Last Lecture

- Single View Modeling

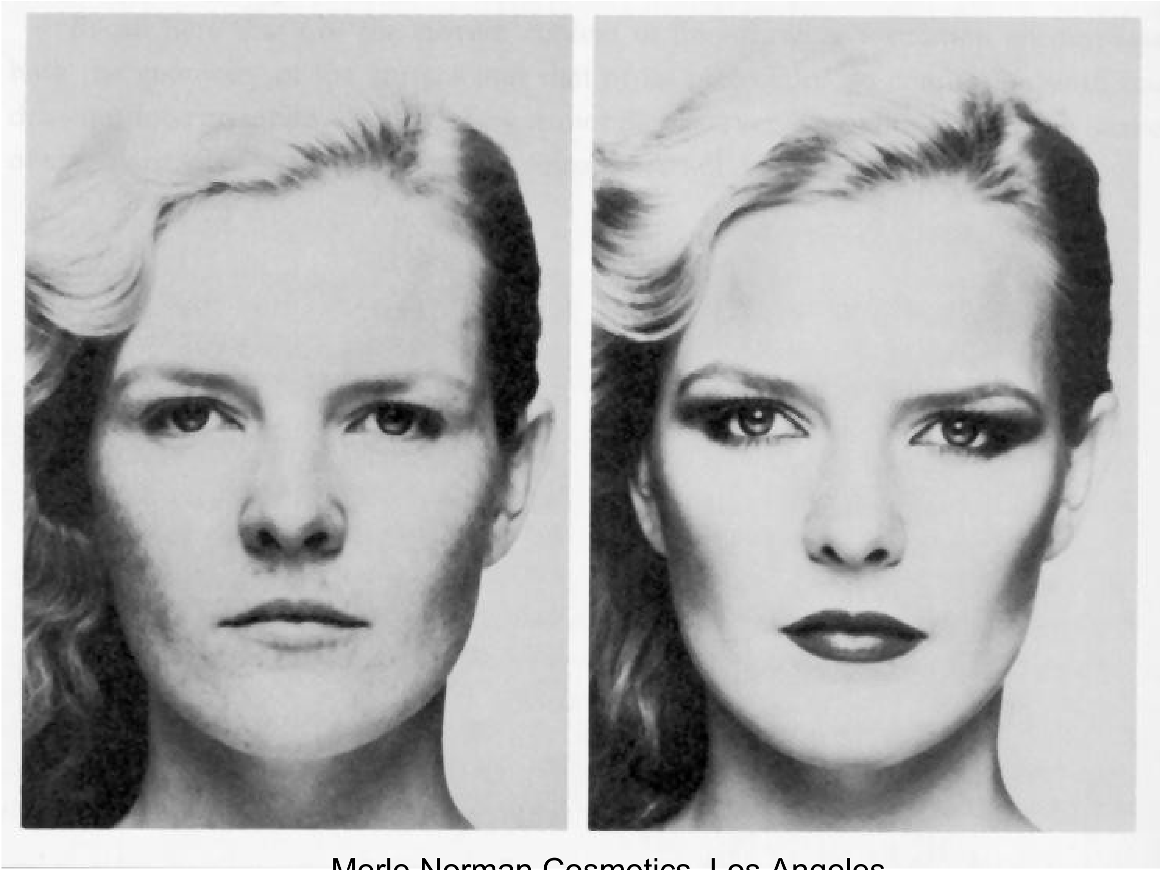
Vermeer's *Music Lesson*

Reconstructions by Criminisi et al.

Today

- Photometric Stereo
- Separate Global and Direct Illumination

Photometric Stereo

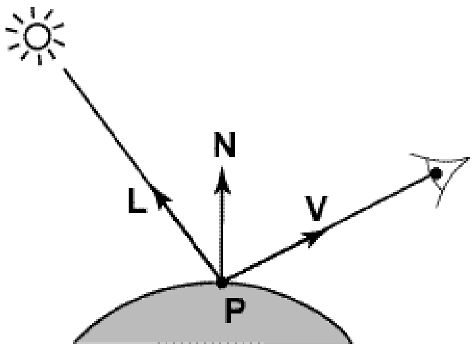


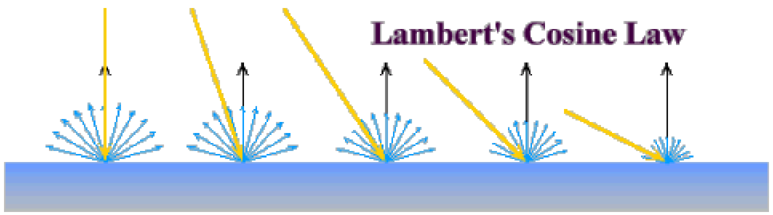
Merle Norman Cosmetics, Los Angeles

Readings

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

Diffuse reflection





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

$$I = k_d \mathbf{N} \cdot \mathbf{L}$$

L = Incidence vector

N = Normal vector

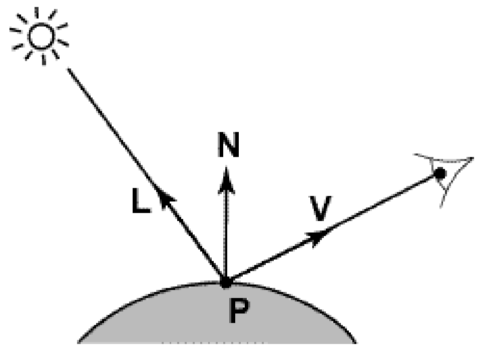
R_i = Intensity of incoming light

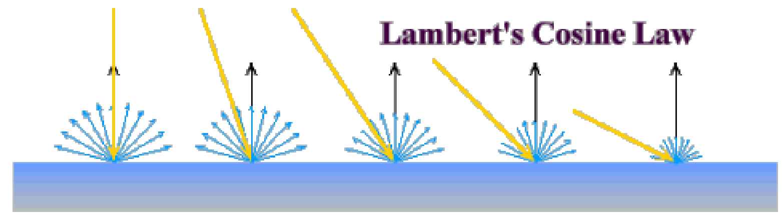
R_e = Outgoing light

K_d = Albedo

I = Image intensity of point **P**

Diffuse reflection





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

$$I = k_d \mathbf{N} \cdot \mathbf{L}$$

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

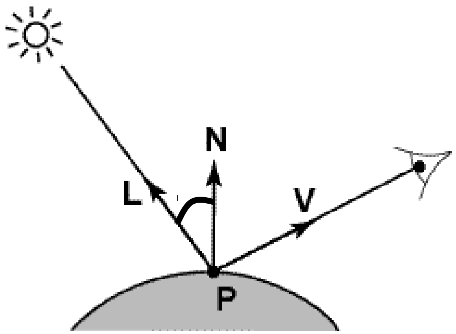
Albedo

Portion of light incident on a surface which is reflected back.

$$\frac{reflected}{incident}$$

Varies with the frequency of the light.

