COLOR

Computer Vision I

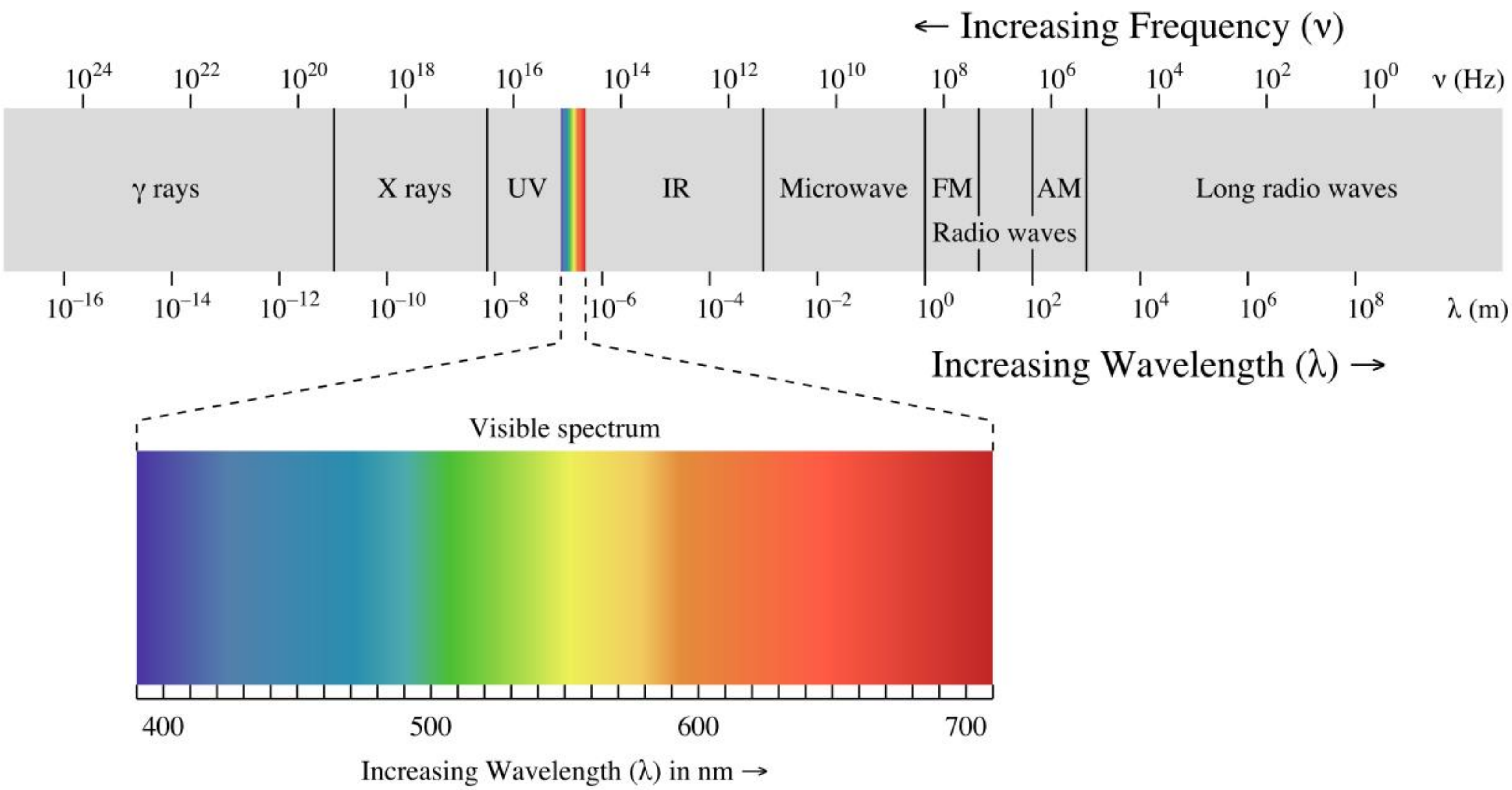
CSE 252A

Lecture 17

Announcements

- Assignment 4 is due Dec 6, 11:59 PM
- Final exam is Dec 14, 7:00 PM-9:59 PM
- Please complete TA and course evaluations

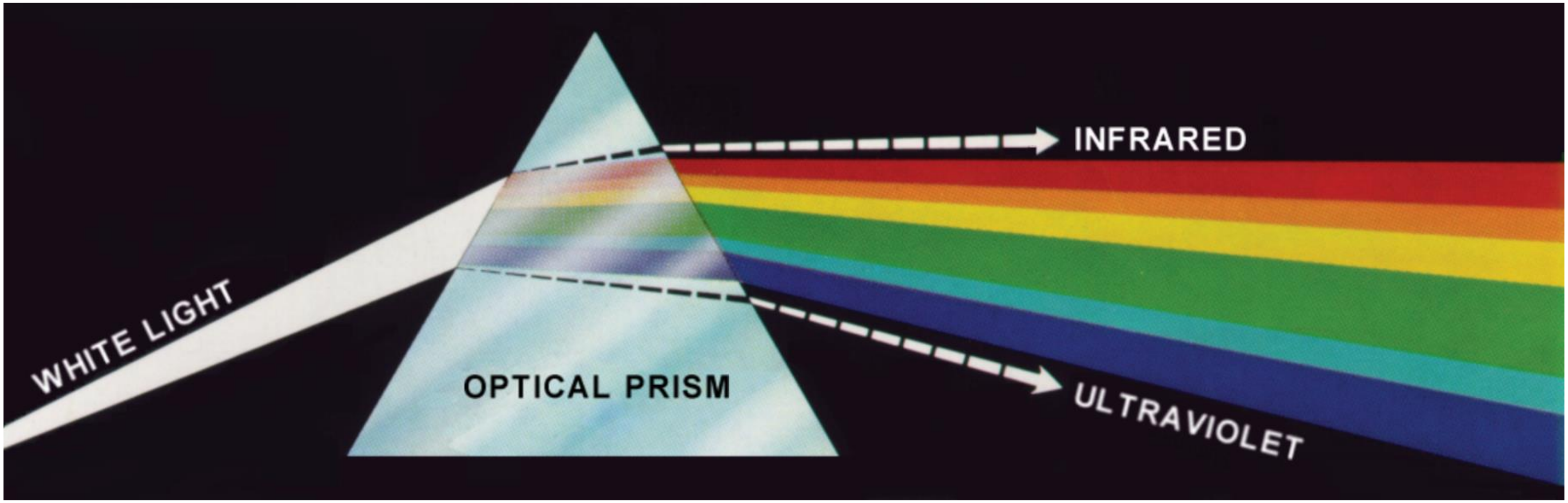
Electromagnetic Spectrum

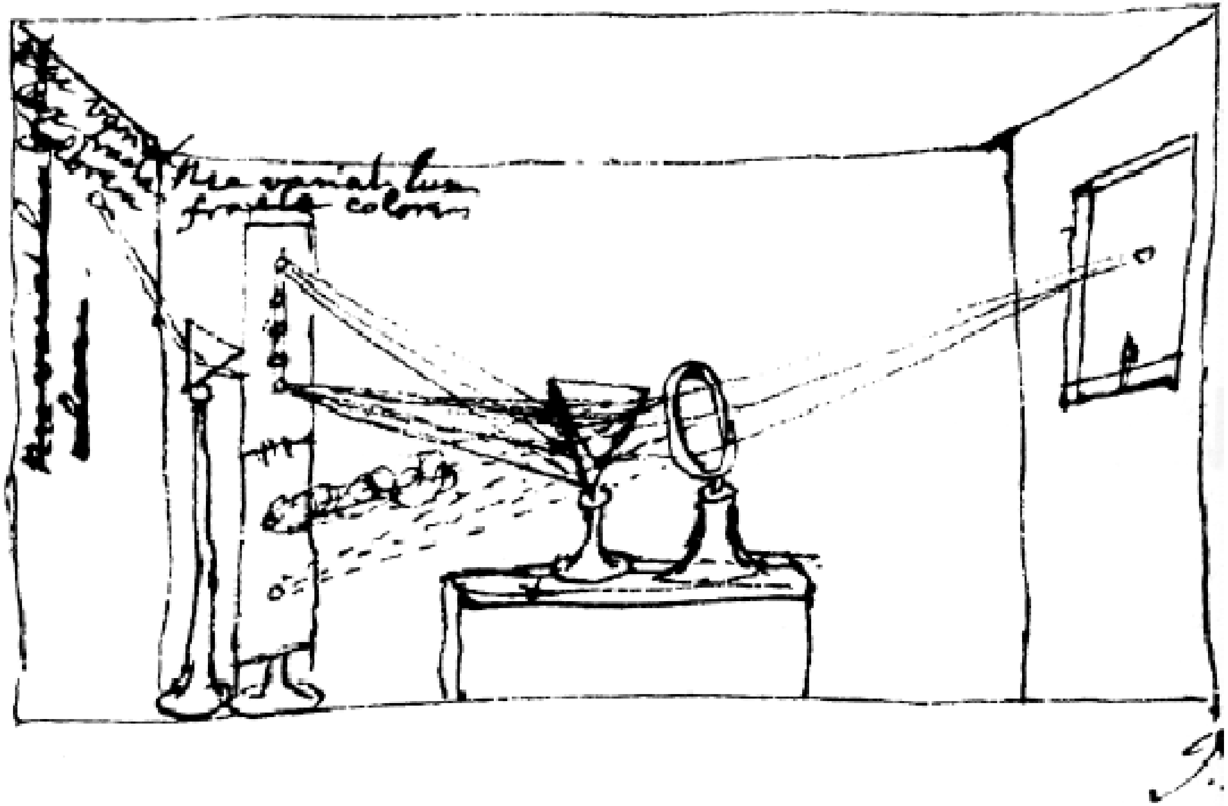


The appearance of colors

- Color appearance is strongly affected by (at least):
  - spectrum of lighting striking the retina
  - other nearby colors (space)
  - adaptation to previous views (time)
  - "state of mind"

