Computer Vision

Spring 2006 15-385,-685

Instructor: S. Narasimhan

Wean 5403

T-R 3:00pm – 4:20pm

Lightness and Retinex: An Early Vision Problem

Lecture #10

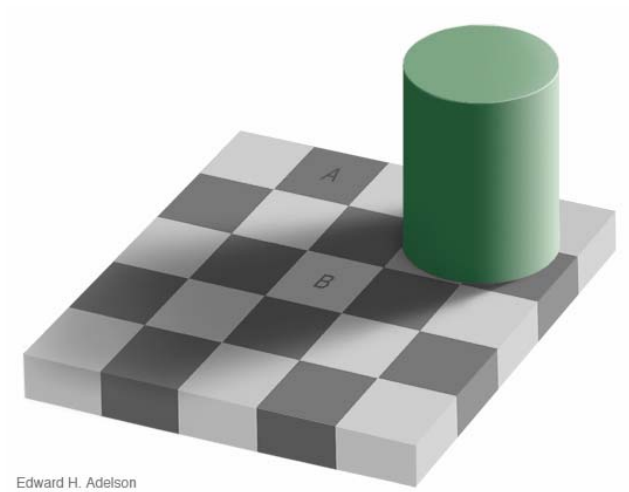
Readings: Horn Chapter 9.

Vision (Marr): pgs 250-258.

“The perception of Surface Blacks and Whites”, A. L. Gilchrist, Scientific American, 240 (pgs 112-114), 1979

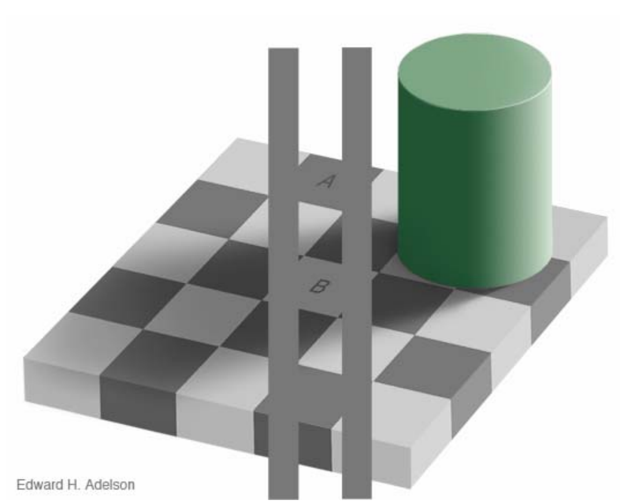
Webpages of Prof. Edward Adelson, MIT

Checker Shadow Illusion



[E. H. Adelson]

Checker Shadow Illusion



[E. H. Adelson]

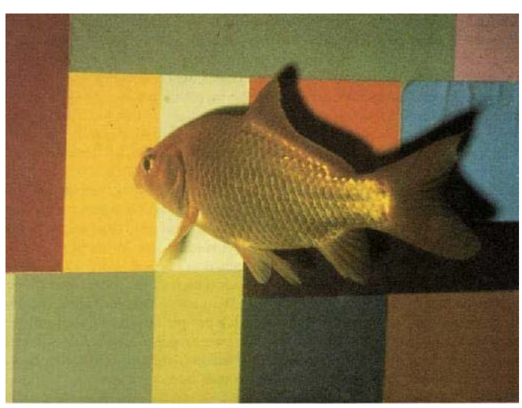
Land's Experiment (1959)

- Cover all patches except a blue rectangle
- Make it look gray by changing illumination
- Uncover the other patches

Color Constancy

We filter out illumination variations

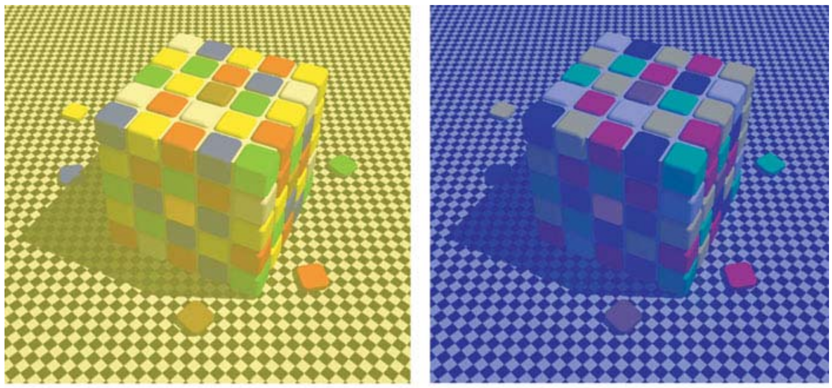
Color Constancy in Gold Fish



In David Ingle's experiment, a goldfish has been trained to swim to a patch of a given color for a reward—a piece of liver. It swims to the green patch regardless of the exact setting of the three projectors' intensities. The behavior is strikingly similar to the perceptual result in humans.

