CS 4501: Introduction to Computer Vision

Image Formation

Connelly Barnes

Some slides from Jason Lawrence, Alexei Efros, Steve Seitz, Stephen Palmer, Fredo Durand, Edward Adleson
Outline

• Human eyes
  • How do they sense light?
  • Visible light and human color perception
• Electronic eyes
  • How do they sense light?
  • Image representation
  • Color spaces
  • Lens models and camera parameters
Image Formation

Digital Camera

The Eye

Slide by Efros
The Eye

- The human eye is a camera!
  - **Iris** - colored annulus (ring) with radial muscles
  - **Pupil** - the hole (aperture) whose size is controlled by the iris
  - What’s the “film”? photoreceptor cells (rods and cones) in the **retina**
The Retina

Cross-section of eye

Cross section of retina

- Ganglion axons
- Ganglion cell layer
- Bipolar cell layer
- Receptor layer
- Pigmented epithelium
Two types of light-sensitive receptors

**Cones**
- cone-shaped
- less sensitive
- operate in high light
- color vision

**Rods**
- rod-shaped
- highly sensitive
- operate at night
- gray-scale vision

Image from Jason Lawrence and Szymon Rusinkiewicz
Distribution of Rods and Cones

From [Wikipedia](https://en.wikipedia.org/wiki/)
Rod / Cone Sensitivity

- Dazzling light; bright sun on snow
- Outdoors in full sunlight
- Outdoors under a tree on a sunny day
- Comfortable indoor illumination; night sports events
- Threshold for perception of color; bright moonlight
- Threshold when dark-adapted
Some “Goals” of Human Eye

• Recognize food
• Recognize friends, mates
• Detect predators
• Navigation -- identify 3D structure

Limited memory, computation budget

• Highest resolution in fovea
  - (2 degrees, 50% of visual cortex)
• Absolute luminance discarded
• Edges, corners retained
• Store only a tiny fraction of what is observed
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What is Visible Light?

• Electromagnetic radiation with frequencies (wavelengths) between:
  • Red: $4.3 \times 10^{14}$ Hz (700 nm)
  • Violet: $7.5 \times 10^{14}$ Hz (400 nm)
Electromagnetic Spectrum

Human Luminance Sensitivity Function

http://www.yorku.ca/eye/photopik.htm
Why do we see light of these wavelengths?

...because that’s where the Sun radiates EM energy
Any patch of light can be completely described physically by its spectrum: the number of photons (per time unit) at each wavelength 400 - 700 nm.
Some examples of the spectra of light sources

A. Ruby Laser

B. Gallium Phosphide Crystal

C. Tungsten Lightbulb

D. Normal Daylight

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Some examples of the reflectance spectra of surfaces

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>% Photons Reflected</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>Red</td>
</tr>
<tr>
<td>700</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>Yellow</td>
</tr>
<tr>
<td>700</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>Blue</td>
</tr>
<tr>
<td>700</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>Purple</td>
</tr>
<tr>
<td>700</td>
<td></td>
</tr>
</tbody>
</table>

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Ordinary Human Vision (Trichromatism)
Perceptual Sensitivity

ITU Recommendation for HDTV:
\[ Y = 0.21 \, R + 0.72 \, G + 0.07 \, B \]

Evolved to detect vegetation, berries?
Color blindness

- Missing cones (e.g. red or green)
- Or mutated pigments in cones
- Most common type is red-green color-blindness

Image from Wikipedia
Tetrachromatism

• Most birds, and many other animals, have cones for ultraviolet light.
  • Used for courtship, foraging for food (e.g. berries), flowers
• Some humans, mostly female, have slight tetrachromatism.
Metamers

![Graph showing reflectance vs. wavelength for different flowers and petals.](image-url)
Human Eye is Not a Photo-Meter
Human Eye is Not a Photo-Meter

Edward H. Adelson
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Electronic Eyes: Sensor Arrays

**FIGURE 2.17** (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.
Sampling and Quantization

**FIGURE 2.16** Generating a digital image: (a) Continuous image; (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization; (c) Sampling and quantization; (d) Digital scan line.
Interlace vs. progressive scan

1st field: Odd field

2nd field: Even field

One complete frame using interlaced scanning

One complete frame using progressive scanning


Slide by Steve Seitz
Progressive scan

Interlace
Rolling Shutter

SLR cameras at high shutter speed, most CMOS cameras

YouTube video
Bayer RGB mosaic

- Each photosite has a different color filter
Bayer RGB mosaic

• Why more green?
  – We have 3 channels and square lattice don’t like odd numbers
  – It’s the spectrum “in the middle”
  – More important to human perception of luminance
Demosaicing

- Interpolate missing values
Linear Interpolation

- Average of the 4 or 2 nearest neighbors
  - Linear (tent) kernel
- Smoother kernels can also be used (e.g. bicubic) but need wider support
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Color Image

Color channels:
- R (Red)
- G (Green)
- B (Blue)
Images in Python/MATLAB

- Image as array: \( h \times w \times \text{channels} \)
  \( I(y,x,\text{channel}) \)

- Red channel, upper left corner:
  - MATLAB: \( I(1,1,1) \)
  - Python: \( I[0,0,0] \)

Common ranges of pixel values:
- Float (typical range: \([0, 1]\))
- Unsigned 8-bit integer (range: \([0, 255]\))

- Which is easier to work with?
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Some drawbacks

- Strongly correlated channels
- Non-perceptual
Color spaces: HSV

Intuitive color space

H (S=1,V=1)

S (H=1,V=1)

V (H=1,S=0)
Color spaces: L*a*b*

“Perceptually uniform” color space

L
(a=0,b=0)

a
(L=65,b=0)

b
(L=65,a=0)
Color Problems: White Balance

Slide by Alexei Efros
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- Pinhole camera has small aperture size.
- All objects are in focus – depth of field infinite
Pinhole Camera

Object

Screen

$h_o$

$d_o$

$d_i$

$h_i$

Similar triangles gives optics law:

$$\frac{h_i}{h_o} = \frac{d_i}{d_o}$$
Fix object size and imaging plane distance: \[ h_i \propto \frac{1}{d_o} \]
Perspective
Limitations of Pinhole Camera

- **Pros:**
  - Infinite depth of field

- **Cons:**
  - Not much light => higher noise
  - Diffraction for small aperture size
Lenses

Let in more light!

Object

Focal Length

Focal Point

$d_o$

$f$

$d_i$

Image

Let in more light!
Lenses

Thin lens equation:

\[ \frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \]
Lenses

- Focal length reported in mm, e.g. 50 mm lens.
- For zoom lenses, a range, e.g. 18-55 mm.
Angle of View (Field of View)

\[ \alpha = 2 \tan^{-1} \left[ \frac{d}{2f} \right] \approx \frac{d}{f} \text{ (radians)} \]
Angle of View (Field of View)

[Diagram showing different angles of view with corresponding field of view measurements: 180°, 135°, 83°, 46°, 18°, 5°, 7.5 mm, 24 mm, 50 mm, 135 mm, 500 mm, and 180°]

[Images showing different angles of view with lenses: 24mm, 50mm, 135mm]
Shutter Speed

- Expressed in fractions of a second, e.g. 1/100 sec
- If shutter is open longer, integrates across a longer time
- If shutter open too short, can cause noise
Shutter Speed

Was the shutter open a long time or a short time?
Shutter Speed
Was the shutter open a long time or a short time?
Shutter Speed
Aperture

- Trades off more/less light.
- Controls depth of field
Depth of Field
Depth of Field
Depth of Field
Next class

- Filtering and edge detection