BSB 663
Image Processing

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Color Perception and Color Spaces

Review - image formation

• What determines the brightness of an image pixel?

Light source properties
Sensor characteristics
Exposure
Optics
Surface shape and orientation
Surface reflectance properties

Review - 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
• http://electronics.howstuffworks.com/digital-camera.htm

Review – digital images

Slide credit: L. Fei-Fei
Slide credit: S. Seitz
Slide credit: D. Hoiem
Review - digital images

- **Sample** the 2D space on a regular grid
- **Quantize** each sample (round to nearest integer)
- Image thus represented as a matrix of integer values.

\[
\begin{array}{cccccccc}
 & & & & & & & \\
 & & & & & & & \\
 & & & & & & & \\
 & & & & & & & \\
 & & & & & & & \\
 & & & & & & & \\
 & & & & & & & \\
 & & & & & & & \\
\end{array}
\]

Outline

- Perception of color and light
- Color spaces

Review – image representation

- **Digital image**: 2D discrete function f
- **Pixel**: Smallest element of an image f(x,y)

Why does a visual system need color?

Slide credits: K. Grauman, S. Seitz
Slide credit: M. J. Black
**Why does a visual system need color? (an incomplete list...)**

- To tell what food is edible.
- To distinguish material changes from shading changes.
- To group parts of one object together in a scene.
- To find people’s skin.
- Check whether a person’s appearance looks normal/healthy.

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**The structure of ambient light**

Adelson & Bergen, 91

The intensity $P$ can be parameterized as:

$$P(\theta, \phi, \lambda, t, X, Y, Z)$$

“The complete set of all convergence points constitutes the permanent possibilities of vision.” Gibson
A photon's life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection

The incident ray might be fully absorbed by the material.

The incident ray might be reflected from the material at many angles.

The incident ray might be reflected from the material only at a single direction.

Slide credit: James Hays
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection

The material might allow the ray to pass through it without being scattered.

Slide credit: James Hays

A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection

The incident ray might be bented as it passes from a material.

Slide credit: James Hays

A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection

The material might absorb the light and then emit the light.

Slide credit: James Hays

A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection

The light might penetrate the surface of a translucent material, and be scattered by interacting with the material.

Slide credit: James Hays
A photon's life choices

• Absorption
• Diffusion
• Reflection
• Transparency
• Refraction
• Fluorescence
• Subsurface scattering
• Phosphorescence
• Interreflection

The light might be absorbed by a phosphorescent material but (unlike fluorescence), the material does not immediately re-emit the light it absorbs.

Image formation

• What determines the brightness of an image pixel?

Light source properties
Surface shape and orientation
Sensor characteristics

Exposure
Optics
Surface reflectance properties

Color

White light: composed of about equal energy in all wavelengths of the visible spectrum

Newton 1665

Slide credits: James Hays, L. Fei-Fei, B. Freeman, A. Torralba, K. Grauman
**Interaction of light and surfaces**

- Reflected color is the result of interaction of light source spectrum with surface reflectance

**What is color?**

- Color is the result of interaction between physical light in the environment and our visual system
- Color is a psychological property of our visual experiences when we look at objects and lights, not a physical property of those objects or lights (S. Palmer, *Vision Science: Photons to Phenomenology*)

**Color and light**

- **Color of light** arriving at camera depends on
  - Spectral reflectance of the surface light is leaving
  - Spectral radiance of light falling on that patch

- **Color perceived** depends on
  - Physics of light
  - Visual system receptors
  - Brain processing, environment

- Color is a phenomenon of human perception; it is **not** a universal property of light

**Brightness perception**

http://web.mit.edu/persci/people/adelson/illusions_demos.html

Edward Adelson

Slide credits: A. Efros, K. Grauman, S. Marschner
Color perception

Addition Reading

• Watch Beau Lotto’s TED talk on “Optical illusions show how we see” [link available on course webpage]
Electromagnetic spectrum

- Light is electromagnetic radiation
  - exists as oscillations of different frequency (or, wavelength)

The Physics of light

Any source of light can be completely described physically by its spectrum: the amount of energy emitted (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

The Physics of light

Some examples of the reflectance spectra of surfaces

Red
Yellow
Blue
Purple
**Image formation**

- What determines the brightness of an image pixel?

