ΗΥ416
ΓΡΑΦΙΚΑ ΥΠΟΛΟΓΙΣΤΩΝ

Χρωματικά Μοντέλα

Π. ΤΣΟΜΠΑΝΟΠΟΥΛΟΥ
ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ
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Outline

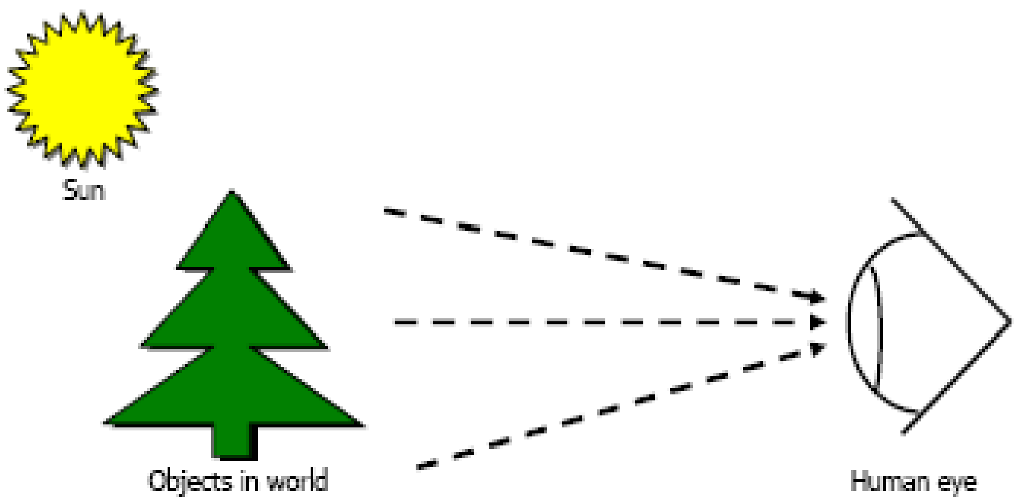
Color Models

Image representation

Required readings: HB 12-1 to 12-8

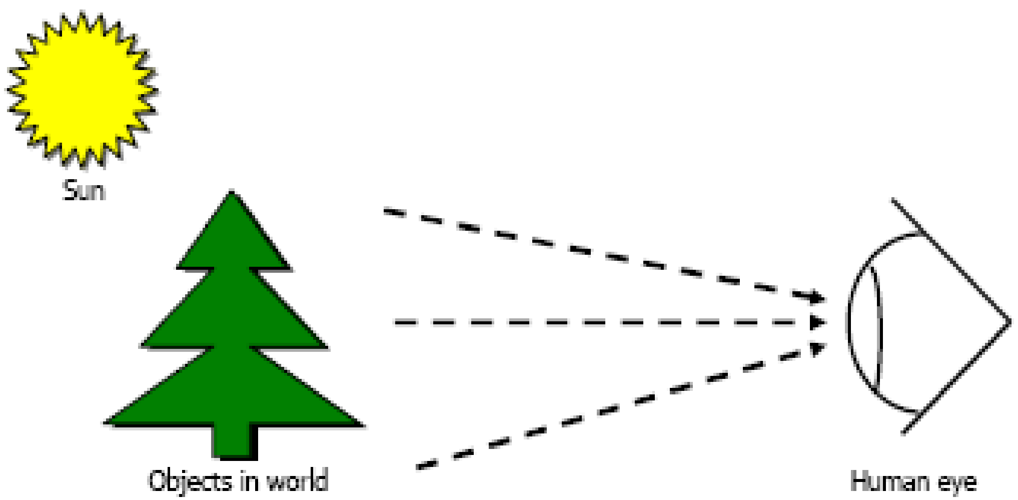
Human Vision

Model of human vision



Human Vision

Model of human vision



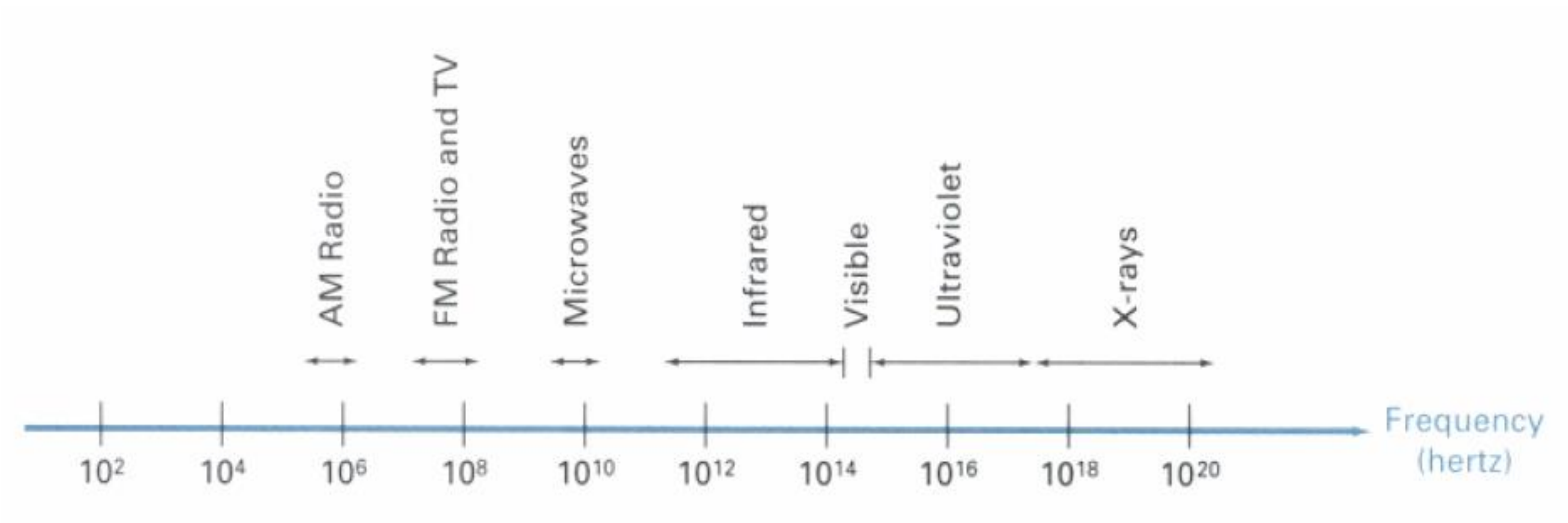
Vision components:

