Photometric stereo
Notes about online lectures

- Zoom link has been posted on Piazza and is also available on Canvas.

- Lectures are recorded, including all discussions. This is to facilitate students that cannot attend the lectures live.

- Recorded lectures become available by Zoom a few hours after the lecture.

- Please keep cameras closed to try and reduce bandwidth use as much as possible.

- Please keep your Zoom window muted throughout the lecture.

- If you have questions, either use the “Raise hand” option (preferable), or post in the chat. If I miss you, please repeat. And if I keep missing you, please remove mute and mention that you have a question.

- We will post an “online lecture feedback” thread once this lecture is over. This situation is new to all of us, so any thoughts you have on how to make the lectures better will be highly appreciated.
Notes about office hours

- Regular office hours on Mondays, Tuesdays, and Fridays continue.
- Throughout the semester, there are additional office hours on Thursdays, 4-6 pm.
- We will post updated Zoom links for office hours on Piazza.
Notes about homework logistics

• Take-home quizzes have been reduced to 11. You can still skip 3 of them.
• Take-home quiz 6 is due on Sunday, March 22.
• Programming assignment 4 was posted yesterday and is due on Wednesday, March 25.
• Programming assignment schedule has been shifted, as shown on the course website.
• Last programming assignment will need to be a little shorter, to fit within 1.5 weeks instead of the usual two.
Questions?
Overview of today’s lecture

• Some notes about radiometry.
• Quick overview of the n-dot-l model.
• Photometric stereo.
• Uncalibrated photometric stereo.
• Generalized bas-relief ambiguity.
• Shape from shading.
• Start image processing pipeline.
Slide credits

Many of these slides were adapted from:

• Srinivasa Narasimhan (16-385, Spring 2014).
• Todd Zickler (Harvard University).
• Steven Gortler (Harvard University).
• Kayvon Fatahalian (Stanford University; CMU 15-462, Fall 2015).
Quick overview of radiometry
Five important equations/integrals to remember

Flux measured by a sensor of area $X$ and directional receptivity $W$:

$$\Phi(W, X) = \int_X \int_W L(\hat{\omega}, x) \cos \theta d\omega dA$$

Reflectance equation:

$$L_{\text{out}}(\hat{\omega}) = \int_{\Omega_{\text{in}}} f(\hat{\omega}_{\text{in}}, \hat{\omega}_{\text{out}}) L_{\text{in}}(\hat{\omega}_{\text{in}}) \cos \theta_{\text{in}} d\hat{\omega}_{\text{in}}$$

Radiance under directional lighting and Lambertian BRDF ("n-dot-l shading"):

$$L_{\text{out}} = a\hat{n}^\top \hat{\ell}$$

Conversion of a (hemi)-spherical integral to a surface integral:

$$\int_{H^2} L_i(p, \omega', t) \cos \theta d\omega' = \int_A L(p' \rightarrow p, t) \frac{\cos \theta \cos \theta'}{||p' - p||^2} dA'$$

Computing (hemi)-spherical integrals:

$$d\omega = \frac{dA}{r^2} = \sin \theta d\theta d\phi$$

and

$$\int d\omega = \int_0^{\pi} \int_0^{2\pi} \sin \theta d\theta d\phi$$
Quiz 1: Measurement of a sensor using a thin lens

What integral should we write for the power measured by infinitesimal pixel p?
Quiz 1: Measurement of a sensor using a thin lens

What integral should we write for the power measured by infinitesimal pixel p?

\[ E(p, t) = \int_{H^2} L_i(p, \omega', t) \cos \theta \, d\omega' \]

Can I transform this integral over the hemisphere to an integral over the aperture area?
Quiz 1: Measurement of a sensor using a thin lens

**Lens aperture**

What integral should we write for the power measured by infinitesimal pixel $p$?

$$E(p, t) = \int_{H^2} L_i(p, \omega', t) \cos \theta \, d\omega'$$

Can I transform this integral over the hemisphere to an integral over the aperture area?

$$E(p, t) = \int_A L(p' \rightarrow p, t) \frac{\cos \theta \cos \theta'}{||p' - p||^2} \, dA'$$