**Light source properties**

**Surface shape and orientation**

**Surface reflectance properties**

**Optics**

**Sensor characteristics**

**Exposure**

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**Color mixing**

**Cartoon spectra for color names:**

- **Red**
  - 400 nm
  - 500 nm
  - 600 nm
  - 700 nm

- **Green**
  - 400 nm
  - 500 nm
  - 600 nm
  - 700 nm

- **Blue**
  - 400 nm
  - 500 nm
  - 600 nm
  - 700 nm

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**Additive color mixing**

- **Red**
  - 400 nm
  - 500 nm
  - 600 nm
  - 700 nm

- **Green**
  - 400 nm
  - 500 nm
  - 600 nm
  - 700 nm

- **Yellow**
  - 400 nm
  - 500 nm
  - 600 nm
  - 700 nm

**Colors combine by adding color spectra**

**Light adds to black.**

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**Examples of additive color systems**

- **CRT phosphors**
- **Multiple projectors**

Credit: W. Freeman

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Credit: K. Grauman

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Credit: L. Fei-Fei

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Credit: W. Freeman
Subtractive color mixing

Colors combine by multiplying color spectra.

Pigments remove color from incident light (white).

Examples of subtractive color systems

- Printing on paper
- Crayons
- Photographic film

Reflection from colored surface

The Eye

- Iris - colored annulus with radial muscles
- Pupil - the hole (aperture) whose size is controlled by the iris
- Lens - changes shape by using ciliary muscles (to focus on objects at different distances)
- Retina - photoreceptor cells
The eye as a measurement device

- We can model the low-level behavior of the eye by thinking of it as a light-measuring machine
  - its optics are much like a camera
  - its detection mechanism is also much like a camera

- Light is measured by the photoreceptors in the retina
  - they respond to visible light
  - different types respond to different wavelengths

- The human eye is a camera!

Layers of the retina

Receptors Density - Fovea

Receptors Density - Fovea
Human Photoreceptors

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

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

Two types of light-sensitive receptors

3.4 THE SPATIAL MOSAIC OF THE HUMAN CONES. Cross sections of the human retina at the base of the fovea segments showing: (a) cones at the fovea, and (b) cones in the periphery. Note the grading of cone density as a function of a small separation between cones grouped, the rod receptor field is the unipolar. (c) Cone density profile as a function of distance from the center of the fovea for several human retinas; cone density decreases with distance from the fovea. Source: Carslow et al., 1990.

Slide Credit: B. Freeman and A. Torralba

Human eye photoreceptor spectral sensitivities

3.3 SPECTRAL SENSITIVITIES OF THE L, M, AND S- CONES in the human eye. The measurements are based on a light source at the cones, so that the wavelength less due to the cone, lens, and other inret pigments of the eye plays a role in determining the sensitivity. Source: Stockman and MacLeod, 1993.

Slide Credit: B. Freeman and A. Torralba

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

Images by Shimon Ullman

Rods and cones

Rods are responsible for intensity, cones for color perception
Rods and cones are non-uniformly distributed on the retina
- Fovea - Small region (1° or 2°) at the center of the visual field containing the highest density of cones (and no rods)

Images by Shimon Ullman

Slide credit: A. Efros
Rod / Cone sensitivity

Three kinds of cones:
- Ratio of L to M to S cones: approx. 10:5:1
- Almost no S cones in the center of the fovea

Physiology of Color Vision

Three kinds of cones:
- Ratio of L to M to S cones: approx. 10:5:1
- Almost no S cones in the center of the fovea

Color perception

Rods and cones act as filters on the spectrum
- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number

Q: How can we represent an entire spectrum with 3 numbers?
A: We can’t! Most of the information is lost.
  - As a result, two different spectra may appear indistinguishable

Digital images

- Sample the 2D space on a regular grid
- Quantize each sample (round to nearest integer)

Image thus represented as a matrix of integer values.
Color Images: Bayer Grid

- Estimate RGB at 'G' cells from neighboring values

Images in Matlab

- Images represented as a matrix
- Suppose we have an N x M RGB image called "im"
  - im(1, 1) = top-left pixel value in R-channel
  - im(y, x, b) = y pixels down, x pixels to right in the b\textsuperscript{n} channel
  - im(N, M, 3) = bottom-right pixel in B-channel
- imread(filename) returns a uint8 image (values 0 to 255)
  - Convert to double format (values 0 to 1) with im2double

Digital color images

Color images, RGB color space

Digital color images

Color spaces

- How can we represent color?
**Color spaces: RGB**

- Single wavelength primaries
- makes a particular monitor RGB standard
- Good for devices (e.g., phosphors for monitor), but not for perception

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**Color spaces: CIE XYZ**

- Standardized by CIE (Commission Internationale de l’Eclairage, the standards organization for color science)
- Based on three “imaginary” primaries X, Y, and Z
  - imaginary = only realizable by spectra that are negative at some wavelengths
  - separates out luminance: X, Z have zero luminance, so Y tells you the luminance by itself

