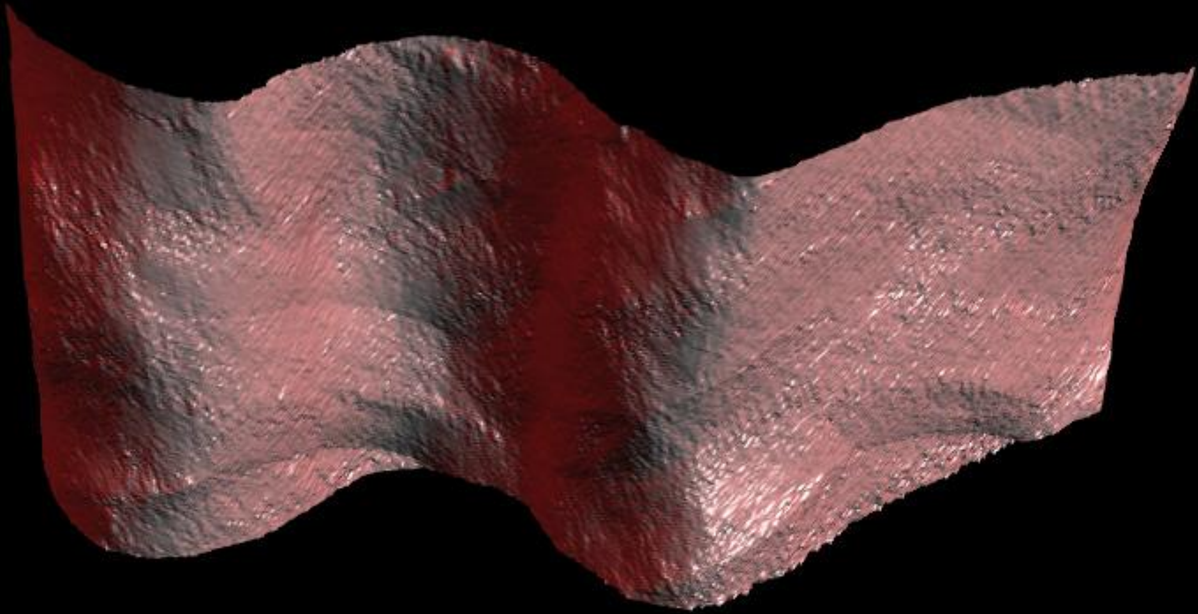
Virtual Views



Brushed Fur

Brushed Fur

Virtual Views



lem Specialty Ball - Company Info - Microsoft Internet Explorer

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ack Address http://www.salemball.com/company.htm

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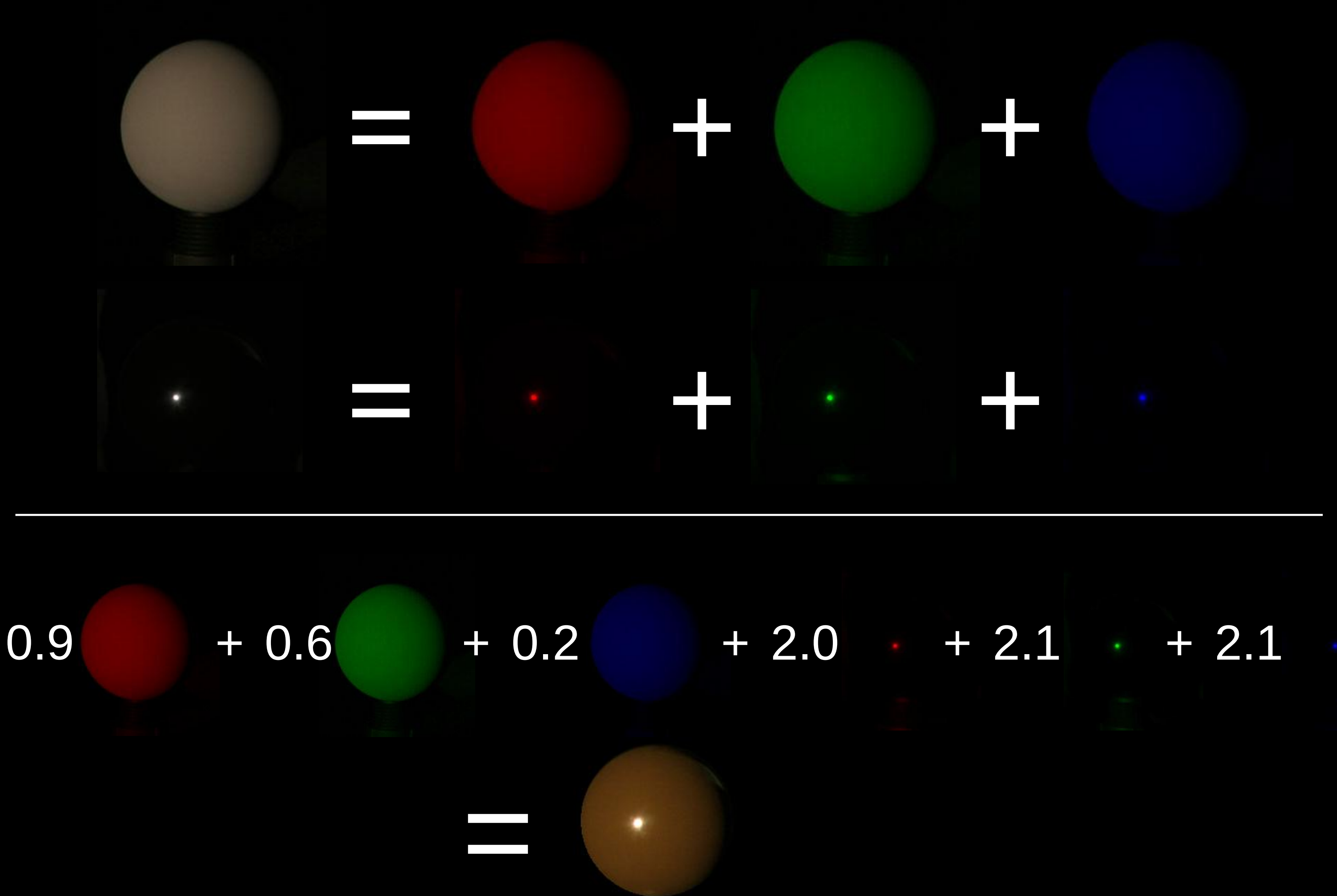
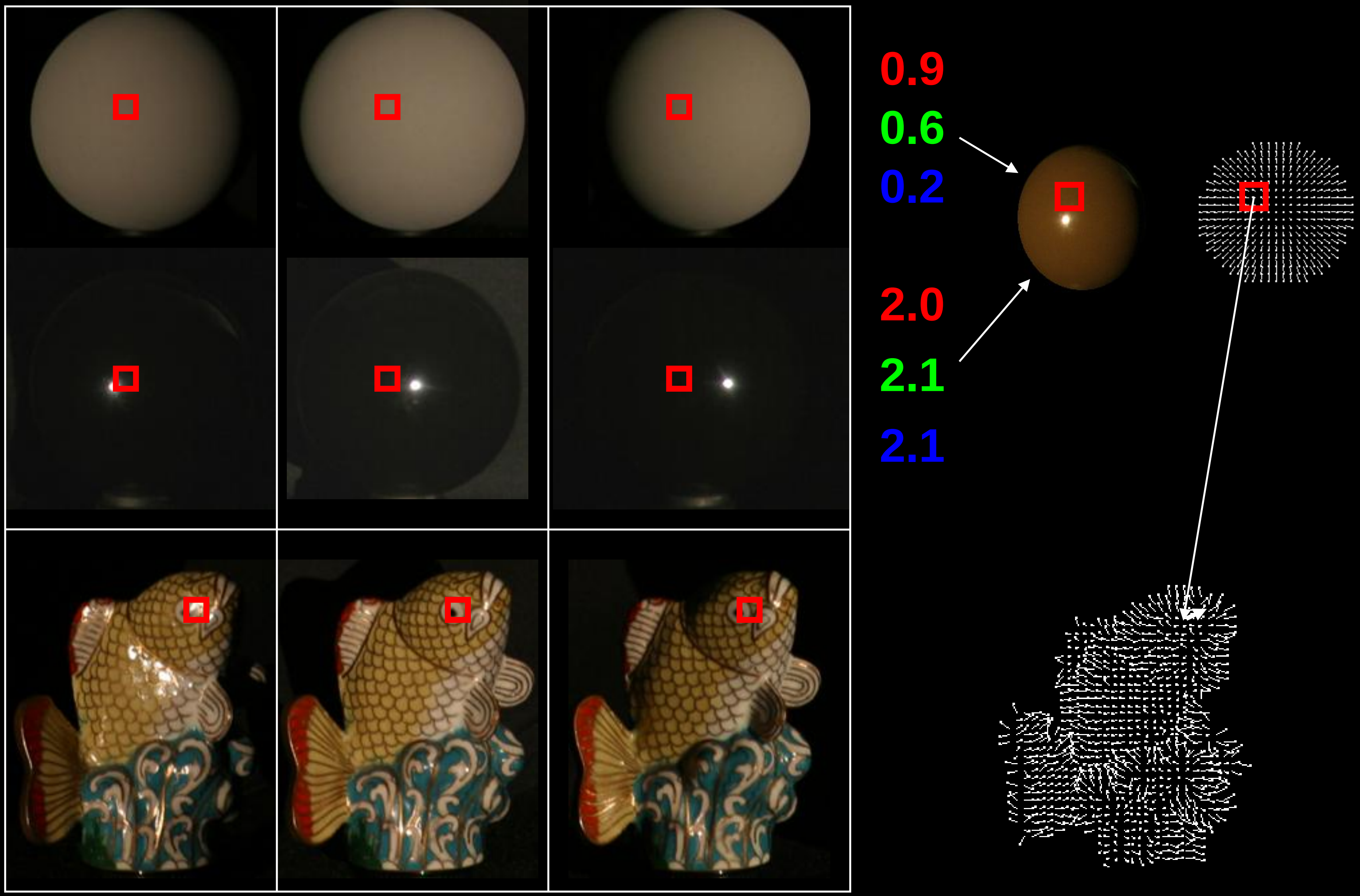
Salem Specialty Ball supplies industrial grade balls that are used in bearings, pumps, valves and other commercial applications. We can supply balls in just about any size that is machineable. We have produced precision balls from .002" all the way up to 12.0" and beyond. We can also produce these balls in any material. Almost without exception, if the material exists, we can make it into a ball. Not only do we specialize in hard to find materials, we also carry standard materials such as chrome steel and the stainless steels. We stock an extensive inventory of ready to ship balls. Most orders are shipped the same day. And if is isn't in stock, we can make it for you in matter of days. In addition, you will find that our prices are very competitive.

