光度立体

目录

- 相机光影成像模型
- 光度立体

1 –相机光影成像模型

Light and Shading

- **The brightness of a pixel in the image is a function of the brightness of the surface patch in the scene that projects to the pixel.**

- **Camera response**
  - **相机的光学感应—线性感应、非线性感应**
- **Surface reflection**
  - **物体的光照反射—漫反射、镜面反射**
- **Illumination**
  - **光照的来源—Lambert’s cosine law**

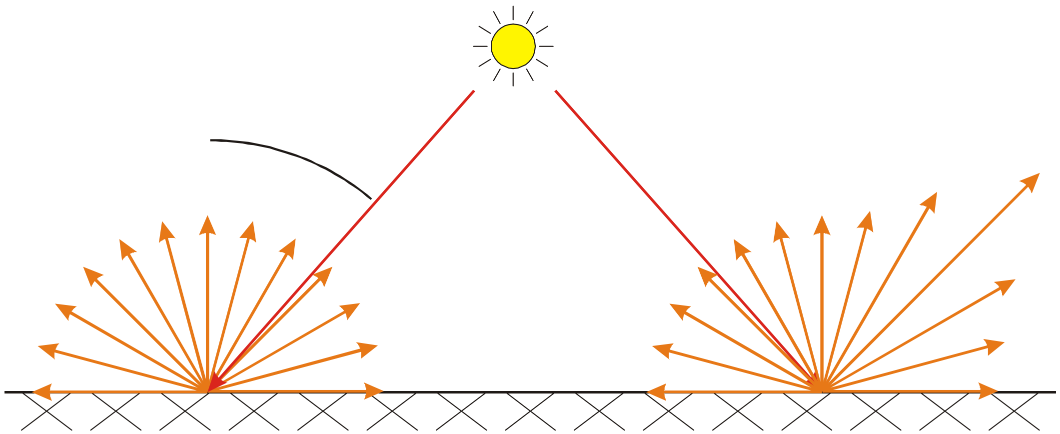
Light and Shading

- **Camera response**
  - $I_{camera}(x)=k\ I_{patch}(x)$

- **Surface reflection**
  - 漫反射、镜面反射

$$I \propto \cos\theta = \mathbf{N}\cdot\mathbf{L}$$

I = radiance (intensity)
$\mathbf{N}$ = unit normal vector
$\mathbf{L}$ = unit source vector
θ = angle between $\mathbf{N}$ and $\mathbf{L}$



Light and Shading

- Illumination

$$\begin{array}{ccccccc} I(\boldsymbol{x}) & = & \rho(\boldsymbol{x})\,(\boldsymbol{N}\cdot\boldsymbol{S})\,\mathrm{Vis}(\boldsymbol{S},\,\boldsymbol{x}) & + & \rho(\boldsymbol{x})A & + & M \\ \text{Image intensity} & = & \text{Diffuse term} & + & \text{Ambient term} & + & \text{Specular (mirror-like) term} \end{array}$$

