No.7

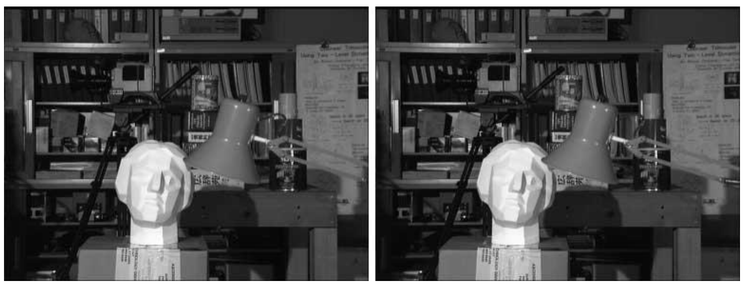
陰影解析

Shape from intensity

担当教員：向川康博・田中賢一郎

Shape-from-X

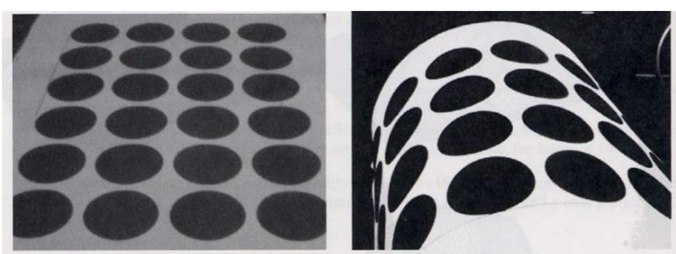
- Shape estimation from "X" as a clue



Stereo / Motion

Kinect

Triangulation



Texture

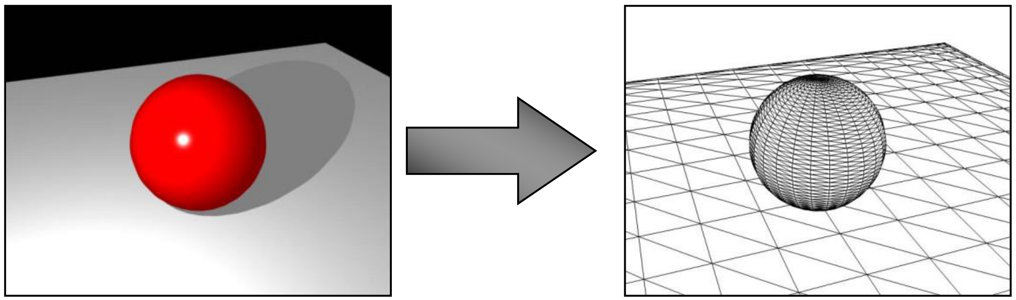
Focus / Defocus

Kinect V2 (ToF)

Time

Shape-from-Intensity

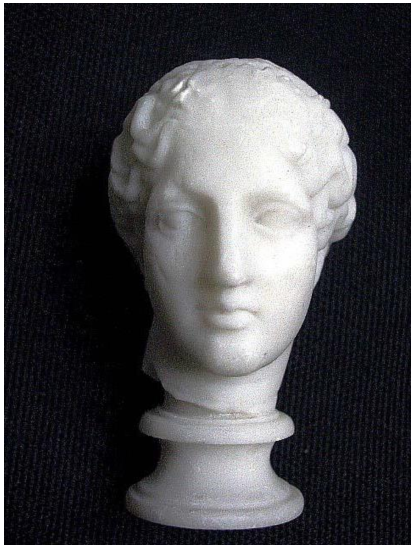
- Shape estimation with observed intensity as a clue
- Inverse process of rendering to determine pixel intensity
  - Inverse geometry
  - **Known** : Illuminations and reflectance properties
  - **Unknown** : Scene shape
- Clue
  - Shading, specular reflection, shadow, etc.



Shape-from-Shading

- Shape estimation based on shading
- Photometric information contains a lot of clues about geometry.
  - Surface normal
  - Depth

- Start with a simple problem setting
  - A point light source at infinity（parallel light）
  - Fixed camera and target object
  - Perfect Lambert reflection
    （No specular reflection, No shadow）
  - No global illumination

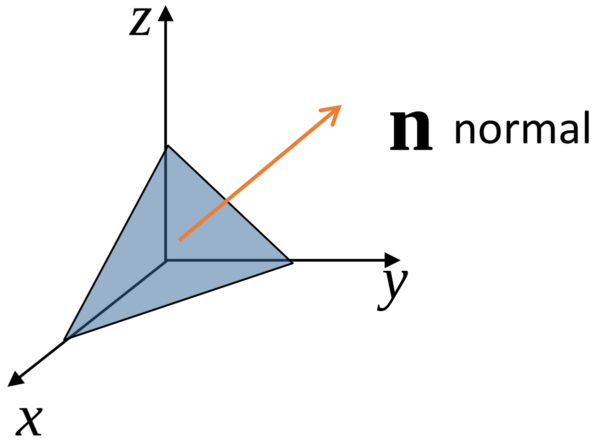


Surface normal

- Plane in 3D Euclidean space

$$Ax + By + Cz + D = 0$$

or $$\frac{A}{C}x + \frac{B}{C}y + z + \frac{D}{C} = 0$$



- Partial differential of z with x and y to define the inclination.

$$-\frac{\partial z}{\partial x} = \frac{A}{C} = p \qquad -\frac{\partial z}{\partial y} = \frac{B}{C} = q$$

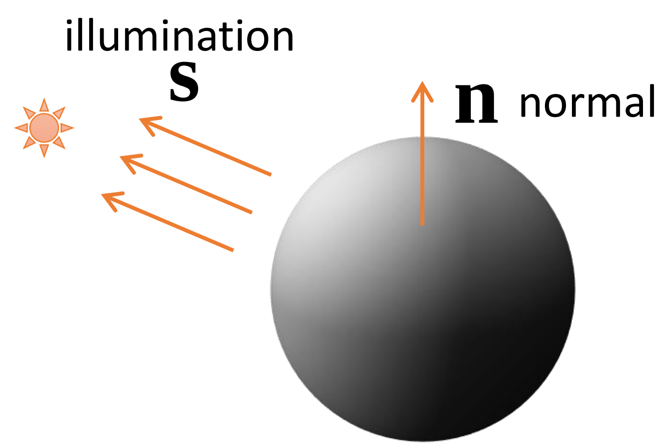
- Unit normal vector from the inclination.
  - defined by two parameters

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

Illumination and reflection

- **Parallel illumination**
  - Ideal illumination coming from a point light source at infinity
  - Every surface point is illuminated with the same irradiance from the same direction
  - Unit parallel illumination vector $$\mathbf{s} = \frac{(p_s, q_s, 1)^{\mathrm{T}}}{\sqrt{p_s^{\,2} + q_s^{\,2} + 1}}$$
- **Lambert diffuse reflection**
  - Ideal reflection that uniformly reflects incident light in all directions
    - i : Observed intensity
    - ρ : Lambert diffuse reflectance $(\rho \geq 0)$

$$i = \rho\,\mathbf{s}^{\mathrm{T}}\mathbf{n}$$



Problem setting

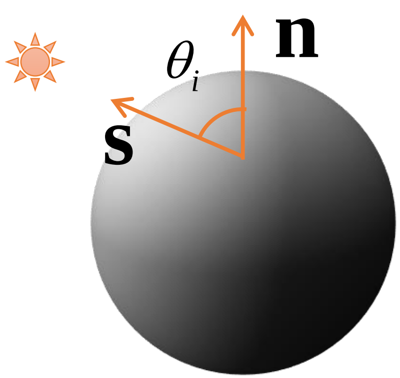
- Known: illumination and observed intensities
- Unknown: normal

Unknown $\mathbf{n} = \frac{(p, q, 1)^{\mathrm{T}}}{\sqrt{p^2 + q^2 + 1}}$ $\quad \mathbf{s} = \frac{(p_s, q_s, 1)^{\mathrm{T}}}{\sqrt{p_s{}^2 + q_s{}^2 + 1}}$ Known

