CSI 4105 Computer Graphics

Spring 2017

Crash Course on Color

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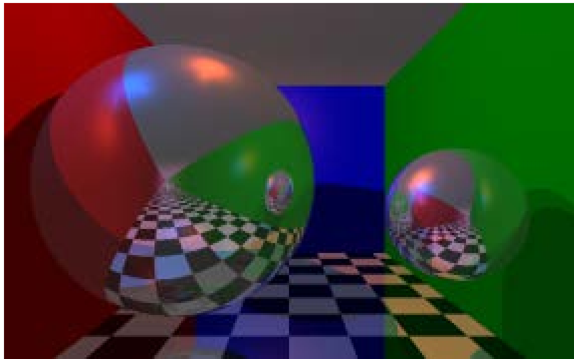


Color

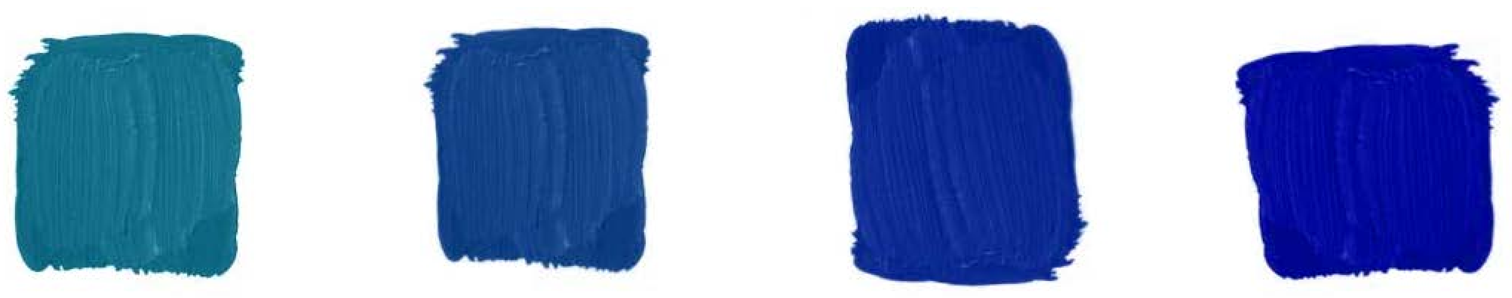
Def *Color* (noun): The property possessed by an object of producing different sensations on the eye as a result of the way it reflects or emits light.

Oxford Dictionary

Def *Colour (noun)*: The word color spelt with the letter 'u' and pronounced with a non-American accent.

Color is perceptual

- **Color is not** a primary physical property
- Red, Green, Blue, Pink, Orange, Atomic Tangerine, Baby Pink, etc. . .
  – Adjectives we assign to "color sensations"



Which is "True Blue"?

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

WHAT COLOUR IS THIS DRESS?

Subjective terms to describe color

Hue
Name of the color
(yellow, red, blue, green, . . .)

Value/Lightness/Brightness
How light or dark a color is.

Saturation/Chroma/Color Purity
How “strong” or “pure” a color is.

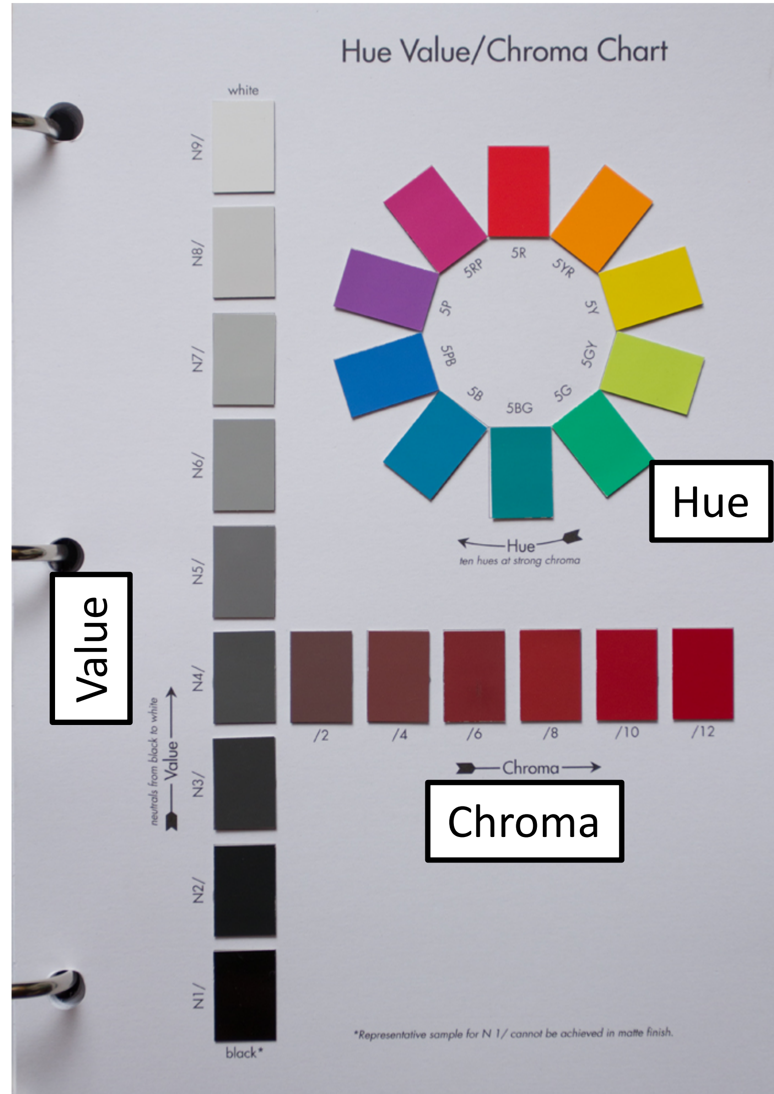
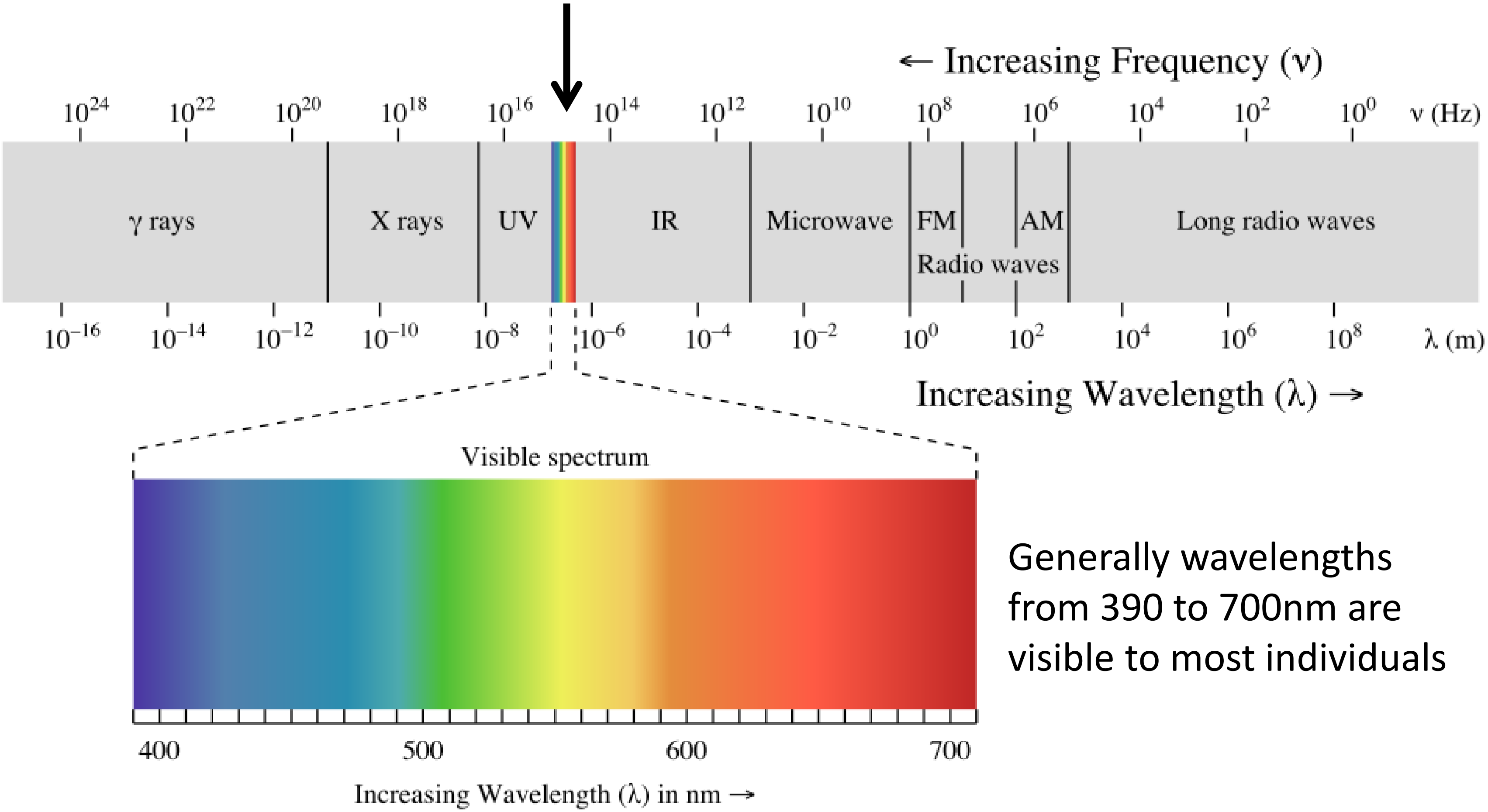


Image from Benjamin Salley
A page from a Munsell Student Color Set

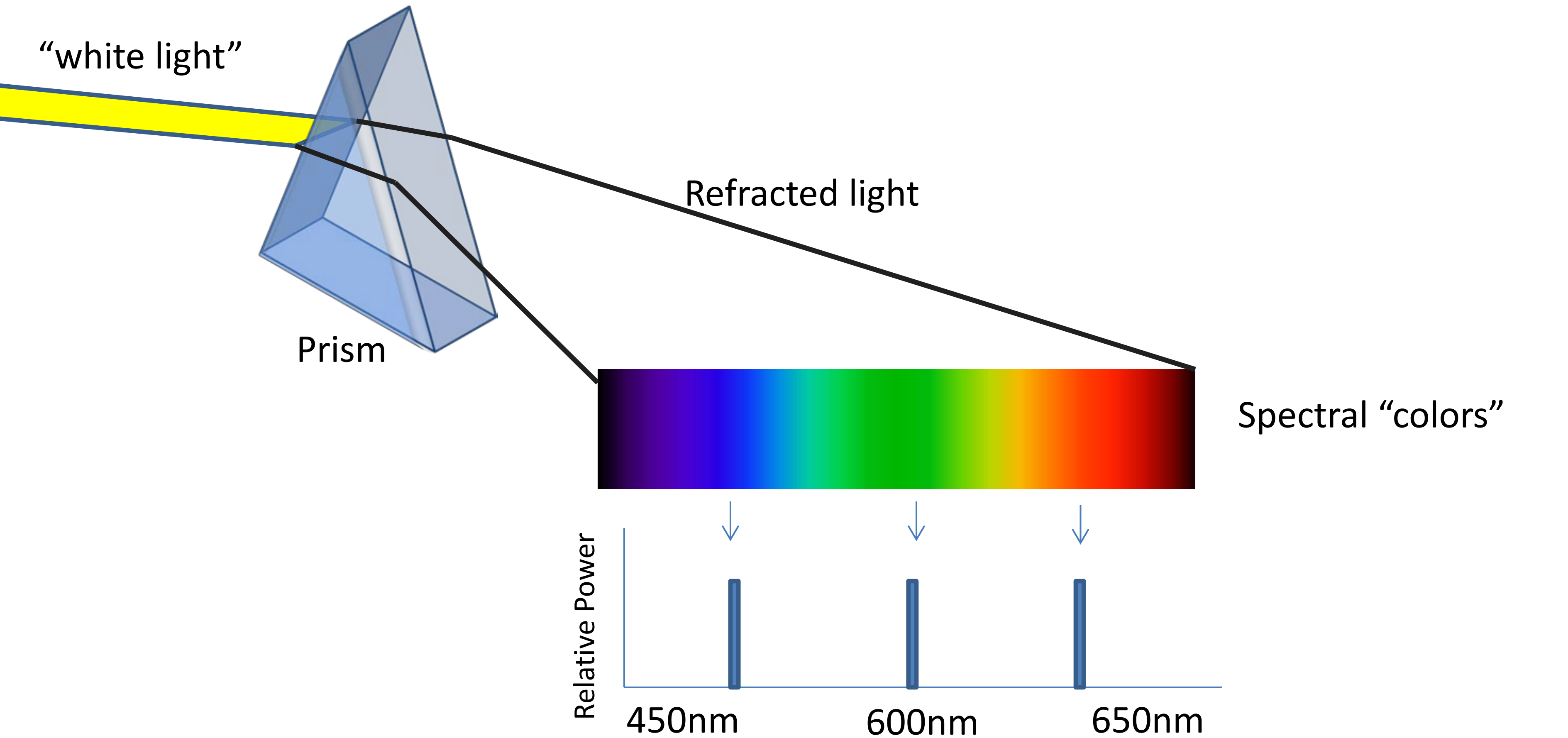
Where do "color sensations" come from?