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

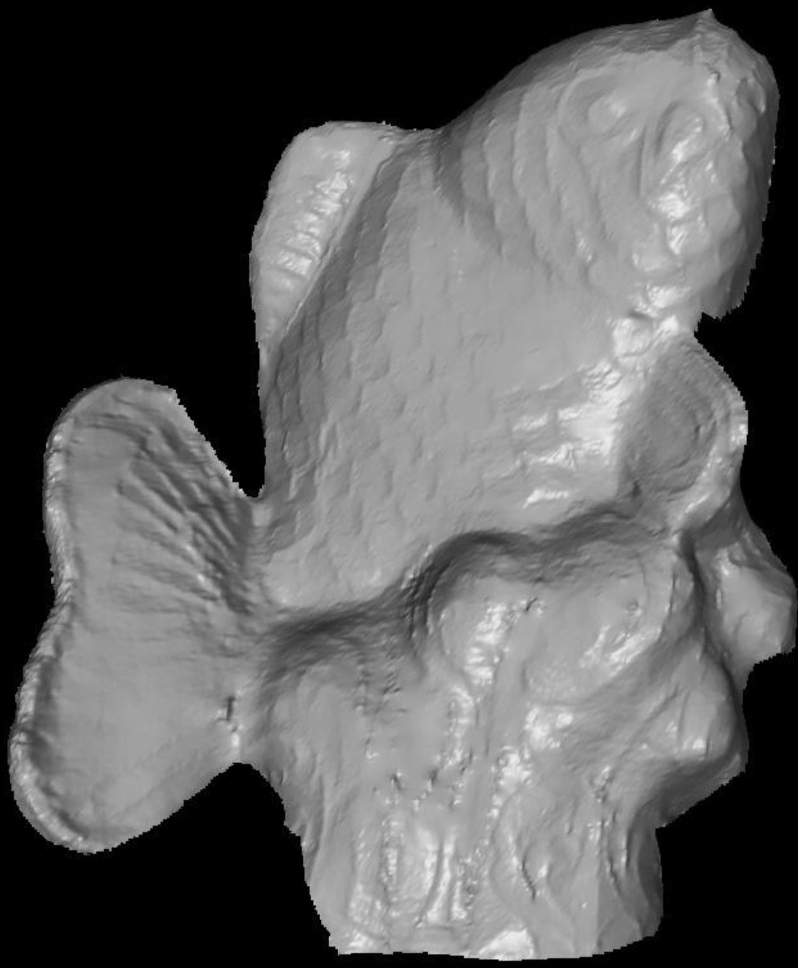

Linear combinations of materials




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
- single material (will relax later...)
- no shadows, interreflections, transparency

Fast Separation of Direct and Global Images Using High Frequency Illumination

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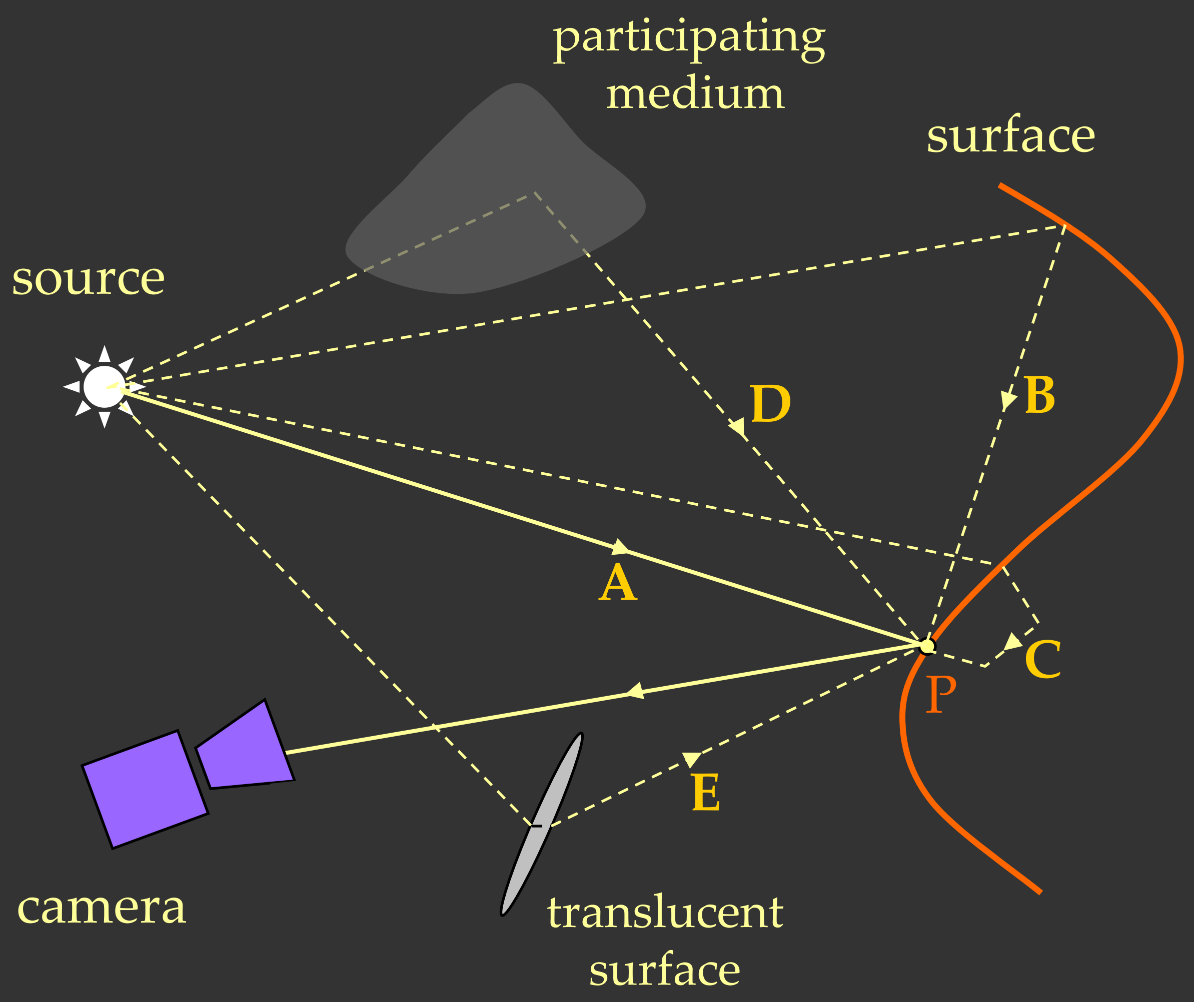
SIGGRAPH Conference
Boston, July 2006

