Light and Color

- Eye perceives EM radiation of different wavelengths as different colors.
- Sensitive only to the range 400nm - 700 nm
- This is a narrow piece of the entire electromagnetic spectrum.
Comparing Sound and Light

- Eye sensitive to 400 nm to 700 nm.
  - Not even a factor of 2
  - In terms of sound, less than one octave
  - If our ears had only this range, variety of sounds, instrumental, etc, would be almost nothing.
  - Ear response to sound covers factor of 1000
    - 20 Hz to 20,000 Hz

- Ear characterizes sound in a variety of ways
  - Pitch, timbre, dynamics, duration

- Eye characterizes light only as
  - Color
  - Intensity

- Partially due to eye’s narrow range of wavelength sensitivity.
- We see only a narrow range of the EM spectrum.
- To someone who could see the entire spectrum, our obsession with a narrow niche might seem odd.
More complicated light

- Just like sound, light can be a single wavelength, or a superposition (addition) of different wavelengths.
- We call a single wavelength a pure color.
- A superposition of light wavelengths can be described by its spectrum.
- The spectrum gives the intensity of each wavelength component in the light.
Seeing colors

• Rods and cones send impulses to brain when they absorb light.
• Brain processes into color information.
Rods and cones

- Rods are responsible for vision at low light levels. No color sensitivity
- Cones are active at higher light levels
- The central fovea is populated only by cones.
- 3 types of cones
  - short-wavelength sensitive cones (S)
  - middle-wavelength sensitive cones (M)
  - long-wavelength sensitive cones (L)
Cone distributions, 1° field

- Figure Represents central visual angle ~ 1°
- S-cones (blue-sensitive) make up ~7%
- M-cones (green) ~ 40%
- L-cones (red) ~ 53%
Eye sensitivity

- Eye’s sensitivity to EM radiation by cone type.
Brain interprets cone impulses

- No matter how complex the spectrum of the light, brain receives only a triplet of three ‘numbers’ ($S, M, L$).
- These are the signals from the cones.
- Many different light spectra can send the same stimulus ($S, M, L$) to the brain. These would be ‘seen’ as the same color.
- Means that eye is not particularly selective.
- Two different light sources ‘seen’ as the same color are called metamers.
Color metamers

• In a simple example, these might just be a combination of two spectrally pure colors.
• For instance, a mixture of two spectrally pure colors might produce the same response in the brain as a third spectrally pure color.
**Example:** red + green = yellow

L cone
\[(3+3)\times3=18\]

M cone
\[5.5\times3=16.5\]

570 nm gives same response as superposition of 485 nm & 652 nm
Some complications

- Color and brightness of light source characterized by the triplet \((S, M, L)\).
- Are \((1,2,3)\) and \((2,4,6)\) different colors, or just different brightness?
- \((2,4,6)\) represents twice as much light as \((1,2,3)\), but otherwise identical.

But are grey and white the same color?
Orange and brown?
These pairs differ only in intensity, with the same relative cone stimulus.
Additive color mixing

Almost all colors can be produced by a mixture of three primary colors

**Primary colors:**
1) One primary cannot be matched by a mixture of the other two
2) Often chosen to produce white when all three combined in equal amounts

Common primaries: red green blue

although others could be used
Grassman’s Laws (1853)

Grassman 1\textsuperscript{st} Law:
Any color stimulus can be ‘matched’ exactly by a combination of three primary lights. The match is independent of intensity.

Grassman 2\textsuperscript{nd} Law:
Adding another light to both of these stimuli changes both in the same way.

Can then lay out a graphical catalog of colors, where position in a plane determines color by superposition of primaries.
Maxwell color triangle

- Arrange colors so that they correctly represent fractional mixing along edges of triangle.
- Then interior colors determined by superposition.
- $R+G+B=1$, so only color is indicated, not brightness.
- This is a way to quantify color.
Another version of the color triangle

Since $B = 1 - R - G$, don’t explicitly plot it

$r = 0.4$
$g = 0.28$
Color triangle rule:

when you add two colors, the resultant color always lies along the line joining the two colors.

Our example:

\[ r = 0.4 \]
\[ g = 0.28 \]
Color triangle rule:
when you add two colors, the resultant color always lies along the line joining the two colors

our example
\[ r = 0.4 \]
\[ g = 0.28 \]
This is a mixed color = corresponding spectral color + white

pink

low saturation red
low purity red
Area of human color vision

Where are the **browns**, the **grays**, the **olives**?
white = 255R + 255G + 255B

gray = 128R + 128G + 128B

**gray** lies on the same spot as **white** on the color triangle

orange = 255R + 128G + 0B

brown = 100R + 50G + 0B

**orange** and **brown** also lie on the same spot on the color triangle
Not all colors inside a color triangle

- Physicist Ogden Rood's analysis of pigment chroma
- Shows location of pigments more saturated than any visual mixture of the three "primary" colors; adapted from Modern Chromatics (1879)
- This means that not all colors obtainable by adding easily obtainable primaries
Color matching experiments

- Try to represent all spectrally pure colors as combinations.
- Three lamps with spectra centered on red, green, blue have weight factors $r$, $g$, $b$. Try to match fourth lamp showing a test color.
- Suggests that all colors could be represented as combination of three ‘primary’ colors.
Additive color matching

- Many colors can be represented as a mixture of A, B, C
- Write
  \[ M = a \, A + b \, B + c \, C \]
  where the \( = \) sign should be read as “matches”
- This is **additive** matching.
- Gives a color description system - two people who agree on primaries A, B, C need only supply \((a, b, c)\) to describe a color.
Subtractive color matching

- Some colors can’t be matched like this.
- Color must be added to the test light in order to make a match.
  
