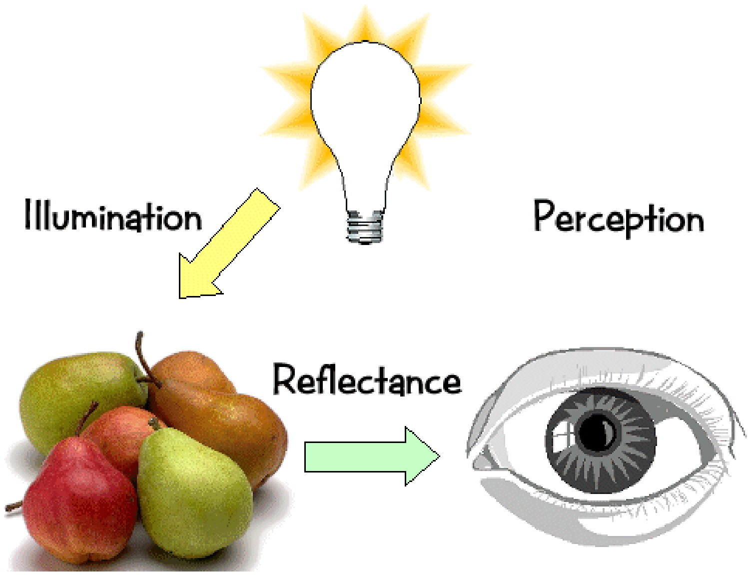
4. Reflectance & Lighting

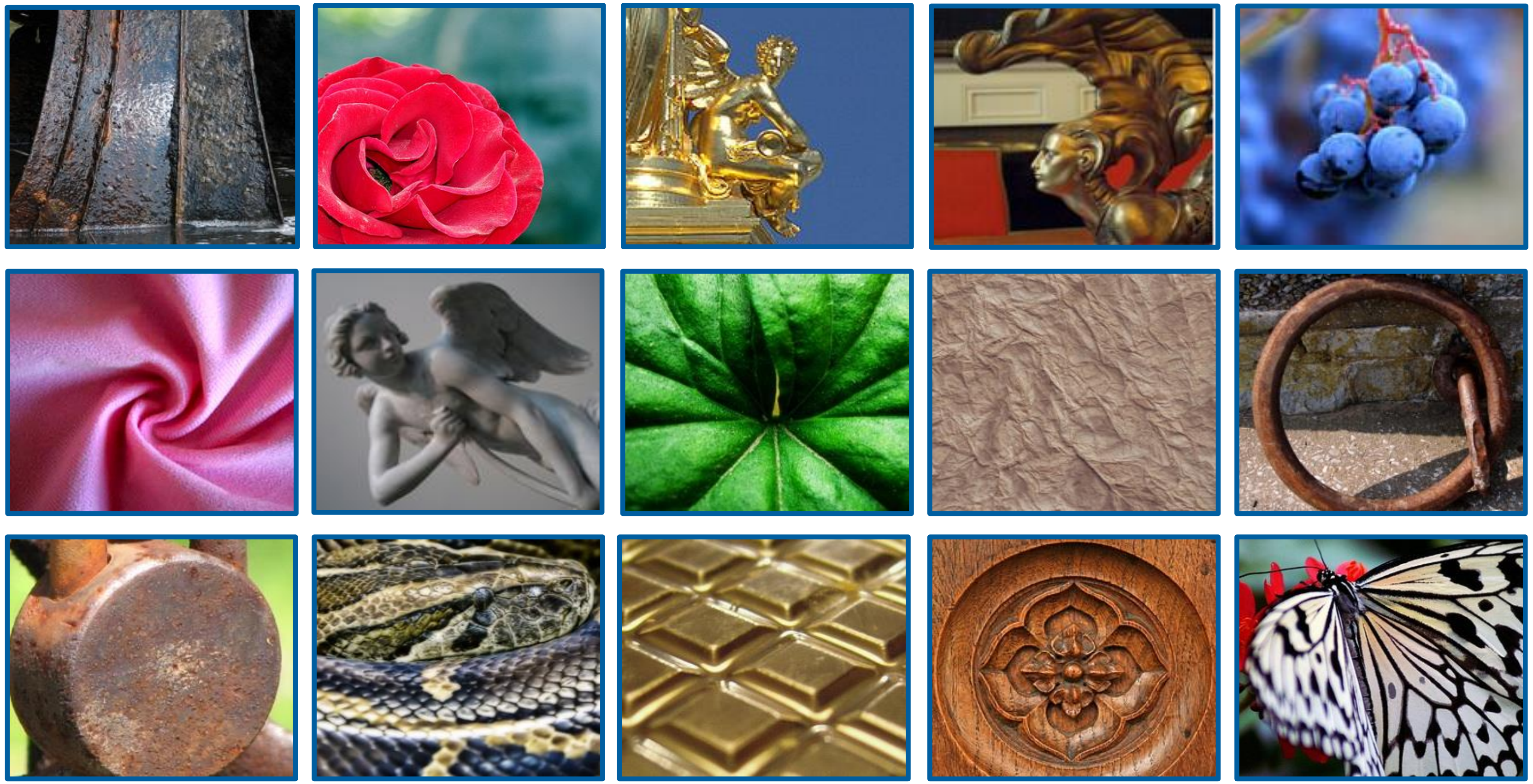
Lights, Material/Reflectance, and Geometry

- The radiance at a pixel is determined by:
  - Lighting (direction & intensity)
  - Material/reflectance
  - Local shape (mainly surface normal direction)



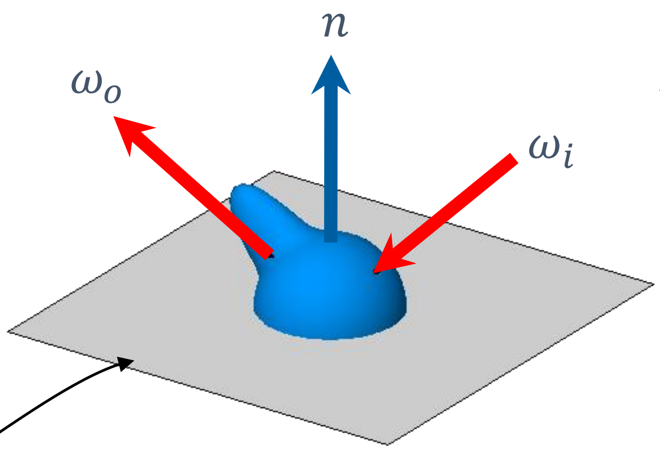
Light at Surfaces

- Many effects when light strikes a surface -- could be:
  - Reflected, refracted, scattered, absorbed, etc.
  - We focus on reflectance today for simplicity



Material/Reflectance

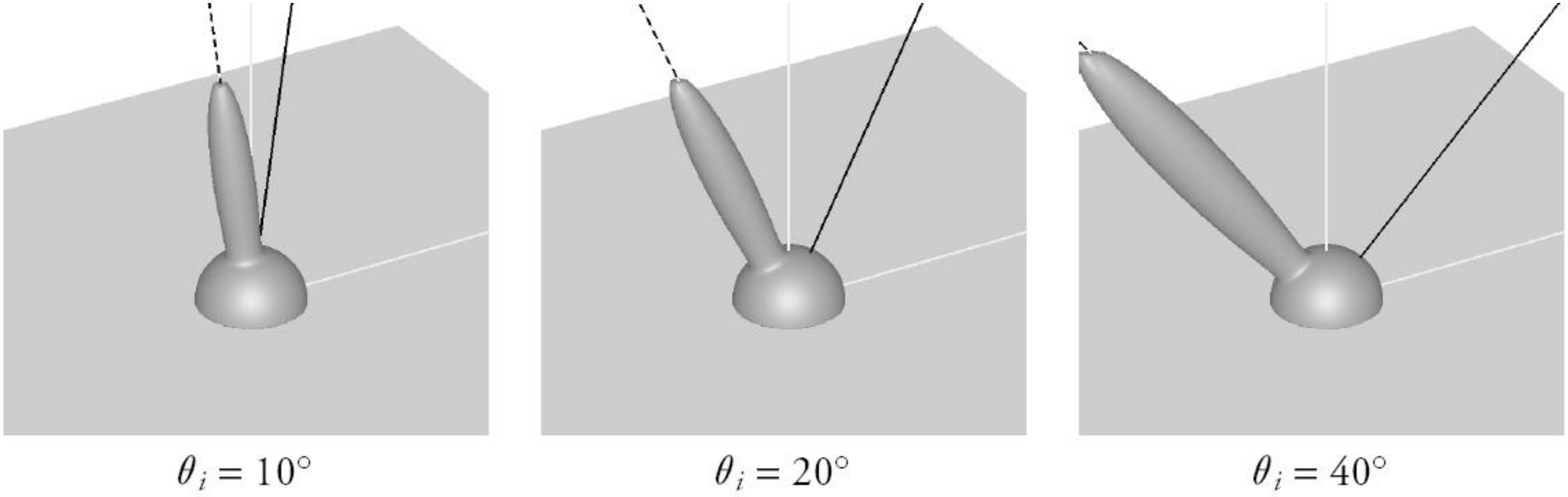
- *Reflectance* is all about the way light interacts with surfaces
- It is an entire field of study on its own
- The most important quantity is the BRDF (Bi-directional Reflectance Distribution Function)
- A BRDF $\rho(\omega_o, \omega_i)$ is a function of two directions
    - Incident lighting direction ω_i
    - Reflected lighting direction ω_o



Both directions are defined in a local coordinate system where typically the surface normal direction n is the z-axis

The BRDF

- It describes how reflected lights are distributed
- It is a pdf function for each fixed ω_i
  (the distribution of reflected energy)
- This distribution changes when the incoming ray changes



visualize a BRDF as a function of ω_o for a fixed ω_i;
the radius along each direction is set to the radiance of the reflected light at that direction.

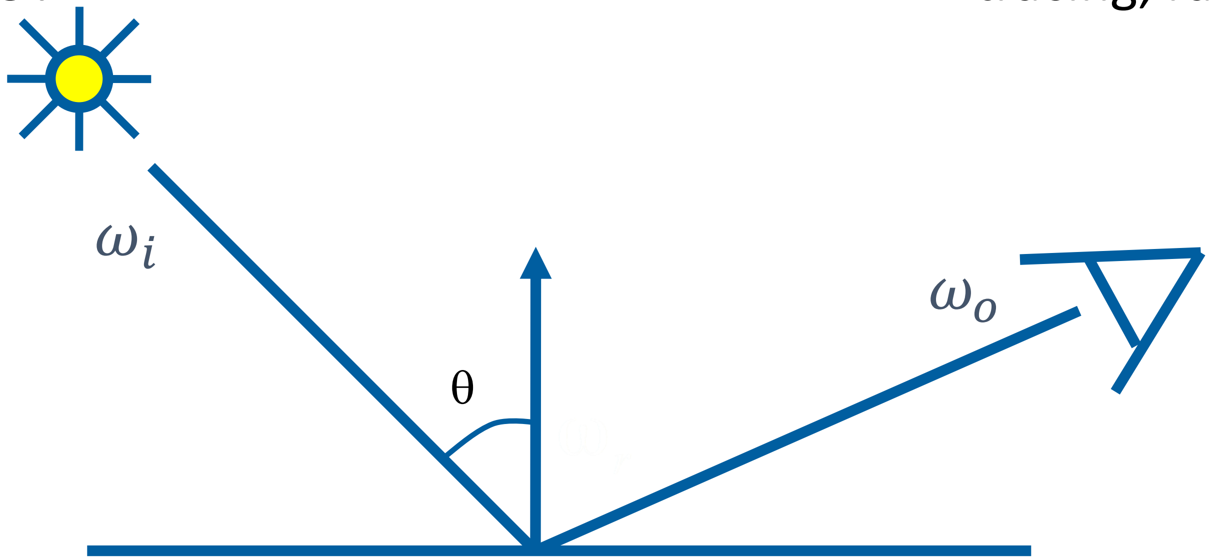
Local Assumption

- BRDFs assume reflectance is local: all light leaving a point depends ONLY on the light arriving at that point
- It ignores many non-local behavior, e.g.
  - Translucency: semi-transparent materials, e.g. marble, human skin, etc
  - Fluoresce: absorbing lighting in one wavelength and emit in a different wavelength
- In this class, we further ignore non-local effects, e.g.
  - Inter-reflection
  - Cast shadow

The Rendering Equation

The basis for computer graphics rendering (e.g. ray tracing, radiosity, etc)

- Why study BRDFs?



$$L_o(\omega_o) = \rho_{bd}(\omega_o, \omega_i) L_i(\omega_i) cos\,\theta_i$$

Reflected Radiance (Pixel Intensity)

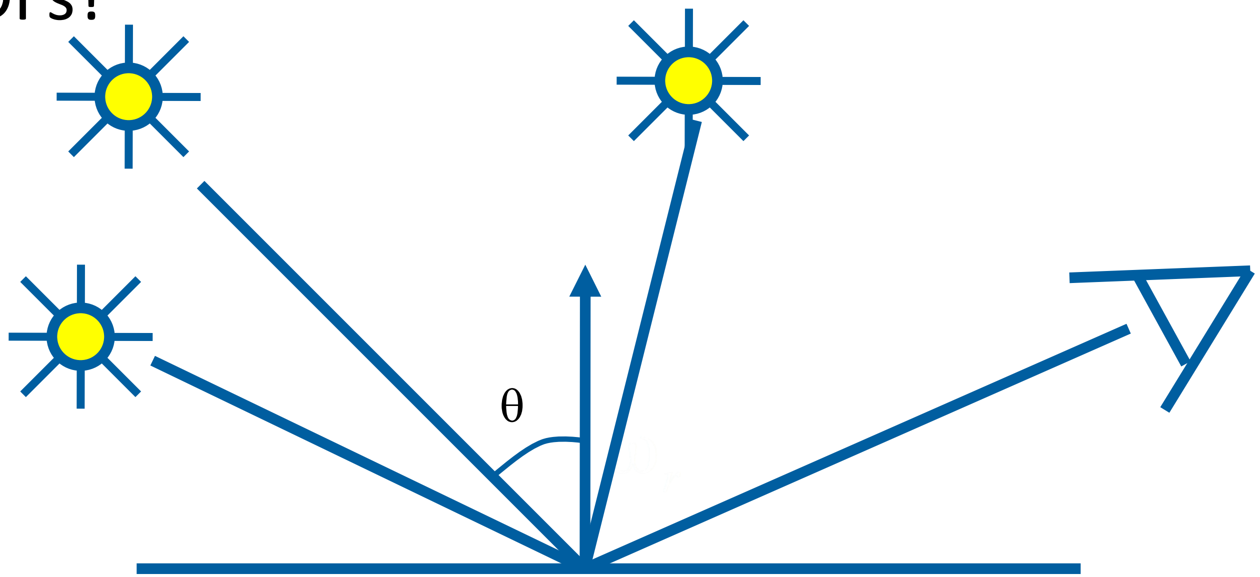
BRDF

Incident radiance (from light source)

Cosine of Incident angle

The Rendering Equation

- Why study BRDFs?



Sum over all light sources

$$L_o(\omega_o) = \sum_i \rho_{bd}(\omega_o, \omega_i) L_i(\omega_i) cos\, \theta_i$$

Reflected Radiance (Pixel Intensity)

BRDF

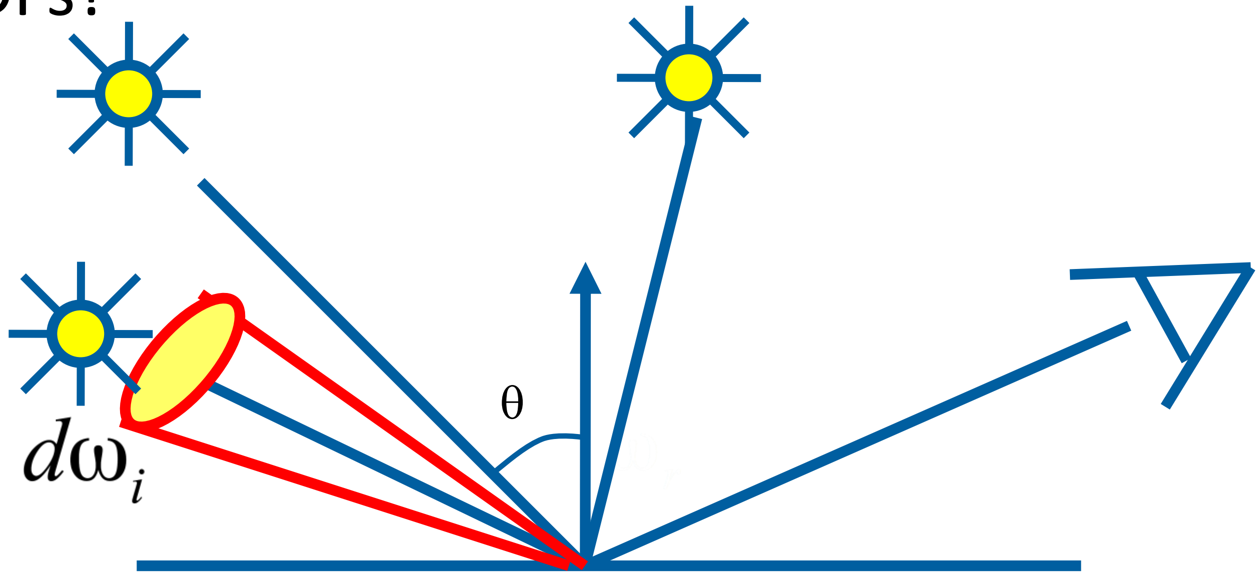
Incident radiance (from light source)

Cosine of Incident angle

The Rendering Equation

The rendering equation consider all points in a scene. What we see here is only one point.

- Why study BRDFs?



Replace sum with integral

$$L_o(\omega_o) = \int_{\Omega} \rho_{bd}(\omega_o, \omega_i) L_i(\omega_i) \cos\theta_i \, d\omega_i$$

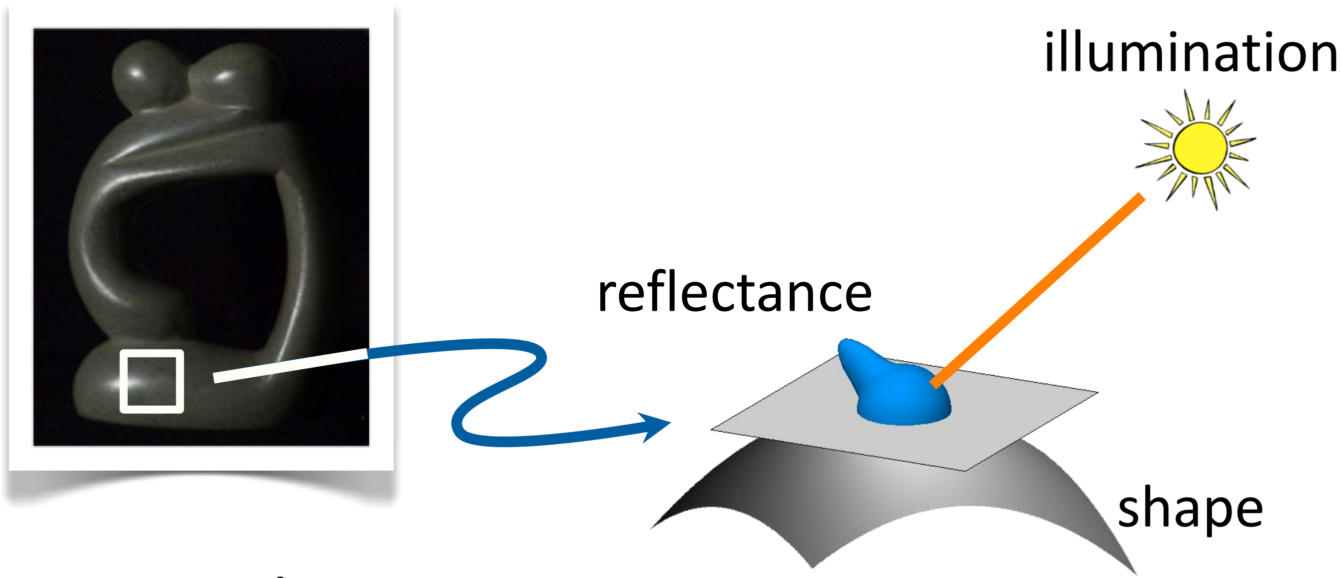
Reflected Radiance (Pixel Intensity)

BRDF

Incident radiance (from light source)

Cosine of Incident angle

Radiometric Image Analysis

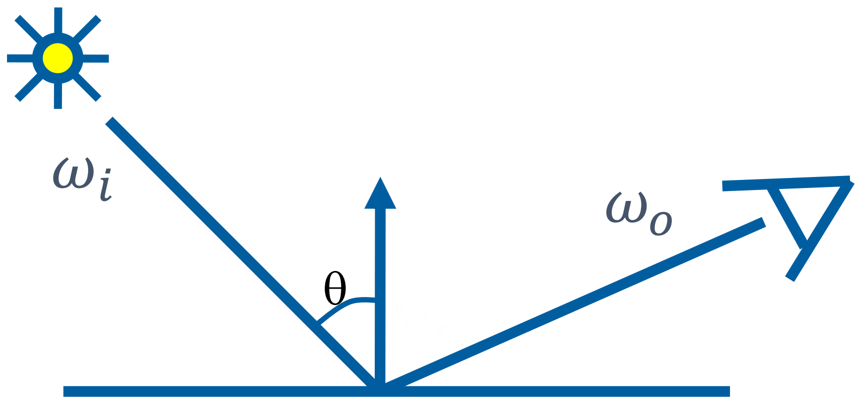


- The rendering equation:
  determine irradiance (pixel values) from shape, lighting, and reflectance
- Radiometric image analysis:
  recover shape, lighting, or reflectance from irradiance (pixel values)

Radiometric Image Analysis

Typical simplification assumptions:

- Single point light source (simplify the light source)
- No inter-reflection, no cast-shadow (ignore global shape effects)
- Simplified BRDF models (simplify the reflectance)

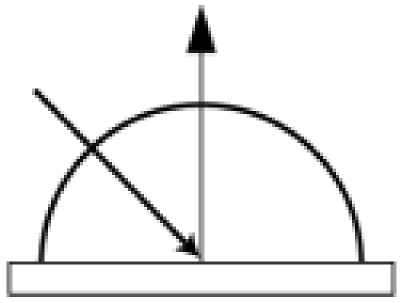


$$L_o(\omega_o) = \rho_{bd}(\omega_o, \omega_i) L_i(\omega_i) cos\,\theta_i$$

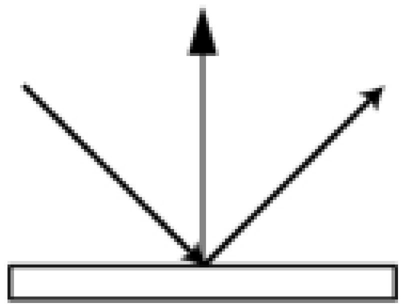
Questions?