Shape from shading



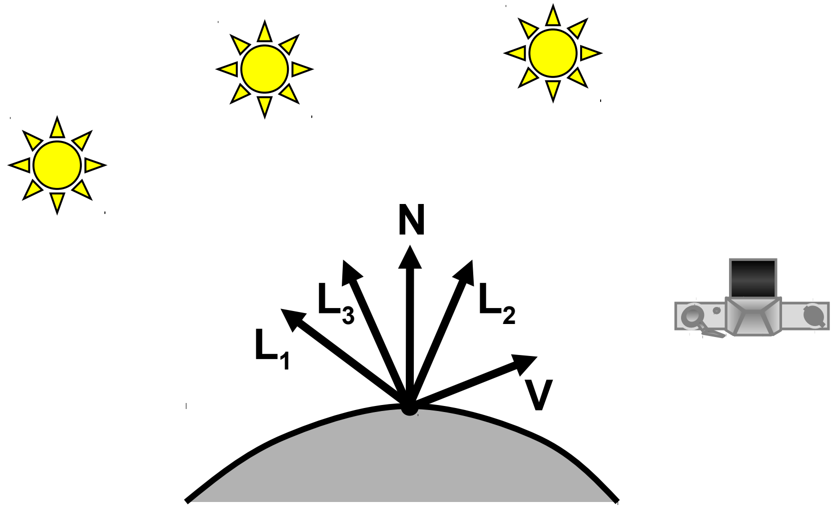
Suppose $k_d = 1$

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

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)
  - 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:

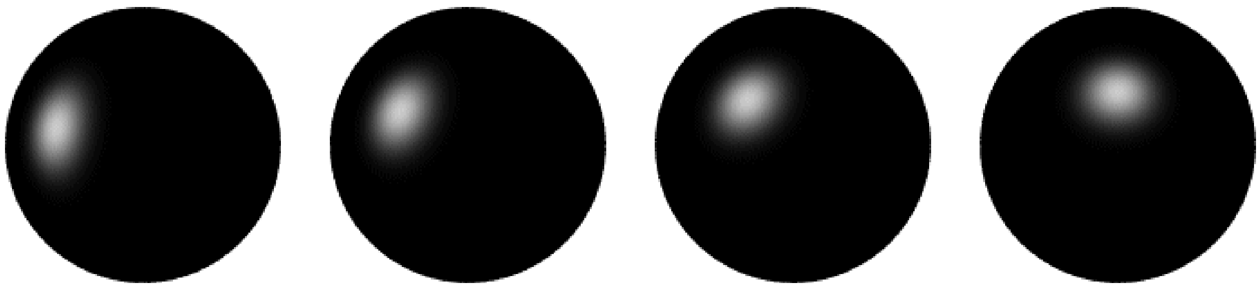
$$\begin{aligned} \mathbf{I} &= \mathbf{LG} \\ \mathbf{L^T I} &= \mathbf{L^T L G} \\ \mathbf{G} &= (\mathbf{L^T L})^{-1}(\mathbf{L^T I}) \end{aligned}$$

Solve for N, k_d as before

L is n×3 → $\mathbf{L^T L}$ is 3×3

Computing light source directions

Trick: place a chrome sphere in the scene

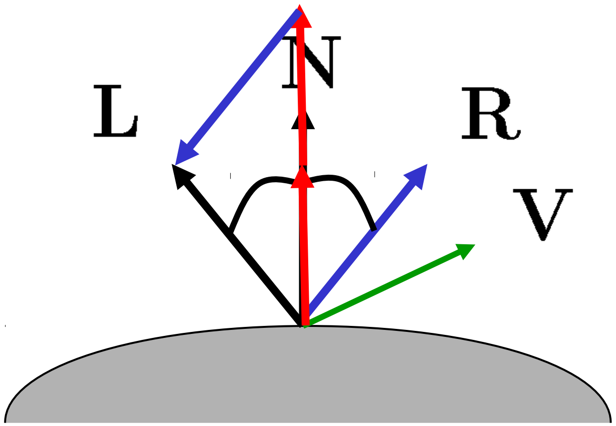


- chrome → purely specular reflection
- the location of the highlight tells you where the light source is

Specular reflection

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

"angle of incidence = angle of reflection"

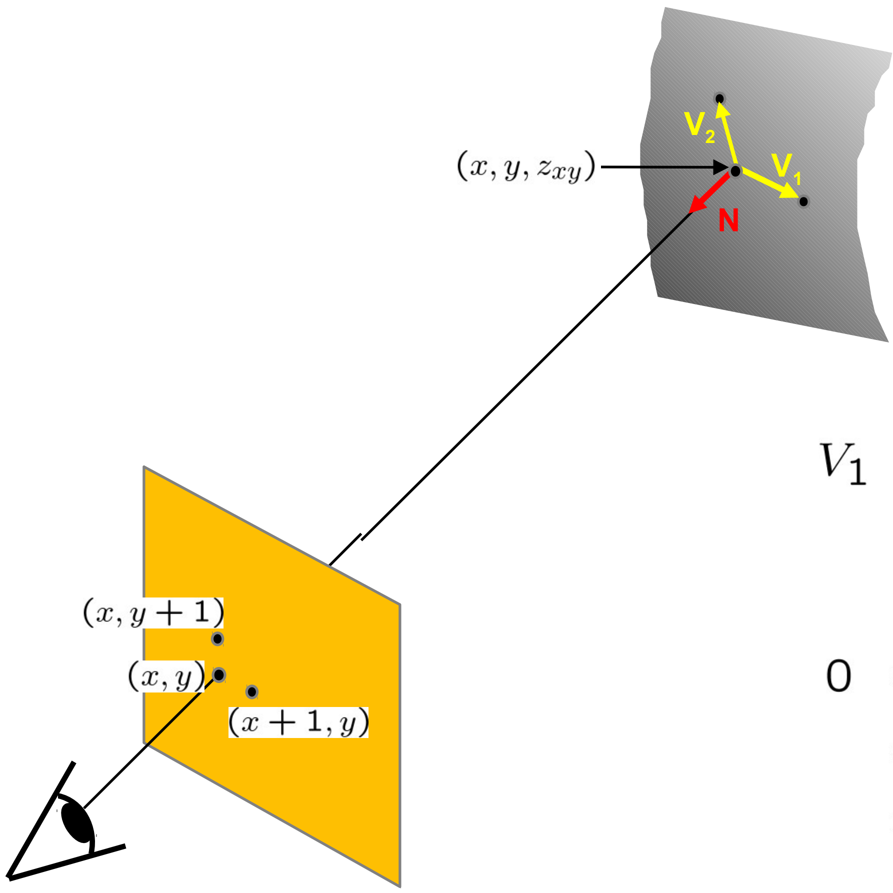


$$R_e = \begin{cases} R_i & \text{if } V = R \\ 0 & \text{otherwise} \end{cases}$$

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

- then L is given as: $\mathbf{L} = 2(\mathbf{N} \cdot \mathbf{R})\mathbf{N} - \mathbf{R}$