http://neuro.med.harvard.edu/site/dh/b45.htm

Color Cube Illusion



D. Purves, R. Beau Lotto, S. Nundy "Why We See What We do," American Scientist

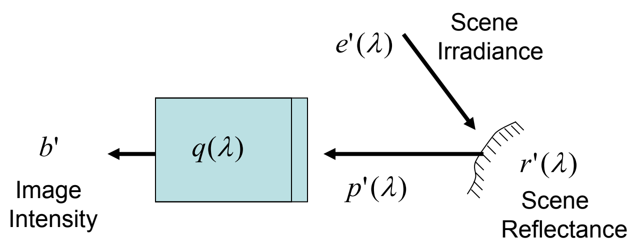
Lightness Recovery and Retinex Theory

- Problem: Recover surface reflectance / color in varying illumination conditions.

- We use tools developed before:

  - Sensing: Intensity / Color
  - Image Processing: Fourier Transform and Convolution
  - Edge Operators
  - Iterative Techniques

Image Brightness (Intensity)



- Monochromatic Light : $(\lambda = \lambda_i)$

$$b'(x,y) = r'(x,y)\, e'(x,y) \qquad\qquad q(\lambda_i) = 1$$

NOTE: The analysis can be applied to COLORED LIGHT using FILTERS

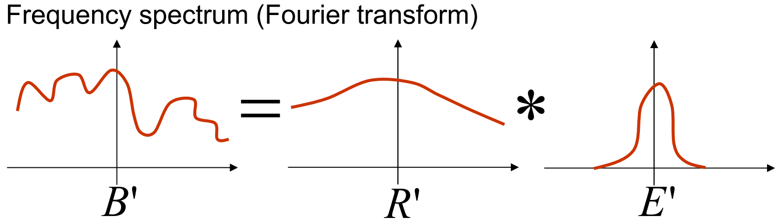
Recovering Lightness

- Image Intensity: $b'(x,y) = r'(x,y)\, e'(x,y)$

  Can we recover e' and r' from b' ?

- Assumptions: - Sharp changes in Reflectance
  - Smooth changes in Illumination

- Frequency spectrum (Fourier transform)



We want to filter out *e'*

Recovering Lightness

- Image Intensity: $b'(x,y) = r'(x,y)\, e'(x,y)$
- Take Logarithm: $\log b'(x,y) = \log r'(x,y) + \log e'(x,y)$

  OR $b(x,y) = r(x,y) + e(x,y)$
- Use Laplacian:

$$d = \nabla^2 b = \nabla^2 r + \nabla^2 e \qquad \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

- Sharp changes in reflectance $r'(x,y)$

  $\nabla^2 r$ has 2 infinite spikes near edges and $\nabla^2 r = 0$ elsewhere
- Smooth changes in illumination $e'(x,y)$

  $\nabla^2 e \approx 0$ everywhere

Lightness Recovery (Retinex Scheme)

Image:
$b = r + e$

Solving the Inverse Problem

Image $b = r + e$ → Laplacian $d = \nabla^2 b = \nabla^2 r + \nabla^2 e$ → Thresholding $t = T(d) \approx \nabla^2 r$ → Lightness $l(x,y)$

Find lightness *l(x,y)* from *t(x,y)*:

Poisson's Equation $\nabla^2 l = t$

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) l(x,y) = t(x,y)$$

We have to find *g(x,y)* which satisfies

$$l(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} t(u,v) g(x-u, y-v) du dv$$

$$\boxed{l(x,y) = t(x,y) * g(x,y)}$$

Solving Poisson's Equation

We have

$$\nabla^2 l(x,y) = t(x,y) \quad \text{and} \quad l(x,y) = t(x,y) * g(x,y)$$

$$\Big\downarrow \text{Fourier transform}$$

$$? = T(u,v) \qquad \text{and} \qquad L(u,v) = T(u,v) G(u,v)$$

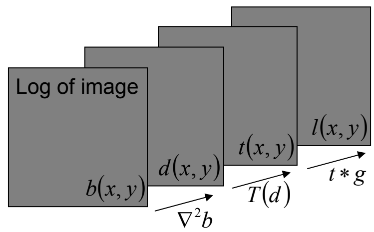
So

$$-\left(u^2 + v^2\right) L(u,v) = T(u,v) \quad \text{and} \quad L(u,v) = T(u,v) G(u,v)$$

