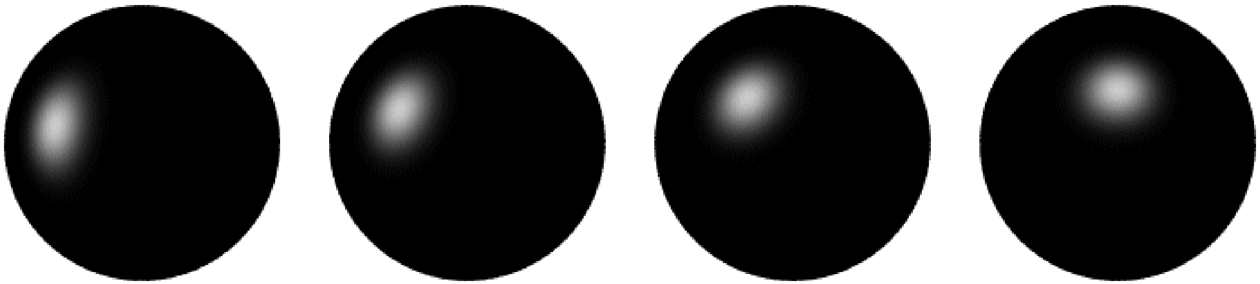
Computing light source directions

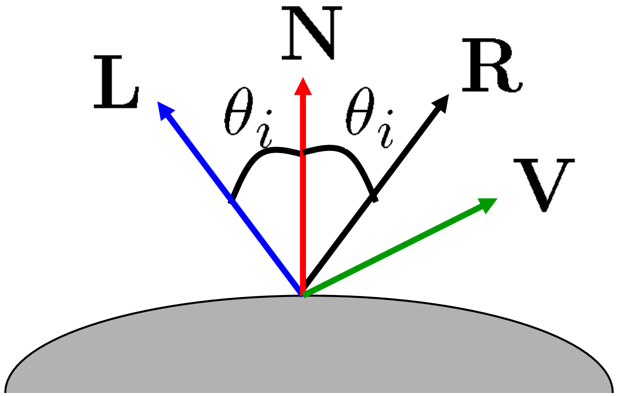
Trick: place a chrome sphere in the scene



- 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**



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

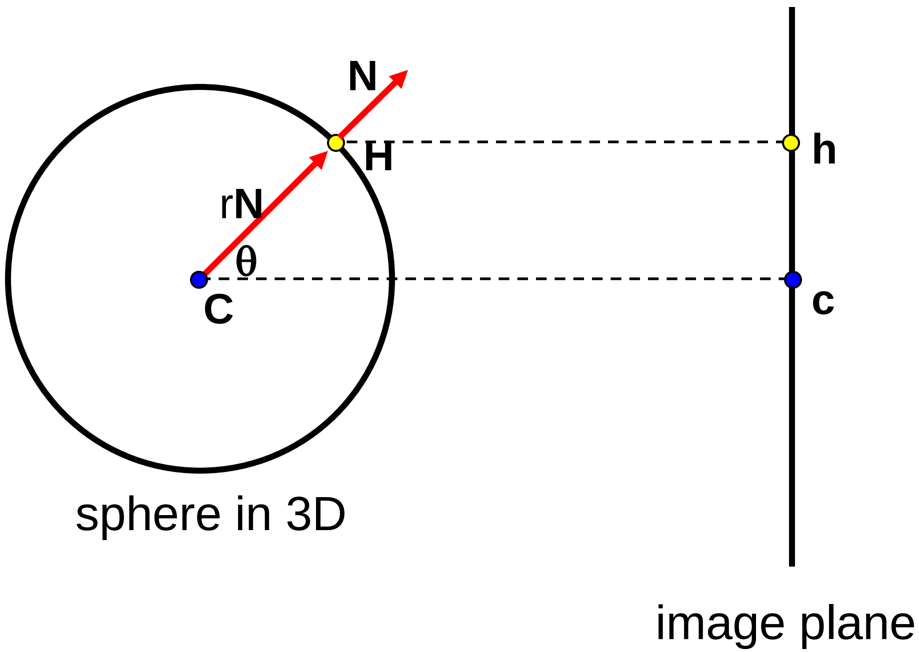
We see a highlight when **V** = **R**

- then L is given as follows:

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

Computing the light source direction

Chrome sphere that has a highlight at position **h** in the image

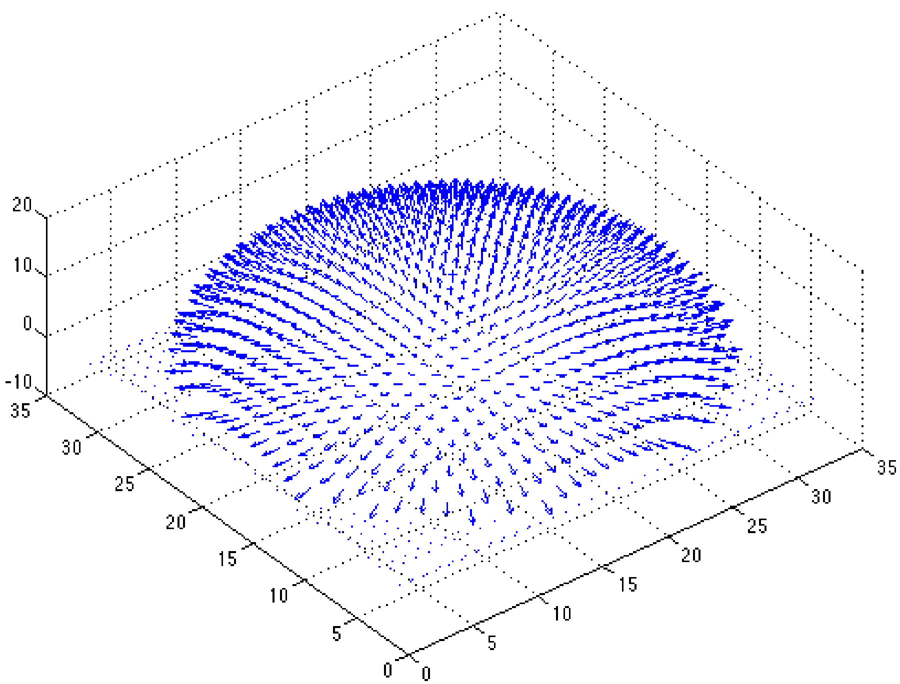


$$N = \begin{pmatrix} \dfrac{x_h - x_c}{r} \\ \dfrac{y_h - y_c}{r} \\ \dfrac{\sqrt{r^2 - x^2 - y^2}}{r} \end{pmatrix}$$

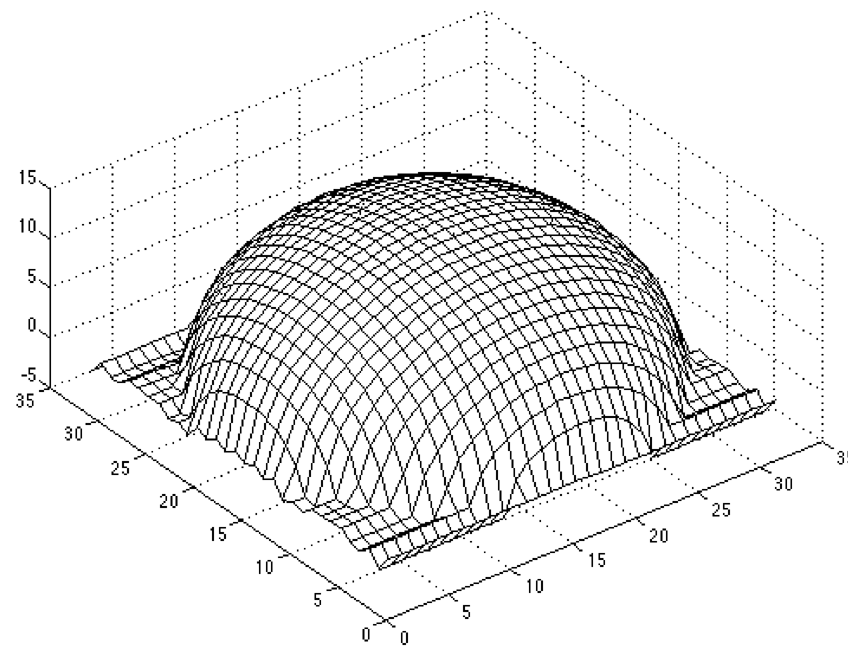
Can compute θ (and hence **N**) from this figure

Now just reflect **V** about **N** to obtain **L**

Depth from normals



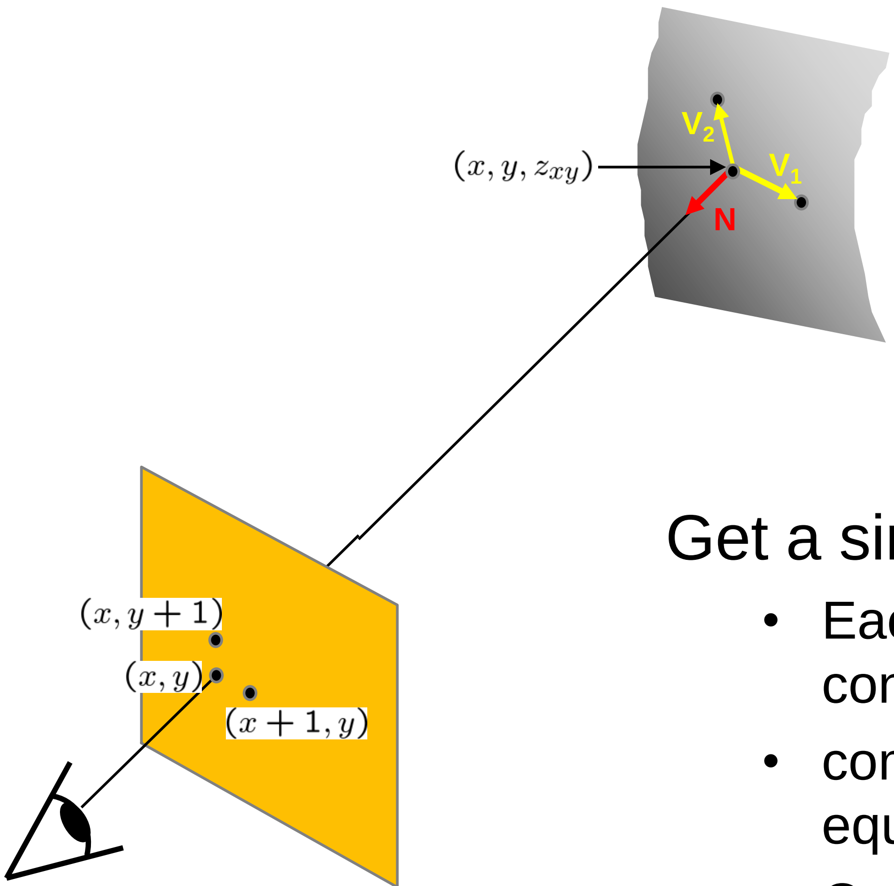
What we have



What we want

Forsyth & Ponce, Sec. 5.4

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
- On the boundary we have only one constraint.