- For simplicity, assuming that diffuse reflectance $\rho = 1$

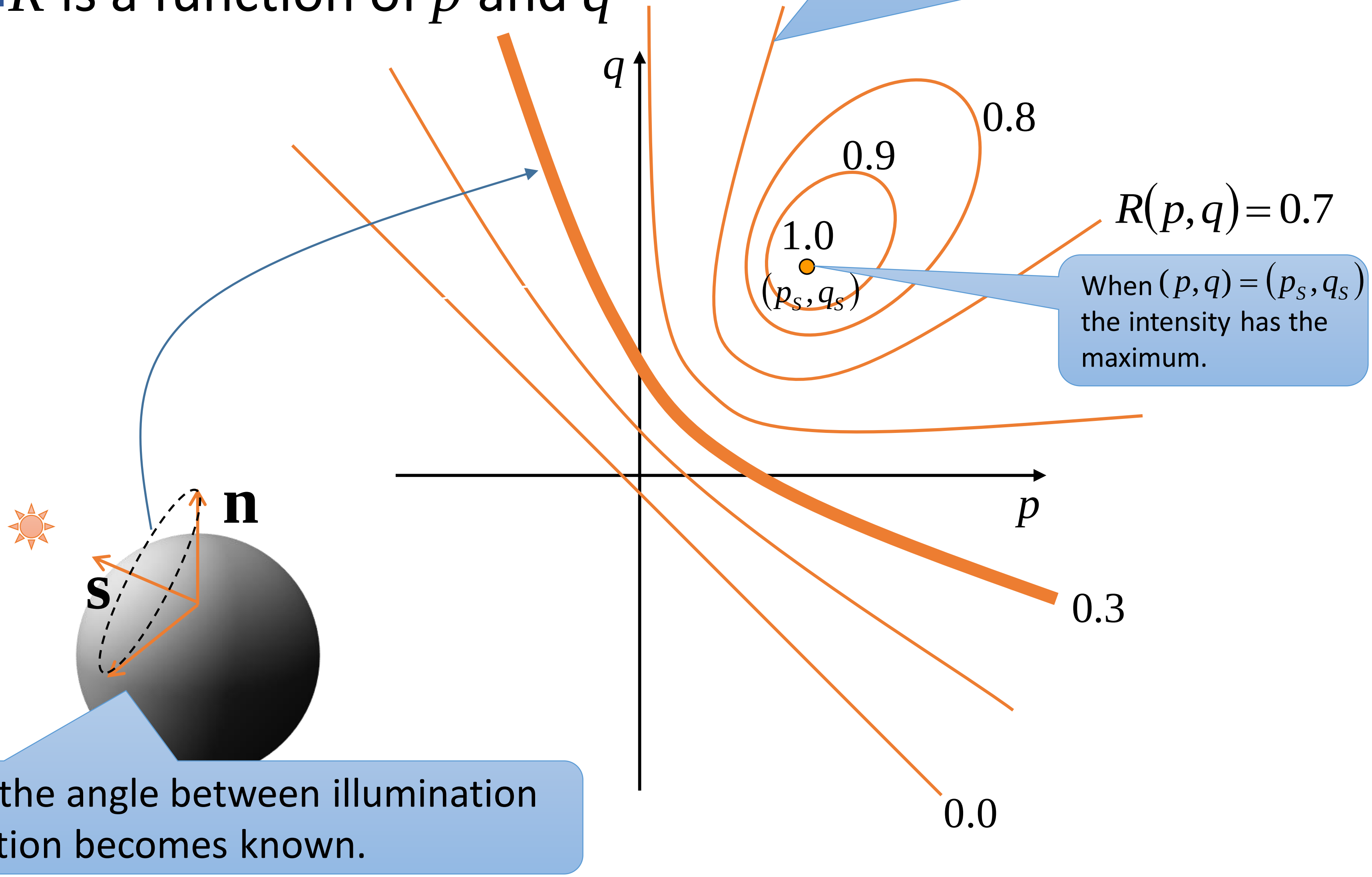
$$I = \cos\theta_i = \mathbf{n}^{\mathrm{T}}\mathbf{s} = \frac{(pp_s + qq_s + 1)}{\sqrt{p^2 + q^2 + 1}\sqrt{p_S^2 + q_S^2 + 1}} = R(p, q)$$

Reflectance map



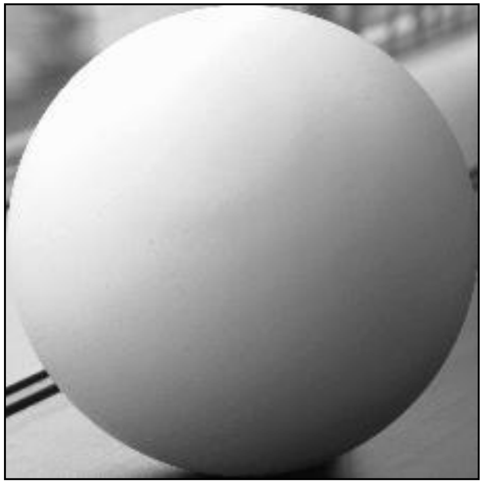
Reflectance map

- R is a function of p and q



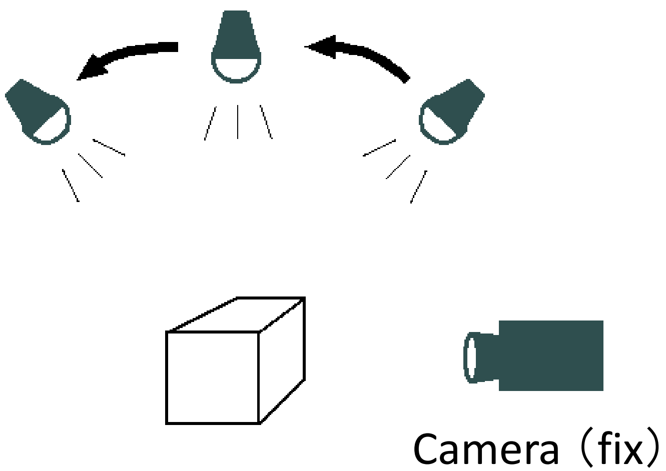
Shape-from-Shading

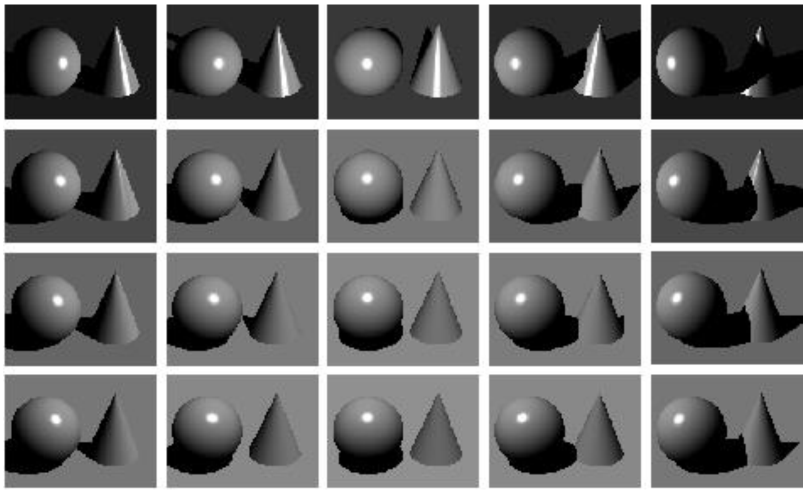
- The normal (p, q) cannot be uniquely determined from one observed intensity
  - One equation and two unknown parameters
- Need to add some information
  - Assumption that the object surface is smooth
  - Prior knowledge of shape
  - Increase Illumination directions



Photometric Stereo（照度差ステレオ）

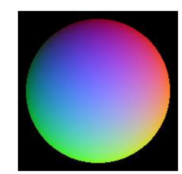
- Taking multiple images with changing illumination directions
- Solving ambiguity in the reflectance map
- Assuming Lambert diffuse reflection, it can be solved linearly