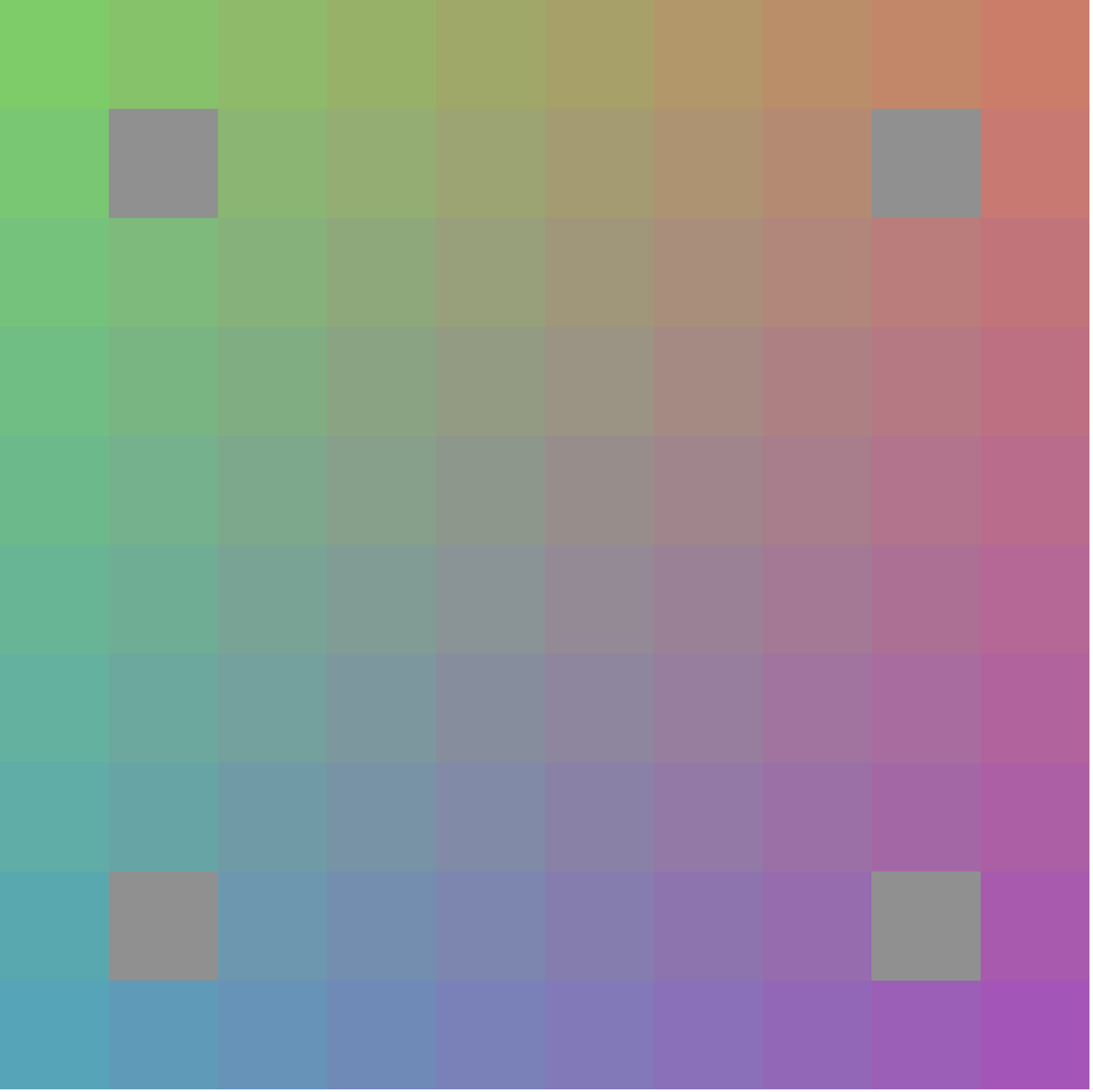
Separating visible light

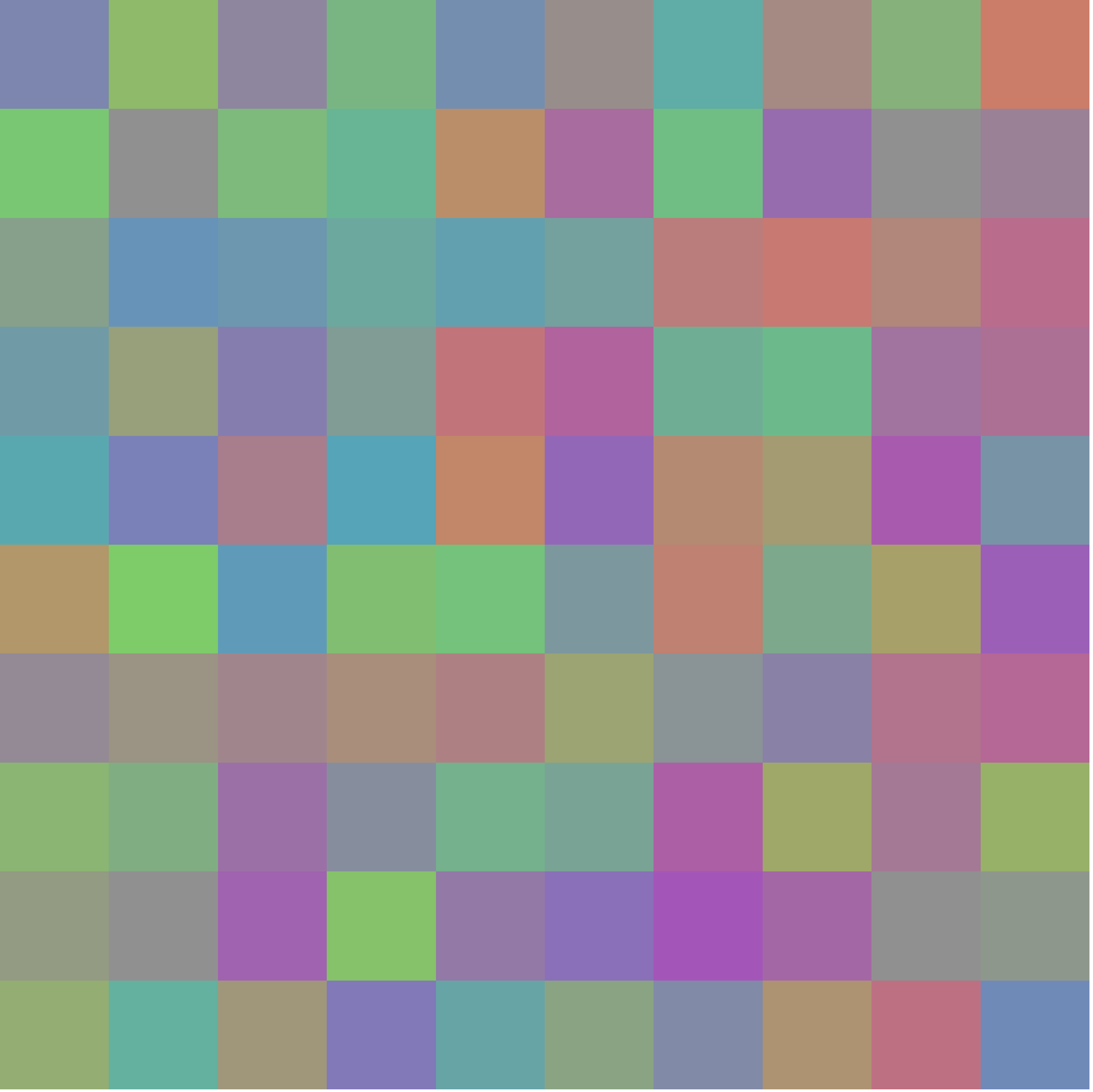


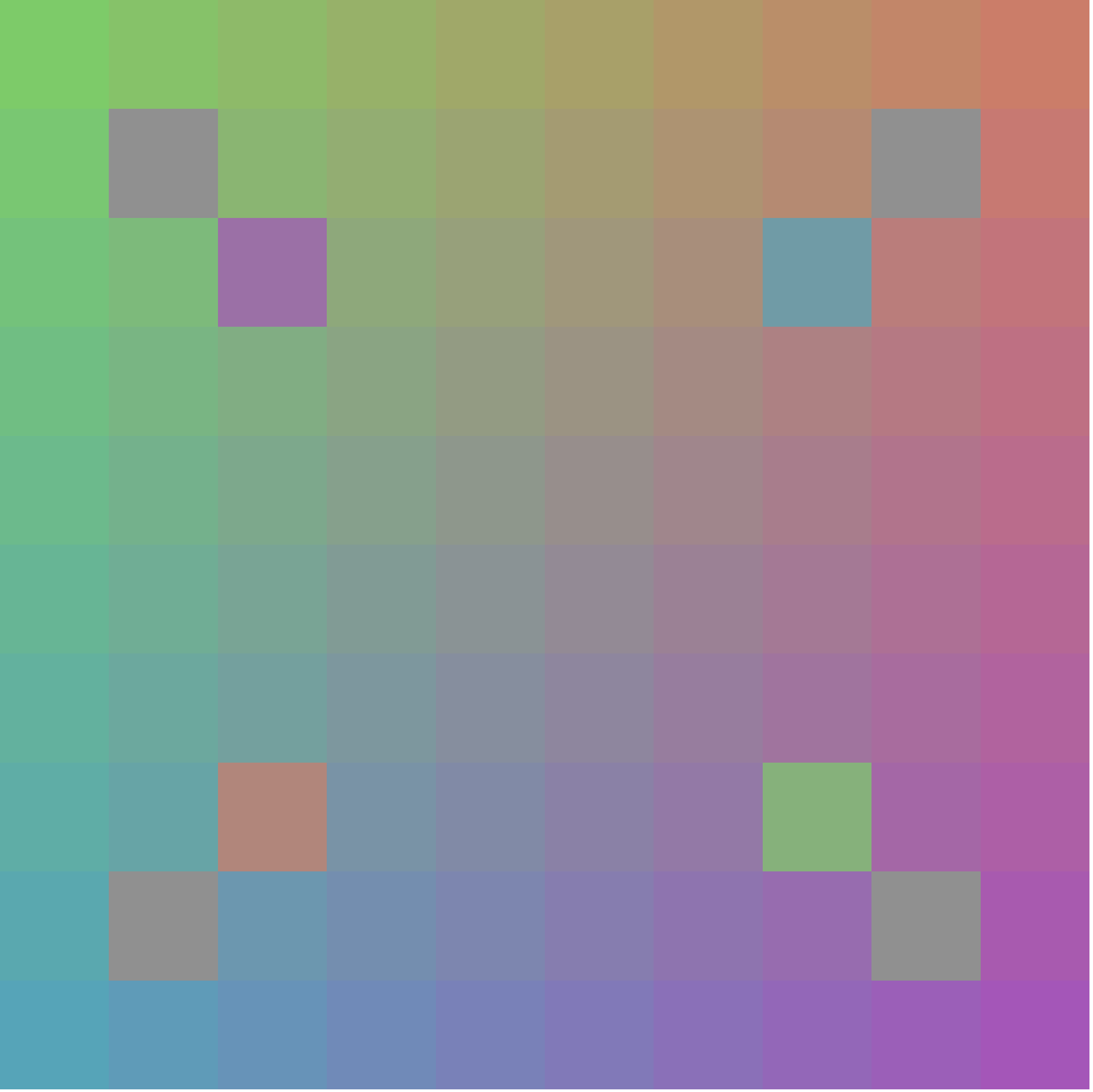


4.1 **NEWTON'S SUMMARY DRAWING** of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

From Foundations of Vision, Brian Wandell, 1995, via B. Freeman slides



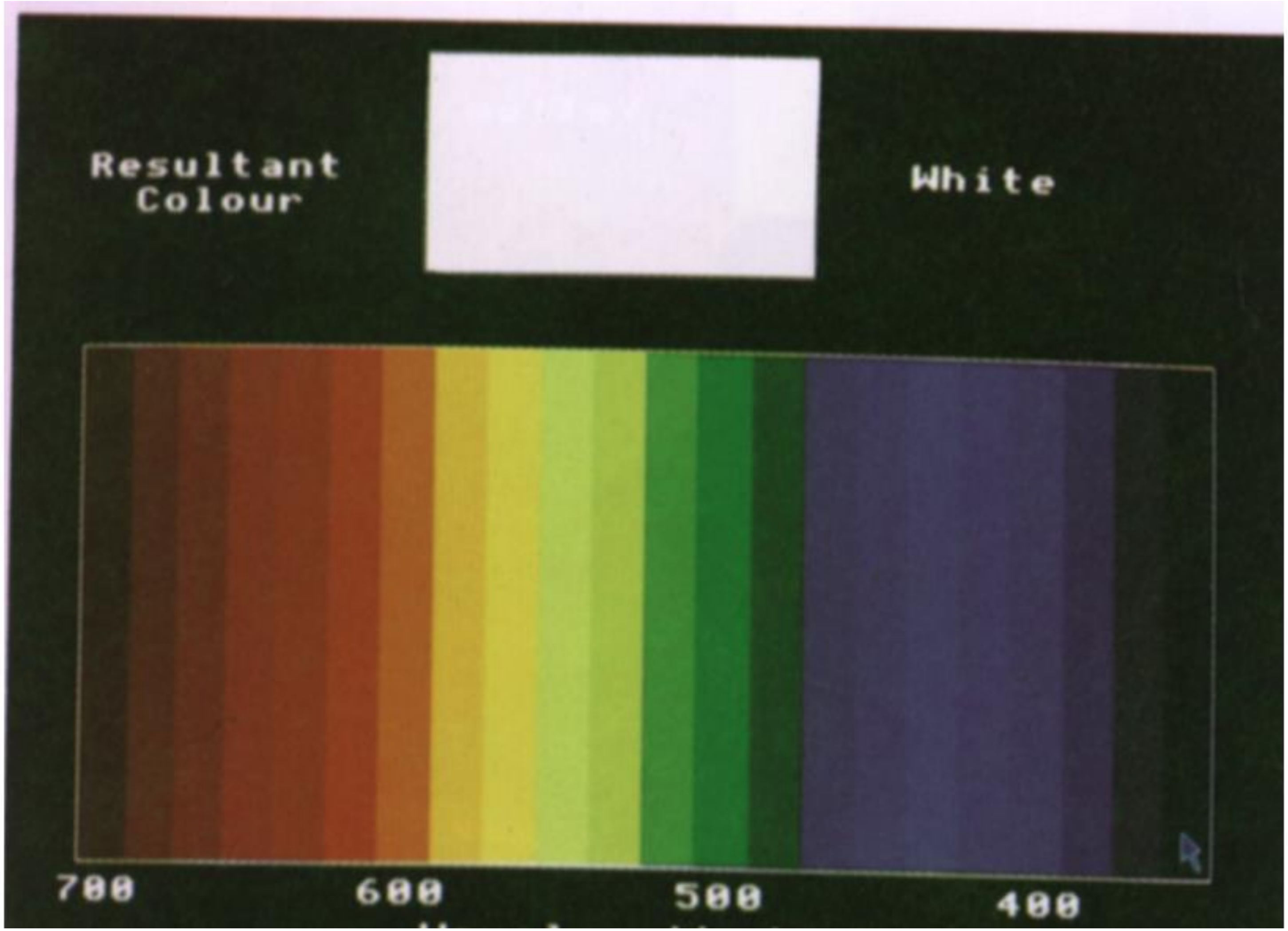





note:
black & white
gifbin.com

XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	RED	RED
XXXXXX	WHITE	WHITE
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	BLUE	BLUE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	WHITE	WHITE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE

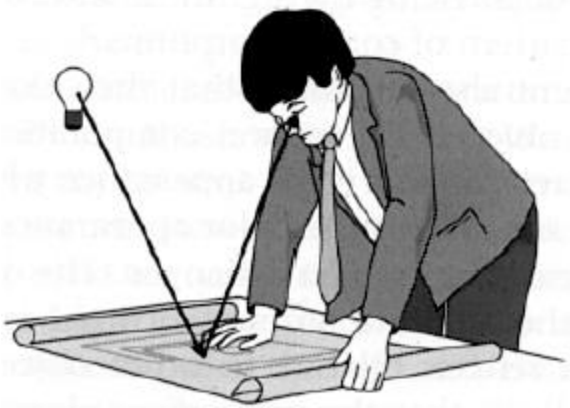
Light Spectrum



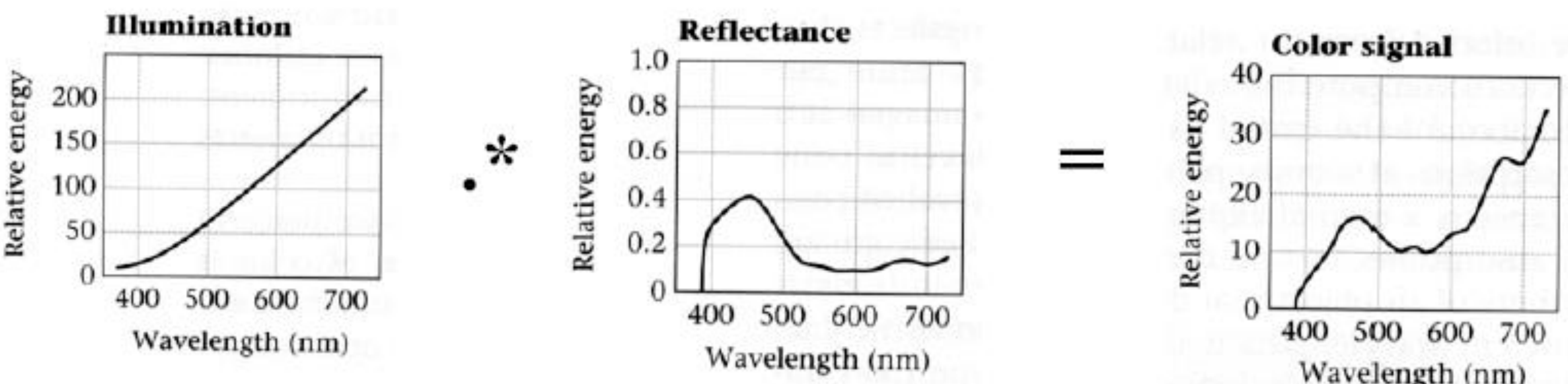
Talking about colors

1. Spectrum –
   - A positive function over interval 400nm-700nm
   - "Infinite" number of values needed.
2. Names
   - red, harvest gold, cyan, aquamarine, auburn, chestnut
   - A large, discrete set of color names
3. R,G,B values
   - Just 3 numbers

Color Reflectance



Measured color spectrum is a function of the spectrum of the illumination and reflectance



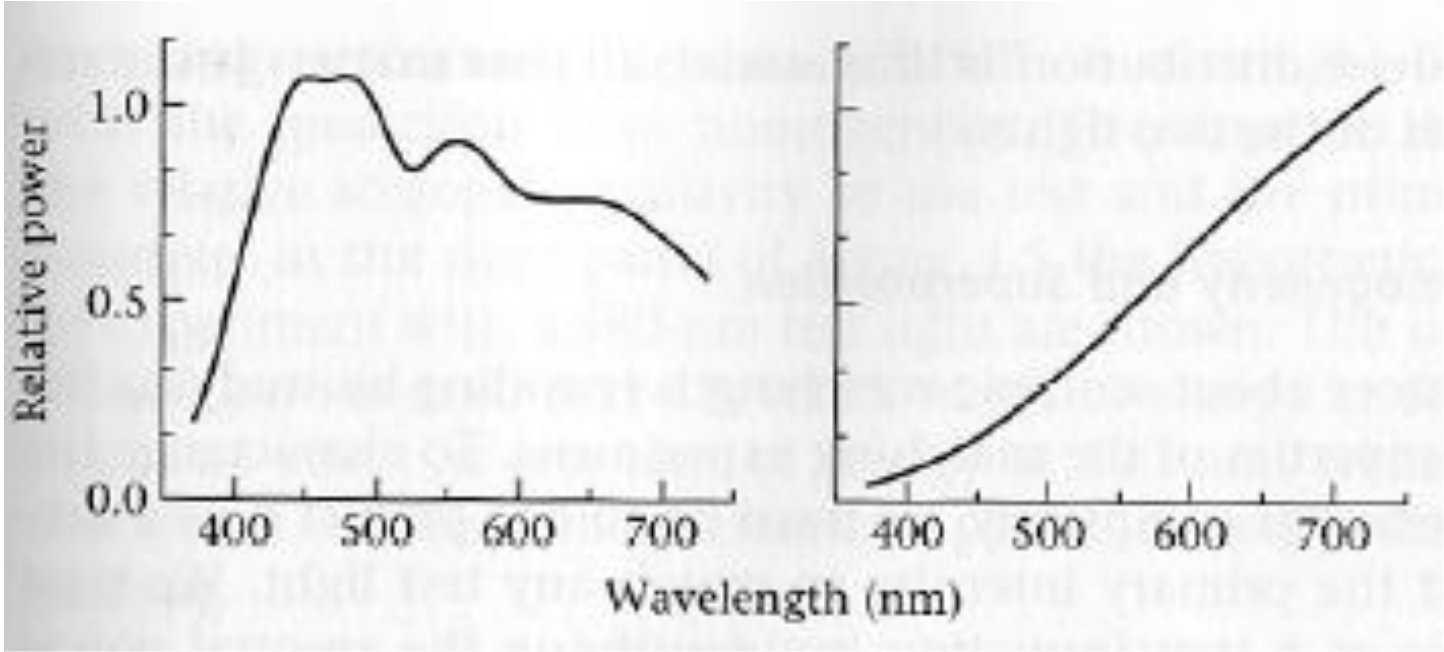
From Foundations of Vision, Brian Wandell, 1995, via B. Freeman slides