$$I = \rho I_0 \cos\theta,$$

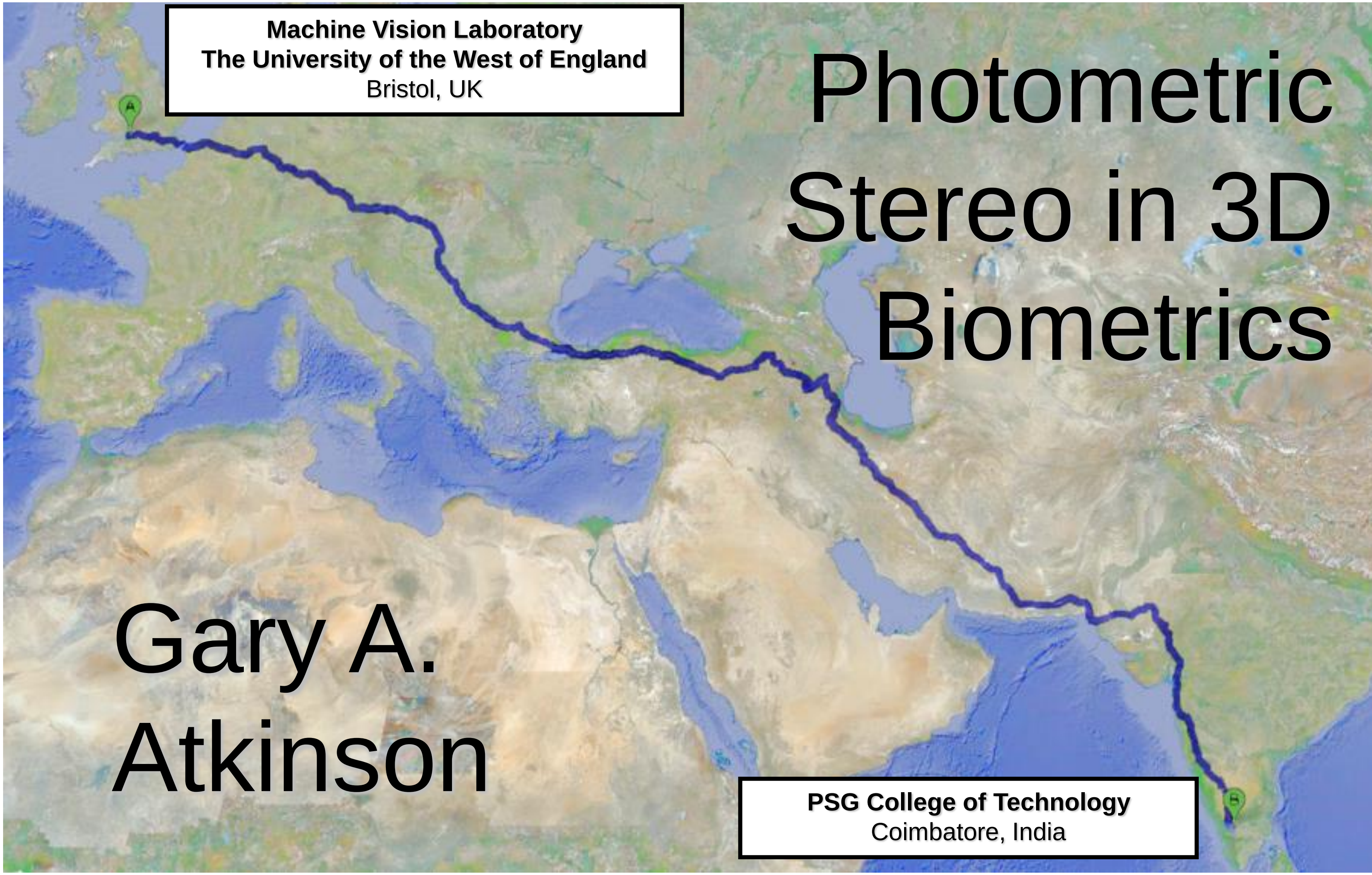
漫反射

2 –光度立体

University of the West of England
BRISTOL

Machine Vision Laboratory

2nd September 2010
ICEBT



Machine Vision Laboratory
The University of the West of England
Bristol, UK

Photometric Stereo in 3D Biometrics

Gary A. Atkinson

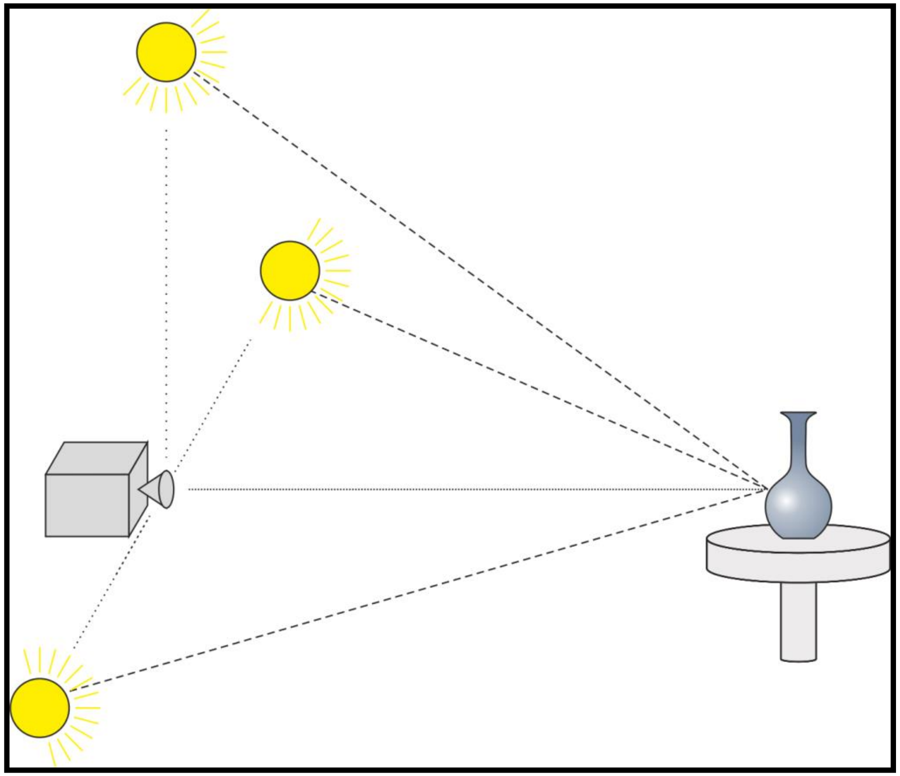
PSG College of Technology
Coimbatore, India

Overview

1. What is photometric stereo?
2. Why photometric stereo?
3. The basic method
4. Advanced methods
5. Applications

1. What is Photometric Stereo?

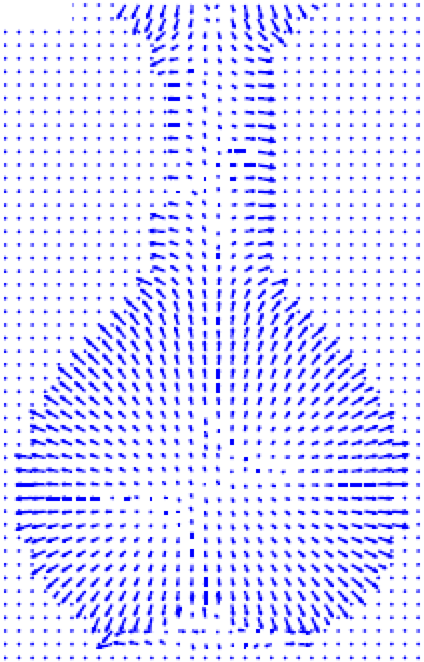
A method of estimating surface geometry using multiple light source directions



Captured images

1. What is Photometric Stereo?

A method of estimating surface geometry using multiple light source directions



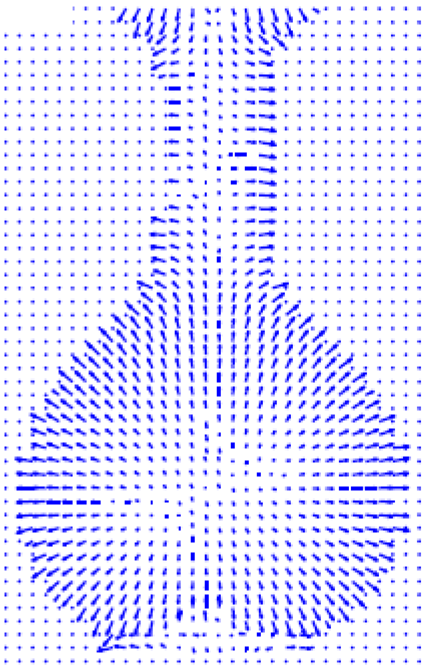
Captured images

Surface normals

1. What is Photometric Stereo?

A method of estimating surface geometry using multiple light source directions

Depth map



Surface normals

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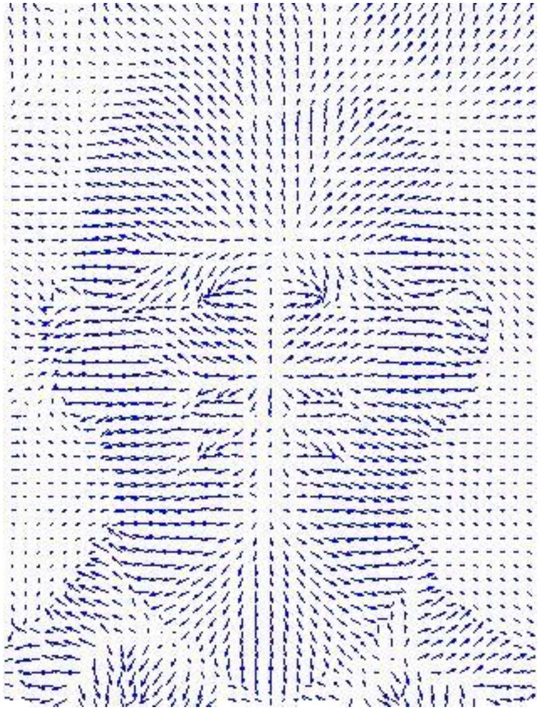

Depth map

Surface normals

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1. What is photometric stereo?
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2. Why photometric Stereo?

Why 3D?

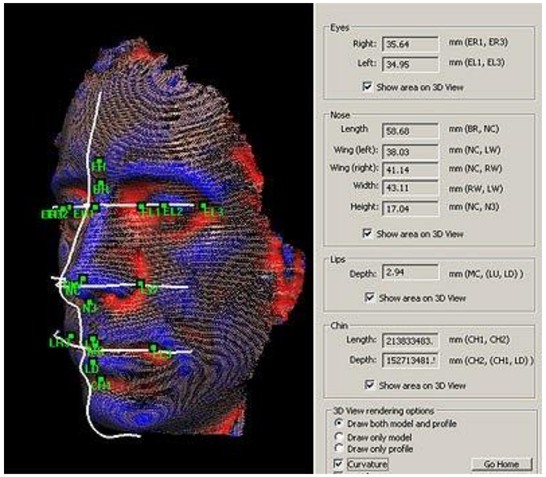
Why PS in particular?

2. Why photometric Stereo?

Why 3D?

Why PS in particular?

1. Robust face recognition
2. Ambient illumination independence
3. Facilitates pose correction
4. Non-contact fingerprint analysis



Richer dataset in 3D

2. Why photometric Stereo?

Why 3D? Why PS in particular?

1. Robust face recognition
2. Ambient illumination independence
3. Facilitates pose, expression correction
4. Non-contact fingerprint analysis

- Same day
- Same camera
- Same expression
- Same pose
- Same background
- Even same shirt
- Different illumination

Completely different image

2. Why photometric Stereo?

Why 3D? Why PS in particular?

1. Robust face recognition
2. Ambient illumination independence
3. Facilitates pose, expression correction
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   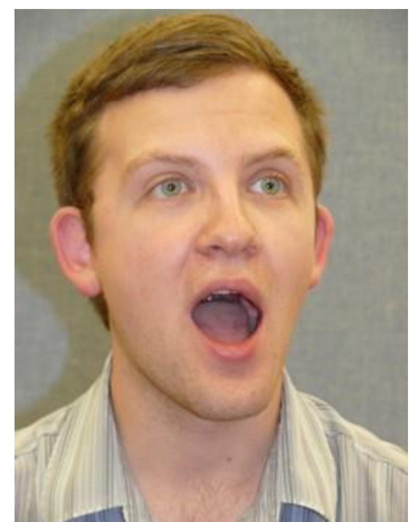

Overview

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3. The Basic Method – Assumptions

Assumptions:

1. No cast/self-shadows or specularities
2. Greyscale/linear imaging
3. Distant and uniform light sources
4. Orthographic projection
5. Static surface
6. Lambertian reflectance