Trick for handling shadows

Weight each equation by the pixel brightness:

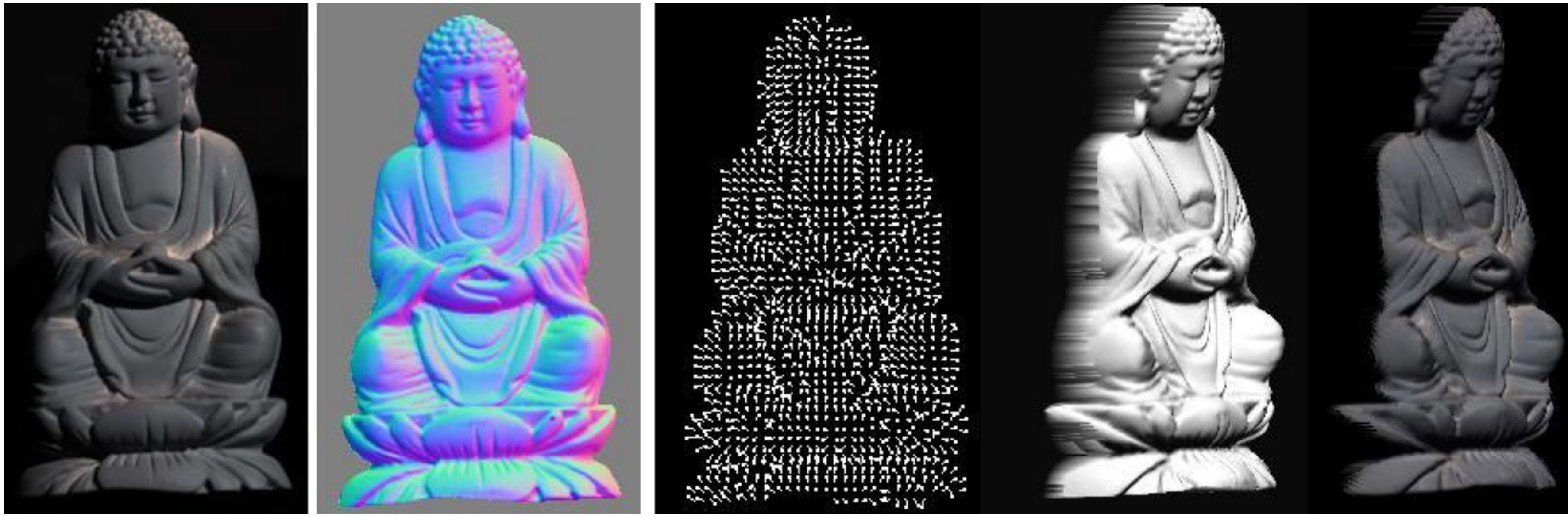
$$I_i(I_i) \;=\; I_i[k_d \mathbf{N} \cdot \mathbf{L_i}]$$

Gives weighted least-squares matrix equation:

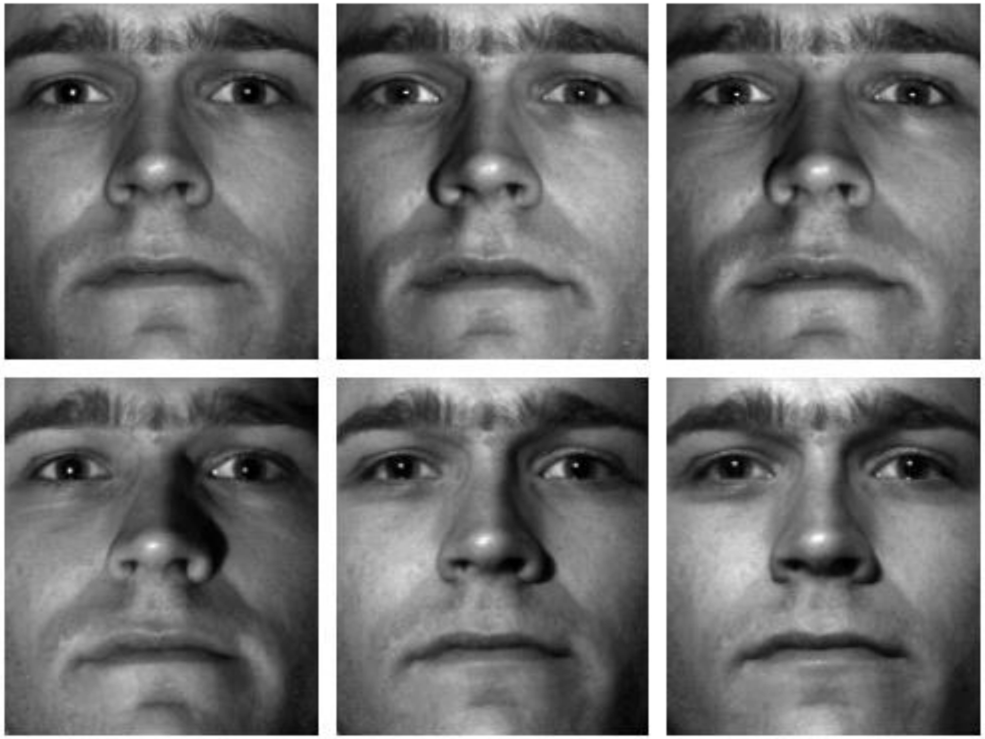
$$\left[\begin{array}{ccc} I_1^2 & \ldots & I_n^2 \end{array}\right] = k_d \mathbf{N}^T \left[\begin{array}{ccc} I_1 \mathbf{L_1} & \ldots & I_n \mathbf{L_n} \end{array}\right]$$

Solve for N, k_d as before

Example



Results…



from Athos Georghiades

http://cvc.yale.edu/people/Athos.html

Limitations

- doesn't work for shiny things, semi-translucent things
- shadows, inter-reflections are difficult
- Single light source illumination
- camera and lights have to be distant
- calibration requirements
  – measure light source directions, intensities
  – camera response function

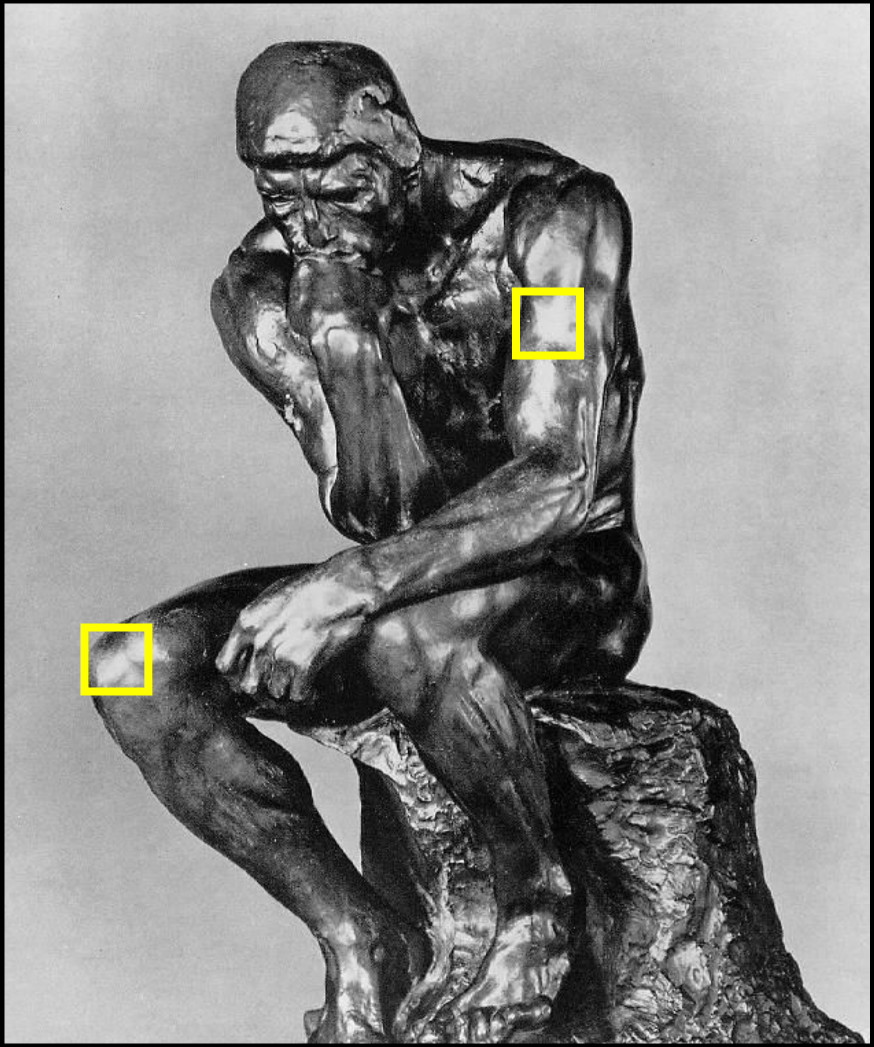
Newer work addresses some of these issues