Illumination Spectra

Different illumination spectra yield different measured color spectra

Blue skylight

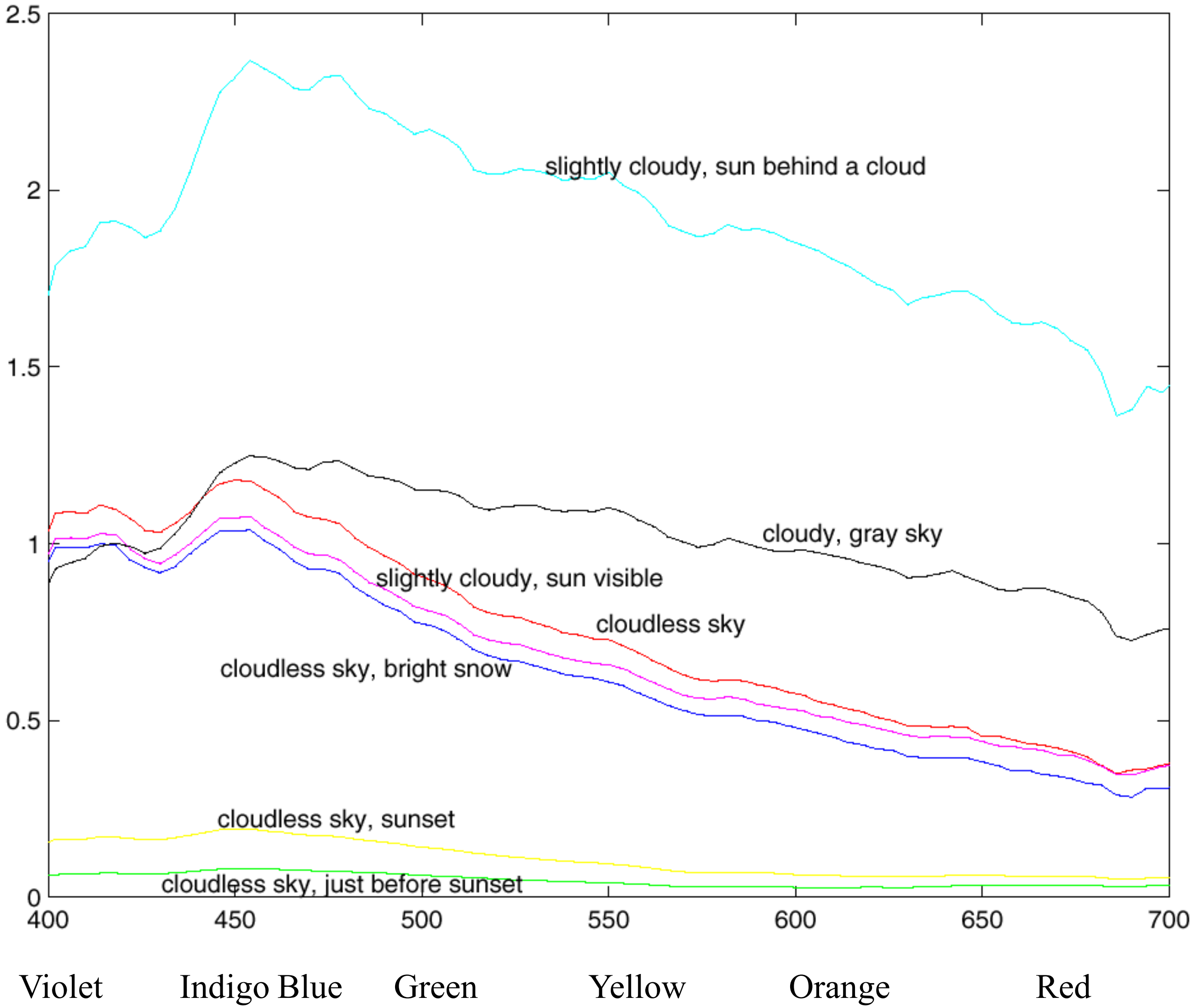
Tungsten bulb



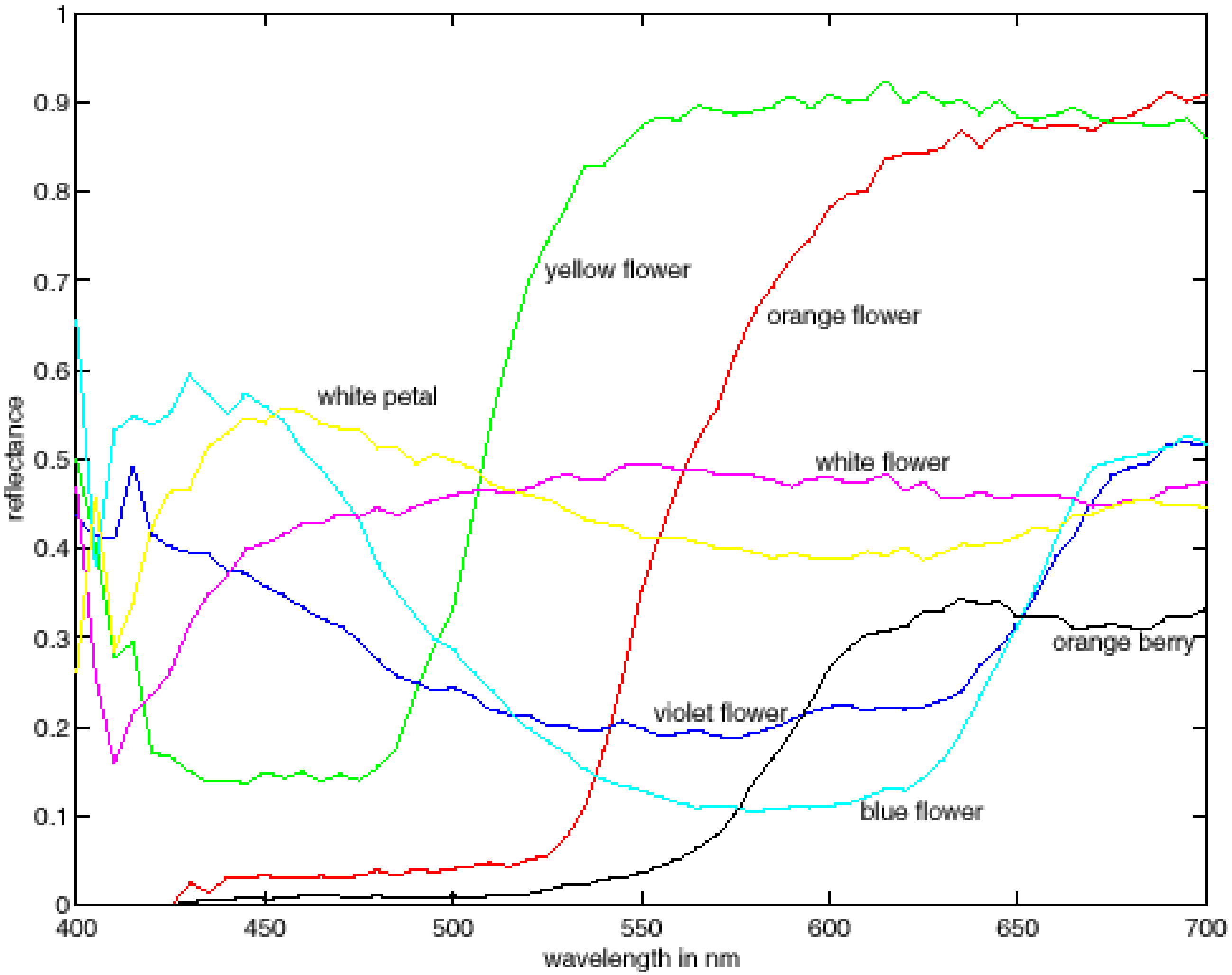
From Foundations of Vision, Brian Wandell, 1995, via B. Freeman slides

Why is this important?

- The color measured by a camera depends on
  - The camera response function
  - Spectrum of illuminant
  - Reflectance properties of objects in the scene
- The “color” of an object does not actually make a lot of sense, unless you talk about it under a reference light

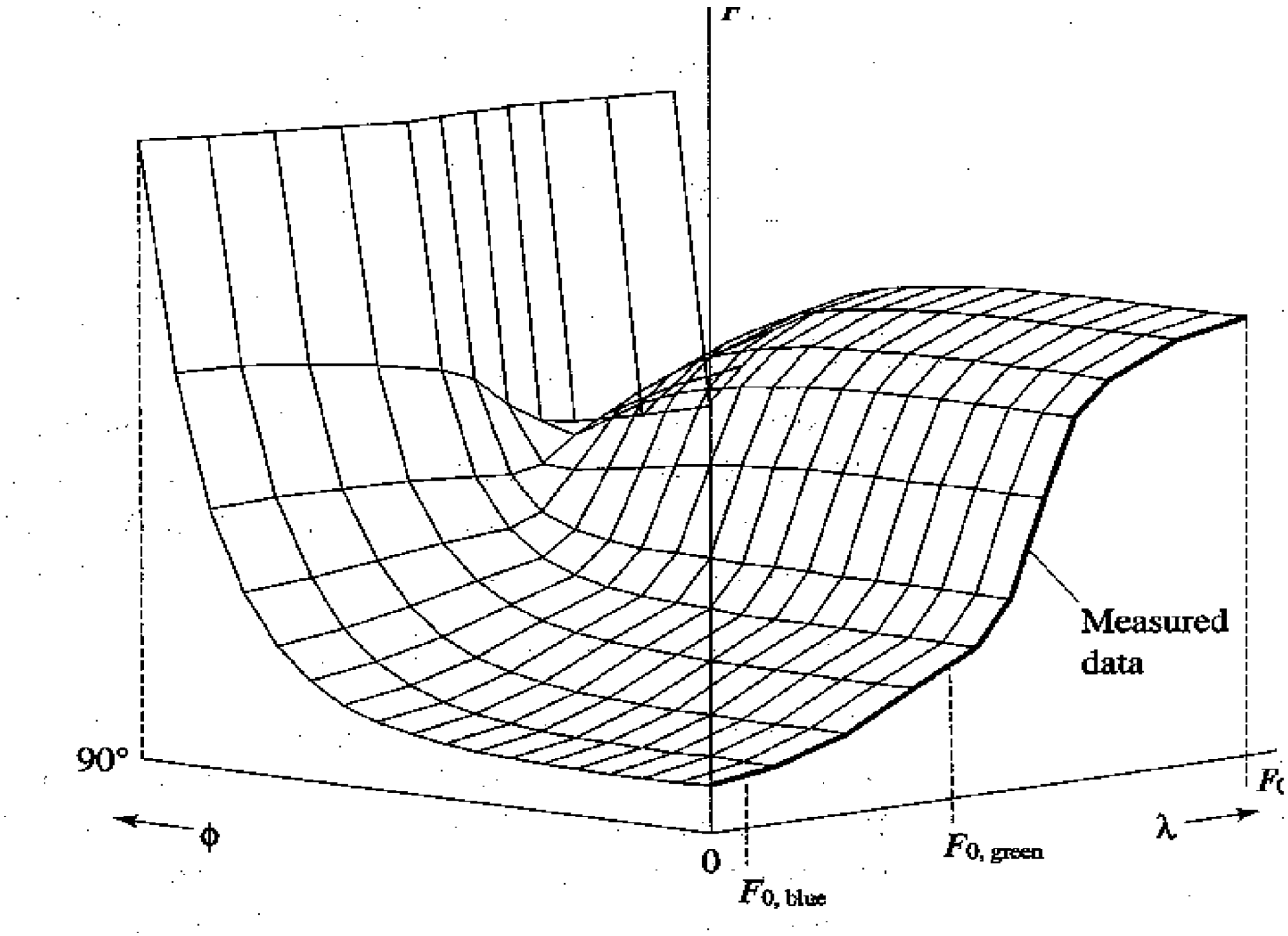


Measurements of relative spectral power of sunlight, made by J. Parkkinen and P. Silfsten. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm. The color names on the horizontal axis give the color names used for monochromatic light of the corresponding wavelength --- the “colors of the rainbow”. Mnemonic is “Richard of York got blisters in Venice”.



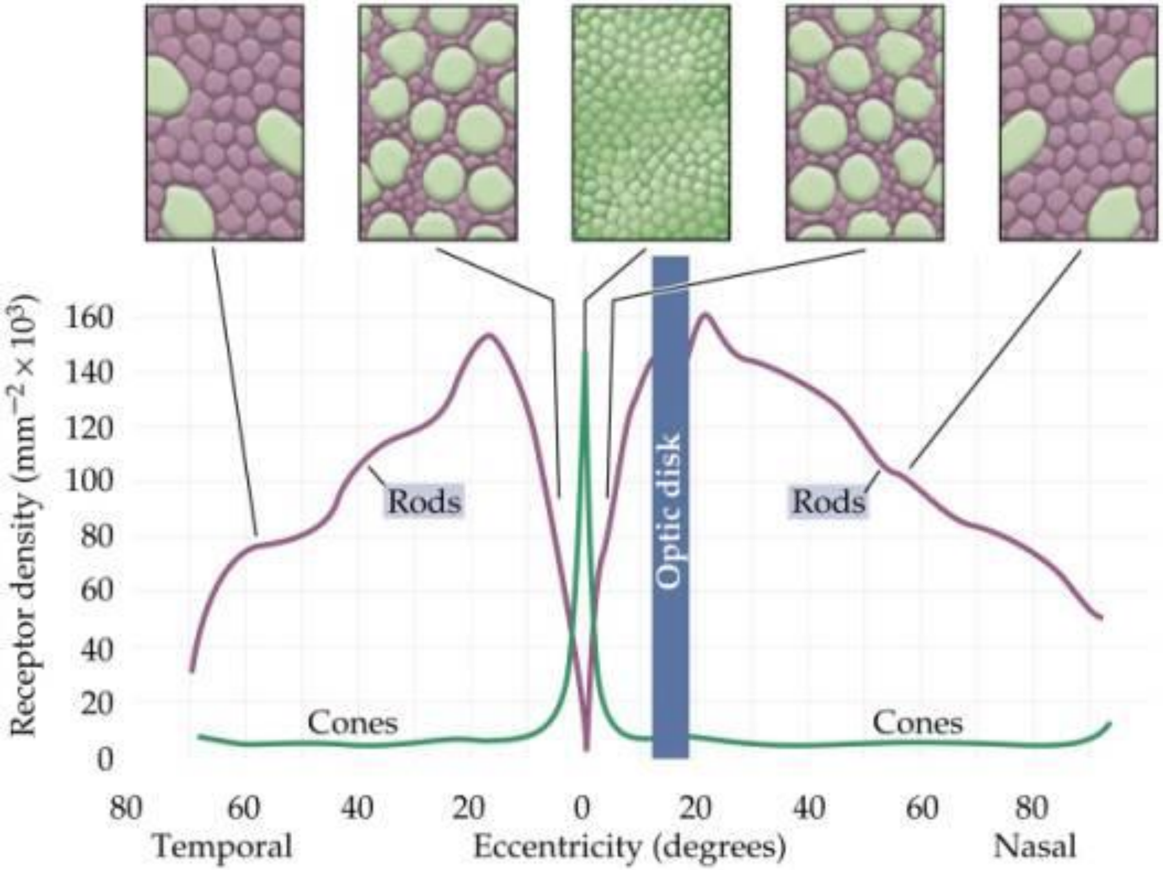
Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions. Measurements by E.Koivisto.

