Why does a visual system need color?
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.

http://www.pouted.com/know-10-points-information-unicorn/sick-child/
Lecture outline

- Color physics.
- Color perception.
Lecture outline

• Color physics.
• Color perception.
4.1 NEWTON'S SUMMARY DRAWING of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995
Spectral colors

http://hyperphysics.phy-astr.gsu.edu/hbase/vision/specol.html#c2
Figure 6.3: (a) A spectrograph constructed using a compact disk (CD). Light enters through a slit at the top and diffracting from the narrowly spaced lines of the CD. (b) Photograph of diffraction pattern from light, seen through hole at bottom left.
Figure 6.5: Some real-world objects and the reflected light spectra (photographed using Fig. (6.3) (a)) from outdoor viewing. (a) Leaf and (b) its reflected spectrum. (c) A red door and (d) its reflected spectrum.
Figure 6.6: More real-world objects and the reflected light spectra. (a) Blue-green chair and (b) its reflected light. (c) Toby the dog and (d) his reflected spectrum.
Blue sky  Tungsten light bulb

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995
Color names for cartoon spectra

- red
- green
- blue
- cyan
- magenta
- yellow

Wavelength in nanometers

400  500  600  700 nm
Additive color mixing

When colors combine by adding the color spectra. Example color displays that follow this mixing rule: tiny display dots on a monitor screen, multiple projectors aimed at a screen.

Red and green make…

Yellow!
Subtractive color mixing

When colors combine by multiplying the color spectra. Examples that follow this mixing rule: most photographic films, paint, cascaded optical filters, crayons, light reflecting off a diffuse surface.

Cyan and yellow (in crayons, called “blue” and yellow) make…

Green!
The interaction of light with surfaces

Spectral radiance: power in a specified direction, per unit area, per unit solid angle, per unit wavelength

\[ BRDF = f(\theta_i, \phi_i, \theta_e, \phi_e, \lambda) = \frac{L(\theta_e, \phi_e, \lambda)}{E(\theta_i, \phi_i, \lambda)} \]

Spectral irradiance: incident power per unit area, per unit wavelength
Simplified rendering models:

BRDF → reflectance as function of wavelength

\[ I_{\text{out}} = I_{\text{in}}(\lambda) A(\lambda) \hat{n} \cdot \hat{p} \]

For diffuse reflections, we replace the BRDF calculation with a wavelength-by-wavelength scalar multiplication.
Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions. Measurements by E.Koivisto.
Simplified rendering models: transmittance

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995
Overhead projector demo

Subtractive color mixing
Lecture outline

• Color physics.
• Color perception.
What’s the machinery in the eye?
Eye Photoreceptor responses

(Where do you think the light comes in?)
3.4 THE SPATIAL MOSAIC OF THE HUMAN CONES. Cross sections of the human retina at the level of the inner segments showing (A) cones in the fovea, and (B) cones in the periphery. Note the size difference (scale bar = 10 μm), and that, as the separation between cones grows, the rod receptors fill in the spaces. (C) Cone density plotted as a function of distance from the center of the fovea for seven human retinas; cone density decreases with distance from the fovea. Source: Curcio et al., 1990.
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 cornea,
so that the wavelength loss
due to the cornea, lens, and
other inert pigments of the eye
plays a role in determining the
sensitivity. Source: Stockman
and MacLeod, 1993.
L, M, and S cone receptor types colored as R, G, B
What are some color artifacts we might expect our visual system to experience, based on this way of measuring the light spectra falling on our eye?
A property of our visual system: these two spectra look the same

4.11 METAMERIC LIGHTS. Two lights with these spectral power distributions appear identical to most observers and are called metamers. (A) An approximation to the spectral power distribution of a tungsten bulb. (B) The spectral power distribution of light emitted from a conventional television monitor whose three phosphor intensities were set to match the light in panel A in appearance.
Two spectra, $t$ and $s$, perceptually match when

$$ \mathbf{C}_\text{eye}^t = \mathbf{C}_\text{eye}^s $$

where $\mathbf{C}_\text{eye}$ are the cone response curves.

Graphically,
Evidence of spatially offset color sampling in an old digital camera

- Color fringes or jaggies
Where you can see color fringe reconstruction artifacts from your own eye

http://static.flickr.com/21/31393422_23013da003.jpg
Brewster’s colors—evidence of interpolation from spatially offset color samples

Scale relative to human photoreceptor size: each line covers about 7 photoreceptors.
Lecture outline

• Color physics.

• Color perception
  – part 1: assume perceived color only depends on light spectrum.
  – part 2: the more general case.
The assumption for color perception, part 1

• We know color appearance really depends on:
  – The illumination
  – Your eye’s adaptation level
  – The colors and scene interpretation surrounding the observed color.

