Lighting affects appearance
Photometric Stereo: using this variability to reconstruct

Albedos ➔ Shape (normals only)
Recognition: Accounting for this variability in matching

Basics: How do we represent light? (1)

- Ideal distant point source:
  - No cast shadows
  - Light distant
  - Three parameters
  - Example: lab with controlled light
Basics: How do we represent light? (2)

- Environment map: \( f(\theta, \phi) \)
  - Light from all directions
  - Diffuse or point sources
  - Still distant
  - Still no cast shadows.
  - Example: outdoors (sky and sun)
Basics

- How do objects reflect light?
- Lambertian reflectance

$\lambda_{\text{max}} (\cos \theta, 0)$

Reflectance map

- Reflected light is function of surface normal: $i = f(\theta, \phi)$
- Suitable for environment map.
- Can be measured with calibration object.
Photometric stereo

- Given reflectance map:
  \( i = f(\theta, \phi) \) each image constrains normal to one degree of freedom.
- Given multiple images, solve at each point.

Lambertian + Point Source

\[ \vec{l} = l \cdot \vec{l} \]

- \( \vec{l} \) is direction of light
- \( l \) is intensity of light
- \( i = \max(0, \lambda(\vec{l} \cdot \hat{n})) \)
- \( i \) is radiance
- \( \lambda \) is albedo
- \( \hat{n} \) is surface normal
Lambertian, point sources, no shadows. (Shashua, Moses)

- *Whiteboard*
- Solution linear
- Linear ambiguity in recovering scaled normals
- Lighting, reflectance map not known.
- Recognition by linear combinations.

Linear basis for lighting

\[
\lambda Z \quad \lambda X \quad \lambda Y
\]
Integrability

- Means we can write height: $z=f(x,y)$.
- *Whiteboard*
- Reduces ambiguity to bas-relief ambiguity.
- Also useful in shape-from-shading and other photometric stereo.

Bas-relief Ambiguity
Shadows

With Shadows: Empirical Study

( Epstein, Hallinan and Yuille; see also Hallinan; Belhumeur and Kriegman)

<table>
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<th>Ball</th>
<th>Face</th>
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<th>Parrot</th>
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</tbody>
</table>

Dimension: $5 \pm 2D$
Attached Shadows

- Lambertian
- Environment map

\[ n \]  \[ l \]  \[ \theta \]  \[ \lambda_{\text{max}} \] \[ (\cos \theta, 0) \]

Images

Lighting

Reflectance

Images

...
Lighting to Reflectance: Intuition
Forming Harmonic Images

$$b_{nm}(p) = \lambda r_{nm}(X,Y,Z)$$

- $\lambda$
- $\lambda Z$
- $\lambda X$
- $\lambda Y$
- $2\lambda(Z^2 - X^2 - Y^2)$
- $\lambda(X^2 - Y^2)$
- $\lambda XY$
- $\lambda XZ$
- $\lambda YZ$
Models

Find Pose

Query

Compare

Vector: I

Harmonic Images

Matrix: B

Experiments

- 3-D Models of 42 faces acquired with scanner.
- 30 query images for each of 10 faces (300 images).
- Pose automatically computed using manually selected features (Blicher and Roy).
- Best lighting found for each model; best fitting model wins.
Results

- 9D Linear Method: 90% correct.
- 9D Non-negative light: 88% correct.
- Ongoing work: Most errors seem due to pose problems. With better poses, results seem near 97%.
Summary

- Linear solutions are good.
- For pose variation with points, each image is linear combination of 2 others.
- For Lambertian lighting no shadows, each image is linear combination of 3.
- With attached shadows, linear combination of 9.
- Only diffuse lighting affects images, unless there are shadows or specularities.