Fresnel Equation for Polished Copper



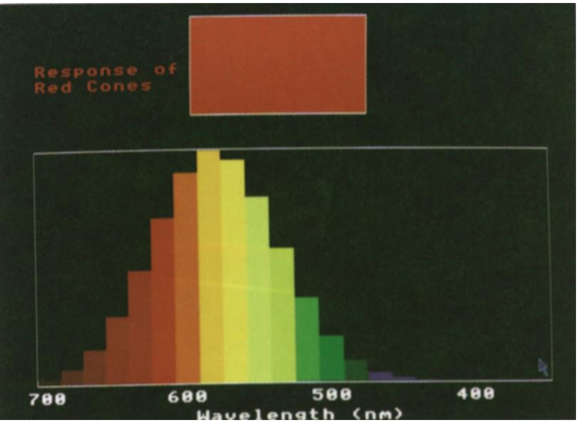
RGB Color Model

- Based on human perception of color

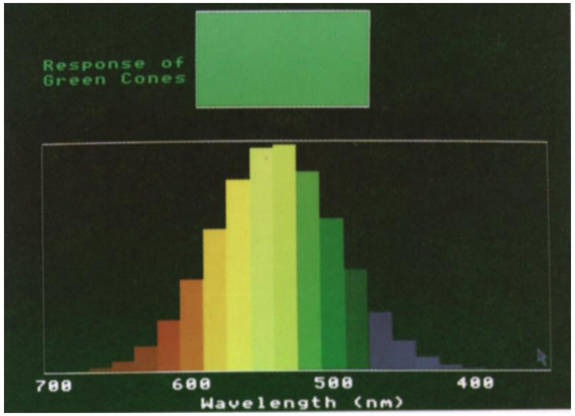


Red cones
Green cones
Blue cones

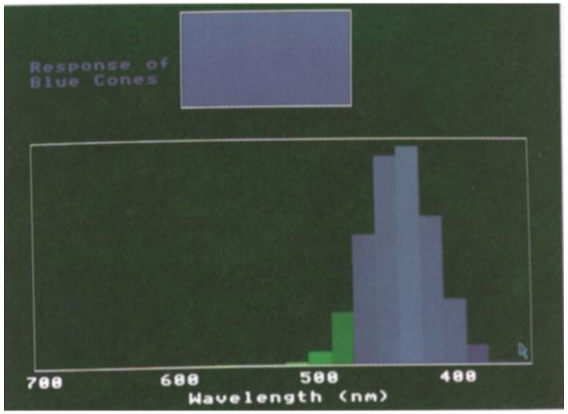
Color receptors



"Red" cone



"Green" cone

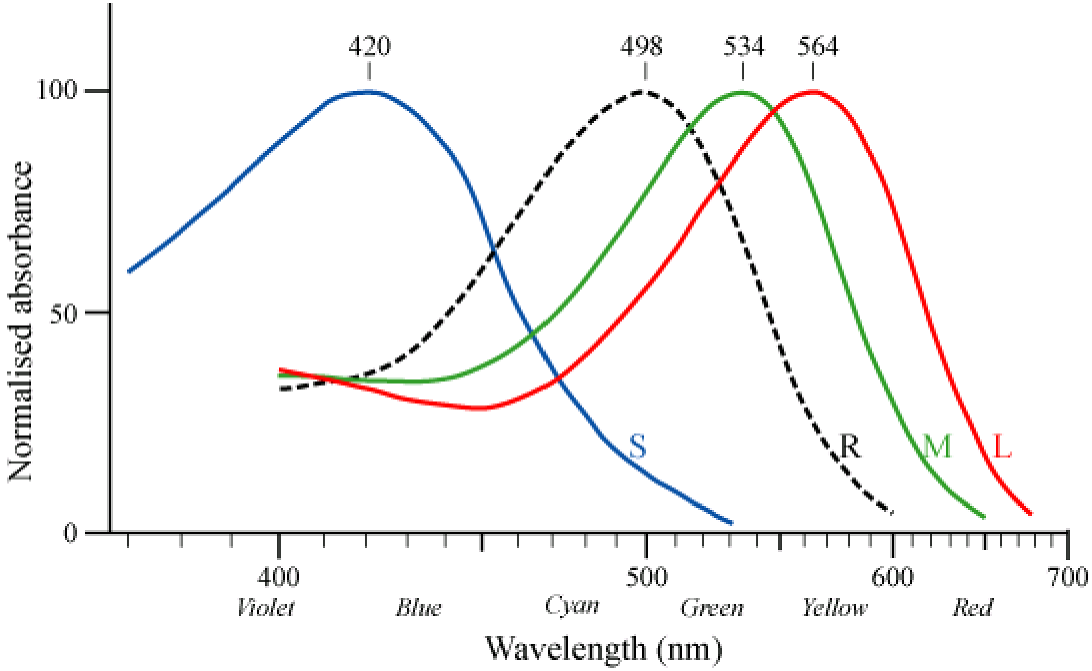


"Blue" cone

Response of kth cone = $$\int \rho_k(\lambda)E(\lambda)d\lambda$$

Three types of cones: R,G,B

$$\text{Response of } k\text{th cone} = \int \rho_k(\lambda) E(\lambda) d\lambda$$



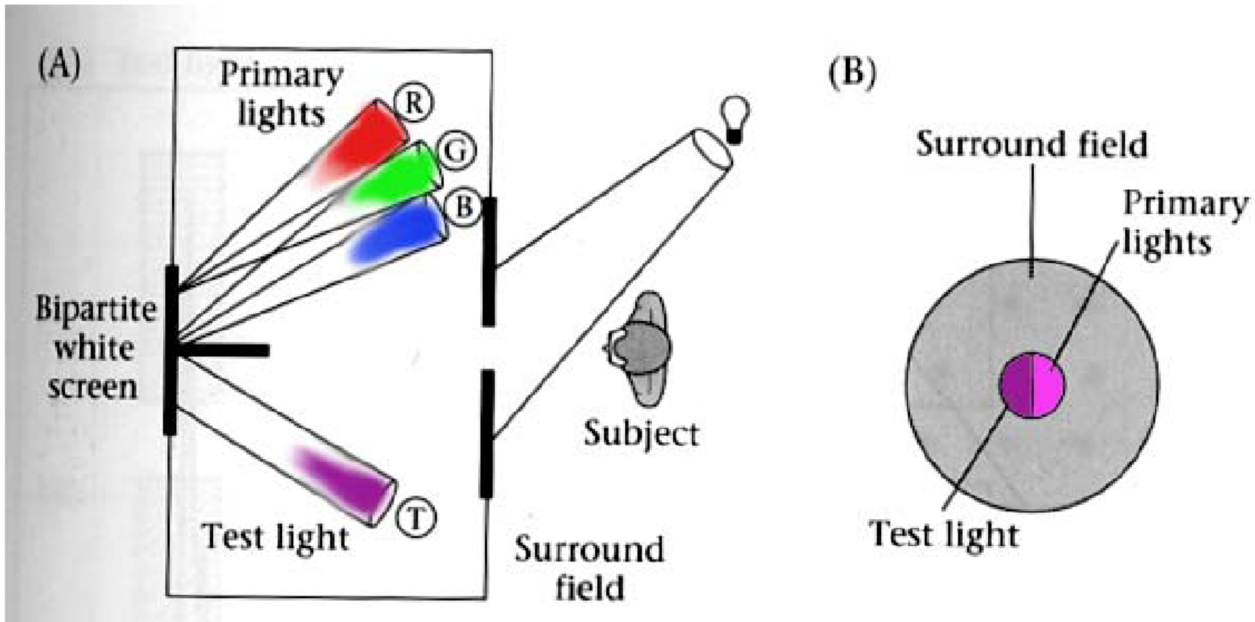
There are three types of cones

- S: Short wave lengths (Blue)
- M: Mid wave lengths (Green)
- L: Long wave lengths (Red)

→

- Three attributes to a color
- Three numbers to describe a color

Color matching experiment



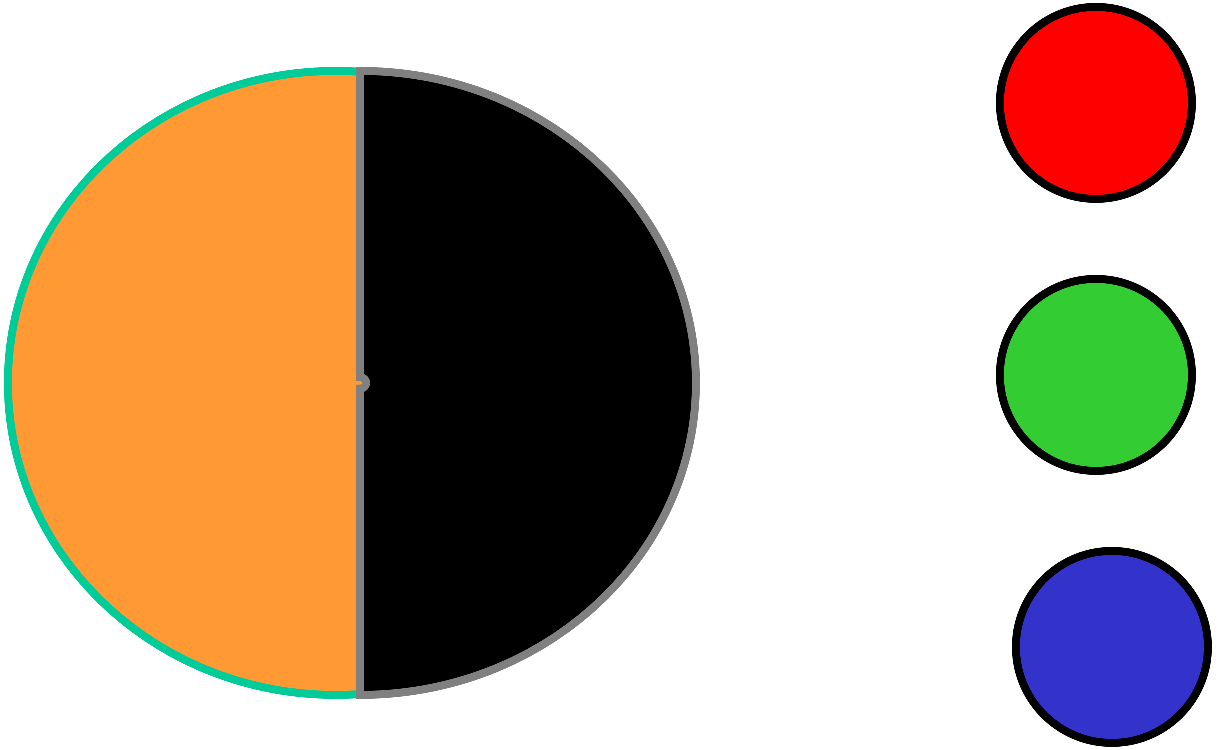
4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Not on a computer Screen