*Transform integral over solid angle to integral over lens aperture*
Quiz 1: Measurement of a sensor using a thin lens

\[ E(p, t) = \int_A L(p' \rightarrow p, t) \frac{\cos \theta \cos \theta'}{||p' - p||^2} \, dA' \]

\[ = \int_A L(p' \rightarrow p, t) \frac{\cos^2 \theta}{||p' - p||^2} \, dA' \]

Transform integral over solid angle to integral over lens aperture

Assume aperture and film plane are parallel: \( \theta = \theta' \)

Can I write the denominator in a more convenient form?
Quiz 1: Measurement of a sensor using a thin lens

**Lens aperture**

\[ ||p' - p|| = \frac{d}{\cos \theta} \]

**Sensor plane**

\[ E(p, t) = \int_A L(p' \rightarrow p, t) \frac{\cos^2 \theta}{||p' - p||^2} \, dA' \]

\[ = \frac{1}{d^2} \int_A L(p' \rightarrow p, t) \cos^4 \theta \, dA' \]

What does this say about the image I am capturing?
Vignetting

Fancy word for: pixels far off the center receive less light

Four types of vignetting:

• Mechanical: light rays blocked by hoods, filters, and other objects.
• Lens: similar, but light rays blocked by lens elements.
• Natural: due to radiometric laws (“cosine fourth falloff”).
• Pixel: angle-dependent sensitivity of photodiodes.
Quiz 2: BRDF of the moon

What BRDF does the moon have?
Quiz 2: BRDF of the moon

What BRDF does the moon have?
• Can it be diffuse?
Quiz 2: BRDF of the moon

What BRDF does the moon have?
• Can it be diffuse?

Even though the moon appears matte, its edges remain bright.
Rough diffuse appearance

Surface Roughness Causes Flat Appearance

Actual Vase

Lambertian Vase
Photometric stereo
Even simpler: Directional lighting

- Assume that, over the observed region of interest, all source of incoming flux is from one direction.

\[
L(x, \omega, t, \lambda) \rightarrow L(x, t, \lambda) \rightarrow s(t, \lambda)\delta(\omega = \omega_o(t)) \\
L(x, \omega) \rightarrow L(\omega) \rightarrow s\delta(\omega = \omega_o)
\]

- Convenient representation

\[
\vec{\ell} = (\ell_x, \ell_y, \ell_z) \\
\hat{\ell} = \frac{\vec{\ell}}{||\vec{\ell}||}
\]

“light direction” \[ \hat{\ell} \]

“light strength” \[ ||\vec{\ell}|| \]
Simple shading

ASSUMPTION 1: LAMBERTIAN

\[ L^{\text{out}}(\hat{\omega}) = \int_{\Omega_{\text{in}}} f(\hat{\omega}_{\text{in}}, \hat{\omega}_{\text{out}}) L^{\text{in}}(\hat{\omega}_{\text{in}}) \cos \theta_{\text{in}} d\hat{\omega}_{\text{in}} \]

ASSUMPTION 2: DIRECTIONAL LIGHTING

\[ I = a \hat{n} \top \hat{l} \]
“N-dot-l” shading

ASSUMPTION 1: LAMBERTIAN

\[ L^{\text{out}}(\hat{\omega}) = \int_{\Omega_{\text{in}}} f(\hat{\omega}_{\text{in}}, \hat{\omega}_{\text{out}}) L^{\text{in}}(\hat{\omega}_{\text{in}}) \cos \theta_{\text{in}} d\hat{\omega}_{\text{in}} \]

\[ I = a \hat{n} \vec{T} \cdot \vec{l} \]

ASSUMPTION 2: DIRECTIONAL LIGHTING
Image Intensity and 3D Geometry

- *Shading* as a cue for shape reconstruction
- What is the relation between intensity and shape?
“N-dot-l” shading

ASSUMPTION 1: LAMBERTIAN

ASSUMPTION 2: DIRECTIONAL LIGHTING

\[ L^{\text{out}}(\hat{\omega}) = \int_{\Omega_{\text{in}}} f(\hat{\omega}_{\text{in}}, \hat{\omega}_{\text{out}}) L^{\text{in}}(\hat{\omega}_{\text{in}}) \cos \theta_{\text{in}} \, d\hat{\omega}_{\text{in}} \]

\[ I = a\hat{n} \cdot \hat{l} \]

Why do we call these normal “shape”?
what is a camera like this called?