- Incoming light
- Human eye

Electromagnetic Spectrum

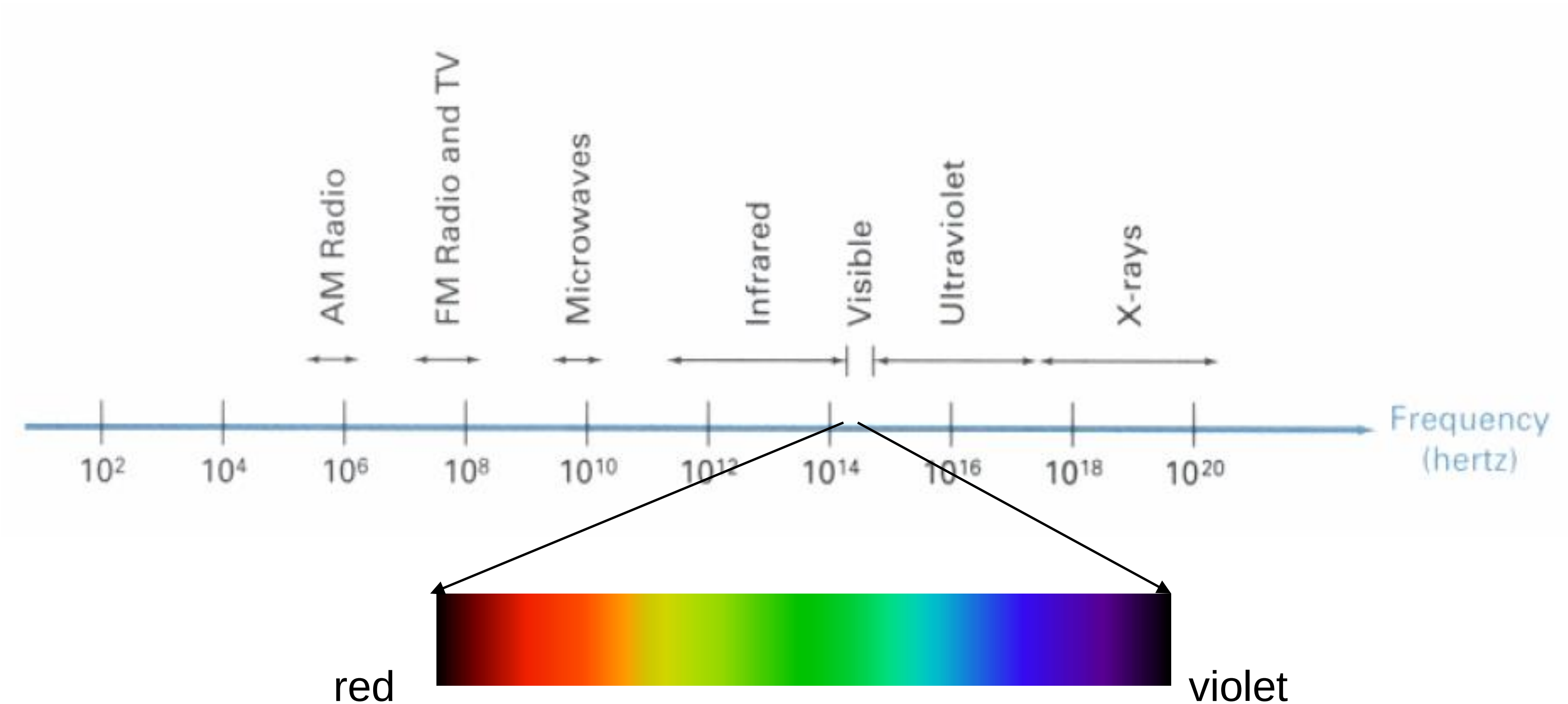
Visible light frequencies range between:

- Red: 4.3×10^{14} hertz (700nm)
- Violet: 7.5×10^{14} hertz (400nm)



Visible Light

The human eye can see "visible" light in the frequency between 400nm-700nm



Visible Light

The human eye can see "visible" light in the frequency between 400nm-700nm

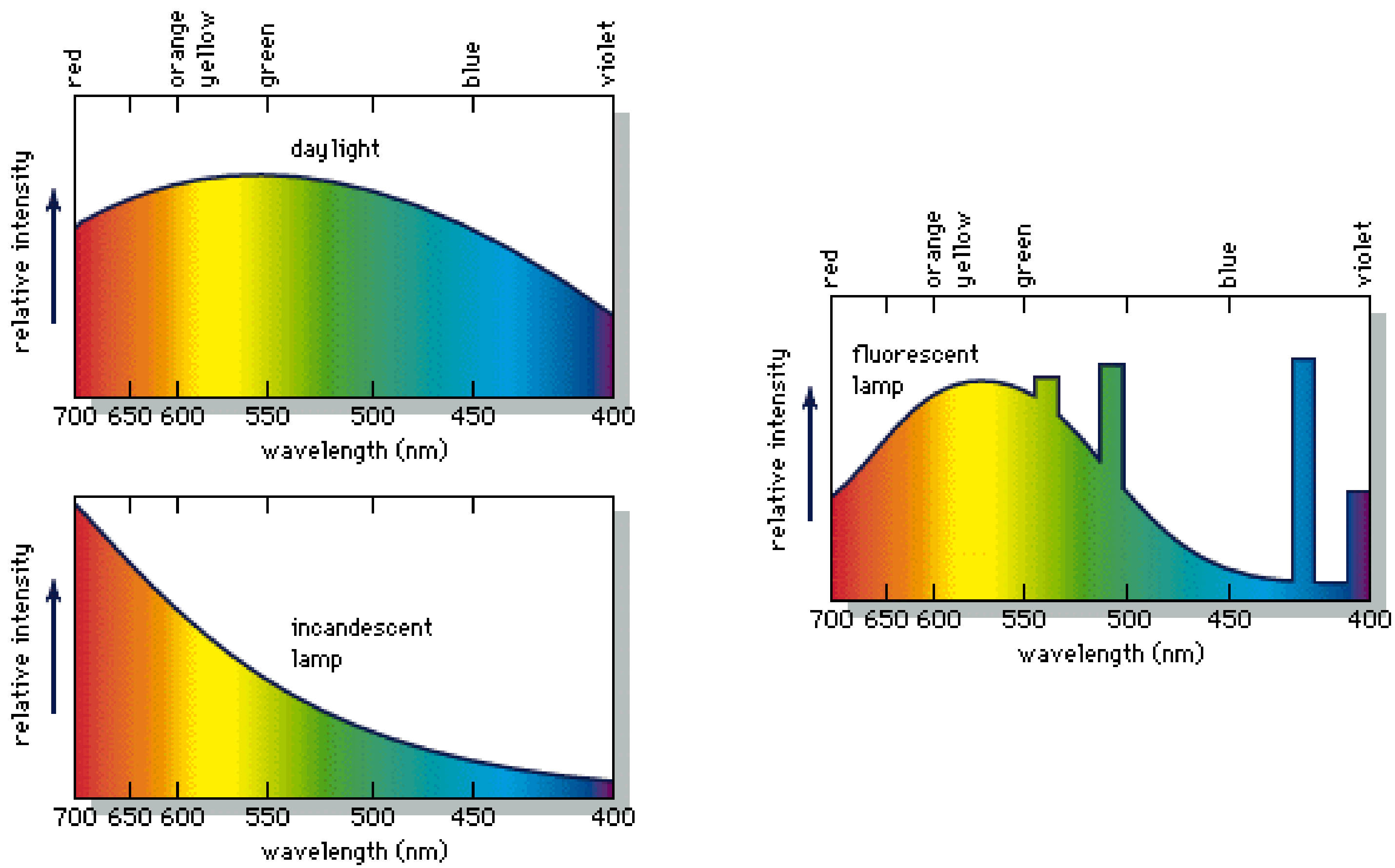
Visible Light

The human eye can see "visible" light in the frequency between 400nm-700nm

- Each frequency value between 400nm-700nm corresponds to a distinct spectral color
- Not strict boundary
- Some colors are absent (brown, pink)