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
- Basri, Jacobs and Kemelmacher Photometric Stereo with General Unknown Lighting, International Journal of Computer Vision (IJCV) 2007

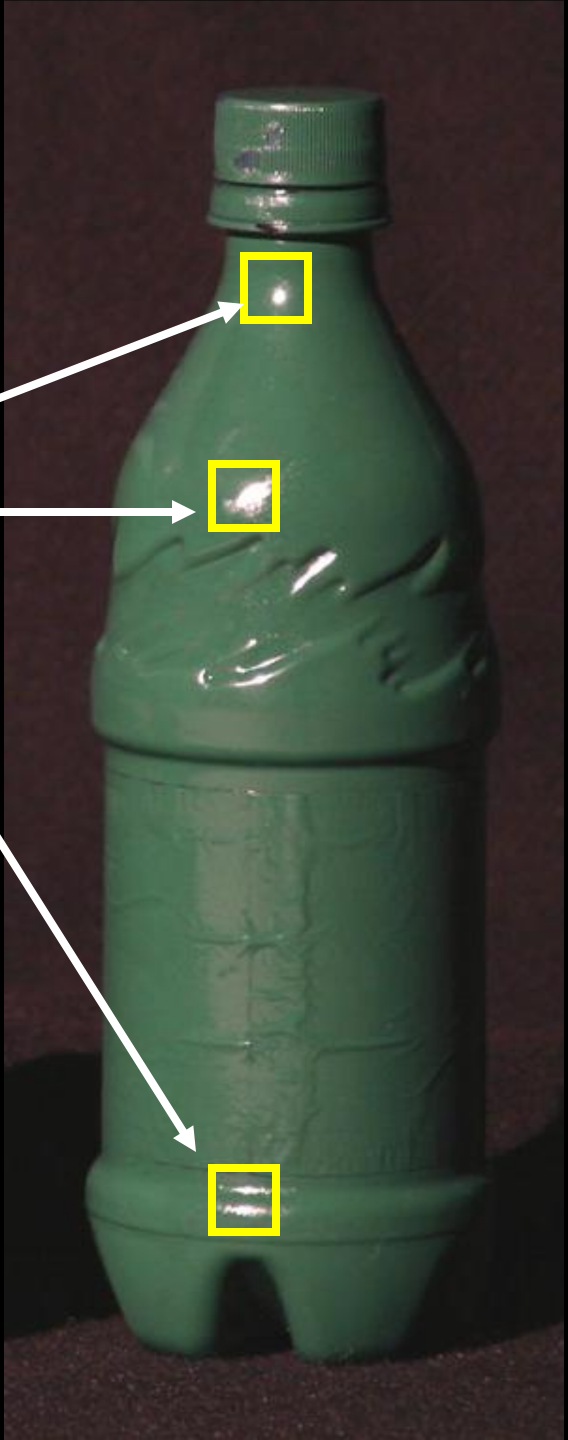
Hertzmann & Seitz, *Example-Based Photometric Stereo: Shape Reconstruction with General, Varying BRDFs*." IEEE Trans. PAMI 2005

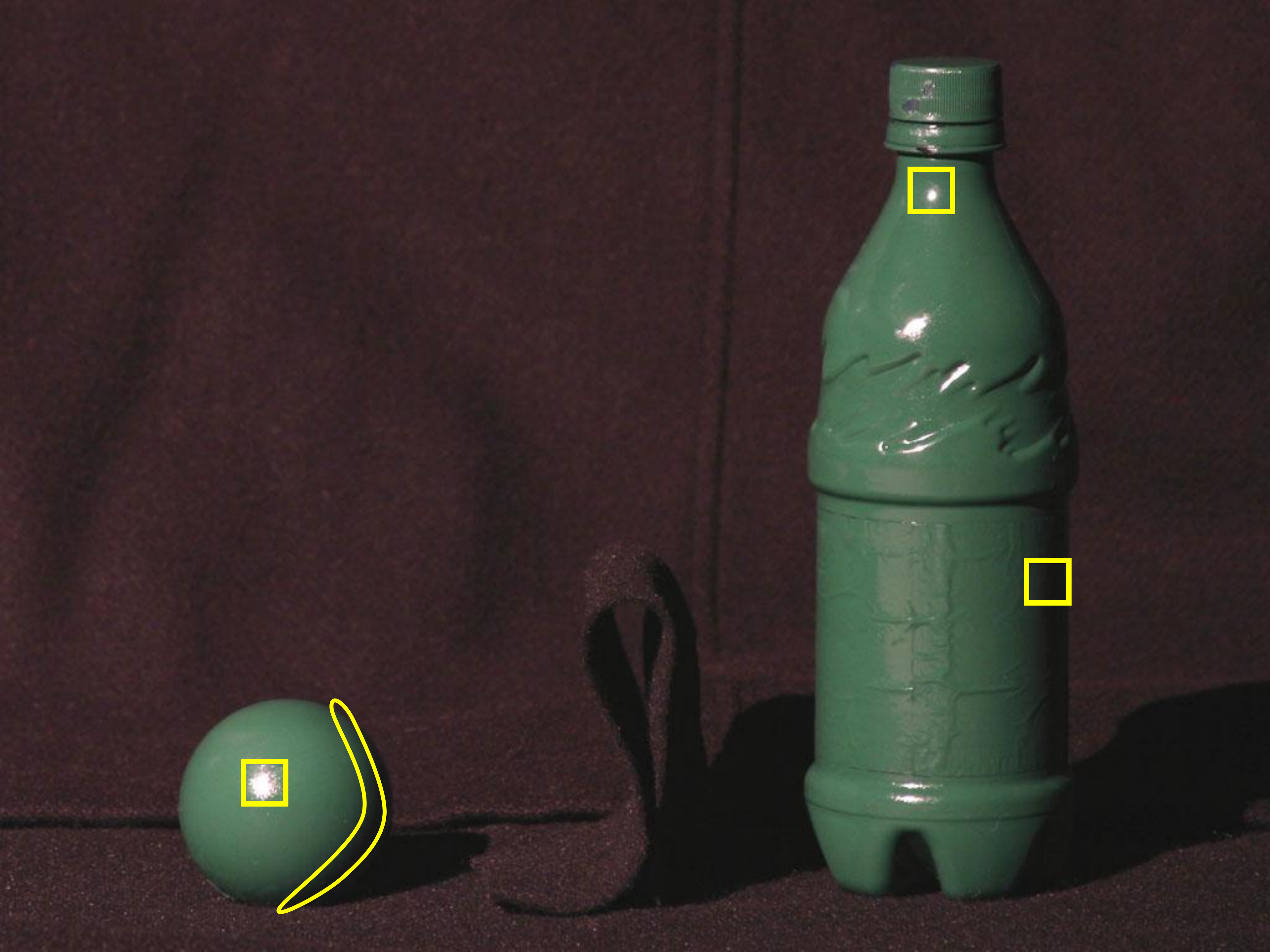
Shiny things

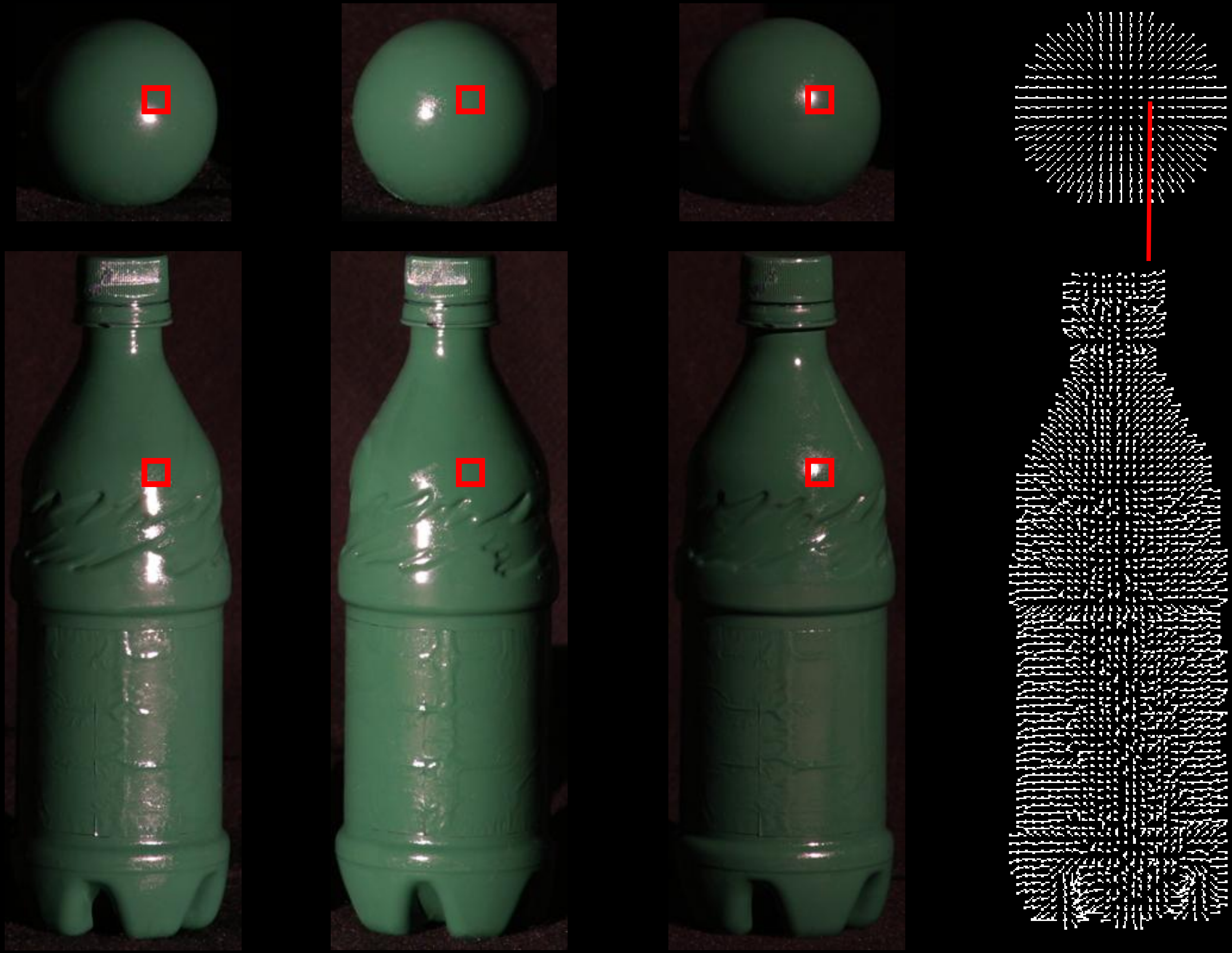


“Orientation consistency”