Example of Photometric Stereo

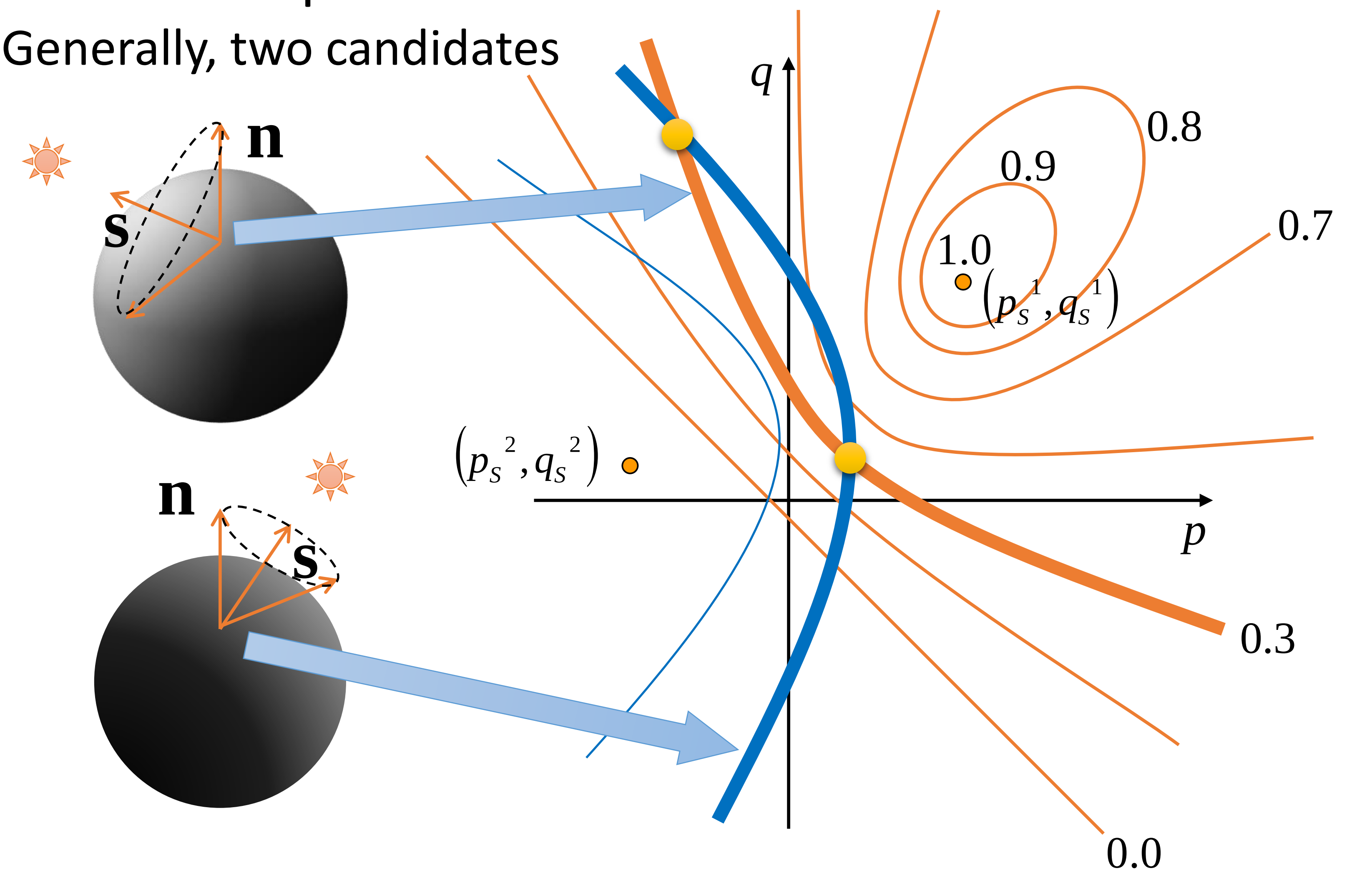
Input images



Normal map

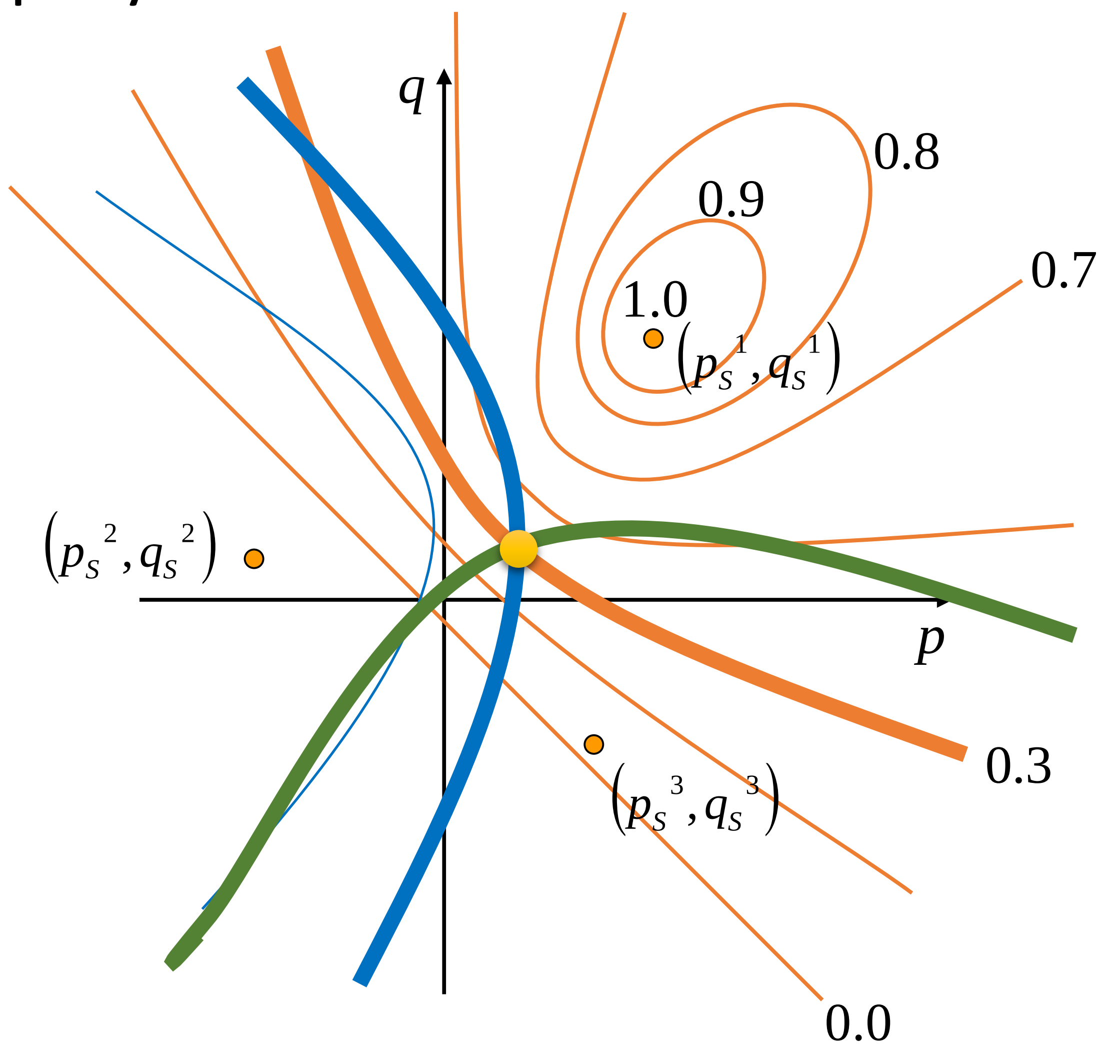
In the case of two light sources

- The intersection of the two solution curves becomes new solution space
  - Generally, two candidates



In the case of three light sources

- Solve uniquely



Linear solution in the case of three light sources

- Assuming that three observation intensities (i_1, i_2, i_3) were obtained for a pixel under three different illumination directions $(\boldsymbol{s}_1, \boldsymbol{s}_2, \boldsymbol{s}_3)$

$$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} \boldsymbol{s}_1^{\mathrm{T}} \\ \boldsymbol{s}_2^{\mathrm{T}} \\ \boldsymbol{s}_3^{\mathrm{T}} \end{bmatrix} \rho \boldsymbol{n}$$

Express by matrix →

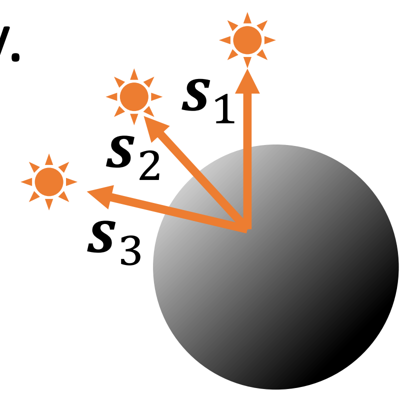
$$\boldsymbol{i} = \boldsymbol{S}\tilde{\boldsymbol{n}}$$

Inverse matrix →

$$\tilde{\boldsymbol{n}} = \text{mini-report}$$

$$\begin{cases} \rho = \|\tilde{\boldsymbol{n}}\| \\ \boldsymbol{n} = \tilde{\boldsymbol{n}}/\|\tilde{\boldsymbol{n}}\| \end{cases}$$

- Stable because it can be solved linearly.
- Reflectance (ρ) is also estimated at the same time.



In the case of more than three light sources

- Assumed that observed brightness $(i_1, i_2, \ldots, i_M)$ was obtained under M (> 3) different illumination directions $(\boldsymbol{s}_1, \boldsymbol{s}_2, \ldots, \boldsymbol{s}_M)$

$$\begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_M \end{bmatrix} = \begin{bmatrix} \boldsymbol{s}_1^{\mathrm{T}} \\ \boldsymbol{s}_2^{\mathrm{T}} \\ \vdots \\ \boldsymbol{s}_M^{\mathrm{T}} \end{bmatrix} \rho \boldsymbol{n}$$

Express by matrix

$$\boldsymbol{i} = \boldsymbol{S}\tilde{\boldsymbol{n}}$$

- Since the illumination matrix $\boldsymbol{S}$ is not a square matrix, calculated using a pseudo inverse matrix