Support: ONR, NSF, MERL

Direct and Global Illumination



A : Direct

B : Interrelection

C : Subsurface

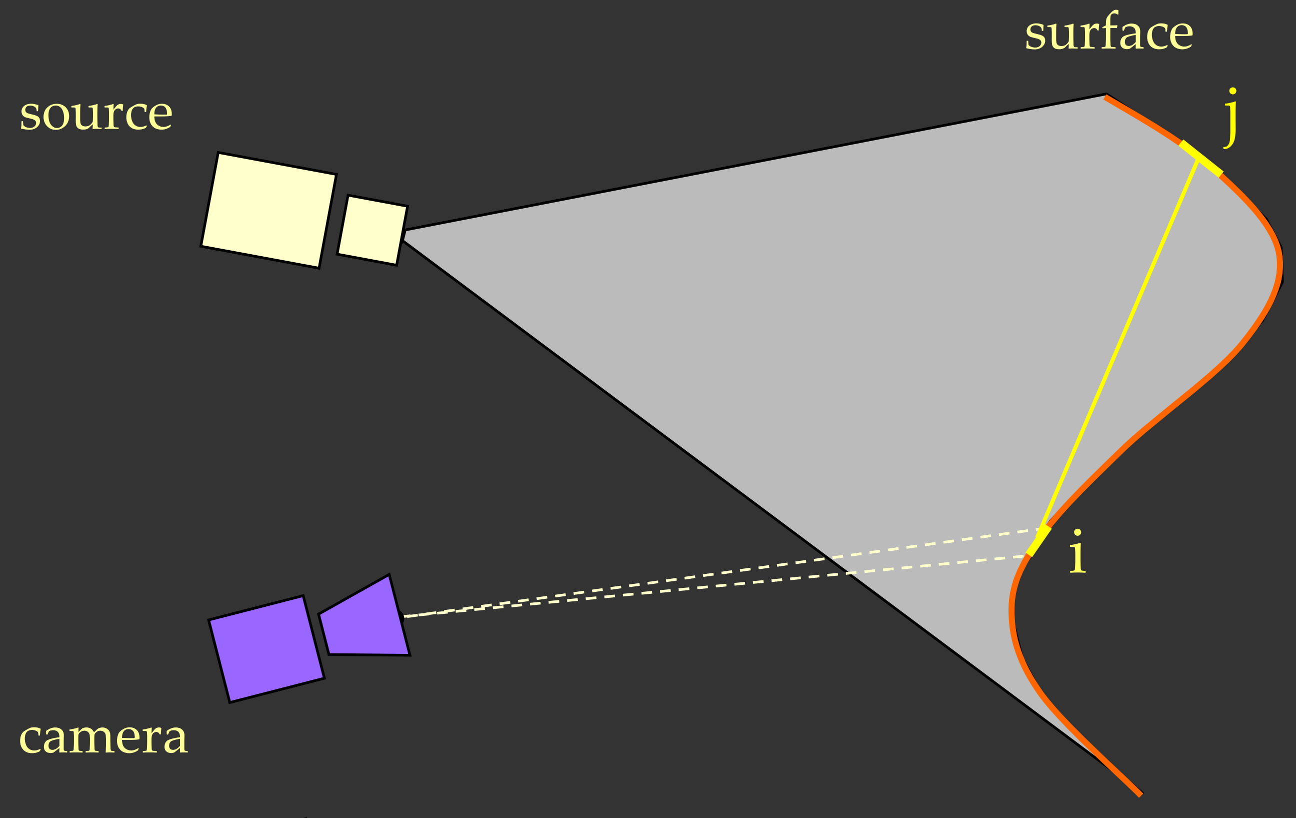
D : Volumetric

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



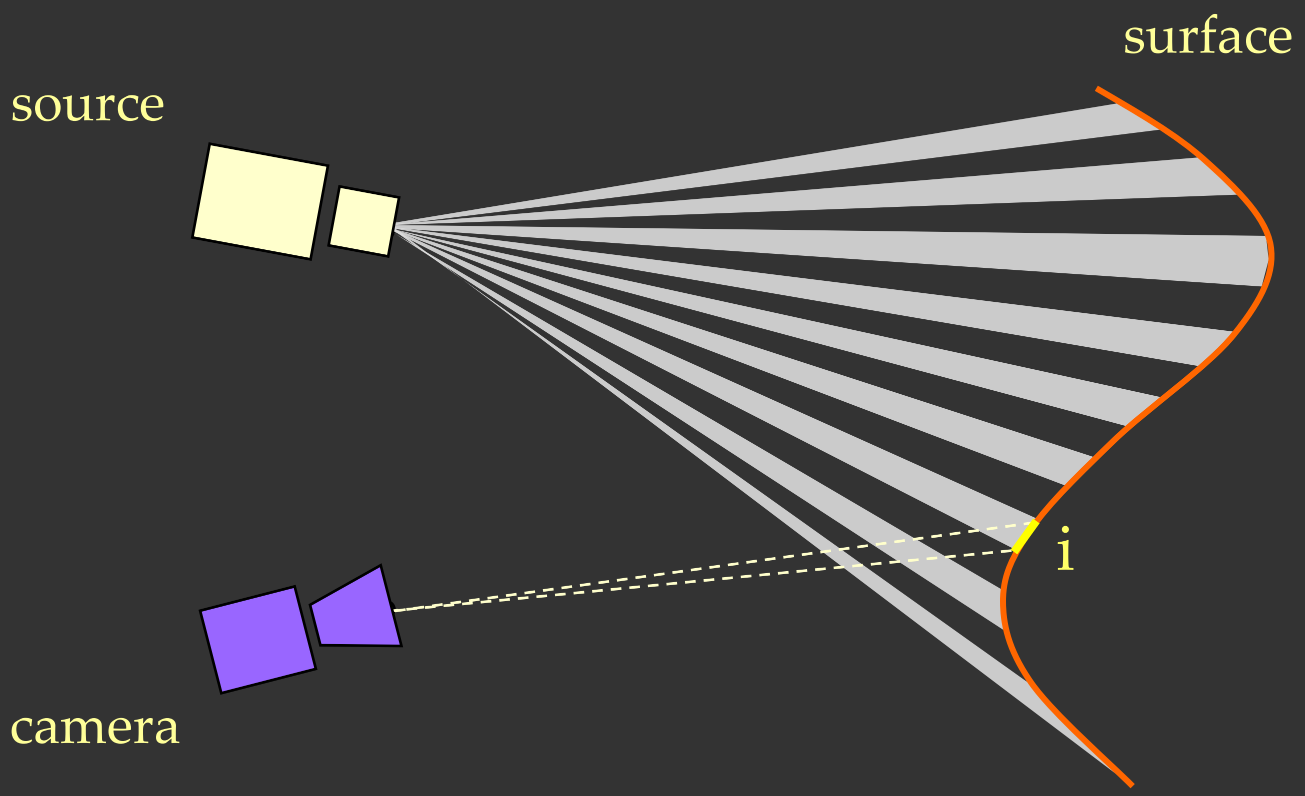
$$L[c,i] = L_d[c,i] + L_g[c,i]$$

radiance — direct — global