Diffuse & Specular Reflection

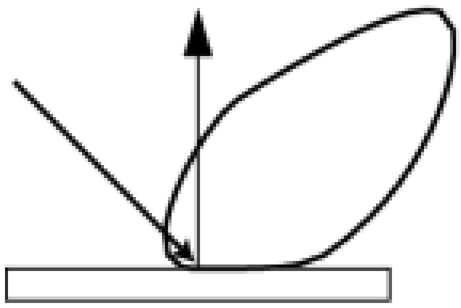
- Diffuse reflection:
  - The surface look the same from all directions (many vision algorithms depend on this!)
  - Matte surfaces
- Specular reflection:
  - The surface look different from different directions (causes troubles to many vision algorithms)
  - Shiny surfaces



ideal diffuse reflection (e.g. walls)



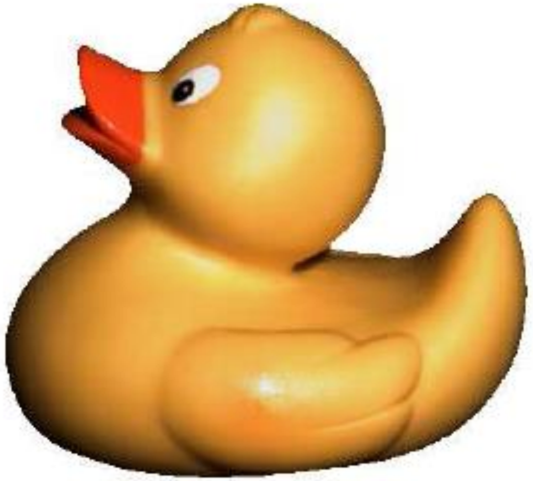
ideal specular reflection (e.g. mirror)



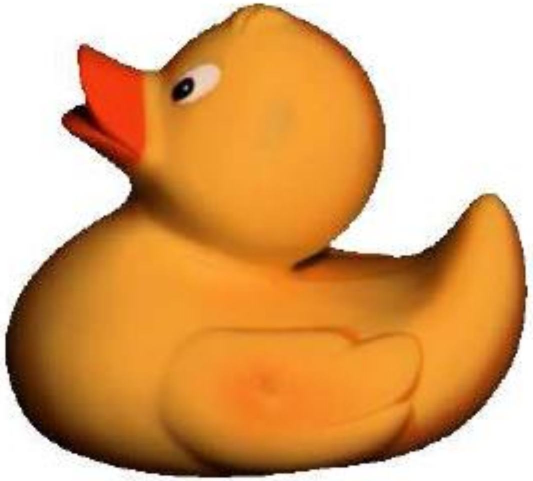
specular reflection (e.g. plastic, metal, porcelain)

Diffuse & Specular Reflection

- Diffuse reflection:
  - has the same color as the object surface
  - is unpolarized
- Specular reflection:
  - has the same color as the light source
  - has the same polarization as the light source



the original image



diffuse reflection

specular reflection

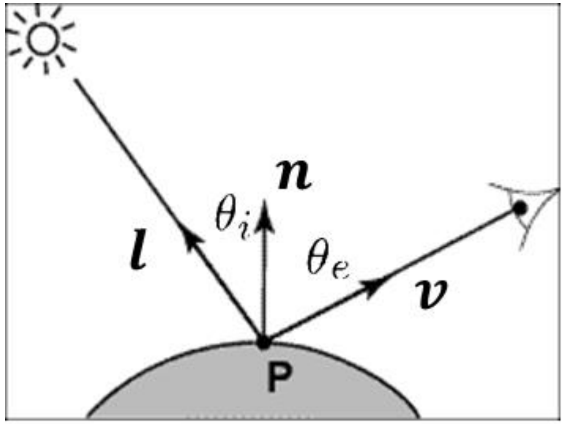
Lambert's Model (Diffuse Reflection)

Johann H. Lambert

- Empirical mathematic model for diffuse reflection
  - Assume the BRDF is a constant $\rho(\omega_o, \omega_i) = \rho_0$
  - Observed Pixel intensity should be

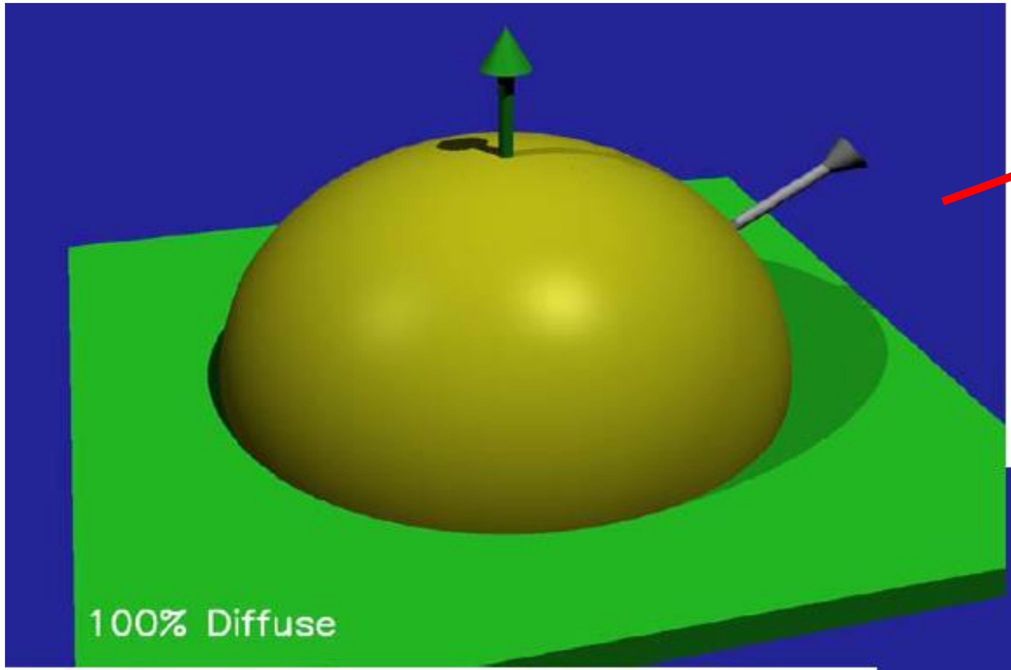
$$L_o = L_i \rho_0 \cos\theta_i = L_i \rho_0 \boldsymbol{n} \cdot \boldsymbol{l}$$

L_i and L_o are intensity of incoming and outgoing light



- Features of this model:
  - A pixel's brightness does not depend on viewing direction
  - Brightness DOES depend on direction of illumination
  - This is the model most commonly used in computer vision (multi-view photo-consistency: the same 3D point look the same across views)

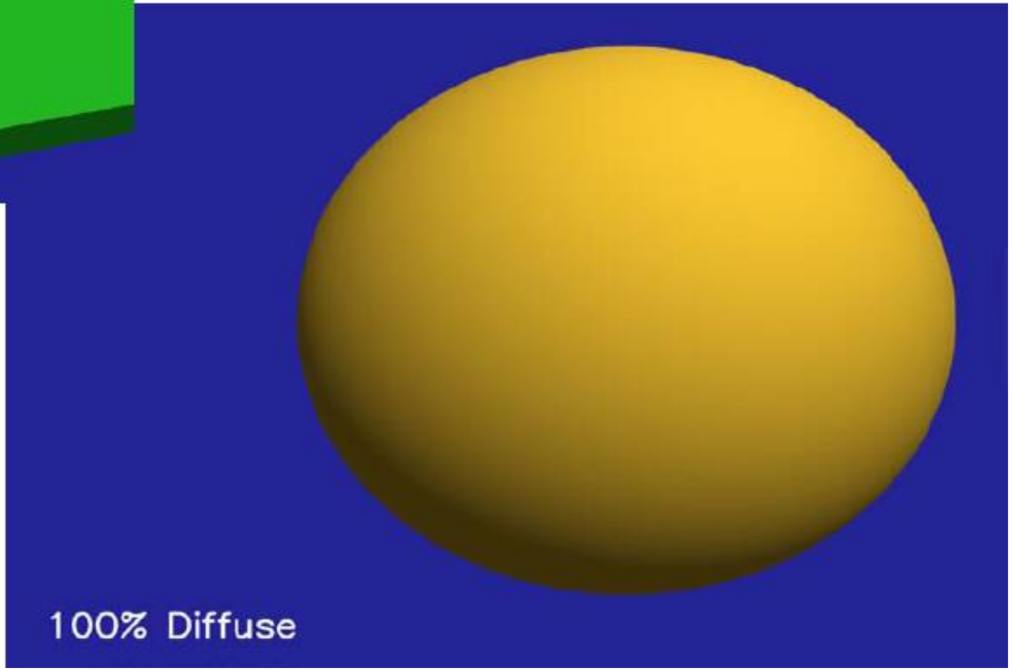
Lambert's Model



plot a BRDF as a function of ω_o for a fixed ω_i

3D plot of reflected intensity

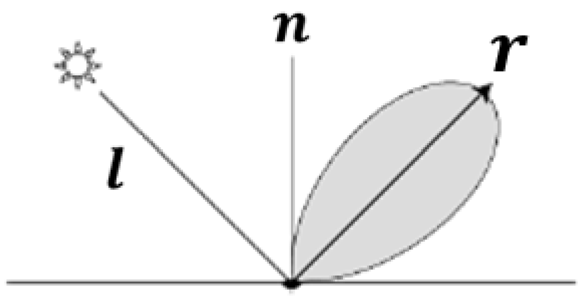
Appearance of a diffuse (dull) sphere



Phong Model (Specular Reflection)

- Mathematic model for specular reflection
  - Assume light is concentrated on the "mirrored direction" $\boldsymbol{r}$, $\boldsymbol{r} = 2(\boldsymbol{n} \cdot \boldsymbol{l})\,\boldsymbol{n} - \boldsymbol{l}$
  - Intensity of light falls off by cosine law
  - Observed Pixel intensity should be

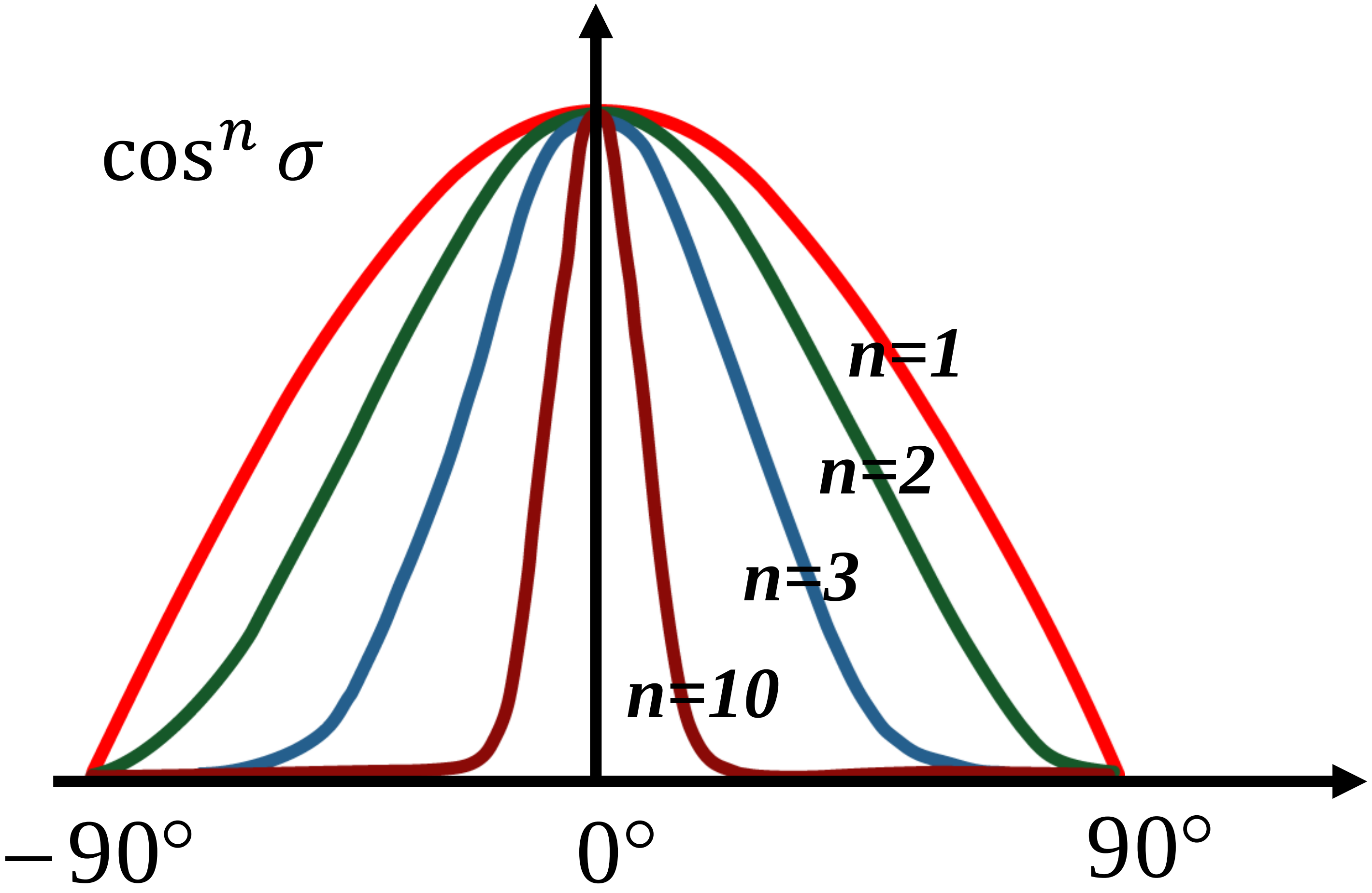
$$L_o = L_i(\boldsymbol{v} \cdot \boldsymbol{r})^n$$



- Features of this model:
  - A pixel's brightness depends on viewing direction
  - This is an empirical model, not physically correct! (e.g. violate energy conservation)

Phong Model

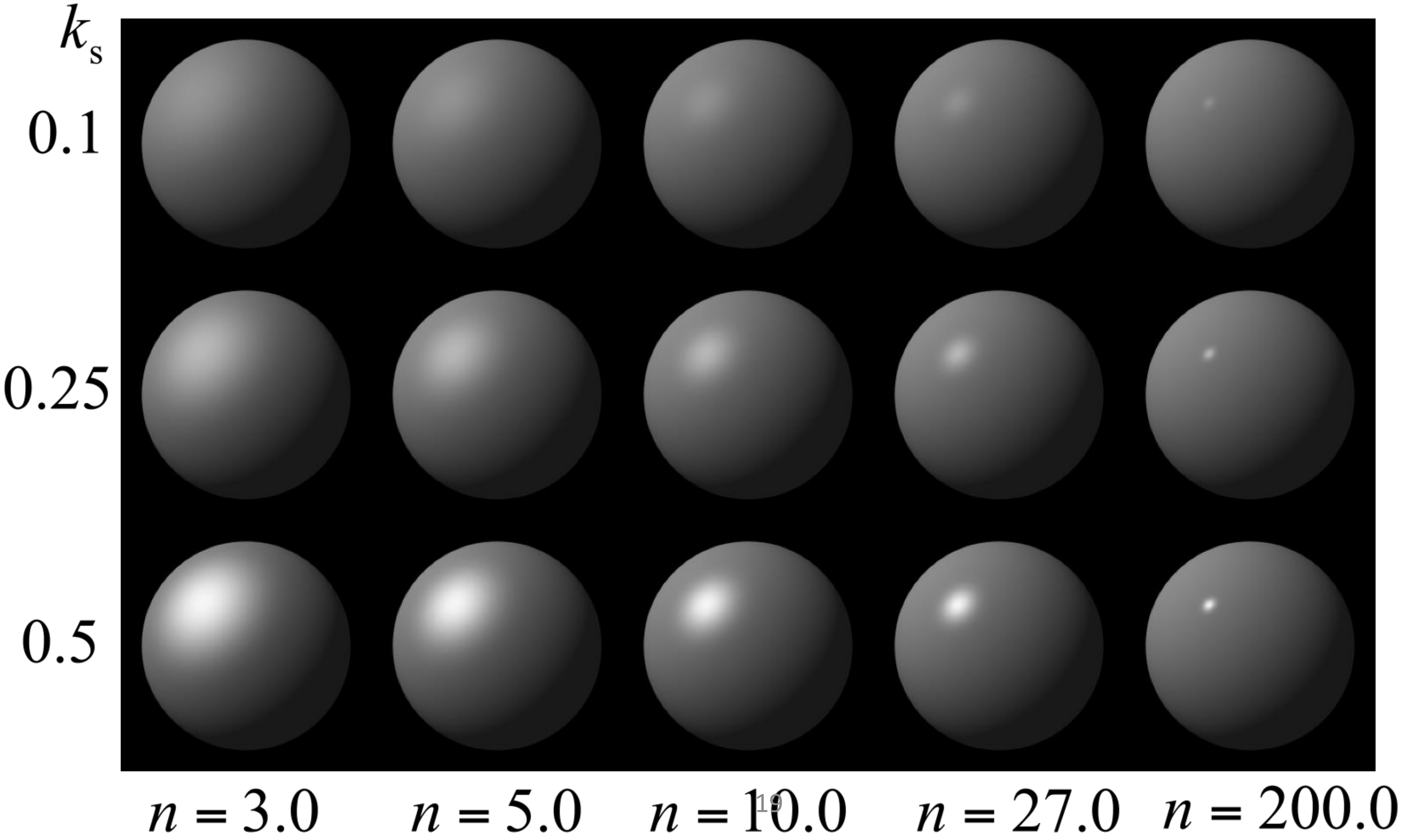
Shininess n controls the size of the highlight spot



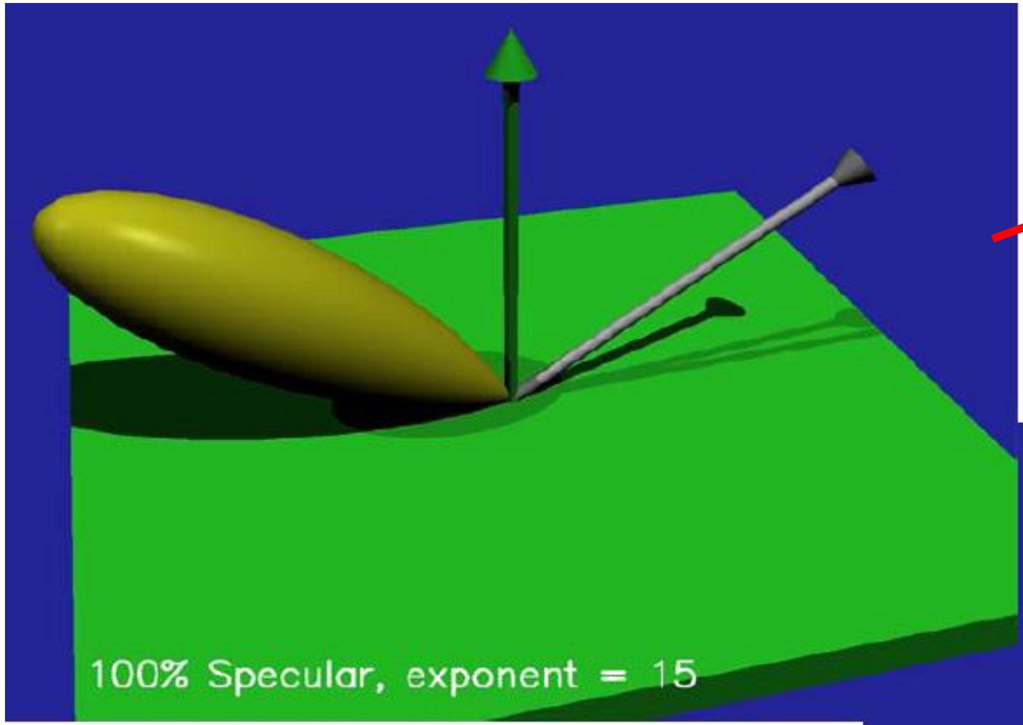
Phong Model

- Linear combination of Lambert's model and Phong Model

$$L_o = k_d \boldsymbol{n} \cdot \boldsymbol{l} + k_s (\boldsymbol{v} \cdot \boldsymbol{r})^n$$