[Argyriou and Petrou]

$$I \propto \cos\theta = \mathbf{N}\cdot\mathbf{L}$$

I = radiance (intensity)
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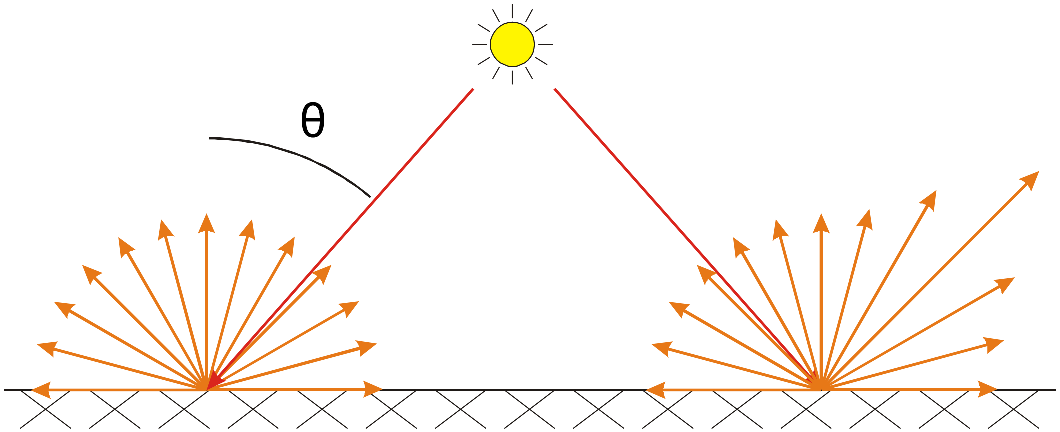
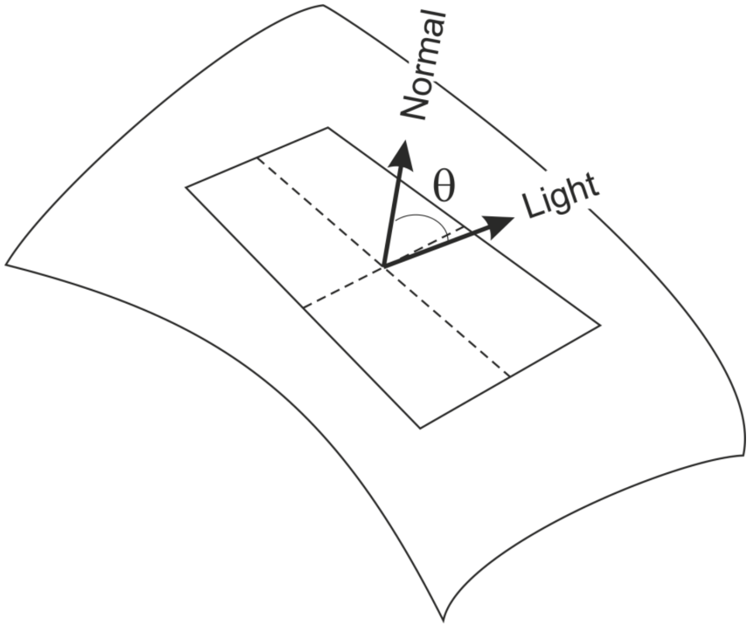


3. The Basic Method – Preliminary notes



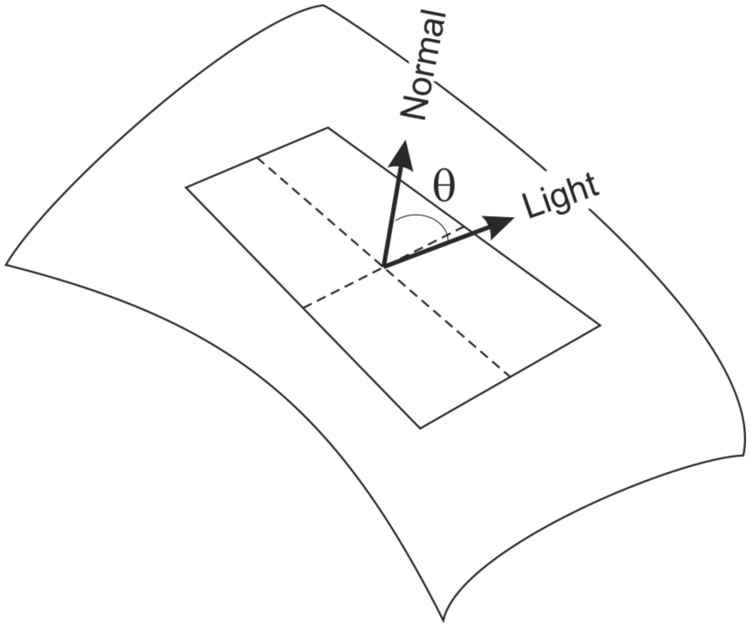
Equation of a plane

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

Surface normal vector to plane

$$\mathbf{N} = [A, B, C]^T$$

3. The Basic Method – Preliminary notes



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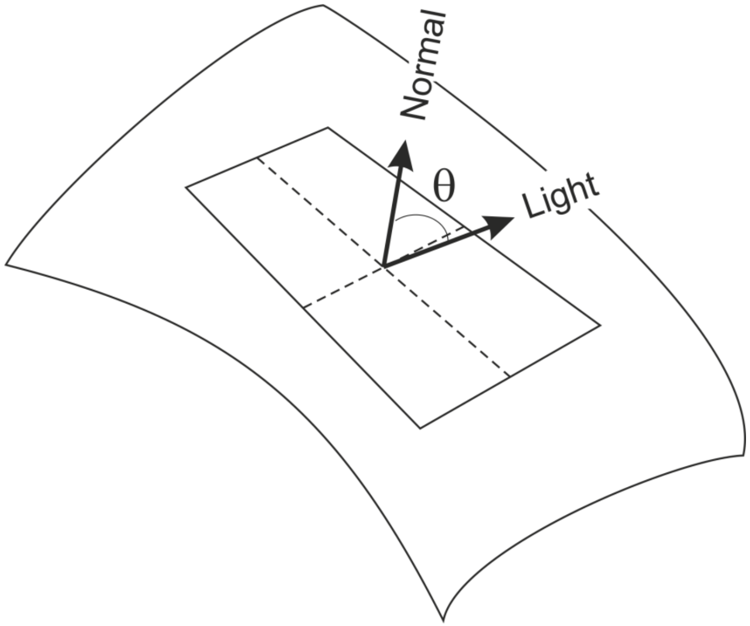

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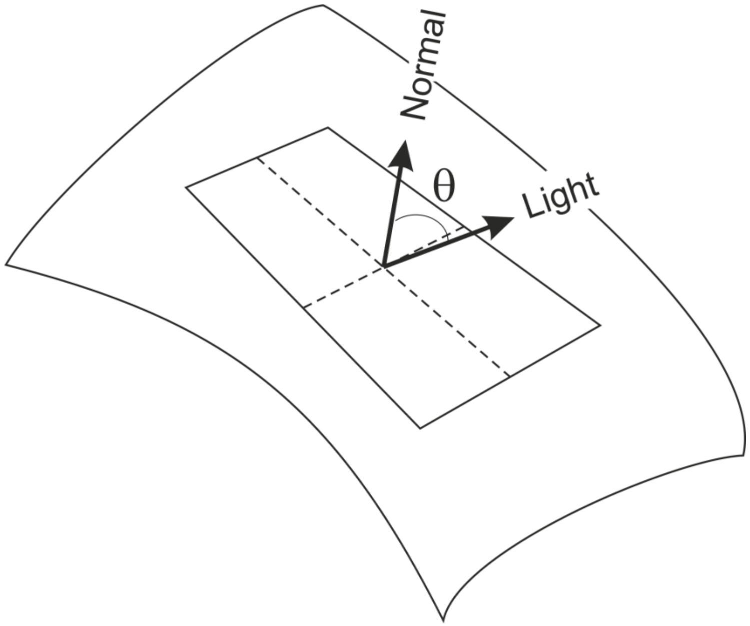