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

BRDF and geometry

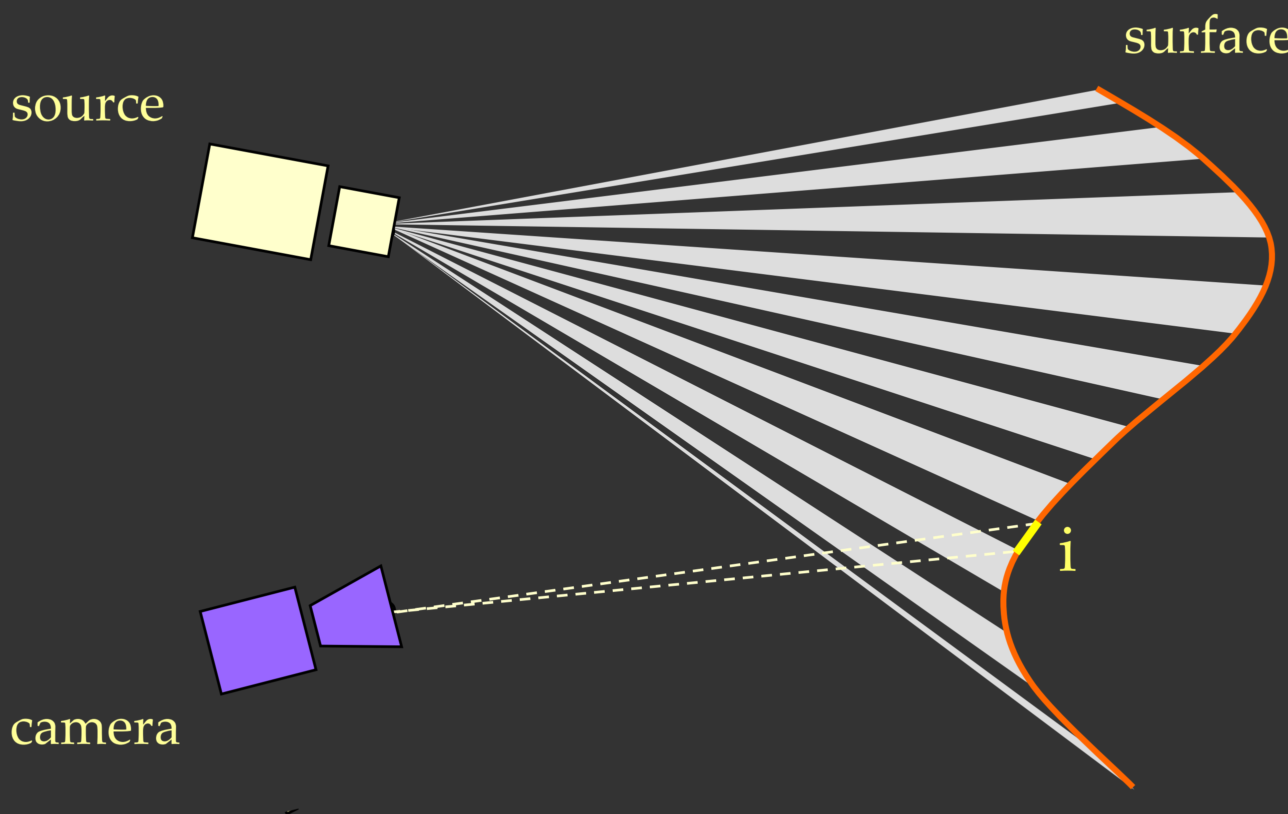
High Frequency Illumination Pattern



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

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

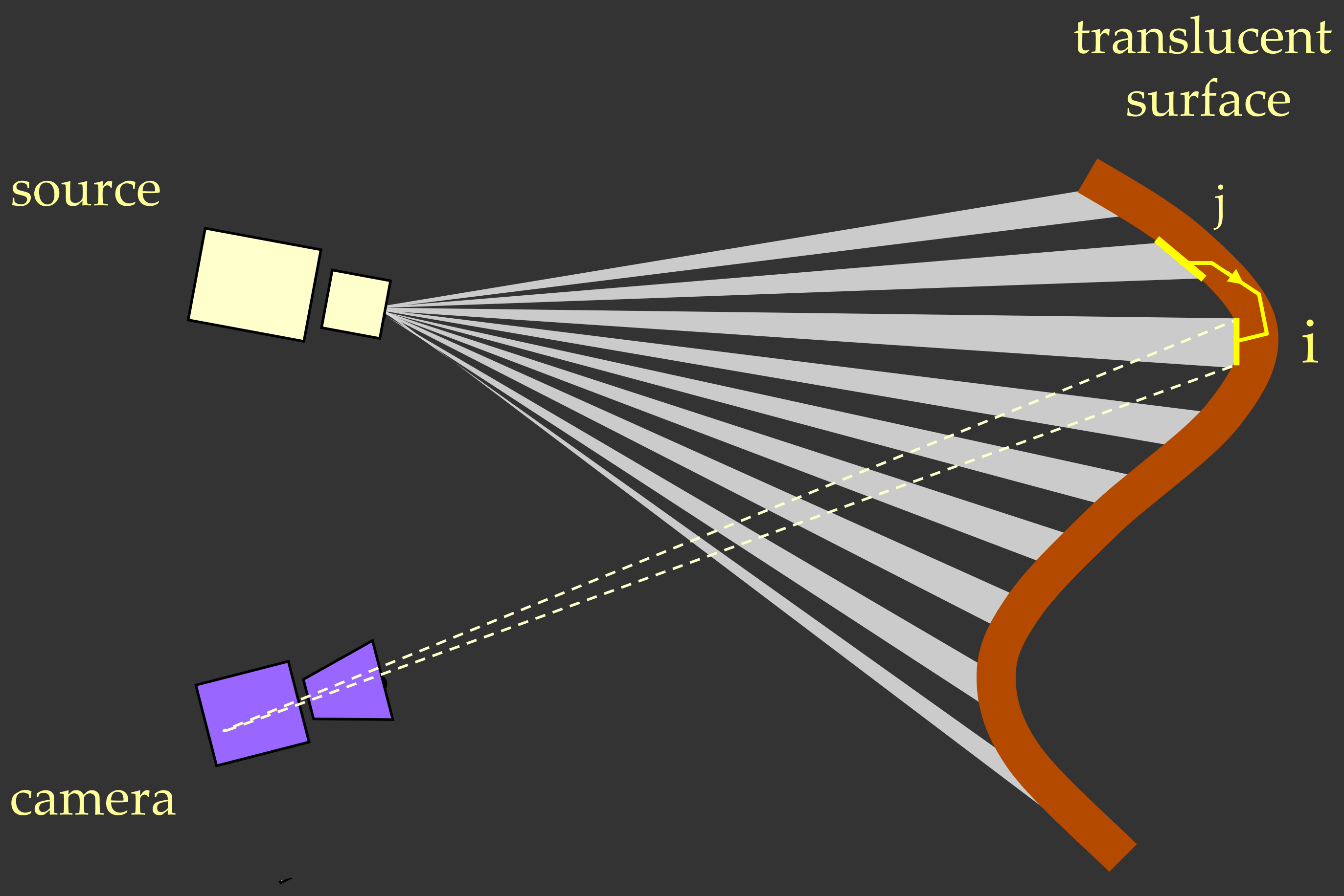
$\alpha = \frac{1}{2}$:

