Motion illusion, rotating snakes
Recap: projection

\[ x = K[R \ t] X \]
Relating multiple views

Figure Credit: Bundler: Structure from Motion (SfM) for Unordered Image Collections
Today’s class

• Image Formation
• Biological Vision
• Light and Color
From the 3D to 2D

- Let’s now focus on 2D
- Extract building blocks
Image Formation

Digital Camera

The Eye
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection
A photon’s life choices

- Absorption
- **Diffuse Reflection**
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection
A photon’s life choices

• Absorption
• Diffusion
• **Specular Reflection**
• Transparency
• Refraction
• Fluorescence
• Subsurface scattering
• Phosphorescence
• Interreflection
A photon’s life choices

• Absorption
• Diffusion
• Reflection
• **Transparency**
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A photon’s life choices

- Absorption
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- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection

(Specular Interreflection)
Lambertian Reflectance

• In computer vision, the complexity of light transport is mostly ignored.
• Surfaces are often assumed to be ideal diffuse reflectors with no dependence on viewing direction.
Digital camera

• A digital camera replaces film with a sensor array
  – Each cell in the array is light-sensitive diode that converts photons to electrons
  – Two common types
    • Charge Coupled Device (CCD)
    • CMOS
Sensor Array

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

CMOS sensor
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

Progressive scan

Interlace

Rolling Shutter
• The human eye is a camera!
  – **Iris** - colored annulus 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**
Aside: why do we care about human vision in this class?

• We don’t, necessarily.
Ornithopters
Why do we care about human vision?

• We don’t, necessarily.
• But cameras necessarily imitate the frequency response of the human eye, so we should know that much.
• Also, computer vision probably wouldn’t get as much scrutiny if biological vision (especially human vision) hadn’t proved that it was possible to make important judgements from 2d images.
Does computer vision “understand” images?

"Can machines fly?" The answer is yes, because airplanes fly.

"Can machines swim?" The answer is no, because submarines don't swim.

"Can machines think?" Is this question like the first, or like the second?

Source: Norvig
The Retina

Cross-section of eye

Cross section of retina

Ganglion axons
Ganglion cell layer
Bipolar cell layer
Receptor layer
Pigmented epithelium

What humans don’t have: tapetum lucidum

Human eyes can reflect a tiny bit and blood in the retina makes this reflection red.
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
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

Distribution of Rods and Cones

Night Sky: why are there more stars off-center?
Averted vision: http://en.wikipedia.org/wiki/Averted_vision
Wait, the blood vessels are in front of the photoreceptors??

https://www.youtube.com/watch?v=L_W-IXqoxHA
Eye Movements

• **Saccades**
  - Can be consciously controlled. Related to perceptual attention.
  - 200ms to initiation, 20 to 200ms to carry out. Large amplitude.

• **Microsaccades**

• **Ocular microtremor (OMT)**
  - Involuntary. High frequency (up to 80Hz), small amplitude.

• **Smooth pursuit** – tracking an object
Intermission

Slow mo guys – Saccades and CRTs

- [https://youtu.be/Fmg9ZOHESgQ?t=21s](https://youtu.be/Fmg9ZOHESgQ?t=21s)
- [https://youtu.be/3BJU2drrtCM](https://youtu.be/3BJU2drrtCM)
Electromagnetic Spectrum

Human Luminance Sensitivity Function

http://www.yorku.ca/eye/photopik.htm
Visible Light

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.
The Physics of Light

Some examples of the spectra of light sources

A. Ruby Laser

B. Gallium Phosphide Crystal

C. Tungsten Lightbulb

D. Normal Daylight

© Stephen E. Palmer, 2002
The Physics of Light

Some examples of the reflectance spectra of surfaces

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<th>Wavelength (nm)</th>
<th>% Photons Reflected</th>
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<td>Yellow</td>
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<td>400</td>
<td>Blue</td>
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<td>Purple</td>
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© Stephen E. Palmer, 2002
Physiology of Color Vision

Three kinds of cones:

- Why are M and L cones so close?
- Why are there 3?
Tetrachromatism

- Most birds, and many other animals, have cones for ultraviolet light.
- Some humans, mostly female, seem to have slight tetrachromatism.
More Spectra

metamers

yellow flower
orange flower
white petal
white flower
violet flower
orange berry
blue flower

reflectance
wavelength in nm
Color can be ambiguous
Color can be ambiguous
The dress is a photograph that became a viral internet sensation on 26 February 2015, when viewers disagreed over whether the dress pictured was coloured black and blue, or white and gold. The phenomenon revealed differences in human colour perception, which have been the subject of ongoing scientific investigations into neuroscience and vision science, producing a number of papers published in peer-reviewed science journals.

The photo originated from a washed-out colour photograph of a dress posted on the social networking service Facebook. Within the first week after the surfacing of the image, more than 10 million tweets mentioned the dress, using hashtags such as #thedress, #whiteandgold, and #blackandblue. Although the colour of the dress was eventually confirmed as black and blue,[3][4] the image prompted many discussions, with users discussing their different perceptions of the dress’s colour. Members of the scientific community began to investigate the photo for fresh insights into human colour vision.

The dress itself, which was identified as a product of the retailer Roman Originals, experienced a major surge in sales as a result of the incident. The retailer also produced a one-off version of the dress in white and gold as a charity campaign.

https://en.wikipedia.org/wiki/The_dress
Practical Color Sensing: Bayer Grid

- Estimate RGB at ‘G’ cells from neighboring values

Slide by Steve Seitz
Color Image
Images in Matlab

- Images represented as a matrix
- Suppose we have a NxM RGB image called "im"
  - \( \text{im}(1,1,1) \) = top-left pixel value in R-channel
  - \( \text{im}(y, x, b) \) = y pixels down, x pixels to right in the b\(^{th}\) channel
  - \( \text{im}(N, M, 3) \) = bottom-right pixel value in B-channel
Images in Matlab Python

- Images represented as a matrix
- Suppose we have a NxM RGB image called “im”
  - \( \text{im}(0,0,0) = \) top-left pixel value in R-channel
  - \( \text{im}(y, x, b) = y \) pixels down, \( x \) pixels to right in the \( b^{th} \) channel
  - \( \text{im}(N-1, M-1, 2) = \) bottom-right pixel in B-channel
Color spaces

- How can we represent color?

[Image of color representation]
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: YCbCr

Fast to compute, good for compression, used by TV
Color spaces: L*a*b* 

“Perceptually uniform”* color space
If you had to choose, would you rather go without luminance or chrominance?
If you had to choose, would you rather go without luminance or chrominance?
Most information in intensity

Only color shown – constant intensity
Most information in intensity

Only intensity shown – constant color
Most information in intensity
Back to grayscale intensity

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Next class: Thinking in Frequency

Slides: Hoiem, Efros, and others