Depth from normals



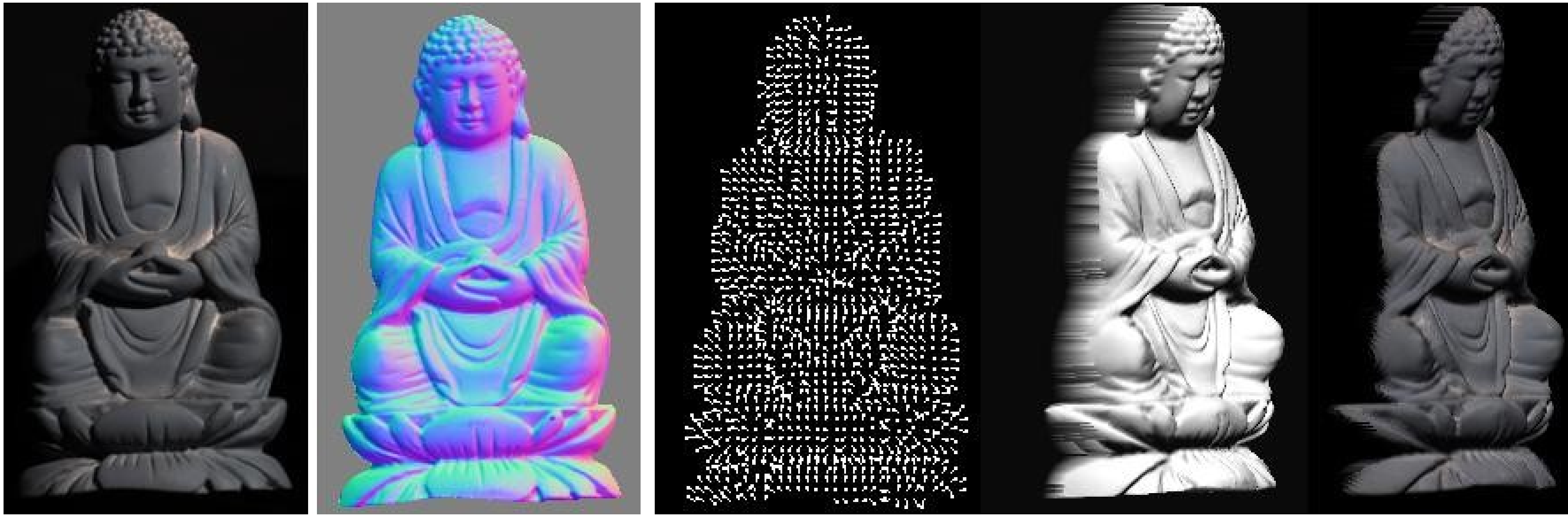
$$
\begin{aligned}
V_1 &= (x+1, y, z_{x+1,y}) - (x, y, z_{xy}) \\
&= (1, 0, z_{x+1,y} - z_{xy})
\end{aligned}
$$

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

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

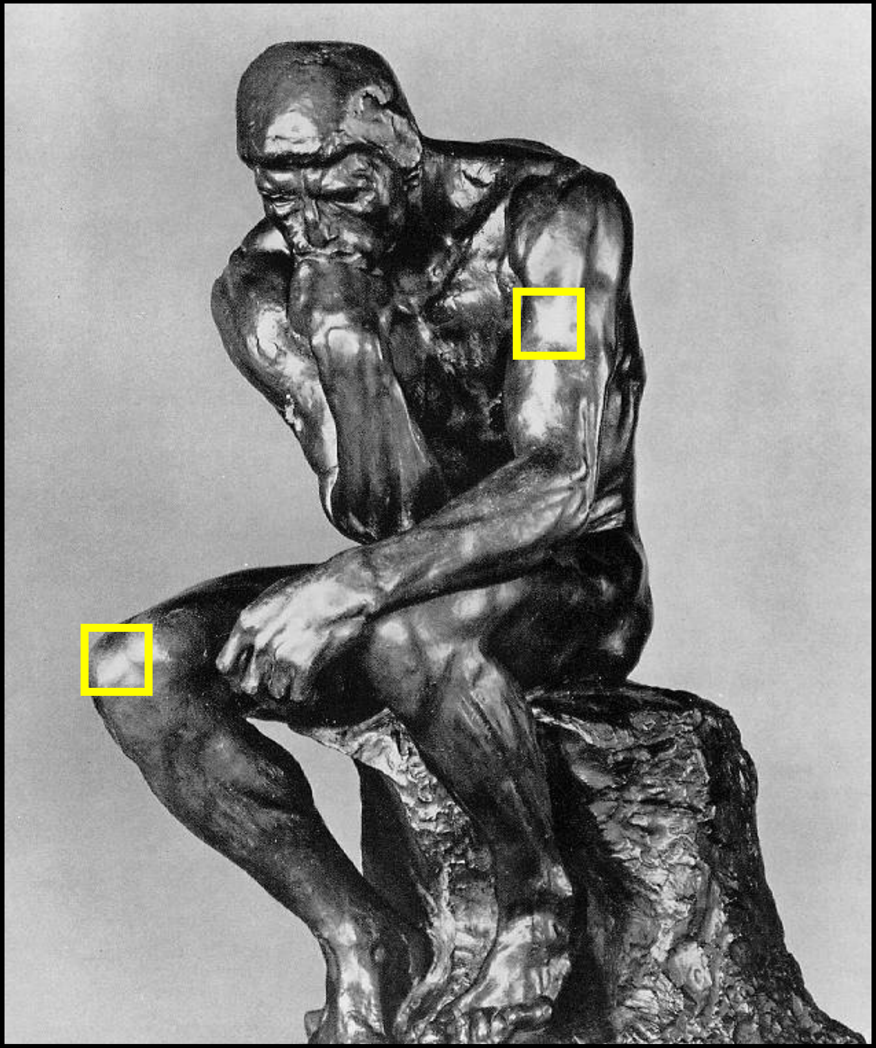
Steven M. Seitz
University of Washington

Overview

Orientation-consistency: two points with the same surface orientation [normal] must have similar appearance in an image.