A *very* small range of electromagnetic radiation



Generally wavelengths from 390 to 700nm are visible to most individuals

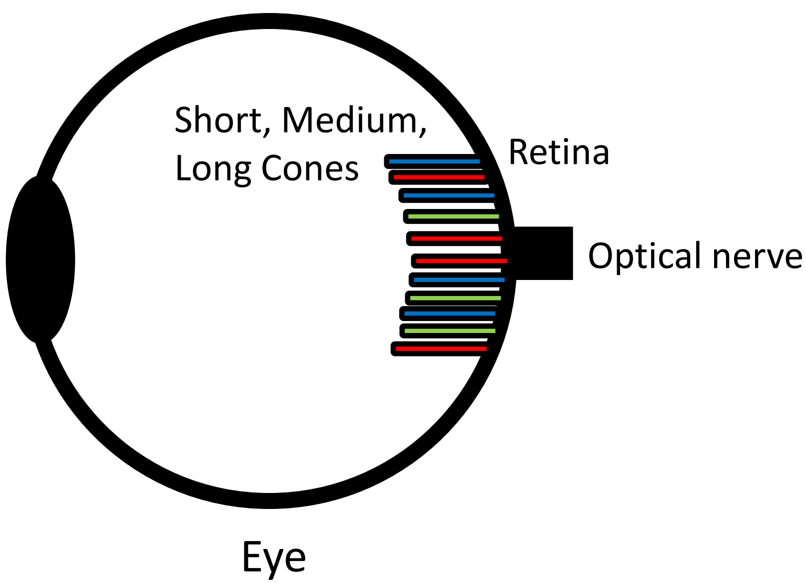
“White light” through a prism

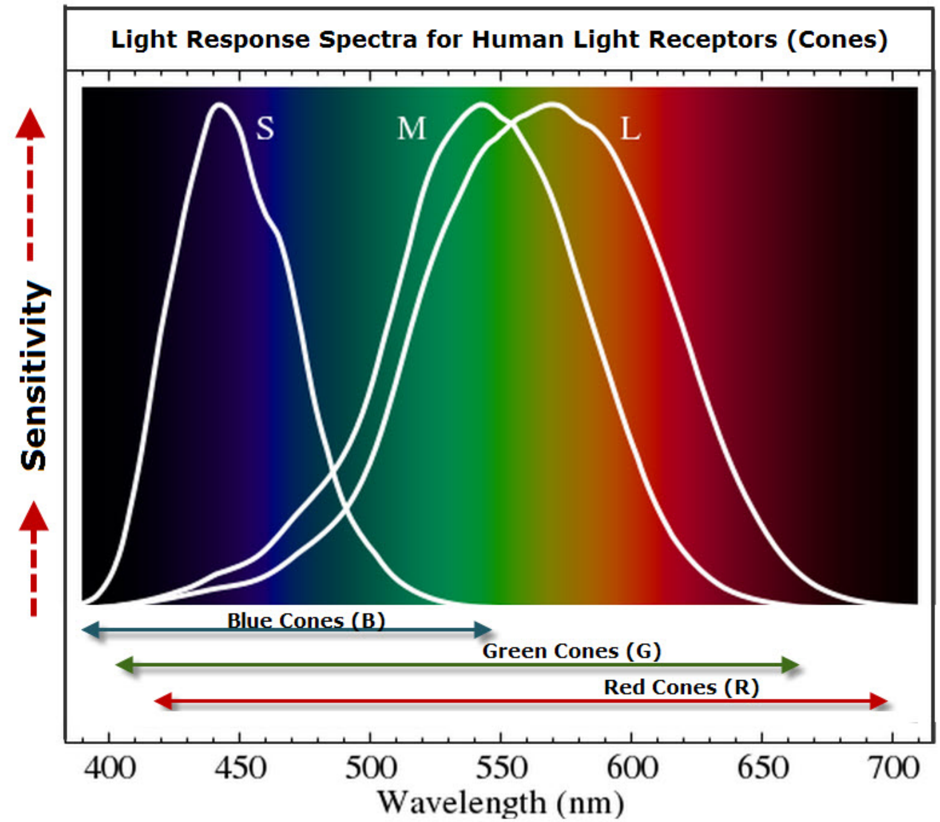


Light is separated into “monochromatic” light at different wave lengths.

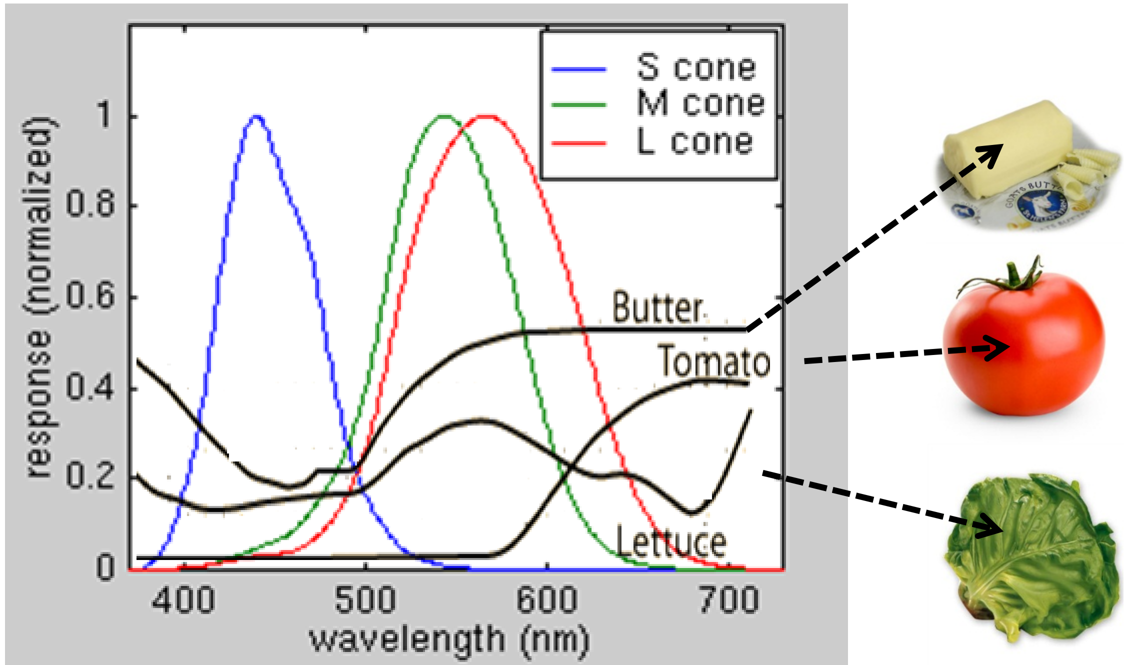
Sensations?

- Our eye has three receptors (cone cells) that respond to visible light and give the sensation of color





Spectral power distribution (SPD)

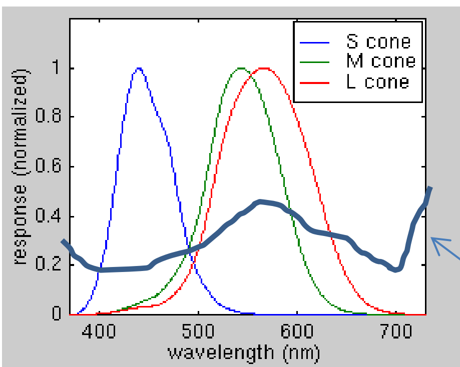


We rarely see monochromatic light in real world scenes. Instead, objects reflect a wide range of wavelengths. This can be described by a *spectral power distribution* (SPD) shown above. The SPD plot shows the relative amount of each wavelength reflected over the visible spectrum.

SPD relation to color is not unique

- Due to the accumulation effect of the cones, two different SPDs can be perceived as the same color

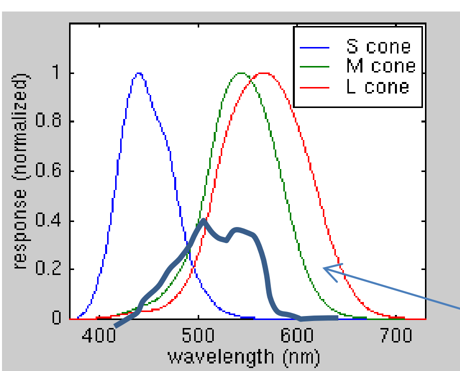
Lettuce SPD



Lettuce SPD stimulating S=0.2, M=0.8, L=0.8

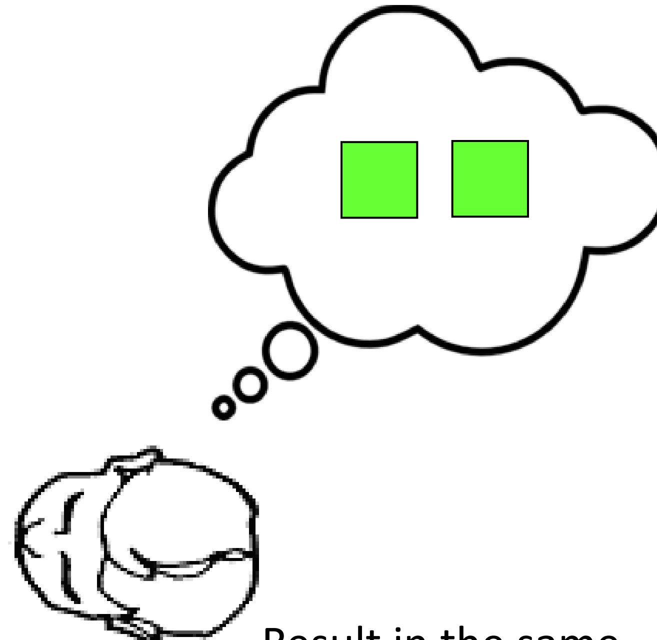
SPD of “real lettuce”

Green Ink SPD



Green ink SPD stimulating S=0.2, M=0.8, L=0.8

SPD of ink in a “picture of lettuce”



Result in the same color “sensation”.

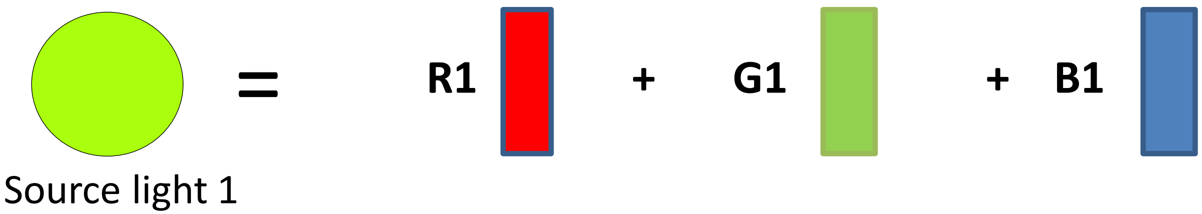
Called “metamers”

Tristimulus color theory

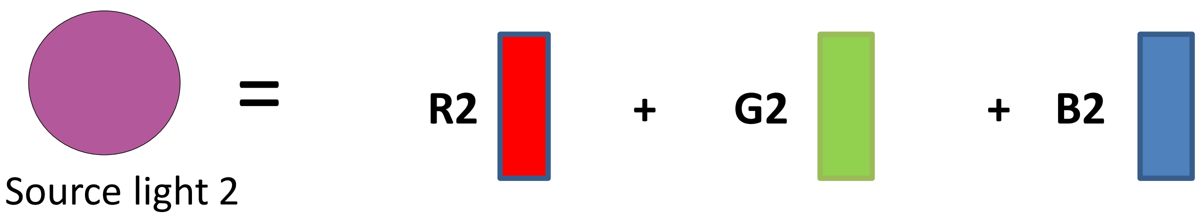
- Even before cone cells were discovered, it was empirically found that only three distinct colors (primaries) could be mixed to produce other colors
- Thomas Young (1803), Hermann von Helmholtz (1852), Hermann Grassman (1853), James Maxwell (1856) all explored the theory of trichromacy for human vision

Tristimulus color theory

Grassman's Law states that a source color can be matched by a **linear** combination of three independent "primaries".



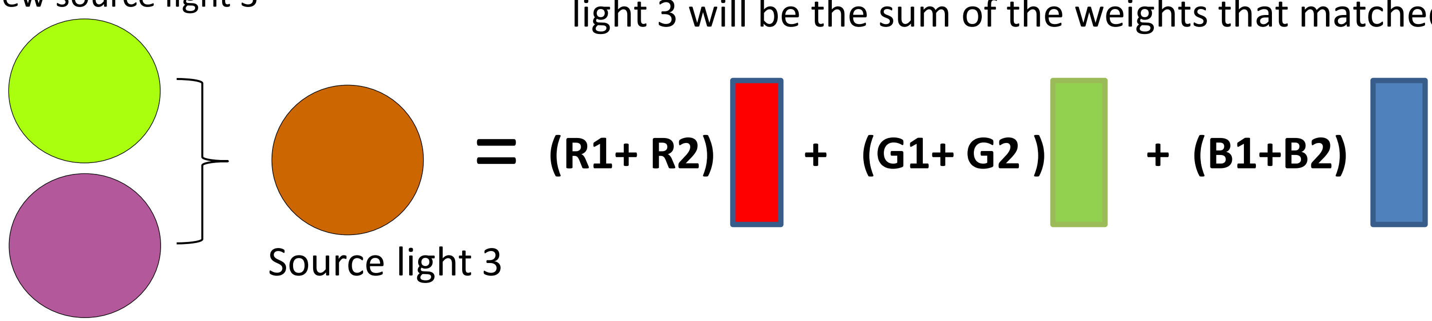
Three primaries and the weights (R1, G1, B1) of each primary needed to match the source light #1 perceived color.



Same three primaries and the weights (R2, G2, B2) of each primary needed to match the source light #2 perceived color

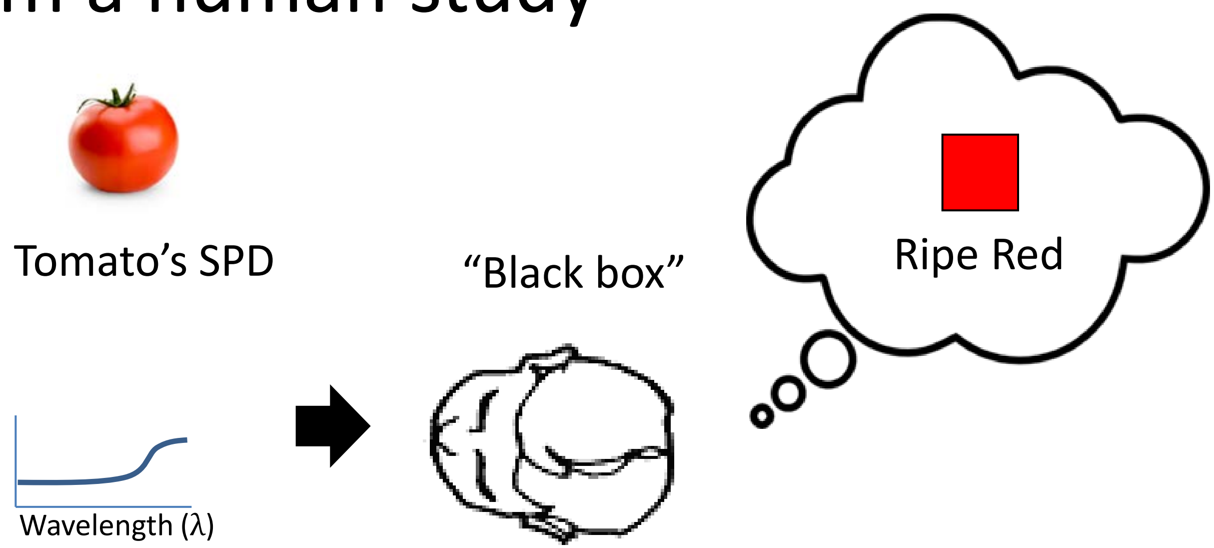
If we combined source lights 1 & 2 to get a new source light 3

The amount of each primary needed to match the new source light 3 will be the sum of the weights that matched lights 1 & 2.

