Color

Phillip Otto Runge (1777-1810)
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*)
## Electromagnetic spectrum

### Human Luminance Sensitivity Function

#### Solar Radiation Spectrum

- **Sunlight at Top of the Atmosphere**
- **5250°C Blackbody Spectrum**
- **Radiation at Sea Level**

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<table>
<thead>
<tr>
<th>Frequency (ν) (Hz)</th>
<th>Wavelength (λ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{14}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>$10^{12}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$10^{10}$</td>
<td>$10^{-2}$</td>
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<tr>
<td>$10^{8}$</td>
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<td>$10^{6}$</td>
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<td>$10^{4}$</td>
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<tr>
<td>$10^{0}$</td>
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#### Wavelength (λ) (nm)

- $400$ to $700$ (Visible spectrum)

#### Relative Sensitivity

- 0 to 1

#### Spectral Irradiance (W/m²/nm)

- 0 to 2.5
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.
Spectra of Light Sources

Some examples of the spectra of light sources

A. Ruby Laser

B. Gallium Phosphide Crystal

C. Tungsten Lightbulb

D. Normal Daylight

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Spectra of light sources

Source: Popular Mechanics
XKCD Christmas Lights

https://www.xkcd.com/1308/
Reflectance Spectra of Surfaces

Some examples of the **reflectance** spectra of **surfaces**

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

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Interaction of light and surfaces

• Reflected color is the result of interaction of light source spectrum with surface reflectance.
Interaction of light and surfaces

• What is the observed color of any surface under monochromatic light?

Olafur Eliasson, Room for one color
The Eye

The human eye is a camera!

- **Lens** - changes shape by using ciliary muscles (to focus on objects at different distances)
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- **Iris** - colored annulus with radial muscles
- **Retina** - photoreceptor cells
Rods and cones, fovea

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*
Rod / Cone sensitivity

Why can’t we read in the dark?
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
Physiology of Color Vision: Fun facts

• “M” and “L” pigments are encoded on the X-chromosome
  • That’s why men are more likely to be color blind
  • “L” gene has high variation, so some women may be tetrachromatic

• Some animals have one (night animals), two (e.g., dogs), four (fish, birds), five (pigeons, some reptiles/amphibians), or even 12 (mantis shrimp) types of cones

http://ngm.nationalgeographic.com/2016/02/evolution-of-eyes-text

http://en.wikipedia.org/wiki/Color_vision
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

- How can we represent an entire spectrum with 3 numbers?
- We can’t! Most of the information is lost
  - As a result, two different spectra may appear indistinguishable
    » such spectra are known as metamers
Metamers
Spectra of some real-world surfaces

metamers
Standardizing color experience

- We would like to understand which spectra produce the same color sensation in people under similar viewing conditions
- Color matching experiments

Wandell, Foundations of Vision, 1995
Color matching experiment 1

Source: W. Freeman
Color matching experiment 1

Source: W. Freeman
Color matching experiment 1

Source: W. Freeman
The primary color amounts needed for a match

Source: W. Freeman
Color matching experiment 2
Color matching experiment 2

Source: W. Freeman
Color matching experiment 2

Source: W. Freeman
We say a “negative” amount of $p_2$ was needed to make the match, because we added it to the test color’s side.

Source: W. Freeman
Trichromacy

• In color matching experiments, most people can match any given light with three primaries
  • Primaries must be independent

• For the same light and same primaries, most people select the same weights
  • Exception: color blindness

• Trichromatic color theory
  • Three numbers seem to be sufficient for encoding color
  • Dates back to 18th century (Thomas Young)
Grassman’s Laws

• Color matching appears to be *linear*

• 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 $B = u_1 P_1 + u_2 P_2 + u_3 P_3$. Then $A = B$.

• If we mix two test lights, then mixing the matches will match the result:
  • 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 $A + B = (u_1 + v_1) P_1 + (u_2 + v_2) P_2 + (u_3 + v_3) P_3$.

• 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 $kA = (ku_1) P_1 + (ku_2) P_2 + (ku_3) P_3$. 


Linear color spaces

- Defined by a choice of three *primaries*
- The coordinates of a color are given by the weights of the primaries used to match it
- In addition to primaries, need to specify matching functions: the amount of each primary needed to match a monochromatic light source at each wavelength

**RGB primaries**
- \( p_1 = 645.2 \text{ nm} \)
- \( p_2 = 525.3 \text{ nm} \)
- \( p_3 = 444.4 \text{ nm} \)
Linear color spaces

• How to compute the weights of the primaries to match any spectral signal?