$$\tilde{\boldsymbol{n}} =$$

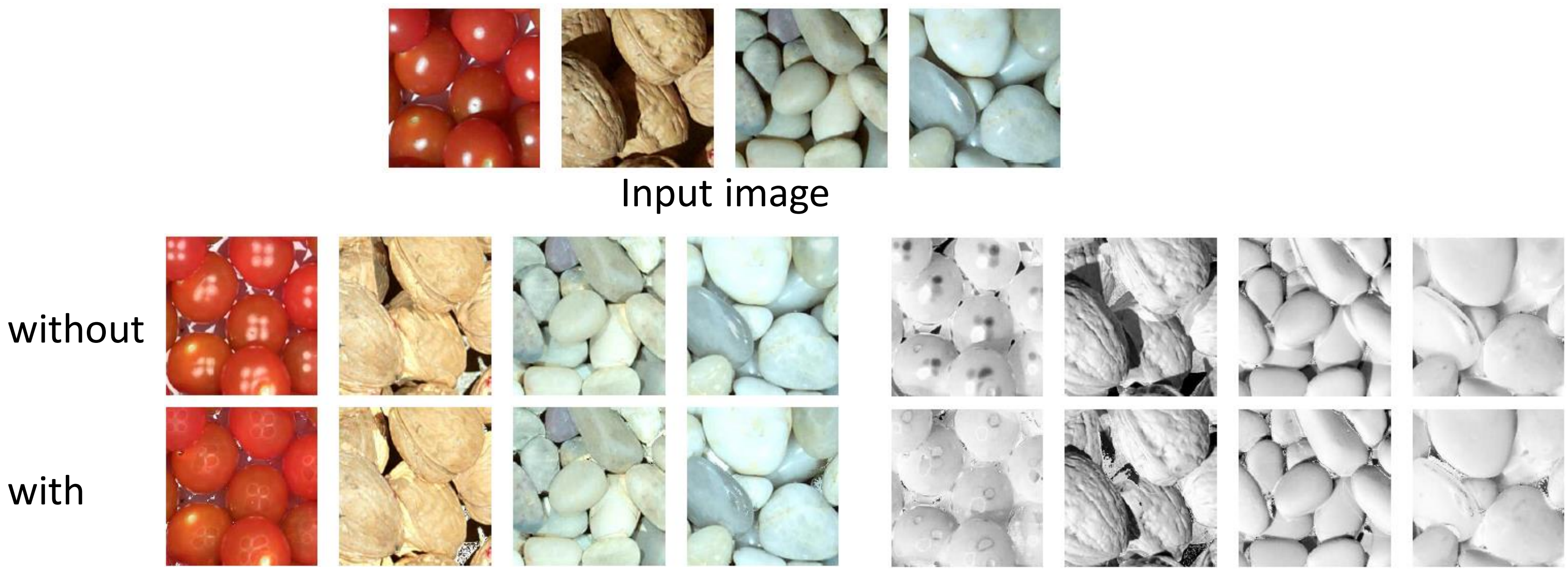
mini-report

Moore Penrose(ムーア・ペンローズ)inverse matrix

- Least squares method assuming that observation error is Gaussian distribution
  - more stable and accurate solution

The merit of multiple light sources

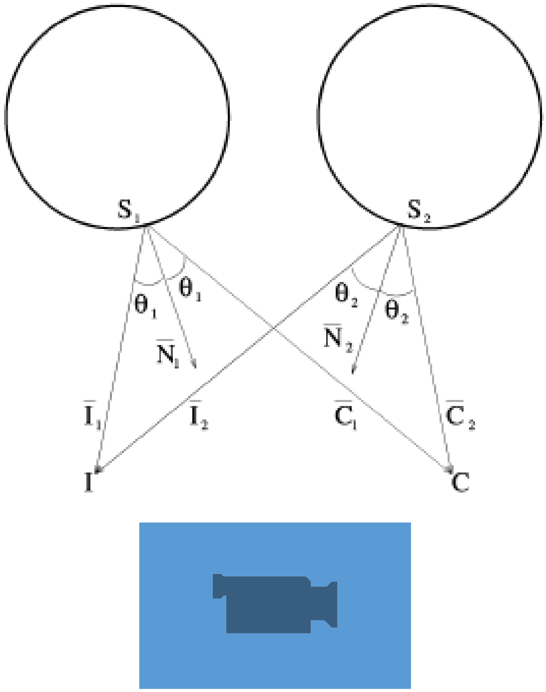
- Avoid specular reflection and shadow
  - Assuming that pure Lambert diffuse reflection can be observed in at least three images.



Barsky, S, et al, The 4-source photometric stereo technique for three-dimensional surfaces in the presence of highlights and shadows

Photometric Stereo in Parthenon

- Near light source photometric stereo.
- Two black hemispheres to determine light source positions.



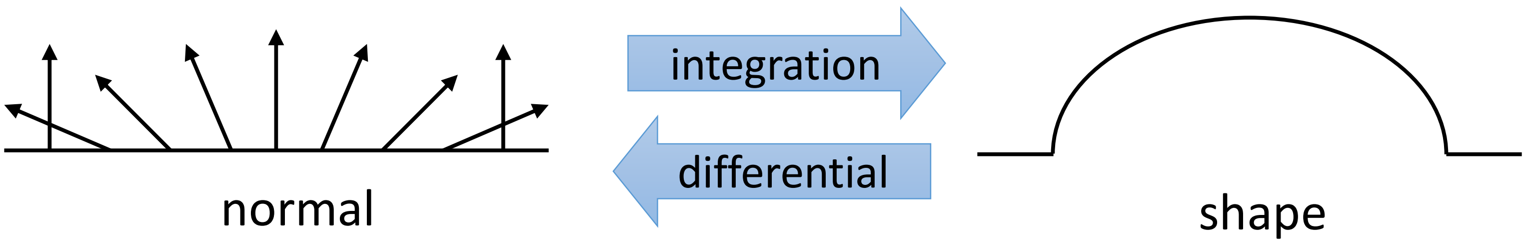
[Per Einarsson et al., Photometric Stereo for Archeological Inscriptions, 2004]

Summary of the number of light sources

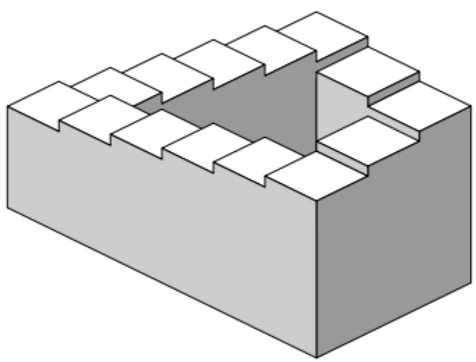
- 1 light source
  - Shape-from-Shading
- 2 light sources
  - Photometric Stereo（照度差ステレオ法）
- 3 light sources
  - Uniquely solved Photometric Stereo
  - Simultaneous estimation of reflectance and normal
- More light sources
  - Robust to specular reflection and shadow

3D shape and normal

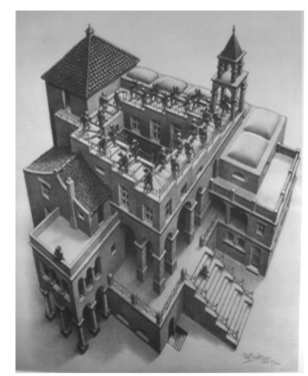
- Even if normals are known, 3D shape cannot be uniquely determined.
  - Height ambiguity due to different integral path.
  - Differential is easy, but integration is difficult.



- Ambiguity in height



A "Penrose stairs" optical illusion



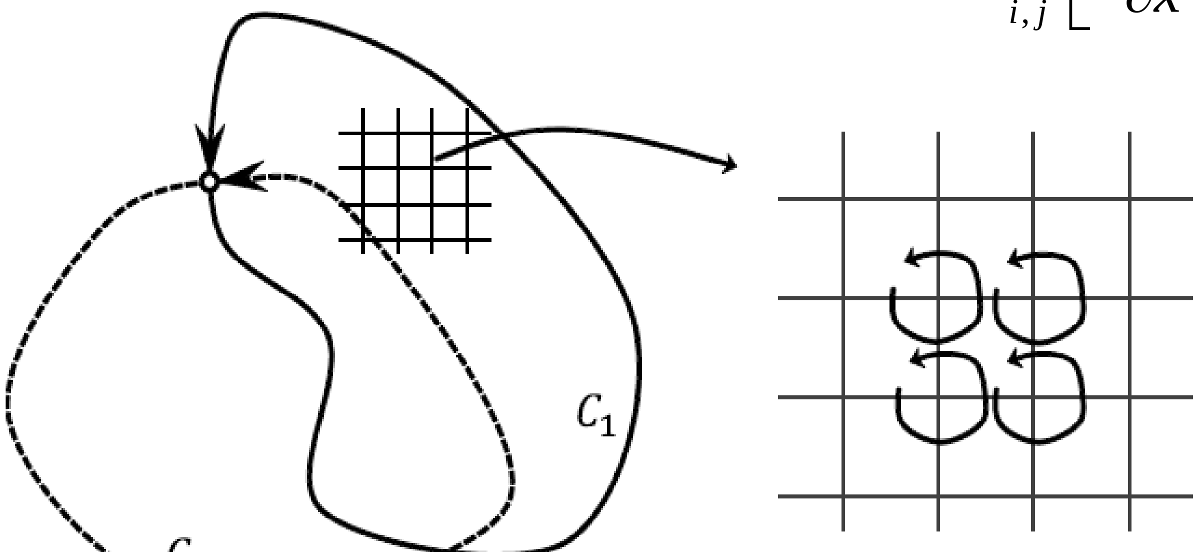
“Ascending and Descending”

MC Escher, 1898-1972

Integrability（可積分性）

- When integrated along a closed loop on a smooth surface, the integral value becomes zero.
  - Independent to the integral path.
  - Minimization of objective function $E(Z)$

$$E(Z) = \sum_{i,j} \left[\left(\frac{\partial Z}{\partial x} + p\right)^2 + \left(\frac{\partial Z}{\partial y} + q\right)^2 \right]$$

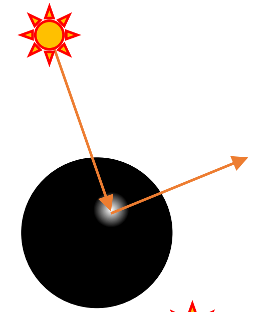


$$\left(\frac{\partial Z}{\partial x}, \frac{\partial Z}{\partial y}\right) = (-p, -q)$$