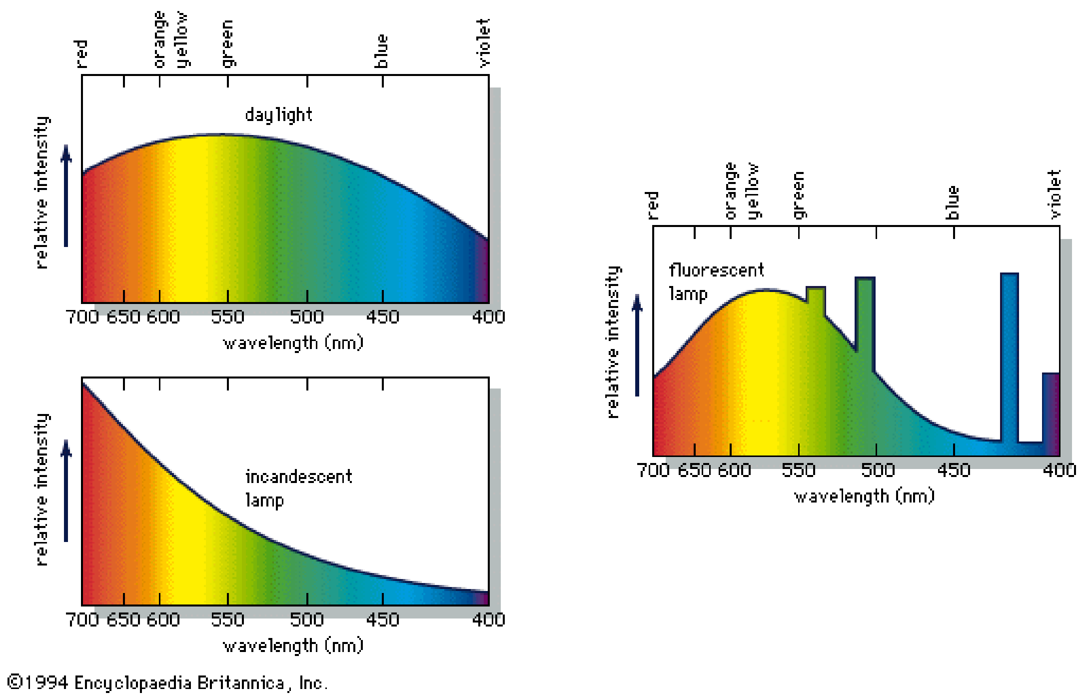
Spectral Energy Distribution

Three different types of lights



Spectral Energy Distribution

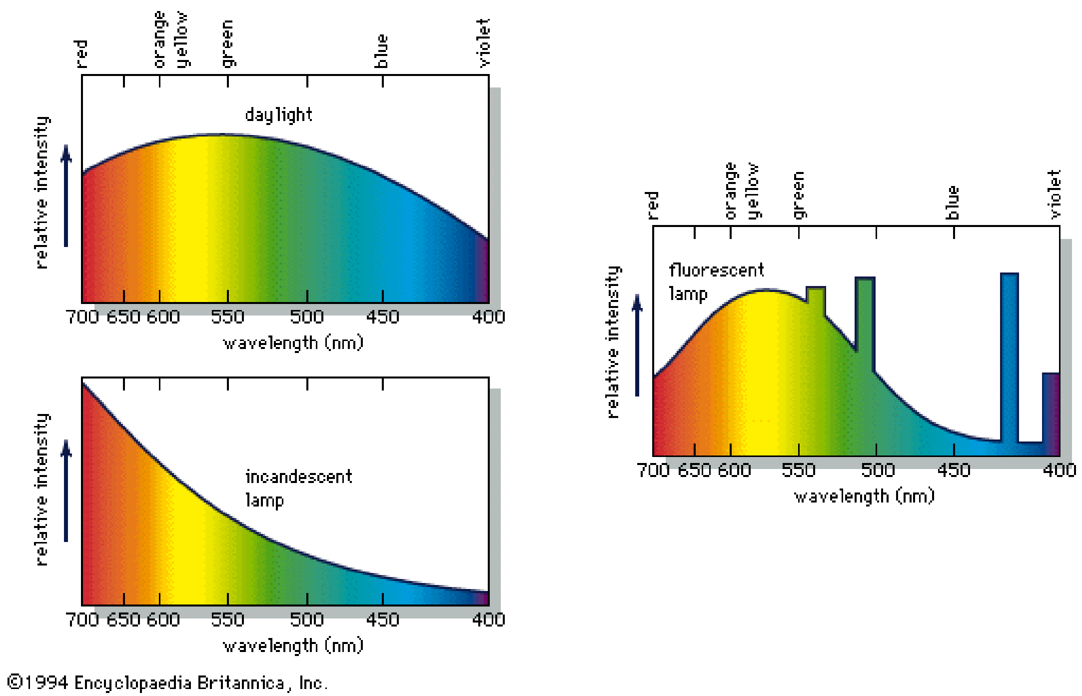
Three different types of lights



Can we use spectral energy distribution to represent color?

Spectral Energy Distribution

Three different types of lights

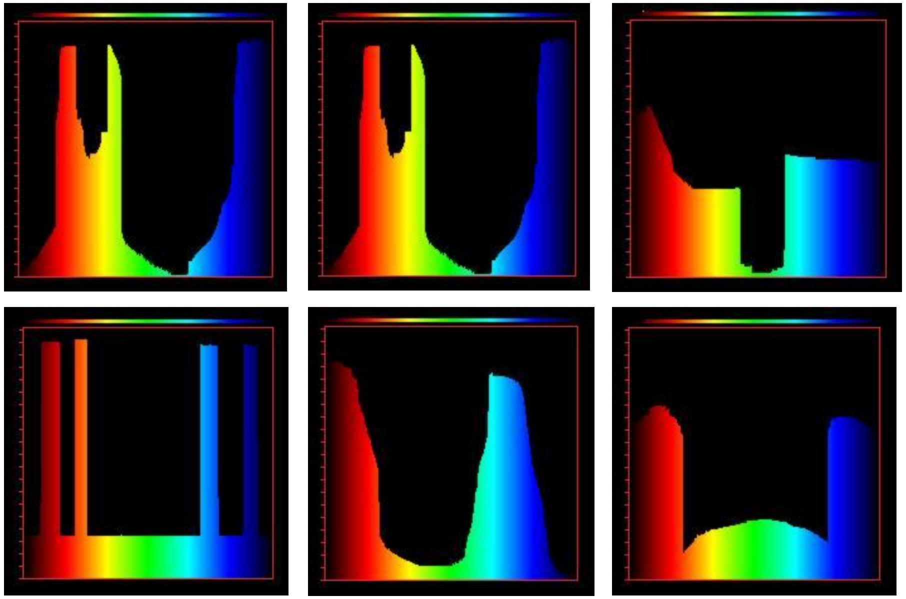


Can we use spectral energy distribution to represent color?

- Not really, different distribution might result in the same color (metamers)!

Spectral Energy Distribution

The six spectra below look the same purple to normal color-vision people



Color Representation?

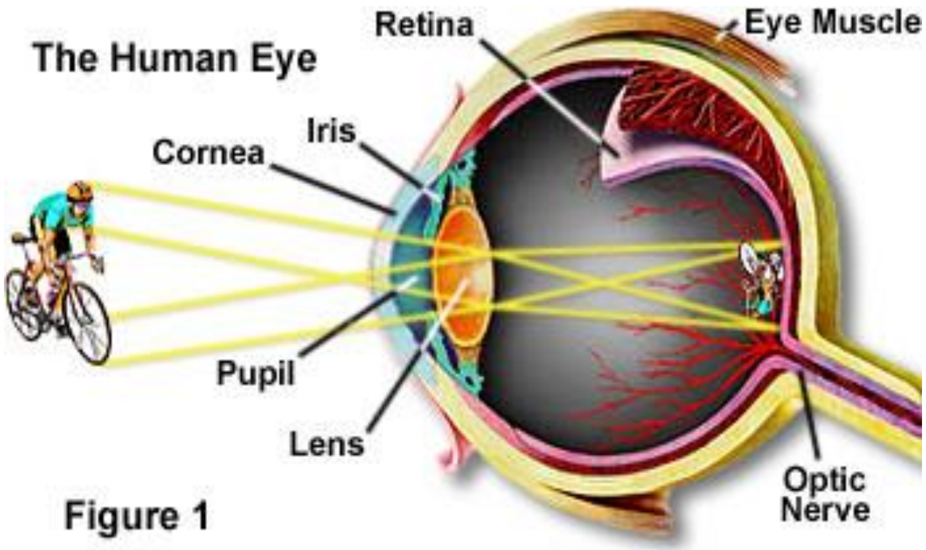
Why not all ranges of light spectrum are perceived?

So how to represent color?