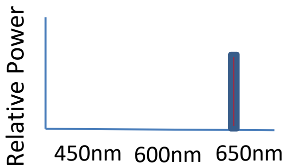


Quantifying color

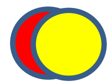
- We still need a way to quantify color & brightness
- SPDs go through a “black box” (human visual system) and are perceived as color
- The only way to quantify the “black box” is to perform a human study



Experiments for photometry



Reference bright light
with fixed radiant power.



(Alternating between source and reference @ 17Hz)

Chromatic **source** light at
a particular wavelength and
adjustable radiant power.

Alternate between the source light and reference light 17 times per second (17 hz). A flicker will be noticeable unless the two lights have the same perceived "brightness".

+

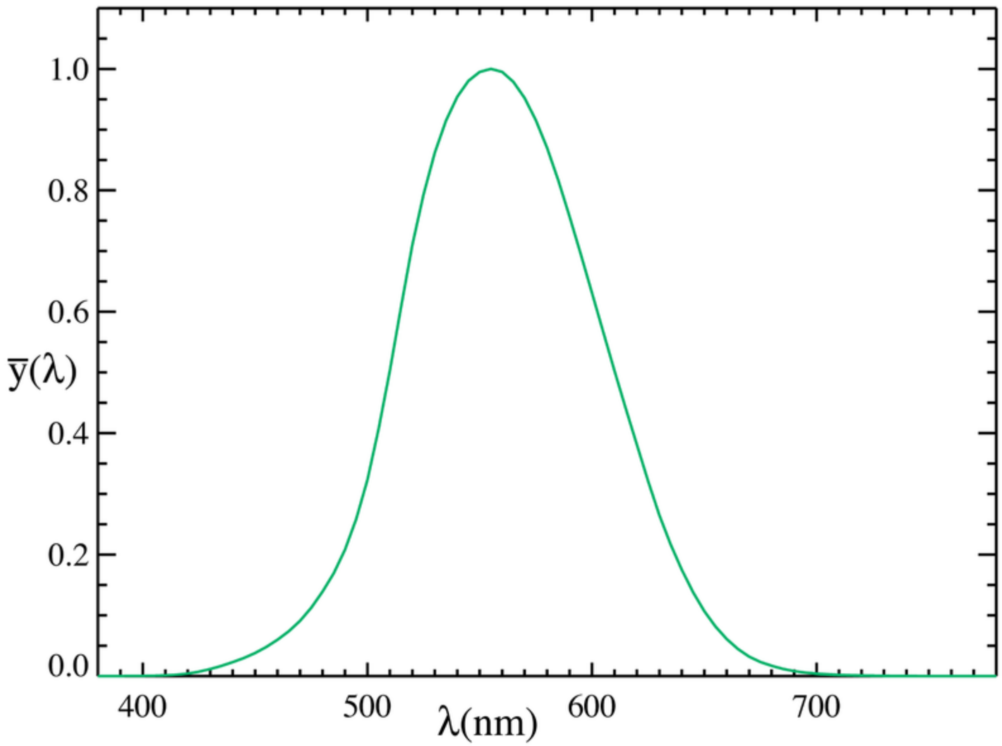
Viewer gradually
increases source
radiant power

The viewer adjusts the radiant power of the chromatic light until the flicker disappears (i.e. the lights fuse into a constant color). The amount of radiant power needed for this fusion to happen is recorded.

Repeat this flicker fusion test for each wave-length in the source light. This allows method can be used to determine the perceived "brightness" of each wavelength.

The "flicker photometry" experiment for photopic sensitivity.

CIE* (1924) Photopic luminosity function

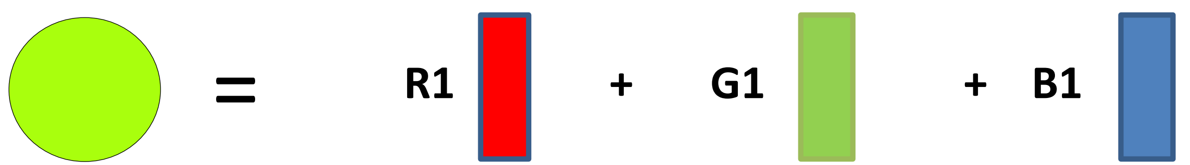


The Luminosity Function (written as $\bar{y}(\lambda)$ or $V(\lambda)$) shows the eye's sensitivity to radiant energy into luminous energy (or perceived radiant energy) based on human experiments (flicker fusion test).

*International Commission on Illumination (CIE comes from the French name *Commission internationale de l'éclairage*) was a body established in 1913 as an authority on light, illumination and color . . CIE is still active today -- http://www.cie.co.at

Colorimetry

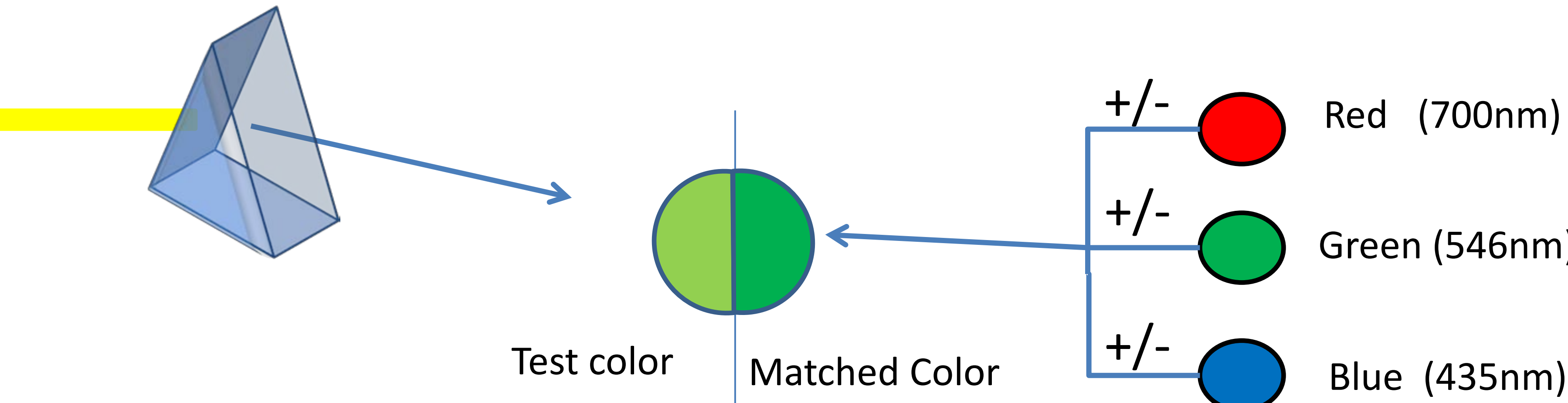
- Based on tristimulus color theory, colorimetry attempts to quantify all visible colors in terms of a standard set of primaries



Target color

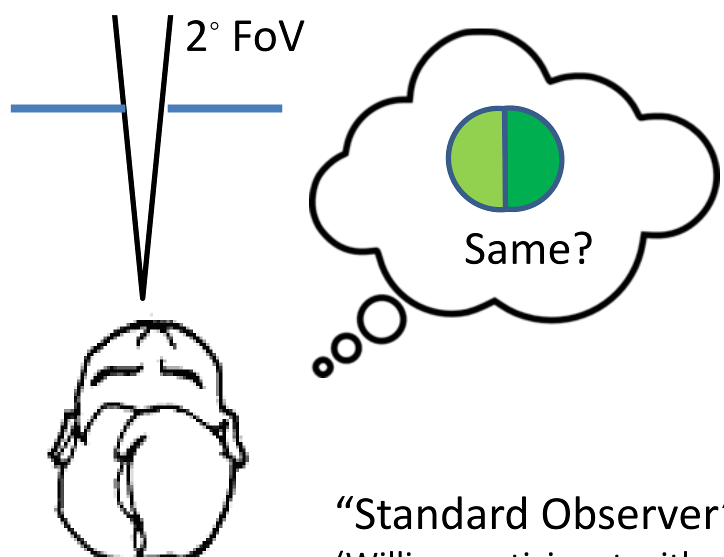
Three fixed primaries

CIE RGB color matching



Human subjects matched test colors by adding or subtracting three primaries.

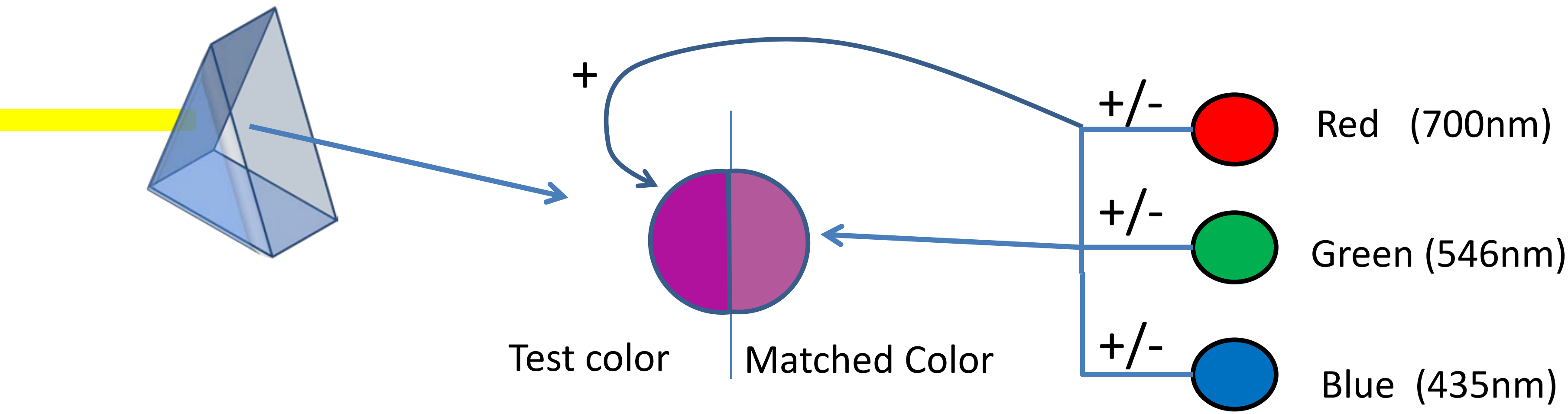
Field of view was 2-degrees (where color cones are most concentrated)



"Standard Observer"
(Willing participant with no eye disease)

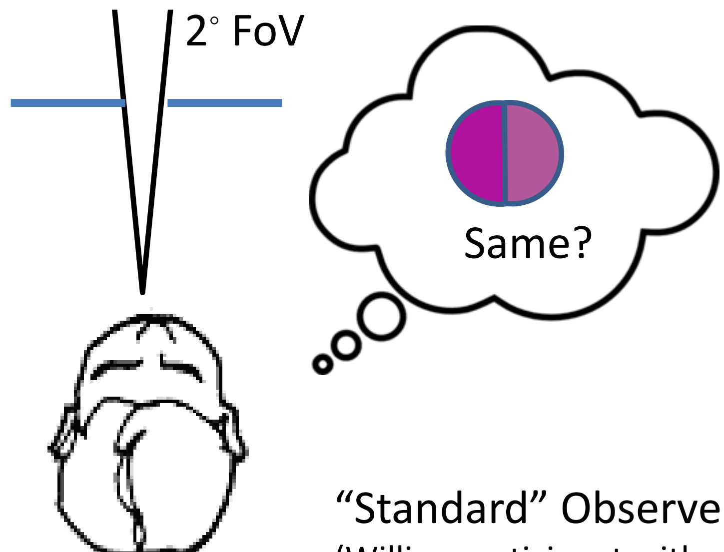
Experiments carried out by
William D. Wright (Imperial College) and John Guild (National Physical Laboratory, London)

CIE RGB color matching



For some test colors, no mix of the primaries could give a match. For these cases, the subjects were ask to add primaries to the test color to make the match.