Surfaces and normals

imaged surface

viewing rays for different pixels

what is a camera like this called?
Surfaces and normals

Surface representation as a depth field (also known as Monge surface):

$$z = f(x, y)$$

pixel coordinates on image plane

depth at each pixel

How does surface normal relate to this representation?
Surfaces and normals

Surface representation as a depth image (also known as Monge surface):

\[ z = f(x, y) \]

pixel coordinates on image place
depth at each pixel

Unnormalized normal:

\[ \hat{n}(x, y) = \begin{pmatrix} \frac{df}{dx} \\ \frac{df}{dy} \\ -1 \end{pmatrix} \]

Actual normal:

\[ n(x, y) = \frac{\hat{n}(x, y)}{\|\hat{n}(x, y)\|} \]

Normals are scaled spatial derivatives of depth image!
Shape from a Single Image?

- Given a single image of an object with known surface reflectance taken under a known light source, can we recover the shape of the object?
Human Perception

How Do We Do It?

• Humans have to make assumptions about illumination: bump (left) is perceived as hole (right) when upside down.

Illumination direction is unknown. It is assumed to come from above.
Examples of the classic bump/dent stimuli used to test lighting assumptions when judging shape from shading, with shading orientations (a) 0° and (b) 180° from the vertical.

Human Perception

• Our brain often perceives shape from shading.

• Mostly, it makes many assumptions to do so.

• For example:

  Light is coming from above (sun).

  Biased by occluding contours.

by V. Ramachandran
Single-lighting is ambiguous

ASSUMPTION 1: LAMBERTIAN

\[ L^{\text{out}}(\hat{\omega}) = \int_{\Omega_{\text{in}}} f(\hat{\omega}_{\text{in}}, \hat{\omega}_{\text{out}}) L^{\text{in}}(\hat{\omega}_{\text{in}}) \cos \theta_{\text{in}} d\hat{\omega}_{\text{in}} \]

\[ I = a \hat{n}^\top \hat{\ell} \]

ASSUMPTION 2: DIRECTIONAL LIGHTING
Lambertian photometric stereo

\[ I_1 = a\hat{n}^\top \hat{l}_1 \]
\[ I_2 = a\hat{n}^\top \hat{l}_2 \]
\[ \vdots \]
\[ I_N = a\hat{n}^\top \hat{l}_N \]

Assumption: We know the lighting directions.
Lambertian photometric stereo

\[ I_1 = a\hat{n}^\top \ell_1 \]
\[ I_2 = a\hat{n}^\top \ell_2 \]
\[ \vdots \]
\[ I_N = a\hat{n}^\top \ell_N \]

define “pseudo-normal” \( \vec{b} \triangleq a\hat{n} \)

solve linear system for pseudo-normal

\[
\begin{bmatrix}
I_1 \\
I_2 \\
\vdots \\
I_N
\end{bmatrix}
= 
\begin{bmatrix}
\ell_1^\top \\
\ell_2^\top \\
\vdots \\
\ell_N^\top
\end{bmatrix}
\begin{bmatrix}
\vec{b}
\end{bmatrix}
\]

What are the dimensions of these matrices?
Lambertian photometric stereo

\[
\begin{align*}
I_1 &= a\hat{n}^\top \hat{\ell}_1 \\
I_2 &= a\hat{n}^\top \hat{\ell}_2 \\
&\vdots \\
I_N &= a\hat{n}^\top \hat{\ell}_N
\end{align*}
\]

Define “pseudo-normal” \( \vec{b} \triangleq a\hat{n} \)

Solve linear system for pseudo-normal:

\[
\begin{bmatrix}
I_1 \\
I_2 \\
\vdots \\
I_N
\end{bmatrix}_{N \times 1} = 
\begin{bmatrix}
\hat{\ell}_1^\top \\
\hat{\ell}_2^\top \\
\vdots \\
\hat{\ell}_N^\top
\end{bmatrix}_{N \times 3} \begin{bmatrix}
\vec{b}
\end{bmatrix}_{3 \times 1}
\]

What are the knowns and unknowns?
Lambertian photometric stereo

\[ I_1 = a\hat{n}^\top \ell_1 \]
\[ I_2 = a\hat{n}^\top \ell_2 \]
\[ \vdots \]
\[ I_N = a\hat{n}^\top \ell_N \]

define “pseudo-normal” \( \vec{b} \triangleq a\hat{n} \)