Human Vision

Photoreceptor cells in the retina:

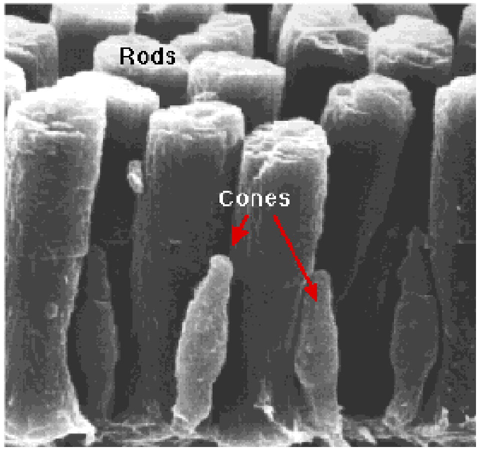
- Rods
- Cones



Light Detection: Rods and Cones

Rods:

-120 million rods in retina
-1000X more light sensitive than Cones
- Discriminate B/W brightness in low illumination
- Short wave-length sensitive

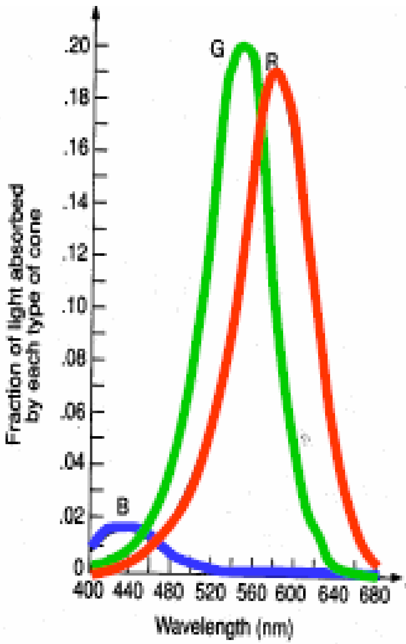


Cones:

- 6-7 million Cones in the retina
- Responsible for high-resolution vision
- Discriminate Colors
- Three types of color sensors (64% red, 32% green, 2% blue)
- Sensitive to any combination of three colors

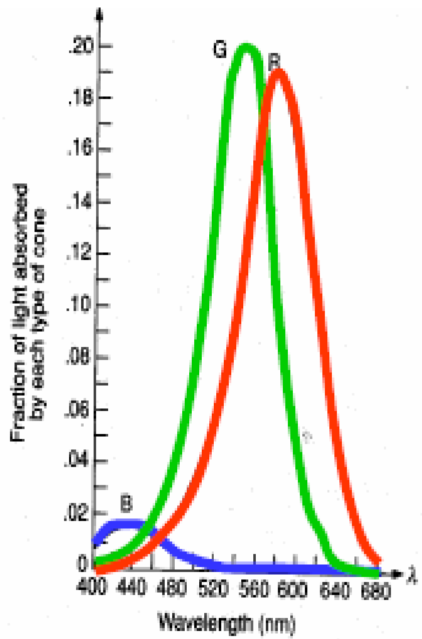
Tristimulus of Color Theory (Τριχρωματική Θεωρία)

Spectral-response functions of each of the three types of cones



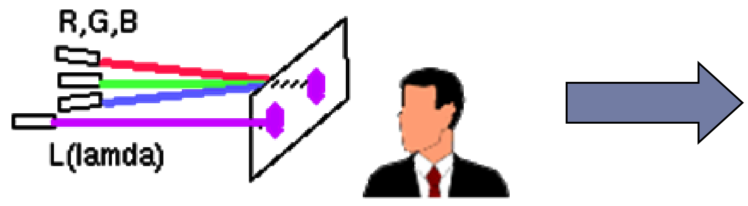
Tristimulus of Color Theory

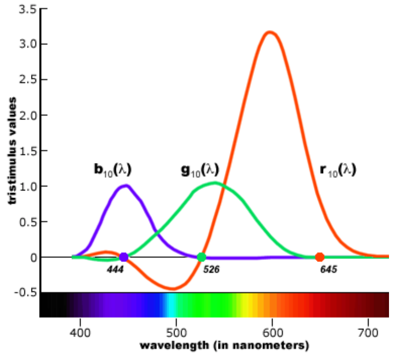
Spectral-response functions of each of the three types of cones



Color matching function based on RGB

- any spectral color can be represented as a linear combination of these primary colors





Tristimulus Color Theory

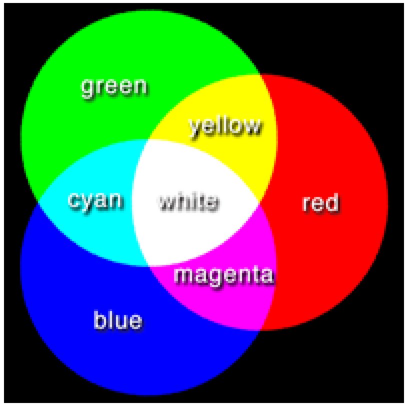
So, color is psychological

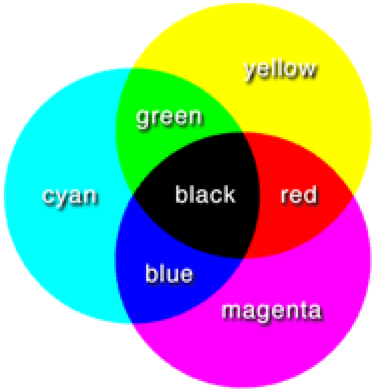
- Representing color as a linear combination of red, green, and blue is related to cones, not physics

- Most people have the same cones, but there are some people who don't – the sky might not look blue to them (although they will call it "blue" nonetheless)

- But many people (mostly men) are colorblind, missing 1,2 or 3 cones (can buy cheaper TVs)

Additive and Subtractive Color





RGB color model

White: $[1\ 1\ 1]^T$

Green: [0 1 0];

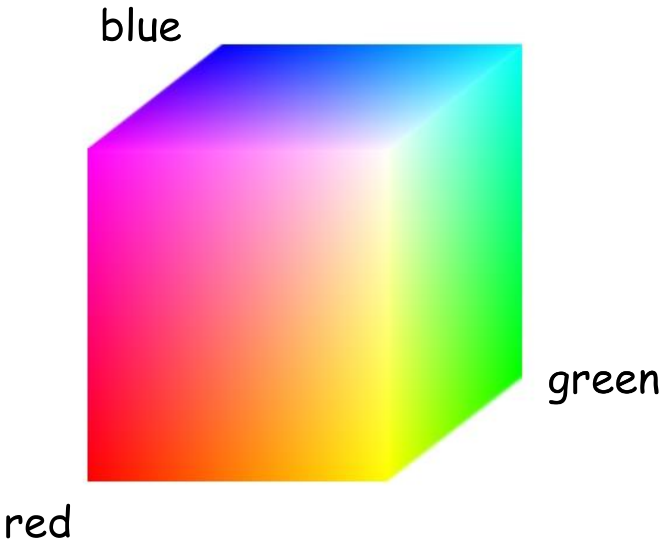
CMY color model

White: $[0\ 0\ 0]^T$

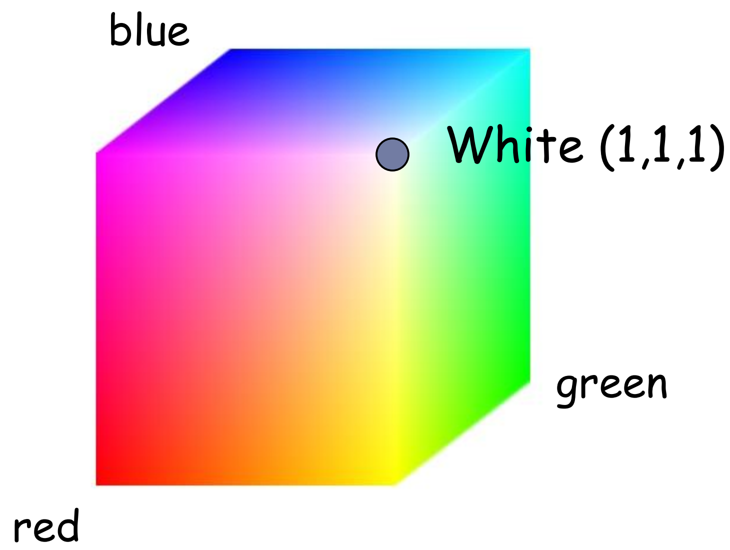
Green: [1 0 1];

Complementary color models: R=1-C; G = 1-M; B=1-Y;