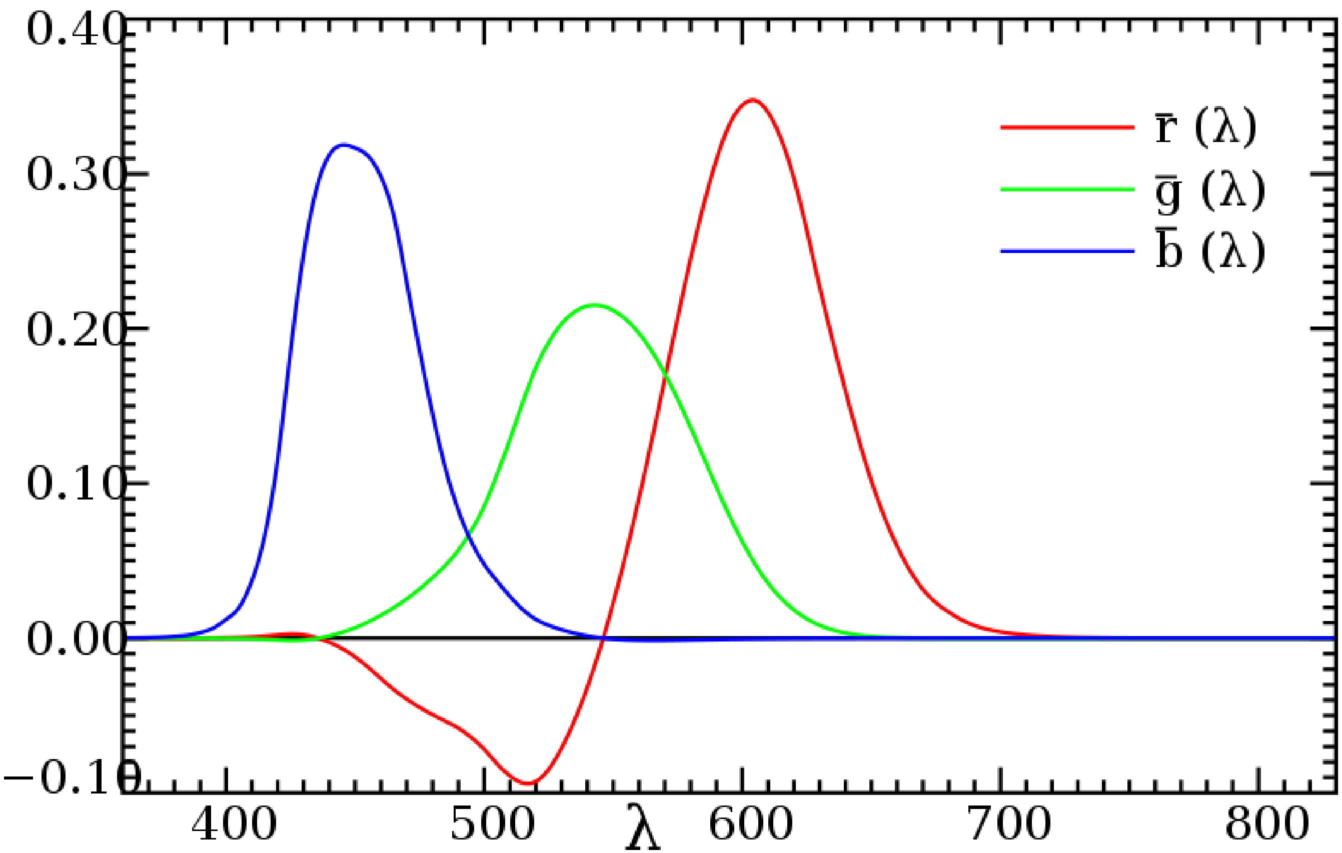
This was treated as a negative value of the primary added to the test color.



“Standard” Observer
(Willing participant with no eye disease)

http://graphics.stanford.edu/courses/cs178-13/applets/colormatching.html

CIE RGB results

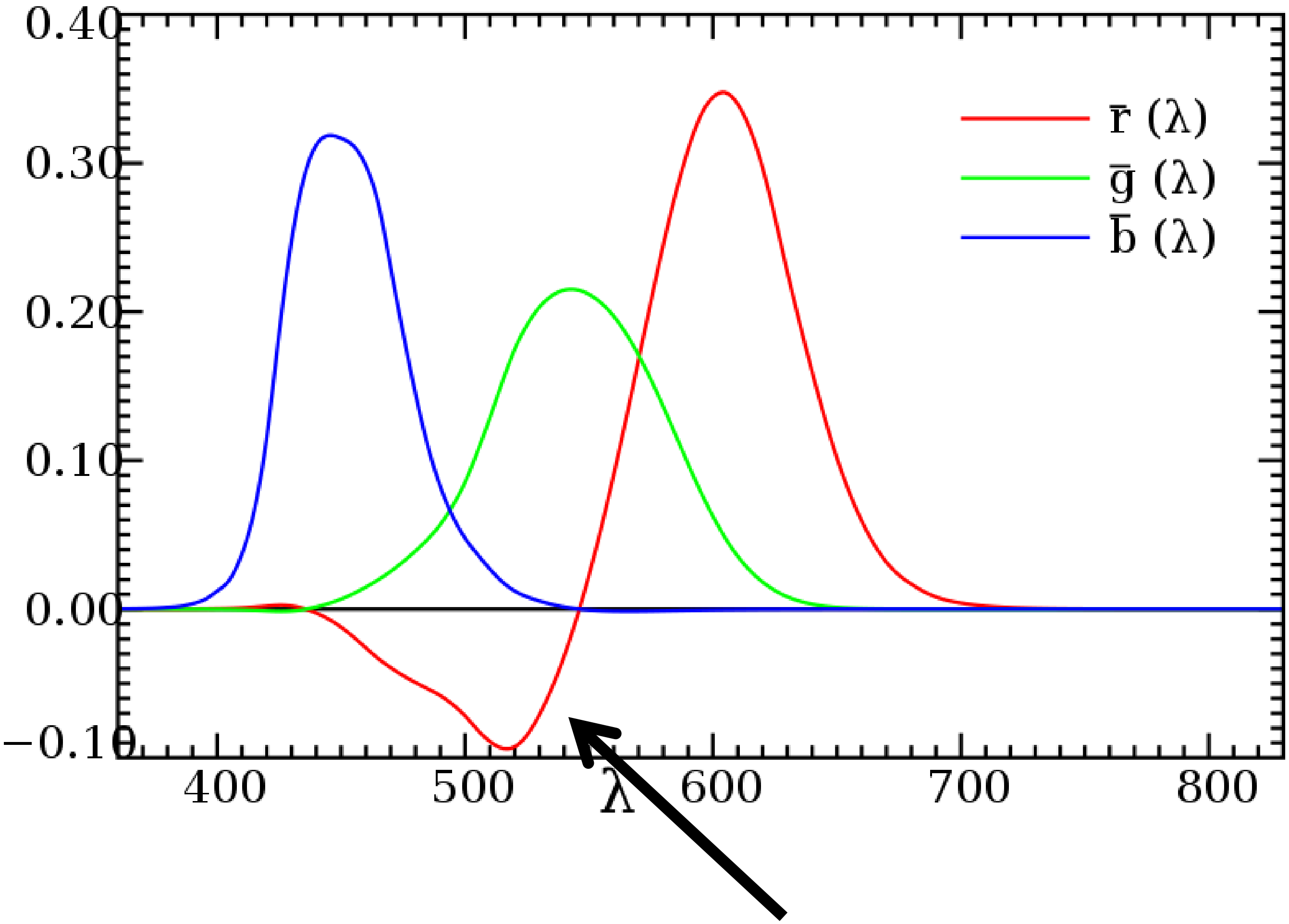


Plots are of the mixing coefficients of each primary needed to produce the corresponding monochromatic light at that wavelength.

Note that these functions have been scaled such that area of each curve is equal.

CIE RGB 2-degree Standard Observer
(based on Wright/Guild's data)

CIE RGB results



Negative points, the primary used did not span the full range of perceptual color.

CIE 1931 - XYZ

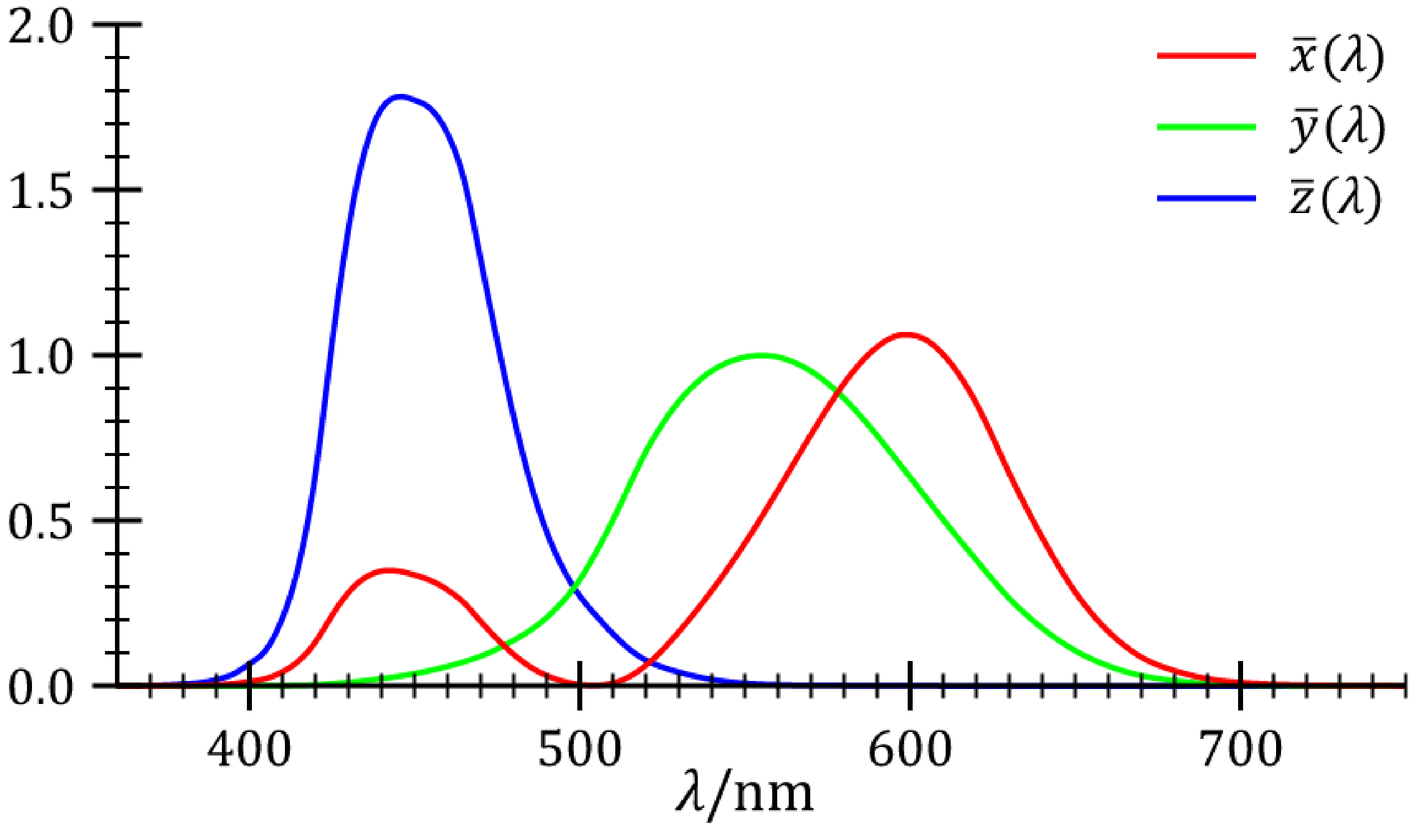
- In 1931, the CIE met and approved defining a new canonical basis, termed XYZ that would be derived from Wright-Guild's CIE RGB data
- Properties desired in this conversion:
  - White point defined at X=1/3, Y=1/3, Z=1/3
  - Y would be the luminosity function ($V(\lambda)$)
  - Quite a bit of freedom in selecting these XYZ basis
  - In the end, the adopted transform was:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4887180 & 0.3106803 & 0.2006017 \\ 0.1762044 & 0.8129847 & 0.0108109 \\ 0.0000000 & 0.0102048 & 0.9897952 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

CIE RGB

Nice article see: Fairman et al "How the CIE 1931 Color-Matching Functions Were Derived from Wright–Guild Data", Color Research & Application, 1997

CIE XYZ



This shows the mixing coefficients $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ for the CIE 1931 2-degree standard observer XYZ basis computed from the CIE RGB data. Coefficients are all now positive. Note that the basis XYZ are not physical SPD like in CIE RGB, but linear combinations defined by the matrix on the previous slide.

What does it mean?

- **We now have a canonical color space to describe SPDs**
- Given an SPD, I(λ), we can find its mapping into the CIE XYZ space

$$X = \int_{380}^{780} I(\lambda)\bar{x}(\lambda)\, d\lambda \qquad Y = \int_{380}^{780} I(\lambda)\bar{y}\,(\lambda)\, d\lambda \qquad Z = \int_{380}^{780} I(\lambda)\bar{z}(\lambda)\, d\lambda$$

- Given two SPDs, if their CIE XYZ values are equal, then they are considered the same perceived color, i.e.
  - $I_1(\lambda), I_2(\lambda) \rightarrow (X_1, Y_1, Z_1) = (X_2, Y_2, Z_2)$ [perceived as the same color]

- So . . we can quantitatively describe color!

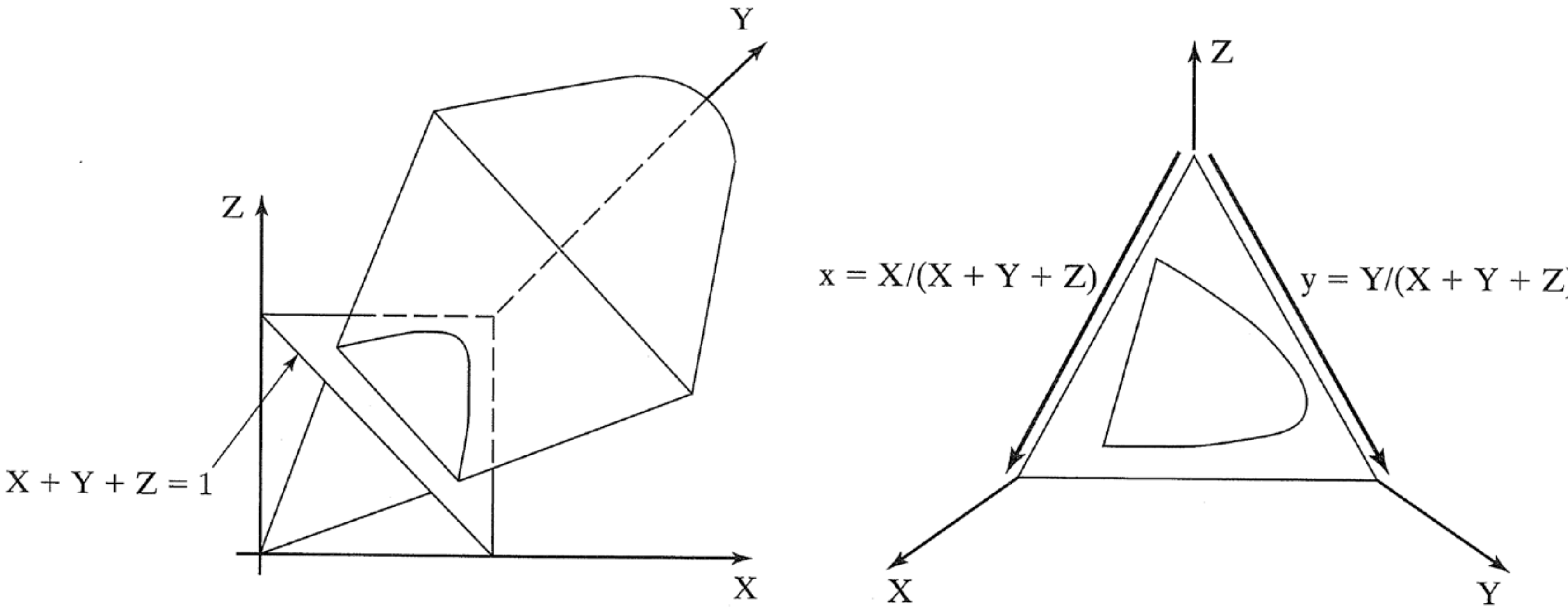
What does it mean?