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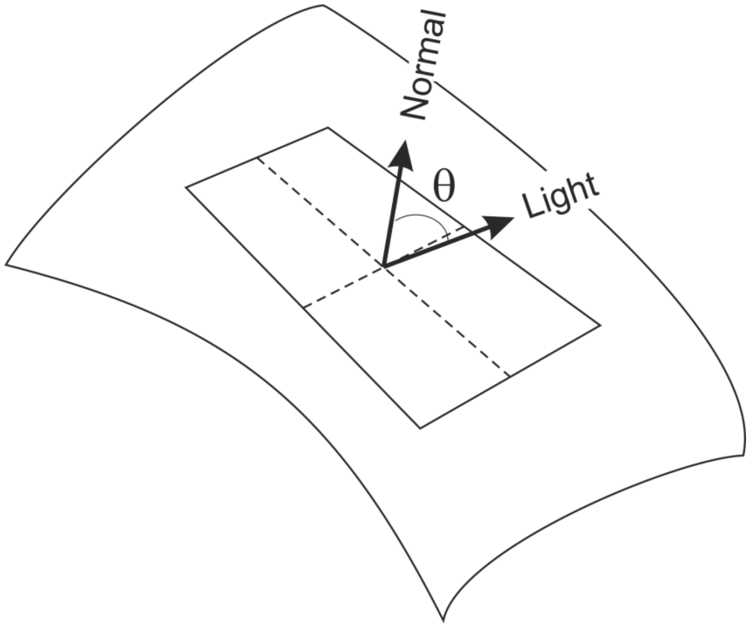
Rescaled surface normal

$$\mathbf{n} = \left[\frac{A}{C}, \frac{B}{C}, 1\right]^T = \left[-\frac{\partial z}{\partial x}, -\frac{\partial z}{\partial y}, 1\right]^T$$

3. The Basic Method – Preliminary notes



Equation of a plane

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

Surface normal vector to plane

$$\mathbf{N} = [A, B, C]^T$$

$$z = -\frac{A}{C}x - \frac{B}{C}y - \frac{D}{C}$$

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

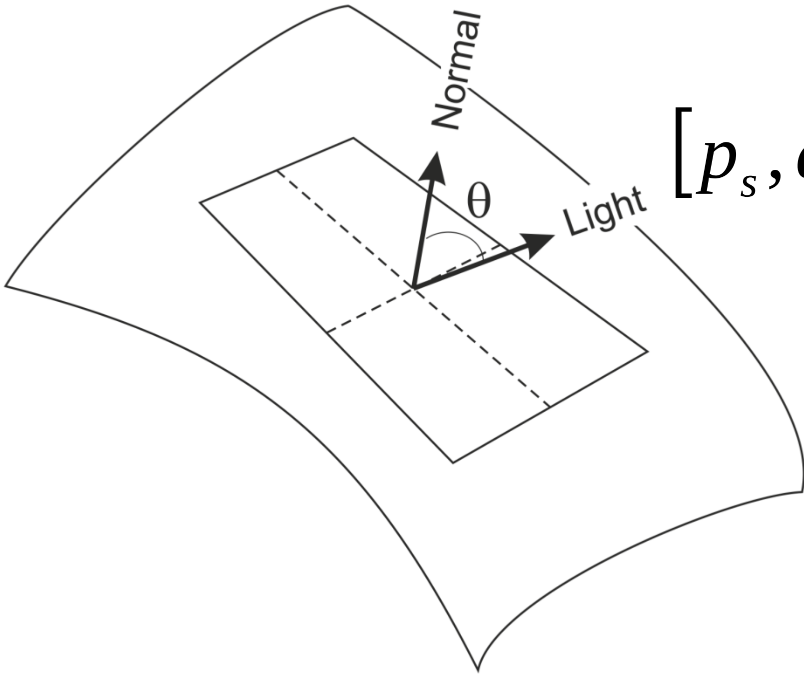
Rescaled surface normal typically written

$$\mathbf{n} = \left[\frac{\partial z}{\partial x}, \frac{\partial z}{\partial y}, -1\right]^T = [p, q, -1]^T$$

3. The Basic Method – Reflectance Equation

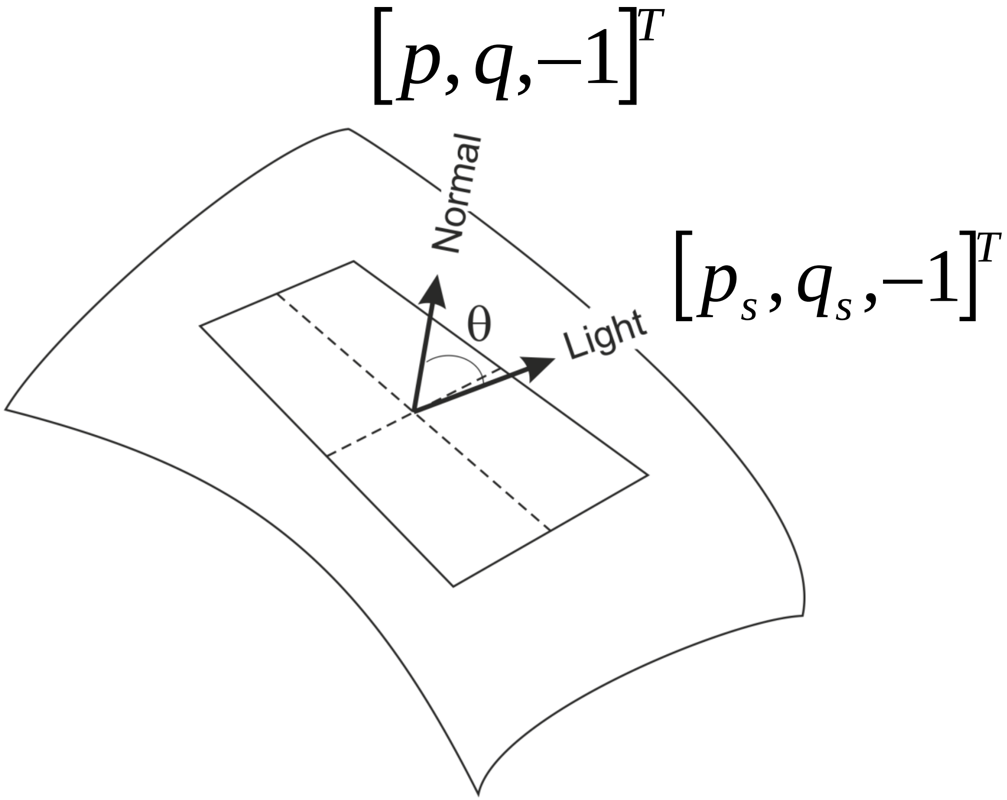
$$[p, q, -1]^T$$

$$[p_s, q_s, -1]^T$$



Consider the imaging of an object with one light source.

3. The Basic Method – Reflectance Equation



Lambertian reflection

$$E = \rho L \cos\theta$$

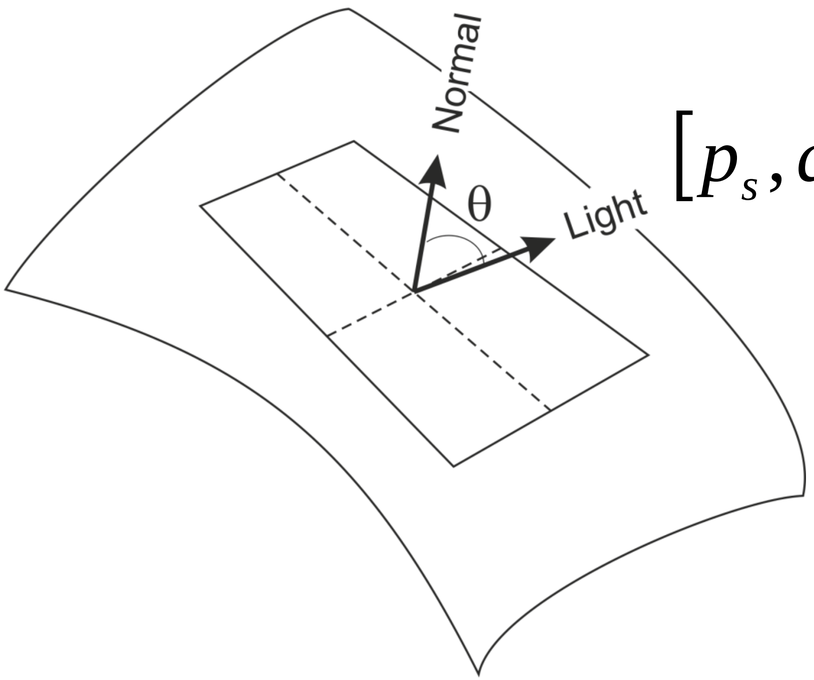
E = emittance

ρ = albedo

L = irradiance

3. The Basic Method – Reflectance Equation

$$[p, q, -1]^T$$



$$[p_s, q_s, -1]^T$$

Lambertian reflection

$$E = \rho L \cos\theta$$

E = emittance

ρ = albedo

L = irradiance

Take scalar product of light source vector and normal vector to obtain $\cos\theta$:

$$pp_s + qq_s + 1 = \sqrt{p^2 + q^2 + 1}\sqrt{p_s{}^2 + q_s{}^2 + 1}\cos\theta$$

3. The Basic Method – Shape-from-Shading

Perform substitution with Lambert's law $E = \rho L \cos\theta$

$$E = \rho L \frac{pp_s + qq_s + 1}{\sqrt{p^2 + q^2 + 1}\sqrt{p_s{}^2 + q_s{}^2 + 1}}$$