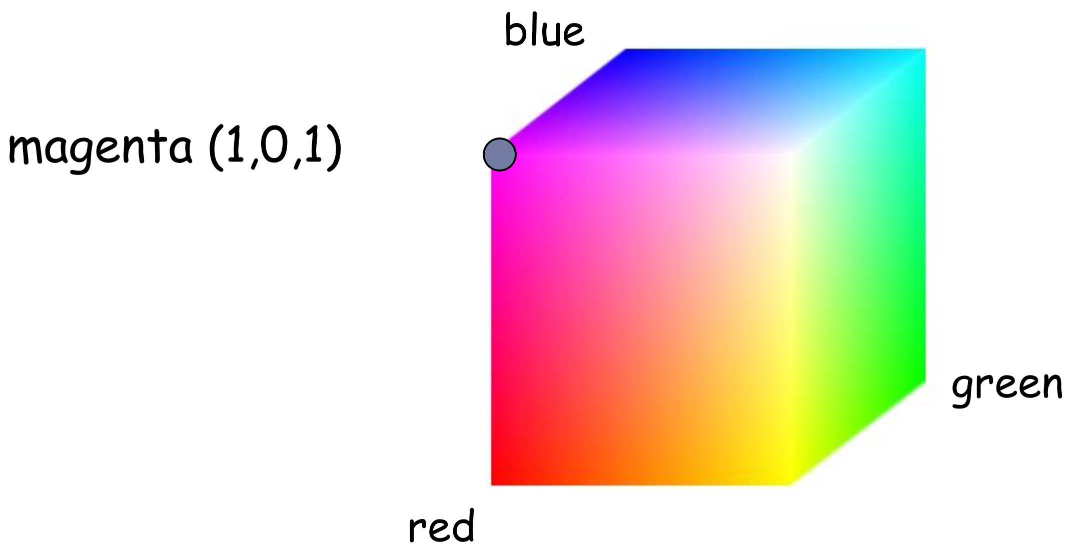
RGB Color Space



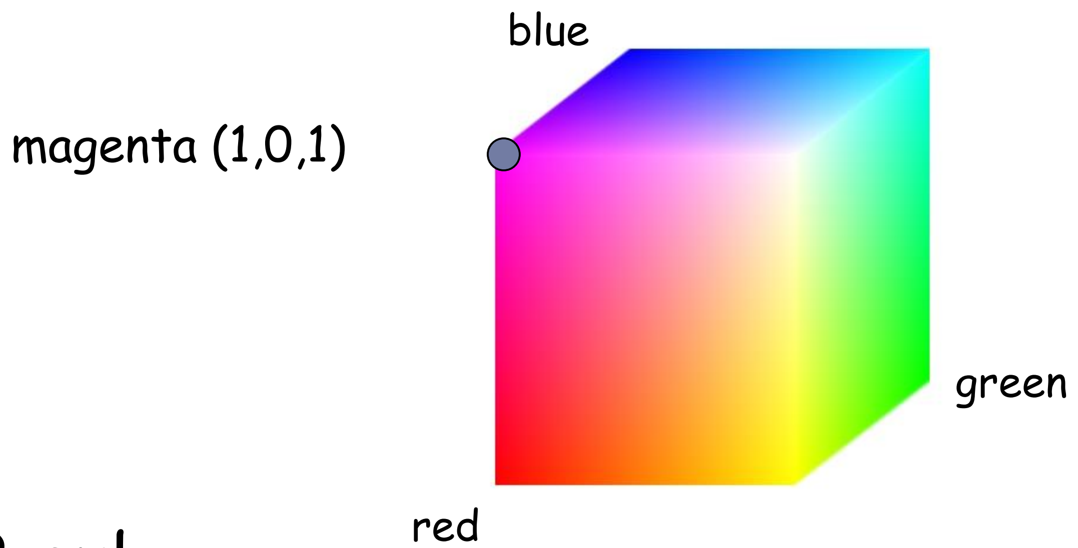
RGB Color Space



RGB Color Space



RGB Color Space



RGB cube

- Easy for devices
- Can represent all the colors?
- But not perceptual
- Where is brightness, hue and saturation?

Tristimulus

- Since 3 different cones, the space of colors is 3-dimensional.
- We need a way to describe color within this 3 dimensional space.
- We want something that will let us describe any visible color with additive combination…

The CIE XYZ system

- CIE – Comission Internationale de l'Eclairage
  - International Commission on Illumination
  - Sets international standards related to light
- Defined the XYZ color system as an international standard in 1931
- X, Y, and Z are three Primary colors.
  - imaginary colors
  - all visible colors can be defined as an **additive** combination of these three colors.
  - defines the 3 dimensional color space

Color Matching Functions

- Given an input spectrum, $p(\lambda)$, we want to find the X, Y, Z coordinates for that color.
- Color matching functions, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ tell how to weight the spectrum when integrating:

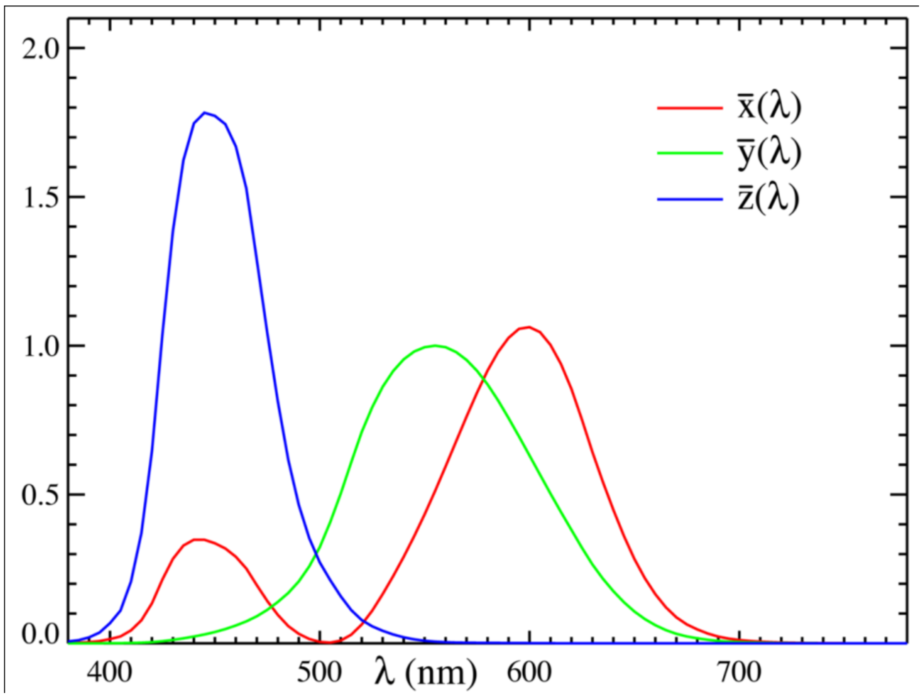


Image taken from http://upload.wikimedia.org/wikipedia/commons/8/87/CIE1931_XYZCMF.png

$$X = \int p(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int p(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int p(\lambda)\bar{z}(\lambda)d\lambda$$

XYZ space

- The visible colors form a "cone" in XYZ space.
  - For visible colors, X, Y, Z are all positive.
  - But, X, Y, and Z themselves are **not** visible colors!