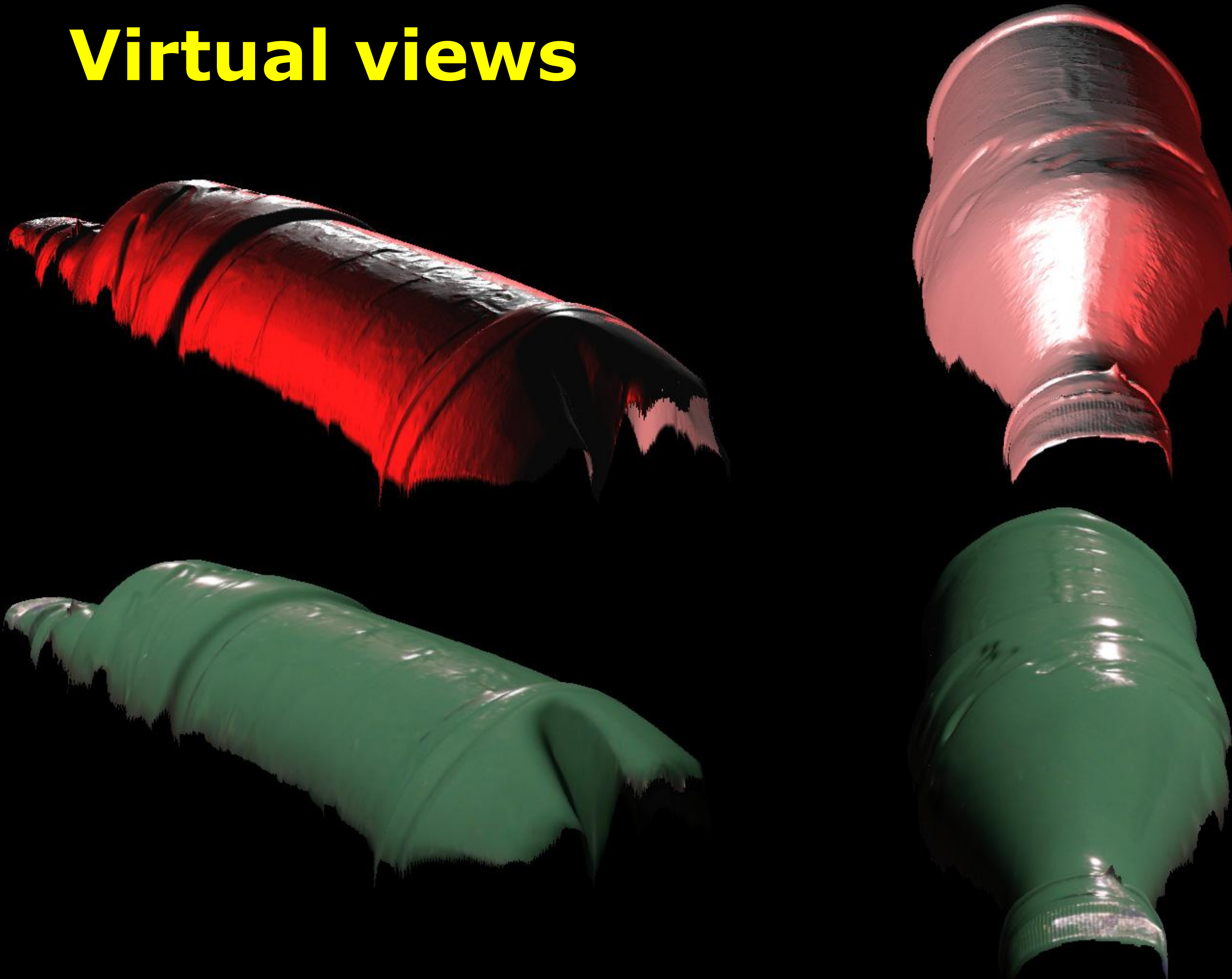
same surface normal





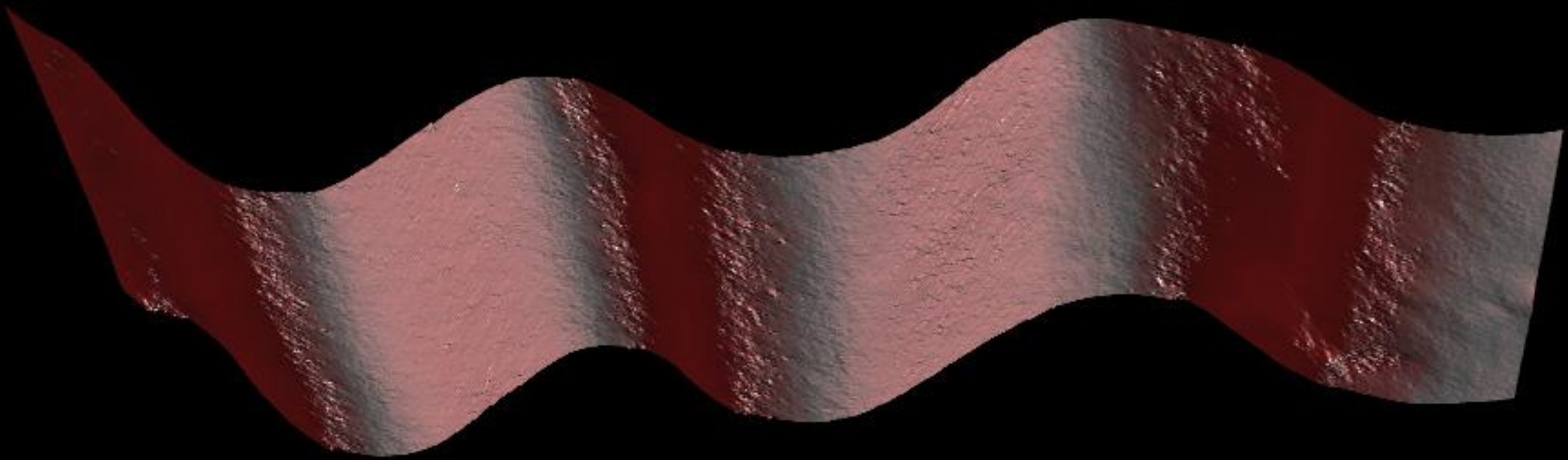


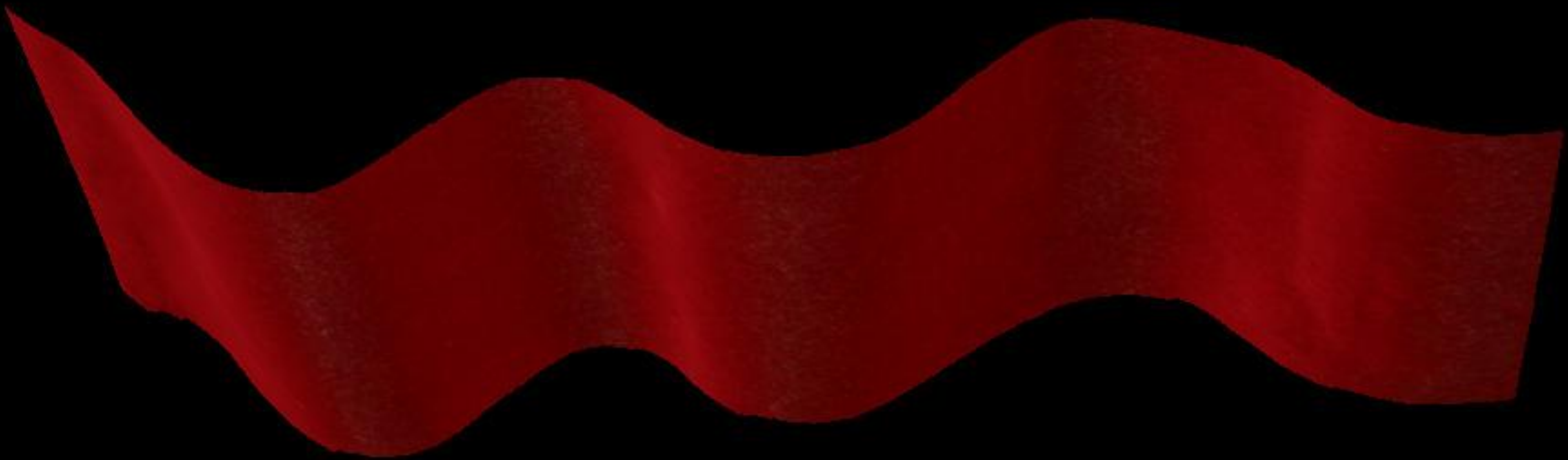
Virtual views



Velvet

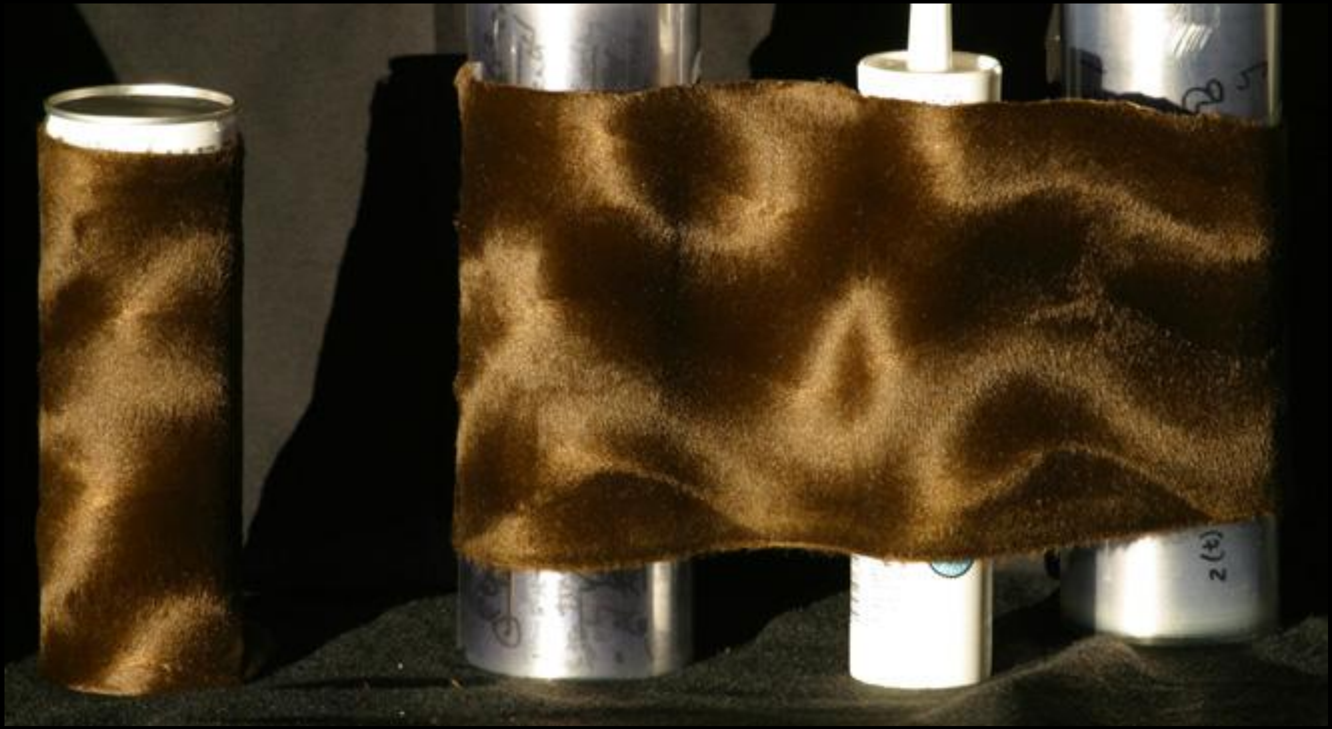
Virtual Views



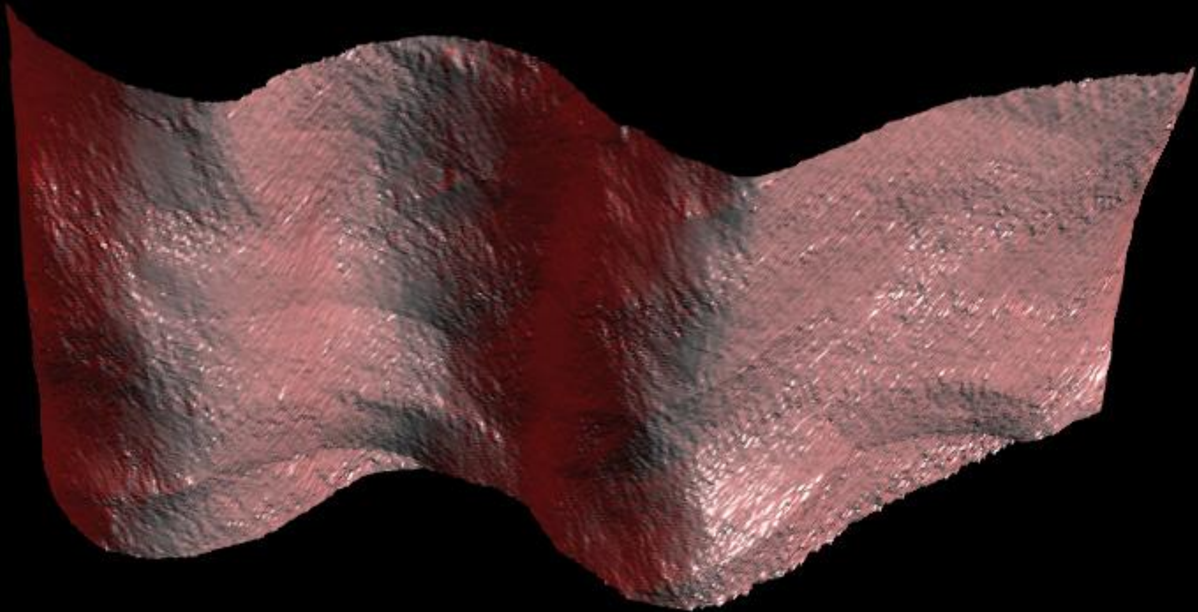


Brushed Fur