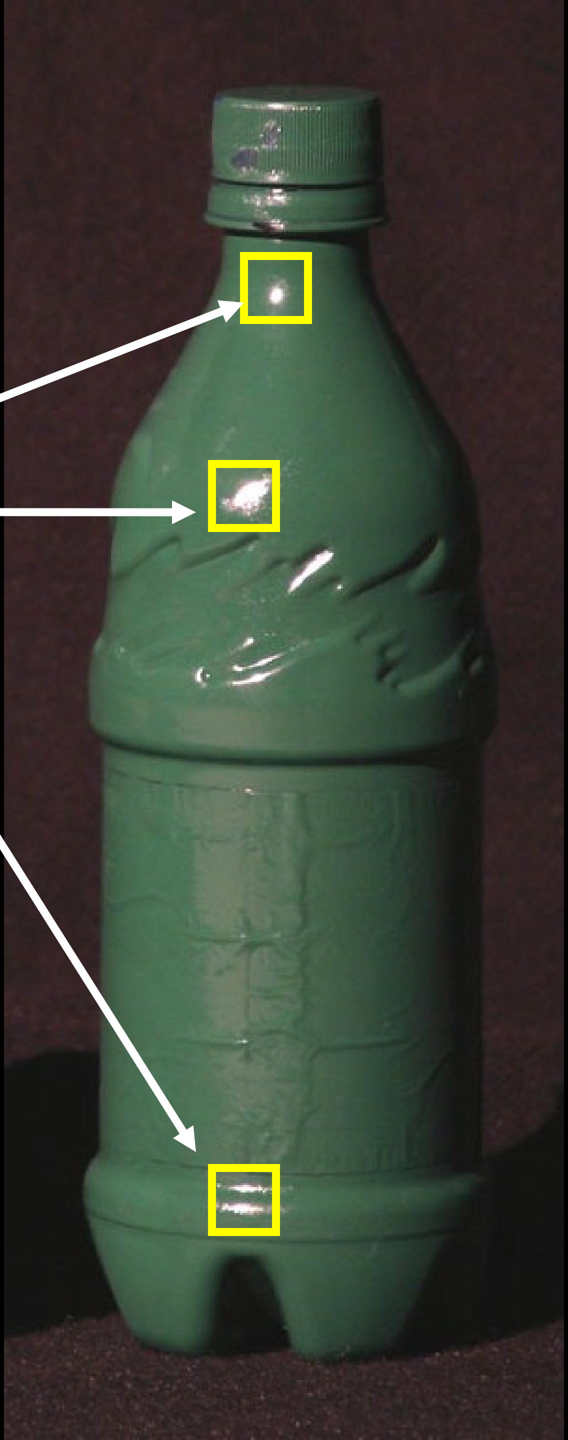
1. Use one or more *reference objects* in scene.
2. Match surface normals between reference and target
3. Match albedo with a multiple reference objects
   + additive color model