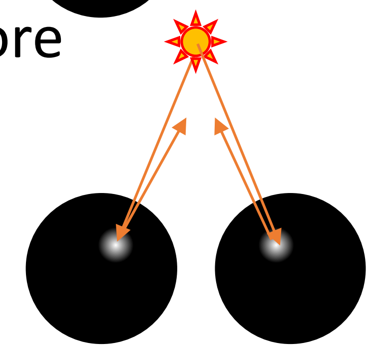
$\mathrm{curl}\,(p, q) = 0$

Estimation of light source direction/position

- Use reference object with known shape
  - Estimate light source direction by a black sphere



  - Estimate near light source position by two or more black spheres



  - In the outdoor, high dynamic range measurement is required
    - Mirror sphere for ambient light
    - Black sphere for position of sun
    - Diffuse sphere for brightness of ambient light

When the illumination direction is unknown

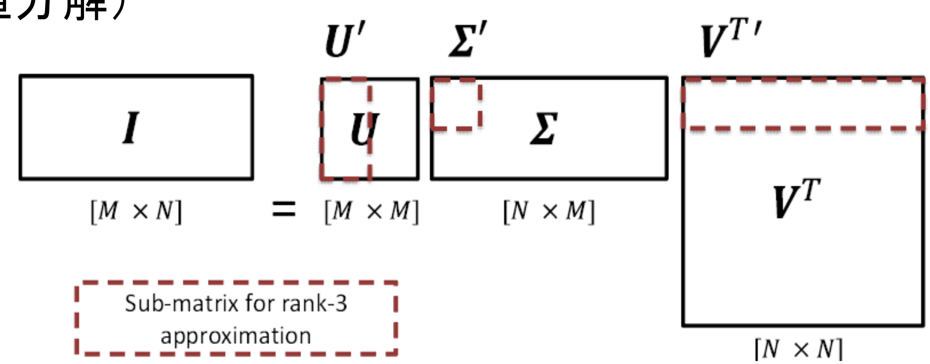
- Illumination directions and strengths are unknown:
  - Uncalibrated Photometric Stereo（未校正照度差ステレオ）

$$\begin{bmatrix} i_{11} & \cdots & i_{1N} \\ \vdots & \ddots & \vdots \\ i_{M1} & \cdots & i_{MN} \end{bmatrix} = \begin{bmatrix} \mathbf{s}_1^{\mathrm{T}} \\ \vdots \\ \mathbf{s}_M^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} \rho_1 \mathbf{n}_1 & \ldots & \rho_N \mathbf{n}_N \end{bmatrix}$$

  - Singular value decomposition $\mathbf{I} = \mathbf{S}\tilde{\mathbf{N}} = \mathbf{U}\mathbf{\Sigma}V^{\mathrm{T}}$

（特異値分解）

$$\begin{cases} \mathbf{S} = \mathbf{U}'(\mathbf{\Sigma}')^{\frac{1}{2}} \\ \tilde{\mathbf{N}} = (\mathbf{\Sigma}')^{\frac{1}{2}} V^{\mathrm{T}}{}' \end{cases}$$



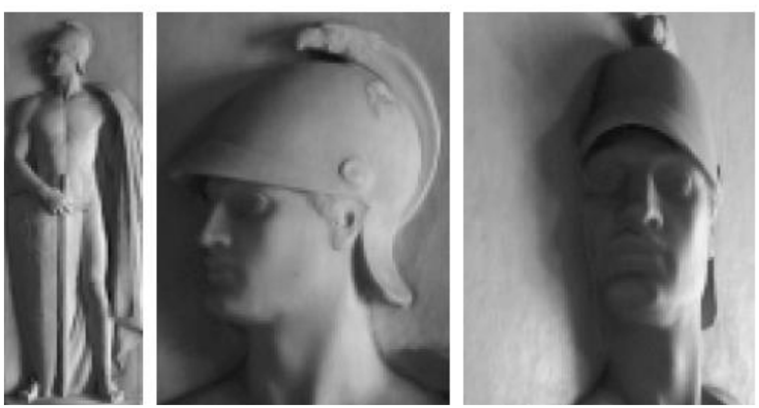
Bas-Relief Ambiguity（浅浮き彫りの曖昧性）

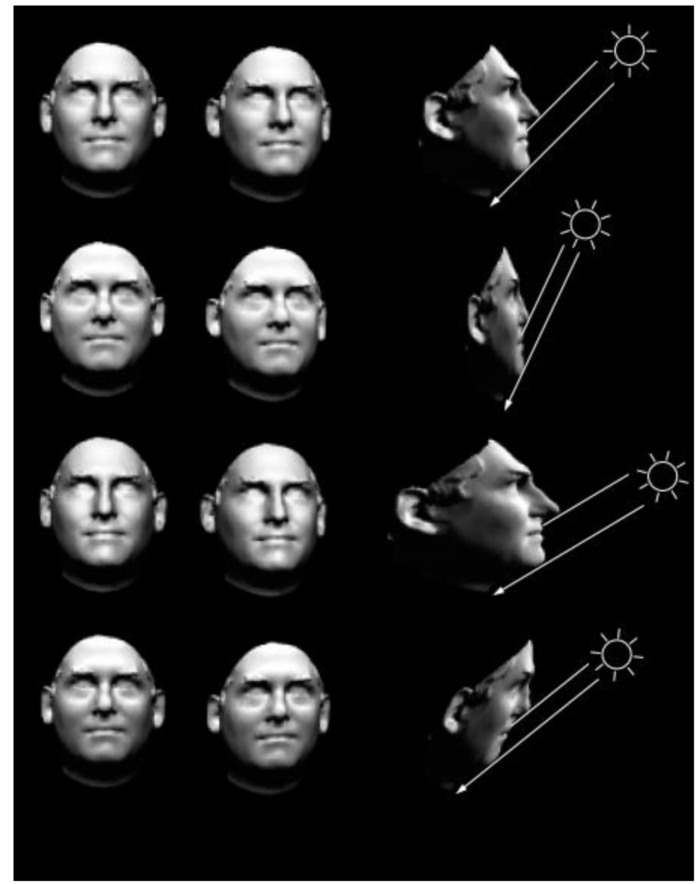
- Decomposition of a matrix is not uniquely determined.

$$\mathbf{I} = \mathbf{S}\tilde{\mathbf{N}} = (\mathbf{S}'\mathbf{H})(\mathbf{H}^{-1}\tilde{\mathbf{N}}')$$

$\mathbf{H}$ is any 3 × 3 matrix

- Linear uncertainty
  - Different incident light and normal pairs produce the same shading



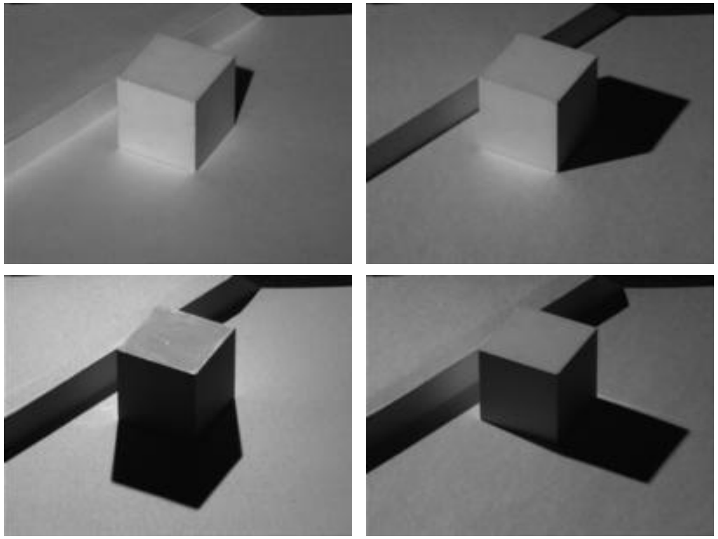


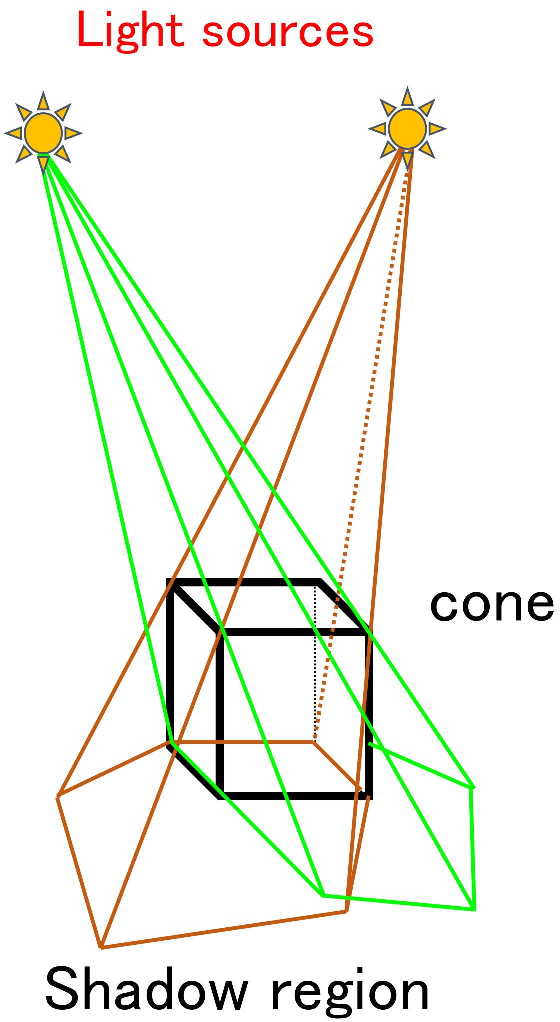
“The Bas-Relief Ambiguity”, Belhumeur et al, 1997