Phong Model

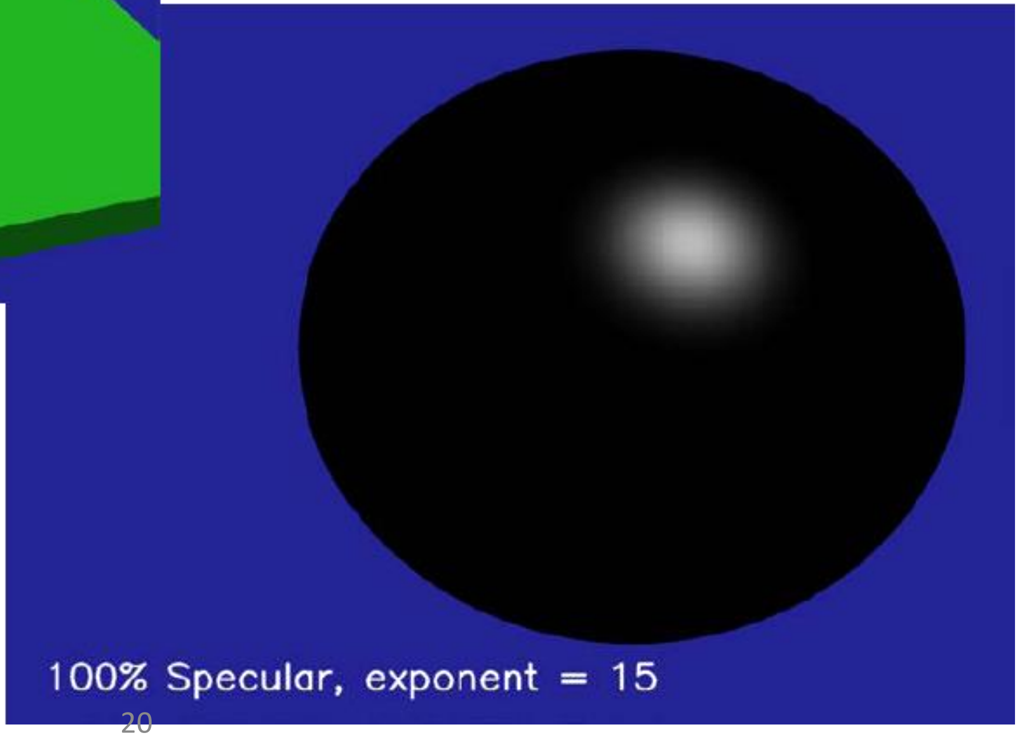


3D plot of reflected intensity

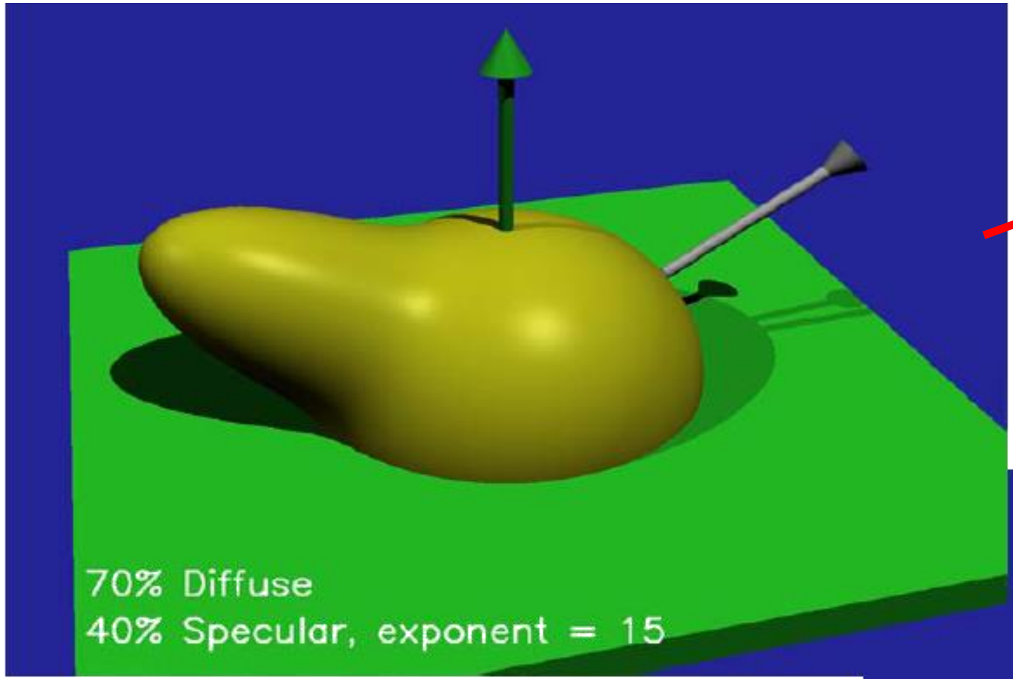
n = 15

plot a BRDF as a function of ω_o for a fixed ω_i

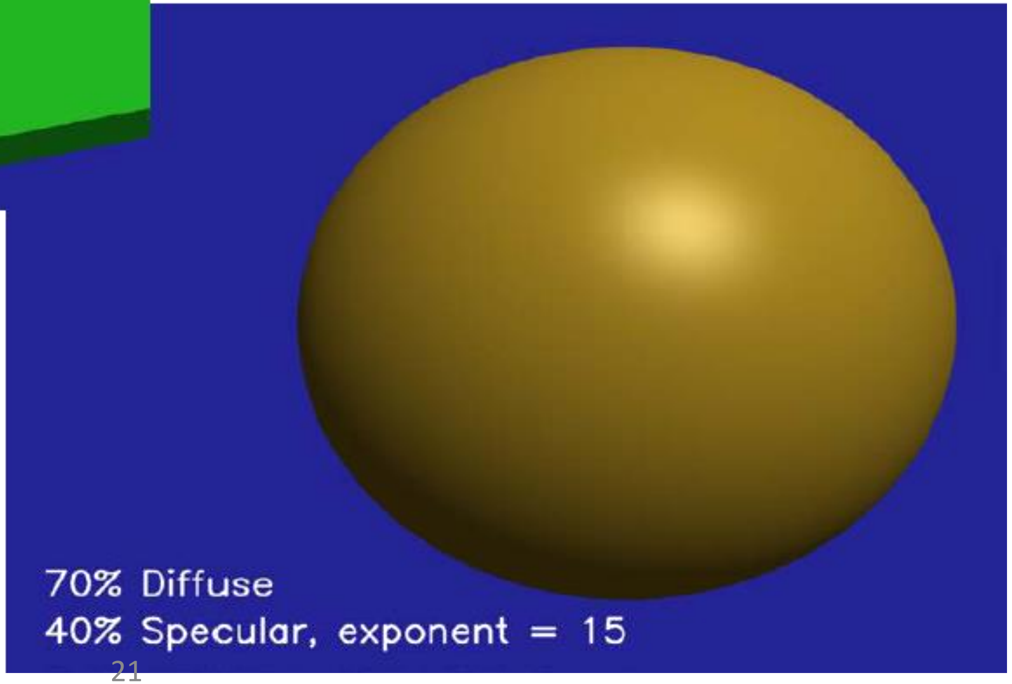
Appearance of a specular sphere



Phong Model



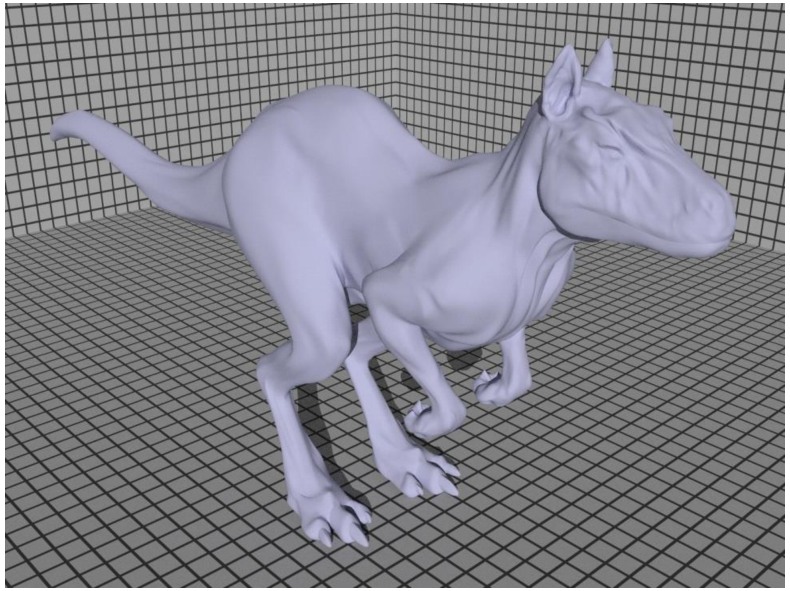
plot a BRDF as a function of ω_o for a fixed ω_i



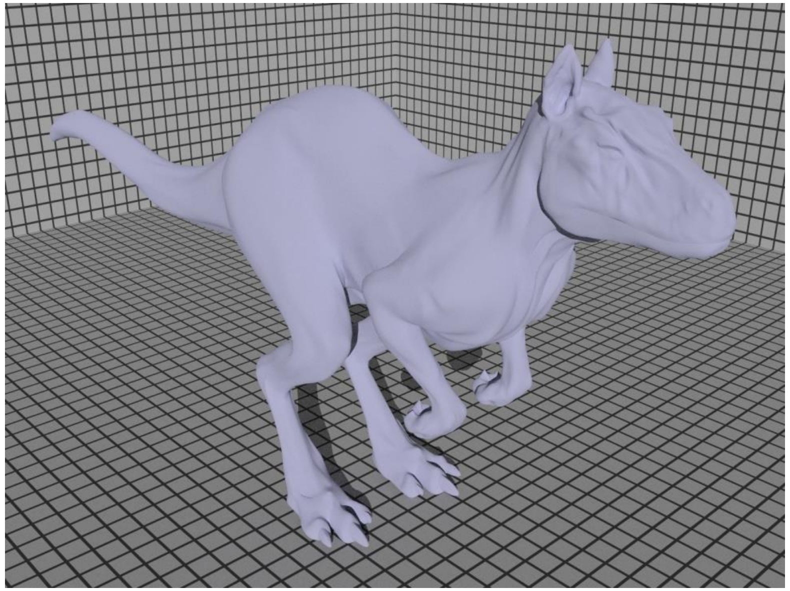
$k_d = 0.7$
$k_s = 0.4$
$n = 15$

Many More Advanced Models

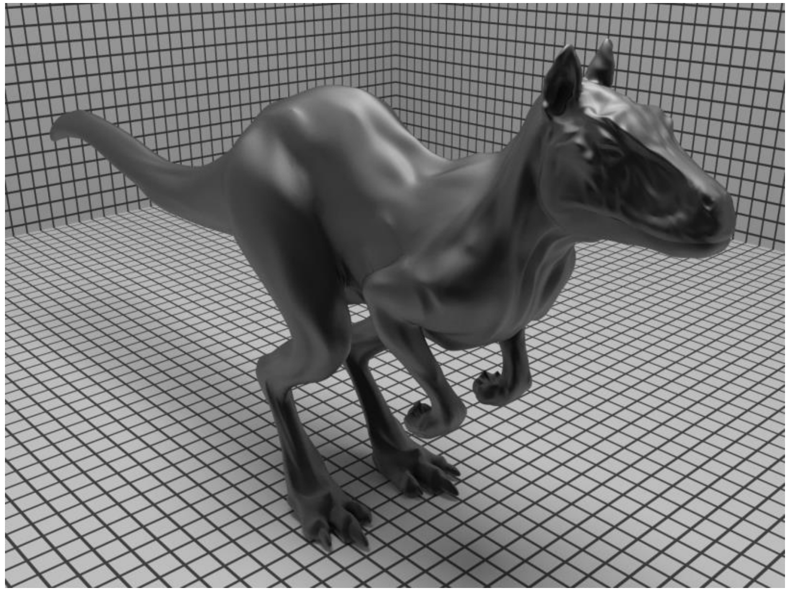
- To describe reflectance more faithfully
  - Oren-Nayar model (a diffuse reflectance model)
  - Cook-Torrance model (a specular reflectance model)
  - Ward's model (a specular reflectance model)



Lambert's model

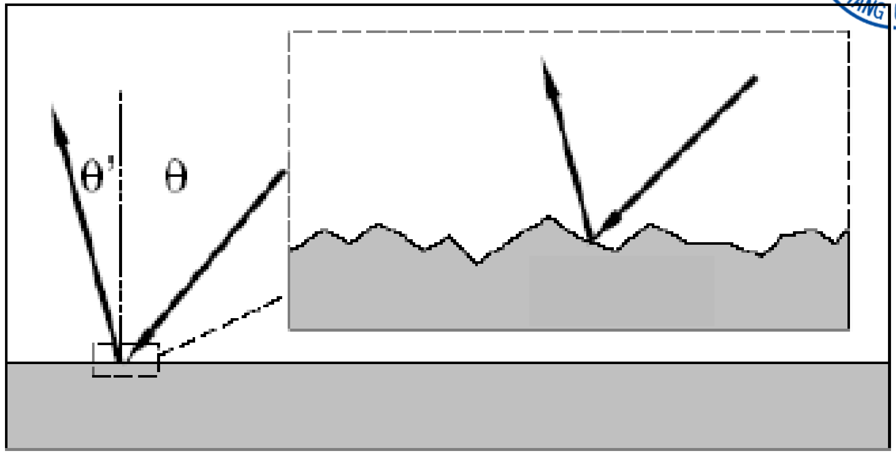


Oren-Nayar model



Cook-Torrance model

Microfacet Theory



- Assumptions:
  - The surface consists of microfacets at the microscopic level.
  - Facets are small enough (not visible) and big enough (no interference & diffraction)
- The aggregate behavior of these facets determines the reflectance.
- Two important factors:
  - How individual facet reflects light?

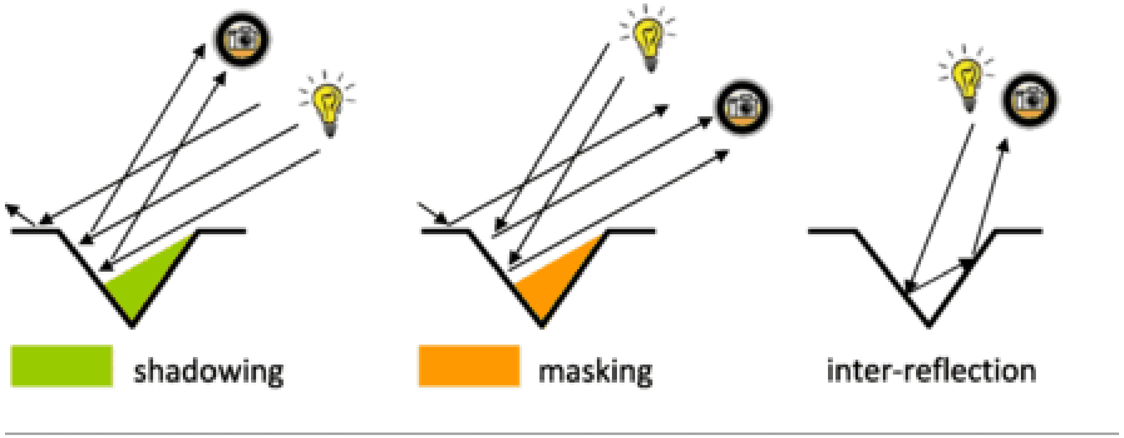
    e.g. perfect mirrors (Cook-Torrance) or perfect Lambertian (Oren-Nayar)

  - What is the distribution of facet orientations (normal distribution function)?

    e.g. Gaussian distribution

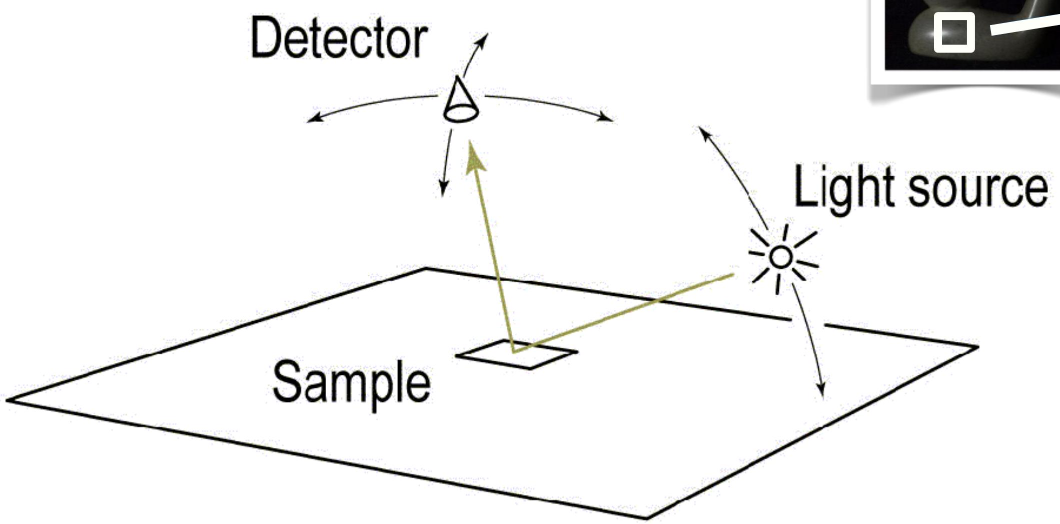
Microfacet Theory

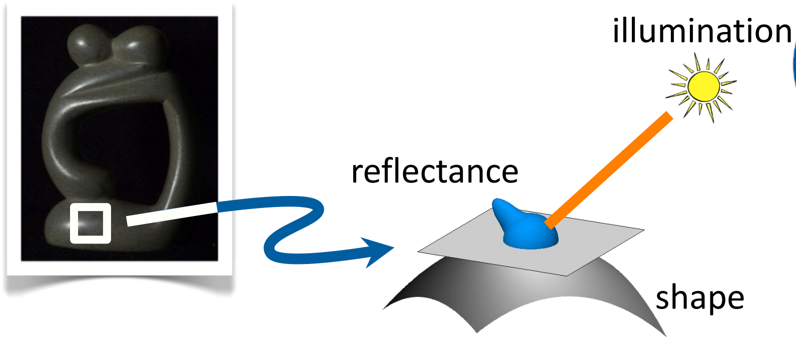
- Example: "V-grooves" on brushed metal surface



Questions?

Capturing BRDFs

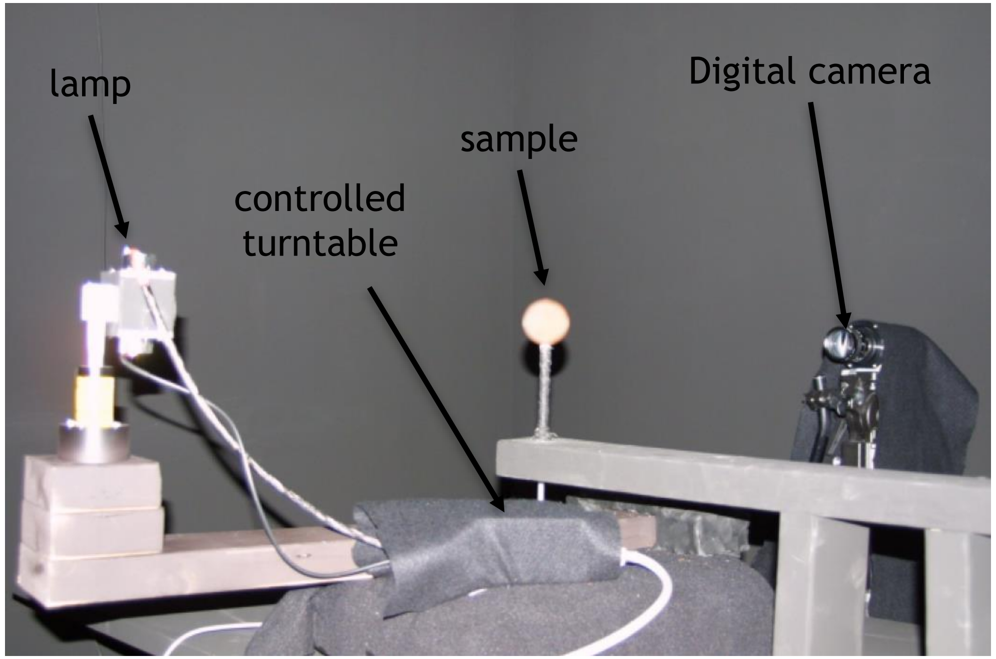


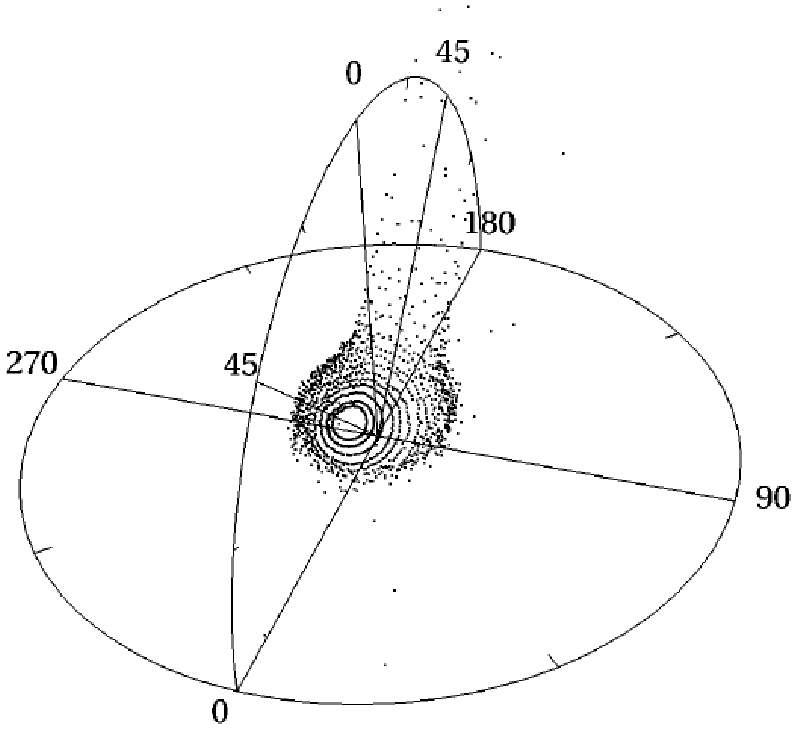


- Radiance (pixel intensity) is determined by shape, lighting, and BRDF
- Capture BRDF from images with known shape and lighting
- Often capture a flat sample with a moving light and camera
  - Need careful calibration of light and camera
    (also a darkroom to avoid inter-reflection, e.g. from the white walls)

More Efficient BRDF Capture

- Use a homogeneous spherical sample of the material
  - A sphere (known shape) contains all kinds of normals
  - So a single image contains many BRDF samples
  - Still need to move the light or camera



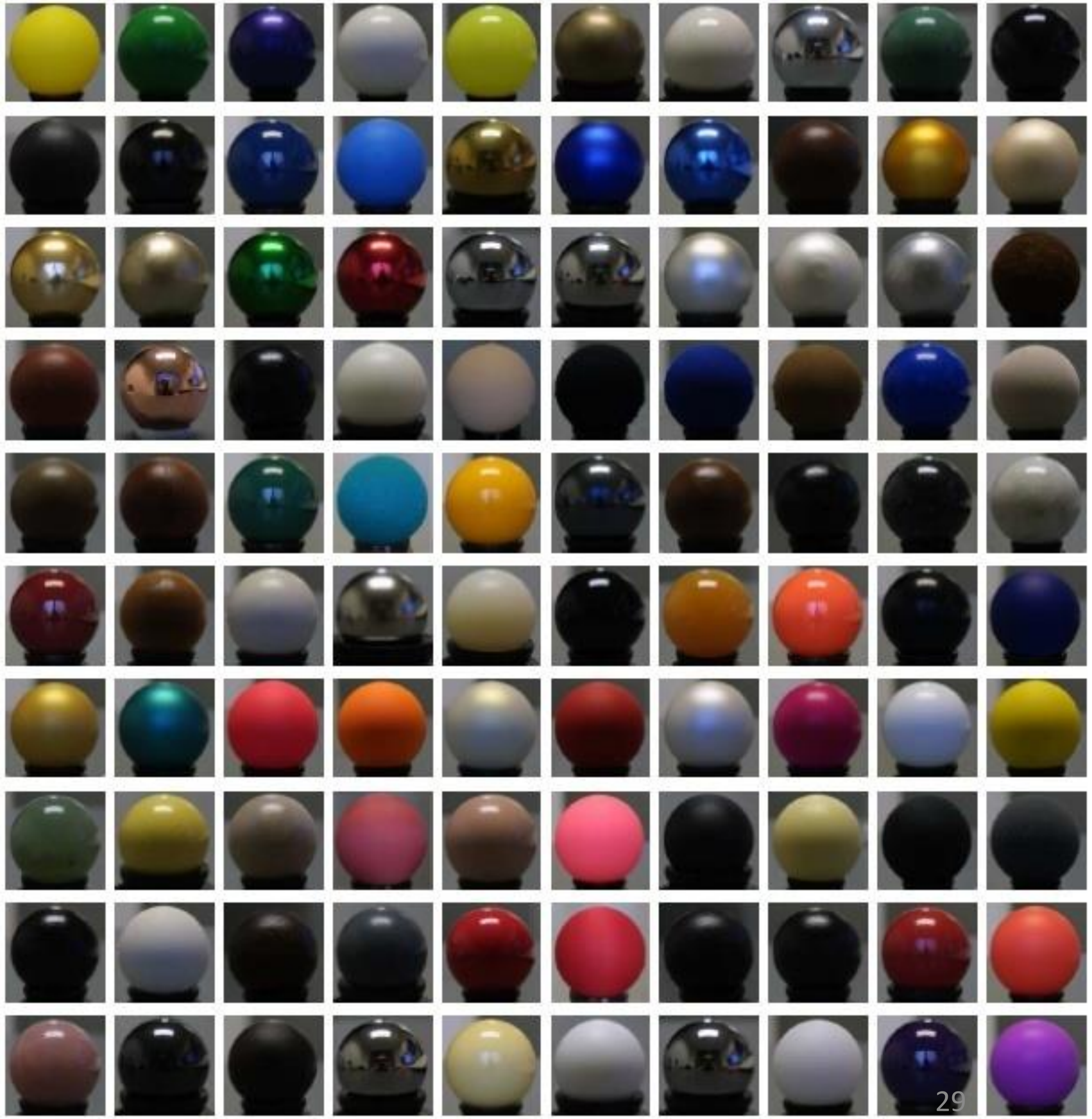


Represent Captured BRDFs

- Tabulated BRDF
  - 4D table $\rho(\omega_i, \omega_o) = \rho(\theta_i, \phi_i, \theta_o, \phi_o)$
  - Not editable