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$$E = \rho L \frac{pp_s + qq_s + 1}{\sqrt{p^2 + q^2 + 1}\sqrt{p_s{}^2 + q_s{}^2 + 1}}$$

If ρ is re-defined and the camera response is linear, then

$$I = \rho' \frac{pp_s + qq_s + 1}{\sqrt{p^2 + q^2 + 1}\sqrt{p_s{}^2 + q_s{}^2 + 1}}$$

3. The Basic Method – Shape-from-Shading

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$$E = \rho L \frac{pp_s + qq_s + 1}{\sqrt{p^2 + q^2 + 1}\sqrt{p_s^{\,2} + q_s^{\,2} + 1}}$$

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Known: p_s, q_s, I

Unknown: p, q, ρ

1 equation,
3 unknowns

→ Insoluble

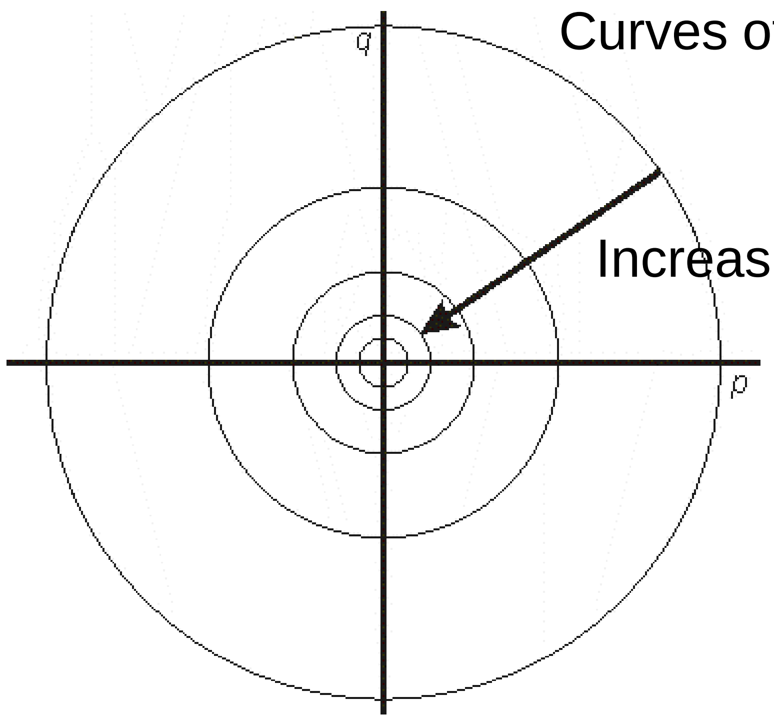
3. The Basic Method – Shape-from-Shading

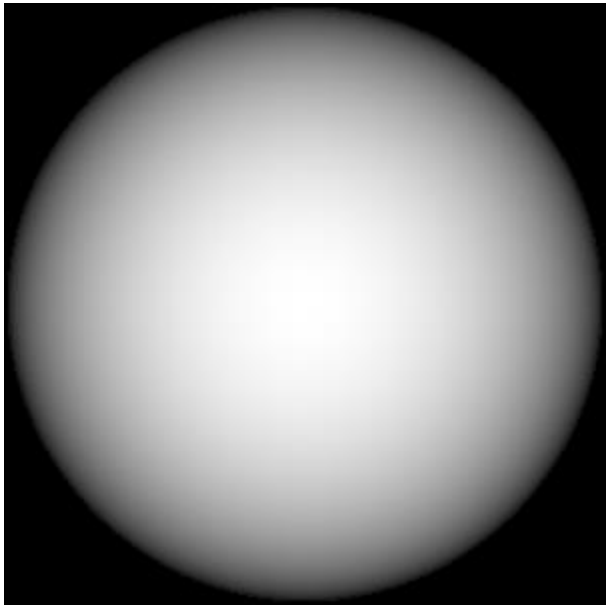
$$I = \rho \frac{pp_s + qq_s + 1}{\sqrt{p^2 + q^2 + 1}\sqrt{p_s^{\,2} + q_s^{\,2} + 1}}$$

For a given intensity measurement, the values of p and q are confined to one of the lines (circles here) in the graph.

Curves of constant I/ρ

$$p_s = q_s = 0$$



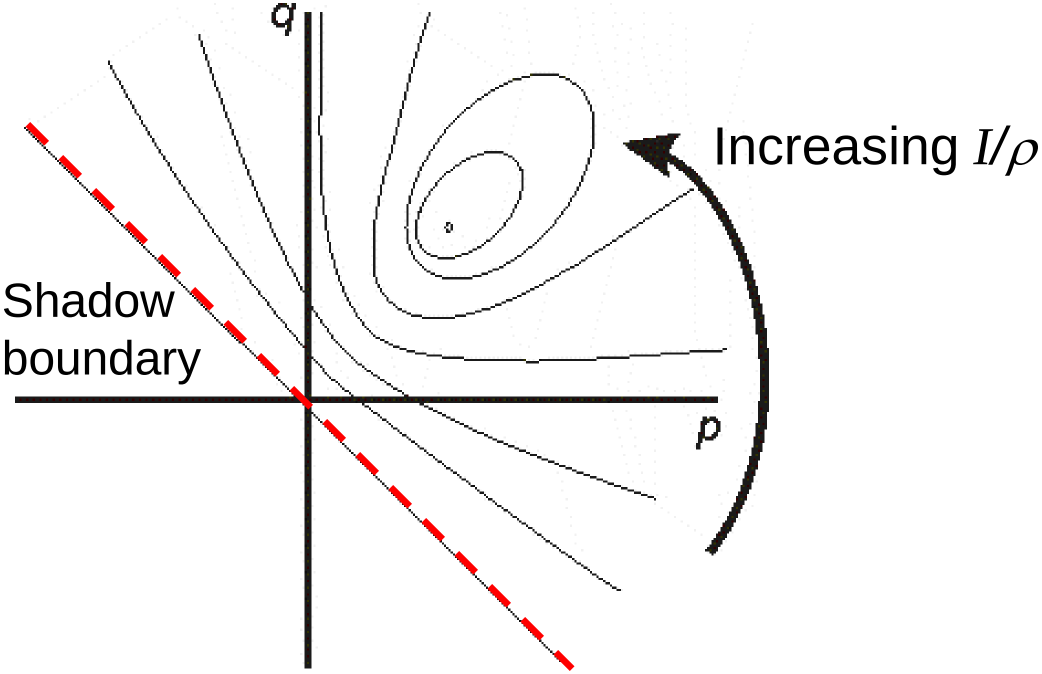


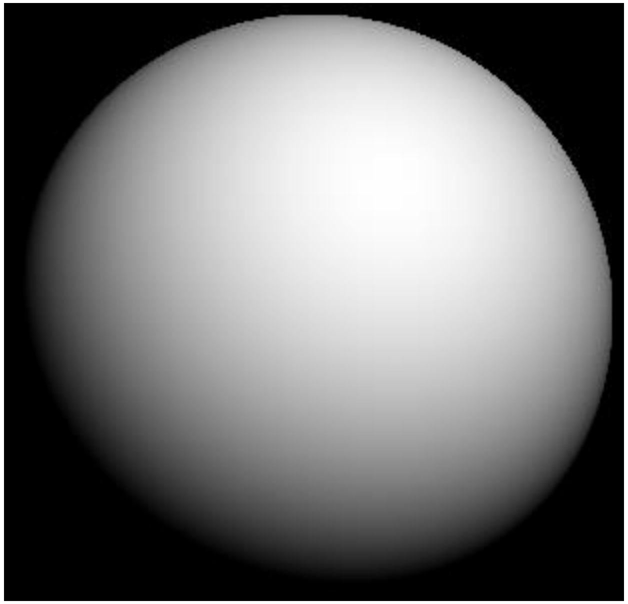
3. The Basic Method – Shape-from-Shading

$$I = \rho \frac{pp_s + qq_s + 1}{\sqrt{p^2 + q^2 + 1}\sqrt{p_s^{\ 2} + q_s^{\ 2} + 1}}$$