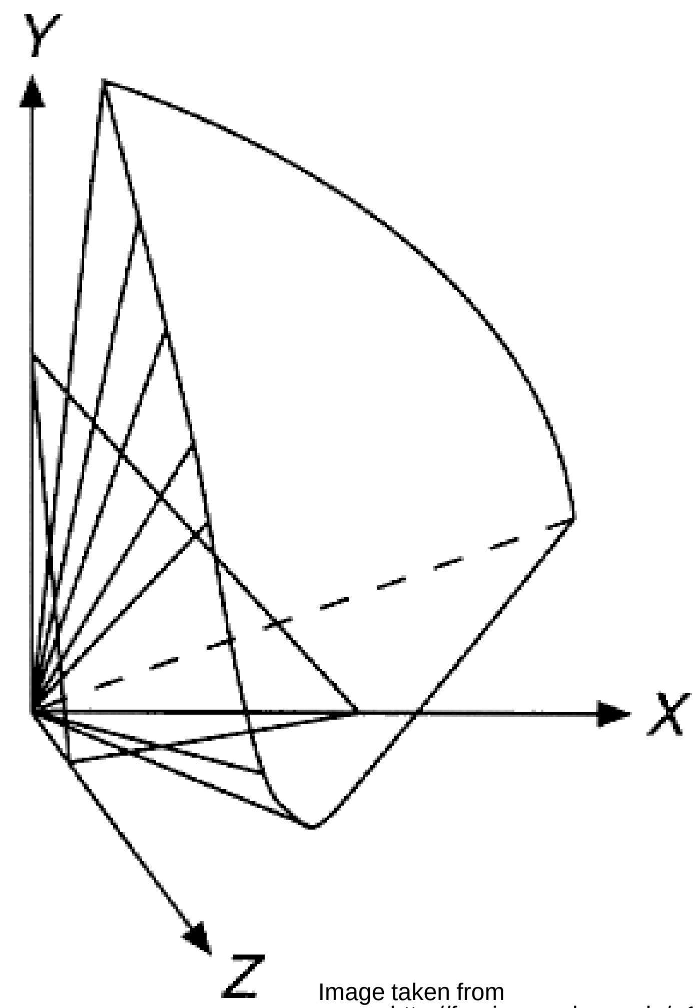


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Luminance and Chromaticity

- The intensity (**luminance**) is just X+Y+Z.
  συνολική φωτεινή ενέργεια
  - Scaling X, Y, Z just increases intensity.
  - We can separate this from the remaining part, **chromaticity** (χρωματικότητα).
- Color = Luminance + Chromaticity
  - Chromaticity is 2D, Luminance is 1D
- To help us understand chromaticity, we'll fix intensity to the X+Y+Z=1 plane.

Chromaticity Diagram

- Project the X+Y+Z=1 slice along the Z-axis
- Chromaticity is given by the x, y coordinates

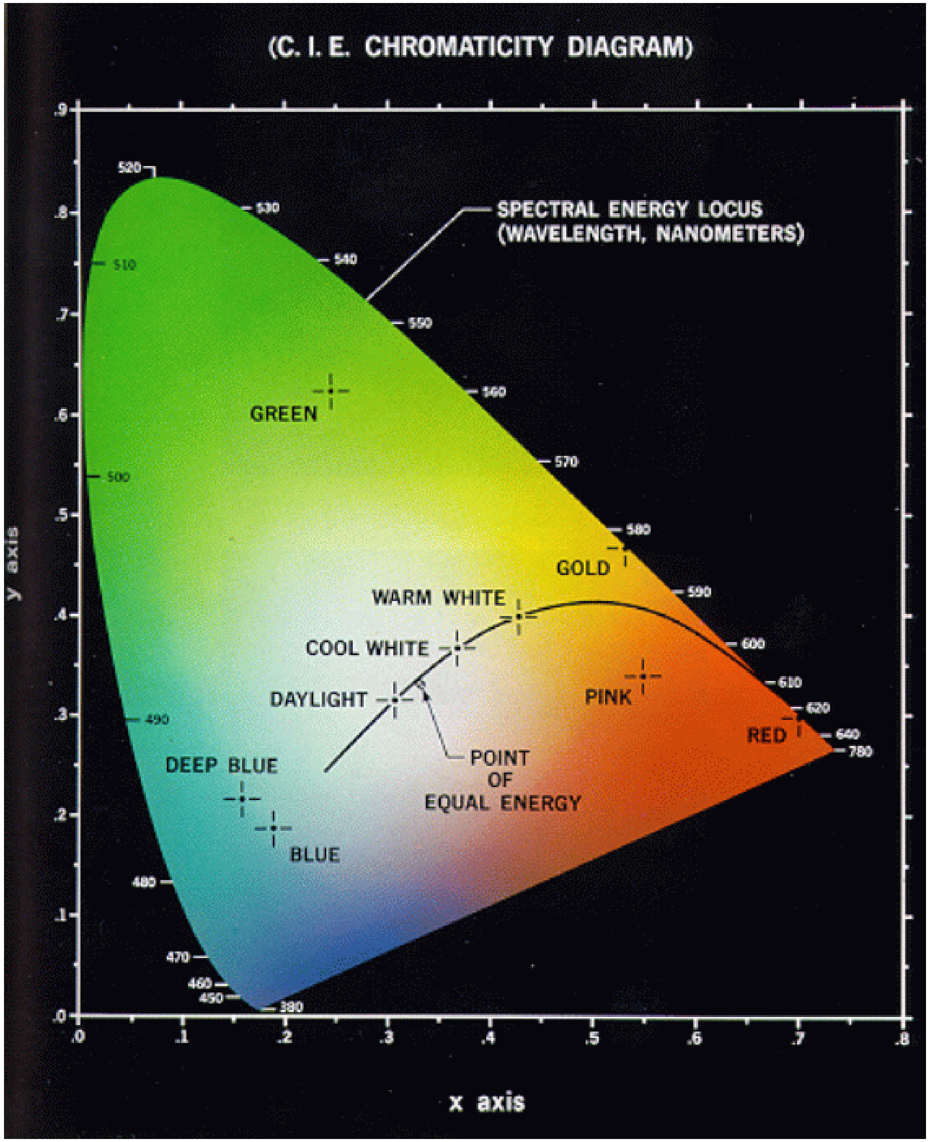


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Chromaticity Diagram

- Determining purity and dominant wave length for a given color
- Identify complementary colors
- Compare color gamut for different primaries