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\ell_2^\top \\
\vdots \\
\ell_N^\top
\end{bmatrix}_{N \times 3}
\begin{bmatrix}
\vec{b}
\end{bmatrix}_{3 \times 1}
\]

How many lights do I need for unique solution?
Lambertian photometric stereo

\[
\begin{align*}
I_1 &= a\hat{n}^\top \ell_1 \\
I_2 &= a\hat{n}^\top \ell_2 \\
\vdots \\
I_N &= a\hat{n}^\top \ell_N
\end{align*}
\]

define “pseudo-normal” \( \vec{b} \triangleq a\hat{n} \)

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\end{bmatrix}_{N \times 1} =
\begin{bmatrix}
\ell_1^\top \\
\ell_2^\top \\
\vdots \\
\ell_N^\top
\end{bmatrix}_{N \times 3}
\begin{bmatrix}
\vec{b}
\end{bmatrix}_{3 \times 1}
\]

How do we solve this system?

once system is solved, \( \vec{b} \) gives normal direction and albedo
Solving the Equation with three lights

\[
\begin{align*}
I_1 & = s_1^T n \\
I_2 & = s_2^T n \\
I_2 & = s_3^T n \\
\end{align*}
\]

\[
\tilde{n} = S^{-1} I
\]

Is there any reason to use more than three lights?
More than Three Light Sources

- Get better SNR by using more lights

\[
\begin{align*}
I_1 & \quad s_1^T \\
\vdots & = \quad \vdots \\
I_N & \quad s_N^T \\
\end{align*}
\]

- Least squares solution:

\[
I = S\tilde{n} \\
S^T I = S^T S\tilde{n} \\
\tilde{n} = \left(S^T S\right)^{-1}S^T I
\]

- Solve for \( n \) as before

Moore-Penrose pseudo inverse
Computing light source directions

• Trick: place a chrome sphere in the scene

  – the location of the highlight tells you the source direction
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
Depth from normals

- Solving the linear system per-pixel gives us an estimated surface normal for each pixel.

How can we compute depth from normals?
- Normals are like the “derivative” of the true depth.
Surfaces and normals

Surface representation as a depth image (also known as Monge surface):

\[ z = f(x, y) \]

- Pixel coordinates in image space
- Depth at each pixel
- Unnormalized normal:
  \[ \hat{n}(x, y) = \left( \frac{df}{dx}, \frac{df}{dy}, -1 \right) \]
- Actual normal:
  \[ n(x, y) = \hat{n}(x, y) / \| \hat{n}(x, y) \| \]

Normals are scaled spatial derivatives of depth image!
Normal Integration

- Integrating a set of derivatives is easy in 1D
  - (similar to Euler’s method from diff. eq. class)

- Could just integrate normals in each column / row separately

- Instead, we formulate as a linear system and solve for depths that best agree with the surface normals
Depth from normals

Get a similar equation for $V_2$

- Each normal gives us two linear constraints on $z$
- compute $z$ values by solving a matrix equation

\[
V_1 = (x + 1, y, z_{x+1,y}) - (x, y, z_{xy})
\]
\[
= (1, 0, z_{x+1,y} - z_{xy})
\]

\[
0 = N \cdot V_1
\]
\[
= (n_x, n_y, n_z) \cdot (1, 0, z_{x+1,y} - z_{xy})
\]
\[
= n_x + n_z(z_{x+1,y} - z_{xy})
\]
1. Estimate light source directions
2. Compute surface normals
3. Compute albedo values
4. Estimate depth from surface normals
5. Relight the object (with original texture and uniform albedo)
Results: Lambertian Sphere

Input Images

Needles are projections of surface normals on image plane

Estimated Surface Normals

Estimated Albedo
Lambertain Mask
Results – Albedo and Surface Normal
Results – Shape of Mask
Results: Lambertian Toy
Non-idealities: interreflections
Non-idealities: interreflections

Shallow reconstruction (effect of interreflections)

Accurate reconstruction (after removing interreflections)
What if the light directions are unknown?
Uncalibrated photometric stereo
What if the light directions are unknown?