For a given intensity measurement, the values of p and q are confined to one of the lines (circles here) in the graph.

$$p_s = q_s = 0.5$$

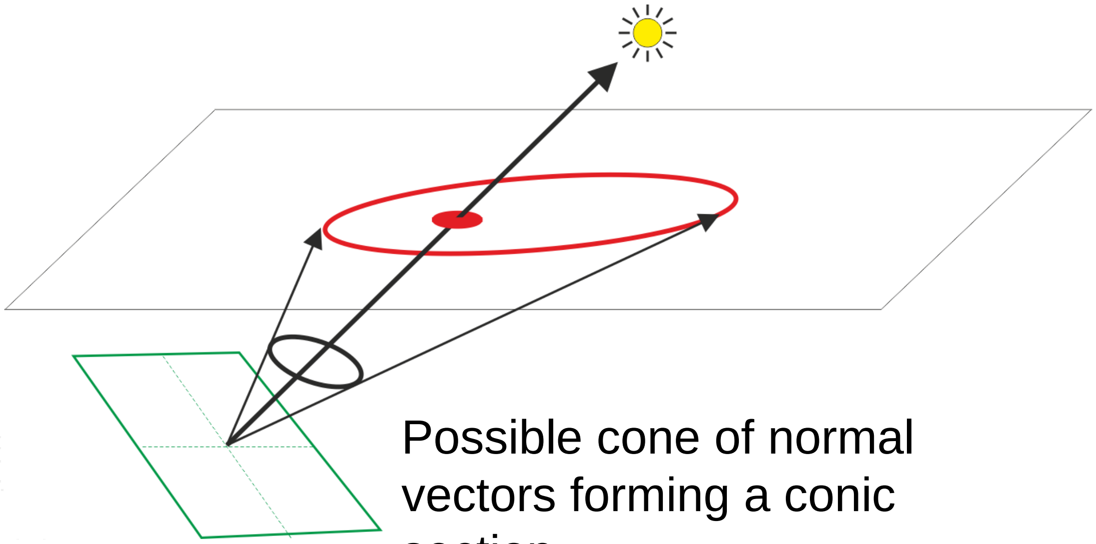




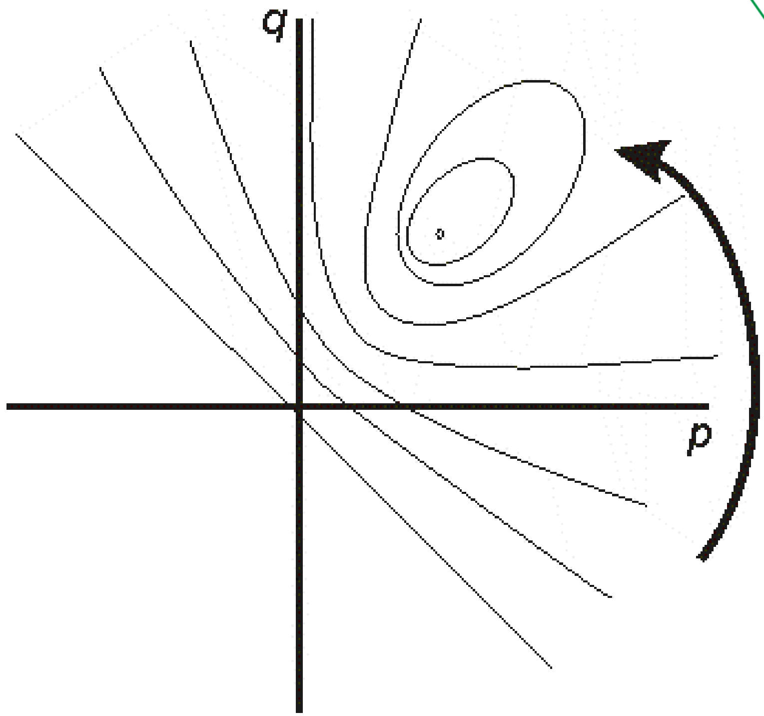
This is the result for a different light source direction.

3. The Basic Method – Shape-from-Shading

Representation using conics

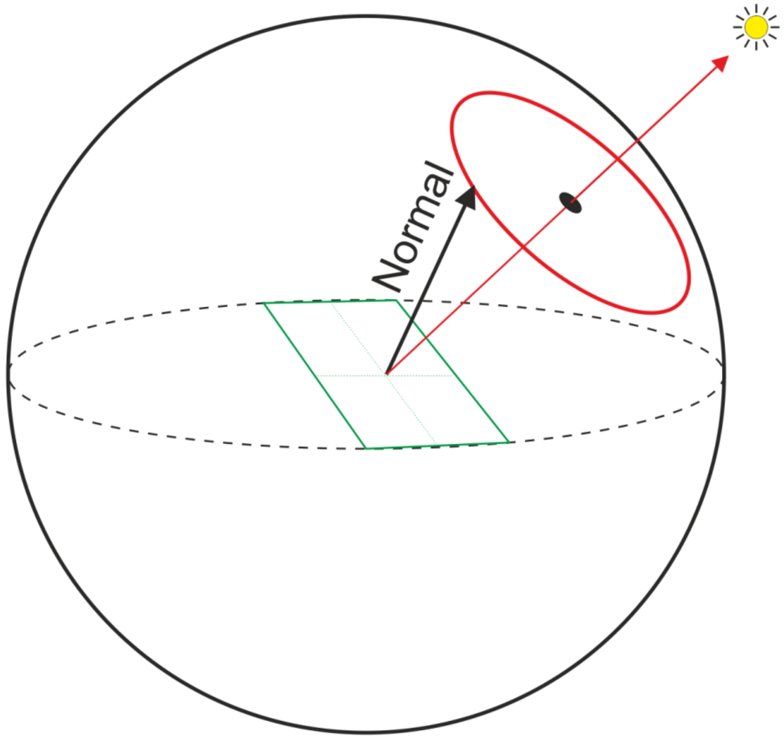


Possible cone of normal vectors forming a conic section.



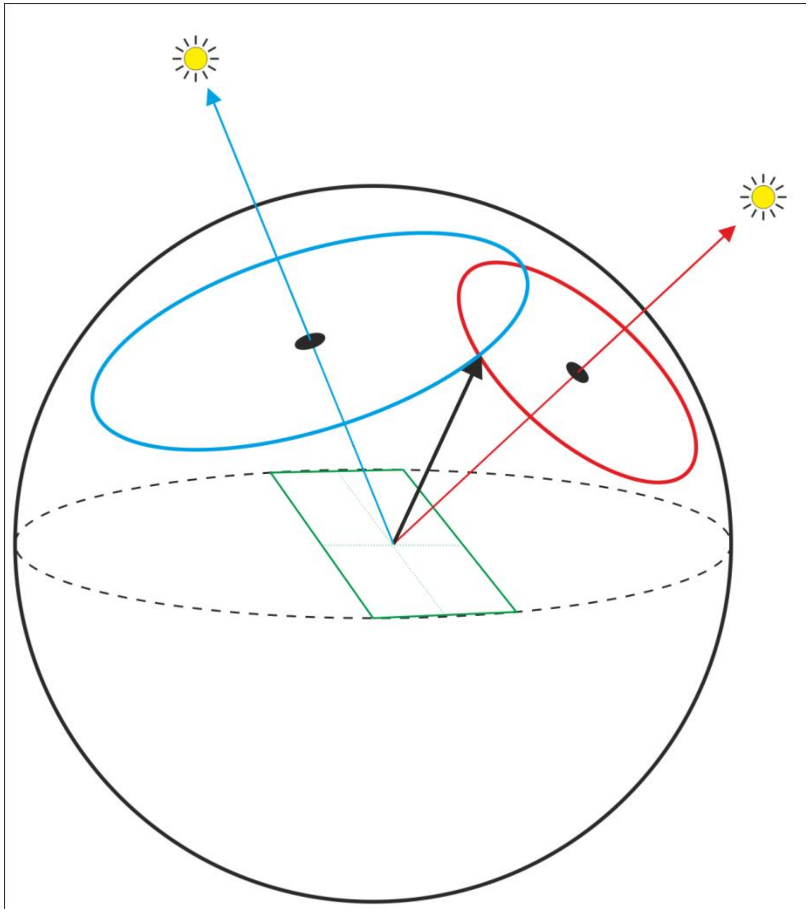
<u>3. The Basic Method – Shape-from-Shading</u>