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

direct

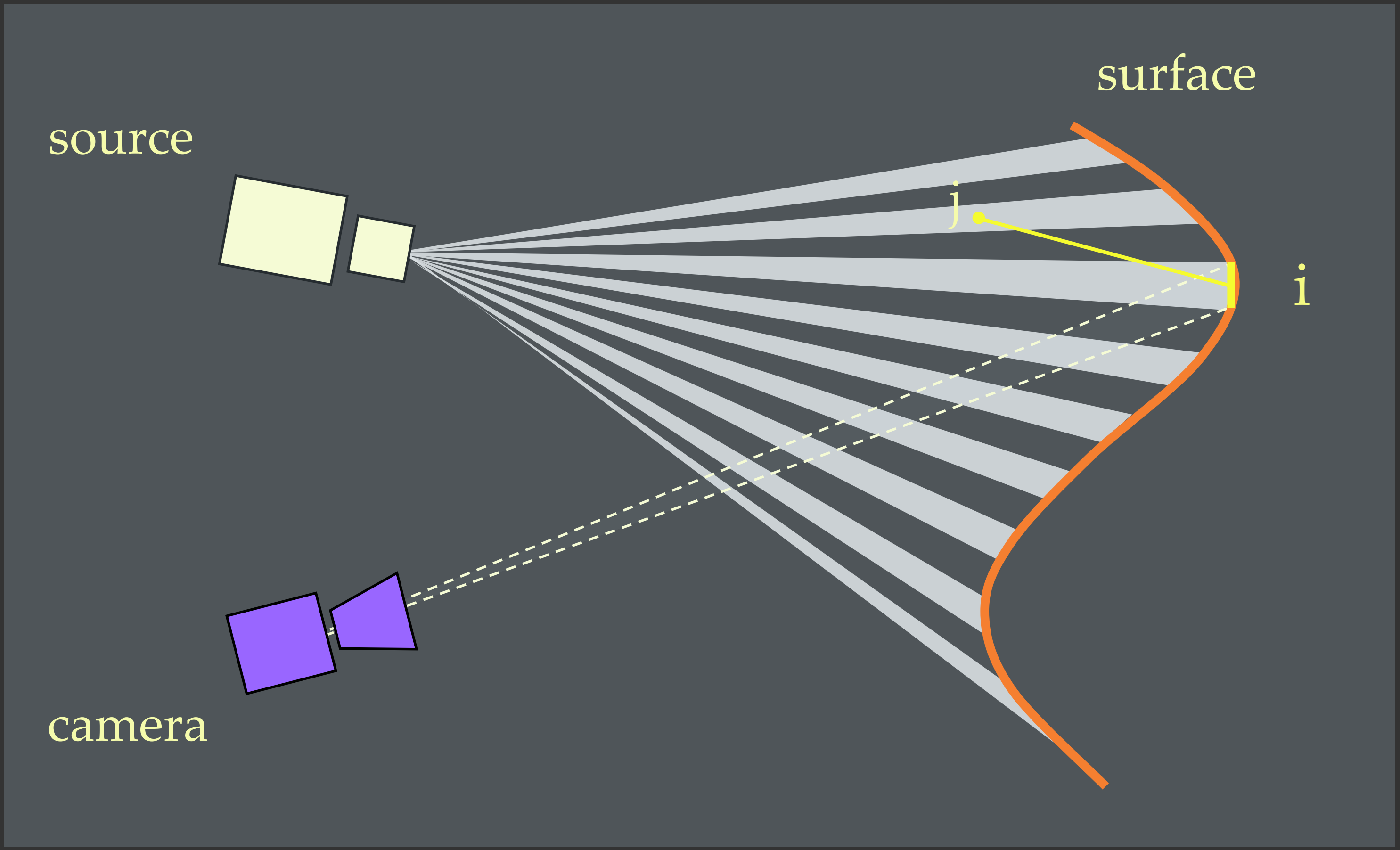
global

Other Global Effects: Subsurface Scattering



Other Global Effects: Volumetric Scattering

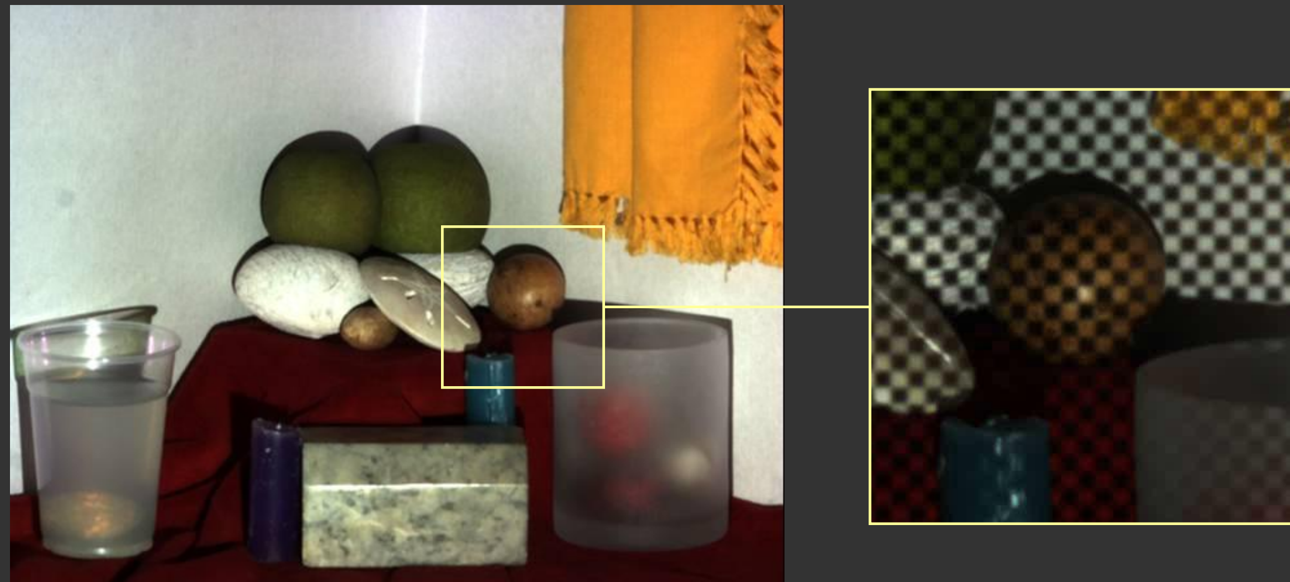
participating medium




Diffuse Interreflections
Specular Interreflections
Diffusion
Volumetric Scattering
Subsurface Scattering

Scene

Scene



Direct

Global

Real World Examples:

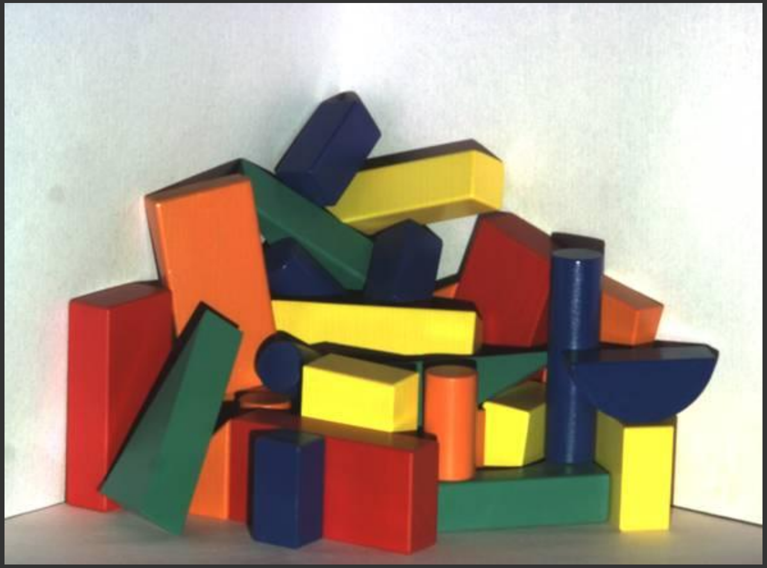
Can You Guess the Images?