- CIE XYZ space is also considered “device independent” – the XYZ values are not specific to any device
- Devices (e.g. cameras, flatbed ,scanners, printers, displays) can find mappings of their device specific values to corresponding CIE XYZ values. This provides a canonical space to match between devices (at least in theory)

Luminance-chromaticity space (CIE xyY)

- CIE XYZ describes a color in terms of linear combination of three primaries (XYZ)
- Sometimes it is useful to discuss color in terms of luminance (perceived brightness) and chromaticity (we can think of as the hue-saturation combined)
- CIE xyY space is used for this purpose

Deriving CIE xyY



Project the CIE XYZ values onto the X+Y+Z=1 plane.

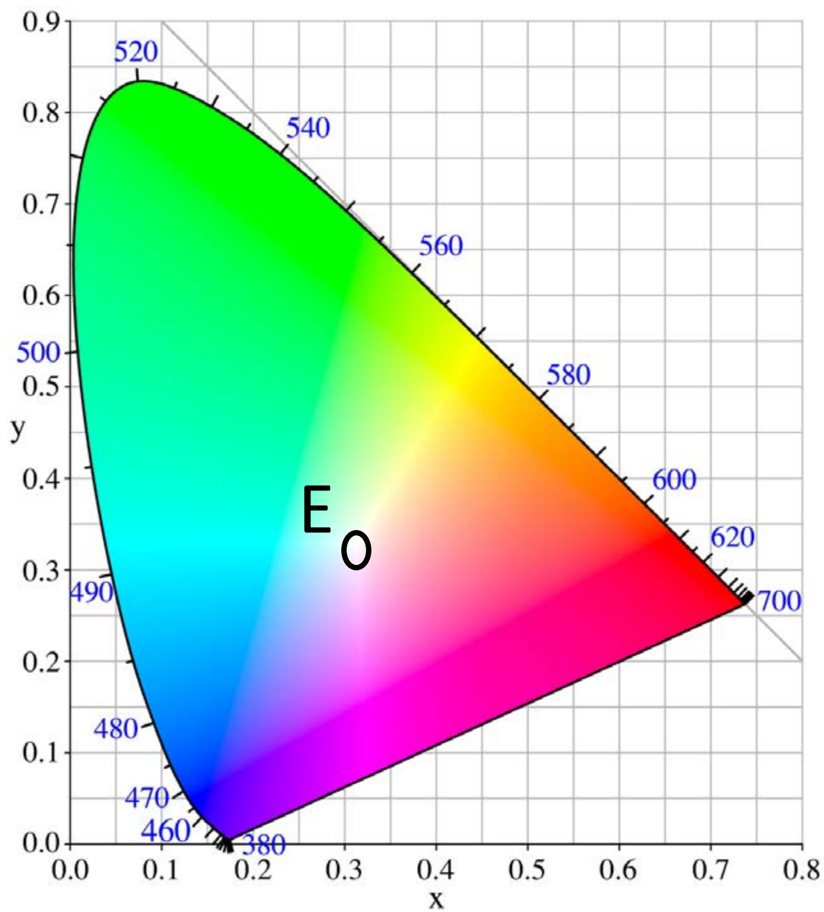
Figure from Ponce and Forsyth

CIE x-y chromaticity diagram

This gives us the familiar horseshoe shape of visible colors as 2D plot. Note the axis are x & y.

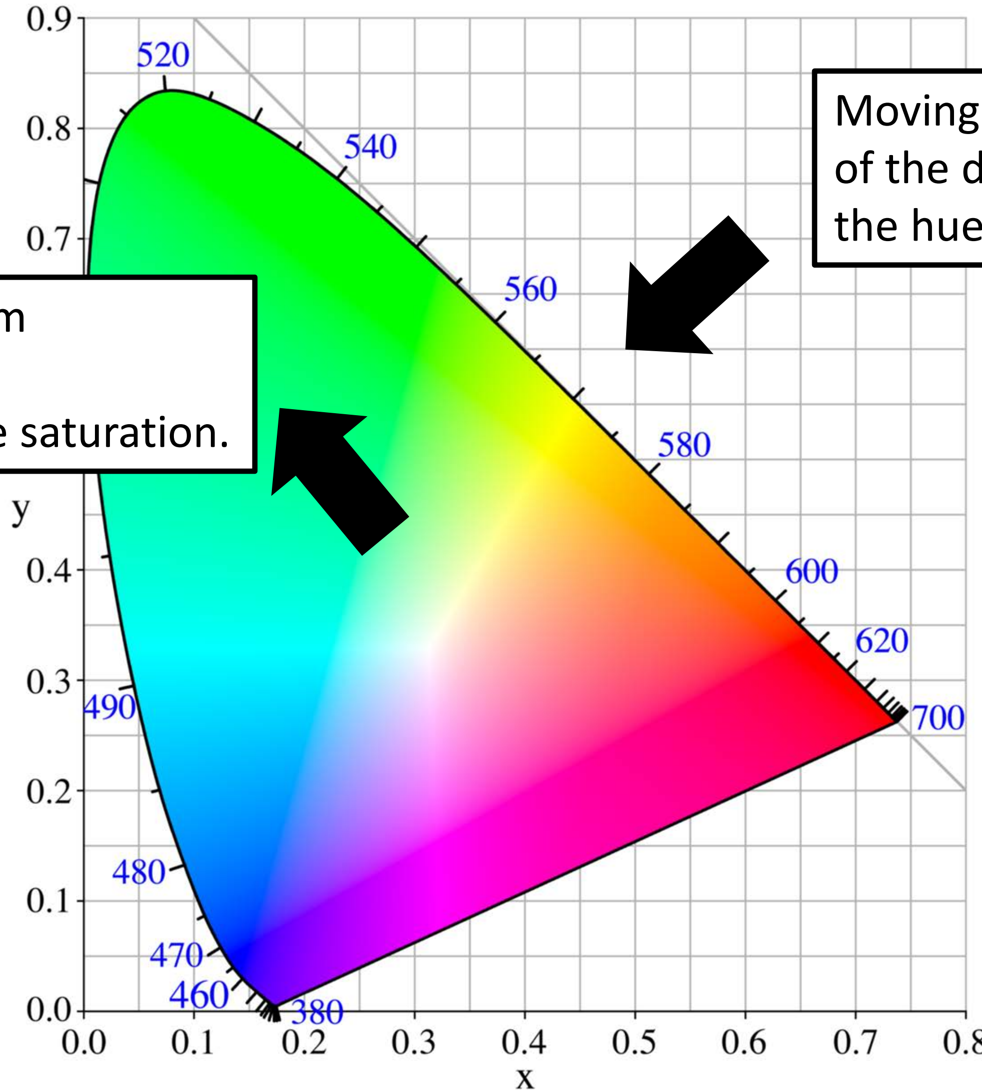
Point "E" represents where X=Y=Z have equal energy (X=0.33, Y=0.33, Z=0.33)

CIE XYZ "white point"



In the 1930s, CIE had a bad habit of over using the variables X, Y. Note that x, y are chromaticity coordinates, $\bar{x}$, $\bar{y}$ (with the bar above) are the matching functions, and X, Y are the imaginary SPDs of CIE XYZ.

CIE x-y chromaticity diagram



Moving along the outside of the diagram gives the hues.

Moving way from the white point represents more saturation.

CIE xyY

- Generally when we use CIE xyY, we only look at the (x,y) values on the 2D diagram CIE x-y chromaticity chart
- However, the Y value (the same Y from CIE XYZ) represents the perceived brightness of the color
- With values (x,y,Y) we can reconstruct back to XYZ

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

Fast forward 80+ years

- CIE 1931 XYZ, CIE 1931 xyY (2-degree standard observer) color spaces have stood the test of time
- Many other studies have followed (most notably - CIE 1965 XYZ 10-degree standard observer), . . .
- But in the literature (and in this tutorial) you'll find CIE 1931 XYZ color space making an appearance often

What is perhaps most amazing?

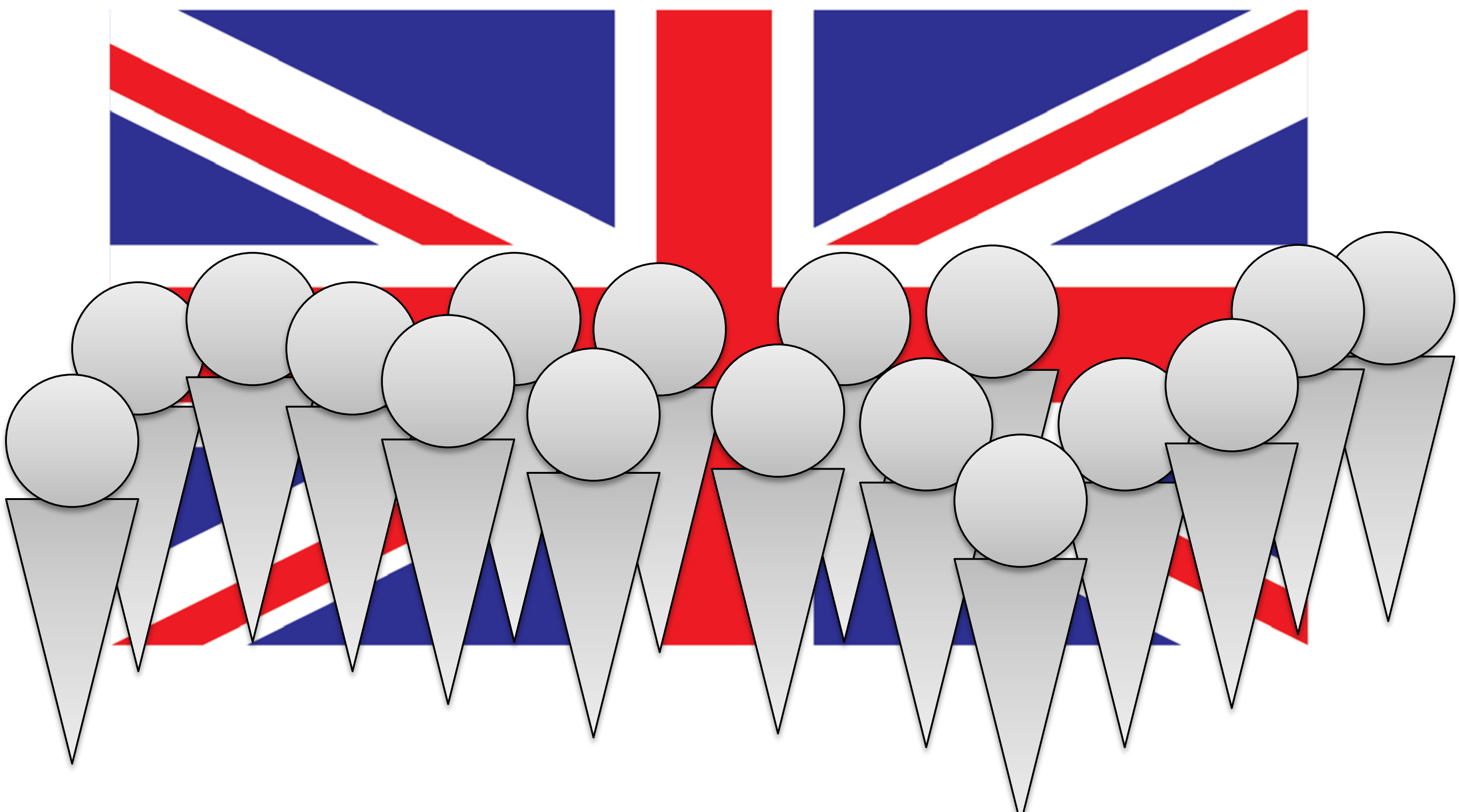
- 80+ years of CIE XYZ is all down to the experiments by the “standard observers”

- How many standard observers were used? 100, 500, 1000?

A Standard Observer

CIE XYZ is based on 17 Standard Observers

10 by Wright, 7 by Guild

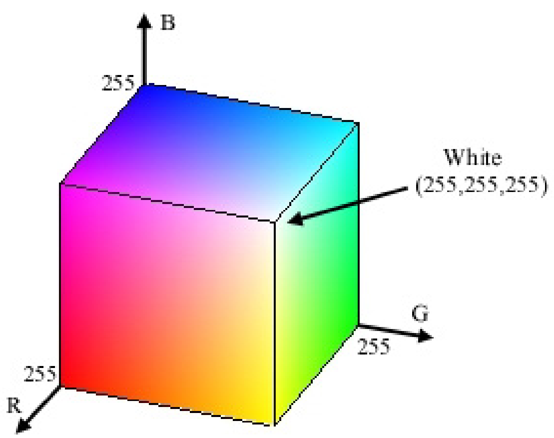


"The Standard Observers"

We are done with color right?
Almost . . .