• But for now we will assume that the spectrum of the light arriving at your eye completely determines the perceived color.
How we sense light spectra

**biophysics**: integrate the response over all wavelengths, weighted by the photosensor’s sensitivity at each wavelength.

**mathematically**: take dot product of input spectrum with the cone sensitivity basis vectors. Project the high-dimensional test light into a 3-d space. \[ R = C \cdot t \]
Perceptual color matching experiment

Arbitrary test light

Mixture of 3 primary lights

[Young, Helmholtz, Grassman, etc., 1800’s; slide c/o D. Brainard]
Perceptual color matching experiment

Arbitrary test light

Mixture of 3 primary lights

[Young, Helmholtz, Grassman, etc., 1800's; slide c/o D. Brainard]
To measure a color

1. Choose a set of 3 primary colors (three power spectra).
2. Determine how much of each primary needs to be added to a probe signal to match the test light.

\[ C_{\text{eye}} \cdot t = C_{\text{eye}} \cdot P \cdot \left( \begin{array}{c} a_1 \\ a_2 \\ a_3 \end{array} \right) \]

\[ C_{\text{eye}} \cdot t = C_{\text{eye}} \cdot \left( \sum \text{weighted sum of primaries} \right) \]

\[ \text{project} \]

\[ \text{L, M, S responses} \]
“Color matching functions” tell us how to control primary lights in order to perceptually match a given spectrum.

$p_1 = 645.2 \text{ nm}$

$p_2 = 525.3 \text{ nm}$

$p_3 = 444.4 \text{ nm}$
Requirements on $C$, $P$ to form a color matching system:

(1) the rows of $C$ must be some (non-degenerate) linear combination of the eye photosensor response curves: $C = A C_{\text{eye}}$, where $A$ is some $3 \times 3$ matrix.

(2) for projecting onto $C$ to tell you how much of each primary $P$ is needed to make a perceptual match, $C$, $P$ must satisfy:

$$CP = I_{3 \times 3}$$

If those conditions hold, then the spectrum $PCt$ will be a perceptual match to $t$, because $Ct = CPCt$
Comparison of color matching functions with best linear combination of cone response curves

4.20 COMPARISON OF CONE PHOTOCURRENT RESPONSES AND THE COLOR-MATCHING FUNCTIONS. The cone photocurrent spectral responsivities are within a linear transformation of the color-matching functions, after a correction has been made for the optics and inert pigments in the eye. The smooth curves show the Stiles and Burch (1959) color-matching functions. The symbols show the matches predicted from the photocurrents of the three types of macaque cones. The predictions included a correction for absorption by the lens and other inert pigments in the eye. Source: Baylor, 1987.
Displaying Contrast Sensitivity Function (CSF)

along one axis

along other axis
Contrast Sensitivity Function (CSF)

Range [-0.5, 0.5]
Dims [1000, 1000]
Contrast Sensitivity Function (CSF)
Another psychophysical fact: luminance and chrominance channels in the brain


Figure 6.1
Contrast sensitivity threshold functions for static luminance gratings (Y) and isoluminance chromaticity gratings (R/Y,B/Y) averaged over seven observers.
luminance, chrominance color components: Y, I, Q

\[
\begin{pmatrix}
  Y \\
  I \\
  Q
\end{pmatrix} = \begin{pmatrix}
  0.299 & 0.587 & 0.114 \\
  0.596 & -0.274 & -0.322 \\
  0.211 & -0.523 & 0.312
\end{pmatrix} \begin{pmatrix}
  R \\
  G \\
  B
\end{pmatrix}
\]
YIQ - RGB
Spatial resolution and color

original
Blurring the R component
Blurring the G component

original

processed
Blurring the B component
Lab color components

A rotation of the color coordinates into directions that are more perceptually meaningful:

L: luminance,
a: red-green,
b: blue-yellow
Blurring the L Lab component

original

processed

L

a

b
Blurring the $a$ Lab component

original

processed

L

a

b
Blurring the b Lab component

original

processed
Lecture outline

• Color physics.

• Color perception
  – part 1: assume perceived color only depends on light spectrum.
  – part 2: the more general case.
Color constancy demo

• We assumed that the spectrum impinging on your eye determines the object color. That’s often true, but not always. Here’s a counter-example…
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208 pages (May 2002)
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The Reproduction of Color
by R. W. G. Hunt
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Addison Wesley, 1998
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• Reading:
  – Chapter 6, Forsyth & Ponce
  – Chapter 4 of Wandell, Foundations of Vision, Sinauer, 1995 has a good treatment of this.