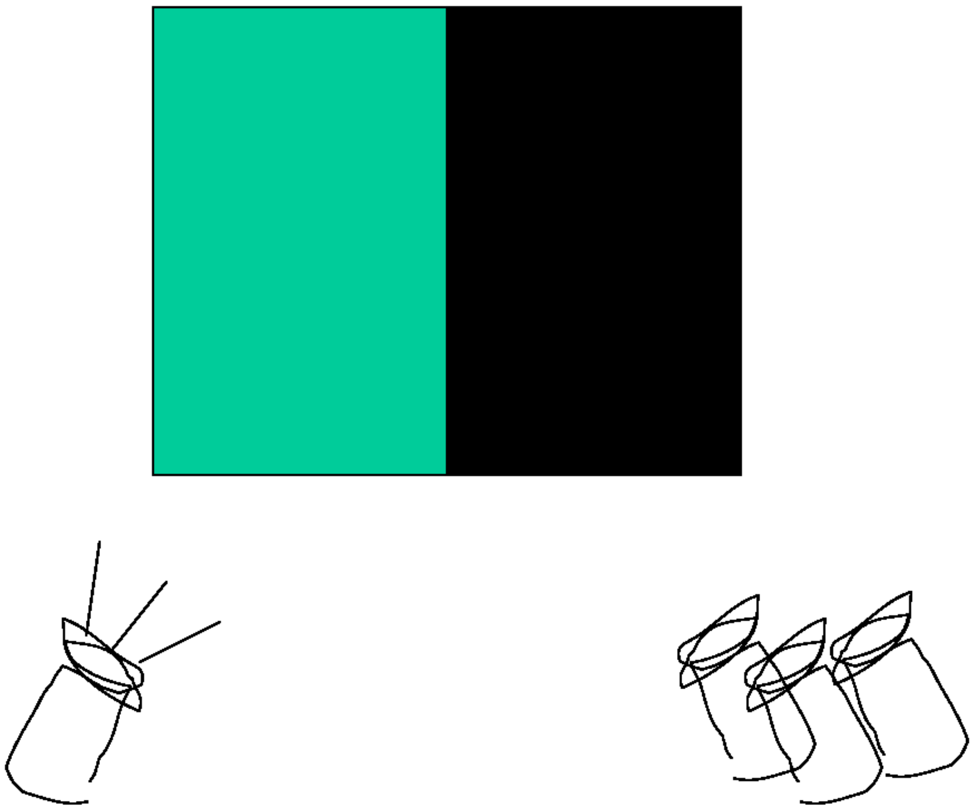
slide from T. Darrel

Color Matching



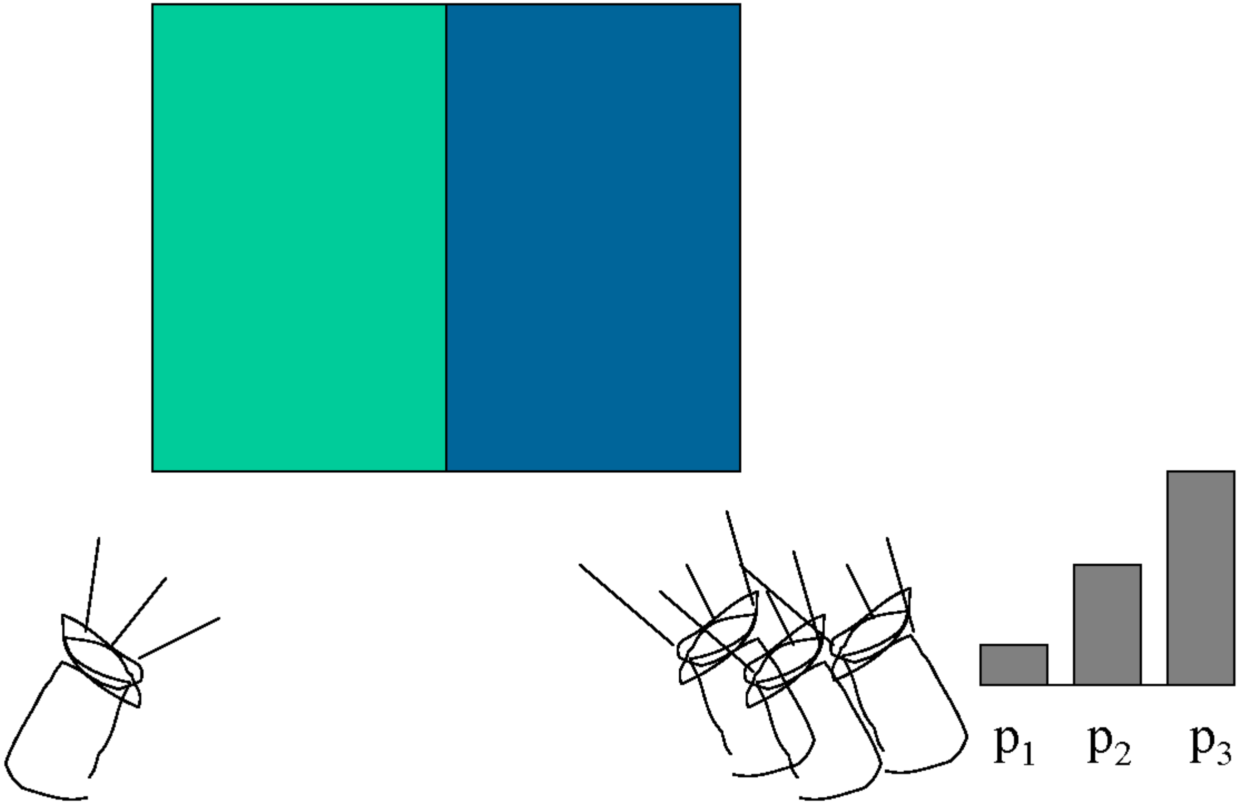
Not on a computer Screen

Color matching experiment 1



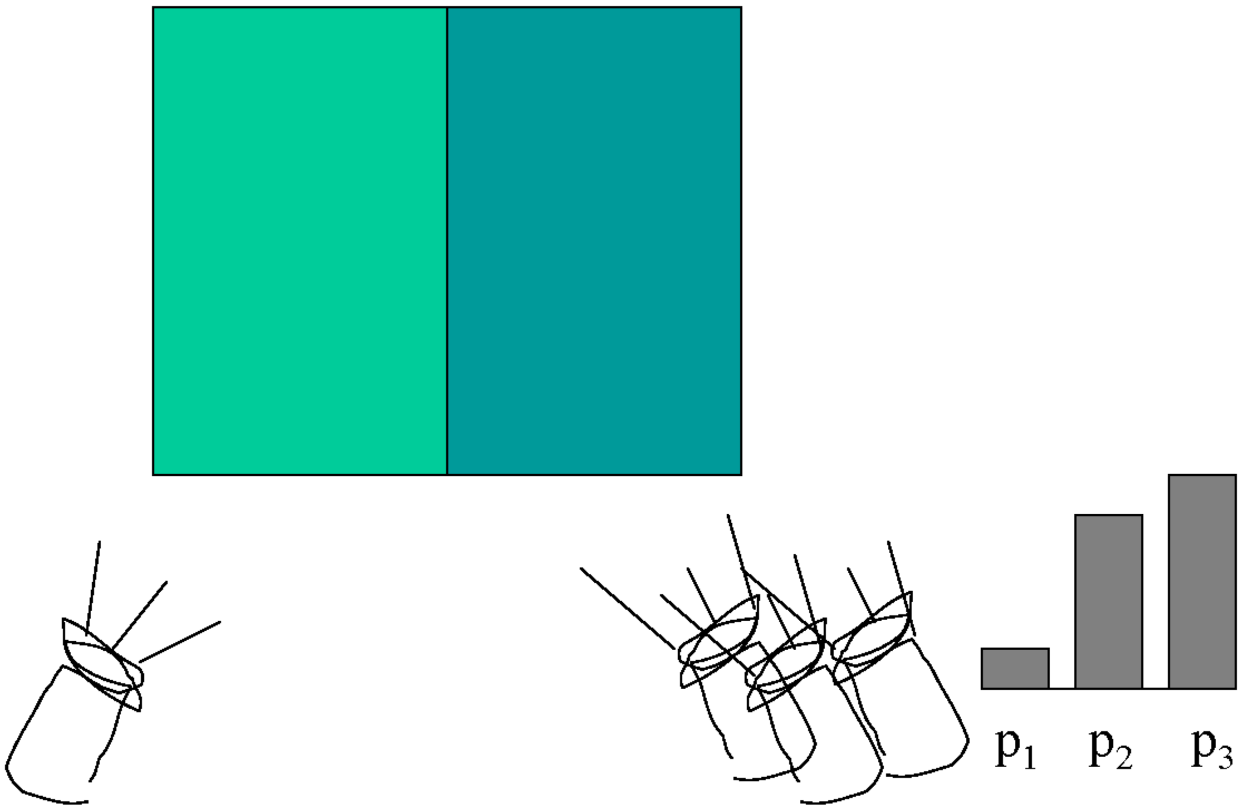
slide from T. Darrel

Color matching experiment 1



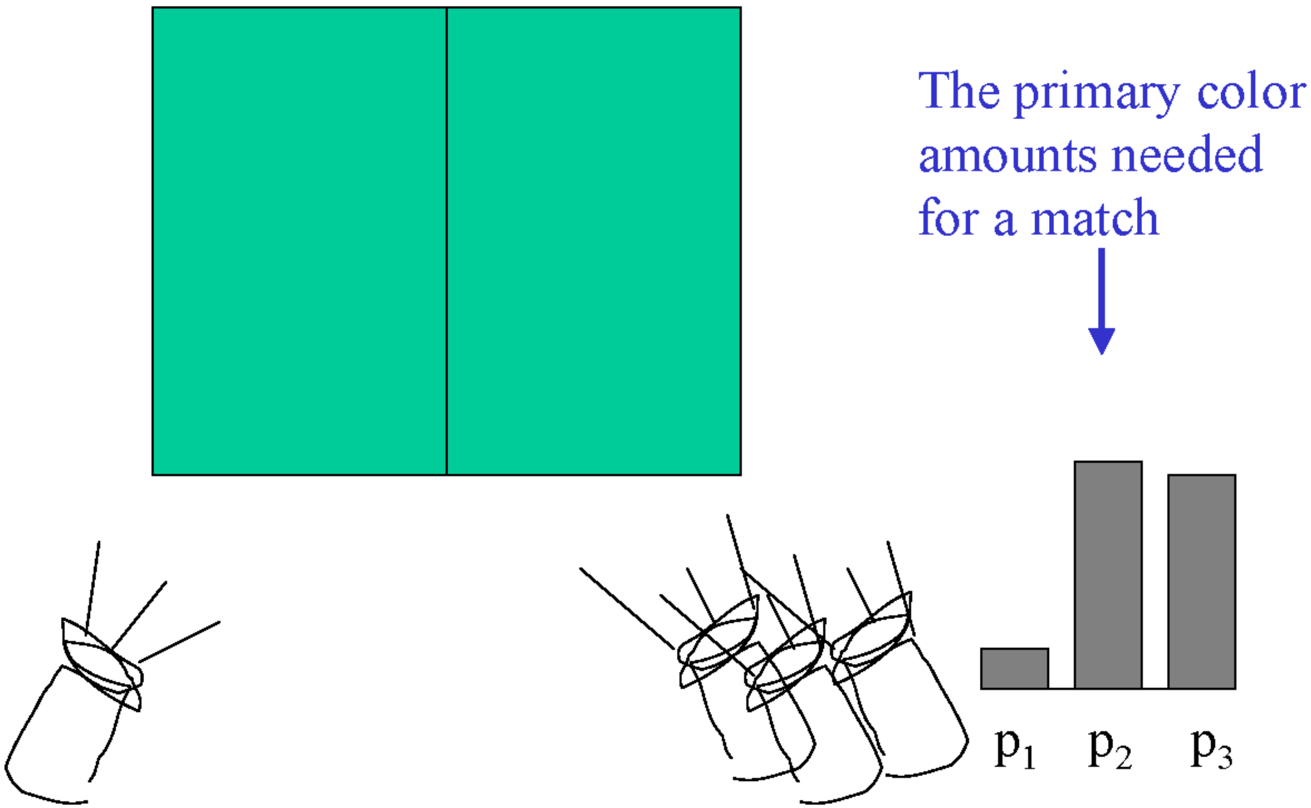
slide from T. Darrel

Color matching experiment 1



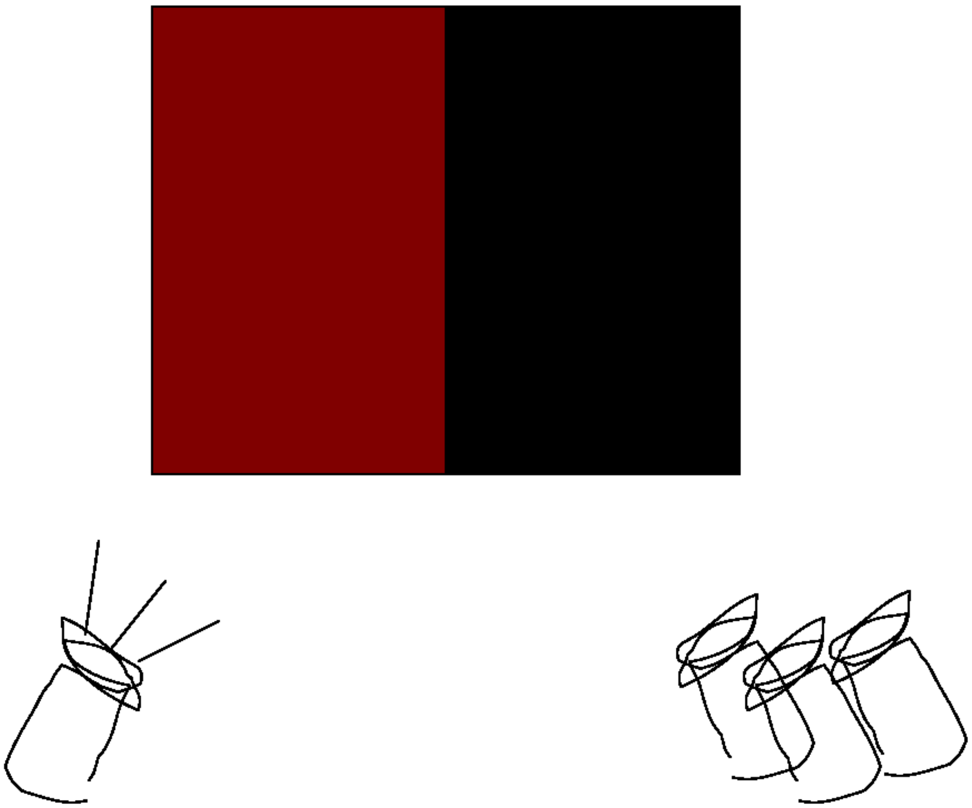
slide from T. Darrel

Color matching experiment 1



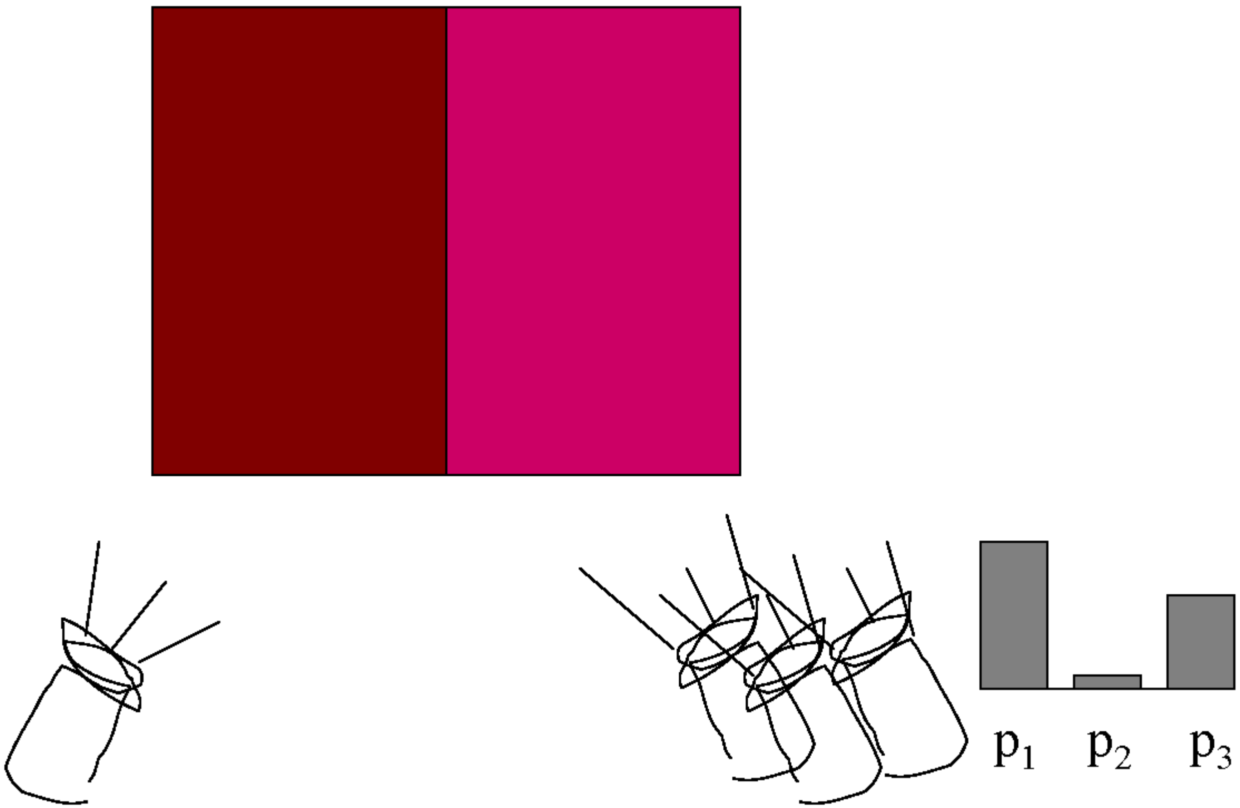
slide from T. Darrel

Color matching experiment 2



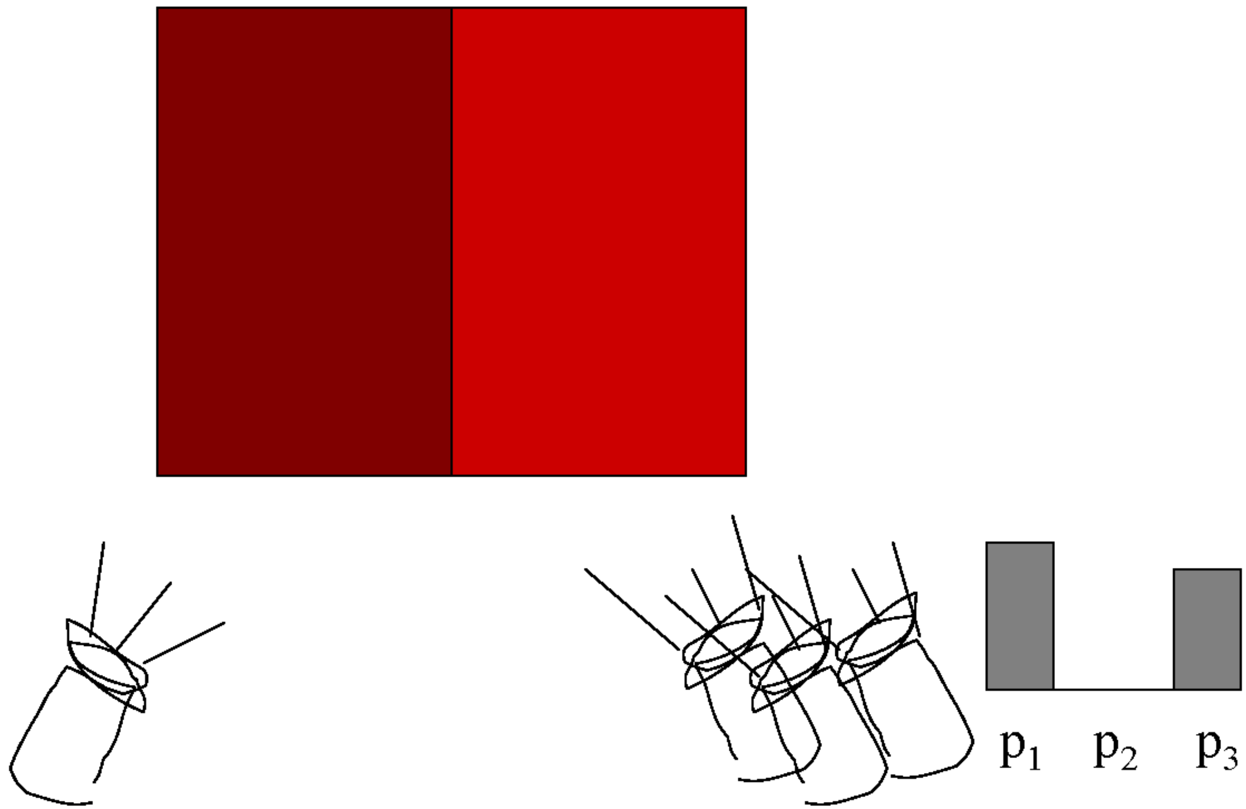
slide from T. Darrel

Color matching experiment 2



slide from T. Darrel

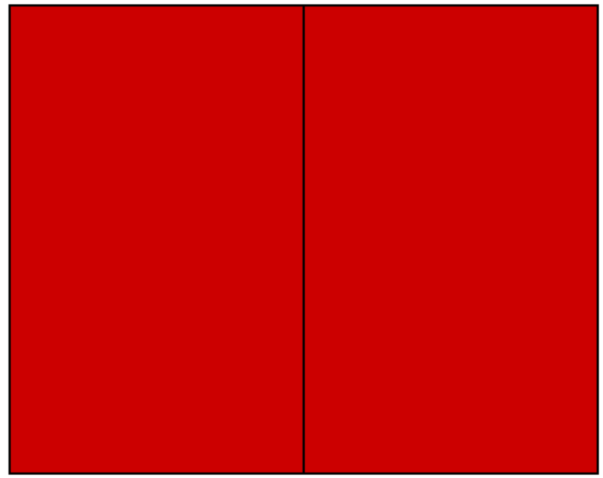
Color matching experiment 2



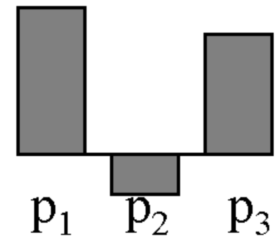
slide from T. Darrel

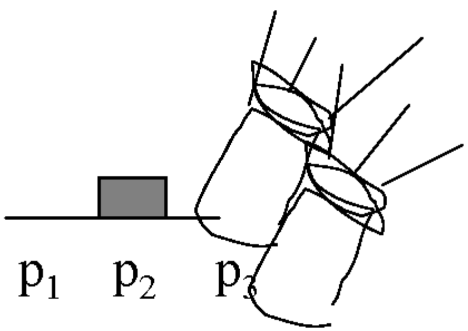
Color matching experiment 2

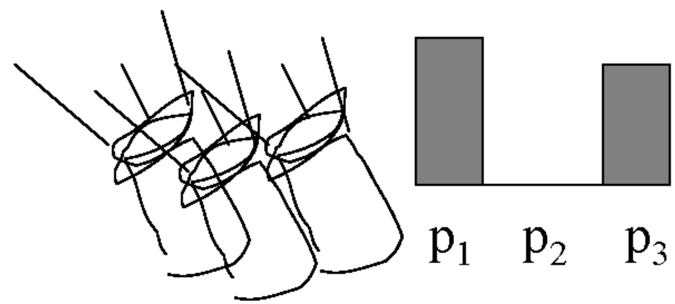
We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.