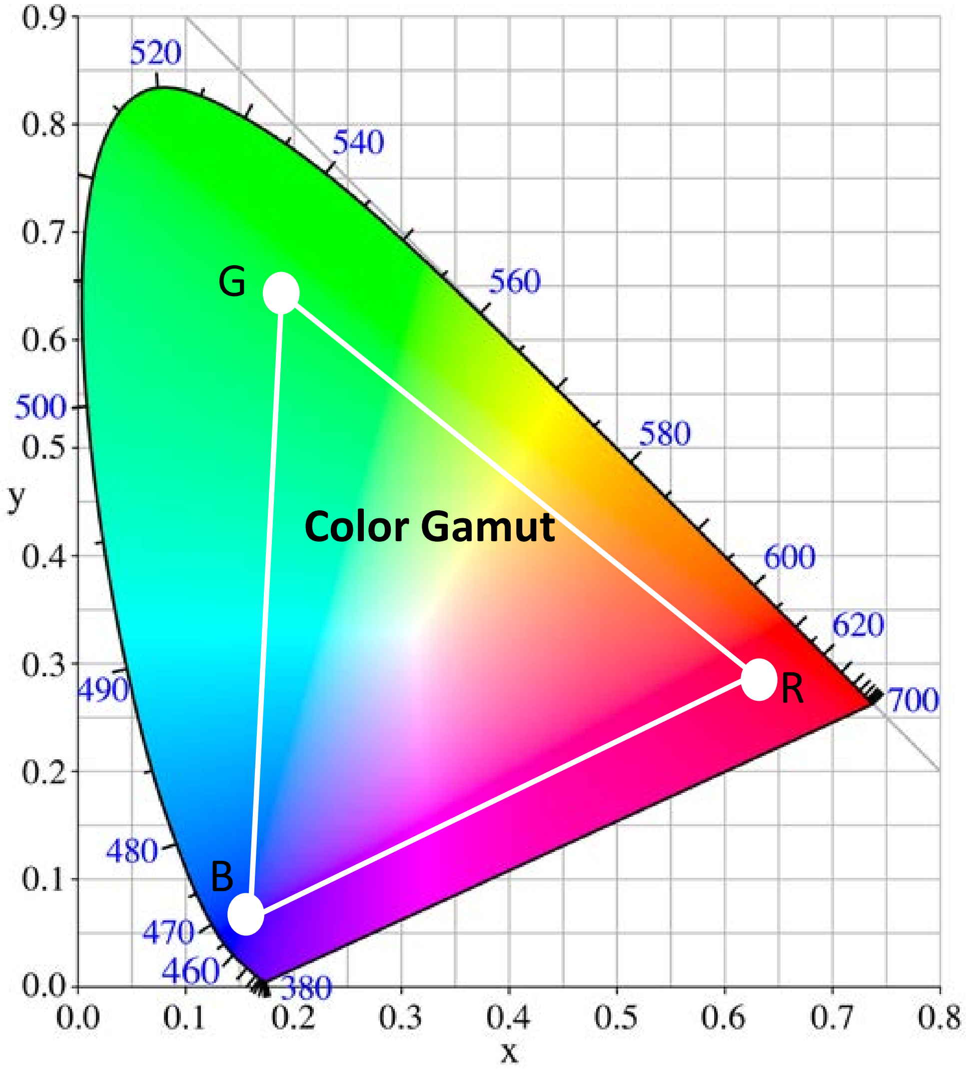
CIE XYZ and RGB

- While CIE XYZ is a canonical color space, images/device rarely work directly with XYZ
- XYZ are not real primaries
- RGB primaries dominate the industry
- We are all familiar with the RGB color cube



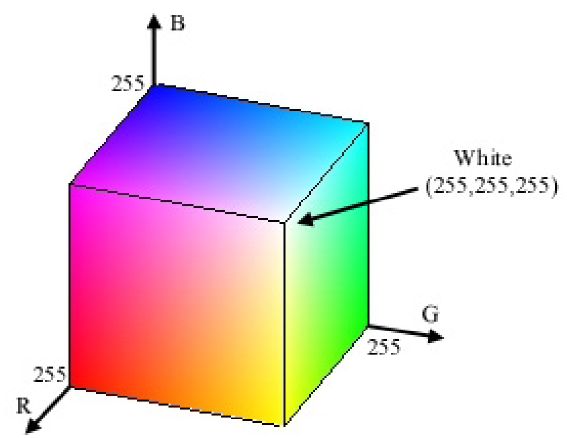
But by now, you should realize that Red, Green, Blue have no quantitative meaning. We need to know their corresponding SPDs or CIE XYZ values

Device specific RGB values

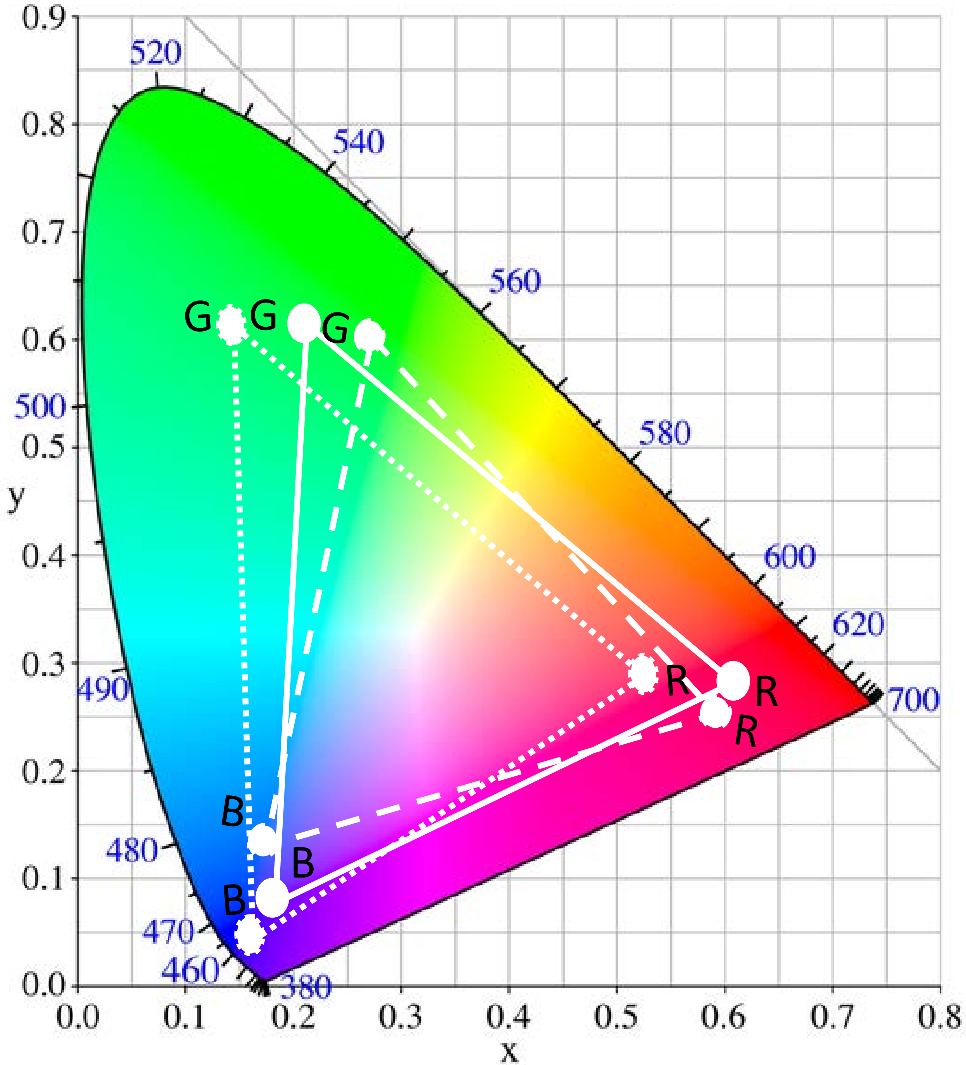


The RGB values span a subspace of CIE-XYZ to define the devices gamut.

If you have RGB values, they are specific to a particular device .



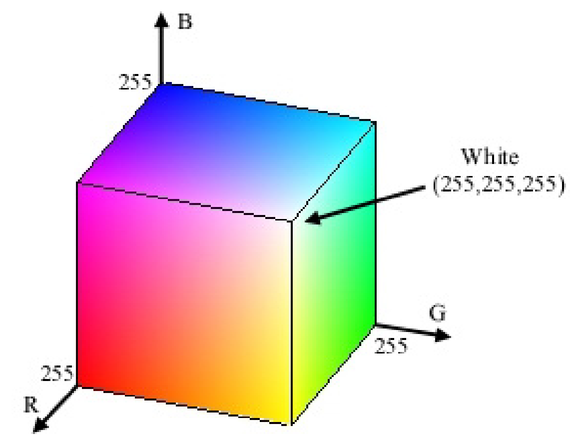
Trouble with RGB



Device 1

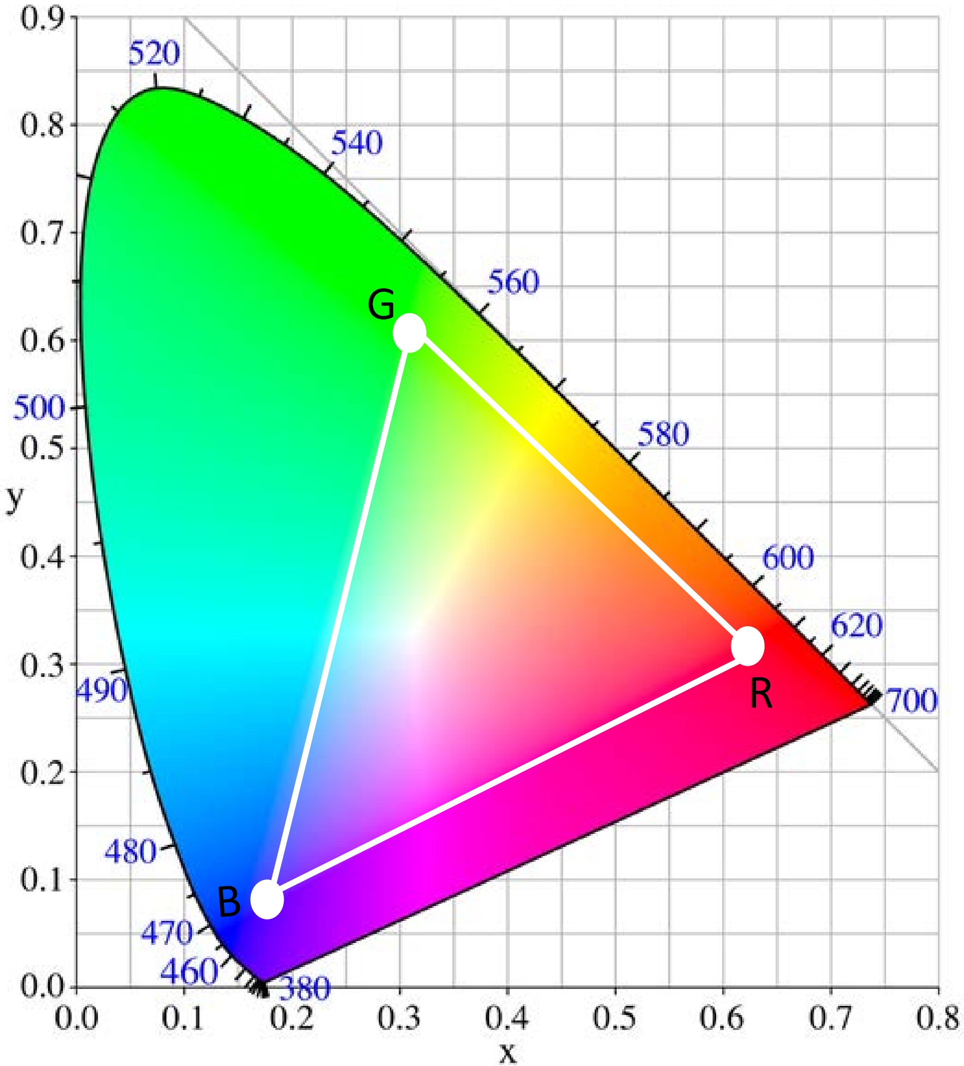
Device 2

Device 3



RGB values have no meaning if the primaries between devices are not the same! This is a **huge** problem for color reproduction from one device to the next.

Standard RGB (sRGB)



In 1996, Microsoft and HP defined a set of "standard" RGB primaries.
R=CIE xyY (0.64, 0.33, 0.2126)
G=CIE xyY (0.30, 0.60, 0.7153)
B=CIE xyY (0.15, 0.06, 0.0721)

This was considered an RGB space achievable by most devices at the time.

White point was set to the D65 illuminant**. This is an important thing to note.** It means sRGB has built in the assumed viewing condition (6500K daylight).