Brushed Fur

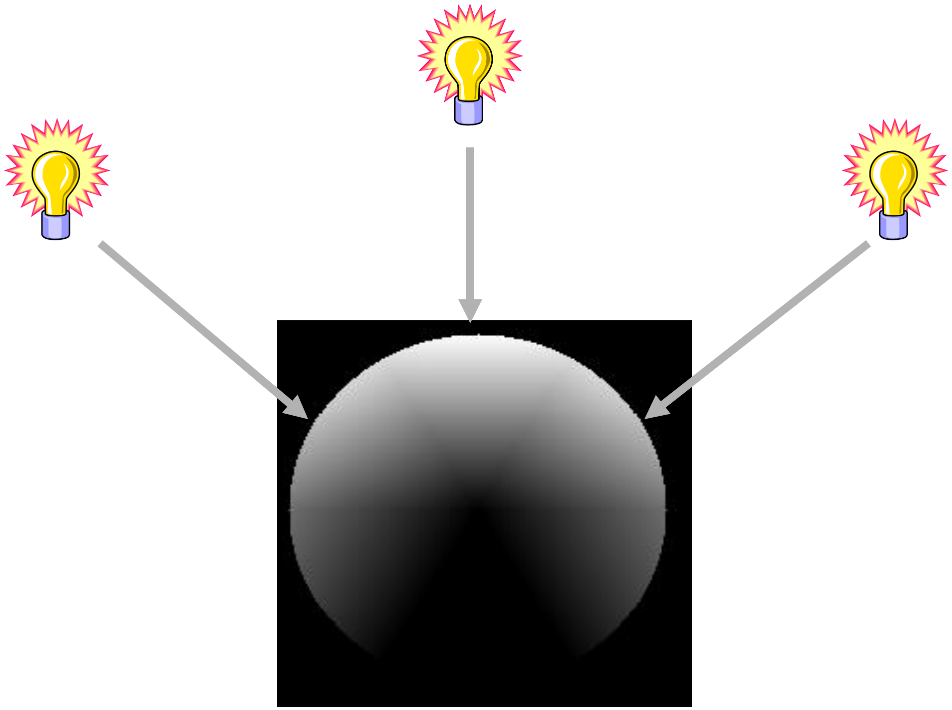


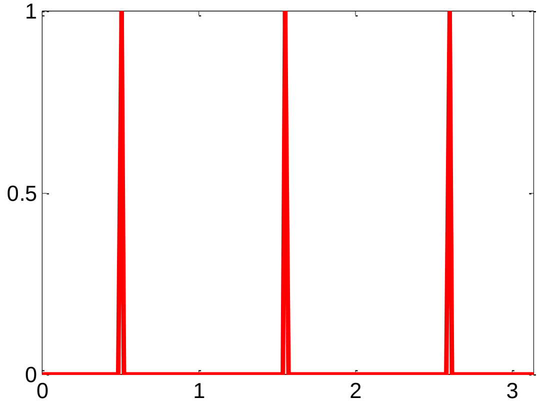
Virtual Views



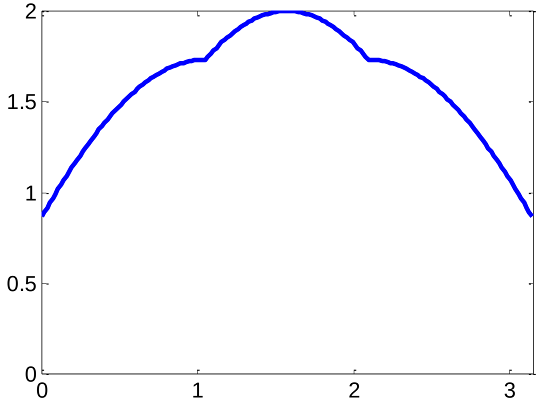
- Basri, Jacobs and Kemelmacher Photometric Stereo with General Unknown Lighting, International Journal of Computer Vision (IJCV) 2007