Shape-from-Shadow

- Limited existing space in the cone
  - top vertex: light source
  - bottom surface: shadow region
- Logical AND of many cones
- Estimate rough convex hull shape

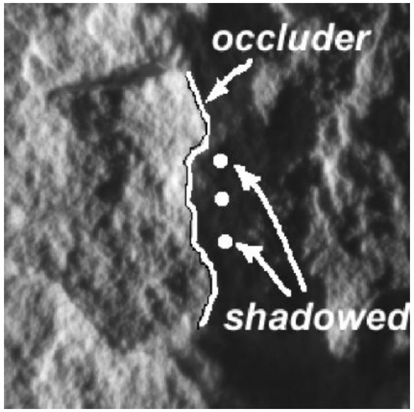
（凸包形状）

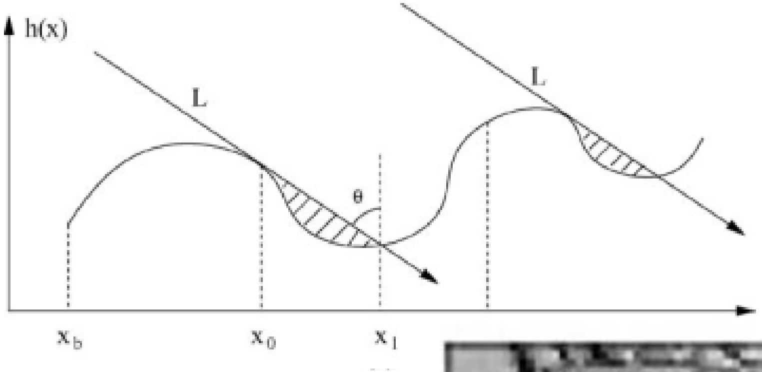




Shadow graphs

- Restrict the existing space of objects from shadows





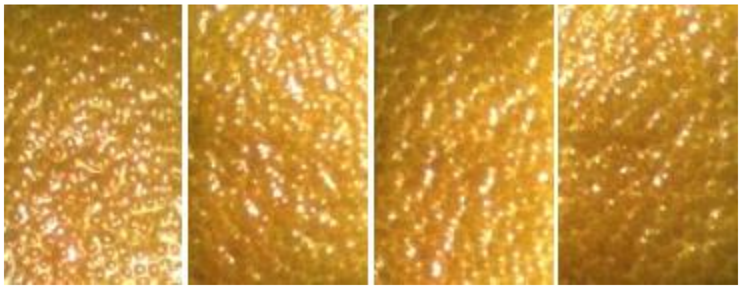
A part of the 48 input images

Shape estimation

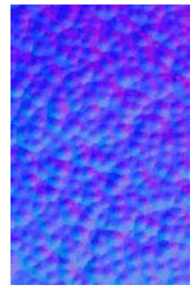
[Shadow Graphs, Yu and Chang 2005]

Shape-from-Specularity

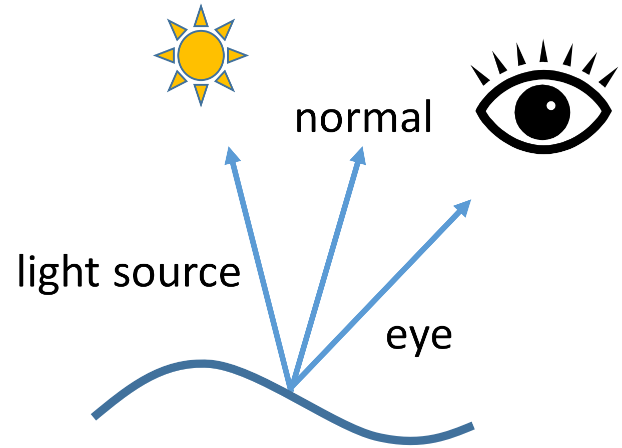
- Shape estimation based on specular reflection
  - Strong specular reflections around the mirror direction



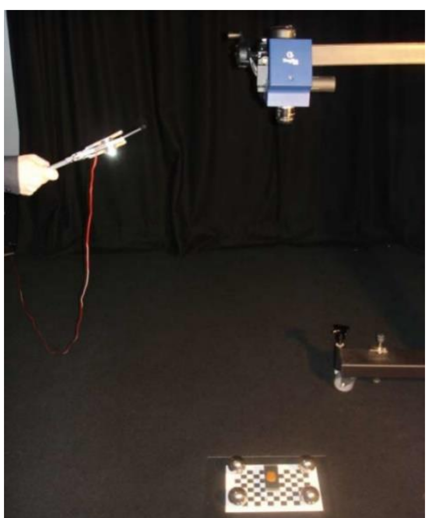
A part of 65 input images



Estimated normal map

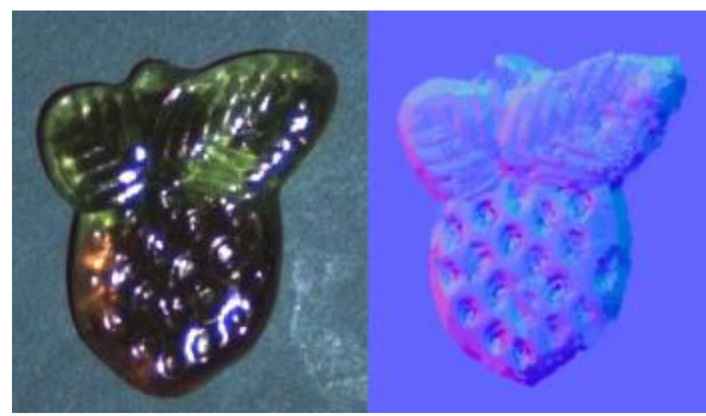


LED



Camera (12bit, 1300x1030)

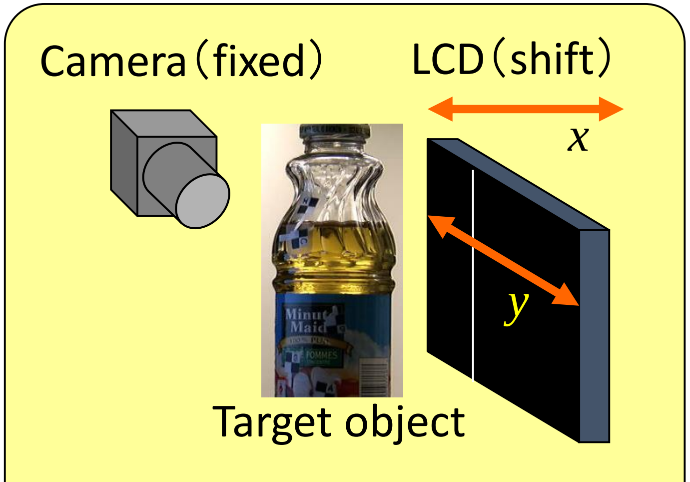
Metallic ball for estimating light source position



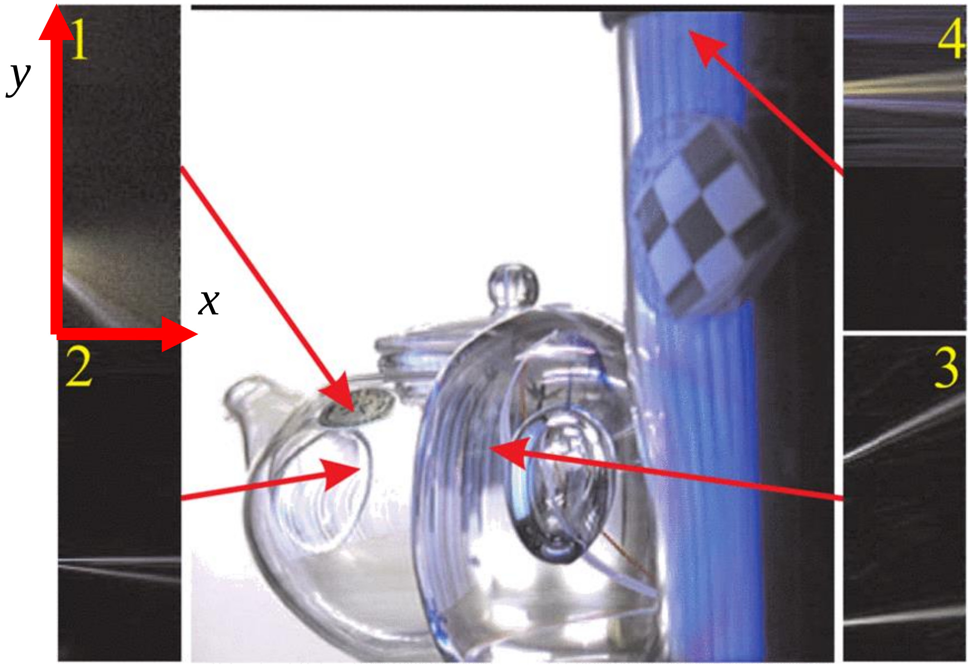
[Chen et al.,Mesostructure from Specularity (CVPR2006)]