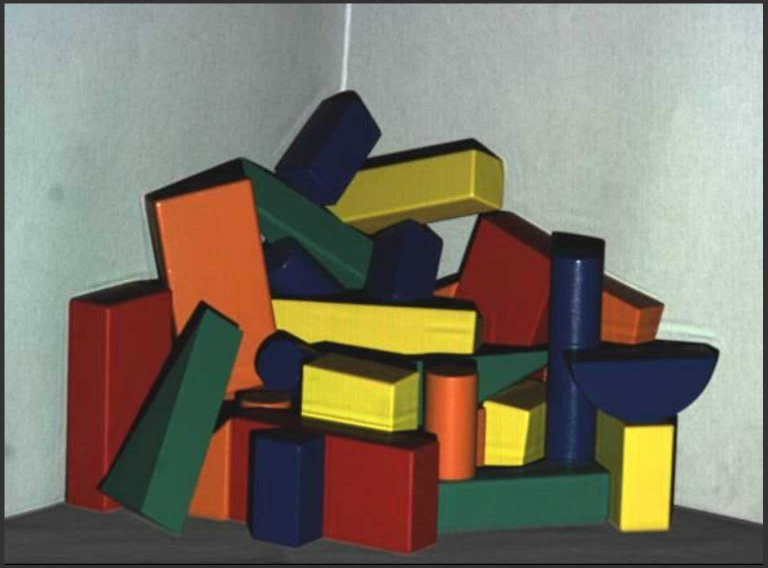
Eggs: Diffuse Interreflections

Direct

Global

Wooden Blocks: Specular Interreflections

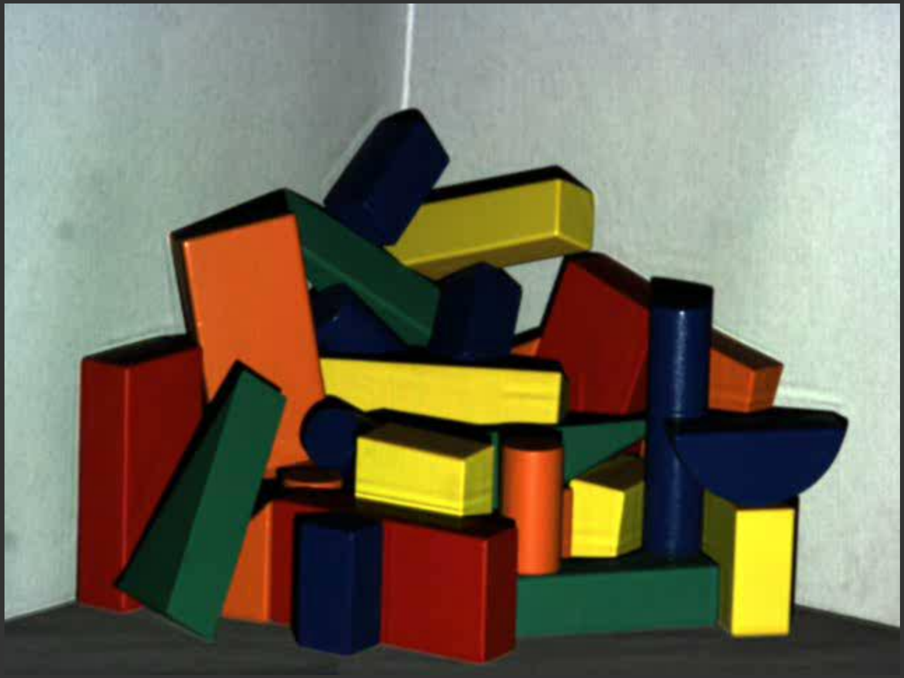




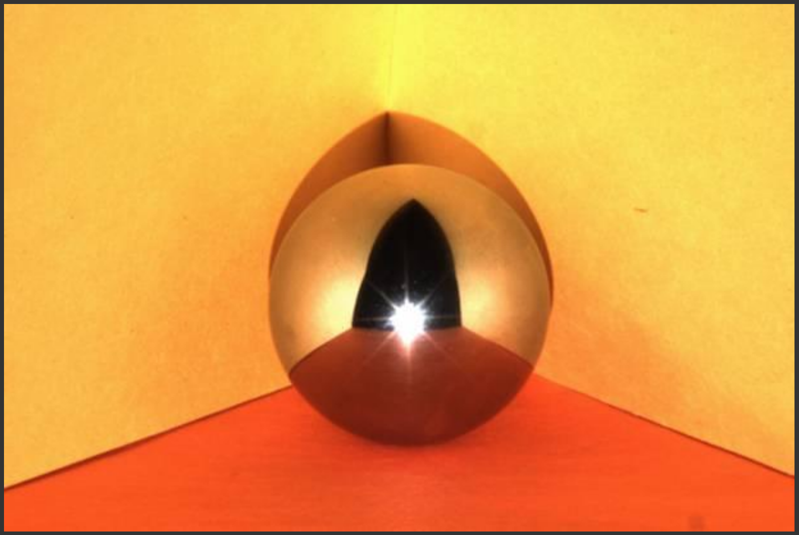
Direct

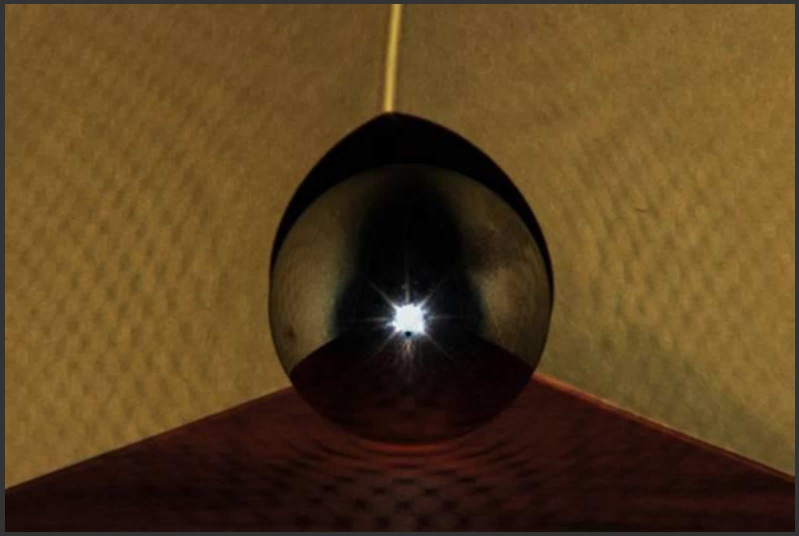
Global

Novel Images

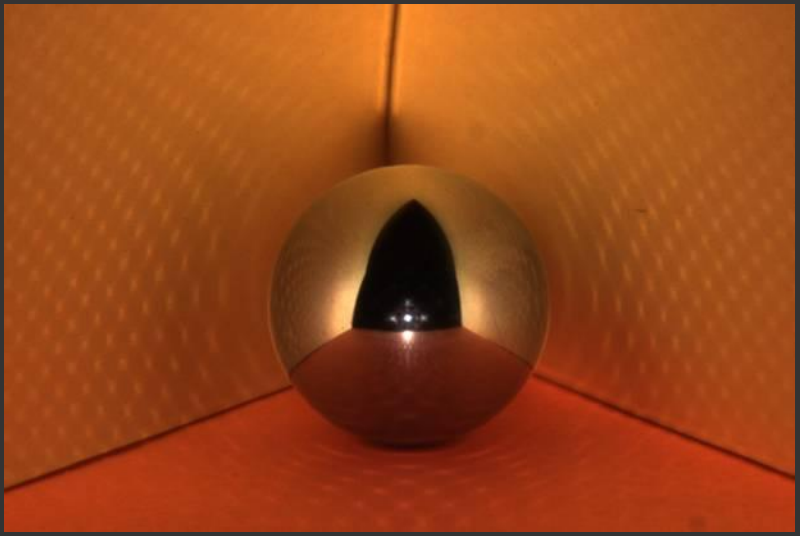


Mirror Ball: Failure Case



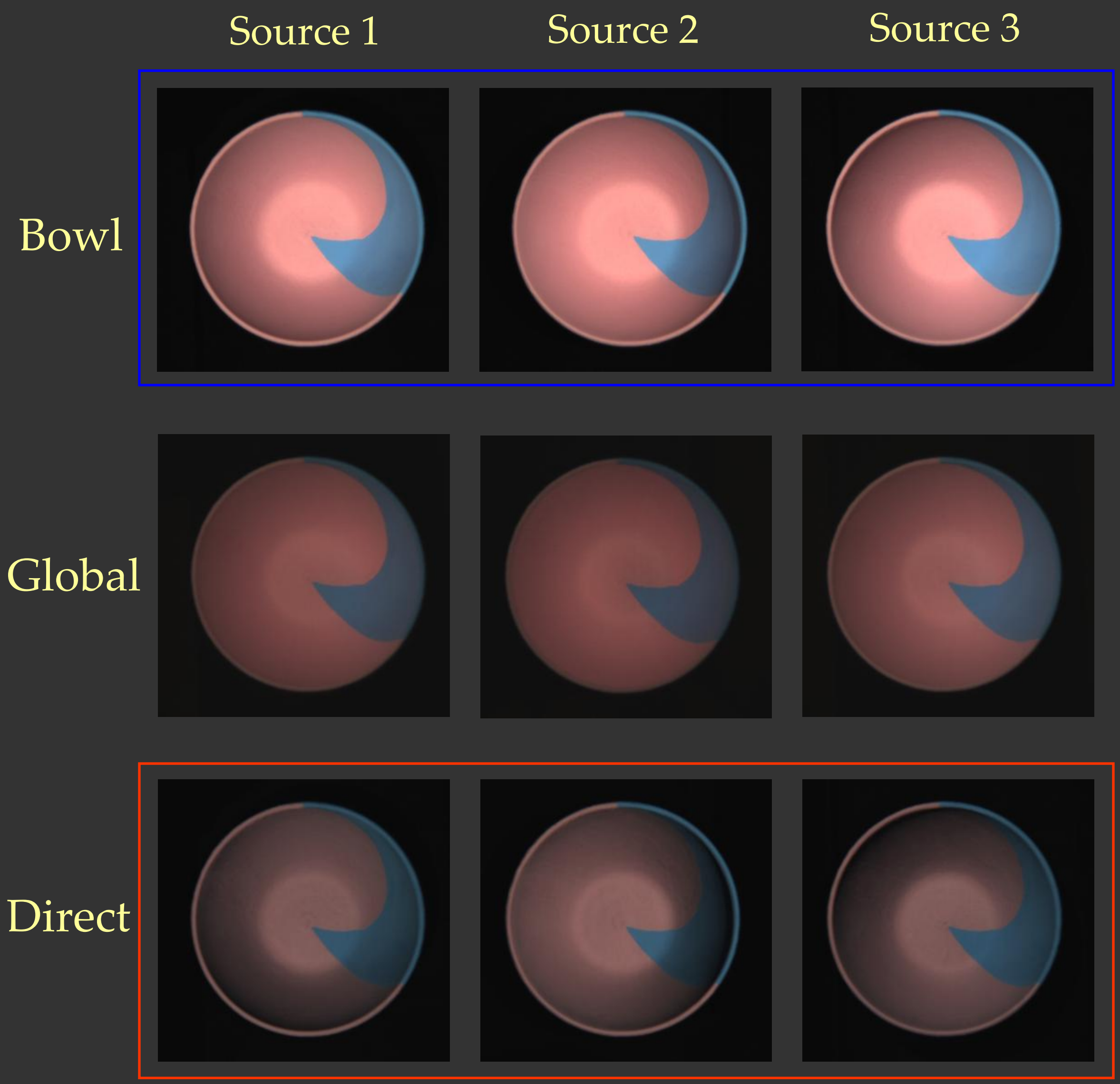


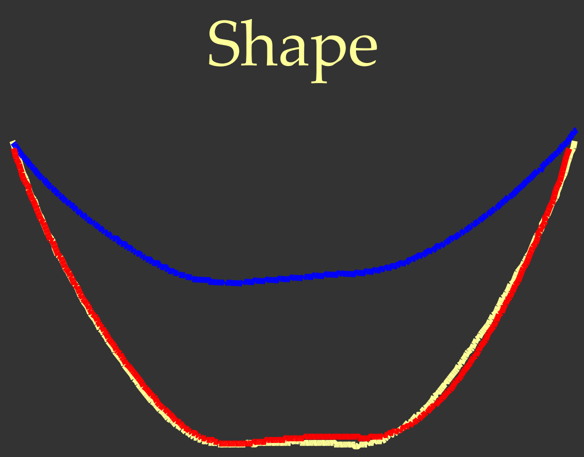