Illumination Modeling



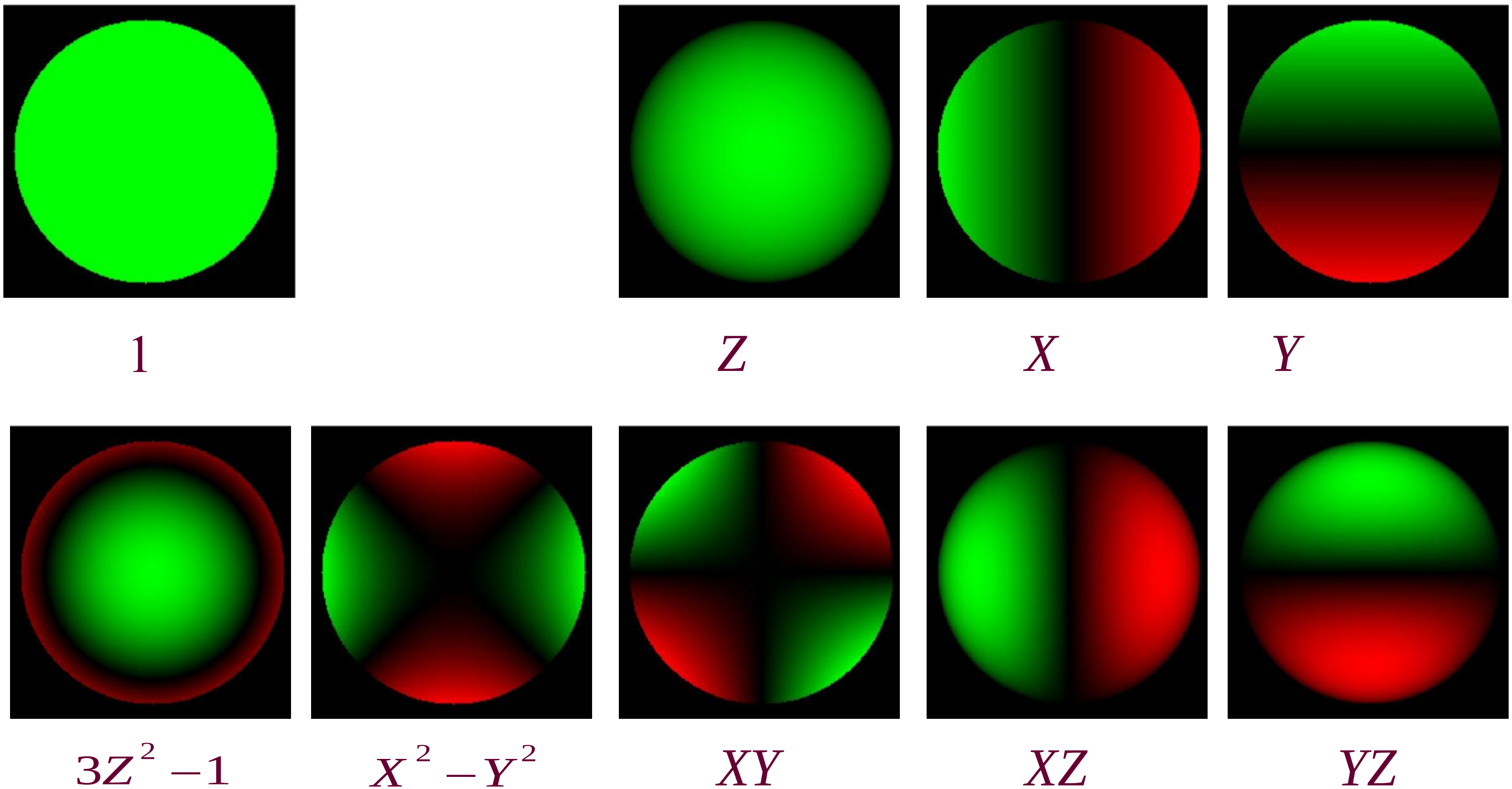


lighting

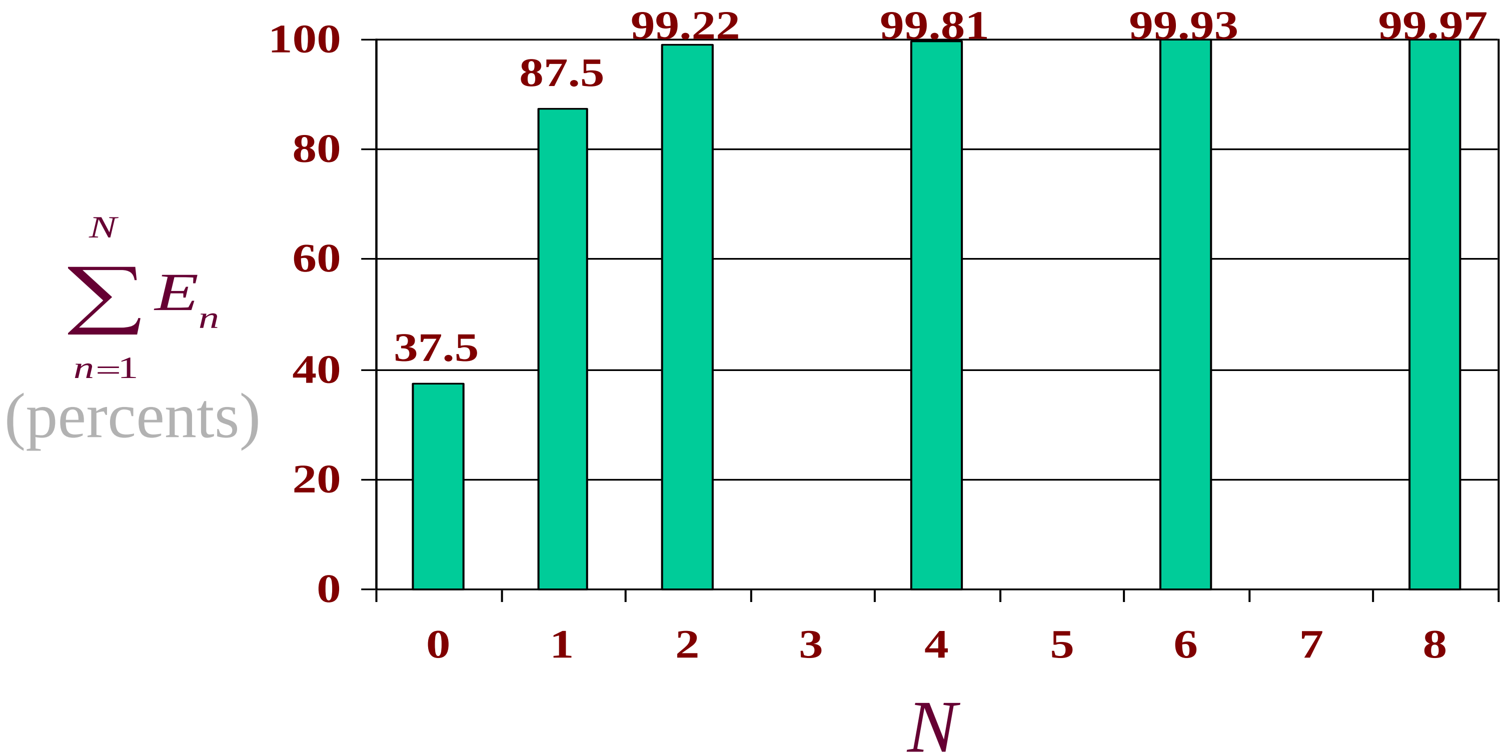


reflectance

Spherical Harmonics



Cumulative Energy



Photometric Stereo

Factorization to Shape and Light

M
Image 1
:
Image n

$\approx$

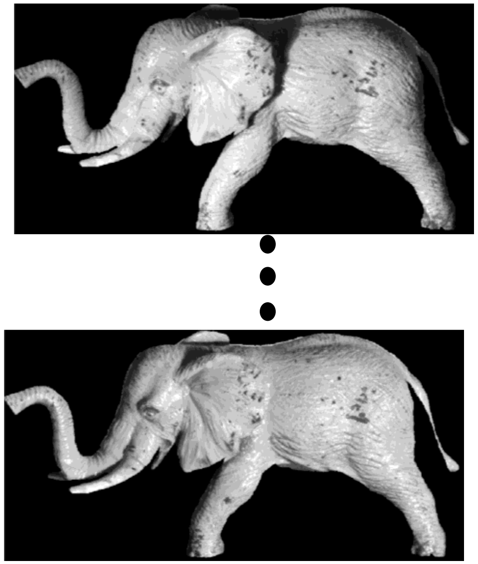
L
Light 1
:
Light n

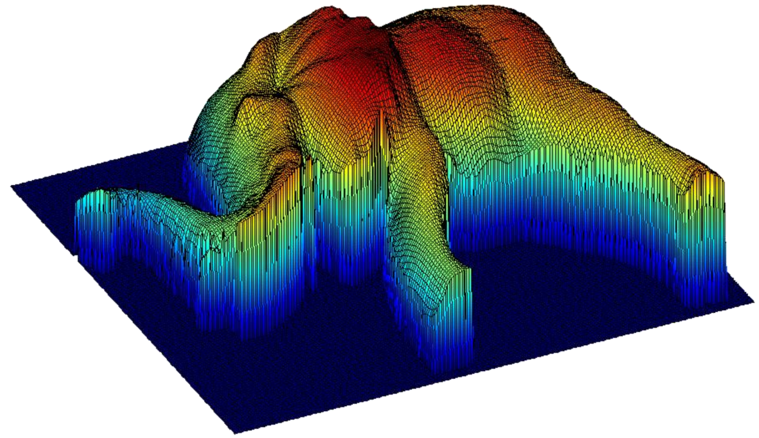
*

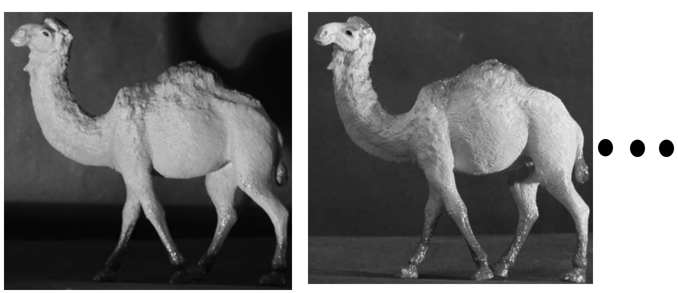
S
ρ
ρn_z
ρn_z
ρn_y
$\rho(3n_z^2-1)$
$\rho(n_x^2-n_y^2)$
$\rho n_x n_y$
$\rho n_x n_z$
$\rho n_y n_z$