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**Color spaces: RGB**

**Default color space**

Some drawbacks
- Strongly correlated channels
- Non-perceptual

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**Color spaces: CIE XYZ**

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\[
\begin{bmatrix}
X \\
Y \\
Z \\
\end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix}
0.49 & 0.31 & 0.20 \\
0.17697 & 0.81240 & 0.01063 \\
0.00 & 0.01 & 0.99 \\
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B \\
\end{bmatrix}
\]
Perceptually organized color spaces

- Artists often refer to colors as *tints*, *shades*, and *tones* of pure pigments
  - tint: mixture with white
  - shade: mixture with black
  - tones: mixture with black and white
  - gray: no color at all (aka. neutral)

- This seems intuitive
  - tints and shades are inherently related to the pure color
    - “same” color but lighter, darker, paler, etc.

Perceptual dimensions of color

- **Hue**
  - the “kind” of color, regardless of attributes
  - colorimetric correlate: dominant wavelength
  - artist’s correlate: the chosen pigment color

- **Saturation**
  - the “colorfulness”
  - colorimetric correlate: purity
  - artist’s correlate: fraction of paint from the colored tube

- **Lightness (or value)**
  - the overall amount of light
  - colorimetric correlate: luminance
  - artist’s correlate: tints are lighter, shades are darker

Color spaces: HSV

- **Hue, Saturation, Value**
- Nonlinear – reflects topology of colors by coding hue as an angle
- *Matlab*: hsv2rgb, rgb2hsv.

Color spaces: HSV

- **Hue, Saturation, Value**
- Nonlinear – reflects topology of colors by coding hue as an angle
- *Matlab*: hsv2rgb, rgb2hsv.
Color spaces: HSV

Intuitive color space

H
S
V

Slide credit: D. Hoiem

Color spaces: YCbCr

Fast to compute, good for compression, used by TV

Y
Cr
Cb

Fast to compute, good for compression, used by TV

Distances in color space

• Are distances between points in a color space perceptually meaningful?

Slide credit: K. Grauman
Distances in color space

- Not necessarily: CIE XYZ is not a uniform color space, so magnitude of differences in coordinates are poor indicator of color “distance”.

McAdam ellipses:
Just noticeable differences in color

Uniform color spaces

- Attempt to correct this limitation by remapping color space so that just-noticeable differences are contained by circles distances more perceptually meaningful.

- Examples:
  - CIE u’v’
  - CIE Lab

Perceptually uniform spaces

- Two major spaces standardized by CIE
  - designed so that equal differences in coordinates produce equally visible differences in color
  - by remapping color space so that just-noticeable differences are contained by circles distances more perceptually meaningful.
  - LUV: earlier, simpler space; L*, u*, v*
  - LAB: more complex but more uniform; L*, a*, b*
  - both separate luminance from chromaticity
  - including a gamma-like nonlinear component is important

Color spaces: L*a*b*

“Perceptually uniform” color space

Slide credits: K. Grauman, S. Marschner
Color spaces: \( L^*a^*b^* \)

"Perceptually uniform" color space

\[
L^* = 116 f \left( \frac{Y}{Y_n} \right)
\]

\[
f(t) = \begin{cases} 
  t^{1/3} & t > \delta^3 \\
  \frac{t}{(3\delta^2)} + 2\delta/3 & \text{else},
\end{cases}
\]

\[
a^* = 500 \left[ f \left( \frac{X}{X_n} \right) - f \left( \frac{Y}{Y_n} \right) \right]
\]

\[
b^* = 200 \left[ f \left( \frac{Y}{Y_n} \right) - f \left( \frac{Z}{Z_n} \right) \right]
\]

\((X_n,Y_n,Z_n)\): measured white point

Most information in intensity

Only intensity shown – constant color

Back to grayscale intensity

Original image

Slide credit: D. Hoiem
Prokudin-Gorskii’s Russia in Color

- Russia circa 1900
- One camera, move the film with filters to get 3 exposures

Images from: https://www.loc.gov/exhibits/empire/

Slide credit: F. Durand

Prokudin-Gorskii’s Russia in Color

- Digital restoration

Slide credit: F. Durand

Emir Seyyid Mur Mohammed Alim Khan, the Emir of Bukhara, ca. 1910.

Self-portrait on the Karolitskhali River, ca. 1910.
A metal truss bridge on stone piers, part of the Trans-Siberian Railway, crossing the Kama River near Perm, Ural Mountains Region, ca. 1910.

On the Sim River, a shepherd boy, ca. 1910.

Peasants harvesting hay in 1909. From the album "Views along the Mariinski Canal and river system, Russian Empire", ca. 1910.