Representation on unit sphere



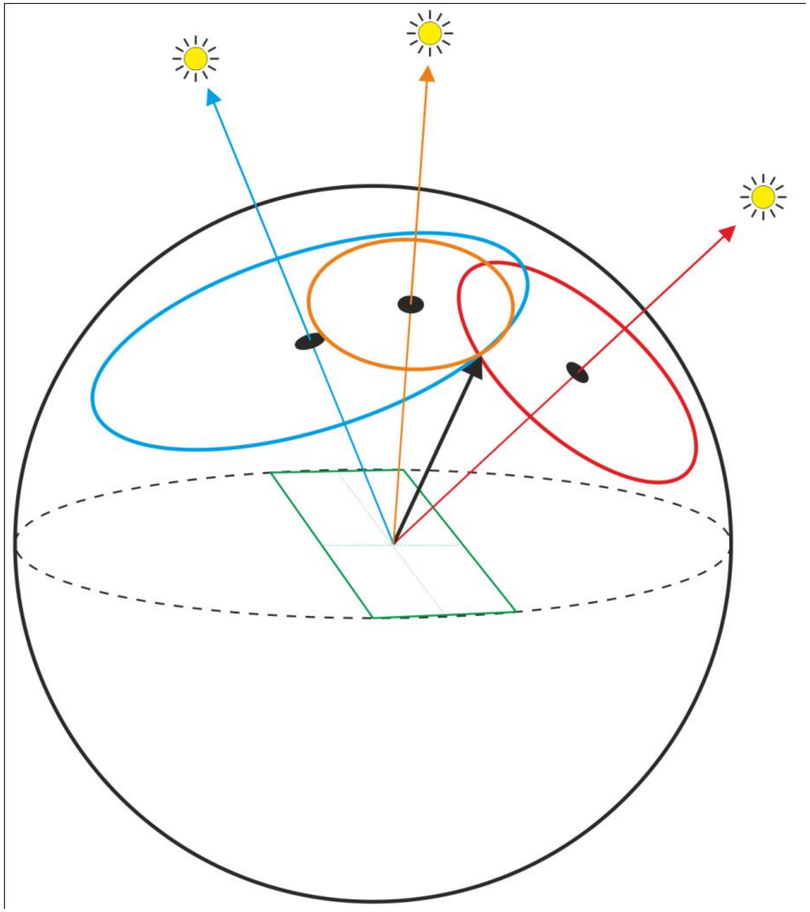
We can overcome the cone ambiguity using several light source directions: <u>Photometric Stereo</u>

3. The Basic Method – Two Sources



Two sources: normal confined to two points
– Or fully constrained if the albedo is known

3. The Basic Method – Three Sources



Three sources: fully constrained

3. The Basic Method – Matrix Representation

$$I = \rho \cos\theta$$

$$I = \rho \mathbf{N} \cdot \mathbf{s} = \rho \begin{bmatrix} s_x \\ s_y \\ s_z \end{bmatrix}^T \begin{bmatrix} N_x \\ N_y \\ N_z \end{bmatrix}$$

$\mathbf{N} =$ **Unit** surface normal

$\mathbf{s} =$ **Unit** light source vector

(using slightly different symbols to aid clarity)

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(using slightly different symbols to aid clarity)

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \rho \begin{bmatrix} s_x^1 & s_y^1 & s_z^1 \\ s_x^2 & s_y^2 & s_z^2 \\ s_x^3 & s_y^3 & s_z^3 \end{bmatrix} \begin{bmatrix} N_x \\ N_y \\ N_z \end{bmatrix}$$

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$$\begin{bmatrix} s_x^1 & s_y^1 & s_z^1 \\ s_x^2 & s_y^2 & s_z^2 \\ s_x^3 & s_y^3 & s_z^3 \end{bmatrix}^{-1} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \rho \begin{bmatrix} N_x \\ N_y \\ N_z \end{bmatrix}$$

3. The Basic Method – Matrix Representation

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Recall that, based on the surface gradients, $\mathbf{n} = [p, q, -1]^T$

$$\mathbf{N} = \left[\frac{p}{\sqrt{p^2 + q^2 + 1}}, \frac{q}{\sqrt{p^2 + q^2 + 1}}, \frac{-1}{\sqrt{p^2 + q^2 + 1}} \right]^T$$

3. The Basic Method – Matrix Representation

$$\begin{bmatrix} s_x^1 & s_y^1 & s_z^1 \\ s_x^2 & s_y^2 & s_z^2 \\ s_x^3 & s_y^3 & s_z^3 \end{bmatrix}^{-1} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \rho \begin{bmatrix} N_x \\ N_y \\ N_z \end{bmatrix} = \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix}$$

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$$\mathbf{N} = \left[\frac{p}{\sqrt{p^2 + q^2 + 1}}, \frac{q}{\sqrt{p^2 + q^2 + 1}}, \frac{-1}{\sqrt{p^2 + q^2 + 1}} \right]^T$$

Substituting and re-arranging these equations gives us

$$p = -\frac{m_x}{m_z}, \quad q = -\frac{m_y}{m_z}, \quad \rho = \sqrt{m_x{}^2 + m_y{}^2 + m_z{}^2}$$

That is, the surface normals/gradient and albedo have been determined.

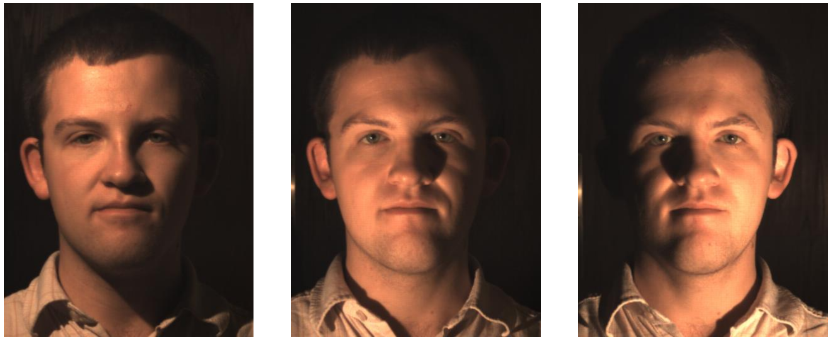
3. The Basic Method – Linear Algebra Note

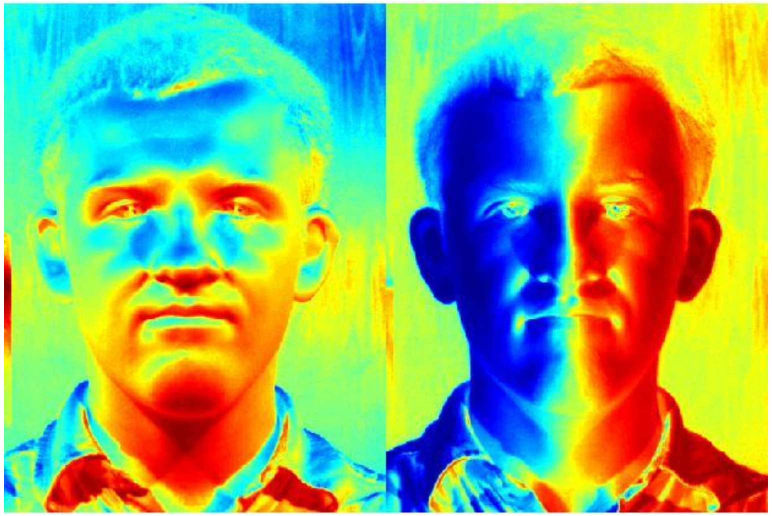
If the three light source vectors are co-planar, then the light source matrix becomes non-singular – i.e. cannot be inverted, and the equations are insoluble.

$$p = -\frac{m_x}{m_z}, \quad q = -\frac{m_y}{m_z}, \quad \rho = \sqrt{{m_x}^2 + {m_y}^2 + {m_z}^2}$$

That is, the surface normals/gradient and albedo have been determined.