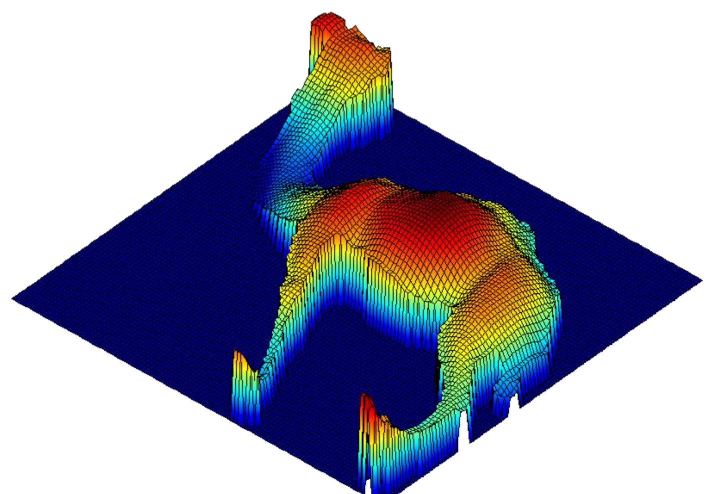
SVD recovers L and S up to an ambiguity

Results with arbitrary unknown lighting





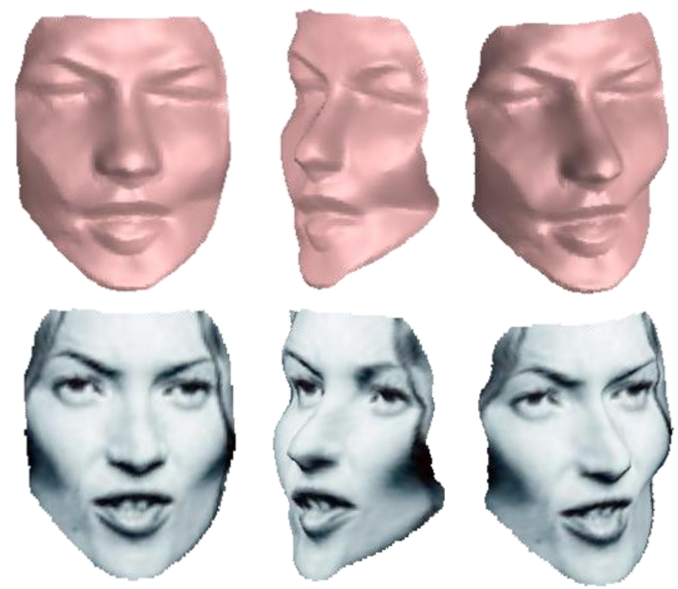




3D Face Shape Reconstruction

Input: Single Image,
general lighting, pose

Output: 3D shape

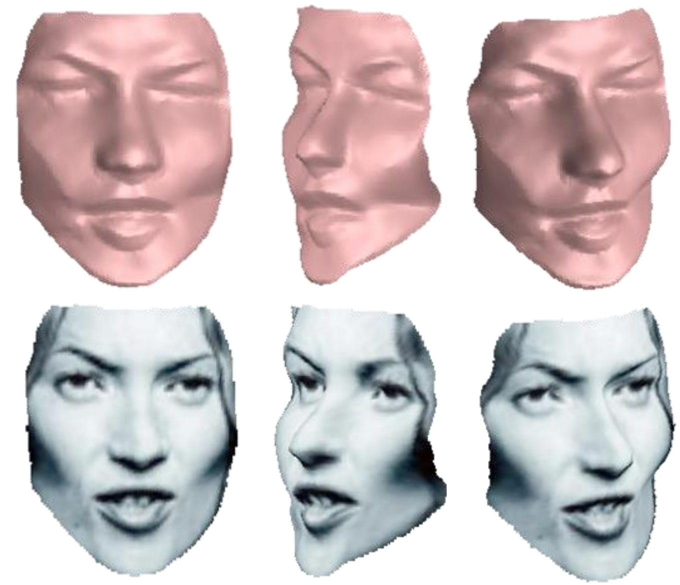


Kemelmacher and Basri Molding Face Shapes by Example
IEEE Trans. PAMI

One approach

- Represent input face as a combination of hundreds of 3D face in a database:

Our approach



Input image

Single reference model

Input image is a guide to “mold” a single reference model.

unknown lighting

unknown boundaries

unknown albedo

significant differences in shape including
- expression
- gender
- race

Harmonic representation of lighting

ρ albedo

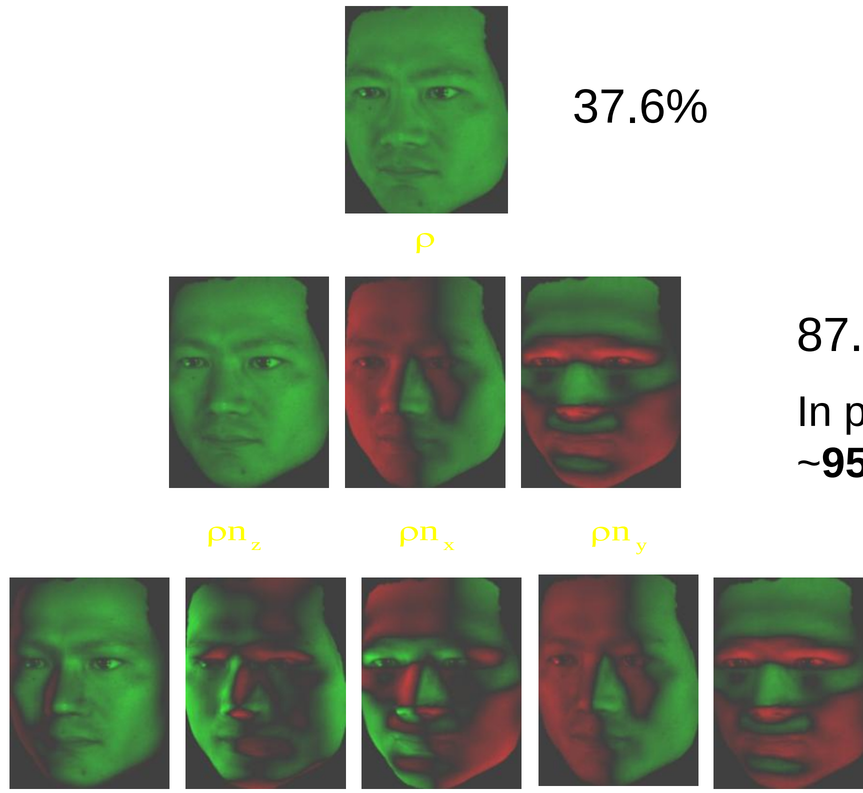
$\mathbf{n}$ surface normal

$\mathbf{n} = (n_x, n_y, n_z)$

Positive values

Negative values

$$I(x,y) = R(\mathbf{n};\rho,\mathbf{l}) \approx \rho \sum_{i=0}^{K-1} l_i Y_i(\mathbf{n})$$



37.6%

87.5%

In practice ~**95%** accuracy

99.2%

- Lambertian reflectance
- Accounts for attached shadows
- Arbitrary illumination (point sources, diffuse, combinations…)

Formulation

$$I(x,y) = R(\mathbf{n};\rho,\mathbf{l}) \approx \rho \sum_{i=0}^{K-1} l_i Y_i(\mathbf{n})$$

Unknown surface normal:

$$\mathbf{n}(x,y) = \frac{1}{\sqrt{p^2+q^2+1}}(p,q,-1)^T$$

$$p(x,y) = \partial z / \partial x$$

$$q(x,y) = \partial z / \partial y$$

Unknown harmonic coeff. $\mathbf{l} = (l_0 \ldots l_{K-1})$

Unknown albedo $\rho(x,y)$

Known image:

Known reference model:

$$\min_{l,z,\rho} \int_\Omega \left(I(x,y) - \rho \sum_{i=0}^{K-1} l_i Y_i(\mathbf{n}) \right)^2 + \lambda_1 (\Delta G * d_z(x,y))^2 + \lambda_2 (\Delta G * d_\rho(x,y))^2 \, dxdy$$

$$d_z(x,y) = z(x,y) - z_{ref}(x,y) \qquad d_\rho(x,y) = \rho(x,y) - \rho_{ref}(x,y)$$

Reconstruction steps

$$\min_{l,z,\rho} \int_{\Omega} \left(I(x,y) - \rho \sum_{i=0}^{K-1} l_i Y_i(\mathbf{n}) \right)^2 + \lambda_1 (\Delta G * d_z(x,y))^2 + \lambda_2 (\Delta G * d_\rho(x,y))^2 \, dxdy$$

Solve for lighting:

$$\min_{l} \sum_{(x,y)\in\Omega} \left(I(x,y) - \rho_{ref} \sum_{i=0}^{K-1} l_i Y_i(\mathbf{n}_{ref}) \right)^2$$

Different faces experience the same lighting in similar way. So use reference face to fill in the missing data.