- Measure-then-fit analytic models
  - Fitting can reduce noise but also is limited by the model
  - Non-obvious error metric for fitting – often biased to specular which has large values
  - Difficult optimization – nonlinear; depends on initial guess

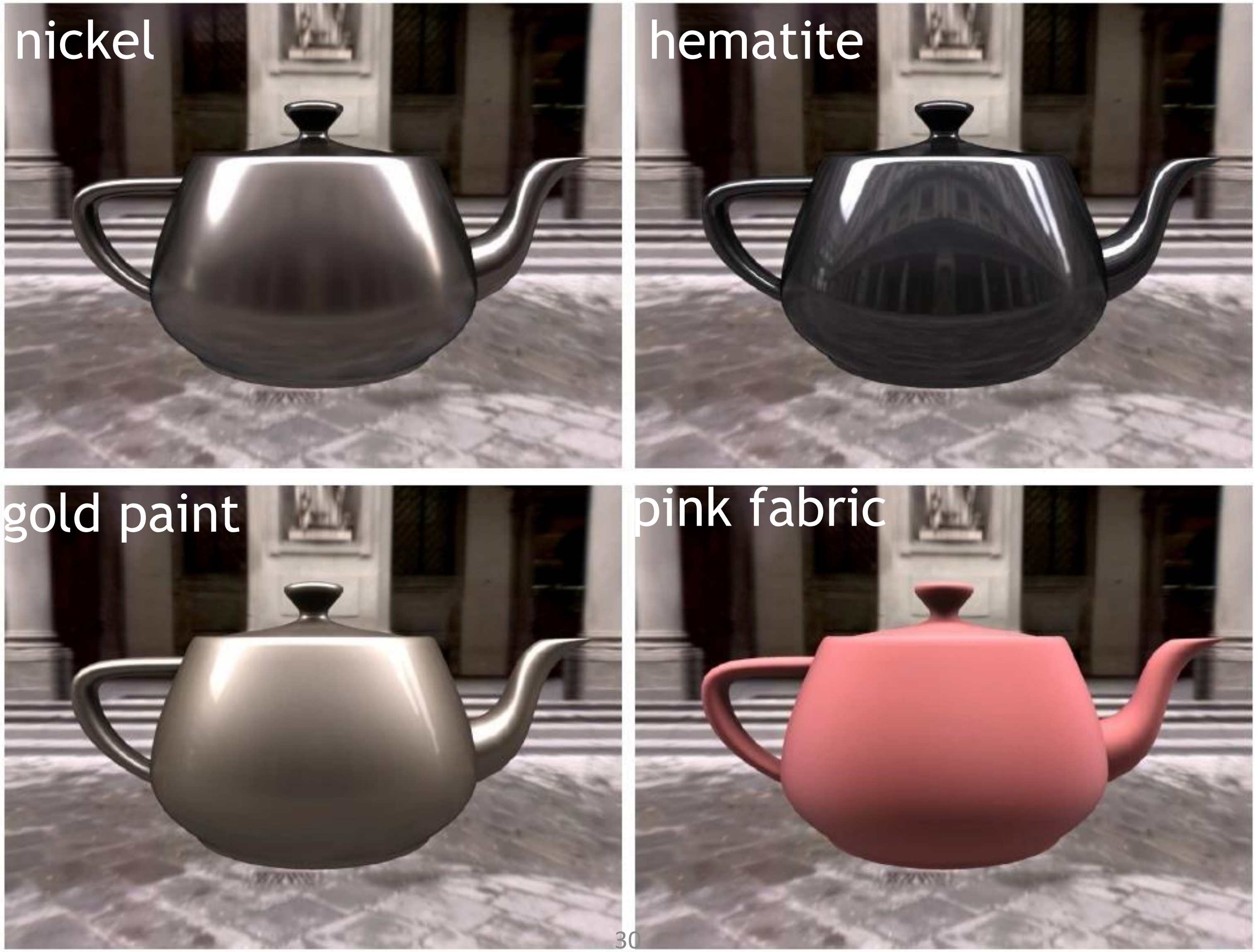
Acquisition



130 materials were scanned;
100 of them shown here

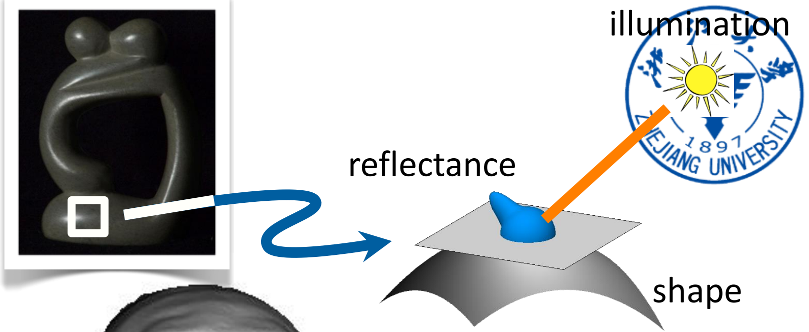
MERL BRDF database, freely available online

Tabulated BRDF

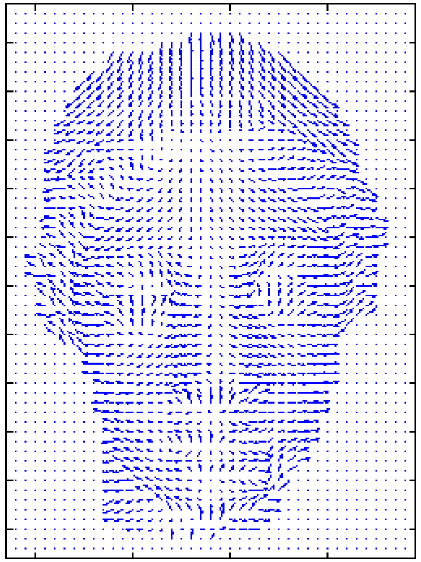


Questions?

Photometric Stereo (Capturing Shapes)



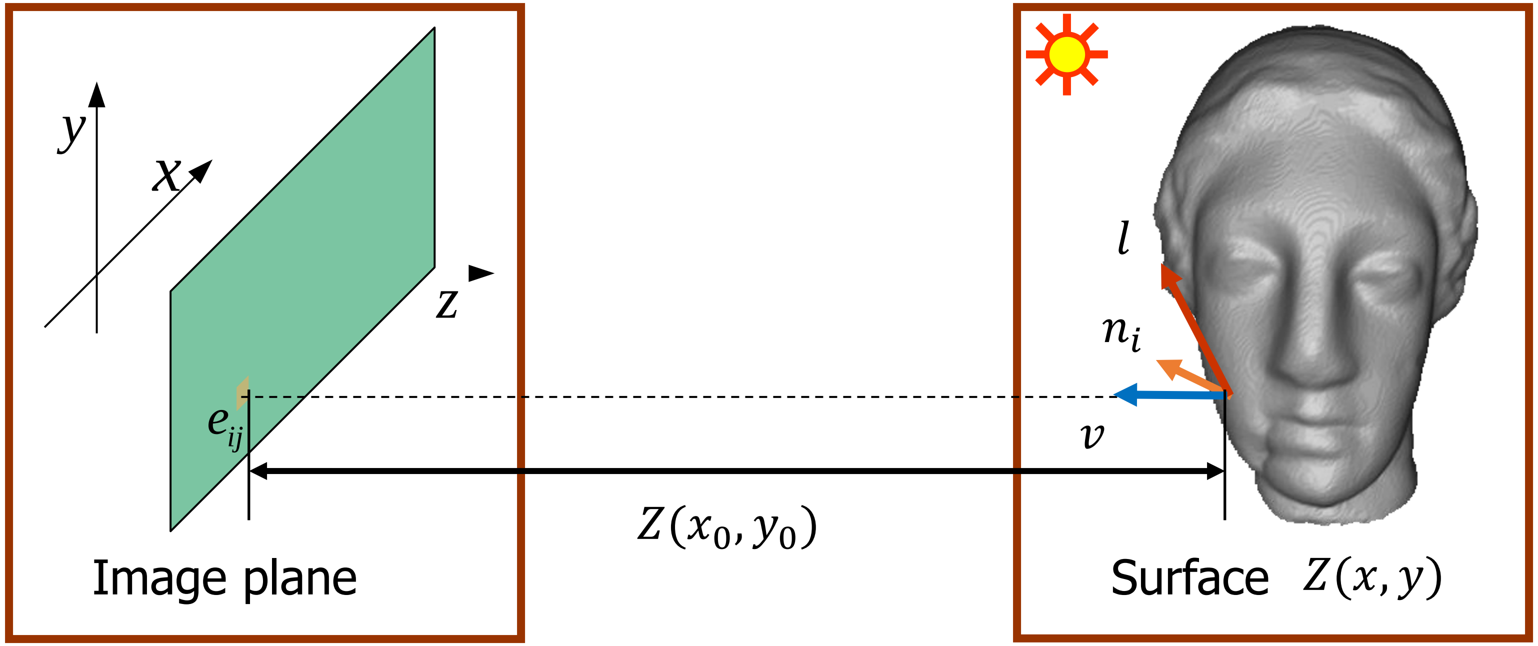
Photometric stereo



Integration

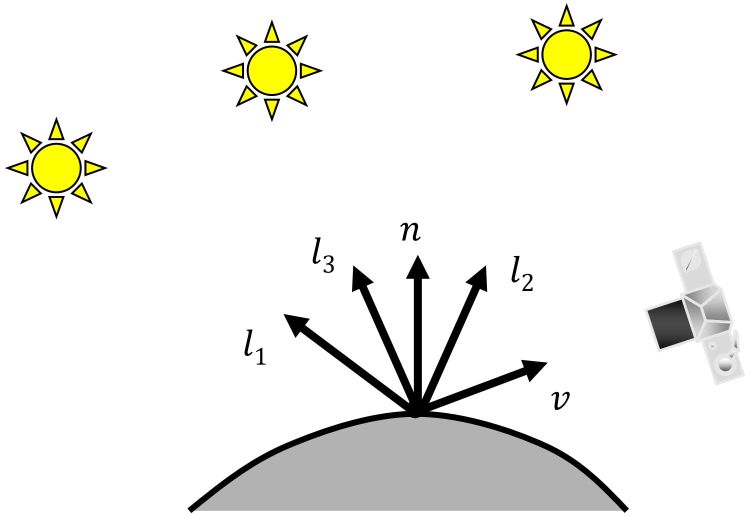
- Radiance (pixel intensity) is determined by shape, lighting, and BRDF
- Capture shape from images with known BRDF and lighting
- Often captured with a fixed camera and a moving light
  - Often assume Lambert’s reflectance (pure diffuse material)
  - Need careful calibration of lighting
    (also a darkroom to avoid inter-reflection, e.g. from the white walls)

Typical Assumptions



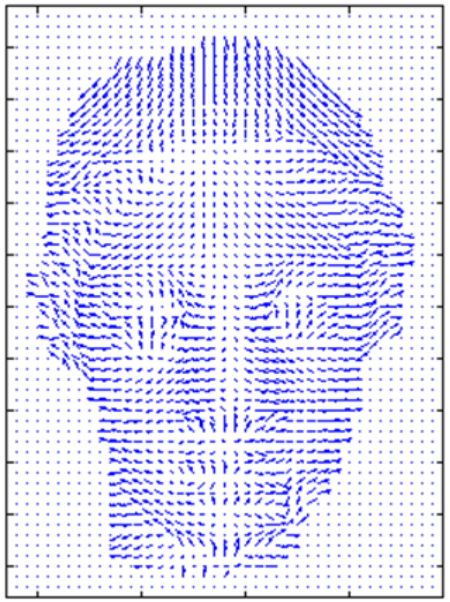
- Lambert’s reflectance model
- Camera centered coordinate system
- Orthographic camera (v is the same for all pixels)
- Directional illumination (l is the same for all pixels)

Lambertian Photometric Stereo



$$I_1 = \rho \boldsymbol{n} \cdot \boldsymbol{l_1}$$
$$I_2 = \rho \boldsymbol{n} \cdot \boldsymbol{l_2}$$
$$I_3 = \rho \boldsymbol{n} \cdot \boldsymbol{l_3}$$

By the Lambert's reflectance model



Write in a matrix equation:

$$\underbrace{\begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix}}_{\substack{\mathbf{I} \\ 3\times 1}} = \underbrace{\begin{pmatrix} \boldsymbol{l}_1^T \\ \boldsymbol{l}_2^T \\ \boldsymbol{l}_3^T \end{pmatrix}}_{\substack{L \\ 3\times 3}} \underbrace{\rho \boldsymbol{n}}_{\substack{\mathbf{b} \\ 3\times 1}} \xrightarrow{L \text{ is known}}$$

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

$$\rho = \|\mathbf{b}\|$$

$$n = \frac{1}{\rho}\mathbf{b}$$

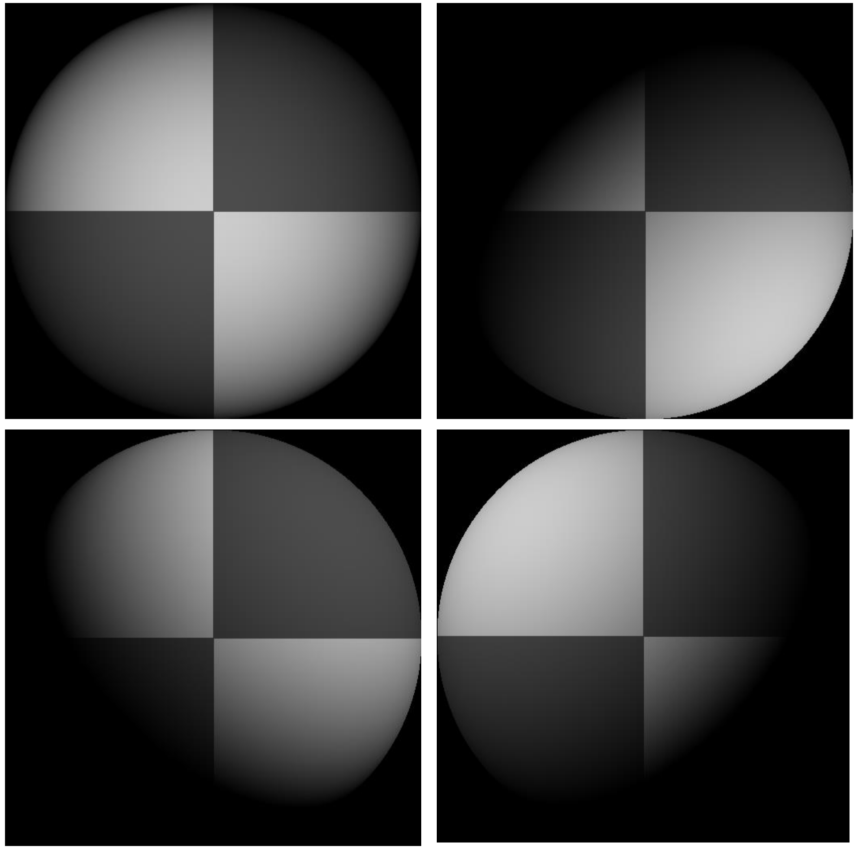
Dealing with Shadows

- The linear formulation, $I = \rho\, \boldsymbol{n} \cdot \boldsymbol{l}$, does not consider shadows
- Pixels in "attached shadows" have zero intensity, $I = 0$, while $\boldsymbol{n} \cdot \boldsymbol{l} < 0$
- A better formulation is nonlinear:

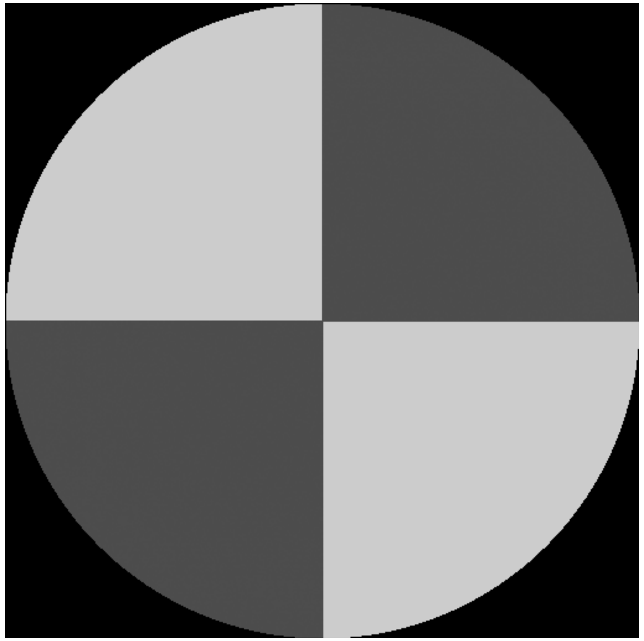
$$I = \max(0, \rho\, \boldsymbol{n} \cdot \boldsymbol{l})$$

  - But $\max(0,\cdot)$ is a nonlinear function, difficult to fit
- A simple way to deal with shadows and keep linear formulation
  - At each pixel, there are multiple observations $I_1, I_2, \cdots I_K$
  - Suppose K is large and the variation in lighting directions is large
    - So there are enough observations in $I_1, I_2, \cdots I_K$ that are free from shadows
  - Thus, we can sort $I_1, I_2, \cdots I_K$ by their values and discard the 20% darkest

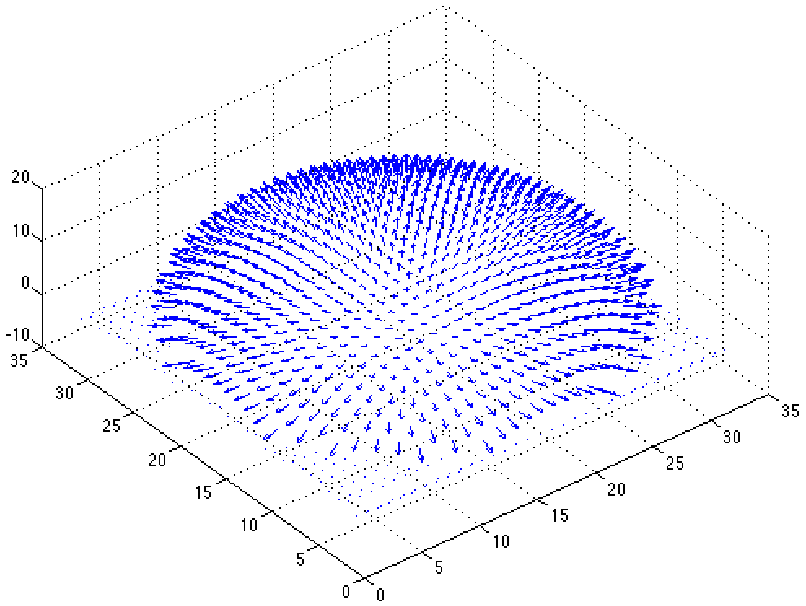
Example Figures



Input images



Albedo ρ



Normal

Questions?

Depth from Normals (Method I)

- Suppose the surface is $(x, y, Z(x, y))$
- The surface normal then should be,

$$\boldsymbol{n}(x, y) = \frac{1}{\sqrt{Z_x^2 + Z_y^2 + 1}} \begin{pmatrix} -Z_x \\ -Z_y \\ 1 \end{pmatrix}$$

- If we denote the normal as,

$$\boldsymbol{n}(x, y) = \begin{pmatrix} n_1(x, y) \\ n_2(x, y) \\ n_3(x, y) \end{pmatrix}$$

- Then we obtain the following partial derivatives:

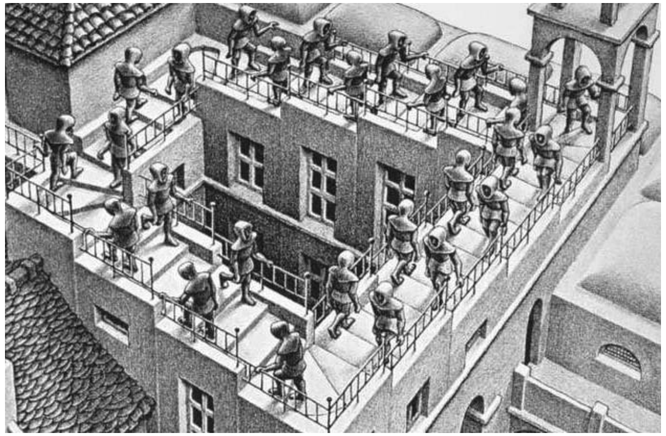
$$Z_x(x, y) = -n_1(x, y)/n_3(x, y)$$

$$Z_y(x, y) = -n_2(x, y)/n_3(x, y)$$

Depth from Normals (Method I)

- We can now recover the surface height at any point by integration along some path, e.g.

$$Z(x,y)=\int_0^x Z_x(s,y)ds+\int_0^y Z_y(x,t)dt+c$$



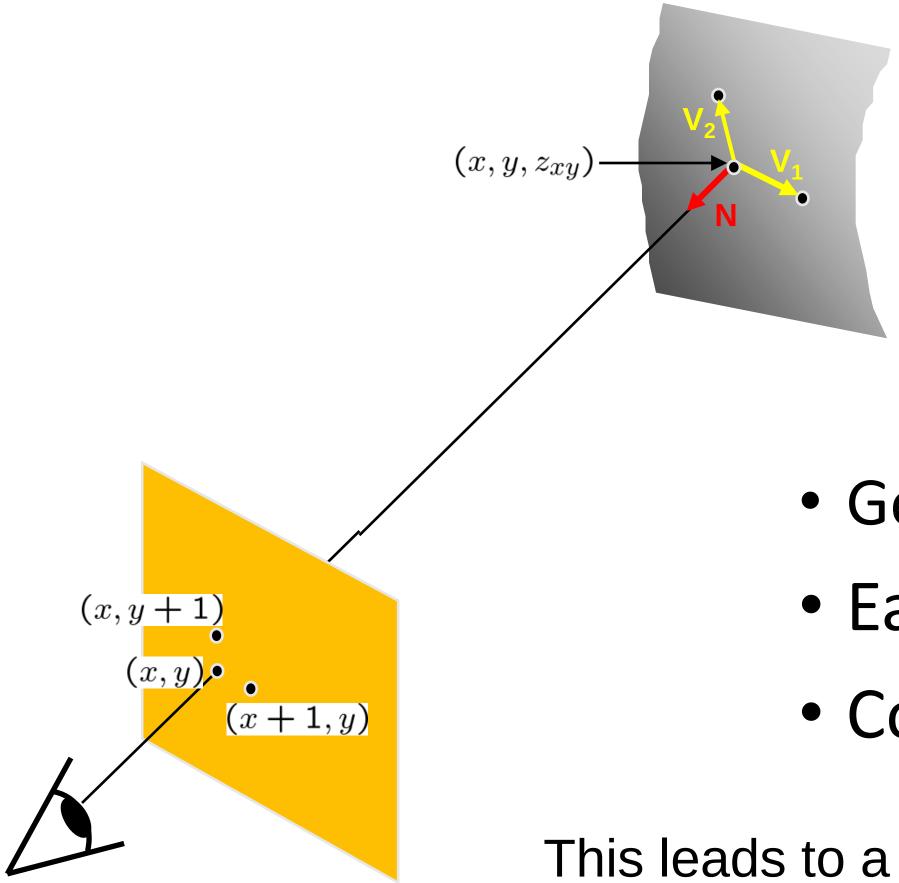
- This method never works on real data. Why?
- The recovered normal is too noisy!
- Recall that mixed second partials are equal --- this gives us a **check.** We must have:

$$\frac{\partial Z_x(x,y)}{\partial y}=\frac{\partial Z_y(x,y)}{\partial x}$$

  (or they should be similar, at least)

- Due to imaging and estimation noise, this almost never happens.