Thus

$$G(u,v) = -\frac{1}{u^2 + v^2} \longrightarrow g(x,y) = \frac{1}{2\pi} \log \sqrt{x^2 + y^2} + c$$

Lightness Recovery



$$g(x,y) = \frac{1}{2\pi} \log \sqrt{x^2 + y^2}$$

$$\underbrace{l(x,y)}_{\text{(lightness)}} = \boxed{k} + \underbrace{r(x,y)}_{\text{(reflectance)}}$$

Which means: $l'(x,y) = kr'(x,y)$

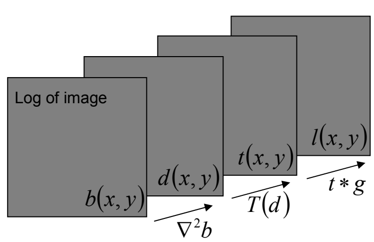
Normalize:

Assume maximum value of $l'(x,y) = l'_{max}$ corresponds to $r' = 1$

Then:

$$\underbrace{r'(x,y)}_{\text{(reflectance)}} = \frac{l'(x,y)}{l_{max}} \qquad \underbrace{e'(x,y)}_{\text{(illumination)}} = \frac{b'(x,y)}{r'(x,y)}$$

Computing Lightness (Discrete Case)



$$g(x,y) = \frac{1}{2\pi} \log \sqrt{x^2 + y^2}$$

$$\frac{1}{6} \begin{bmatrix} 1 & 4 & 1 \\ 4 & -20 & 4 \\ 1 & 4 & 1 \end{bmatrix}$$

Basically, inverse of Laplacian mask

But, discrete approximation of the inverse Laplacian would not be sufficiently accurate!

Solve $\nabla^2 l = t$ directly

Computing Lightness (Discrete Case)

$$\frac{1}{6}\begin{bmatrix}1 & 4 & 1\\ 4 & -20 & 4\\ 1 & 4 & 1\end{bmatrix} \longrightarrow \nabla^2 l = t \longleftarrow T\left(\frac{1}{6}\begin{bmatrix}1 & 4 & 1\\ 4 & -20 & 4\\ 1 & 4 & 1\end{bmatrix} * b\right)$$

$$\downarrow$$

$$-20 l_{i,j} + 4\left(l_{i+1,j} + l_{i,j-1} + l_{i-1,j} + l_{i,j-1}\right) + \left(l_{i+1,j+1} + l_{i-1,j+1} + l_{i-1,j-1} + l_{i+1,j-1}\right) = 6 t_{i,j}$$

Solve iteratively:

$$l^{n+1}_{i,j} = \frac{1}{5}\left(l^n_{i+1,j} + l^n_{i,j+1} + l^n_{i-1,j} + l^n_{i,j-1}\right) + \frac{1}{20}\left(l^n_{i+1,j+1} + l^n_{i-1,j+1} + l^n_{i-1,j-1} + l^n_{i+1,j-1}\right) - \frac{3}{10} t_{i,j}$$

Use a discrete approximation to the inverse of Laplacian to obtain initial estimate of *l*

Lightness from Multiple Images taken under Varying Illumination

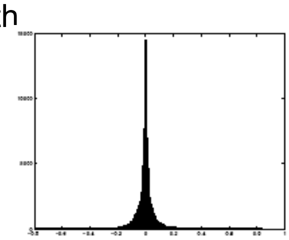
Illumination is not smooth

<u>Use spatial statistics of edges</u>

Derivative operator responses are sparse

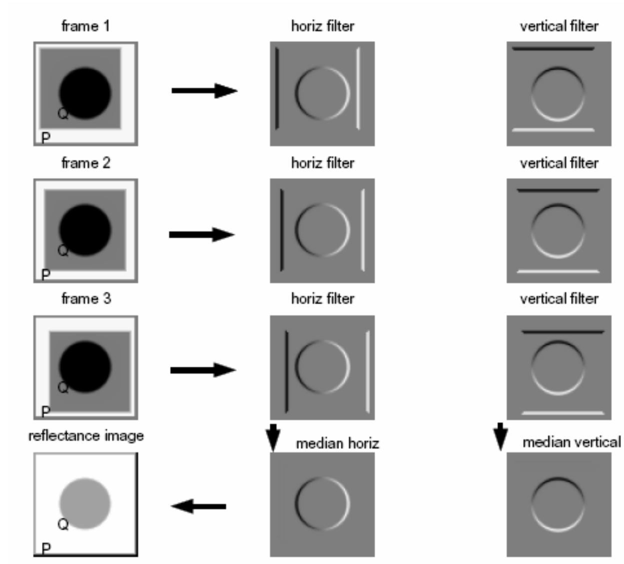
$$\nabla b(x, y, t) = \nabla r(x, y) + \nabla e(x, y, t)$$

$$\nabla r(x, y) \approx \operatorname*{median}_{t}\left(\nabla b(x, y, t)\right)$$