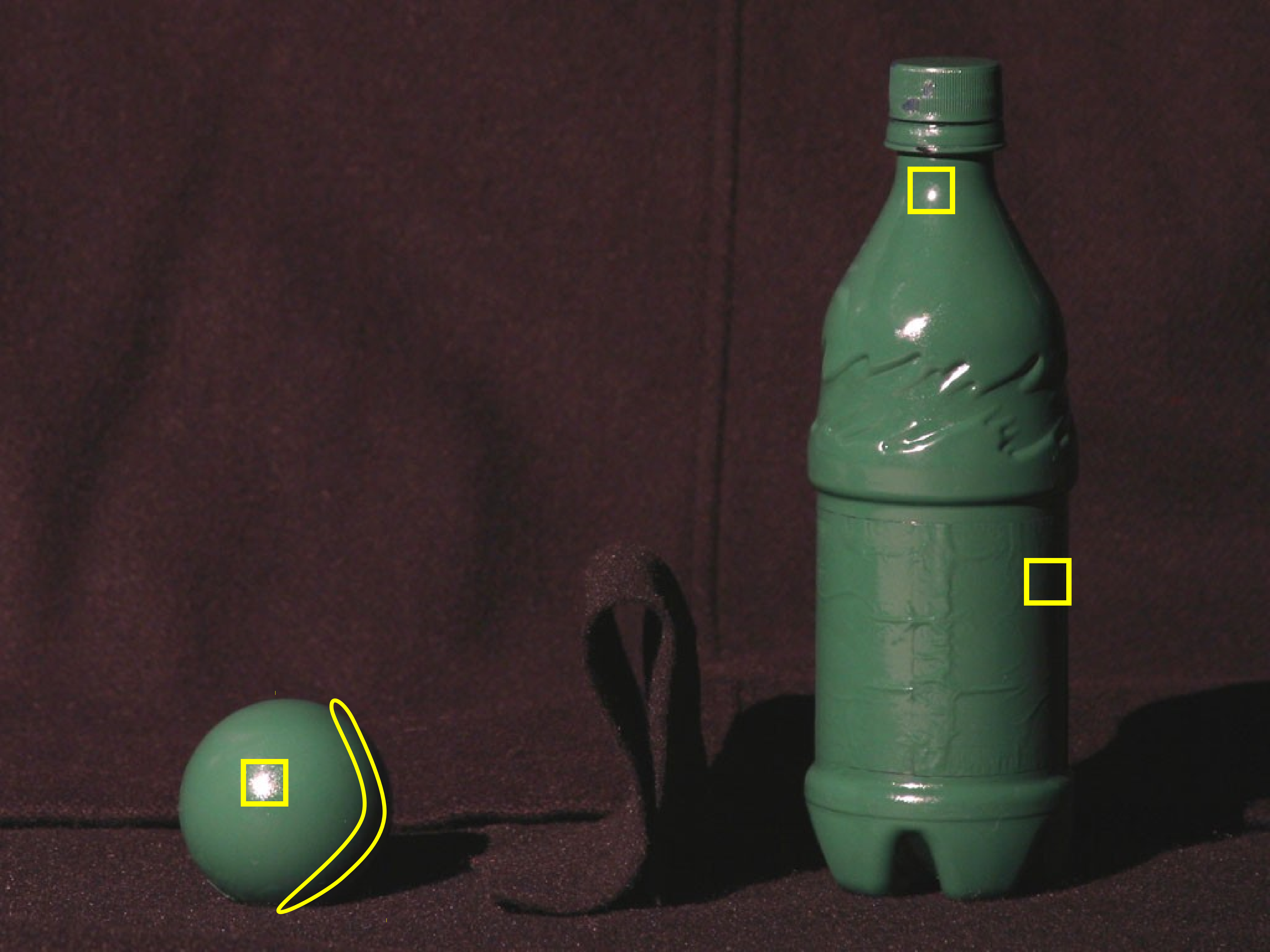
Shiny things

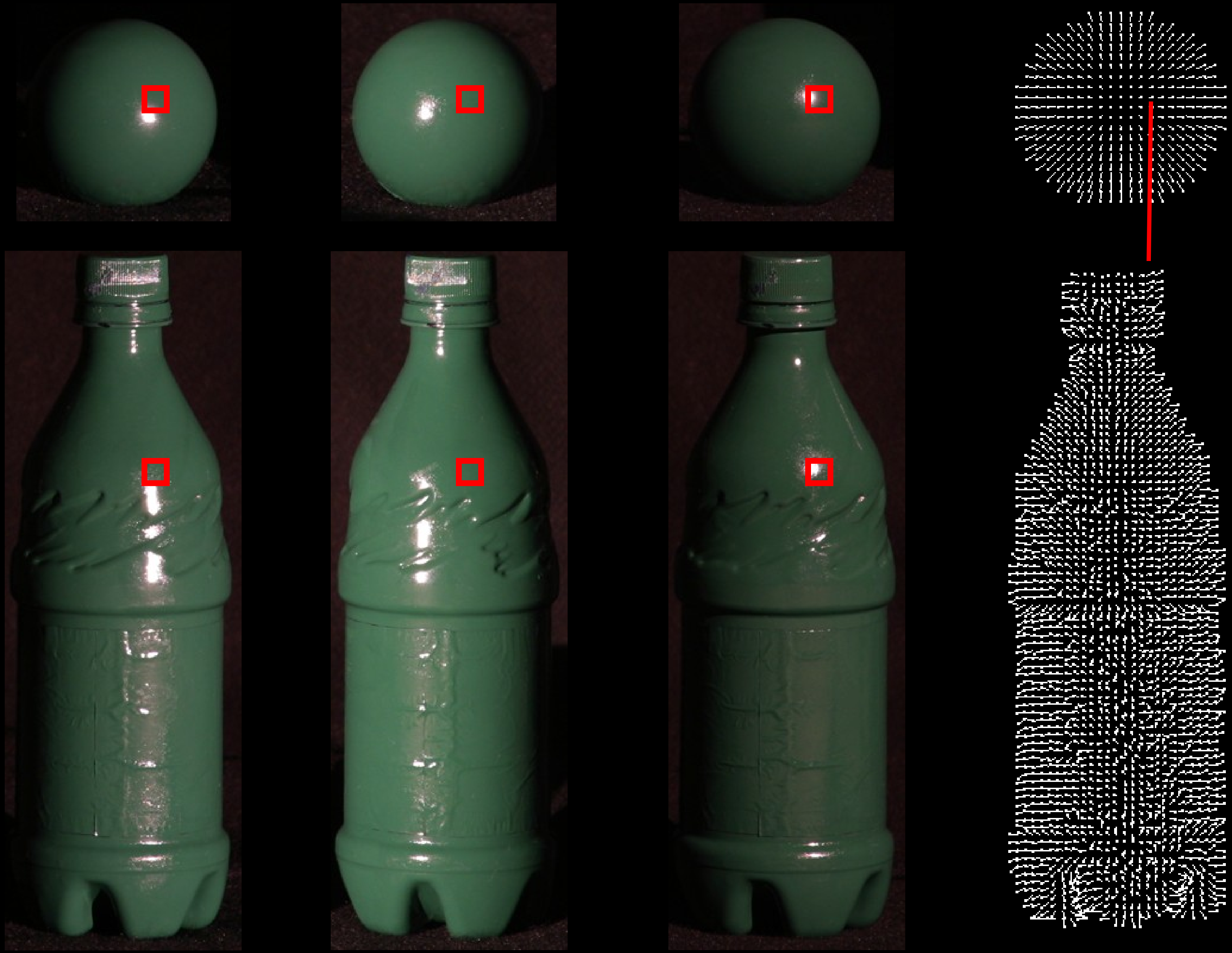


"Orientation consistency"