Depth from Normals (Method II)



- The tangent vector $\boldsymbol{v}_1$ is perpendicular to $\boldsymbol{n}$

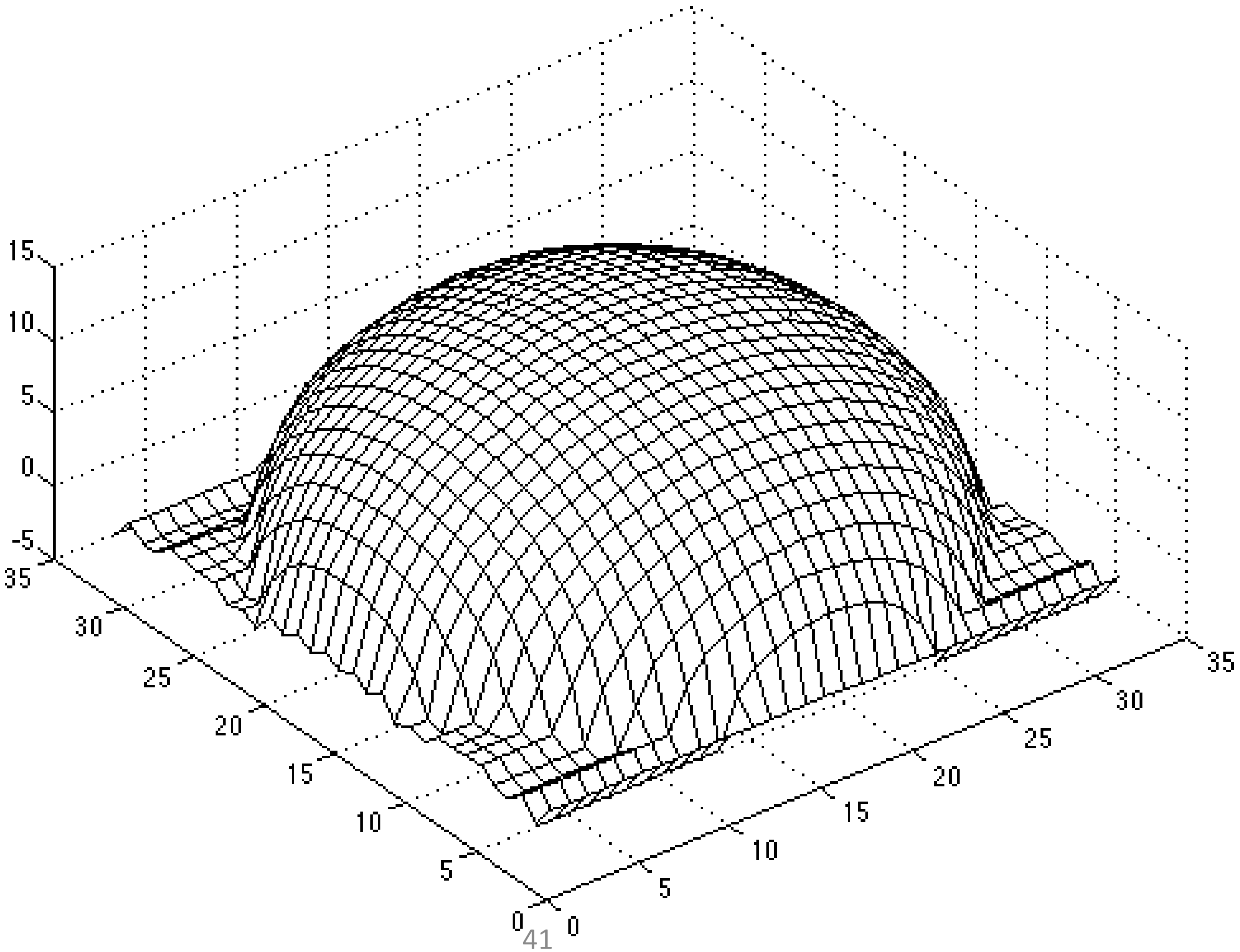
$$\begin{aligned}\boldsymbol{v}_1 &= \big(x+1, y, Z(x+1, y)\big) - (x, y, Z(x, y)) \\ &= (1, 0, Z(x+1, y) - Z(x, y)\ )\end{aligned}$$

$$\begin{aligned}0 &= \boldsymbol{n} \cdot \boldsymbol{v}_1 \\ &= (n_1, n_2, n_3) \cdot (1, 0, Z(x+1, y) - Z(x, y)) \\ &= n_1 + n_3(Z(x+1, y) - Z(x, y))\end{aligned}$$

- Get a similar equation for $\boldsymbol{v}_2$
- Each normal gives two linear constraints on Z
- Compute Z values by solving a matrix equation

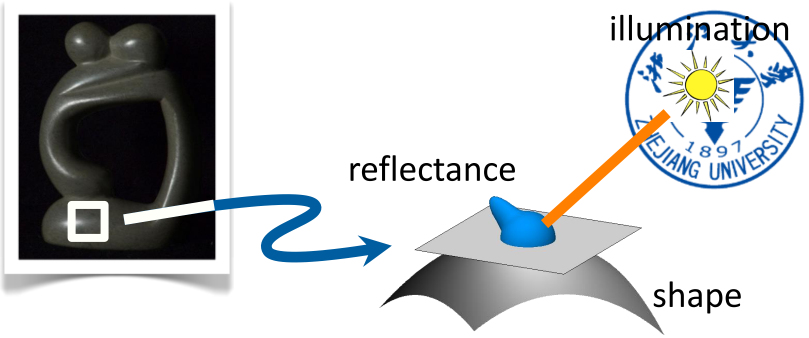
This leads to a large sparse linear equation.
Often solved by the Conjugated Gradient algorithm.

Surface Recovered



Questions?

Capturing Lighting

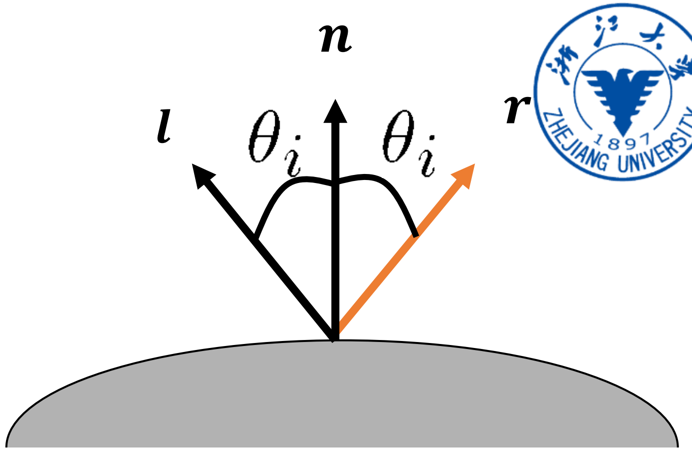


- Radiance (pixel intensity) is determined by shape, lighting, and BRDF
- Capture lighting from images with known BRDF and shape
- Often captured with mirror spheres
  - Known shape (sphere) and known BRDF (mirror)

Capture a Directional Light

- For example, to get the matrix L in photometric stereo (page 34)
- Capture a shiny sphere in the scene
  - the location of the highlight tells the lighting direction

Capture a Directional Light

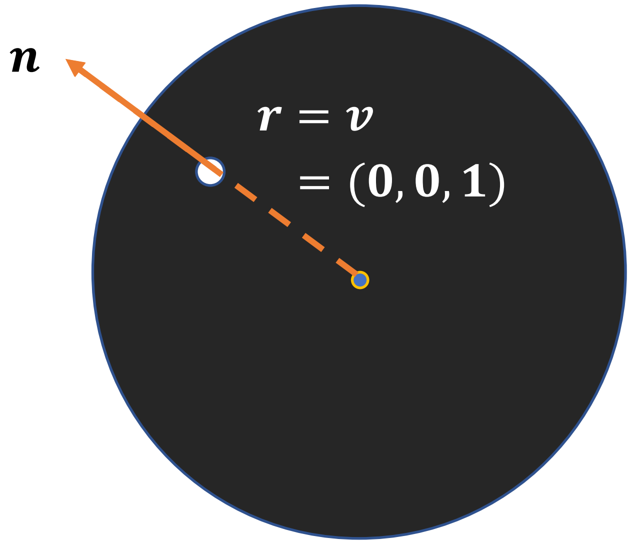


$$\boldsymbol{l} = 2(\boldsymbol{n} \cdot \boldsymbol{r})\boldsymbol{n} - \boldsymbol{r}$$

- For a mirror sphere, light is reflected about $\boldsymbol{n}$

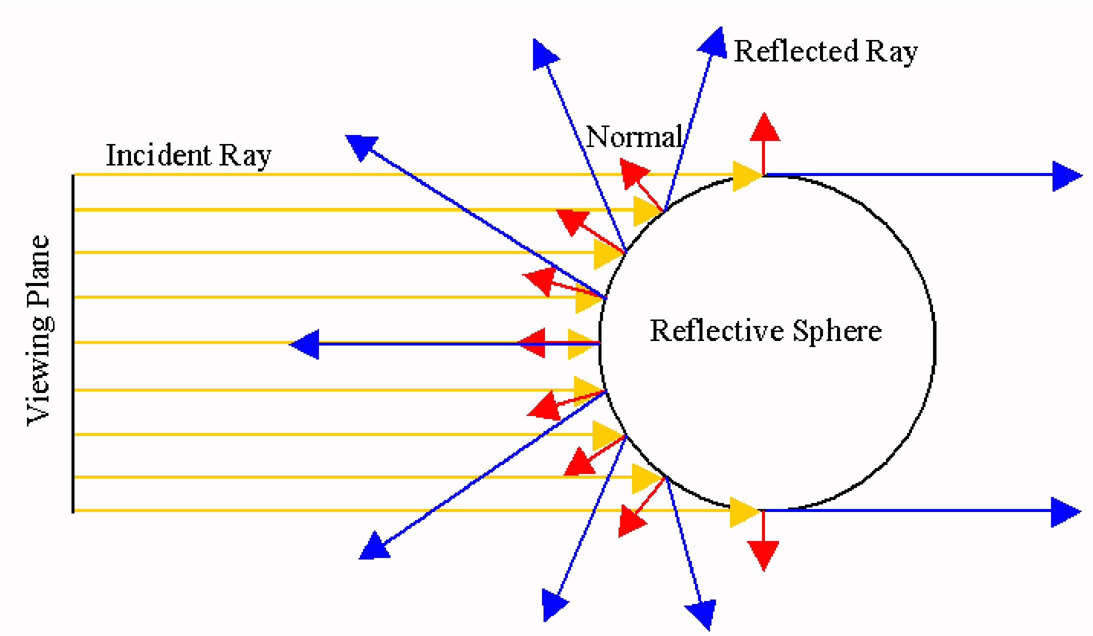
$$L_o = \begin{cases} L_i & \text{if } \boldsymbol{v} = \boldsymbol{r} \\ 0 & \text{otherwise} \end{cases}$$

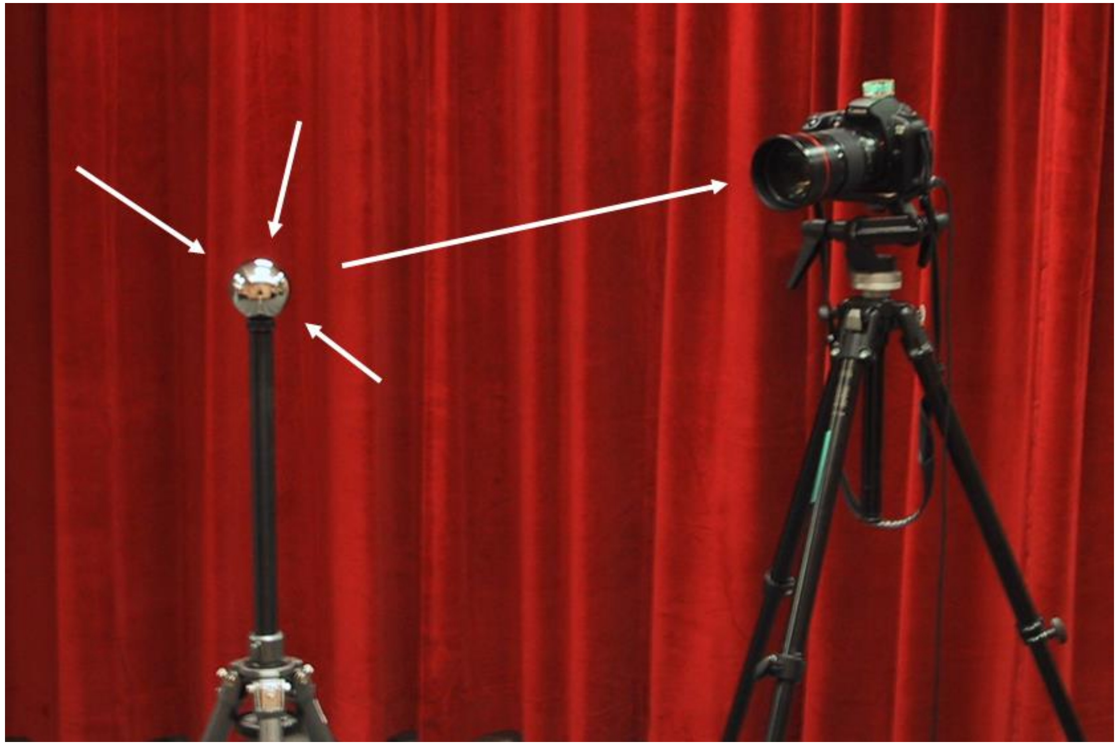
- The light source is seen at a pixel where $\boldsymbol{v} = \boldsymbol{r}$
- Assume orthographic camera
  - $\boldsymbol{v} = (0,0,1)$ for all pixels
- So if we further know $\boldsymbol{n}$, we can compute $\boldsymbol{l}$
  - normal of each point on a sphere can be determined
  - (by some simple geometry, try to derive it yourself)



Capture an Environment Light

- Trace back all light rays reflected from a mirror sphere
- Still assume orthographic camera

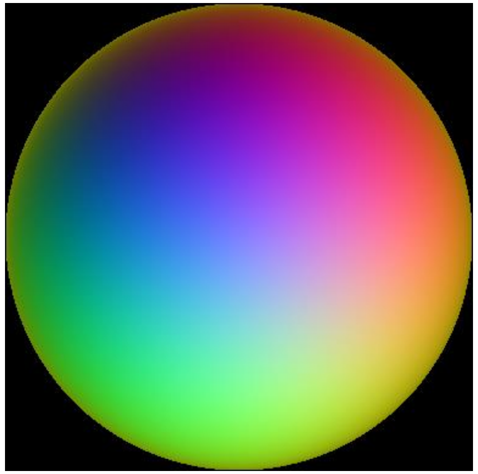




Mirror ball -> equirectangular

Mirror ball

Normals



Reflection vectors

Equirectangular (longitude & latitude)

Applications of Captured Lighting

- Rendering virtual objects into real scenes (e.g. in AR)

from Terminator 2

HDR Environment Lighting

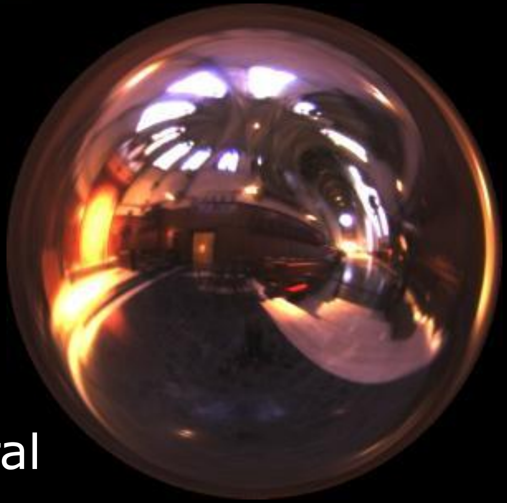
- HDR is needed so that light probes capture full range of radiance

Real-World HDR Lighting Environments

Funston
Beach

Eucalyptus
Grove

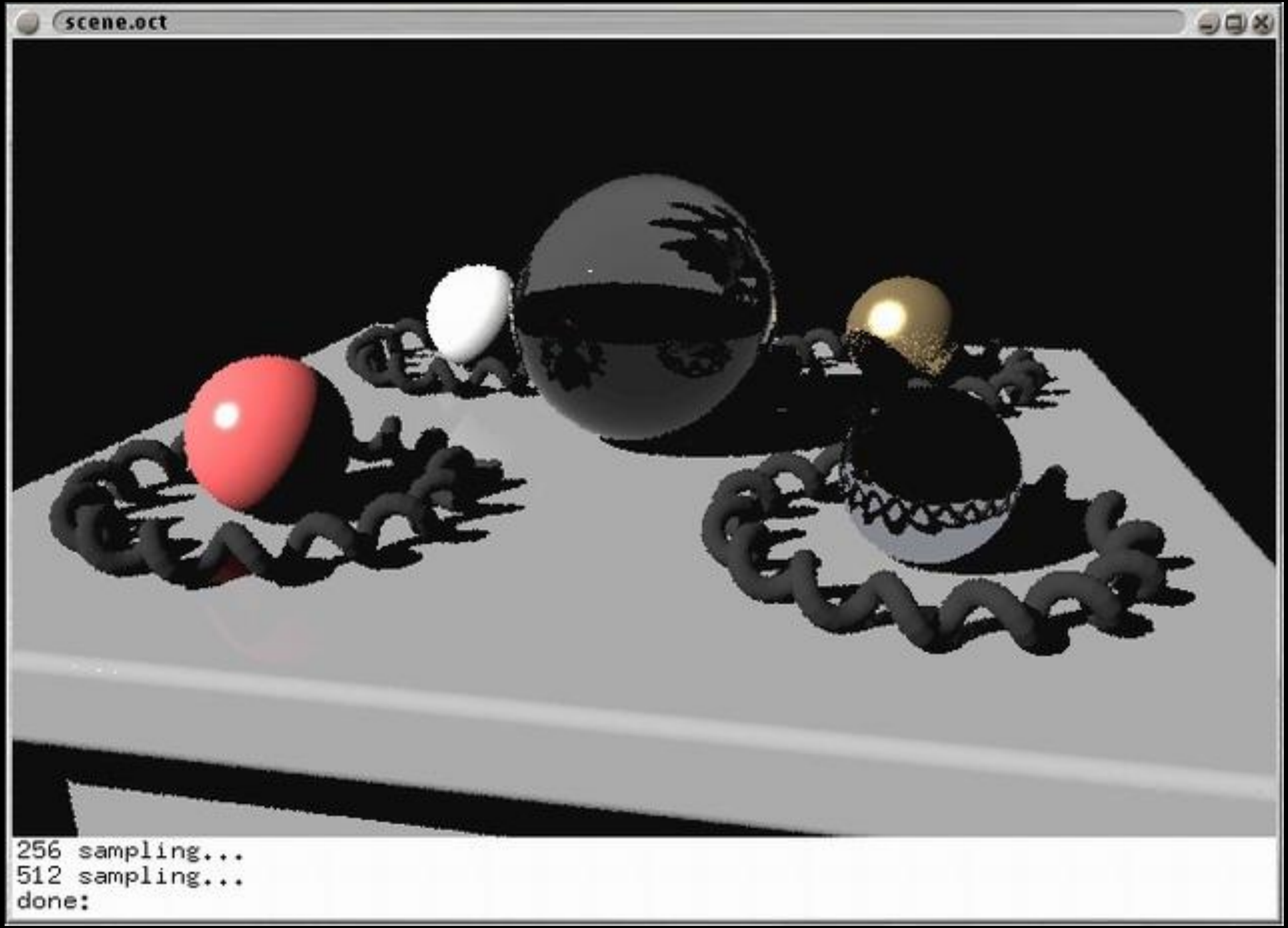
Uffizi
Gallery



Grace
Cathedral

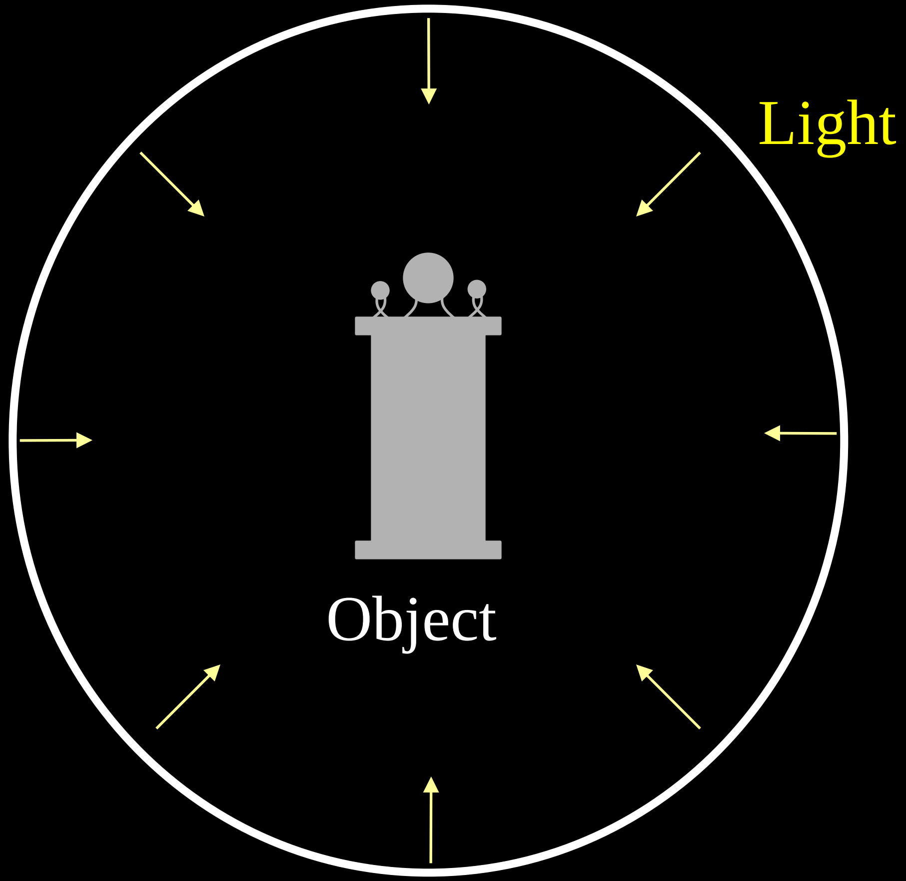
Lighting Environments from the Light Probe Image Gallery:
http://www.debevec.org/Probes/

Slides from Paul Debevec



CG Objects Illuminated by a Traditional CG Light Source

Illuminating Objects using Measurements of Real Light



Environment assigned "glow" material property in Greg Ward's RADIANCE system.

http://radsite.lbl.gov/radiance/

Paul Debevec. A Tutorial on Image-Based Lighting. IEEE Computer Graphics and Applications, Jan/Feb 2002.