**Given:** a choice of three primaries and a target color signal

**Find:** weights of the primaries needed to match the color signal
Linear color spaces

• How to compute the weights of the primaries to match any spectral signal?
• Let $c(\lambda)$ be one of the matching functions, and let $t(\lambda)$ be the spectrum of the signal. Then the weight of the corresponding primary needed to match $t$ is

$$w = \int_{\lambda} c(\lambda)t(\lambda)d\lambda$$
RGB space

- Primaries are monochromatic lights (for CRT monitors, they correspond to the three types of phosphors)
- *Subtractive matching* required for some wavelengths

RGB primaries

\[
\begin{align*}
p_1 &= 645.2 \text{ nm} \\
p_2 &= 525.3 \text{ nm} \\
p_3 &= 444.4 \text{ nm}
\end{align*}
\]
Comparison of RGB matching functions with best 3x3 transformation of cone responses

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.
Linear color spaces: CIE XYZ

- Primaries are *imaginary*, but matching functions are everywhere positive
- The Y parameter corresponds to brightness or *luminance* of a color
- 2D visualization: draw \((x,y)\), where 
  \[ x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z} \]

Matching functions

http://en.wikipedia.org/wiki/CIE_1931_color_space
Uniform color spaces

- Unfortunately, differences in x,y coordinates do not reflect perceptual color differences
- CIE $u'v'$ is a projective transform of x,y to make the ellipses more uniform

**McAdam ellipses:** Just noticeable differences in color
Nonlinear color spaces: HSV

- Perceptually meaningful dimensions: Hue, Saturation, Value (Intensity)
- RGB cube on its vertex
Color perception

- **Color/lightness constancy**
  - The ability of the human visual system to perceive the intrinsic reflectance properties of the surfaces despite changes in illumination conditions

Checker shadow illusion

https://en.wikipedia.org/wiki/Checker_shadow_illusion
Checker shadow illusion

- Possible explanations
  - Simultaneous contrast
  - Reflectance edges vs. illumination edges

https://en.wikipedia.org/wiki/Checker_shadow_illusion
Simultaneous contrast/Mach bands

Source: D. Forsyth
Chromatic adaptation

- The visual system changes its sensitivity depending on the luminances prevailing in the visual field
  - The exact mechanism is poorly understood
- Adapting to different brightness levels
  - Changing the size of the iris opening (i.e., the aperture) changes the amount of light that can enter the eye
  - Think of walking into a building from full sunshine
- Adapting to different color temperature
  - The receptive cells on the retina change their sensitivity
  - For example: if there is an increased amount of red light, the cells receptive to red decrease their sensitivity until the scene looks white again
  - We actually adapt better in brighter scenes: This is why candlelit scenes still look yellow

http://www.schorsch.com/kbase/glossary/adaptation.html
White balance

• When looking at a picture on screen or print, our eyes are adapted to the illuminant of the room, not to that of the scene in the picture
• When the white balance is not correct, the picture will have an unnatural color “cast”

Incorrect white balance

Correct white balance

http://www.cambridgeincolour.com/tutorials/white-balance.htm
What color is the dress?

https://www.wired.com/2015/02/science-one-agrees-color-dress/
This strawberry cake has no red pixels!

https://www.digitaltrends.com/photography/non-red-strawberries/
White balance

• Film cameras:
  • Different types of film or different filters for different illumination conditions

• Digital cameras:
  • Automatic white balance
  • White balance settings corresponding to several common illuminants
  • Custom white balance using a reference object

http://www.cambridgeincolour.com/tutorials/white-balance.htm
White balance

- Von Kries adaptation
  - Multiply each channel by a gain factor

- Best way: gray card
  - Take a picture of a neutral object (white or gray)
  - Deduce the weight of each channel
    - If the object is recoded as $r_w$, $g_w$, $b_w$
      use weights $1/r_w$, $1/g_w$, $1/b_w$
White balance

• Without gray cards: we need to “guess” which pixels correspond to white objects

• Gray world assumption
  • The image average $r_{ave}$, $g_{ave}$, $b_{ave}$ is gray
  • Use weights $1/r_{ave}$, $1/g_{ave}$, $1/b_{ave}$

• Brightest pixel assumption
  • Highlights usually have the color of the light source
  • Use weights inversely proportional to the values of the brightest pixels

• Gamut mapping
  • Gamut: convex hull of all pixel colors in an image
  • Find the transformation that matches the gamut of the image to the gamut of a “typical” image under white light

• Use image statistics, learning techniques
White balance by recognition

- Key idea: For each of the semantic classes present in the image, compute the illuminant that transforms the pixels assigned to that class so that the average color of that class matches the average color of the same class in a database of “typical” images.

Mixed illumination

• When there are several types of illuminants in the scene, different reference points will yield different results.

Reference: moon
Reference: stone

http://www.cambridgeincolour.com/tutorials/white-balance.htm
Spatially varying white balance

E. Hsu, T. Mertens, S. Paris, S. Avidan, and F. Durand,
*Light Mixture Estimation for Spatially Varying White Balance*,
SIGGRAPH 2008
Color cues for image understanding

Image description and matching

Image segmentation