same surface normal



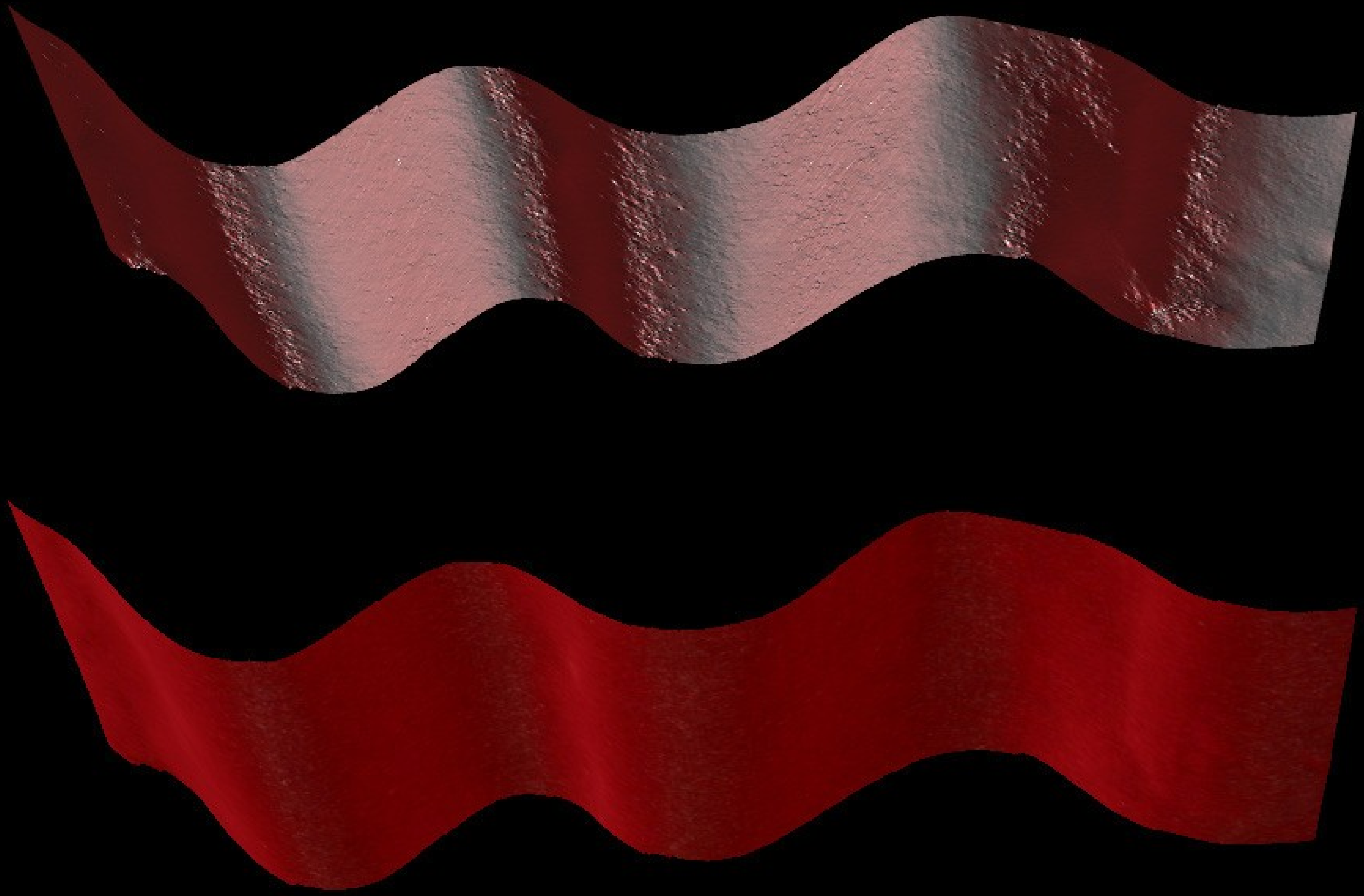




Virtual views

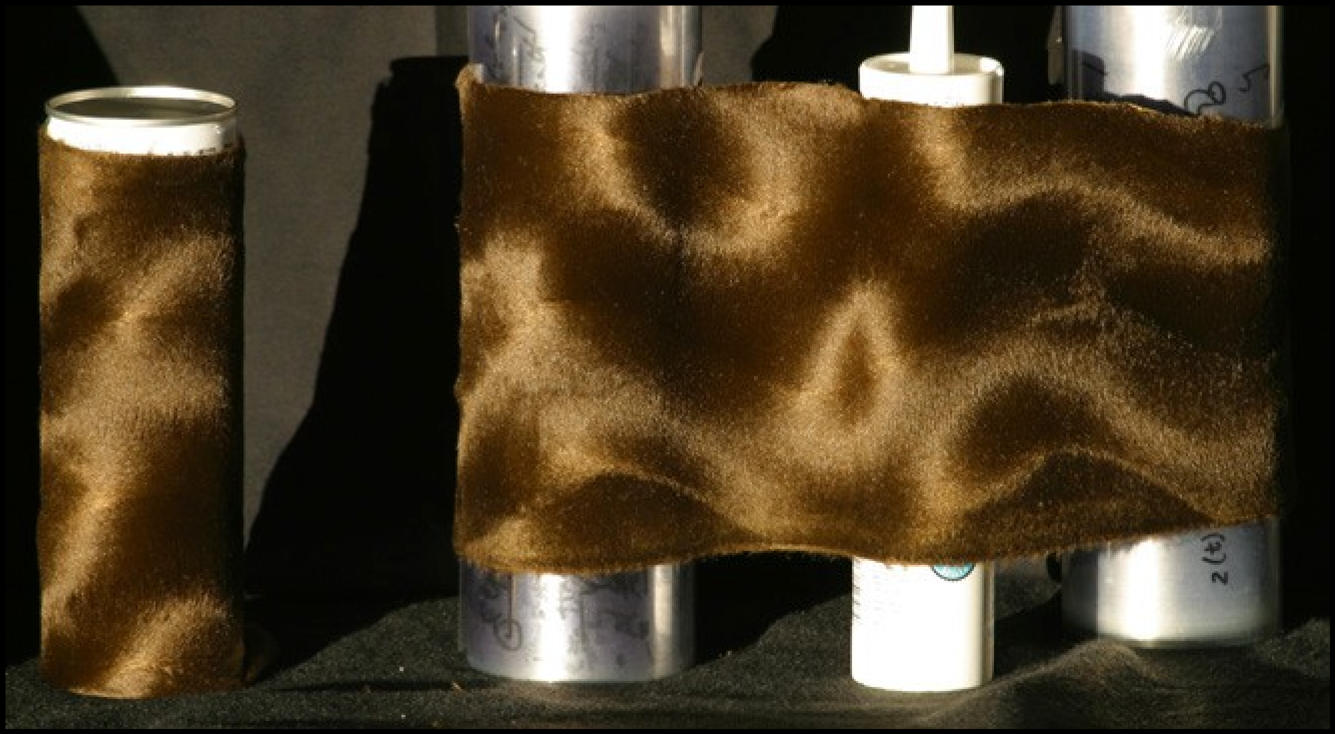
Velvet

Virtual Views

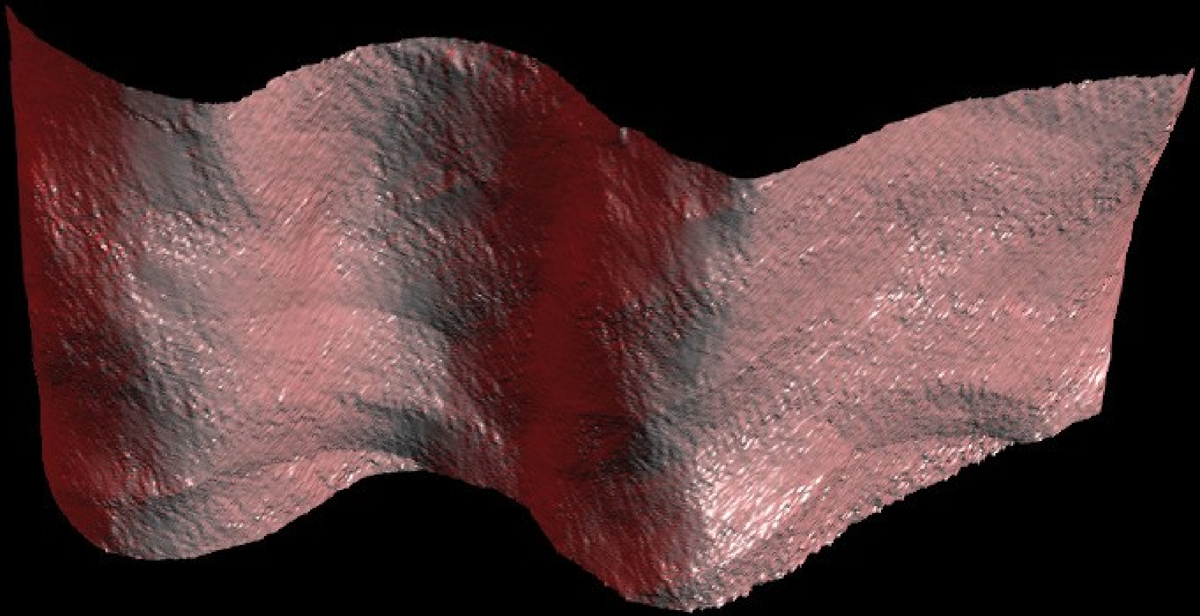


Brushed Fur

Brushed Fur



