Color
Thursday, Sept 4

Announcements

• Class website reminder
• Pset 1 out today

Last time

• Image formation:
  – Projection equations
  – Homogeneous coordinates
  – Lenses
  – Camera parameters’ affect on images

Review questions

• Why does the ideal pinhole camera model imply an infinite depth of field?
• Use the perspective projection equations to explain these:

Today: Color

• Measuring color
  – Spectral power distributions
  – Color mixing
  – Color matching experiments
  – Color spaces
    • Uniform color spaces

• Perception of color
  – Human photoreceptors
  – Environmental effects, adaptation

• Using color in machine vision systems

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 and light

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

Newton 1665

Image from http://micro.magnet.fsu.edu

Electromagnetic spectrum

Human Luminance Sensitivity Function

Image credit: nasa.gov

Measuring spectra

Spectroradiometer: separate input light into its different wavelengths, and measure the energy at each.

Source

Prism

Movable slit

Lens

Sensor

Foundations of Vision, B. Wandell

Spectral power distribution

• The power per unit area at each wavelength of a radiant object

# Photons

(per ms.)

Wavelength (nm.)

Spectral power distributions

Some examples of the spectra of light sources

A. Ruby Laser

# Photons

Wavelength (nm.)

B. Gallium Phosphide Crystal

# Photons

Wavelength (nm.)

C. Tungsten Lightbulb

# Photons

Wavelength (nm.)

D. Normal Daylight

# Photons

Wavelength (nm.)

Forsyth & Ponce, measurements by E. Koivisto

The color viewed is also affected by the surface’s spectral reflectance properties.

Spectral reflectances for some natural objects: how much of each wavelength is reflected for that surface

Fong et. al, measurements by E. Koivisto
Surface reflectance spectra

Some examples of the reflectance spectra of surfaces

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

The Psychophysical Correspondence

There is no simple functional description for the perceived color of all lights under all viewing conditions, but ... A helpful constraint: Consider only physical spectra with normal distributions

The Psychophysical Correspondence

Mean ↔ Hue

Variance ↔ Saturation

Area ↔ Brightness

Color mixing
Cartoon spectra for color names:

Source: W. Freeman
Additive color mixing

Colors combine by adding color spectra

Light adds to black.

Examples of additive color systems

Subtractive color mixing

Colors combine by multiplying color spectra.

Pigments remove color from incident light (white).

Superposition

- Additive mixing:
  The spectral power distribution of the mixture is the sum of the spectral power distributions of the components.

Examples of subtractive color systems

- Printing on paper
- Crayons
- Most photographic film

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Source: W. Freeman
Why specify color numerically?

- Accurate color reproduction is commercially valuable
  - Many products are identified by color (“golden” arches)
- Few color names are widely recognized by English speakers
  - 11: black, blue, brown, grey, green, orange, pink, purple, red, white, and yellow.
  - Other languages have fewer/more.
  - Common to disagree on appropriate color names.
- Color reproduction problems increased by prevalence of digital imaging – e.g. digital libraries of art.
  - How to ensure that everyone perceives the same color?
  - What spectral radiances produce the same response from people under simple viewing conditions?

Color matching experiments

- Goal: find out what spectral radiances produce same response in human observers
- Assumption: simple viewing conditions, where we say test light alone affects perception
  - Ignoring additional factors for now like adaptation, complex surrounding scenes, etc.
We say a "negative" amount of $p_2$ was needed to make the match, because we added it to the test color’s side.
Color matching

• What must we require of the primary lights chosen?
• How are three numbers enough to represent entire spectrum?

Metamers

• If observer says a mixture is a match → receptor excitations of both stimuli must be equal
• But lights forming a perceptual match still may be physically different
  – Match light: must be combination of primaries
  – Test light: any light
• **Metamers**: pairs of lights that match perceptually but not physically

Grassman’s laws

• If two test lights can be matched with the same set of weights, then they match each other:
  – Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = v_1 P_1 + v_2 P_2 + v_3 P_3$.
  Then $A = B$.
• If we scale the test light, then the matches get scaled by the same amount:
  – Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$.
  Then $kA = (ku_1) P_1 + (ku_2) P_2 + (ku_3) P_3$.
• If we mix two test lights, then mixing the matches will match the result (superposition):
  – Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = v_1 P_1 + v_2 P_2 + v_3 P_3$.
  Then $A + B = (u_1 + v_1) P_1 + (u_2 + v_2) P_2 + (u_3 + v_3) P_3$.
  Here “=” means “matches”.