\[
\begin{align*}
I_1 &= a \hat{n}^\top \ell_1 \\
I_2 &= a \hat{n}^\top \ell_2 \\
\vdots \\
I_N &= a \hat{n}^\top \ell_N
\end{align*}
\]

define “pseudo-normal” \( \vec{b} \triangleq a \hat{n} \)

solve linear system for pseudo-normal

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\begin{bmatrix}
I_1 \\
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\end{bmatrix}_{3 \times 1}
\]
What if the light directions are unknown?

\[
\begin{align*}
I_1 &= a\hat{n}^\top \ell_1 \\
I_2 &= a\hat{n}^\top \ell_2 \\
&\vdots \\
I_N &= a\hat{n}^\top \ell_N
\end{align*}
\]

define “pseudo-normal” \( \vec{b} \triangleq a\hat{n} \)

solve linear system for pseudo-normal at each image pixel

\[
\begin{bmatrix}
I_1 \\
I_2 \\
\vdots \\
I_N
\end{bmatrix}_{N \times M}
= 
\begin{bmatrix}
\ell_1^\top \\
\ell_2^\top \\
\vdots \\
\ell_N^\top
\end{bmatrix}_{N \times 3}
\begin{bmatrix}
B
\end{bmatrix}_{3 \times M}
\]

M: number of pixels
What if the light directions are unknown?

\[
\begin{align*}
I_1 &= a \hat{n}^\top \hat{\ell}_1 \\
I_2 &= a \hat{n}^\top \hat{\ell}_2 \\
\vdots \\
I_N &= a \hat{n}^\top \hat{\ell}_N
\end{align*}
\]

define “pseudo-normal” \( \vec{b} \triangleq a \hat{n} \)

solve linear system for pseudo-normal at each image pixel

\[
\begin{bmatrix}
I_1 \\
I_2 \\
\vdots \\
I_N
\end{bmatrix}_{N \times M}
= 
\begin{bmatrix}
\hat{\ell}_1^\top \\
\hat{\ell}_2^\top \\
\vdots \\
\hat{\ell}_N^\top
\end{bmatrix}_{N \times 3}
\begin{bmatrix}
B
\end{bmatrix}_{3 \times M}
\]

How do we solve this system without knowing light matrix \( L \)?
Factorizing the measurement matrix

\[ \text{Measurements} = \text{Lights} \times \text{Pseudonormals} \]

What are the dimensions?
Factorizing the measurement matrix

- Singular value decomposition:

\[ D = U W V^T \]

To reduce to rank 3, we just need to set all the singular values to 0 except for the first 3.

This decomposition minimizes \(|I-LB|^2\).
Are the results unique?
Are the results unique?

We can insert any 3x3 matrix $Q$ in the decomposition and get the same images:

$$I = L B = (L Q^{-1}) (Q B)$$
Are the results unique?

We can insert any 3x3 matrix $Q$ in the decomposition and get the same images:

$$ I = L B = (L Q^{-1}) (Q B) $$

Can we use any assumptions to remove some of these 9 degrees of freedom?
Generalized bas-relief ambiguity
Enforcing integrability

What does the matrix $B$ correspond to?
Enforcing integrability

What does the matrix $B$ correspond to?

- Surface representation as a depth image (also known as Monge surface):
  $$z = f(x, y)$$
  depth at each pixel  
  pixel coordinates in image space

- Unnormalized normal:
  $$\tilde{n}(x, y) = \left(\frac{df}{dx}, \frac{df}{dy}, -1\right)$$

- Actual normal:
  $$n(x, y) = \tilde{n}(x, y) / \|\tilde{n}(x, y)\|$$

- Pseudo-normal:
  $$b(x, y) = a(x, y) n(x, y)$$

- Rearrange into 3xN matrix $B$. 
Enforcing integrability

What does the integrability constraint correspond to?
Enforcing integrability

What does the integrability constraint correspond to?

- Differentiation order should not matter:

\[
\frac{d}{dy} \frac{df(x, y)}{dx} = \frac{d}{dx} \frac{df(x, y)}{dy}
\]

- Can you think of a way to express the above using pseudo-normals \( \mathbf{b} \)?
Enforcing integrability

What does the integrability constraint correspond to?