Y. Weiss ICCV 2001

Lightness from Multiple Images taken under Varying Illumination



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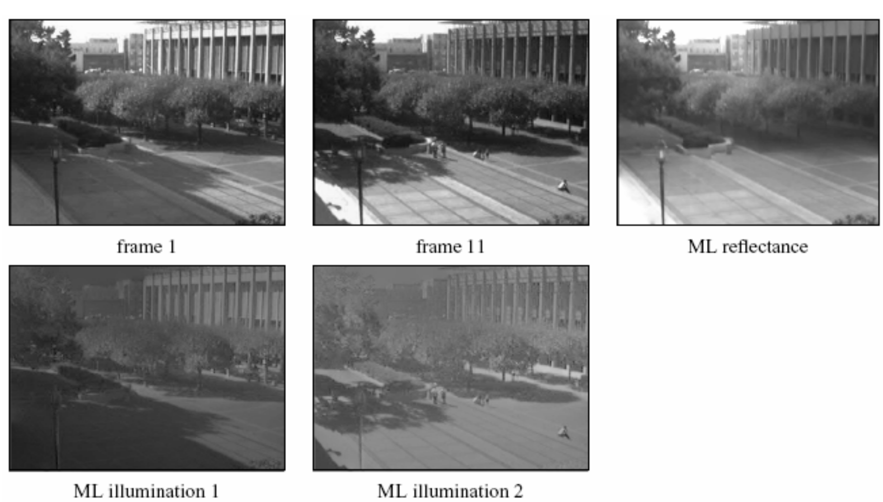

Y. Weiss ICCV 2001

Using Lightness

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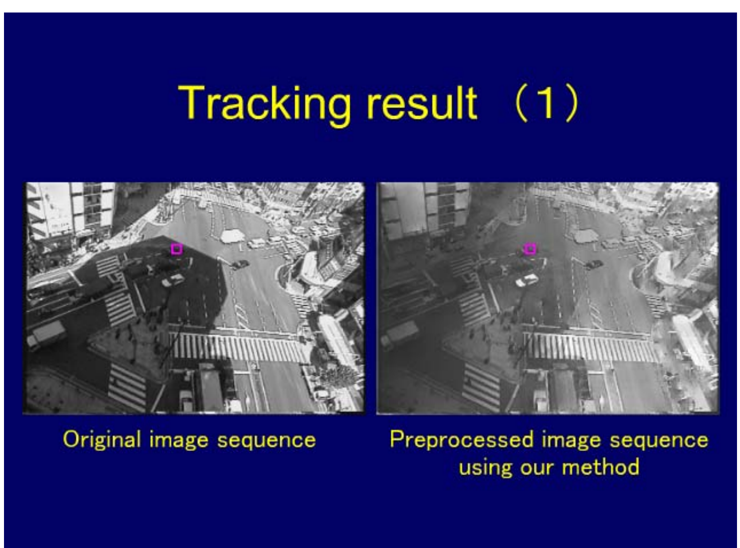
Using Lightness



Y. Matsushita and K. Nishino CVPR 2003

Comments on Retinex Theory

- Not applicable to smooth reflectance variations
- Not applicable to curved objects

In general:

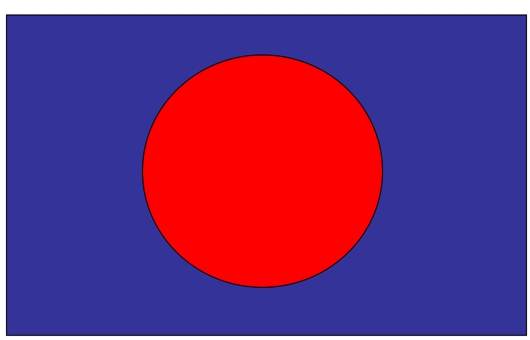
Intensity=*f*(Shape, Reflectance, Illumination)

For very good illusions, see:

http://web.mit.edu/persci/gaz/gaz-teaching/index.html

http://www.michaelbach.de/ot/index.html

Tricking the Human Eye



Eye Tremors (~ 35 cycles/second)

Tremors used for edge detection

Edges disappear when edge motion is synchronous with Tremors!

Next Class

- Surface Reflectance and BRDF
- Reading: Horn, Chapter 10.
- F. E. Nicodemus, J.C. Richmond and J.J. Hsia, "Geometrical Considerations and Nomenclature for Reflectance", Institute of Basic Standards, National Bureau of Standards, October 1977