Virtual Views



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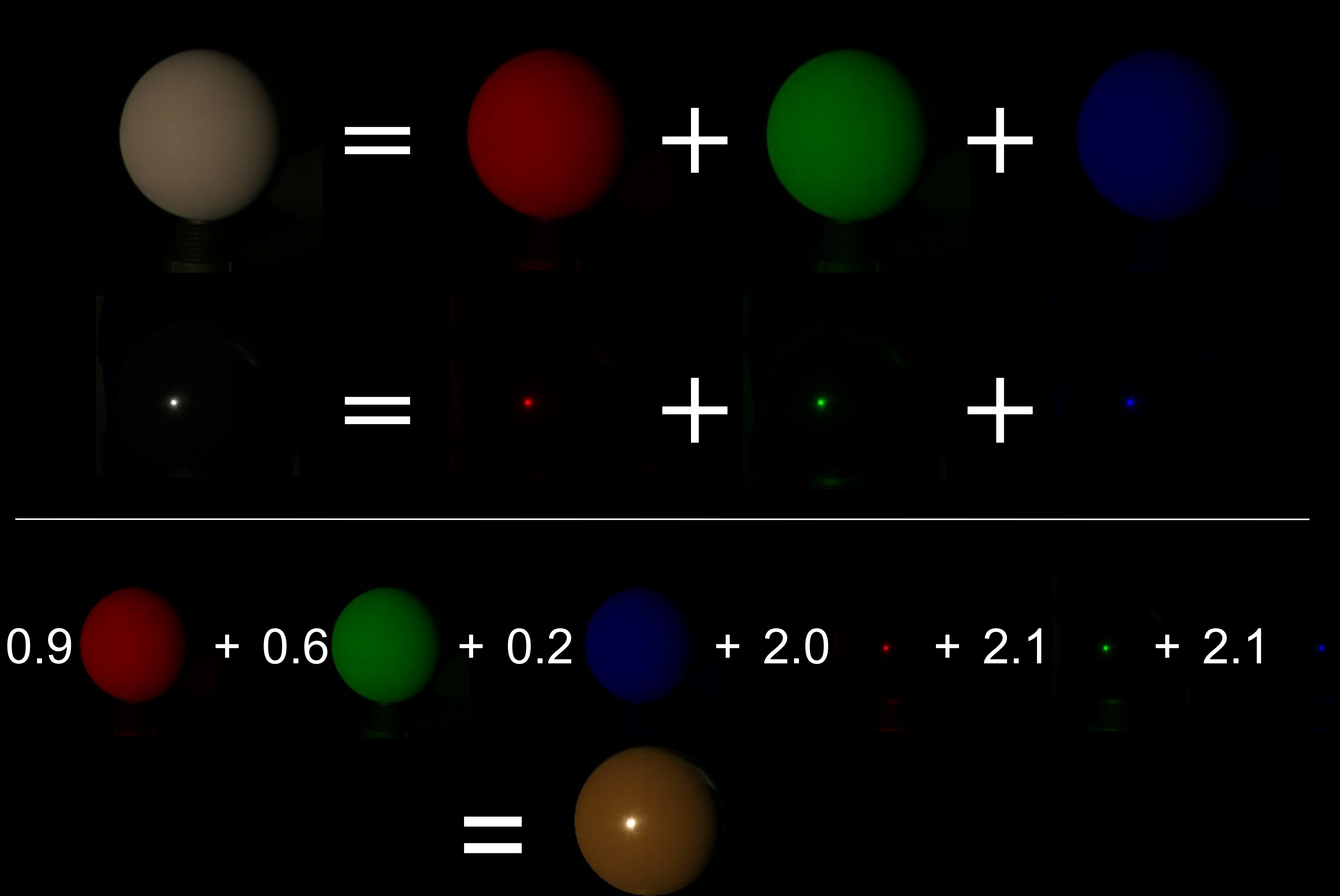
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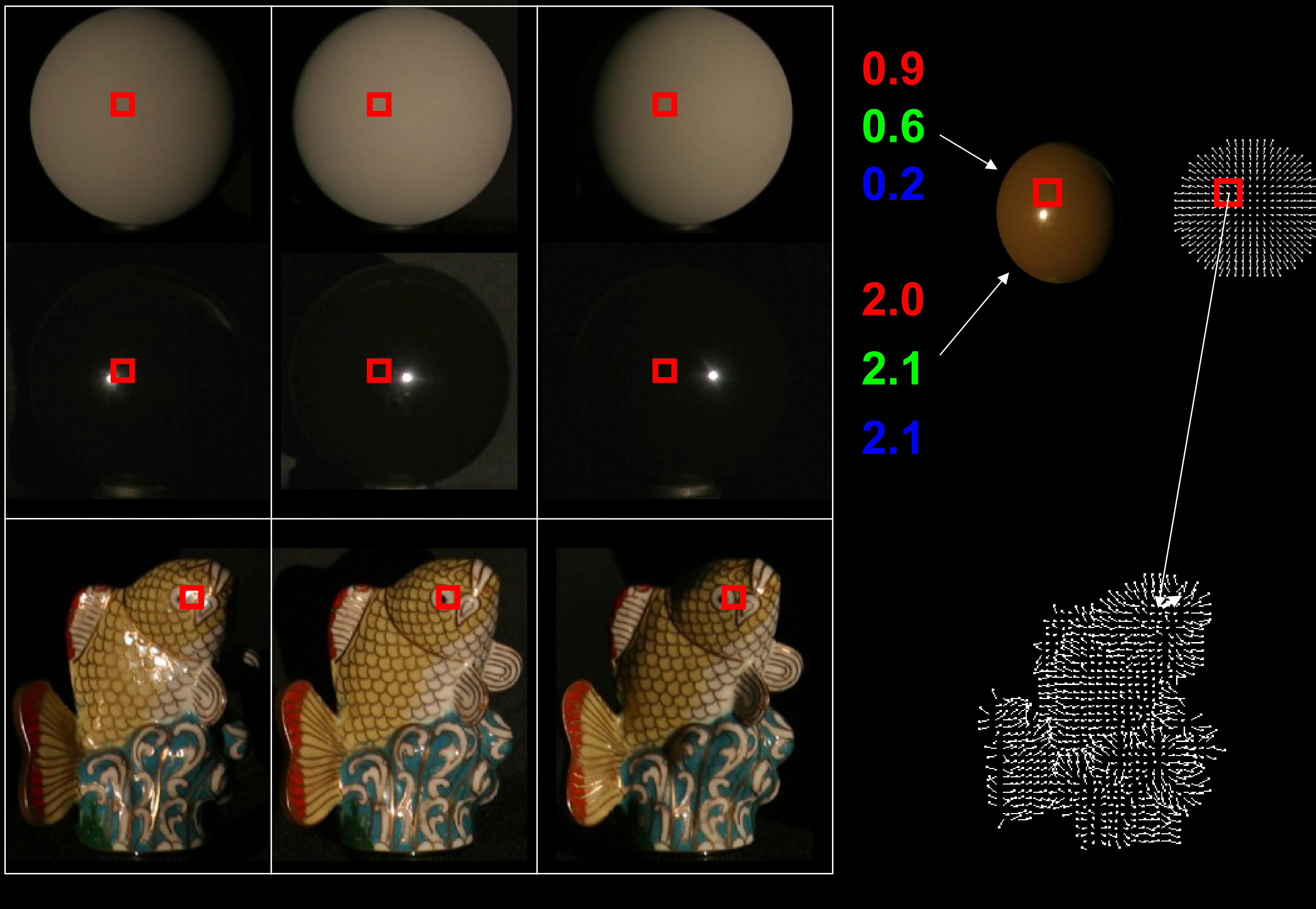