The primary color amounts needed for a match:







slide from T. Darrel

The principle of trichromacy

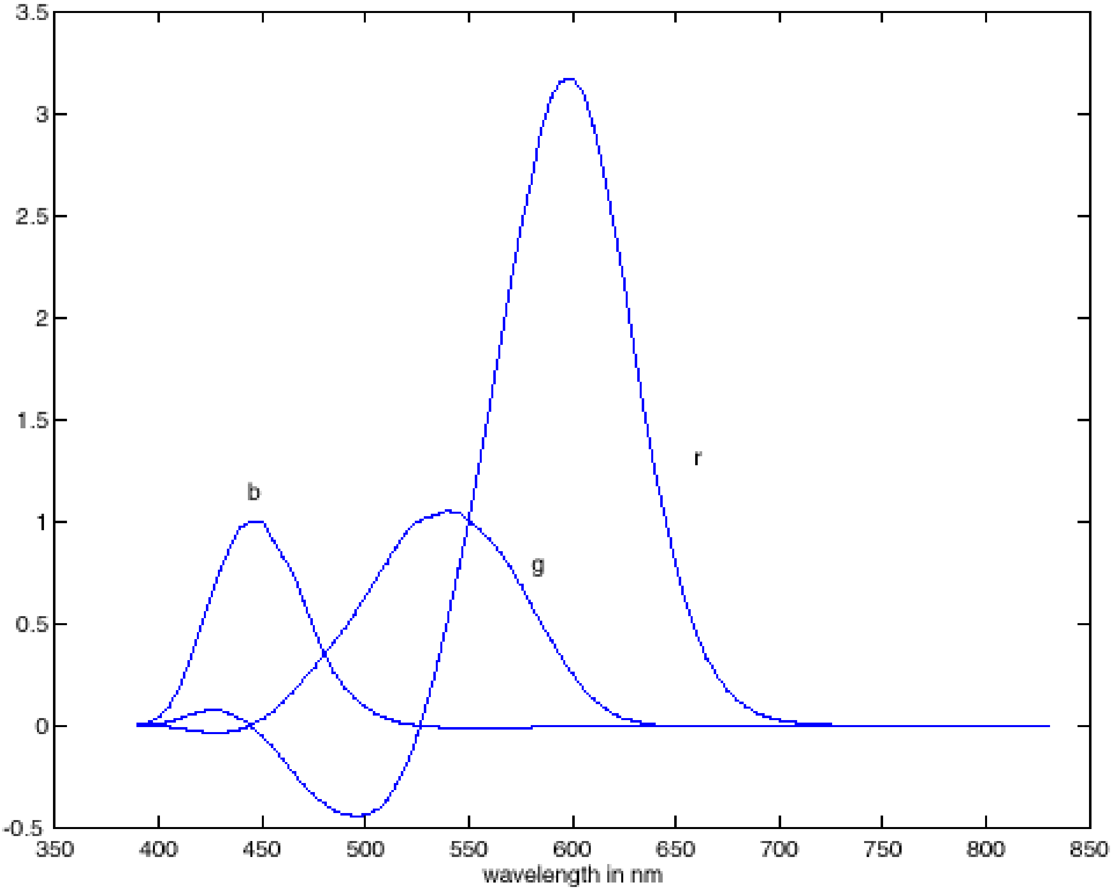
- Experimental facts:
  - Three primaries will work for most people if we allow subtractive matching
    - Exceptional people can match with two or only one primary.
    - This could be caused by a variety of deficiencies.
  - Most people make the same matches.
    - There are some anomalous trichromats, who use three primaries but make different combinations to match.

Color matching functions

- Choose primaries, say $p_1(\lambda)$, $p_2(\lambda)$, $p_3(\lambda)$
- For monochromatic (single wavelength) energy function, what amounts of primaries will match it?

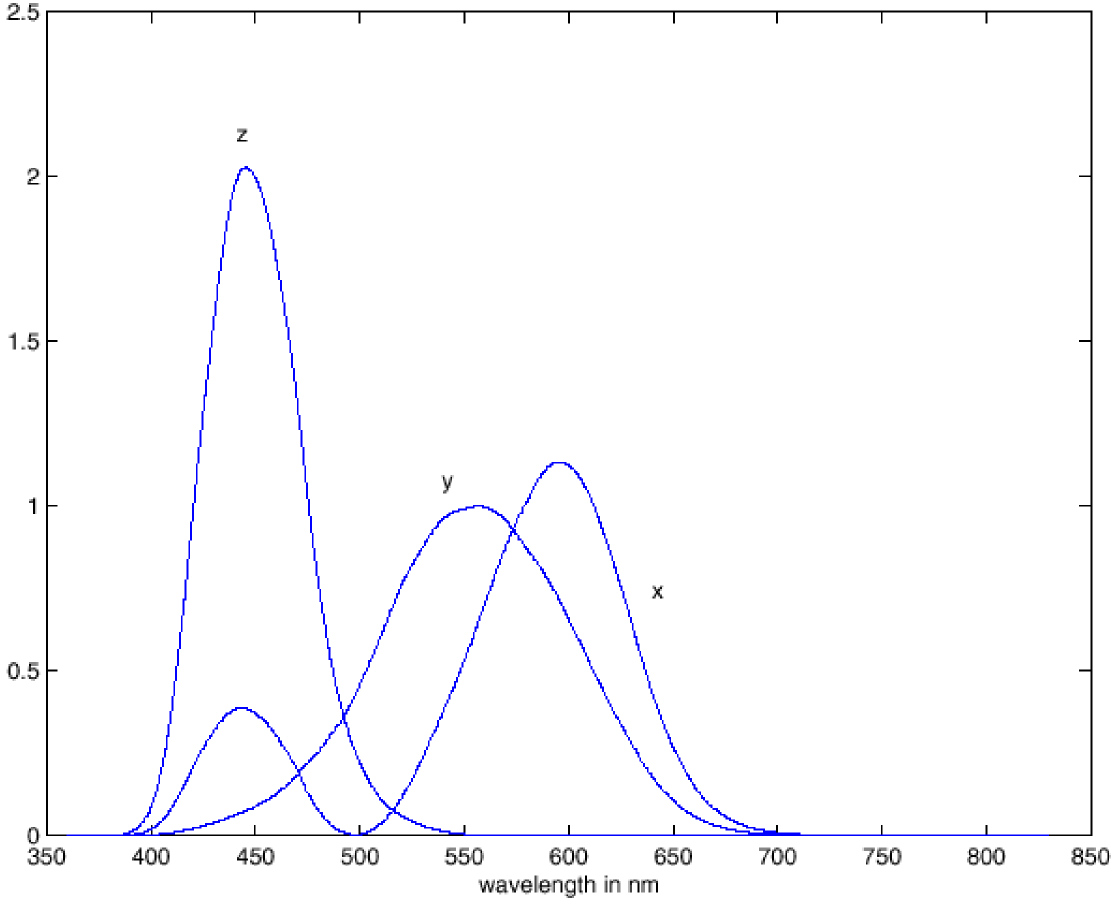
- That is, for each wavelength λ, determine how much of p_1, p_2, and p_3 is needed to match light of that wavelength alone
- These are color matching functions

RGB



RGB: primaries are monochromatic, energies are 645.2nm, 526.3nm, 444.4nm. Color matching functions have negative parts -> some colors can be matched only subtractively.

CIEXYZ



CIEXYZ: Color matching functions are positive everywhere, but primaries are imaginary (i.e., not visible colors).

Color spaces

- Linear color spaces describe colors as linear combinations of primaries
- Choice of primaries = choice of color matching functions = choice of color space
- Color matching functions, hence color descriptions, are all within linear transformations
- RGB: primaries are monochromatic, energies are 645.2nm, 526.3nm, 444.4nm. Color matching functions have negative parts -> some colors can be matched only subtractively
- CIE XYZ: Color matching functions are positive everywhere, but primaries are imaginary (i.e., not visible colors).

Color Spaces

There are many different color spaces, with each describing a color using three numbers:

1. RGB
2. XYZ
3. CIExyz
4. LMS
5. CMY
6. YIQ (NTSC)
7. YUV (PAL)
8. YCbCr
9. SUV
10. CIELAB

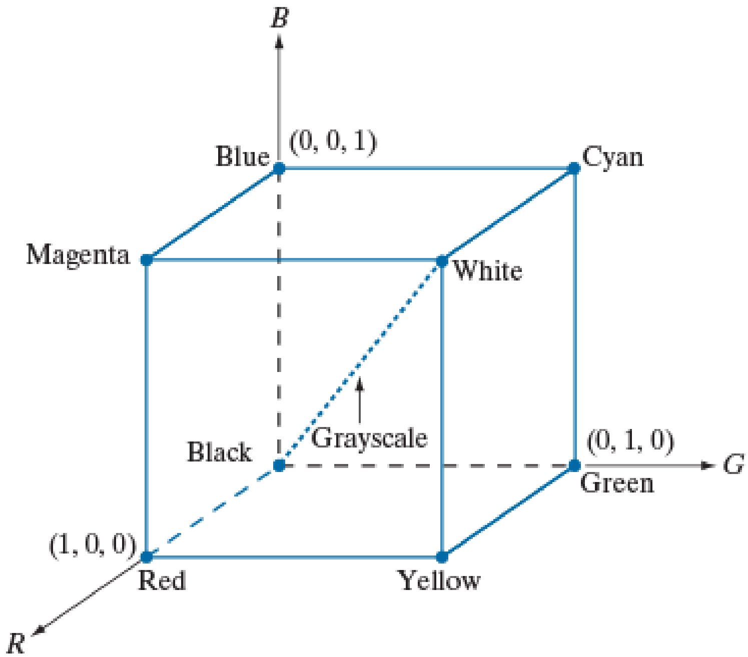
In general a color represented in one color space (say XYZ) can be converted and represented in a second color space (say RGB)

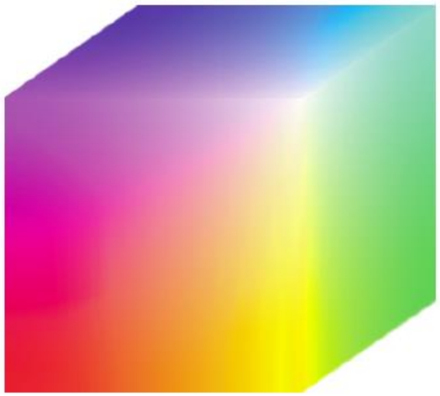
Example: RGB to YIQ

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.532 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Used by NTSC TV standard
- Separates Hue & Saturation (I,Q) from Luminance (Y)

RGB Color Cube





- Block of colors for (r, g, b) in the range (0-1).
- Convenient to have an upper bound on coefficient of each primary.
- In practice:
  - primaries given by monitor phosphors (phosphors are the materials on the face of the monitor screen that glow when struck by electrons)

CIELAB

- Also referred to as CIE L*a*b*
- Designed to approximate human vision
  - Nonlinear response
- Includes 100% of visible colors
- L is lightness
- A and B are color-opponent dimensions
- Nonlinear conversion to/from CIEXYZ colorspace
- Human perceptual difference between two colors is the Euclidean distance between the two 3D points in CIELAB space

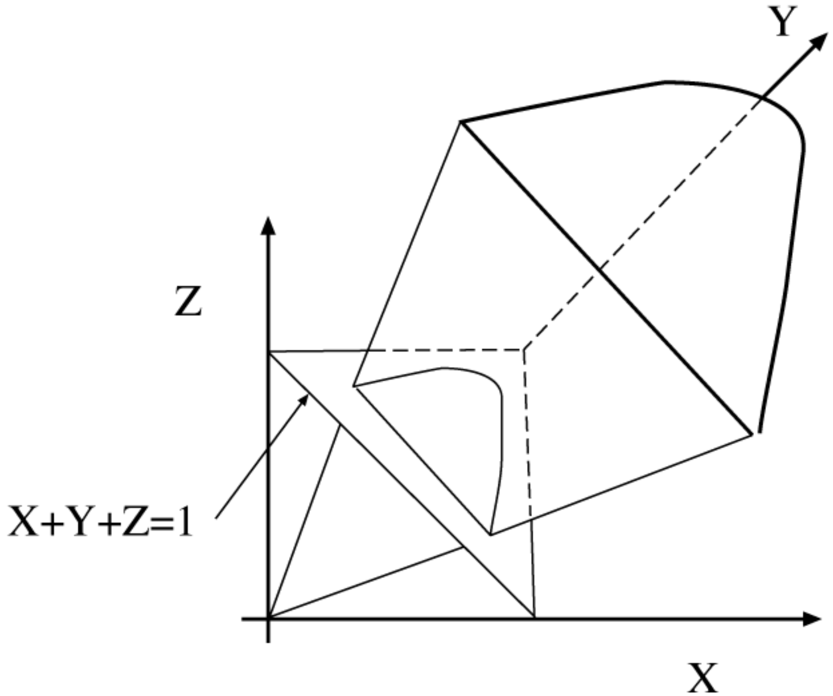
CIEXYZ and CIExyz

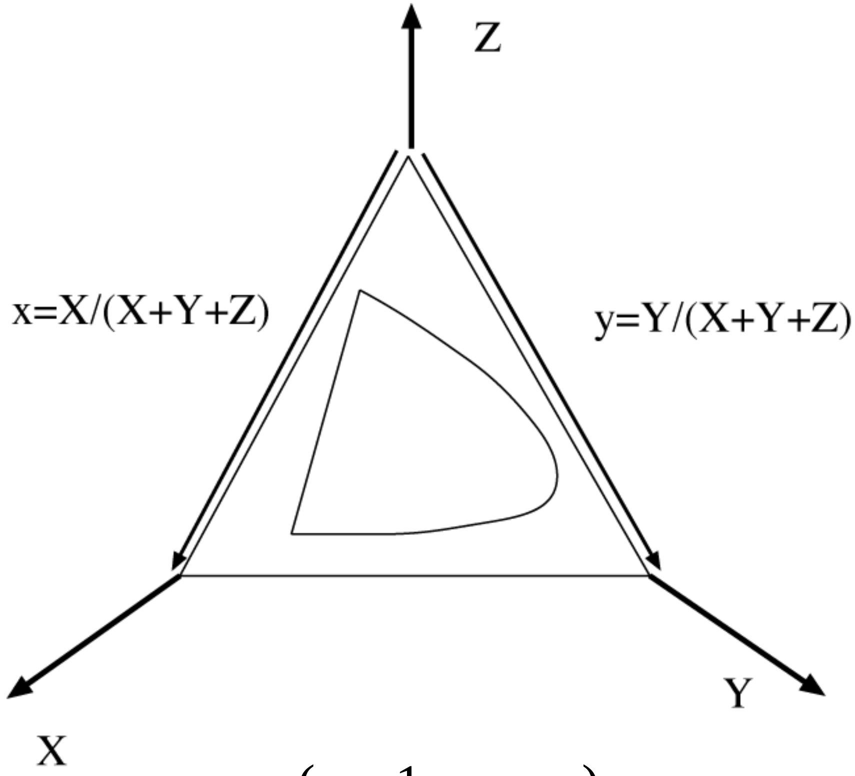
- Encompasses all color sensations the average person can experience
- Standard reference
  - Many other color space definitions are based on XYZ
- Y is luminance
- Z is quasi-equal to blue stimulation
- X is a linear combination of cone response curves chosen to be nonnegative
- The plane X+Y+Z = 1 contains all possible chromaticities xyz