Direct



Global

Photometric Stereo using Direct Images

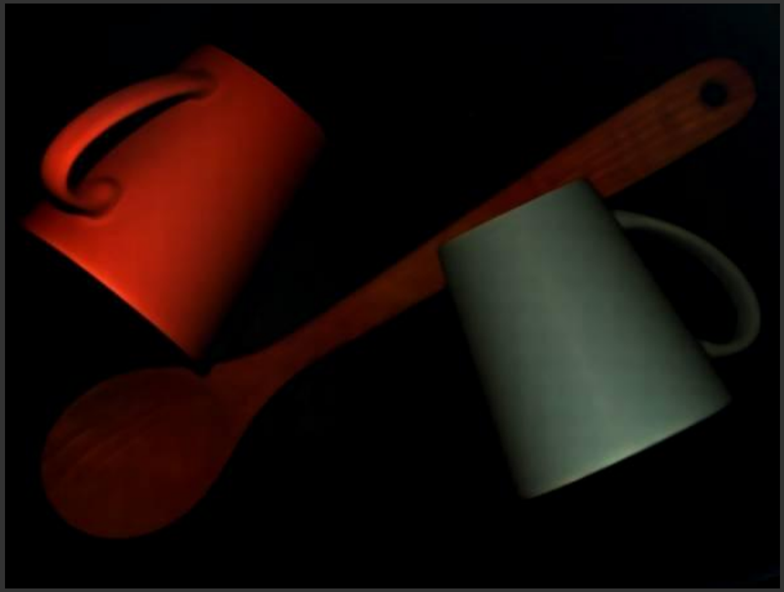




Nayar et al., 1991

Kitchen Sink: Volumetric Scattering

Volumetric Scattering:
Chandrasekar 50, Ishimaru 78



Direct

Global

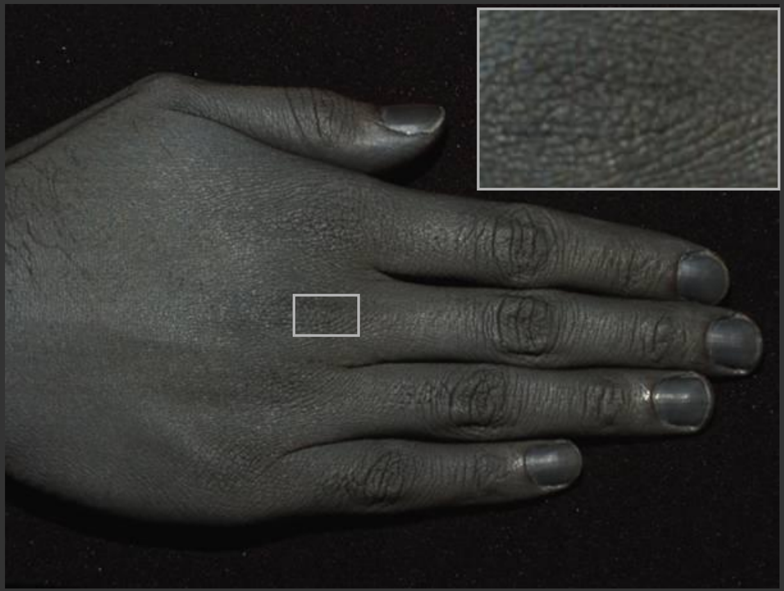
Peppers: Subsurface Scattering

Direct

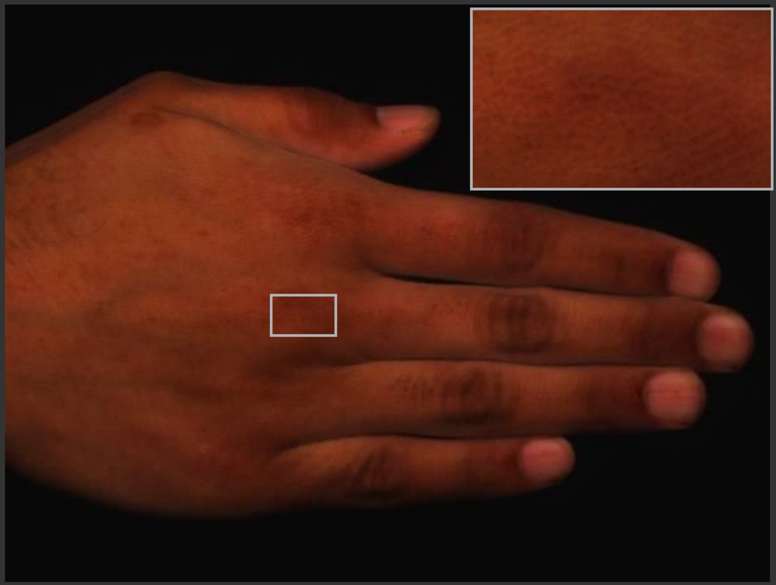
Global

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