• Differentiation order should not matter:

\[
\frac{d}{dy} \frac{df(x, y)}{dx} = \frac{d}{dx} \frac{df(x, y)}{dy}
\]

• Can you think of a way to express the above using pseudo-normals \( b \)?

\[
\frac{d}{dy} \frac{b_1(x, y)}{b_3(x, y)} = \frac{d}{dx} \frac{b_2(x, y)}{b_3(x, y)}
\]
Enforcing integrability

What does the integrability constraint correspond to?

• Differentiation order should not matter:

\[
\frac{d}{dy} \frac{df(x, y)}{dx} = \frac{d}{dx} \frac{df(x, y)}{dy}
\]

• Can you think of a way to express the above using pseudo-normals \( b \)?

\[
\frac{d}{dy} \frac{b_1(x, y)}{b_3(x, y)} = \frac{d}{dx} \frac{b_2(x, y)}{b_3(x, y)}
\]

• Simplify to:

\[
\begin{align*}
    b_3(x, y) \frac{db_1(x, y)}{dy} - b_1(x, y) \frac{db_3(x, y)}{dy} &= b_2(x, y) \frac{db_1(x, y)}{dx} - b_1(x, y) \frac{db_2(x, y)}{dx} \\
\end{align*}
\]
Enforcing integrability

What does the integrability constraint correspond to?

- Differentiation order should not matter:

\[
\frac{d}{dy} \frac{df(x,y)}{dx} = \frac{d}{dx} \frac{df(x,y)}{dy}
\]

- Can you think of a way to express the above using pseudo-normals \( \mathbf{b} \)?

\[
\frac{d}{dy} \frac{b_1(x,y)}{b_3(x,y)} = \frac{d}{dx} \frac{b_2(x,y)}{b_3(x,y)}
\]

- Simplify to:

\[
b_3(x,y) \frac{db_1(x,y)}{dy} - b_1(x,y) \frac{db_3(x,y)}{dy} = b_2(x,y) \frac{db_1(x,y)}{dx} - b_1(x,y) \frac{db_2(x,y)}{dx}
\]

- If \( \mathbf{B}_e \) is the pseudo-normal matrix we get from SVD, then find the 3x3 transform \( \mathbf{D} \) such that \( \mathbf{B} = \mathbf{D} \cdot \mathbf{B}_e \) is the closest to satisfying integrability in the least-squares sense.
Enforcing integrability

Does enforcing integrability remove all ambiguities?
Generalized Bas-relief ambiguity

If $B$ is integrable, then:

• $B' = G^T \cdot B$ is also integrable for all $G$ of the form ($\lambda \neq 0$)

$$G = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \mu & \nu & \lambda \end{bmatrix}$$

• Combined with transformed lights $S' = G \cdot S$, the transformed pseudonormals produce the same images as the original pseudonormals.

• This ambiguity cannot be removed using shadows.

• This ambiguity can be removed using interreflections or additional assumptions.

This ambiguity is known as the generalized bas-relief ambiguity.
Generalized Bas-relief ambiguity

When $\mu = \nu = 0$, $G$ is equivalent to the transformation employed by relief sculptures.

When $\mu = \nu = 0$ and $\lambda = +\, -1$, top/down ambiguity.

Otherwise, includes shearing.
What assumptions have we made for all this?
What assumptions have we made for all this?

• Lambertian BRDF

• Directional lighting

• Orthographic camera

• No interreflections or scattering
Shape independent of BRDF via reciprocity: "Helmholtz Stereopsis"

\[ I = f(\text{shape, illumination, reflectance}) \]

\[ f^{-1} = \]
Shape from shading
Can we reconstruct shape from one image?
Single-lighting is ambiguous

ASSUMPTION 1: LAMBERTIAN

\[ L^{\text{out}}(\hat{\omega}) = \int_{\Omega_{\text{in}}} f(\hat{\omega}_{\text{in}}, \hat{\omega}_{\text{out}}) L^{\text{in}}(\hat{\omega}_{\text{in}}) \cos \theta_{\text{in}} d\hat{\omega}_{\text{in}} \]

\[ I = a\hat{n}^\top \hat{l} \]

ASSUMPTION 2: DIRECTIONAL LIGHTING

[Prados, 2004]
Problem

\((p,q)\)-space (gradient space)