Solve for depth:

$$I(x,y) = \rho_{ref} l_0 + \frac{\rho_{ref}}{N_{ref}} (l_1 p + l_2 q - l_3)$$

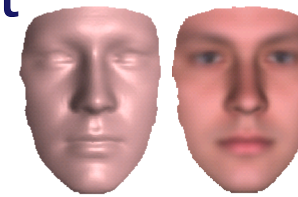
$$N = \sqrt{p^2 + q^2 + 1}$$

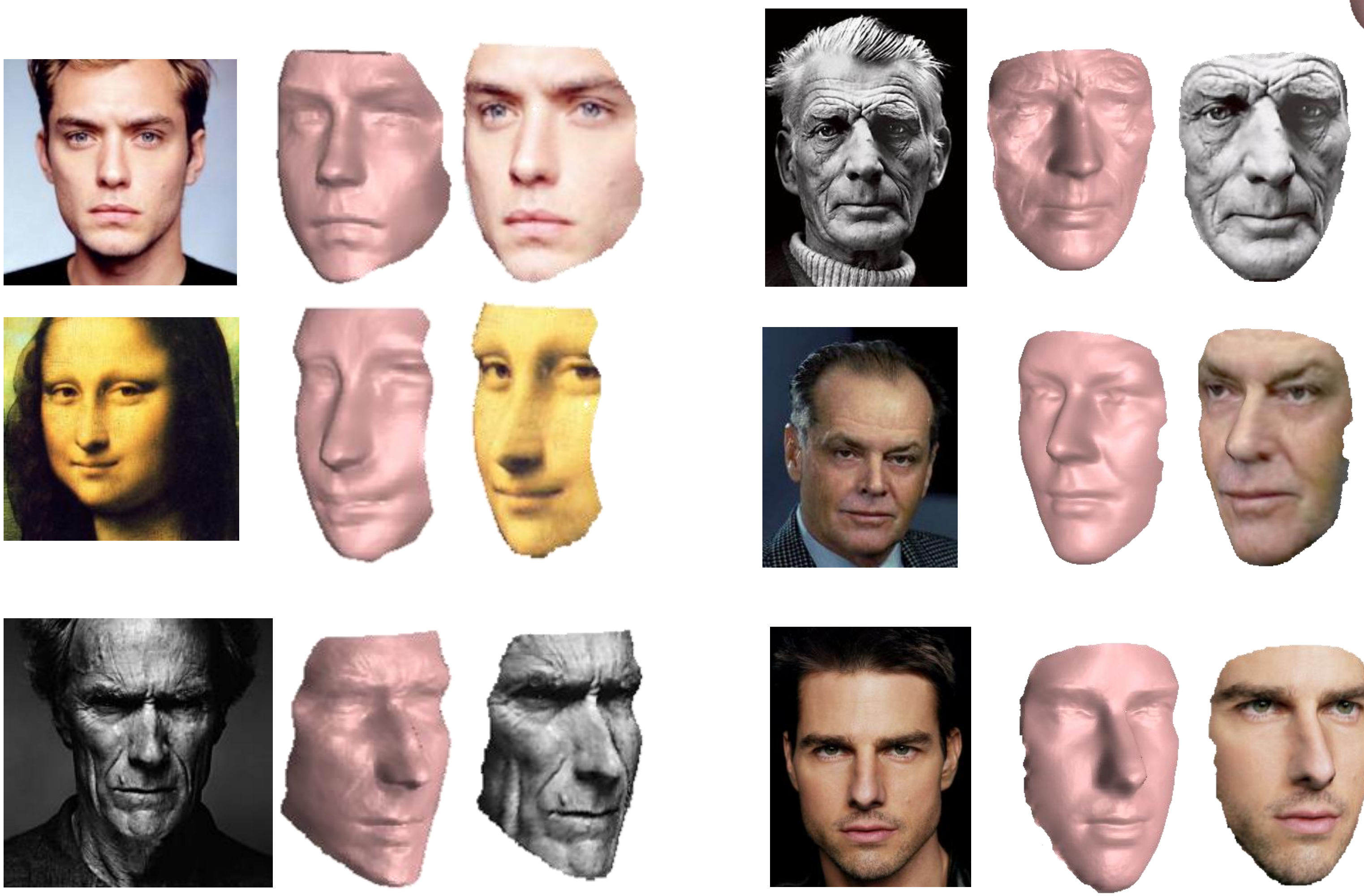
Linear PDE in z(x,y)

Boundaries: We let partial derivatives across boundaries to vanish

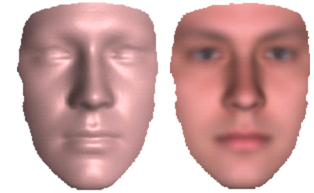
Results

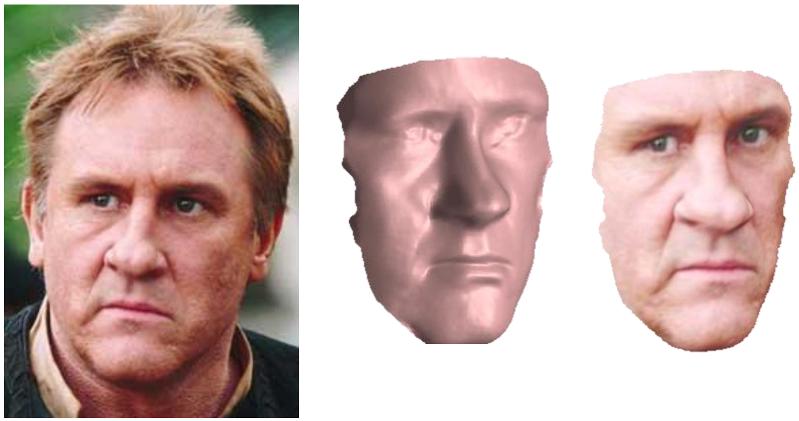
on images downloaded from the internet

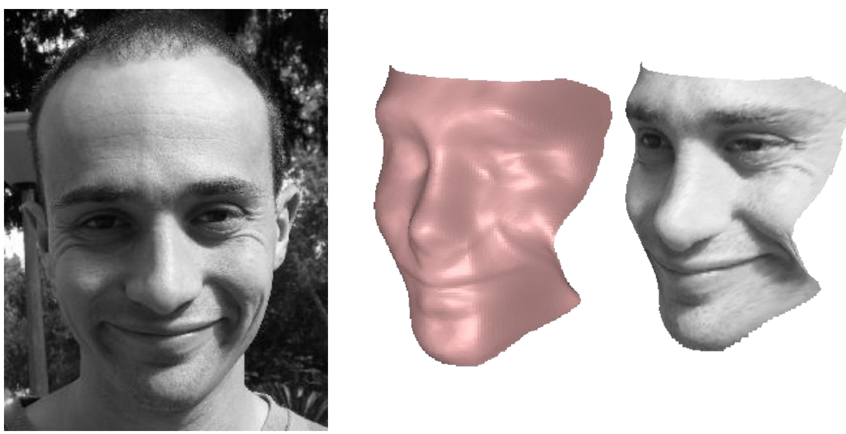


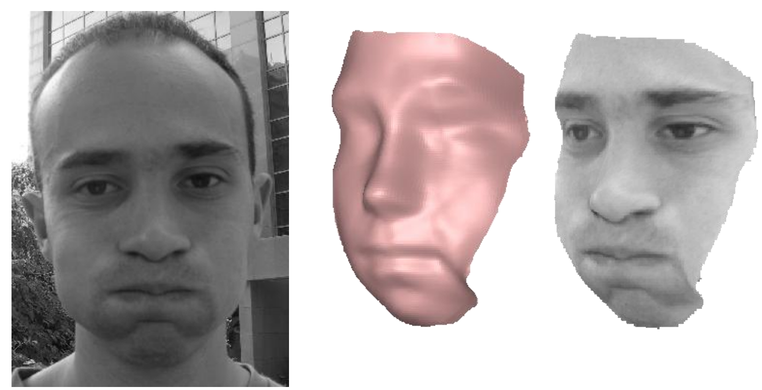


Expressions

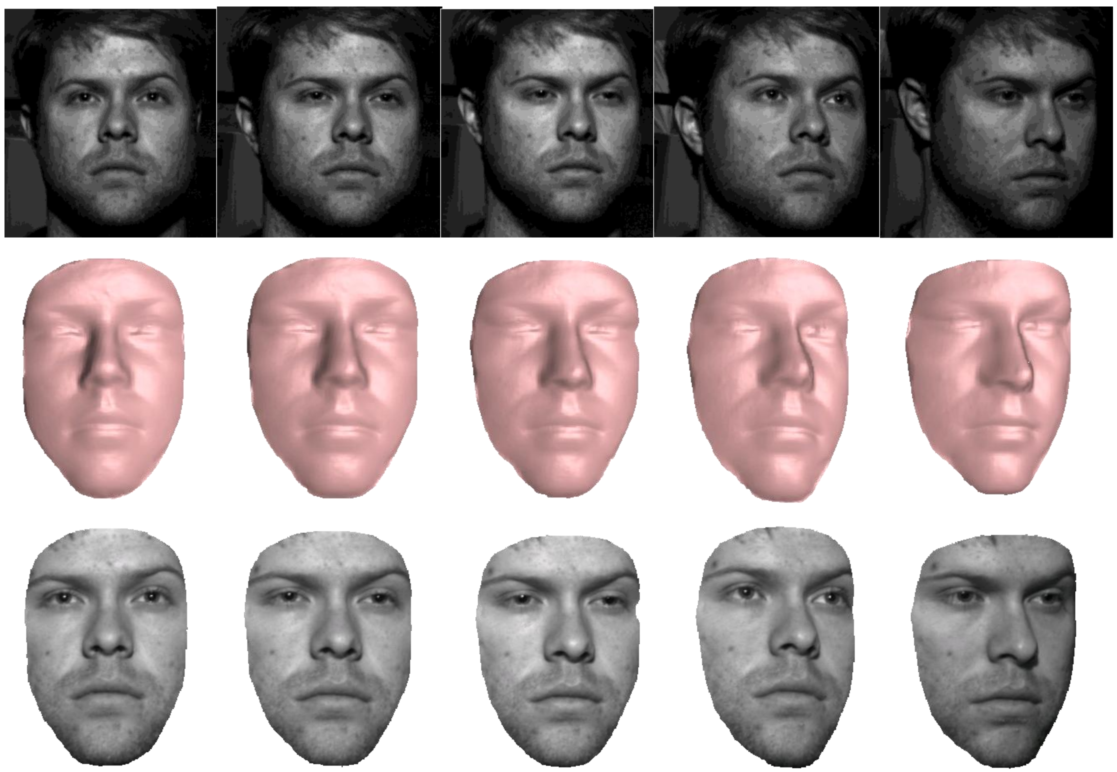








Results: unknown pose



8.1 ± 5.7% | 6.9 ± 5.3% | 7.7 ± 5.7% | 7.3 ± 6.1% | 8 ± 7.2%