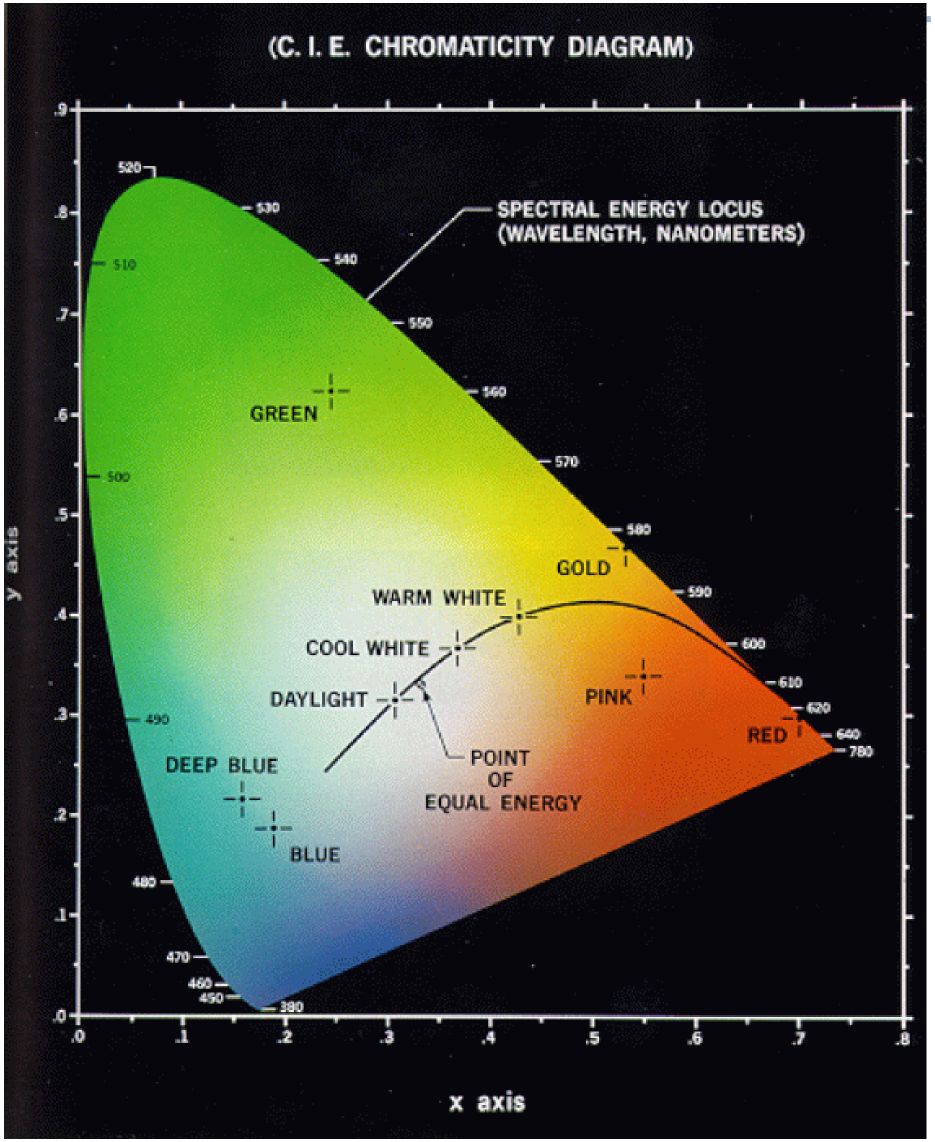


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

White Point

- White: at the center of the diagram.

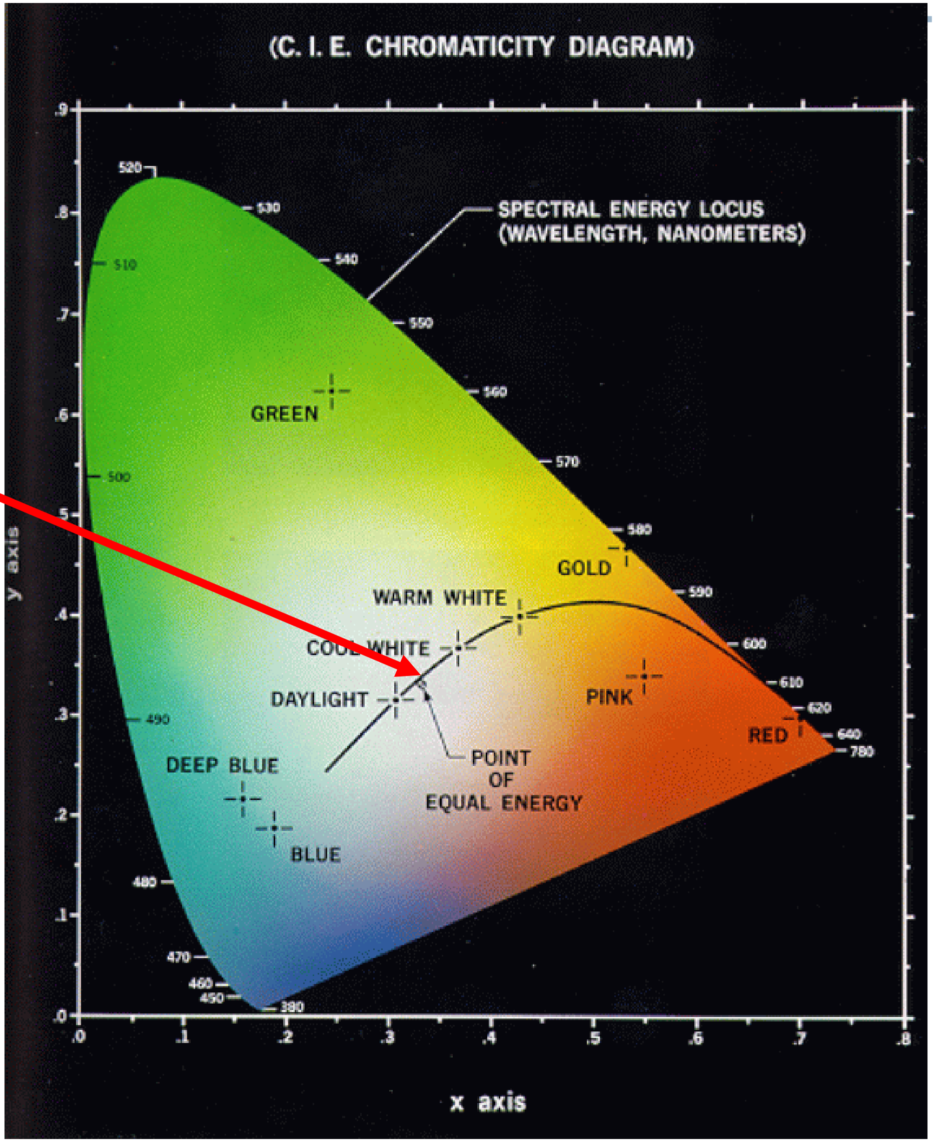


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Spectral Colors

- Visible Spectrum along outside curve

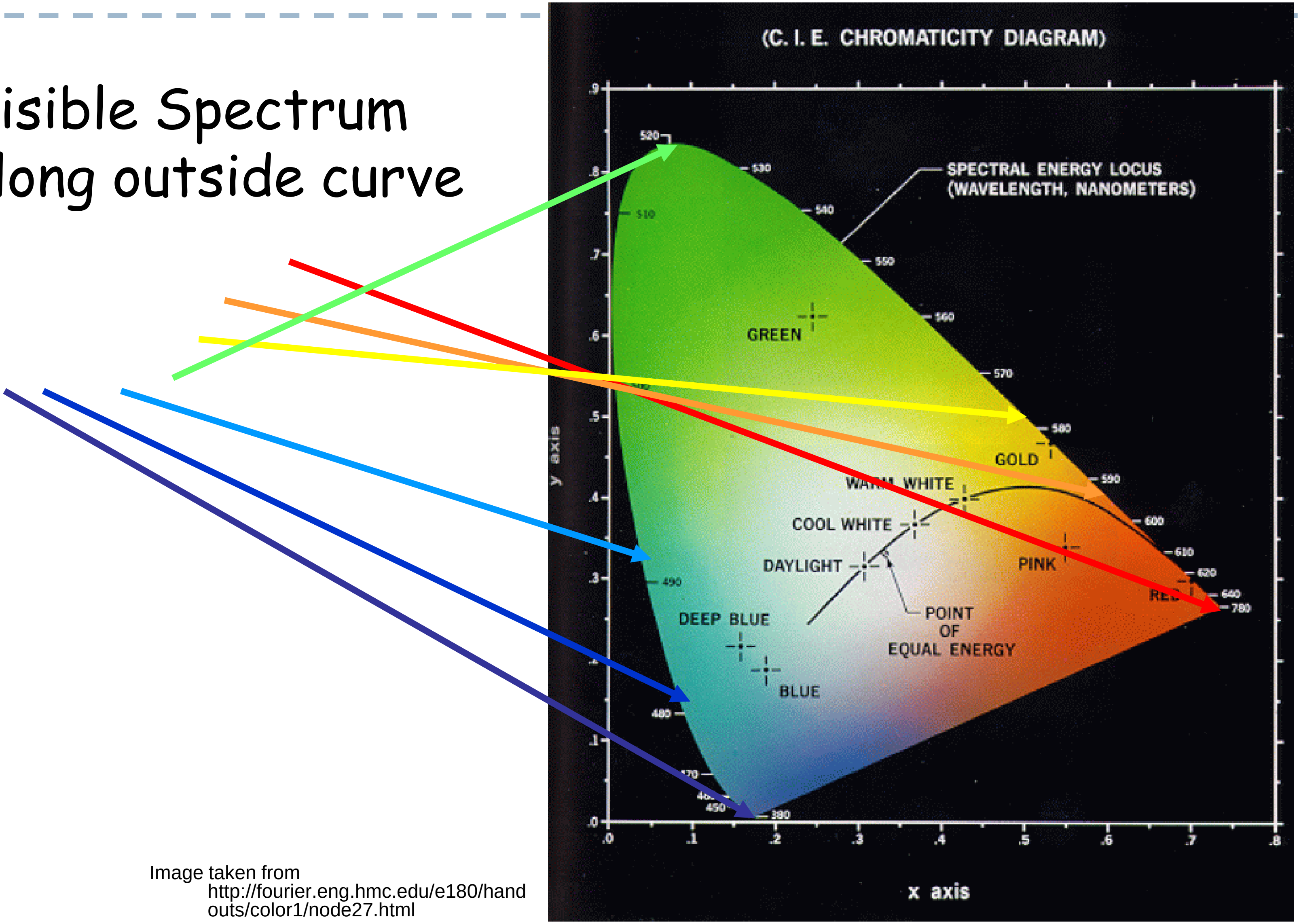


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Saturation/Purity (κορεσμός/καθαρότητα)