Whipassgaming.com
http://www.youtube.com/watch?v=EHBgkeXH9lU

Questions?

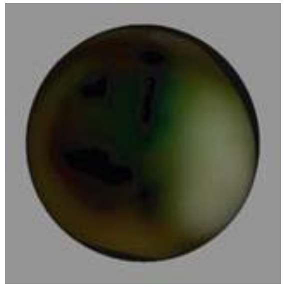
Eyes for Relighting

Ko Nishino* Shree K. Nayar†
Department of Computer Science, Columbia University

SIGGRAPH 2004

what if we don’t have a light probe?

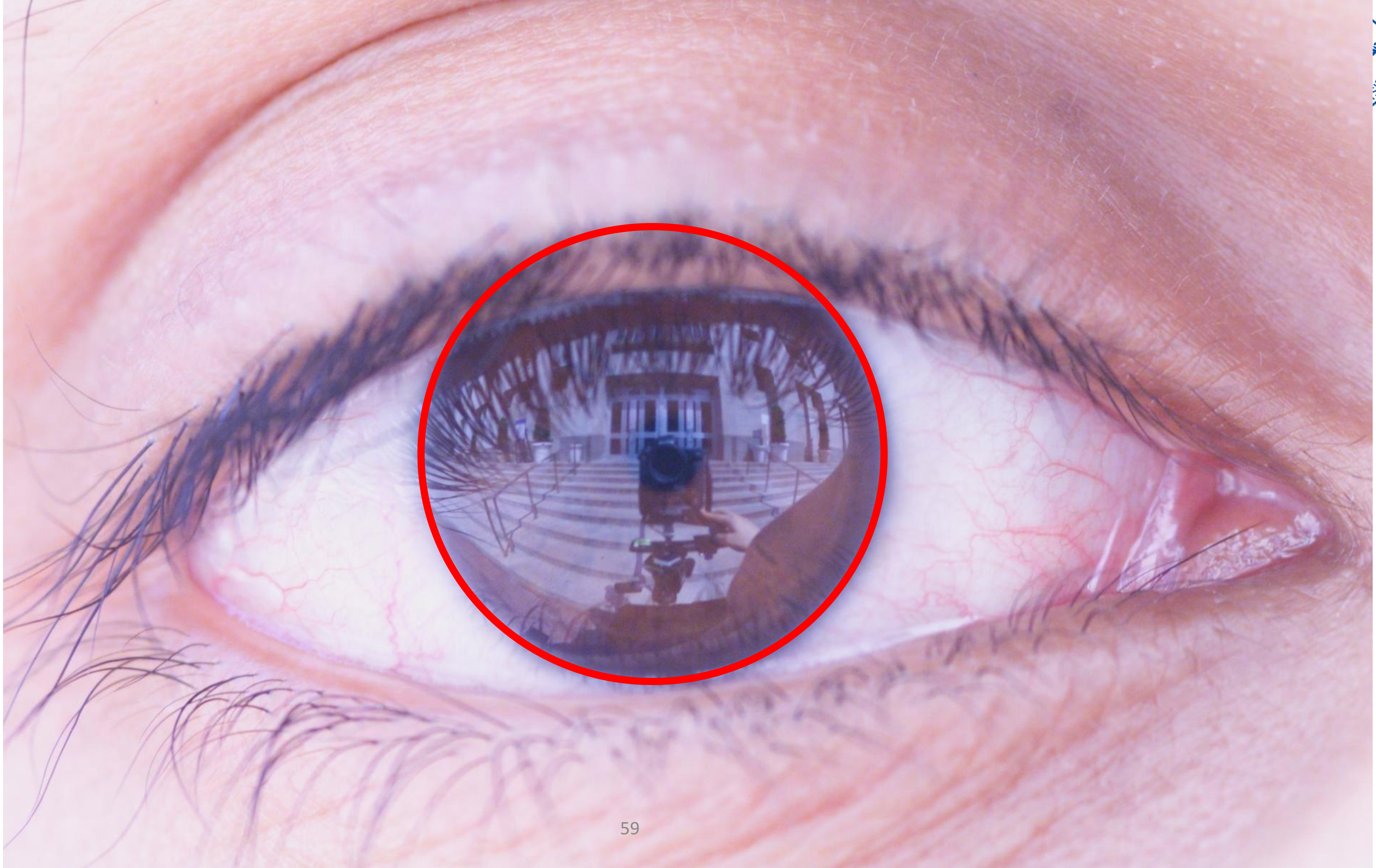
Zoom in on eye



Environment map
from eye

Insert Relit Face

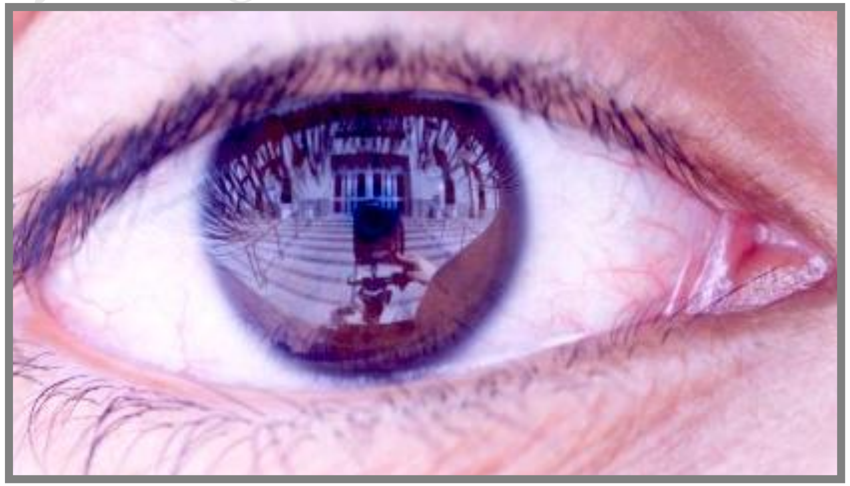
http://www1.cs.columbia.edu/CAVE/publications/pdfs/Nishino_TOG04.pdf -- Nishino Nayar 2004



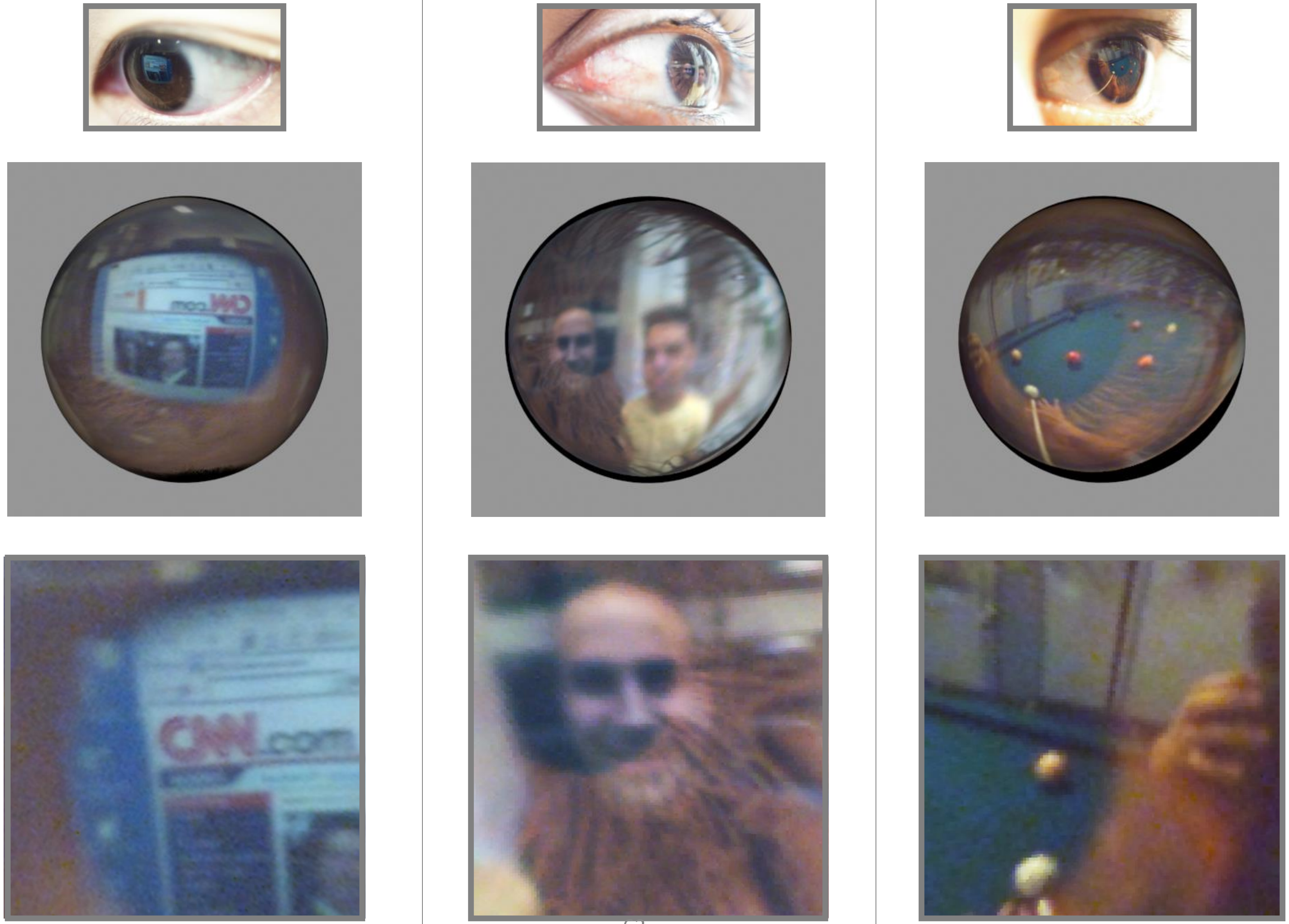
Environment Map from an Eye

Can Tell What You are Looking At

Eye Image:



Computed Retinal Image:


CNN.com

Faces as Lighting Probes via Unsupervised Deep Highlight Extraction

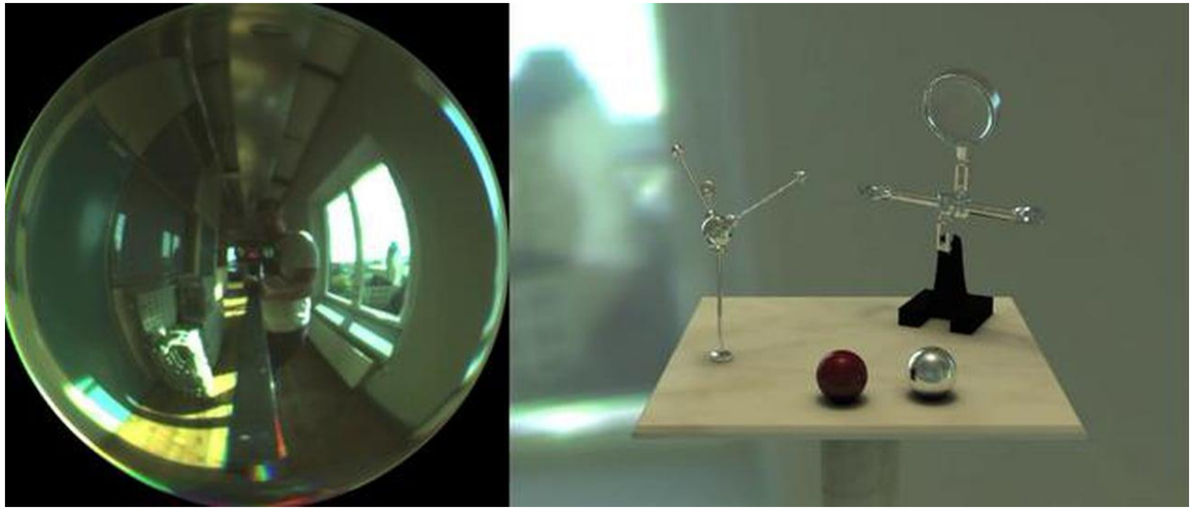
Renjiao Yi[1,2], Chenyang Zhu[1,2], Ping Tan[1], Stephen Lin[3]

ECCV 2018

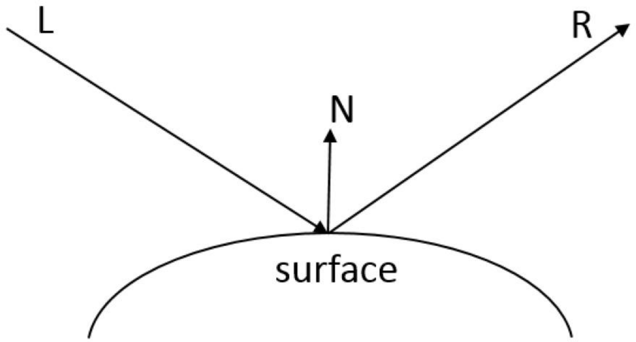
how do people record lighting?

- Use a light probe
  - Typically a mirror sphere

- Why a mirror sphere?
  - Perfect specular reflection
  - Perfect known geometry

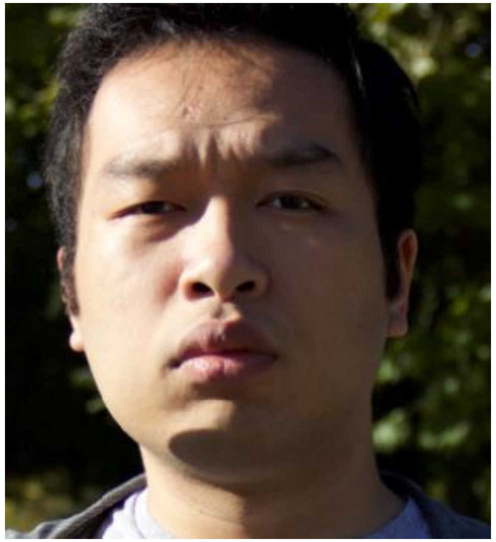


Rendering synthetic objects into real scenes,
Paul Debevec 1998

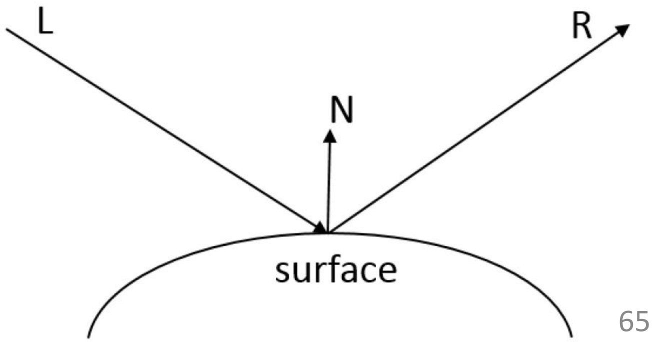


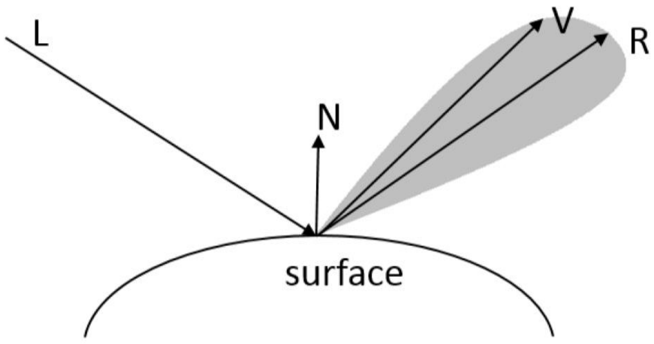
what if we don’t have a light probe?

- Use a face (common in images, especially for AR apps)
  - Almost like a sphere (with all kinds of normals)
  - Almost perfect known geometry (from template 3D faces)
  - Many specular reflections (oils on the skin)



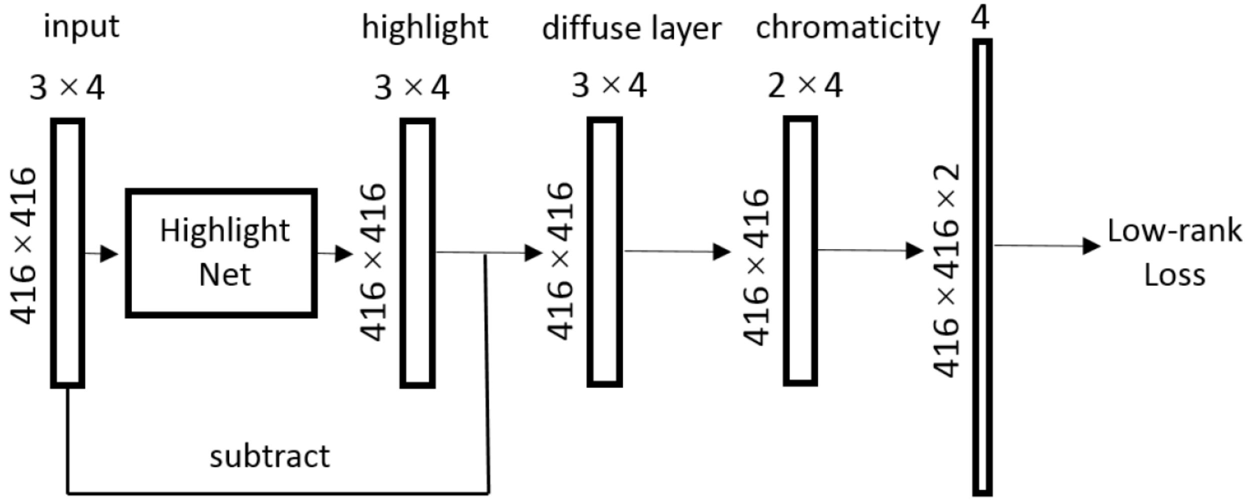
- What are the difficulties?
  - Extract specular (highlight) from a single face image
  - Imperfect specular reflection

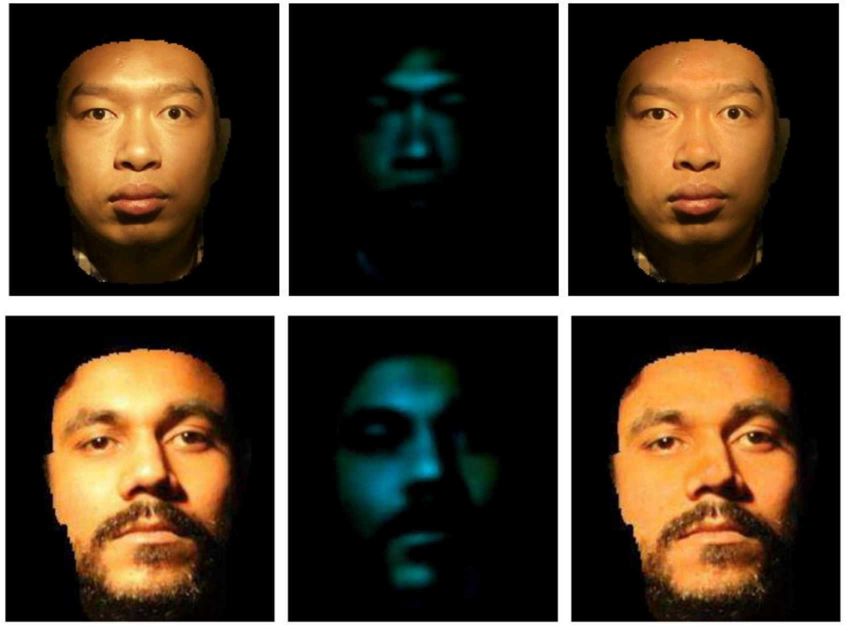




A Neural Network to Separate Face Highlight

- We will talk about neural network later
- For now, assume we have some toolbox to separate highlight from face images