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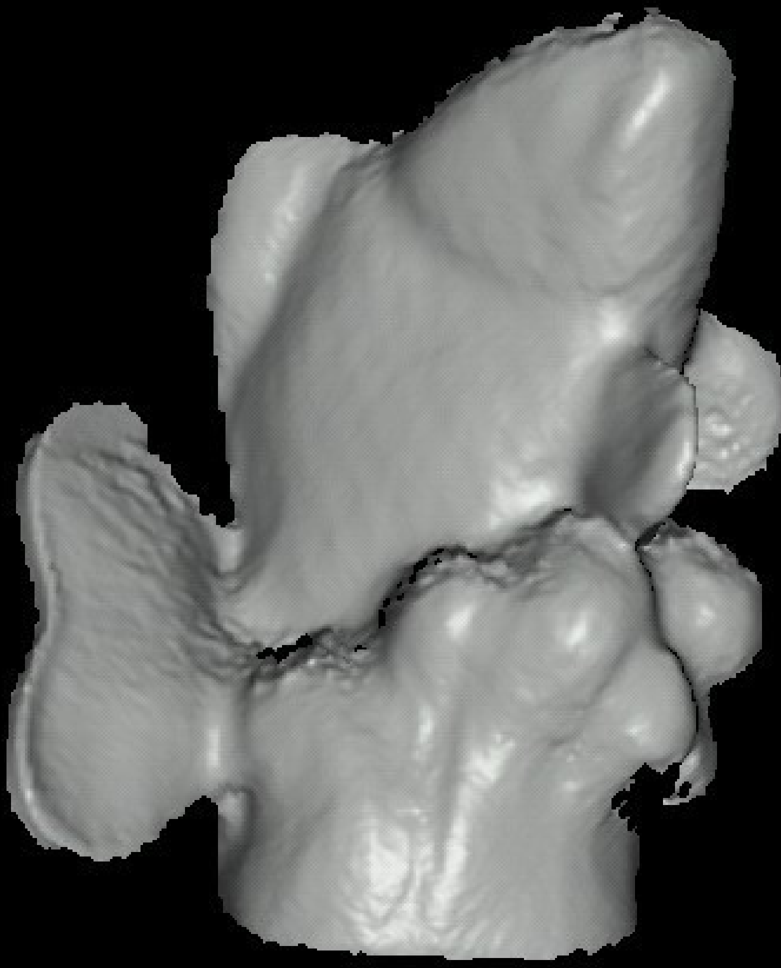
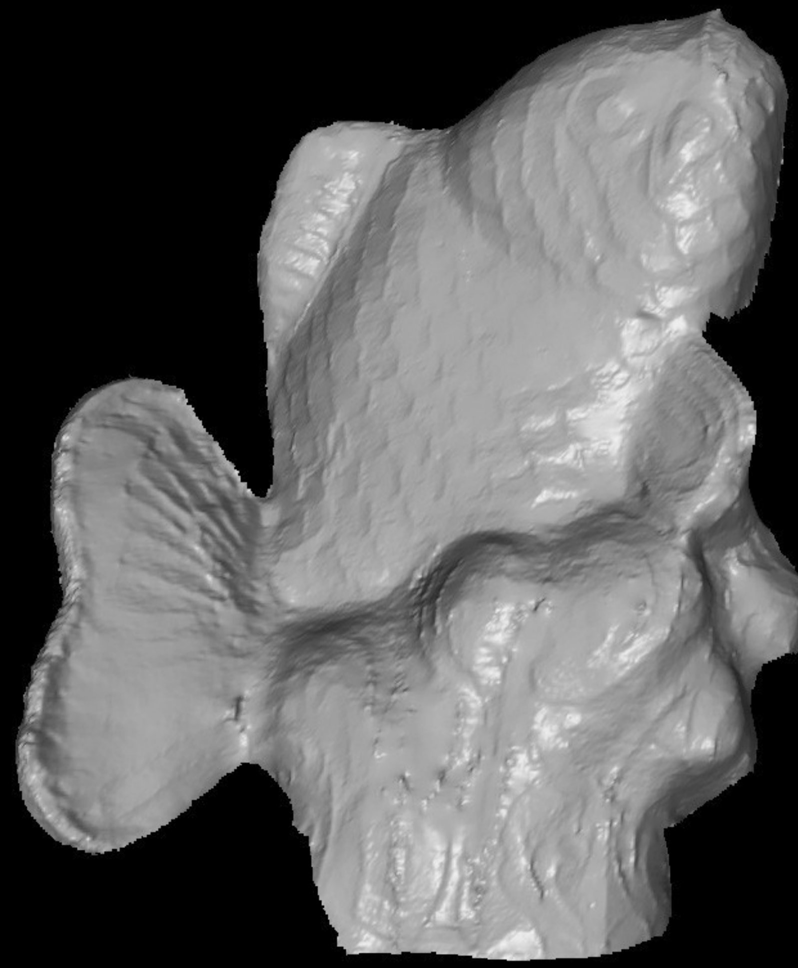
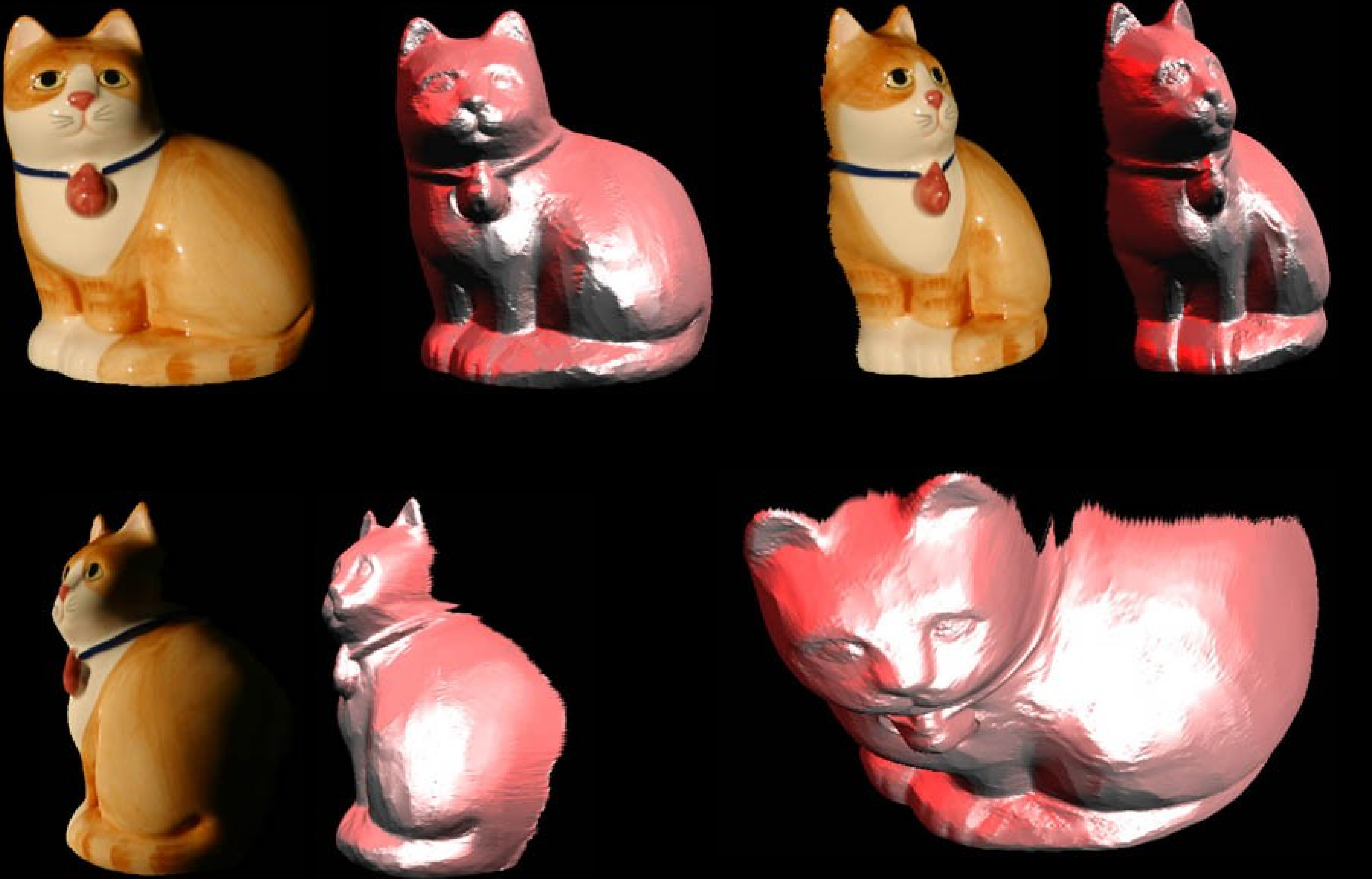
Virtual views



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