Scatter-Trace Photography

- Shape estimation based on specular reflection
- Complex transparent scene with inhomogeneous interior
  - Observed reference pattern on the transparent object
  - Shape estimation by hypothesis and verification



Experimental setup

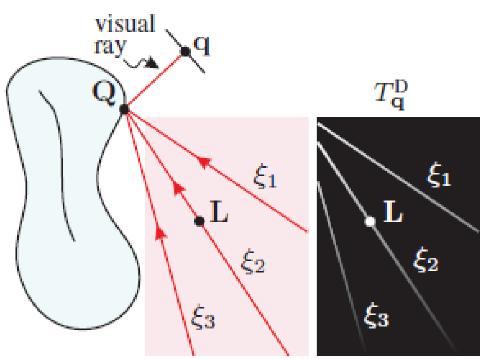


Example of Scatter-Trace at each point on the surface

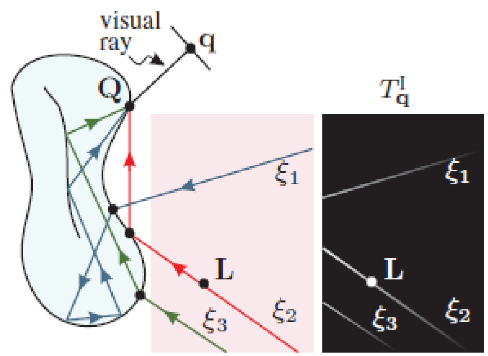
Nigel Morris and Kiriakos Kutulakos,
Reconstructing the Surface of Inhomogeneous Transparent Scenes by Scatter-Trace Photography, ICCV2007.

Analysis of Scatter-Trace

- If direct reflection on the surface, Scatter-Trace stripes
  - intersect with the eye and the surface of the object
  - monotonically decrease as the distance increases

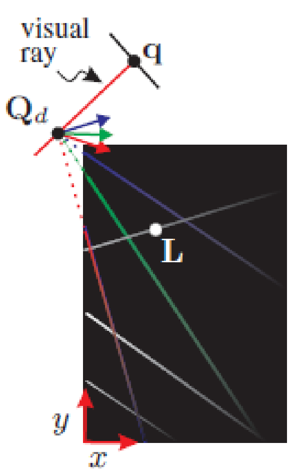


Scatter-Trace of direct reflection



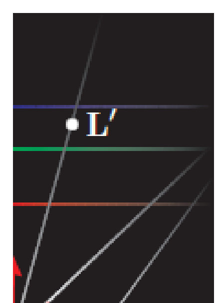
Scatter-Trace of global components

depth normal



Hypothesis

Assuming a depth, coordinate transformation at the distance from the intersection.



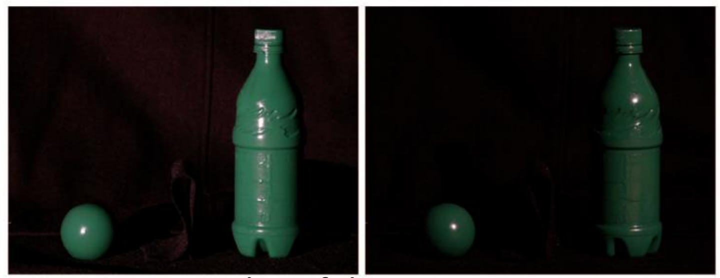
Verification

Removing non-monotonically decreasing component
→ If the direct reflection components remain, the assumed depth is correct.

Example-based Photometric Stereo

[Aaron Hertzmann and Steven M Seitz, 2005]

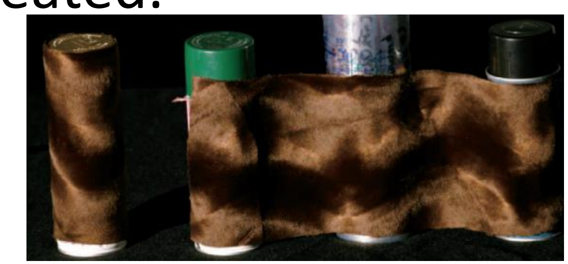
- How to handle any BRDF?
  - Reference object whose shape is known and BRDF is same with the target object to be measured.
  - Used as a look up table to find similar reflection properties.

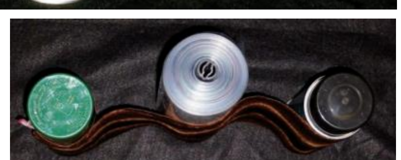


Examples of the input images

Estimated normal

  - If reference objects can be prepared, any BRDF can be treated.





Separation of reflection components
（反射成分の分解）

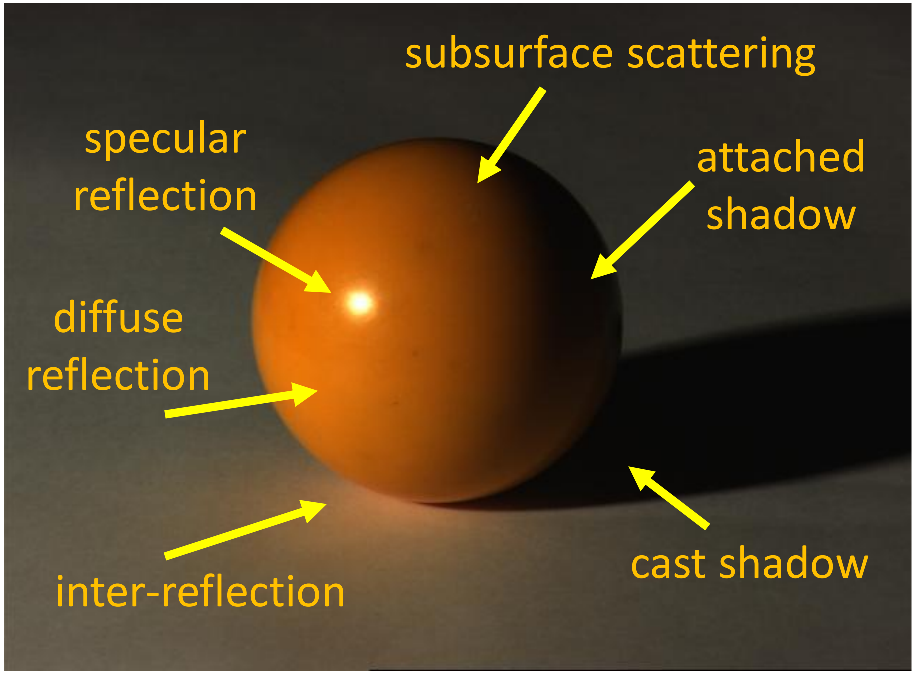
Real scene

- Many phenomena mix in real image.
- Use complex model or decompose in advance.

attached shadow — Specular reflection

$$\mathbf{i} = V(\max(\mathbf{S}^{\mathrm{T}}\tilde{\mathbf{n}}, 0)) + S + G$$

cast shadow — Global components (inter-reflection, subsurface scattering,...)

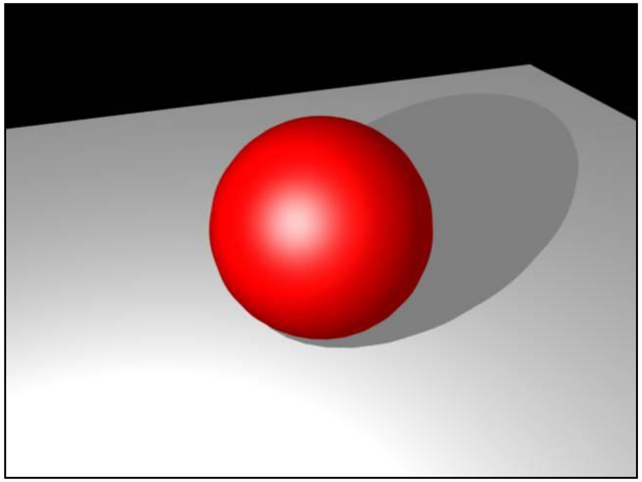


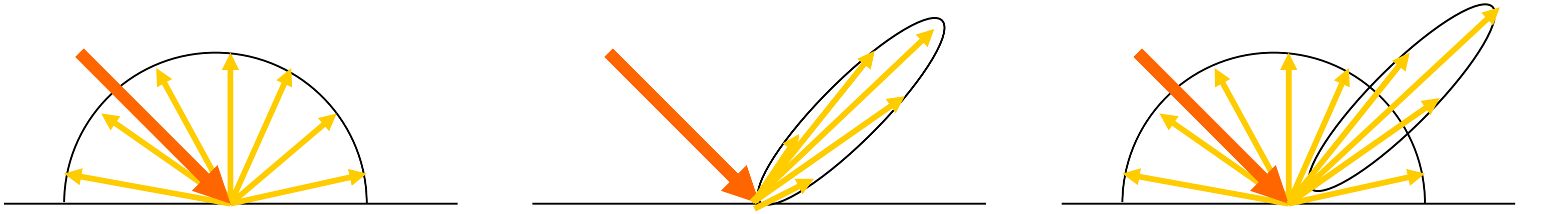
Again

Dichromatic reflection model (Shafer 1985)