Computing color matches

• How do we compute the weights that will yield a perceptual match for any test light using a given set of primaries?
  1. Select primaries
  2. Estimate their color matching functions: observer matches series of monochromatic lights, one at each wavelength
  3. Multiply matching functions and test light

Computing color matches

Now have matching functions for all monochromatic light sources, so we know how to match a unit of each wavelength.

Arbitrary new spectral signal is a linear combination of the monochromatic sources.
Computing color matches

So, given any set of primaries and their associated matching functions \( (C) \), we can compute weights \( (e) \) needed on each primary to give a perceptual match to any test light \( t \) (spectral signal).

\[
e = Ct
\]

Why is computing the color match for any color signal for a given set of primaries useful?

- Want to paint a carton of Kodak film with the Kodak yellow color.
- Want to match skin color of a person in a photograph printed on an ink jet printer to their true skin color.
- Want the colors in the world, on a monitor, and in a print format to all look the same.

Adapted from W. Freeman

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Standard color spaces

- Use a common set of primaries/color matching functions
- Linear color space examples
  - RGB
  - CIE XYZ
- Non-linear color space
  - HSV

RGB color space

- Single wavelength primaries
- Good for devices (e.g., phosphors for monitor), but not for perception

CIE XYZ color space

- Established by the commission international d’éclairage (CIE), 1931
- Usually projected to display:
  \[
  (x,y) = \left( \frac{X}{X+Y+Z}, \frac{Y}{X+Y+Z} \right)
  \]
HSV color space
• **Hue, Saturation, Value** (Brightness)
• Nonlinear – reflects topology of colors by coding hue as an angle
• Matlab: hsv2rgb, rgb2hsv.

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

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”.

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

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Human photoreceptors

- **Rods** responsible for intensity
- **Cones** responsible for color
- **Fovea**: small region (1 or 2°) at the center of the visual field containing the highest density of cones (and no rods).
  - Less visual acuity in the periphery

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

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Human photoreceptors

- React only to some wavelengths, with different sensitivity (light fraction absorbed)
- Brain fuses responses from local neighborhood of several cones for perceived color
- Sensitivities vary from person to person, and with age
- Color blindness: deficiency in at least one type of cone

Environmental effects & adaptation

- **Chromatic adaptation**: we adapt to a particular illuminant
- **Assimilation, contrast effects, chromatic induction**: nearby colors affect what is perceived; receptor excitations interact across image and time
- **Afterimages**
  - Color matching ≈ color appearance
  - Physics of light ≈ perception of light

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Trichromacy

- Experimental facts:
  - Three primaries will work for most people if we allow subtractive matching; "trichromatic" nature of the human visual system
  - Most people make the same matches for a given set of primaries (i.e., select the same mixtures)

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Osorio & Vorobyev, 1996

Wavelength (nm)

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>400</td>
</tr>
<tr>
<td>0.2</td>
<td>500</td>
</tr>
<tr>
<td>0.3</td>
<td>600</td>
</tr>
<tr>
<td>0.4</td>
<td>700</td>
</tr>
</tbody>
</table>

Three kinds of cones
Chromatic adaptation

- If the visual system is exposed to a certain illuminant for a while, color system starts to adapt / skew.

Brightness perception

- Content © 2008 R.Beau Lotto
Contrast effects
After images
• Tired photoreceptors send out negative response after a strong stimulus

http://www.sandlotscience.com/Aftereffects/Andrus_Spiral.htm

Source: Steve Seitz

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Color as a low-level cue for CBIR
• Color histograms: Use distribution of colors to describe image
• No spatial info – invariant to translation, rotation, scale

Given two histogram vectors, sum the minimum counts per bin:

\[ I(x, y) = \sum_{i=1}^{3} \min(x_i, y_i) \]

\[ x = [1, 3, 5] \]
\[ y = [2, 6, 3] \]
\[ \sum_{i=1}^{3} \min(x_i, y_i) = 4 \]
Color-based image retrieval

- Given collection (database) of images:
  - Extract and store one color histogram per image
- Given new query image:
  - Extract its color histogram
  - For each database image:
    - Compute intersection between query histogram and database histogram
  - Sort intersection values (highest score = most similar)
  - Rank database items relative to query based on this sorted order

Example database

Example retrievals

Color-based skin detection


Color-based segmentation for robot soccer


http://www.cs.utexas.edu/users/AustinVilla/?p=research/auto_vis
Color-based appearance models for body tracking

Coming up

• Next time: linear filters
  – Read F&P Chapter 7, sections 7.1, 7.2, 7.5, 7.6
  – See Blackboard for additional reading excerpts on filters
• Pset 1 is out, due Sept 18.