Lecture 2: Color
Tuesday, Sept 4

Why do we need color for visual processing?

**Color**
- **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

**Radiometry: some definitions**
- **Radiance**: power emitted per unit area in a direction
- **Irradiance**: total incident power falling on a surface

**Radiometry: BRDF**
- **Bidirectional reflectance distribution function**: Model of local reflection that tells how bright a surface appears when viewed from one direction when light falls on it from another.

**Radiometry: BRDF**
- **BRDF** is a very general notion
  - some surfaces need it (underside of a CD; tiger eye; etc)
  - very hard to measure
    - illuminate from one direction, view from another, repeat
    - very unstable
      - minor surface damage can change the BRDF
      - e.g. ridges of oil left by contact with the skin can act as lenses
  - For many surfaces, light leaving the surface is largely independent of exit angle
Lambertian surfaces

- E.g.: Lambertian / diffuse surfaces: appear equally bright from all viewing directions

\[ f(\theta, \phi, \theta', \phi') = \text{Constant} \]

Color and light

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

Since light can arrive in different quantities at different wavelengths…

\[ BRDF = f(\theta, \phi, \theta', \phi') = \frac{L(\theta, \phi)}{E(\theta', \phi')} \]

...extend radiometry terms to incorporate spectral units (per unit wavelength)

Measuring spectra

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

Spectral power distribution

- the power per unit area per unit wavelength of a radiant object
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.

Color mixing

Additive color mixing

Subtractive color mixing

Examples of additive color systems

<table>
<thead>
<tr>
<th>CRT phosphors</th>
<th>multiple projectors</th>
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Colors combine by adding color spectra.

Light adds to black.

Colors combine by multiplying color spectra.

Pigments remove color from incident light (white).

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Examples of subtractive color systems

- Printing on paper
- Crayons
- Most photographic film

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
  - About 10; other languages have fewer/more, but not many 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 experiment

Observer adjusts weight (intensity) for primary lights (fixed SPD's) to match appearance of test light.

Color matching experiment 1

After Judd & Wyszecki.
We say a “negative” amount of $p_2$ was needed to make the match, because we added it to the test color’s side.

The primary color amounts needed for a match:

• Lights forming a perceptual match 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

- Mixing the matches for two test lights will match the mixture of the two test lights.
- If same weights used to match two test lights, then test lights match.
- Positive scaling of test light -> scaling of weights (additive matching is linear).

Measuring color by color-matching

- Why is computing the color match for any color signal for any 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.

Computing color matches

- How to compute the weights that will yield a perceptual match for any test light using any set of primaries:
  1. Select primaries
  2. Estimate their color matching functions: observer matches series of monochromatic lights, one at each wavelength

\[
C = \begin{pmatrix}
  c_1(\lambda_1) \\
  c_2(\lambda_2) \\
  c_3(\lambda_3)
\end{pmatrix}
\]

Now have matching functions for all monochromatic light sources

Arbitrary new spectral signal is a linear combination of the monochromatic sources

\[
t = \begin{pmatrix}
  t(\lambda_1) \\
  \vdots \\
  t(\lambda_n)
\end{pmatrix}
\]
Computing color matches

Intensities of primary lights needed to obtain match:

$$e = Ct$$

Fig from B. Wandell, 1996

How do you translate colors between different systems of primaries?

$$e = CP' e'$$

The values of the 3 primaries, in the unprimed system

The values of the 3 primaries, in the primed system

A 3x3 matrix
- Transforms one set of primaries to another
- Each column is vector of intensities of the original primaries (P) that are needed to match the new primaries (P')

Standard color spaces

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

CIE XYZ color space

- Established by the commission international d'éclairage (CIE), 1931
- Usually projected to display: 
  $$(x,y) = (X/(X+Y+Z), Y/(X+Y+Z))$$

RGB color space

- Single wavelength primaries
- Phosphors for monitor

Slides by W. Freeman
Color images, RGB color space

CMY
- Cyan Magenta Yellow
- Subtractive mixing (inks, pigment)

HSV
- Hue, Saturation, Value (Brightness)
- Nonlinear – reflects topology of colors by coding hue as an angle

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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
Human photoreceptors

- React only to some wavelengths, with different sensitivities
- 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

Trichromacy

- Experimental facts:
  - Three primaries will work for most people if we allow subtractive matching
  - Exceptional people can match with two or only one primary.
  - This could be caused by a variety of deficiencies.
  - Most people make the same matches (i.e., select the same mixtures)
  - Suggests three common types of receptors
  - ...observed color matching functions obtainable from some 3x3 matrix transformation of the human photopigment response curves?

Computing color matches

- Color matching functions for a particular set of primaries
- Colors of light arriving at camera depends on
  - Spectral reflectance of the surface light is leaving
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- Color perceived depends on
  - Physics of light
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Color, shading perception

- Chromatic adaptation: we adapt to a particular illuminant
- Assimilation & contrast effects: nearby colors affect what is perceived

Color matching \(\approx\) color appearance

Physics of light \(\approx\) perception of light
Perceptual color matching

- Recall: lights forming a *perceptual* match 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
Metameric spectral power distributions

Fig from B. Wandell, 1996

Forsyth & Ponce

Variations in color matches in CIE x,y space
Euclidean distance in x,y not a good metric for perceptual similarity.

MacAdam ellipses

• Projective transform of CIE x, y
• Closer to uniform color space (want MacAdam ellipses to be circles)

See also: CIE Lab

Forsyth & Ponce

Color histograms

• A simple cue: use distribution of colors to describe image (region)
• No spatial info - invariant to translation, rotation, scale.


Skin detection

M. Jones and J. Rehg, Statistical Color Models with Application to Skin Detection, IJCV 2002

Color as a low-level cue for CBIR

IBM's Query by Image content (QBIC) system
From Ashley et al., SIGMOD 1995

Blobworld system
Carson et al., 1999

When is color not a good indicator?
Color-based segmentation for robot soccer

http://www.cs.utexas.edu/users/AustinVilla/?p=research/auto_vis

Next
• Pset0 due Thursday before class – turn in hardcopy
• Read Chapter 7 for Tuesday

Matlab