（2色性反射モデル）

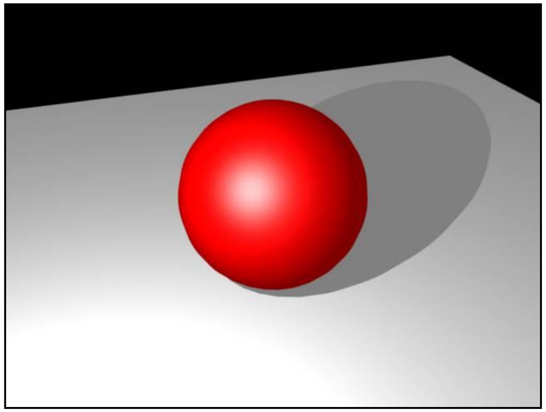
- Reflected light = **Diffuse reflection** + **Specular reflection**
- Diffuse reflection（拡散反射）:
  - Reflection inside the surface layer
  - Object color
- Specular reflection（鏡面反射）：
  - Reflection at the border between air and surface layer
  - Light color

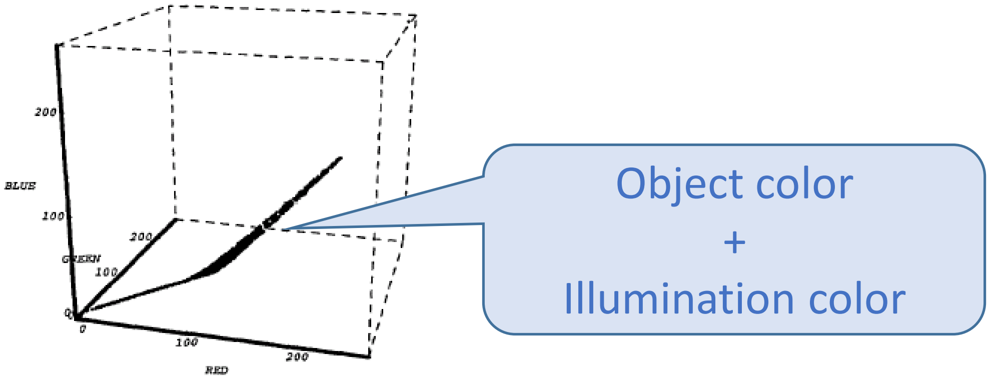


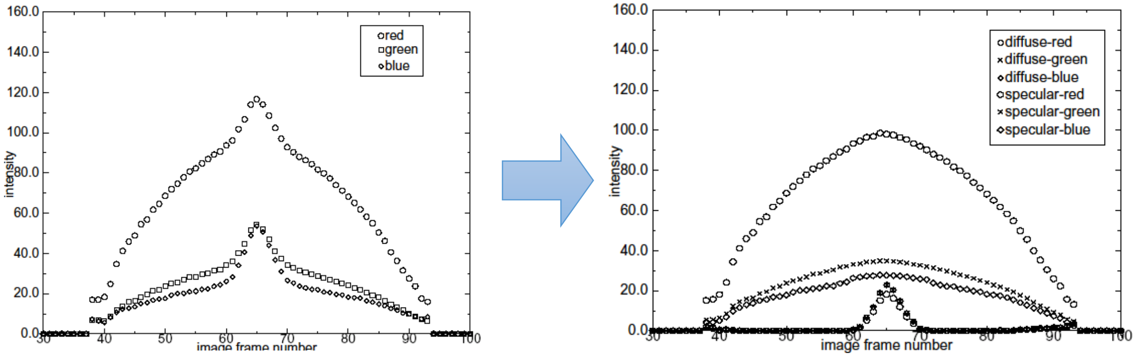


Dichromatic reflection model

- Decomposition based of color difference



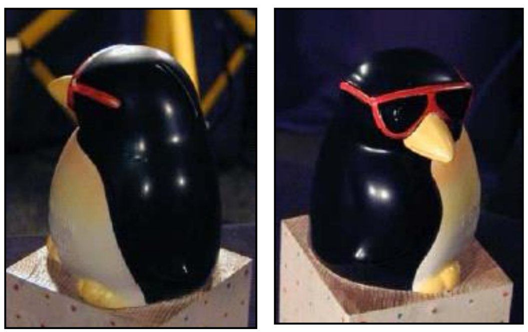




[Sato94]

Viewpoint dependency

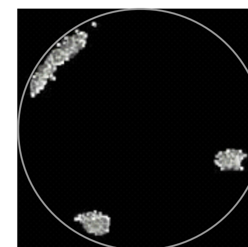
- Diffuse reflection : dependent or independent? on viewpoint
- Specular reflection : dependent or independent? on viewpoint
  - Assume uniform specular reflection characteristics
  - Simultaneous estimation of light source distribution from specular reflection components



Input image（different viewpoint ）

Diffuse reflection

Specular reflection

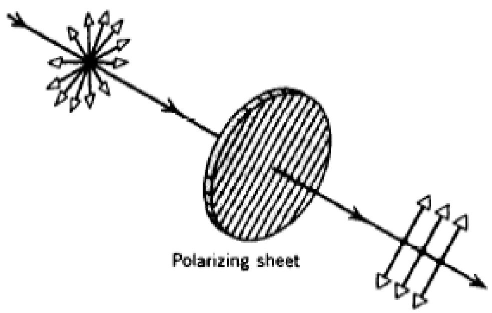


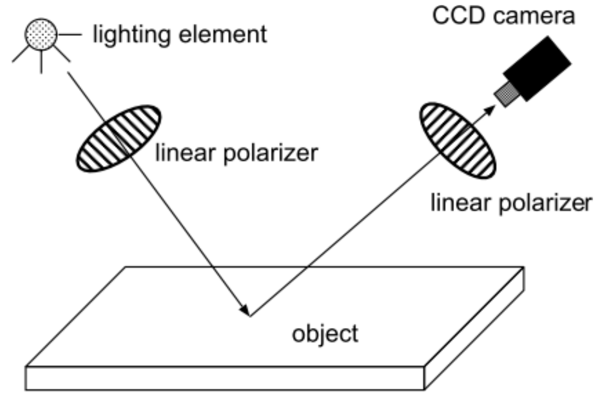
Light source distribution

[Nishino01]

Difference in polarization（偏光）

- Separate specular reflection components using polarization
- Simultaneous estimation of specular reflection parameter and near light source position
- Assuming monochromatic uniform reflection characteristics





[原02]

Input image　Diffuse reflection component　Specular reflection component

RANSAC-based method

- Convert real image into pure Lambert image based on RANSAC (RANdom SAmple Consensus)
  - Choose three images randomly from the input image set, converted to fully satisfy Lambert model (linearization)
  - Remove shadows and specular reflections as outliers

attached shadow

$$\mathbf{i} = V(\max(\mathbf{S}^{\mathrm{T}}\tilde{\mathbf{n}},0)) + S$$

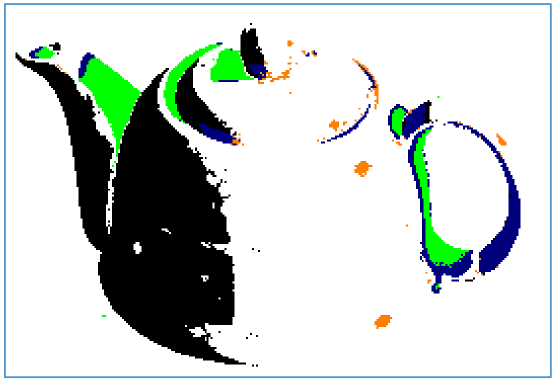
cast shadow | Specular reflection

conversion →

$$\mathbf{i} = \mathbf{S}^{\mathrm{T}}\tilde{\mathbf{n}}$$

One of the input image

Linearized image (Negative: red)

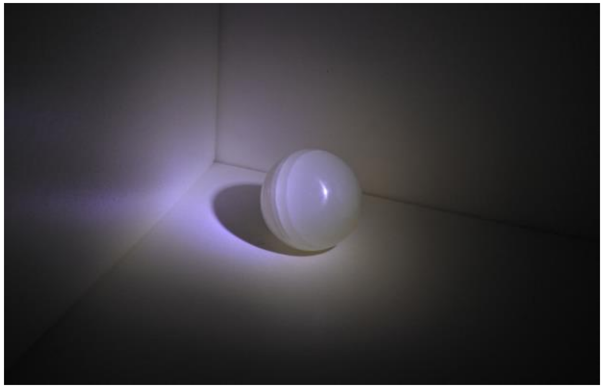


Estimation of optical phenomena

Y. Mukaigawa, et al, ``Analysis of photometric factors based on photometric linearization'', JOSA2007

Some approaches to handle more complex scene

- Preprocess to extract pure Lambert diffuse reflection component
  - Optically or mathematically
- Use mode complex model
  - Since the parameter increases, it may become unstable
- Solve in the framework of robust estimation
  - Use many input images and consider non-Lambert components as outliers
- Solve by deep learning



Summary

- From the shading information, not only photometric information such as color and reflection properties, but also geometric information such as normal can be extracted.
- Photometric stereo cannot estimate mini-report. It can estimate mini-report.
- Many traditional methods assume Lambert diffuse reflection, but extended to more complex scene in recent years.