$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z}$$
$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

$$X = \frac{Y}{y}x$$
$$Z = \frac{Y}{y}(1 - x - y)$$

CIEXYZ and CIExy

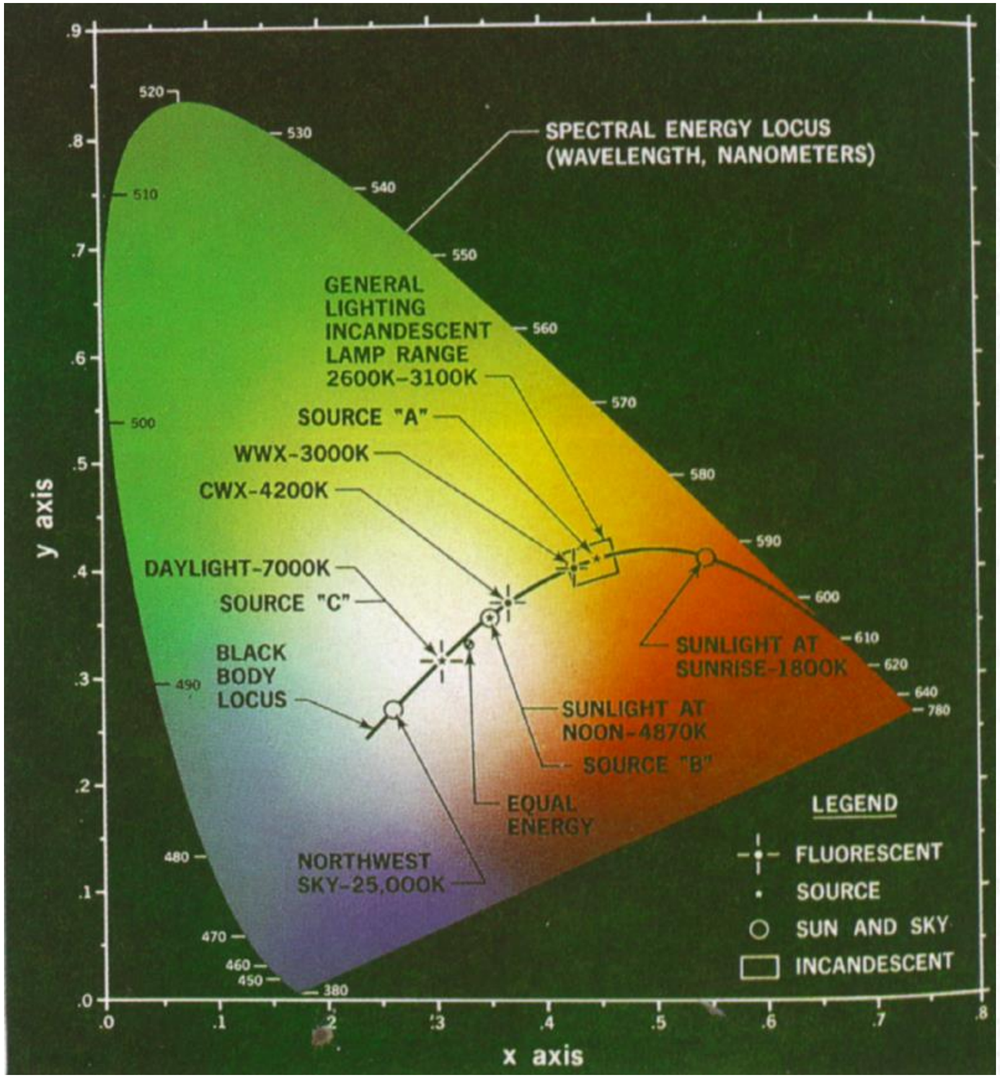


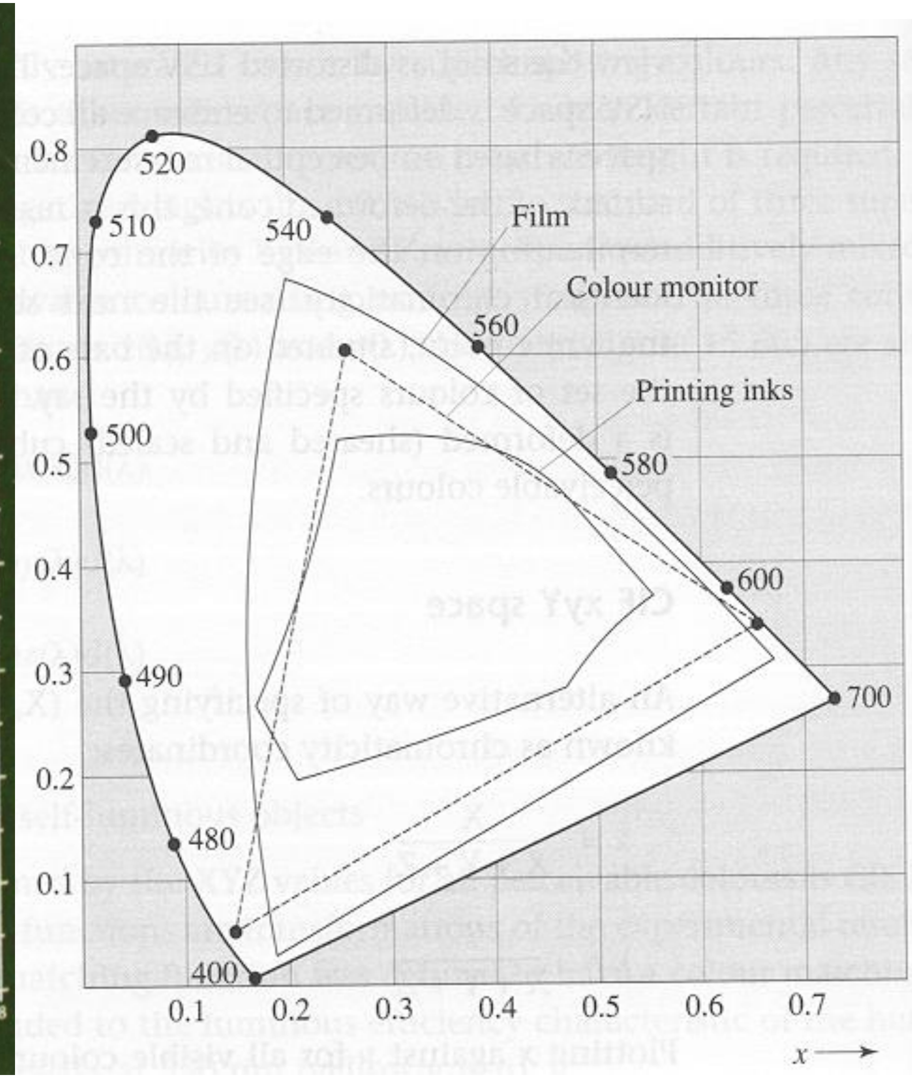


Usually draw x, y, where
$x=X/(X+Y+Z)$ and
$y=Y/(X+Y+Z)$

$(z = 1 - x - y)$

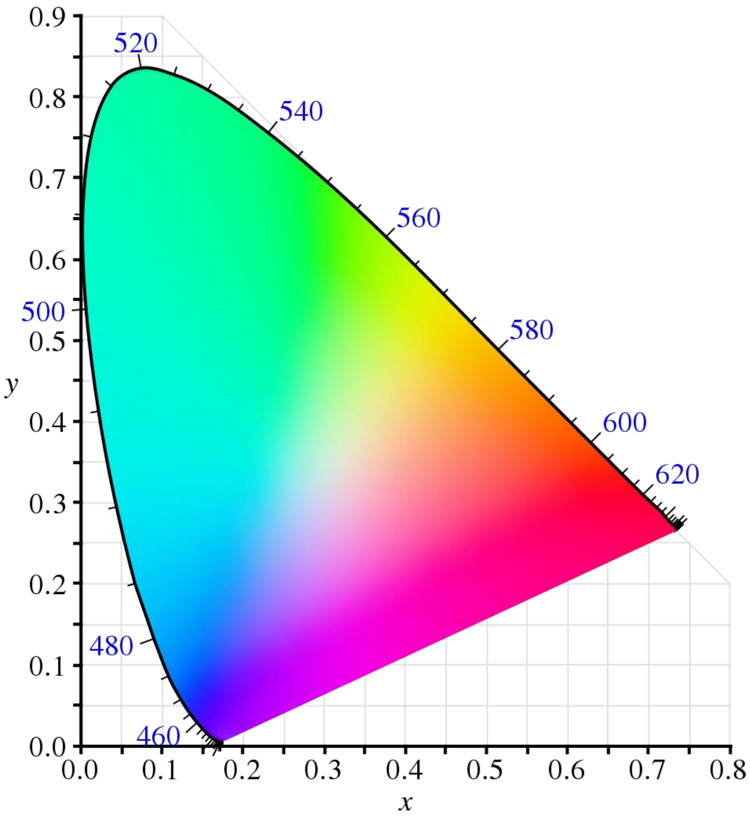
CIExyY (Chromaticity Space)





Color Specification: Chromaticity

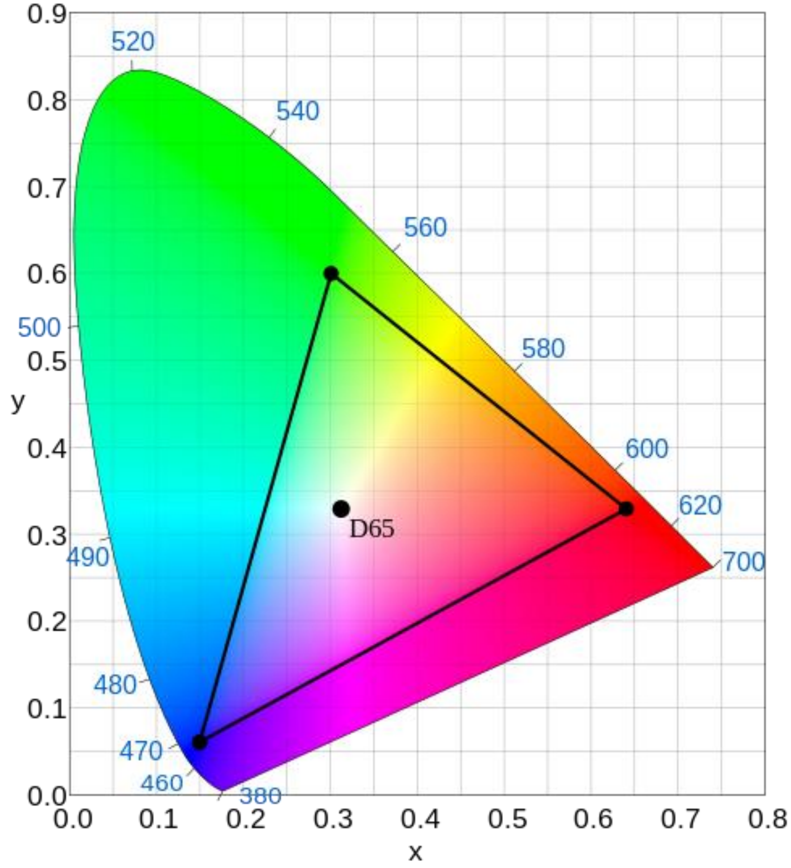
- Chromaticity coordinates
  - (x, y, z)
    where $x + y + z = 1$
  - Usually specified by (x, y)
    where $z = 1 - x - y$



The CIE 1931 color space chromaticity diagram

Chromaticities

- Set of chromaticities
  - Red
  - Green
  - Blue
  - White (point)

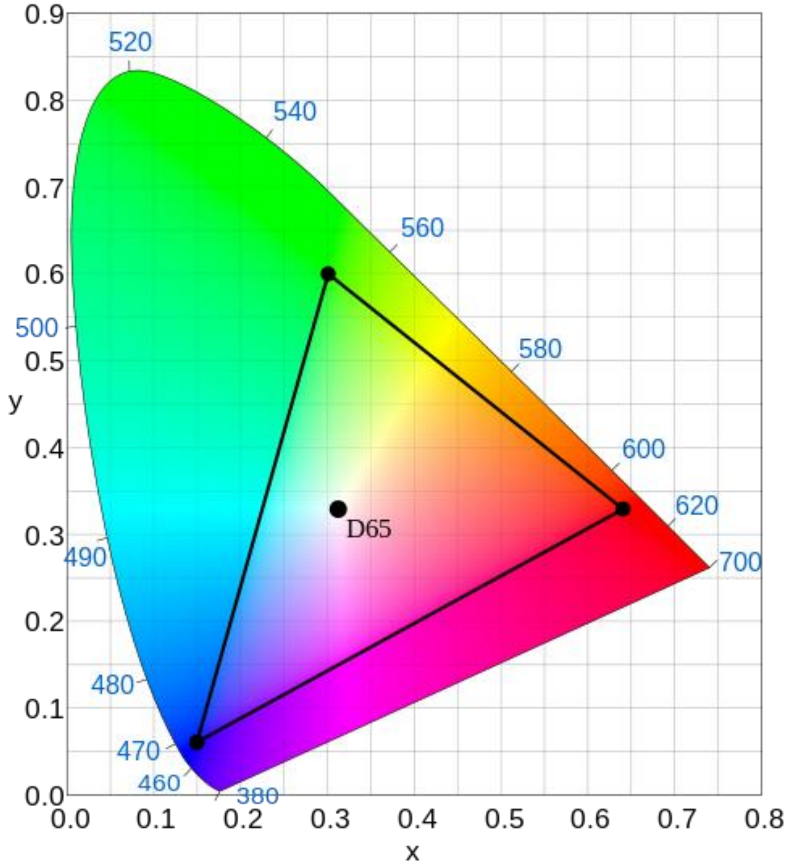


Standard Illuminants

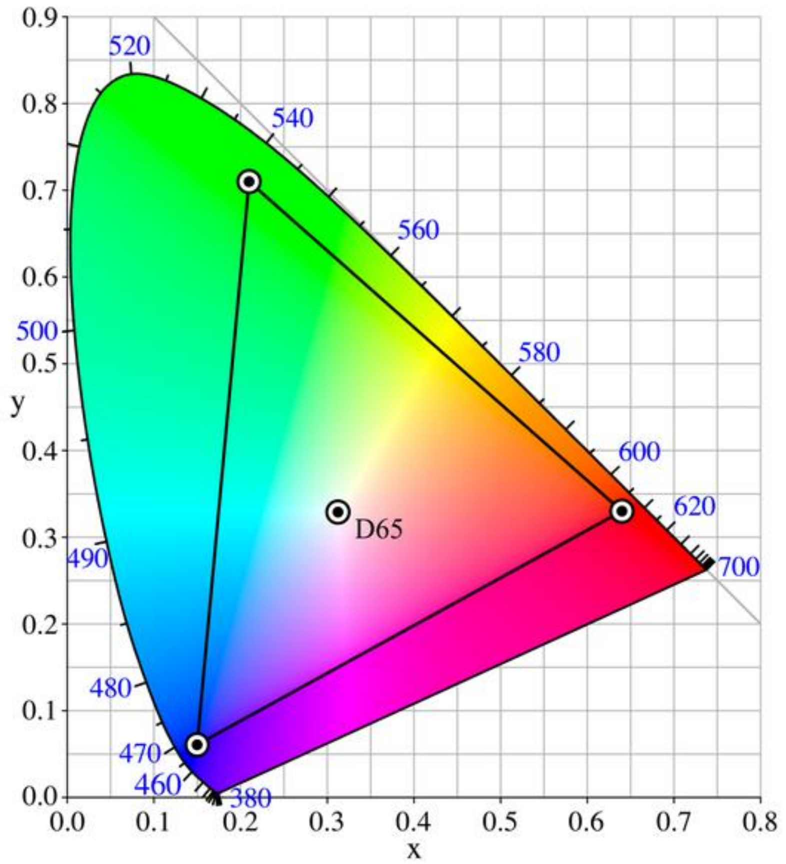
Name	CIE 1931 2°		CIE 1964 10°		CCT (K)	Hue	Note
	x_2	y_2	x_{10}	y_{10}			
A	0.44757	0.40745	0.45117	0.40594	2856		Incandescent / Tungsten
B	0.34842	0.35161	0.34980	0.35270	4874		{obsolete} Direct sunlight at noon
C	0.31006	0.31616	0.31039	0.31905	6774		{obsolete} Average / North sky Daylight
D50	0.34567	0.35850	0.34773	0.35952	5003		Horizon Light. ICC profile PCS
D55	0.33242	0.34743	0.33411	0.34877	5503		Mid-morning / Mid-afternoon Daylight
D65	0.31271	0.32902	0.31382	0.33100	6504		Noon Daylight: Television, sRGB color space
D75	0.29902	0.31485	0.29968	0.31740	7504		North sky Daylight
E	1/3	1/3	1/3	1/3	5454		Equal energy
F1	0.31310	0.33727	0.31811	0.33559	6430		Daylight Fluorescent
F2	0.37208	0.37529	0.37925	0.36733	4230		Cool White Fluorescent
F3	0.40910	0.39430	0.41761	0.38324	3450		White Fluorescent
F4	0.44018	0.40329	0.44920	0.39074	2940		Warm White Fluorescent
F5	0.31379	0.34531	0.31975	0.34246	6350		Daylight Fluorescent
F6	0.37790	0.38835	0.38660	0.37847	4150		Lite White Fluorescent
F7	0.31292	0.32933	0.31569	0.32960	6500		D65 simulator, Daylight simulator
F8	0.34588	0.35875	0.34902	0.35939	5000		D50 simulator, Sylvania F40 Design 50
F9	0.37417	0.37281	0.37829	0.37045	4150		Cool White Deluxe Fluorescent
F10	0.34609	0.35986	0.35090	0.35444	5000		Philips TL85, Ultralume 50
F11	0.38052	0.37713	0.38541	0.37123	4000		Philips TL84, Ultralume 40
F12	0.43695	0.40441	0.44256	0.39717	3000		Philips TL83, Ultralume 30