CIE XYZ to sRGB conversion

Matrix conversion:

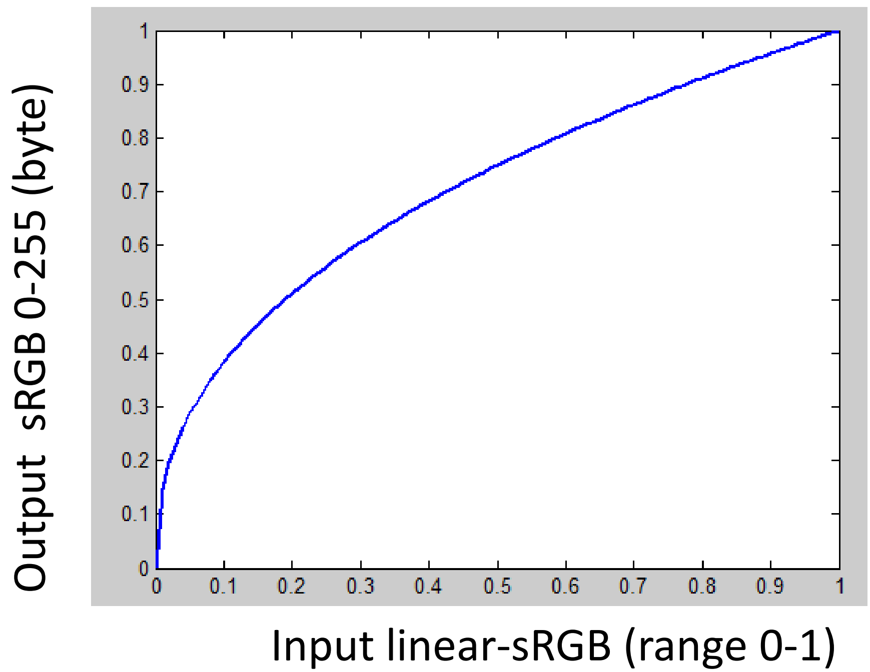
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.2404542 & -1.5371385 & 0.4985314 \\ -0.9692660 & 1.8760108 & 0.0415560 \\ 0.0556434 & -0.2040259 & 1.0572252 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Linearized sRGB (D65)

CIE XYZ

- R=G=B=1 is defined as illuminant D65 is in CIE XYZ*
- This is the linear-sRGB space
- sRGB also specifies a gamma correction of the values

sRGB gamma curve



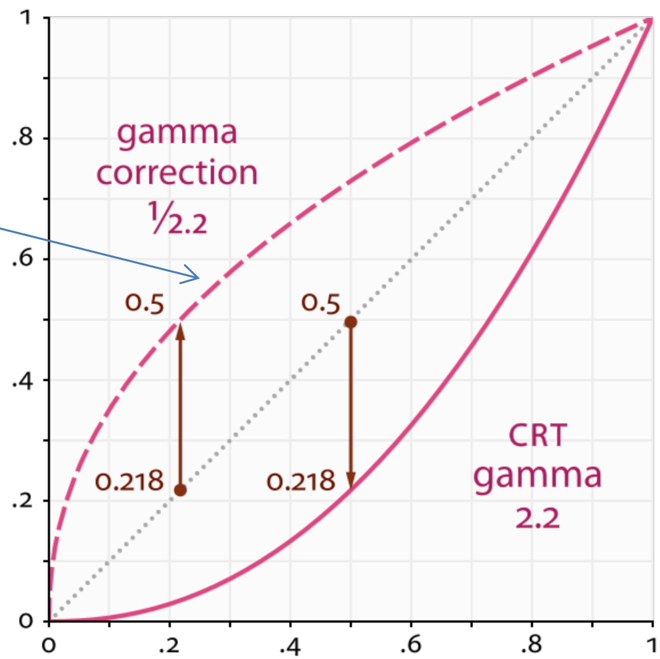
This is a close approximation of the actual sRGB gamma

Actual formula is a bit complicated, but effectively this is gamma ($I' = 255 * I^{(1/2.2)}$), where I’ is the output intensity and I is the linear sRGB ranged 0-1, with a small linear transfer for linearized sRGB values close to 0 (not shown in this plot).

Gamma justification

- When sRGB was defined (1996), the main viewing device was a CRT
- CRTs had a well known nonlinear relation between voltage and display intensity (see below)
- The application of the gamma=1/(2.2) to the linearized-sRGB is an "encoding gamma" (or gamma correction) that will be undone by the CRT to produce the desired result

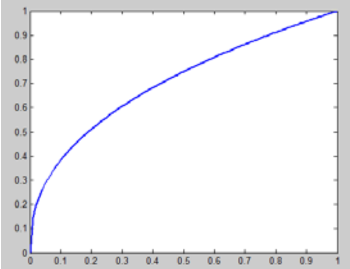
sRGB gamma



Before (linear sRGB) & after (sRGB)

Linear sRGB

Final sRGB



Linear sRGB

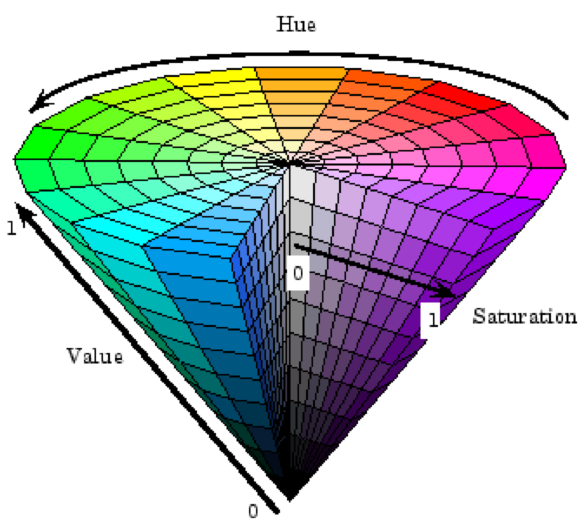
Final sRGB

Benefits of sRGB

- Like CIE XYZ, sRGB is a device independent color space (often called an output color space)
- If you have two pixels with the same sRGB values, they will have the same CIE XYZ value, which means “in theory” they will appear as the same perceived value
- Does this happen in practice?

HSV color space

- **H**ue, **S**aturation, **V**alue
- Nonlinear – reflects topology of colors by coding **hue** as an angle
- Matlab: `hsv2rgb`, `rgb2hsv`.



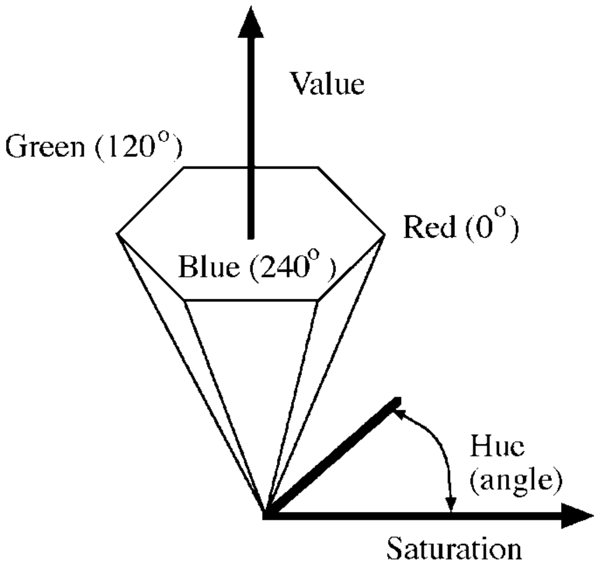


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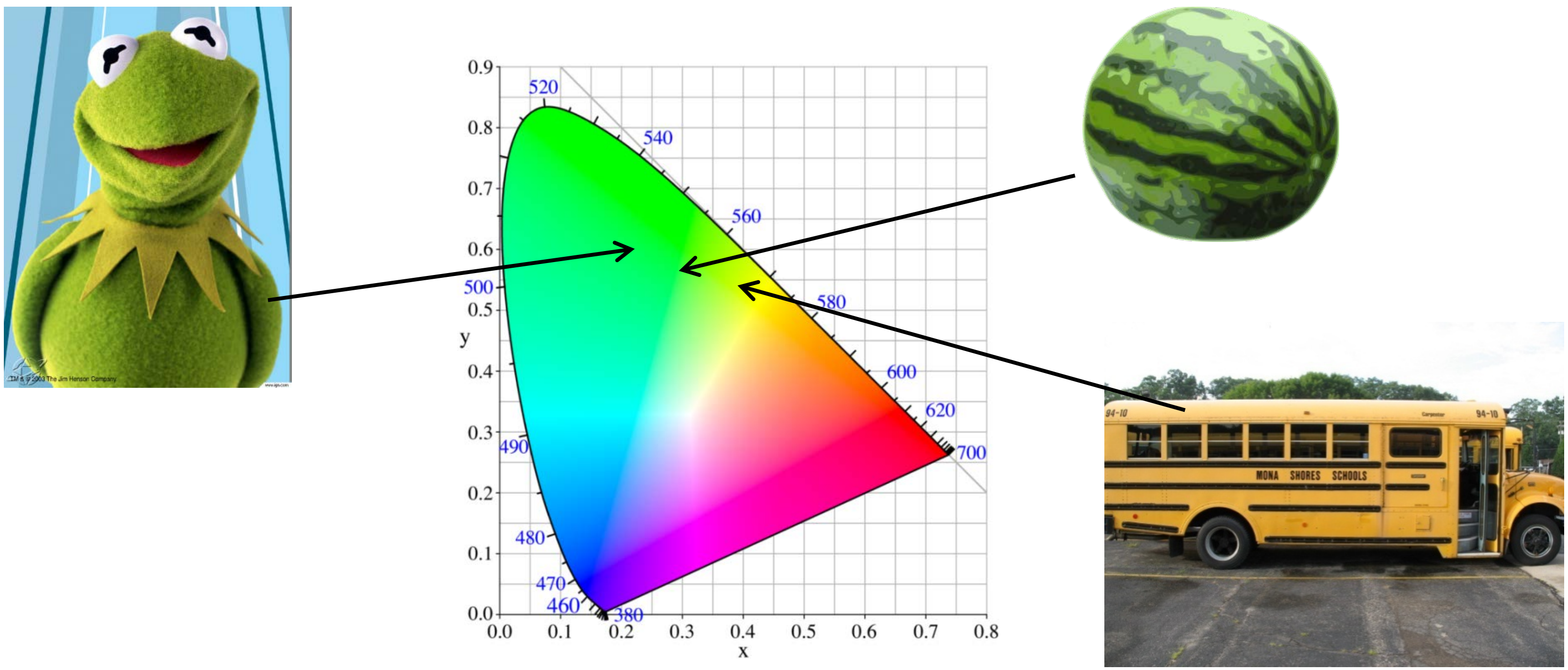
Image from mathworks.com

Distances in color space

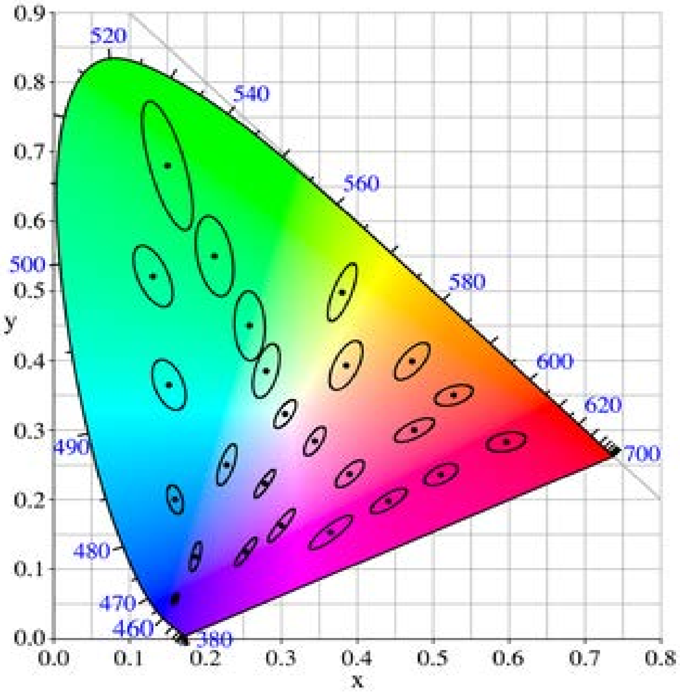
- Are distances between points in a color space perceptually meaningful?



Kristen Grauman

Distances in color space

- Not necessarily: CIE XYZ is **not** a *uniform* color space, so magnitude of differences in coordinates are poor indicator of color "distance".

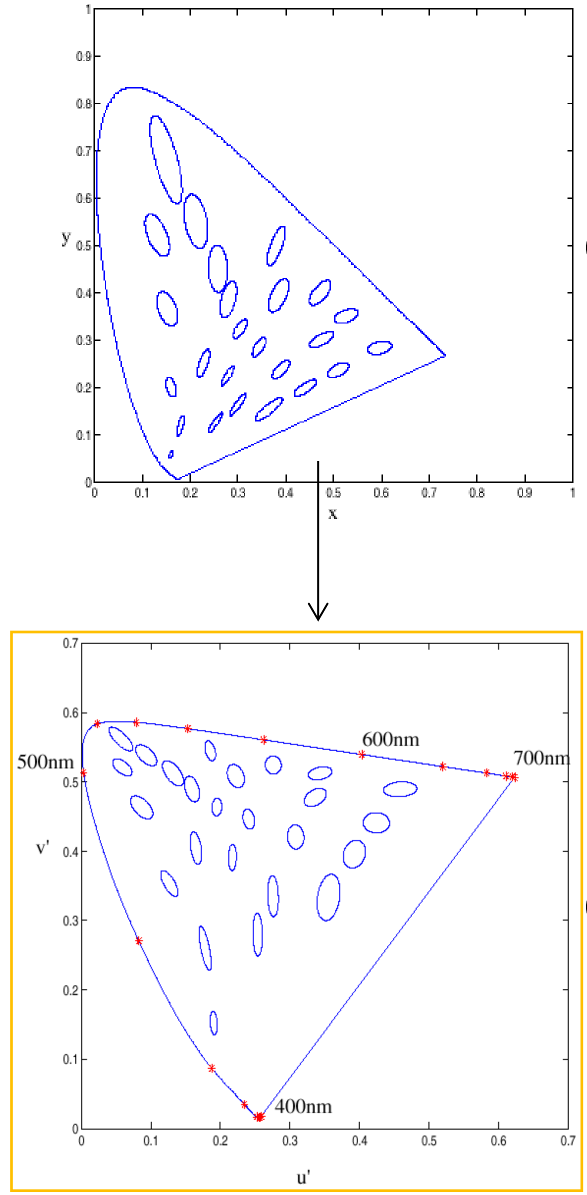


McAdam ellipses:
Just noticeable differences in color

Uniform color spaces

- Attempt to correct this limitation by remapping color space so that just-noticeable differences are contained by circles → distances more perceptually meaningful.