3. The Basic Method – Example results





Surface normals

Albedo map

More on applications of this later...

What about the depth?

3. The Basic Method – Surface Integration

Recall the relation between surface normal and gradient:

$$\mathbf{n} = \left[\frac{\partial z}{\partial x}, \frac{\partial z}{\partial y}, -1 \right]^T$$

Memory jogger from calculus:

$$p = \frac{\mathrm{d}z}{\mathrm{d}x}$$

$$z = \int \mathrm{d}z = \int p\,\mathrm{d}x$$

$$z = \sum \delta z = \sum p\,\delta x$$

3. The Basic Method – Surface Integration

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$$z = \int \mathrm{d}z = \int p\,\mathrm{d}x$$

$$z = \sum \delta z = \sum p\,\delta x$$

So the height can be determined via an integral (or summation in the discrete world of computer vision). This can be written in several ways:

$$z(P) = z(P_0) + \int_{P_0}^{P} (p\,\mathrm{d}x + q\,\mathrm{d}y)$$

$$z(u,v) = \int_0^u q(0,y)\,\mathrm{d}y + \int_0^v p(x,v)\,\mathrm{d}x + c$$

$$z(x,y) = \oint_C (p,q)\,d\boldsymbol{l} + c$$

3. The Basic Method – Surface Integration

So we can generate a height map by summing up individual normal components. Simple, right?

WRONG!!!

3. The Basic Method – Surface Integration

So we can generate a height map by summing up individual normal components. Simple, right?

WRONG!!!

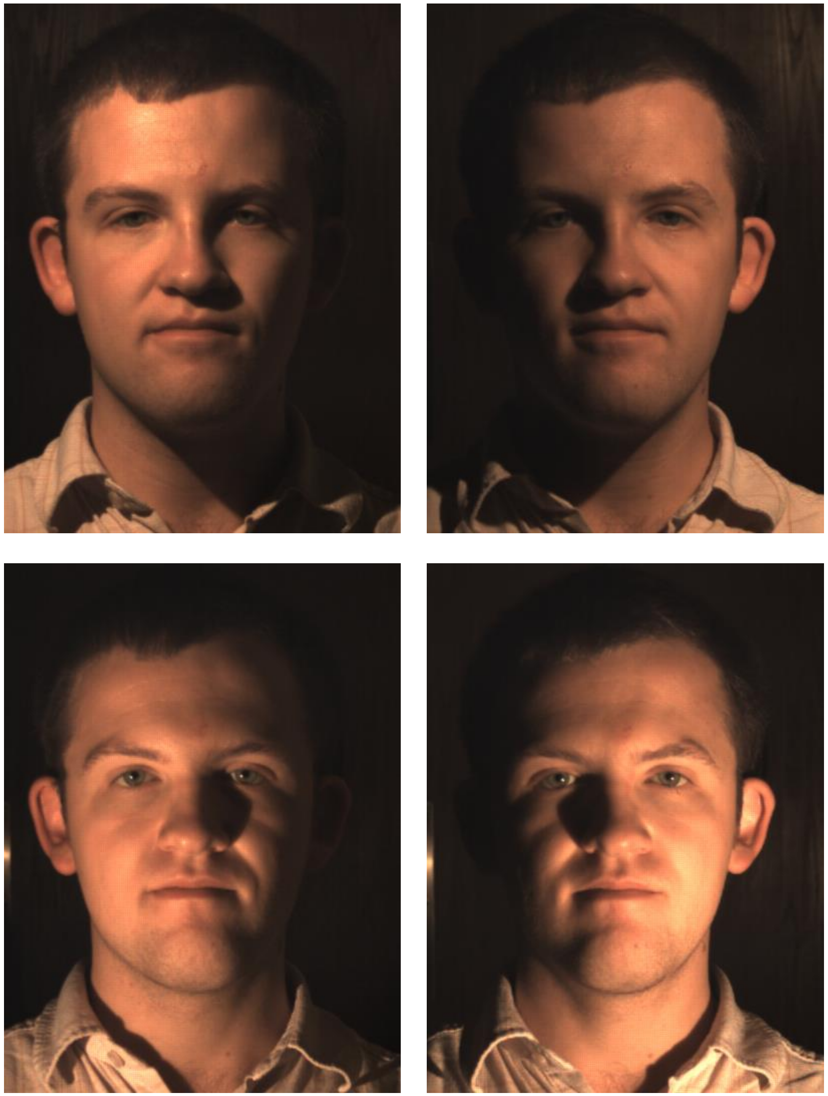
- Depends on the path taken
- Is affected by noise
- Cannot handle discontinuities
- Suffers from non-integrable regions

(there's some overlap here)

$$\frac{\partial^2 z}{\partial x \partial y} = \frac{\partial^2 z}{\partial y \partial x}$$

Further details are beyond the scope of this talk.

3. The Basic Method – Surface Integration



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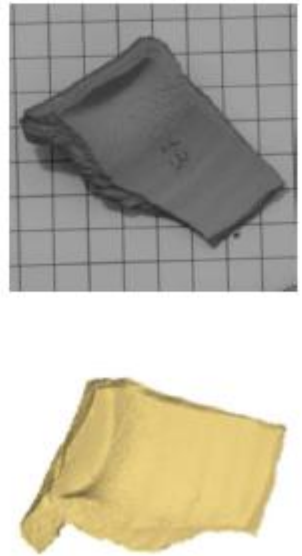
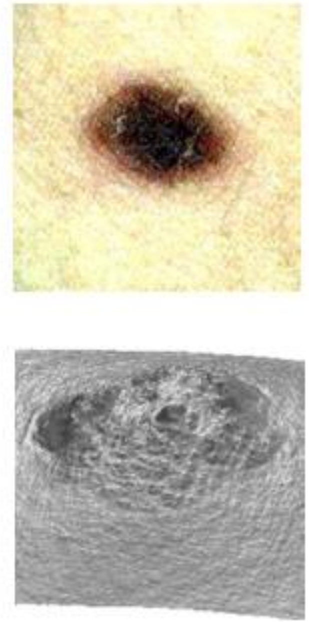
5. Applications




Face recognition

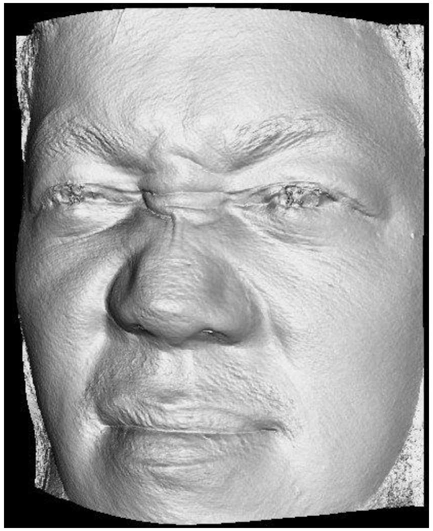
Weapons detection

Archaeology

Skin analysis

Fingerprint recognition

5. Applications – Face recognition



Computer monitor [Schindler]

Recognition rates (on 61 subjects)

2D Photograph: 91.2%
Surface normals: 97.5%

5. Applications – Fingerprint recognition

Demo

[Sun et al.]

Conclusion

1. What is photometric stereo?

   Shape / normal estimation from multiple lights

2. Why photometric stereo?

   Cheap, high resolution, efficient

3. The basic method – Covered

4. Advanced methods – Introduced

5. Applications

   Faces, weapons, fingerprints