  *write this as*

\[ M + a A = b B + c C \]

- This is called **subtractive** matching.
- Interpret this as \((-a, b, c)\).
- If we need to *generate* the color from three primaries, subtractive matching is a problem. *(e.g. for a TV or computer monitor).*
Additive Matching

The primary color amounts needed for a match

Image courtesy Bill Freeman
Subtractive Matching

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:

\[ p_1 \quad p_2 \quad p_3 \]
Color matching results

- Use spectrally pure primaries:
  - red (700 nm)
  - green (546.1 nm)
  - blue (438.1 nm)

- Determine red, green, blue required to match pure spectral test color.

- Graph shows relative fractions of three primaries required to make a match.

- Region of subtractive color mixing shows up as negative amounts of the red source in the 500 nm range.
The principle of trichromacy

- Experimental facts:
  - Three primaries will work for most people if we allow subtractive matching
  - Most people make the same matches.
    - There are some anomalous trichromats, who use three primaries but make different combinations to match.
New ‘red’, ‘green’, ‘blue’ primaries

- Define new primaries $X$, $Y$, $Z$
- Sources not spectrally pure, but combinations of old primaries.
- Eye response to spectrally pure colors can be reproduced with only additive color matching.

\[ \text{color}_\lambda = \bar{x}(\lambda)X + \bar{y}(\lambda)Y + \bar{z}(\lambda)Z \]

- More importantly, $X$, $Y$, $Z$ chosen so that $\bar{y}(\lambda)$ matches the total spectral sensitivity of eye (brightness).
- $X$, $Y$, $Z$ are called the CIE primaries.
The CIE primaries

- The CIE primaries are unphysical colors.
- For example, here are the amounts of red (700nm) green (546.1 nm) blue (438.1 nm) to make the CIE X primary.
- Note the negative amount of green.
- But we can still express colors as a certain fraction \( X \), fraction \( Y \), and fraction \( Z \).
The CIE XYZ color space

- This makes a three-dimensional color space. Each color represented by a point \((X, Y, Z)\).
- Represents color and intensity. Includes all whites, grays, etc.
- But some combinations of \(X\), \(Y\), \(Z\) do not represent physical lights.
- The unphysical combinations are shown here in gray.
- Spectrally pure colors lie on the boundary with the unphysical region.
A more useable color space

Goals

• Would like to discuss color without worrying about brightness.
• Also need something easier to use than a 3D space.

Process

• Define fractional primaries

\[ x \equiv \frac{X}{X+Y+Z}, \quad y \equiv \frac{Y}{X+Y+Z}, \quad z \equiv \frac{Z}{X+Y+Z} \]

• Sum \( x+y+z \) always one since these are fractional amounts.

• Independent of overall intensity \( (X+Y+Z) \).
• Represent only color, not brightness.
• Need only two of them to represent color.
• Use \( x, y \), with \( Y \) the brightness.
• \( Yxy \) is another 3D color space, but color information is in \( xy \).
xy plane of Yxy color space

- Point determined by xy labels a particular color.
- Boundary are the pure spectral colors labeled by wavelength.
- The Y axis (out of page) determines brightness (luminosity).
- The colors shown in this picture are representative.
Using the CIE color space in the $xy$ plane

- Can be used the same way as the color triangle.
- Additive mixing of two colors produces a color on the line between them.
- Distance along line determined by relative fraction of mixing colors.
Dominant wavelength of a color

E is the white point.
S is a test color.
From the previous discussion, S can be obtained by mixing the pure spectral color D with white.
We then say that the dominant wavelength of S is the wavelength of the pure spectral color D.
The complement of a color

- Shows that white can be produced by adding only two colors.
- A color can be mixed with its complement to produce pure white.
Gamut: the range of colors

- Many of the physical colors can be obtained by mixing three primary colors.
- Since result of mixing two colors lies on line joining them, total range of possible colors lie inside triangle formed by three primaries.
- This is the gamut projected to the xy plane.

Colors obtainable by additive mixing of spectrally pure primaries of 650nm, 540nm, and 450nm lie within this triangle.
How are colors displayed on screen?

- Electron beam
- Funnel
- Face Plate
- Shadow mask
- Phosphor screen

Diagram components:
- Electron gun
- Deflection yoke
- Neck
- Convergence magnet
- Base

Mon. Oct 11
Phy107 Lecture 15
Color CRT Phosphor Pattern

- Light from R, G, B phosphors combine to produce a color \( rR + gG + bB \)
- But the emitted light is not exactly red, blue, green.
What exactly are these R, G, B?

- Light emitted by phosphors not spectrally pure colors.
- Can still make colors by combining these, but which ones?
Computer monitor gamut in the Yxy color space

- Top view, showing xy plain.
- Each phosphor described by a pair \((x,y)\).
- Three primaries are vertices of the gamut triangle.
- Gamut does not appear as perfect triangle due to perspective effects.
Other views of monitor gamut

Pure spectral colors

Y (Luminance)