- Examples:
  - CIE u’v’
  - CIE Lab

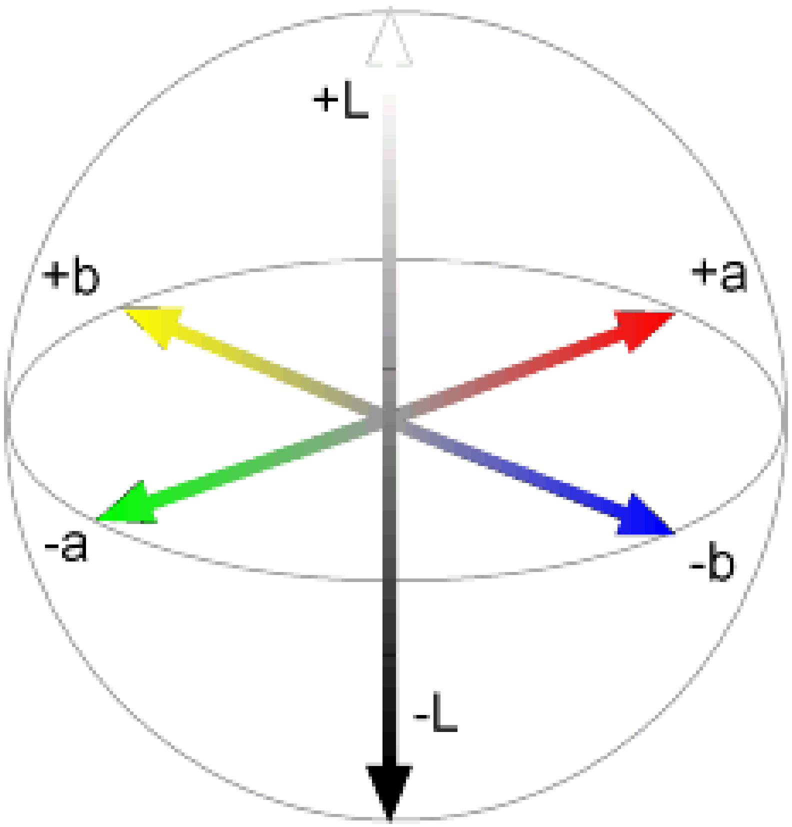


CIE XYZ

CIE u’v’

Color spaces: L*a*b*

“Perceptually uniform”* color space



L
(a=0,b=0)

a
(L=65,b=0)

b
(L=65,a=0)

James Hayes

If you had to choose, would you rather go without luminance or chrominance?

If you had to choose, would you rather go without luminance or chrominance?

Most information in intensity

Only color shown – constant intensity

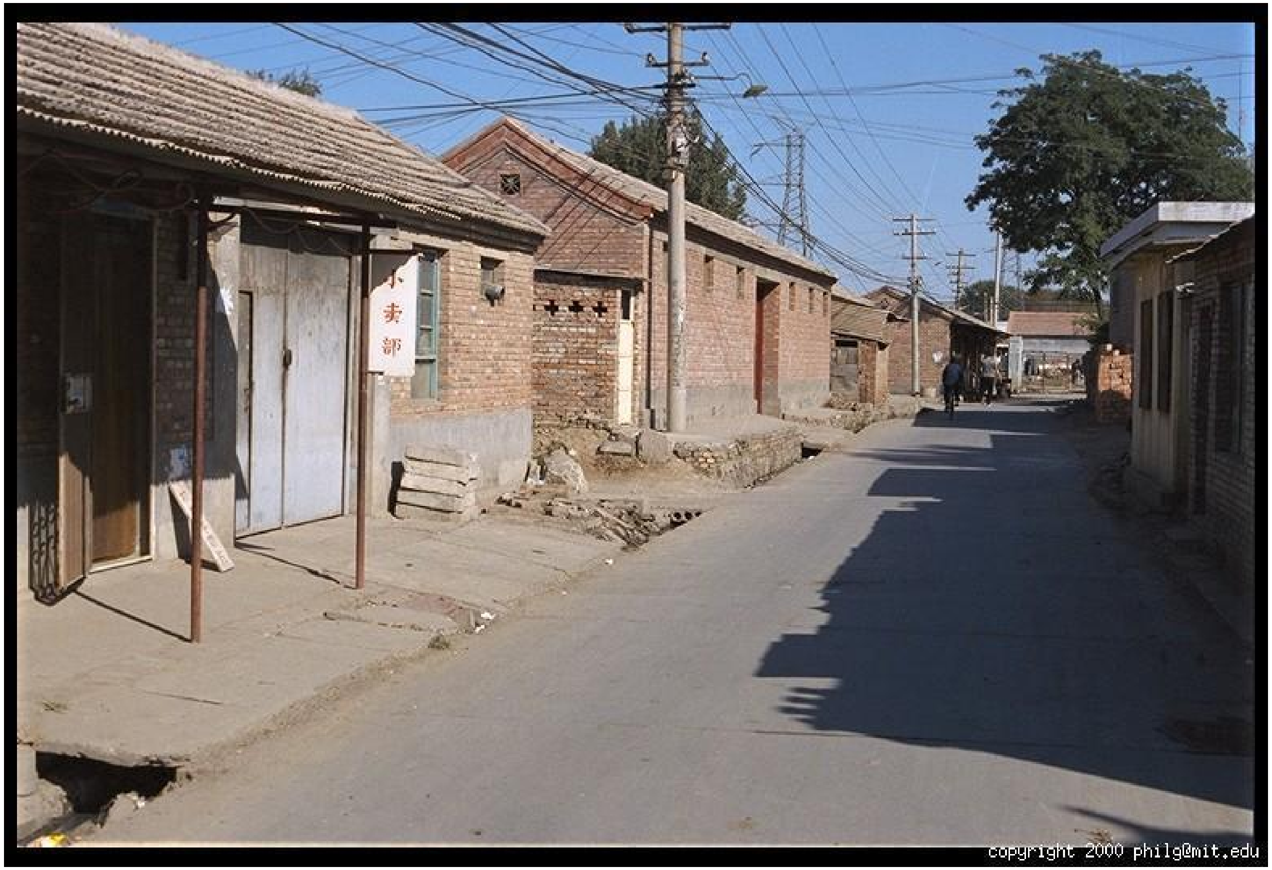
James Hayes

Most information in intensity

Only intensity shown – constant color

James Hayes

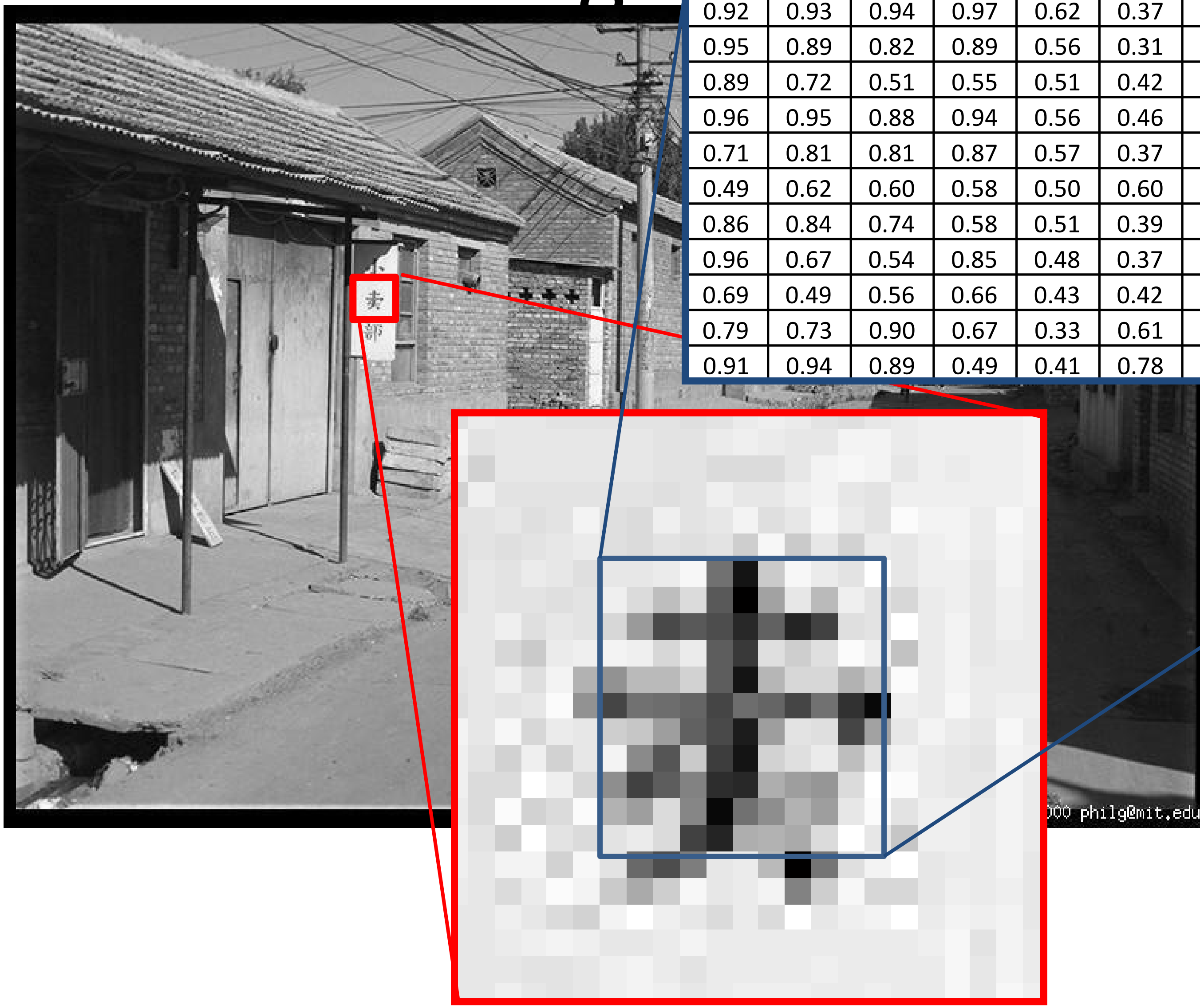
Most information in intensity



Original image

James Hayes

Back to grayscale intensity

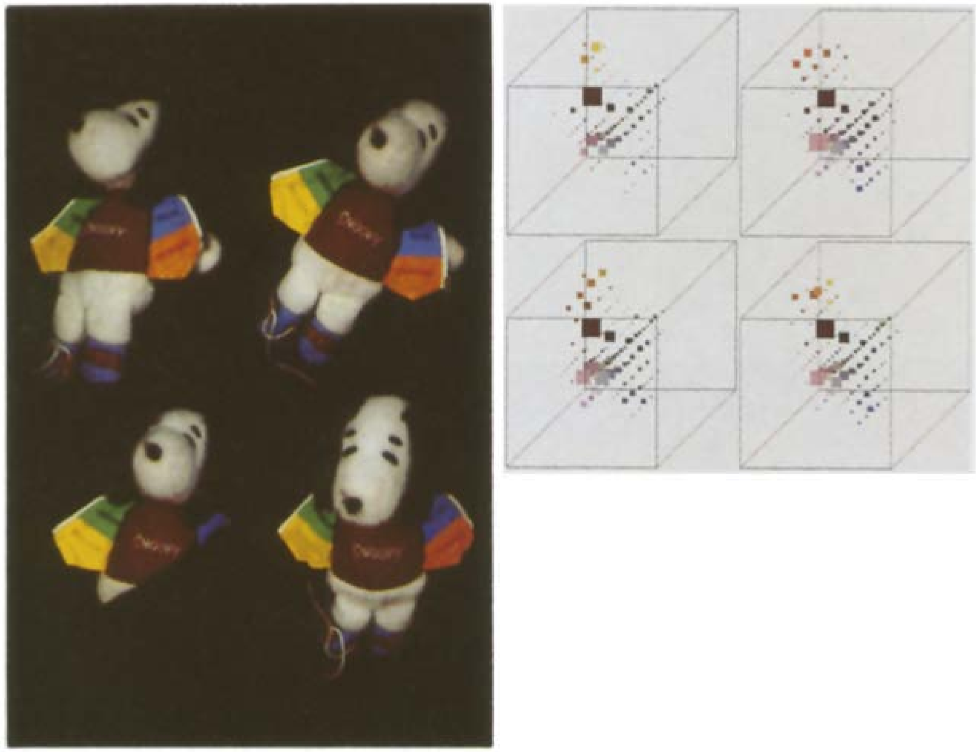


0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33
0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74
0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

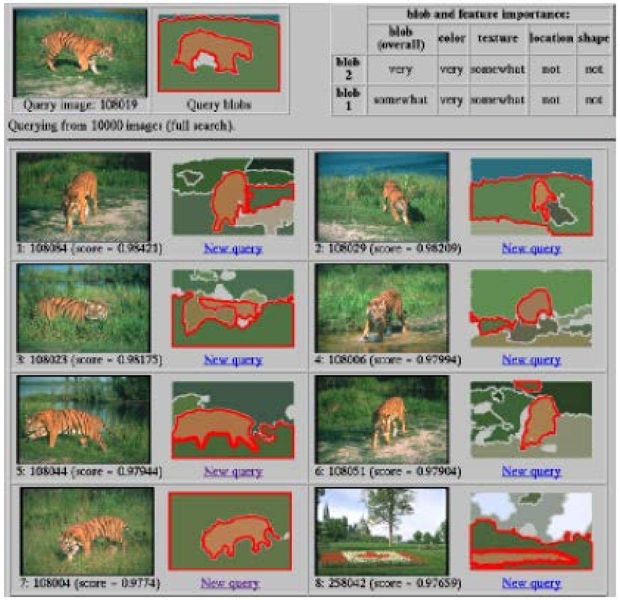
James Hayes

Color Applications

Color as a low-level cue for CBIR



Swain and Ballard, Color Indexing, IJCV 1991

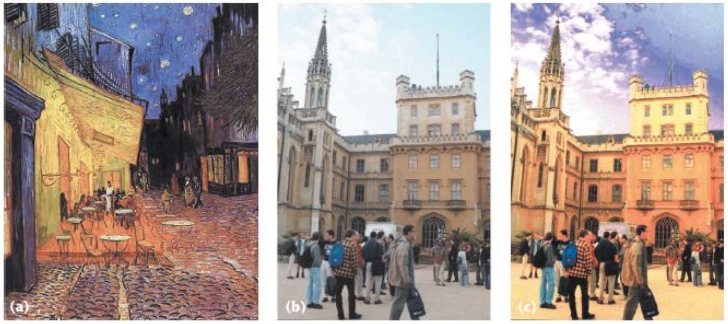


Blobworld system
Carson et al, 1999

Computational Photography

Color Harmony

Color Theme



Color Transfer

Colorization

Crash course on color is over!

- A lot of information to absorb
- Understanding colorimetry is required to understand imaging devices
- CIE XYZ and CIE illuminants will make many appearances in color imaging/processing discussions