\((f,g)\)-space

\(\theta = 90^\circ\)

\[ f = \frac{2p}{1 + \sqrt{1 + p^2 + q^2}} \]

\[ g = \frac{2q}{1 + \sqrt{1 + p^2 + q^2}} \]

Redefine reflectance map as \( R(f, g) \)
Image Irradiance Constraint

- Image irradiance should match the reflectance map

Minimize

\[ e_i = \left( I(x, y) \cdot R(f, g) \right)^2 \int_{\text{image}} dxdy \]

(minimize errors in image irradiance in the image)
Smoothness Constraint

- Used to constrain shape-from-shading
- Relates orientations \((f, g)\) of neighboring surface points

Minimize

\[
e_s = \left( f_x^2 + f_y^2 \right) + \left( g_x^2 + g_y^2 \right) \int \int dx \, dy
\]

\((f, g)\): surface orientation under stereographic projection

\[
f_x = \frac{f}{x}, \, f_y = \frac{f}{y}, \, g_x = \frac{g}{x}, \, g_y = \frac{g}{y}
\]

(penalize rapid changes in surface orientation \(f\) and \(g\) over the image)
Shape-from-Shading

- Find surface orientations \((f, g)\) at all image points that minimize

\[
e = e_s + e_i
\]

Minimize

\[
e = \left( f_x^2 + f_y^2 \right) + \left( g_x^2 + g_y^2 \right) + \left( I(x, y) \cdot R(f, g) \right)^2 dx \, dy
\]
Numerical Shape-from-Shading

• **Smoothness error** at image point \((i,j)\)

\[
s_{i,j} = \frac{1}{4} \left( (f_{i+1,j} - f_{i,j})^2 + (f_{i,j+1} - f_{i,j})^2 + (g_{i+1,j} - g_{i,j})^2 + (g_{i,j+1} - g_{i,j})^2 \right)
\]

Of course you can consider more neighbors (smoother results)

• **Image irradiance error** at image point \((i,j)\)

\[
r_{i,j} = (I_{i,j} - R(f_{i,j}, g_{i,j}))^2
\]

Find \(\{f_{i,j}\}\) and \(\{g_{i,j}\}\) that minimize

\[
e = \sum_{i,j} \left( s_{i,j} + r_{i,j} \right)
\]

(Ikeuchi & Horn 89)
Results

by Ikeuchi and Horn
Results

Scanning Electron Microscope image (inverse intensity)

by Ikeuchi and Horn
More modern results

Resolution: 640 x 500; Re-rendering Error: 0.0075.

Resolution: 590 x 690; Re-rendering Error: 0.0083.
References

Basic reading:
• Szeliski, Section 2.2.
• Gortler, Chapter 21.
  This book by Steven Gortler has a great introduction to radiometry, reflectance, and their use for image formation.

Additional reading:
  The paper introducing the most common model for rough diffuse reflectance.
• Debevec, “Rendering Synthetic Objects into Real Scenes,” SIGGRAPH 1998.
  The paper that introduced the notion of the environment map, the use of chrome spheres for measuring such maps, and the idea that they can be used for easy rendering.
  A paper on estimating outdoors environment maps from just one image.
• Sloan et al., “Precomputed radiance transfer for real-time rendering in dynamic, low-frequency lighting environments,” SIGGRAPH 2002.
  Three papers describing the use of spherical harmonics to model low-frequency illumination, as well as the low-pass filtering effect of Lambertian reflectance on illumination.
  A review of perceptual and computational aspects of shape from shading.
  The paper that introduced photometric stereo.
  Three papers discussing uncalibrated photometric stereo. The first paper shows that, when the lighting directions are not known, by assuming integrability, one can reduce unknowns to the bas-relief ambiguity. The second paper discusses the bas-relief ambiguity in a more general context. The third paper shows that, if instead of an orthographic camera one uses a perspective camera, this is further reduced to just a scale ambiguity.
  A popular technique for resolving the bas-relief ambiguity in uncalibrated photometric stereo.
  A method for photometric stereo reconstruction under arbitrary BRDF.
  Two papers discussing how one can perform photometric stereo (calibrated or otherwise) in the presence of strong interreflections.
• Agrawal et al., “What is the range of surface reconstructions from a gradient field?,” ECCV 2006.
  Two papers discussing how one can integrate a normal field to reconstruct a surface.