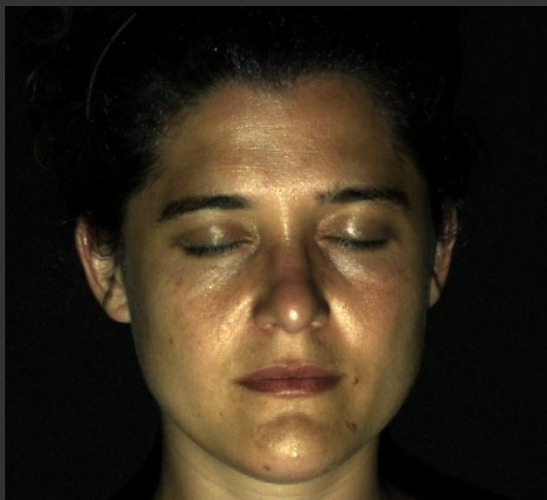
Direct



Global

Face: Without and With Makeup

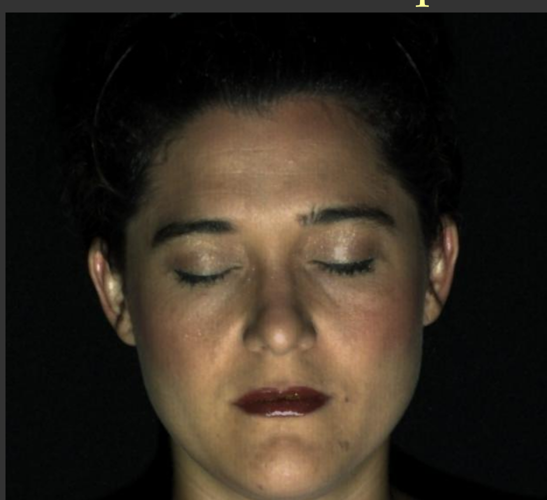
Without Makeup



Direct

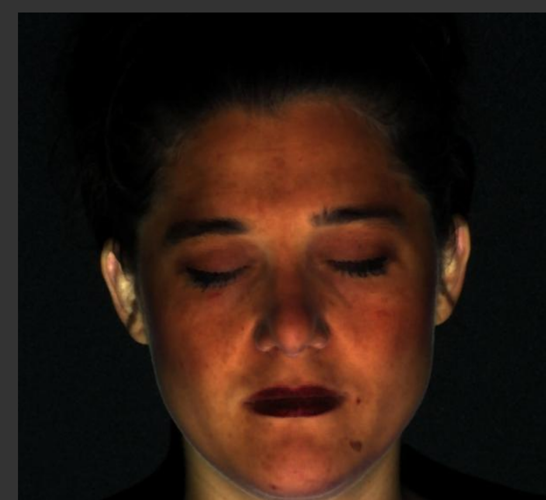
Global

With Makeup



Direct

Global



Blonde Hair

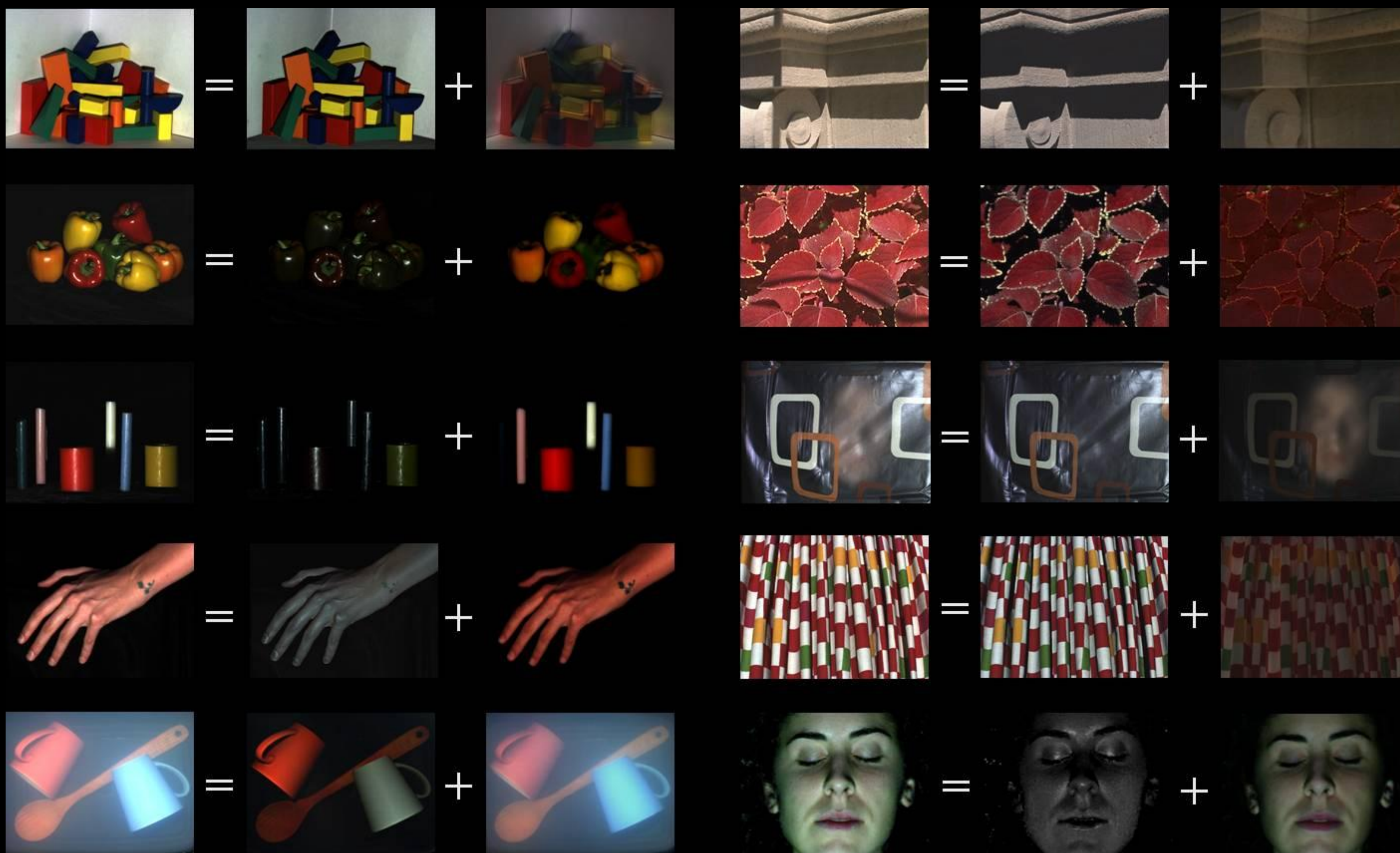
Hair Scattering: Stamm et al. 77, Bustard and Smith 91, Lu et al. 00 Marschner et al. 03

Direct

Global

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