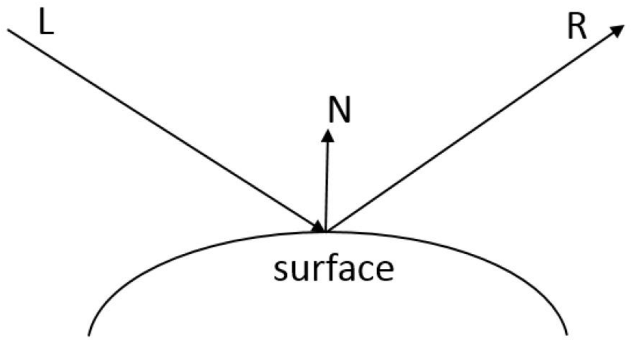




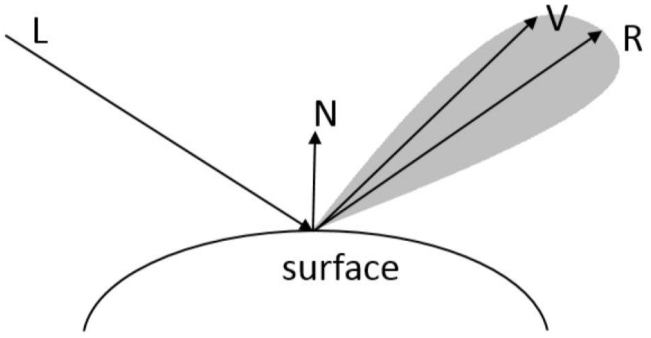
De-convolution the Environment Map

- The captured reflectance map = the real environment ⊛ the BRDF

A Signal-Processing Framework for Inverse Rendering, Ramamoorthi & Hanrahan 2001



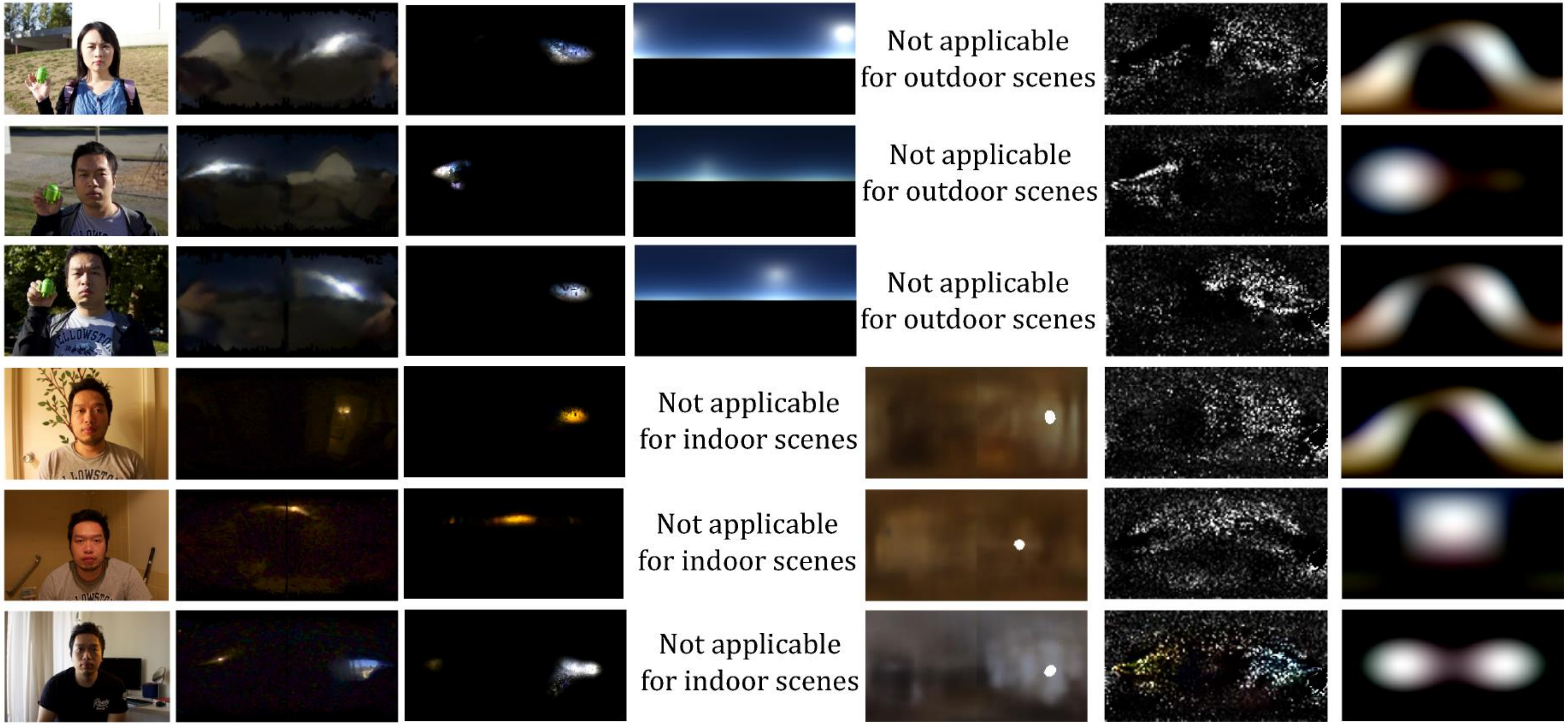
a delta-function



a Gaussian-like function

- Face reflectance is known
  - From the MERL-ETH database
  - Apply de-convolution by the Richard-Lucy algorithm to compute illumination

Final Results



our results | results by alternative methods

Virtual Object Insertion

(a) (b) (c) (d) (e)

Fig. 7. Virtual object insertion results for indoor (first row) and outdoor (second row) scenes. (a) Photos with real object. Object insertion by (b) our method, (c) [5] for the first row and [9] for the second row, (d) [19], (e) [12]. More results in the supplement.

Questions?

Retrographic sensing for the measurement of surface texture and shape

Micah K. Johnson
MIT

Edward H. Adelson
MIT

CVPR 2009

Microgeometry Capture using an Elastomeric Sensor

Micah K. Johnson* Forrester Cole† Alvin Raj‡ Edward H. Adelson§
Massachusetts Institute of Technology

SIGGRAPH 2011

Soft Gel + Photometric Stereo = Robot Skin

(a) (b) (c)

Figure 1. (a) A cookie is pressed against the skin of an elastomer block. (b) The skin is distorted, as shown in this view from beneath. (c) The cookie's shape can be measured using photometric stereo and rendered at a novel viewpoint.


GelSight
Retrographic sensing for touch, texture and shape
Micah K. Johnson, Edward H. Adelson and Alvin Raj
MIT Department of Brain and Cognitive Sciences
MIT Computer Science and Artificial Intelligence Lab
Massachusetts Institute of Technology
Presented at SIGGRAPH Emerging Technologies, 2009

Microgeometry Capture using

GelSight

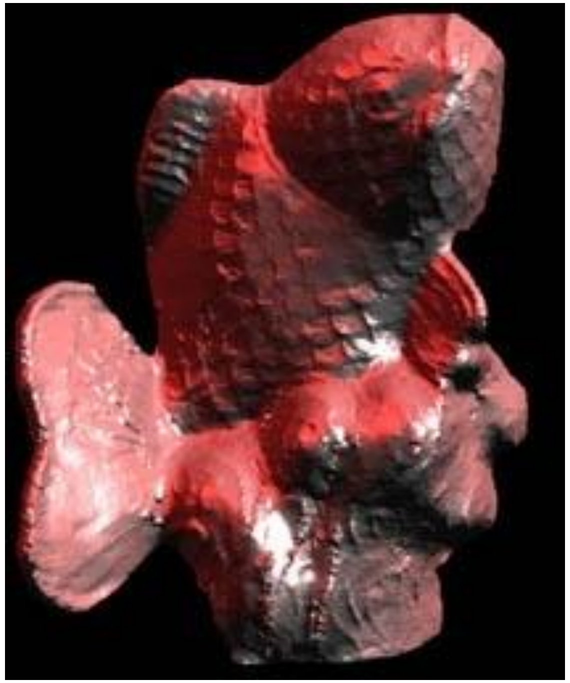
Micah K. Johnson, Forrester Cole,
Alvin Raj and Edward H. Adelson

MIT Computer Science and Artificial Intelligence Lab

Massachusetts Institute of Technology

CSAIL

Example-based Photometric Stereo

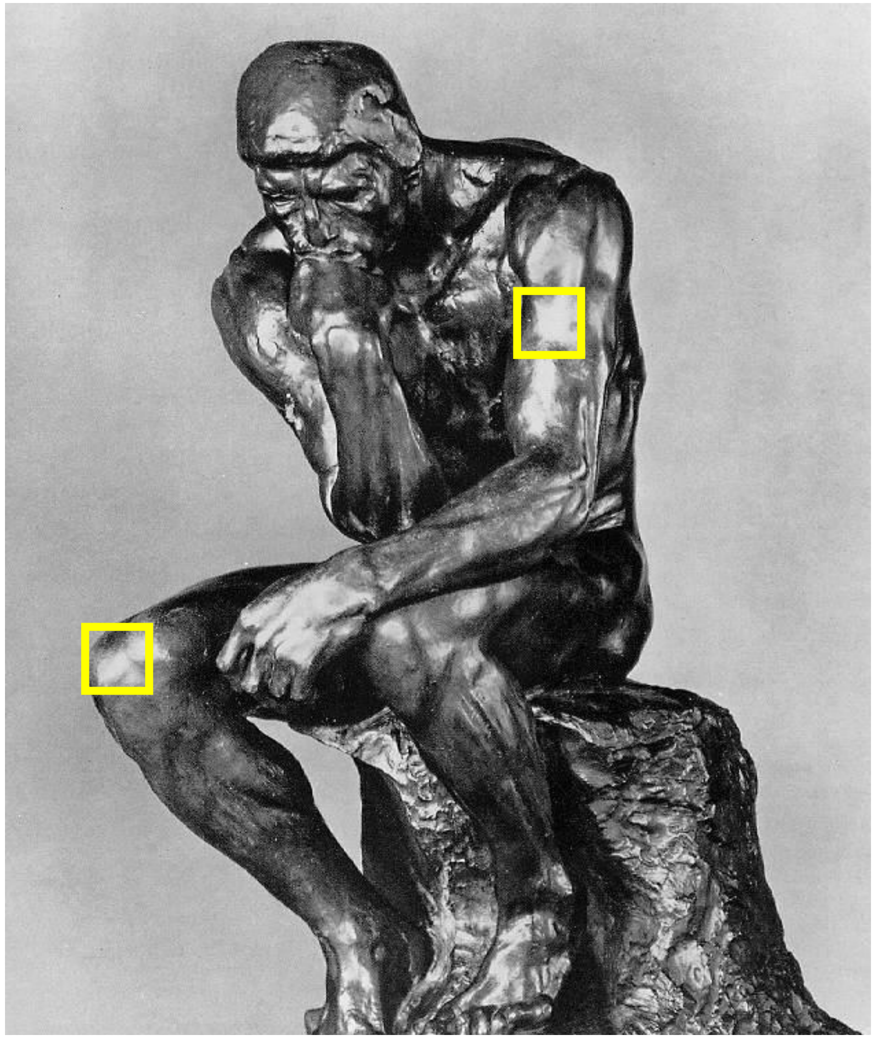


PAMI 2005

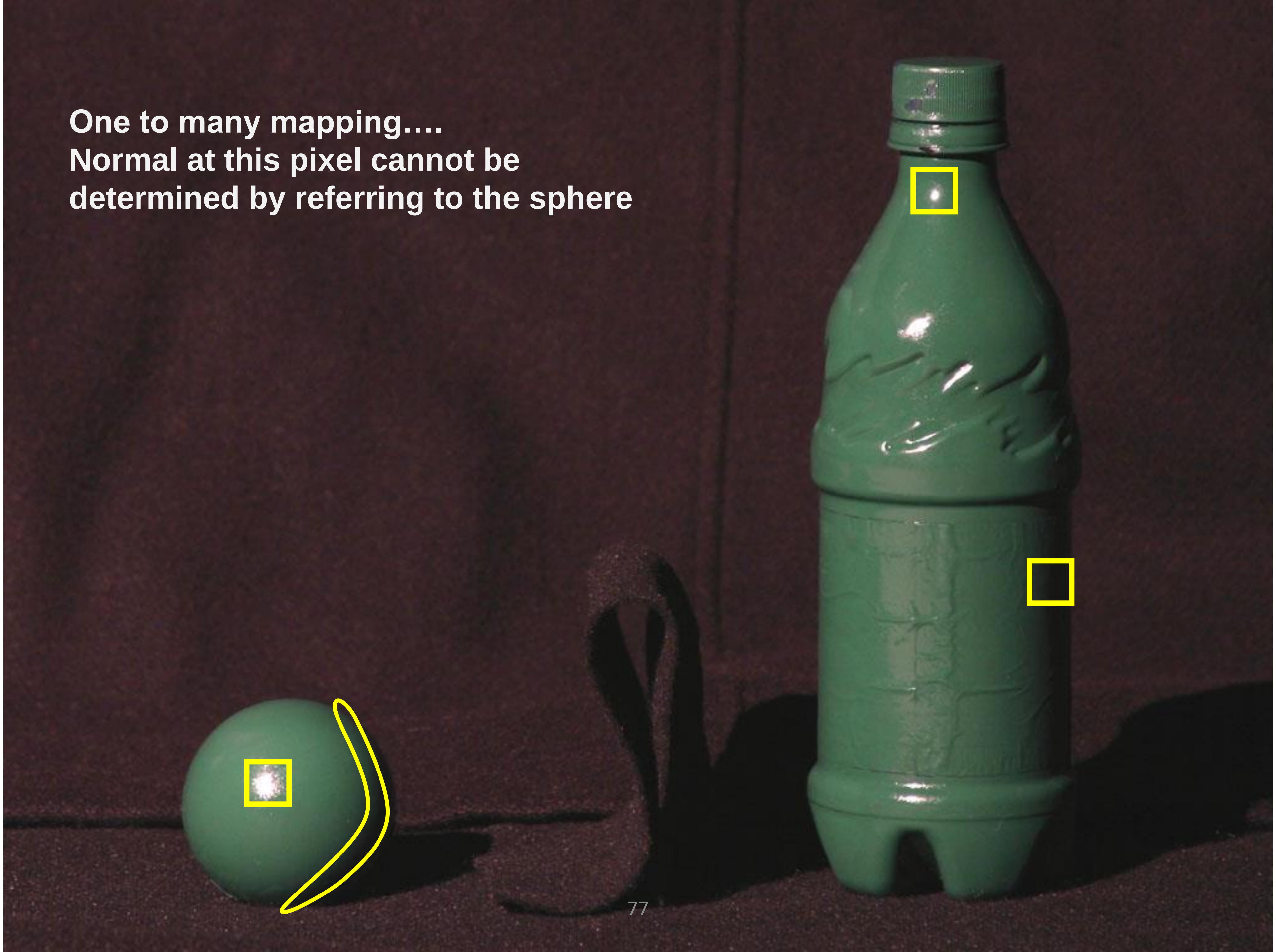
Aaron Hertzmann
University of Toronto

Steven M. Seitz
University of Washington

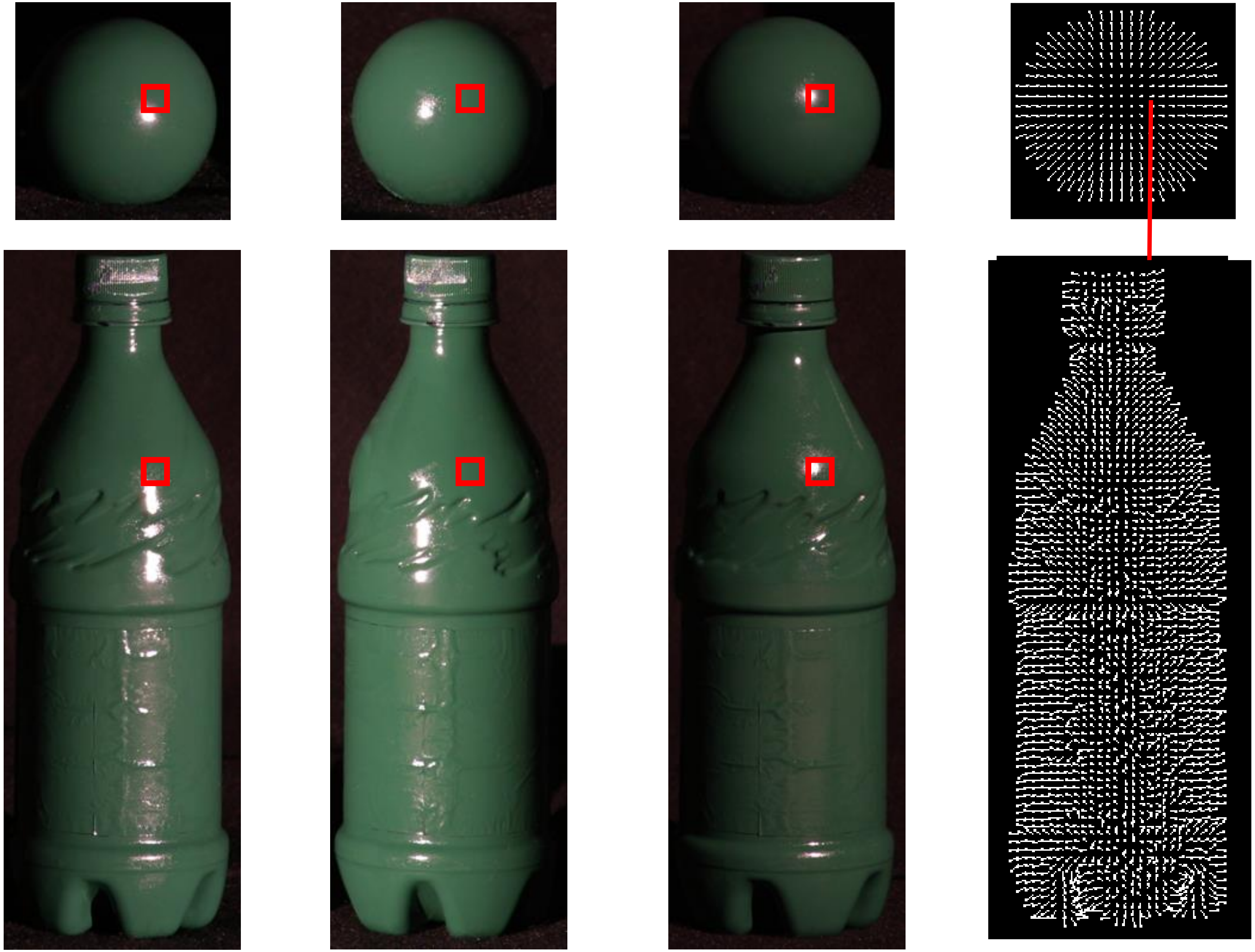
Shiny things



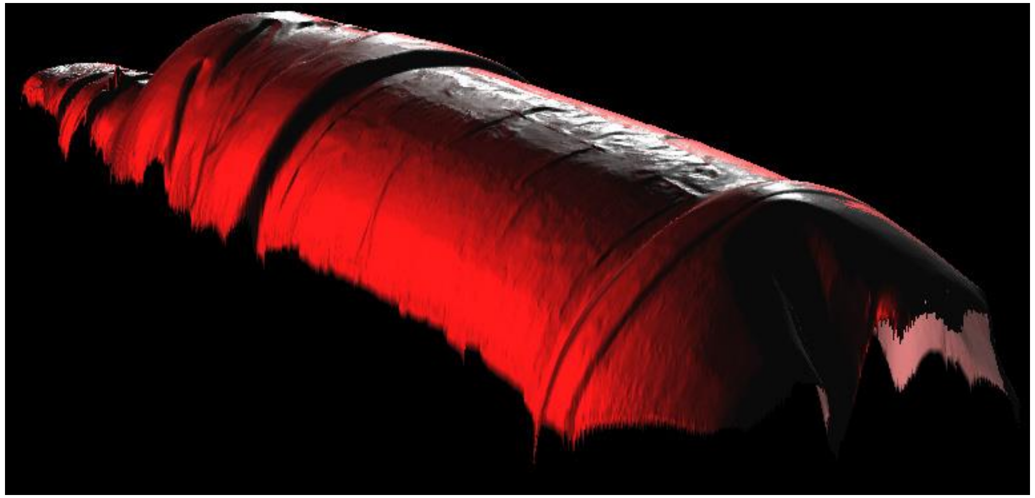
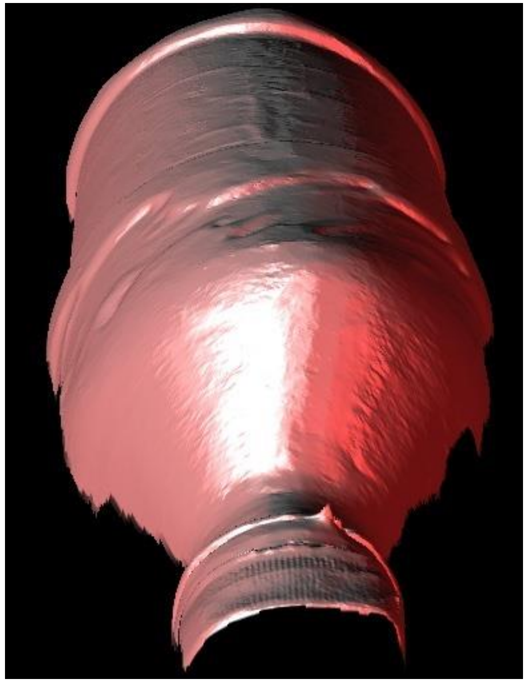
"Orientation consistency": points of similar orientation have similar intensity


One to many mapping….
Normal at this pixel cannot be
determined by referring to the sphere

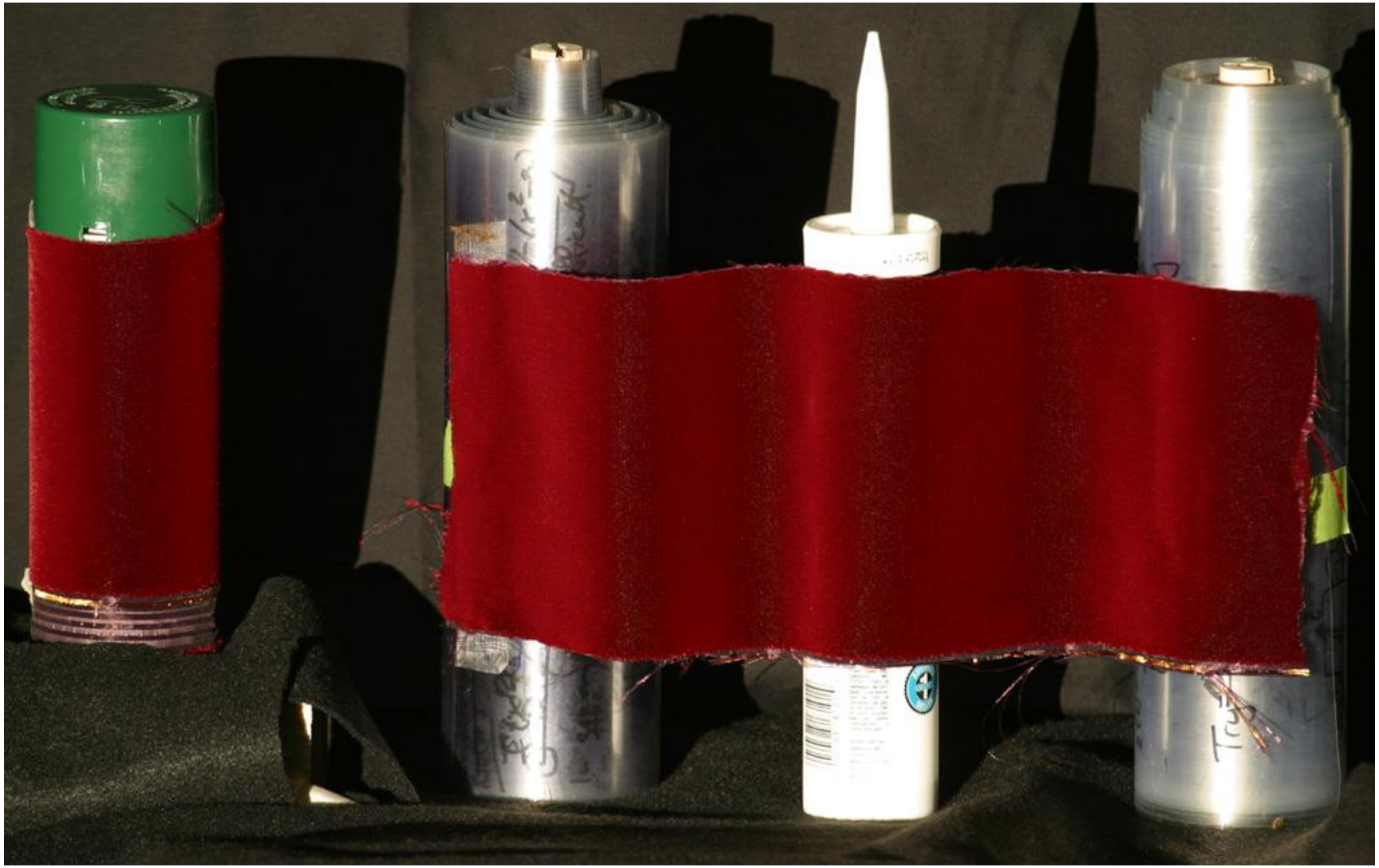
Let’s get multiple images….