Hue of each white point,
calculated with luminance Y = 0.54

Chromaticity Diagrams

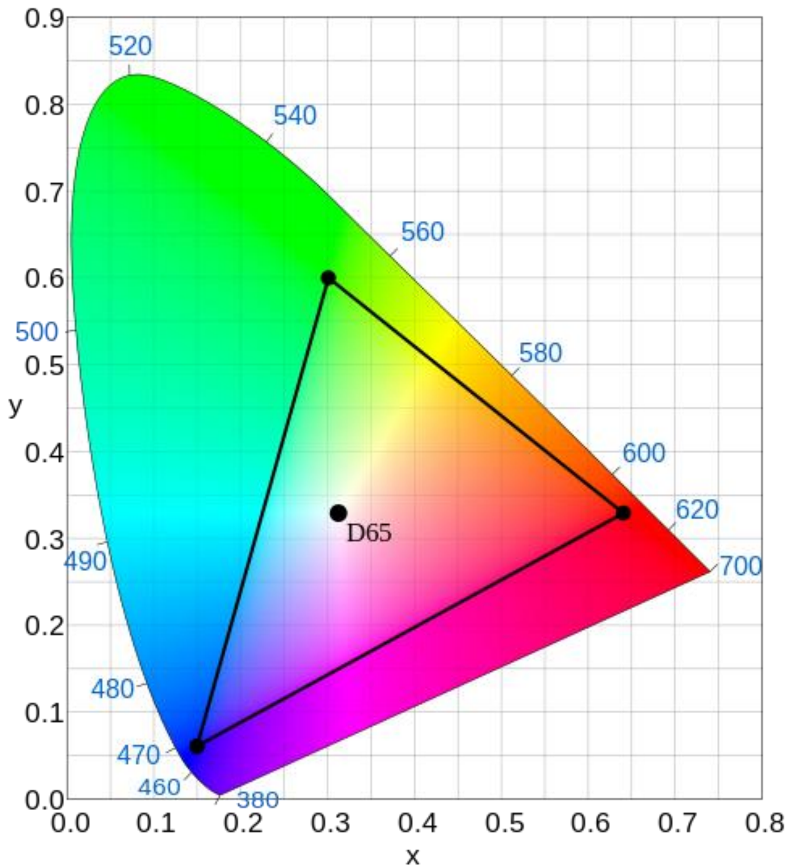


Rec. 709 and sRGB
35.9% of visible colors

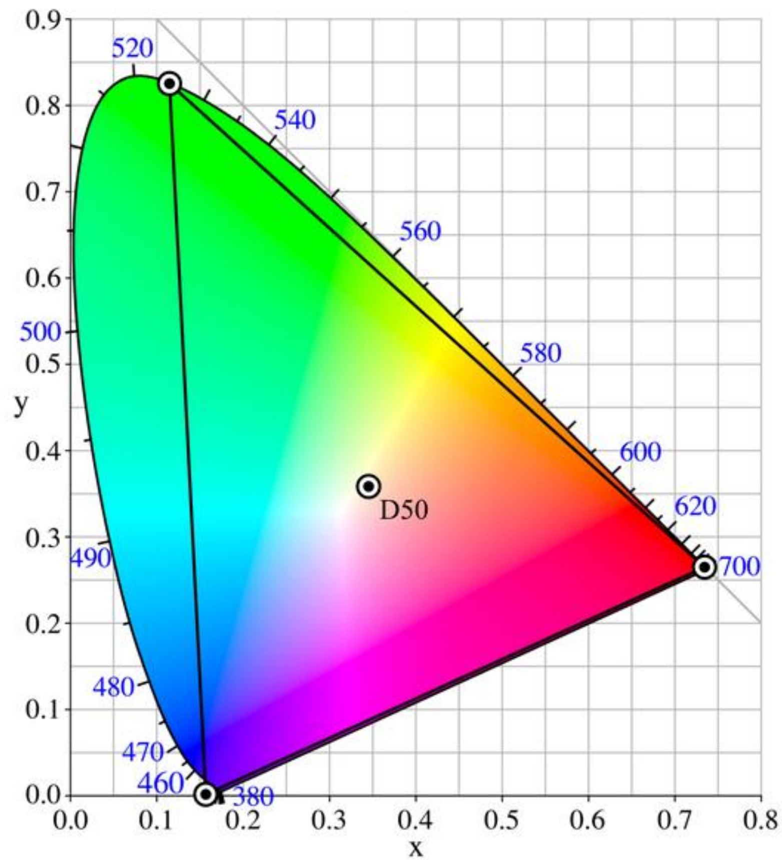


Adobe RGB
52.1% of visible colors

Chromaticity Diagrams

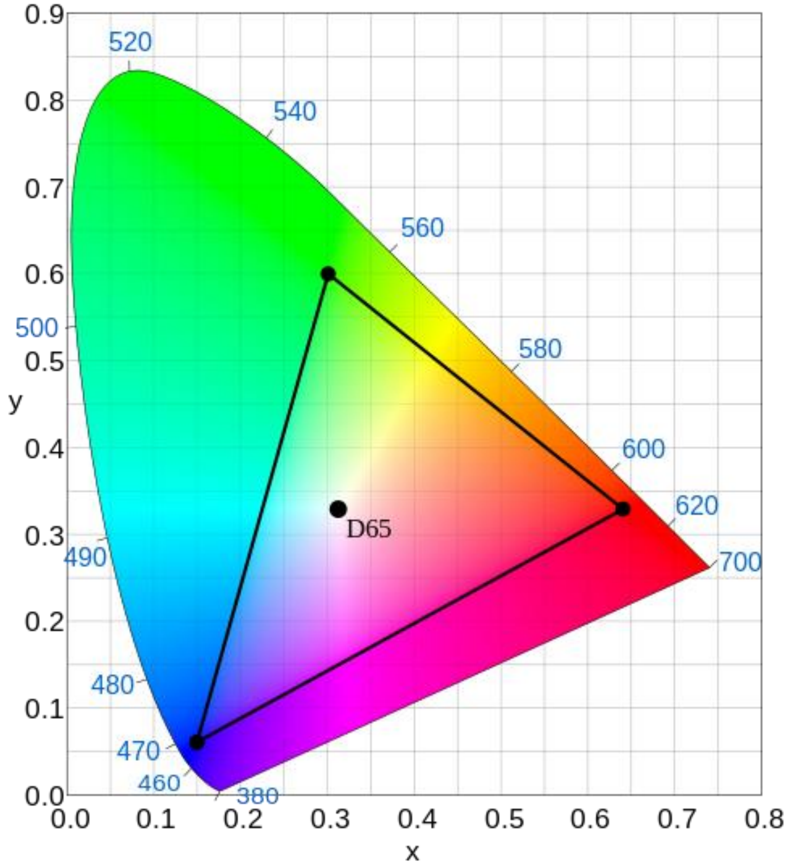


Rec. 709 and sRGB
35.9% of visible colors

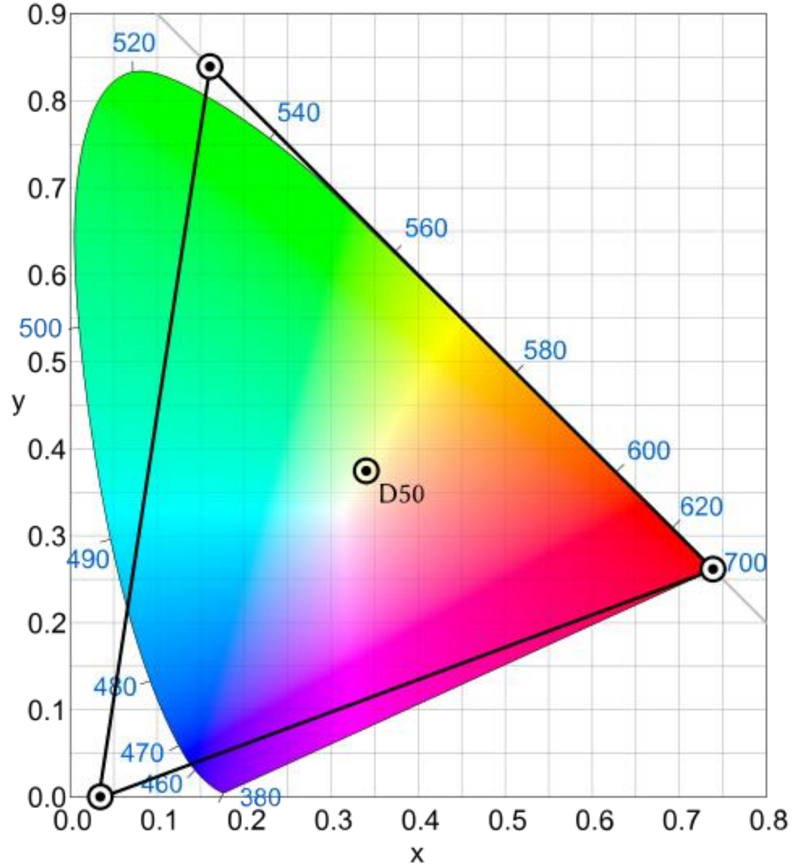


Wide gamut RGB
77.6% of visible colors

Chromaticity Diagrams



Rec. 709 and sRGB
35.9% of visible colors



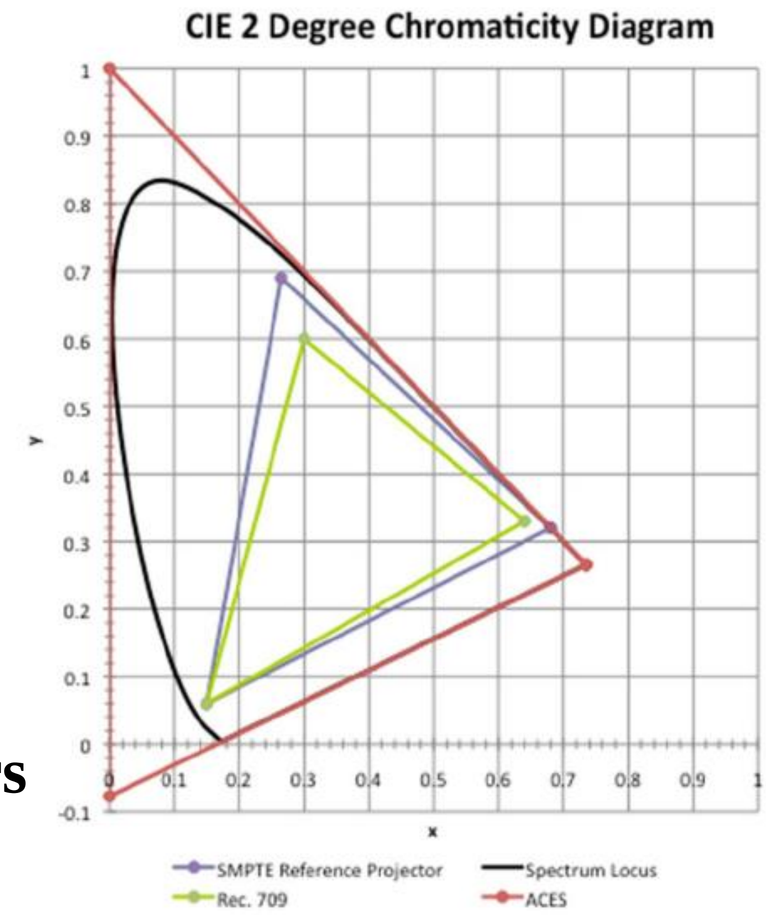
ProPhoto RGB
90% of visible colors

Academy Color Encoding Specification (ACES)

ACES

Color	CIE x	CIE y	CIE z
Red	0.73470	0.26530	0.00000
Green	0.00000	1.00000	0.00000
Blue	0.00010	-0.07700	1.07690
White	0.32168	0.33767	0.34065

Approximately D60



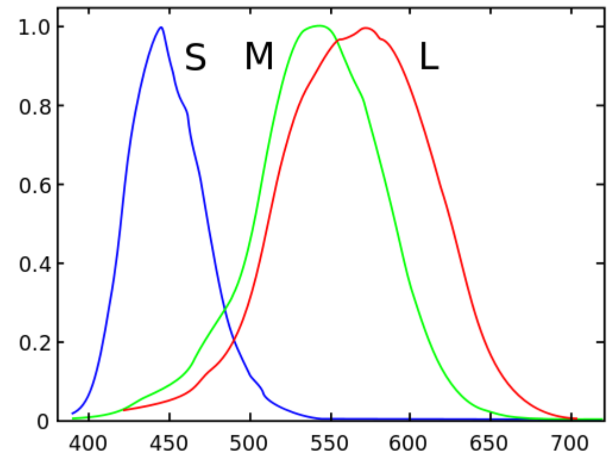
100% of visible colors

Incorrect Image Conversion

Same pixel values stored in files,
but with different sets of chromaticities

Chromatic Adaptation

- Estimating the appearance of a sample under a different illuminant
  – Convert between different white points
- LMS color space
  – Response of the three types of cones in the human eye
    - Long, medium, and short wavelengths
- XYZ to LMS
  – Bradford transformation matrix
- Chromatic adaptation
  – Adaptation matrix



$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$D = D_1^{-1} D_2 = \begin{bmatrix} L_2/L_1 & 0 & 0 \\ 0 & M_2/M_1 & 0 \\ 0 & 0 & S_2/S_1 \end{bmatrix}$$

Application: Color Transfer

- RGB to XYZ with white point of standard illuminant E (use chromatic adaptation)
- XYZ to Lab
- Map source pixels such that the L*a*b* mean and standard deviations match those of the target image

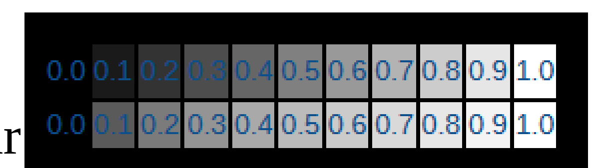
Nonlinear Encoding

- All of these standards use nonlinear encoding (gamma encoding)
  - Video
    - Recommendation ITU-R BT.601 (standard-definition television (SDTV))
    - SMPTE standard 240M (precursor to Rec. 709)
    - Recommendation ITU-R BT.709 (high-definition television (HDTV))
  - Image
    - sRGB
    - Adobe RGB
    - Wide gamut RGB (or Adobe Wide Gamut RGB)
    - ProPhoto RGB (or reference output medium metric (ROMM) RGB)
- Must convert to linear colorspace first for most color processing

Nonlinear Encoding and Conversion to Linear

- Typical CRT monitors have a transfer function of gamma = 2.2
- Image and video standards were designed to be directly displayed on CRTs
  - Pixel values are encoded to approximate gamma = 2.2
- Nonlinear to linear (floating-point) using a lookup table
- Linear to nonlinear calculation

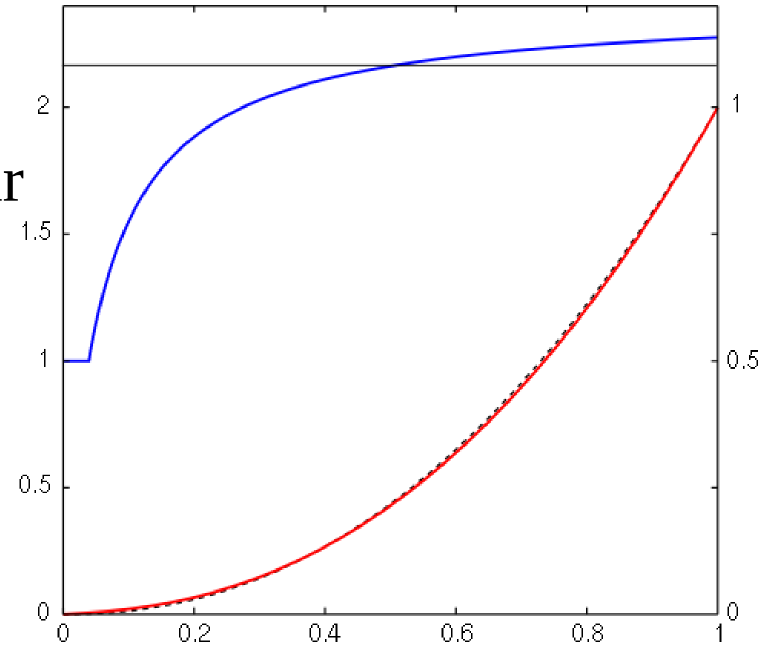
Linear
Nonlinear



Nonlinear R'G'B' Color Space and Linear RGB Color Space

- Example: sRGB

Slope of sRGB nonlinear in log-log space



RGB linear

sRGB nonlinear

Luminance Y and Luma Y'

- **Luminance is different than Luma**
- Luminance is calculated from linear RGB
  - Y coordinate of XYZ
- Luma is calculated from nonlinear R'G'B'
- Example: sRGB

$Y = 0.21263903 * R + 0.71516871 * G + 0.072192319 * B$

$Y' = 0.21263903 * R' + 0.71516871 * G' + 0.072192319 * B'$

Next Lecture

- Human visual system