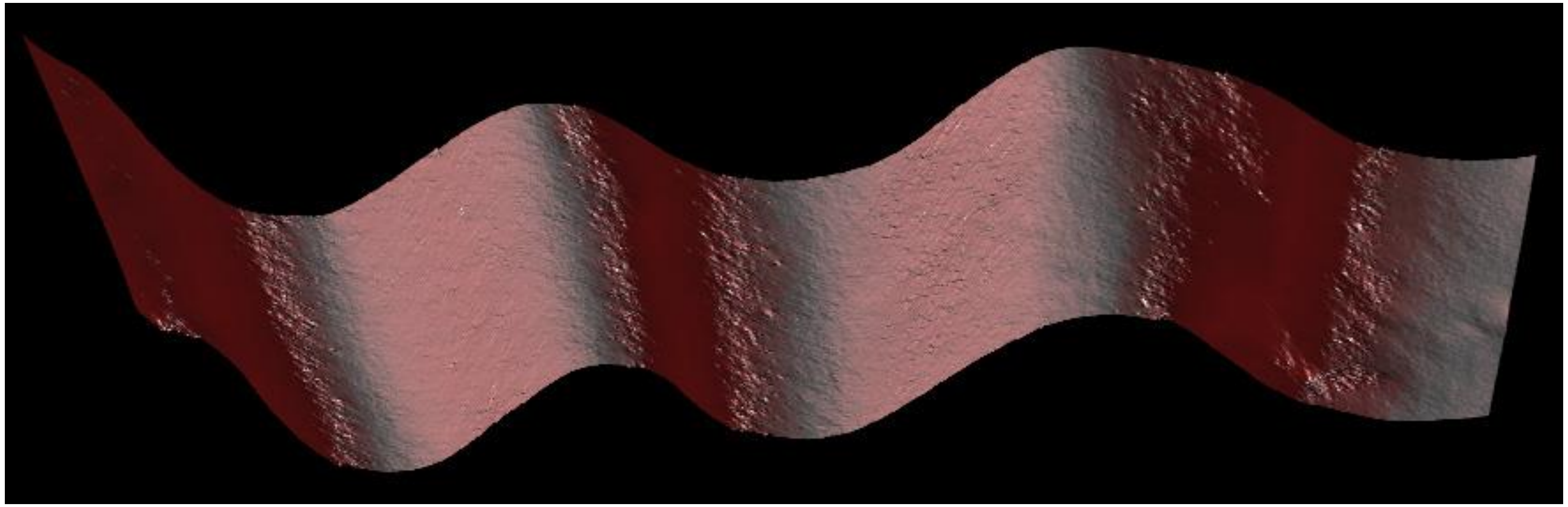
Virtual views

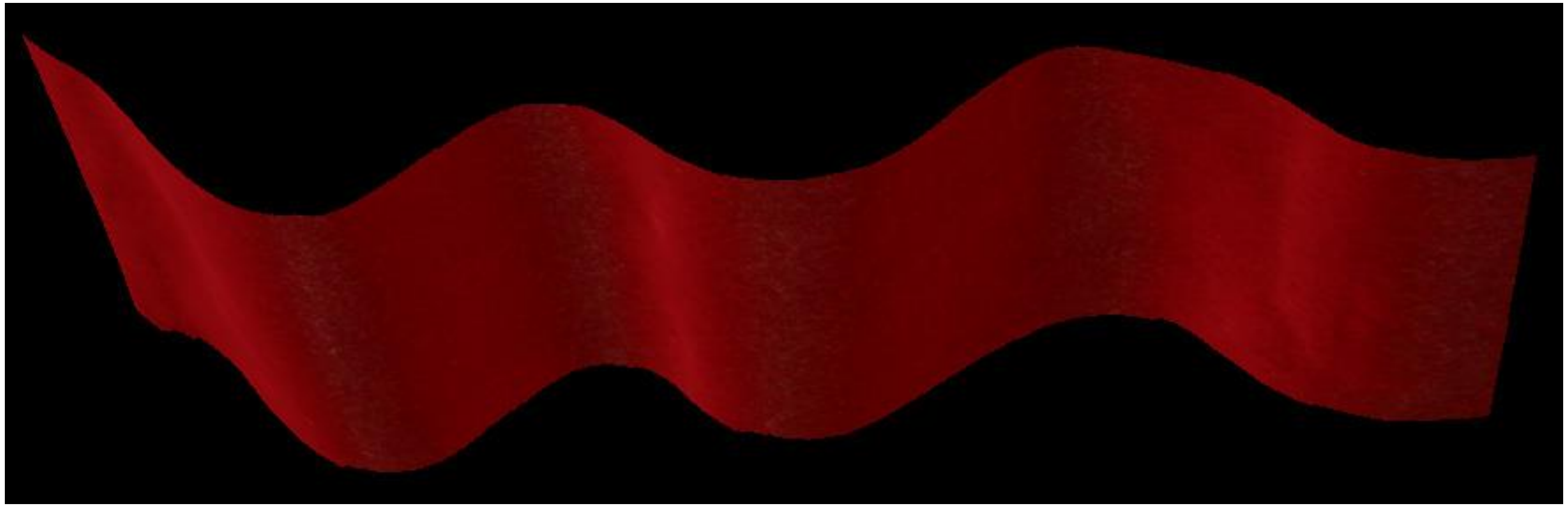



Velvet

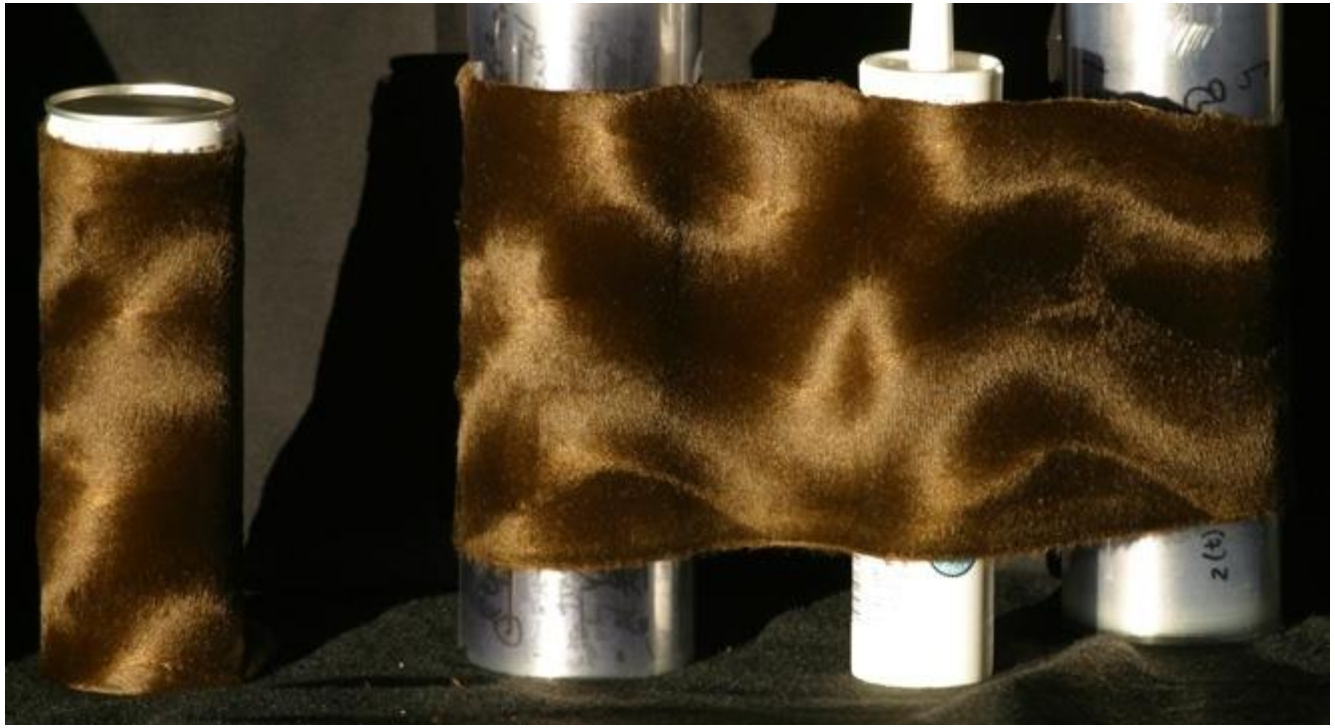


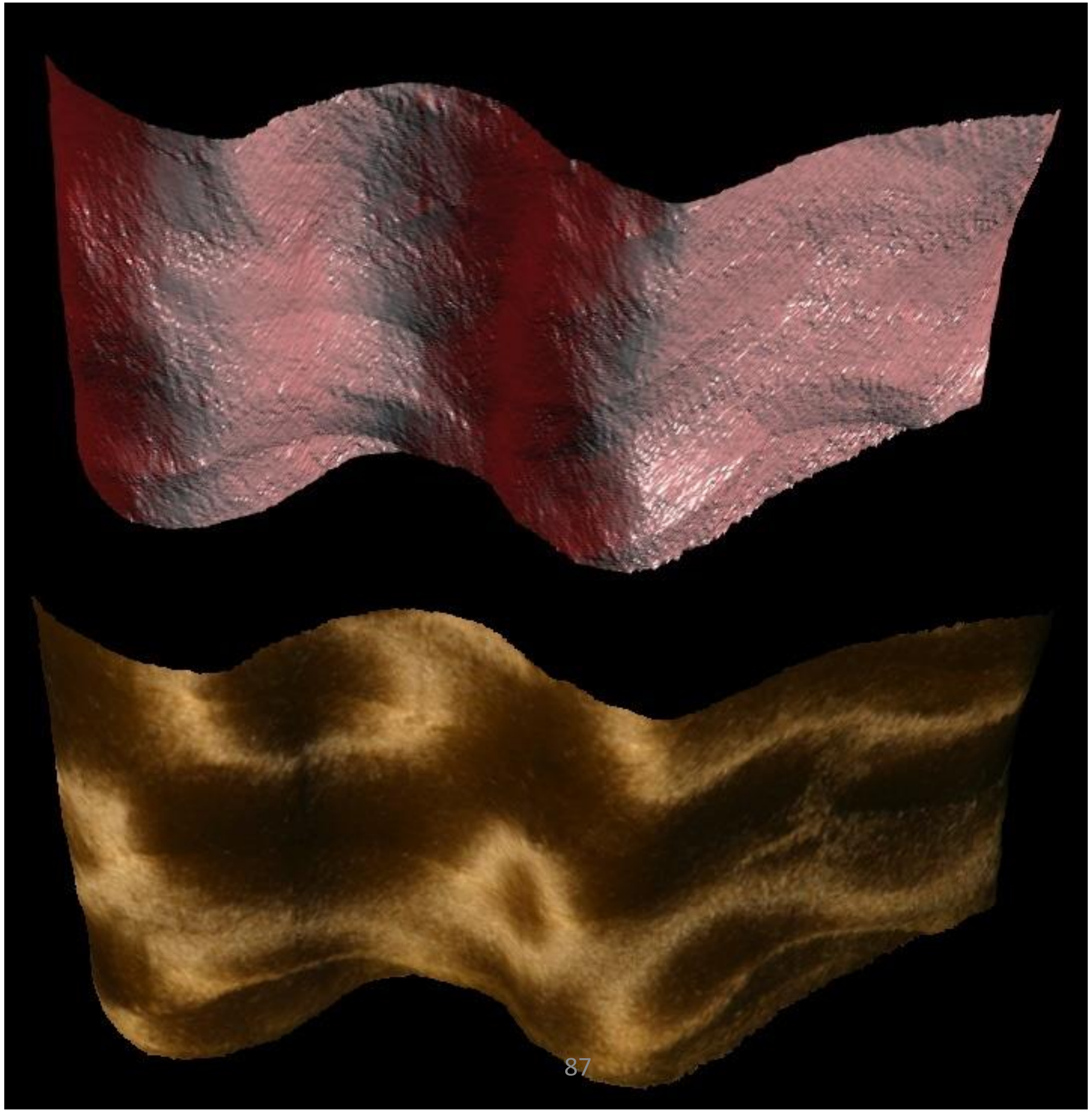
Virtual Views





Brushed Fur





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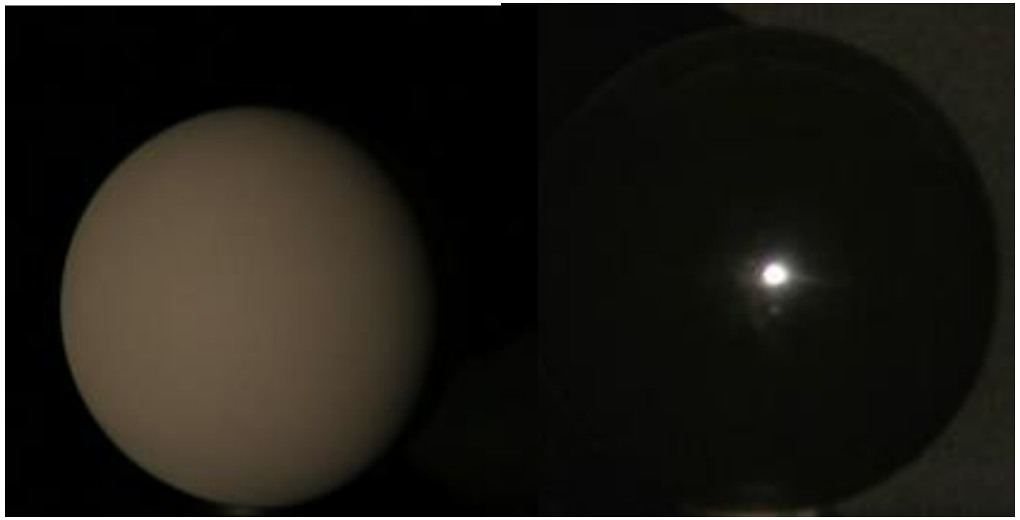
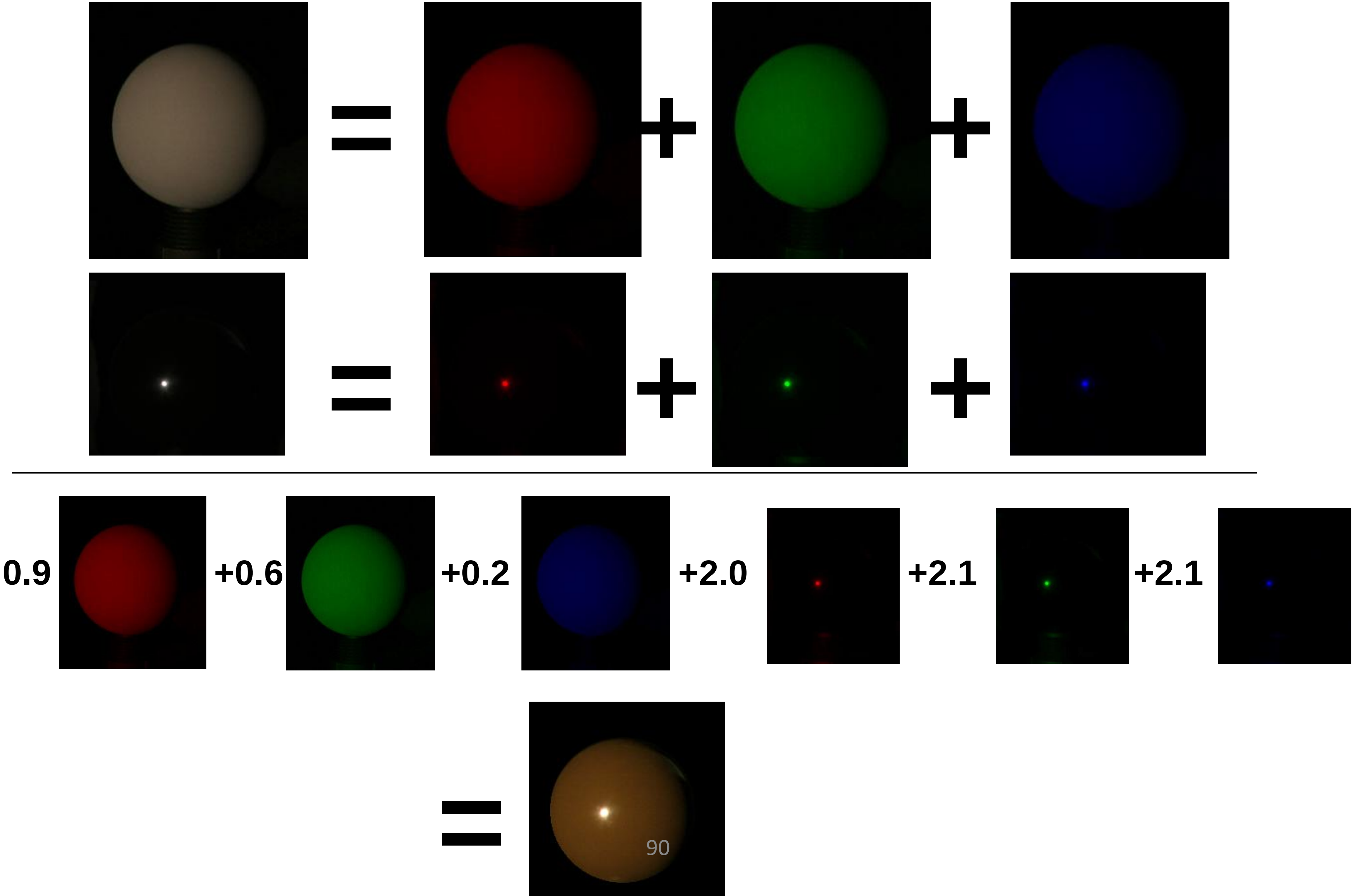
Quality Control Phone & Fax Addresses E-mail Directory Methods of Payment

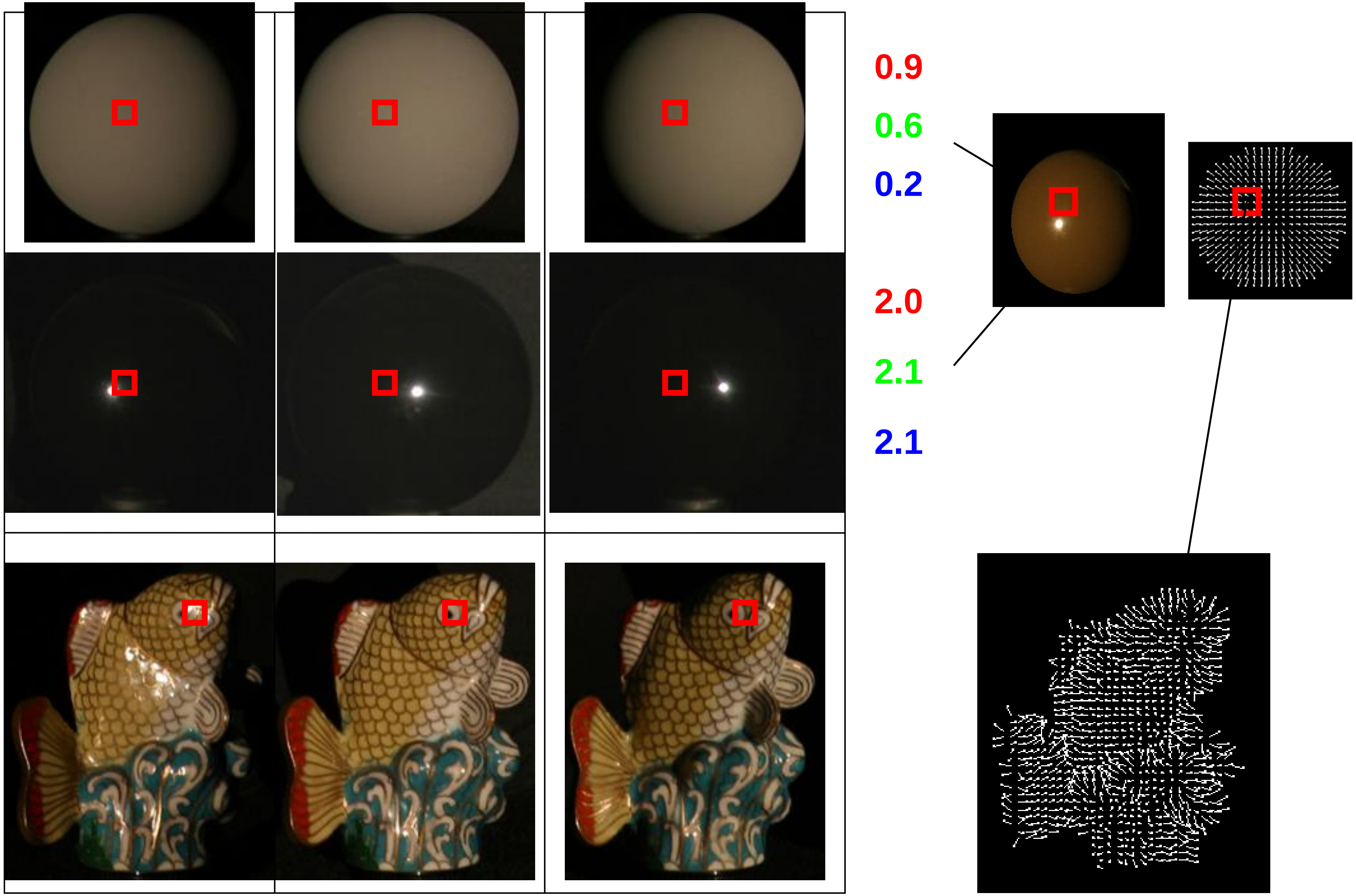
Salem Specialty Ball supplies industrial grade balls that are used in bearings, pumps, valves and other commercial applications. We can supply balls in just about any size that is machineable. We have produced precision balls from .002" all the way up to 12.0" and beyond. We can also produce these balls 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