- As you move on line from white to edge, you increase the **saturation** of that color.
- Royal blue, red: high saturation
- Carolina blue, pink: low saturation

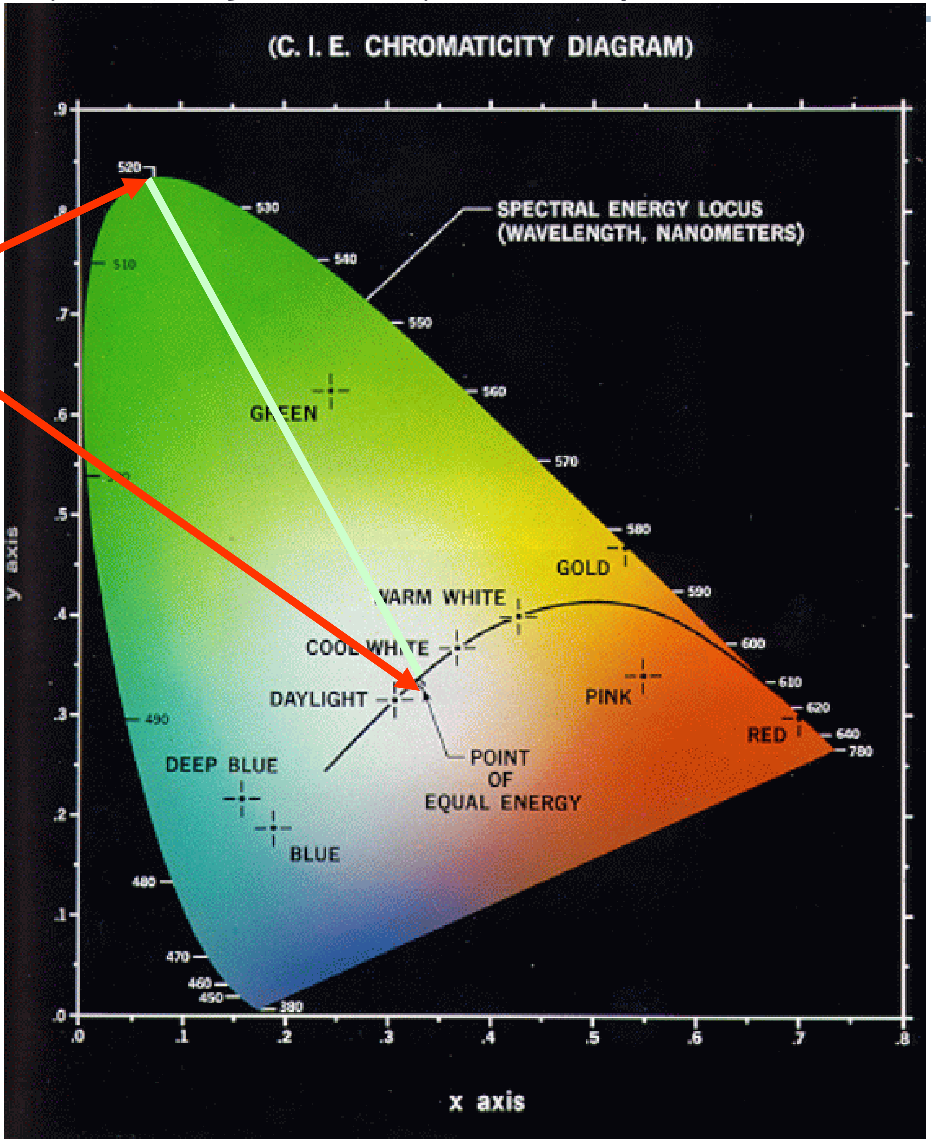


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Saturation/Purity

- How to compute the purity of this color?

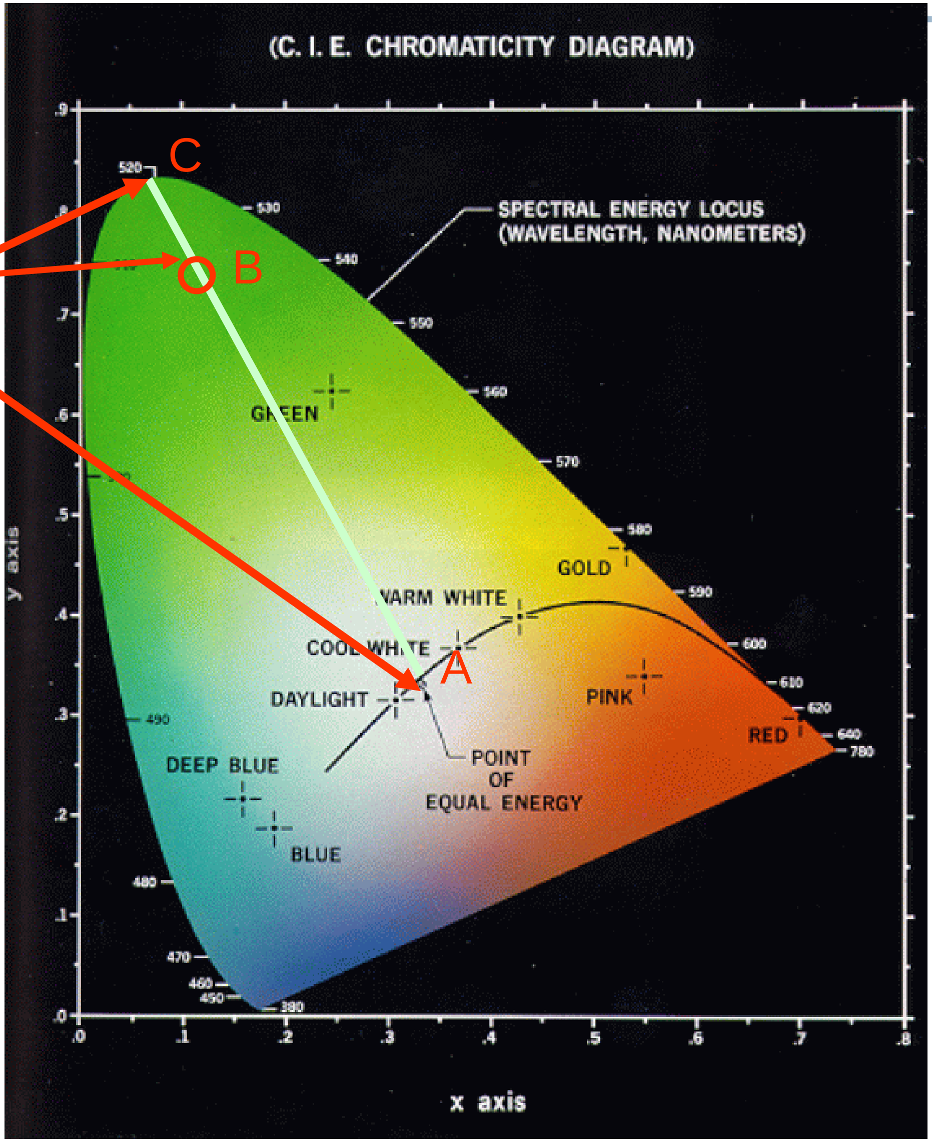


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Hue (απόχρωση)

- Hue is the "direction" from white.
- Combined with saturation, it gives another way to describe color
- Also called dominant wavelength

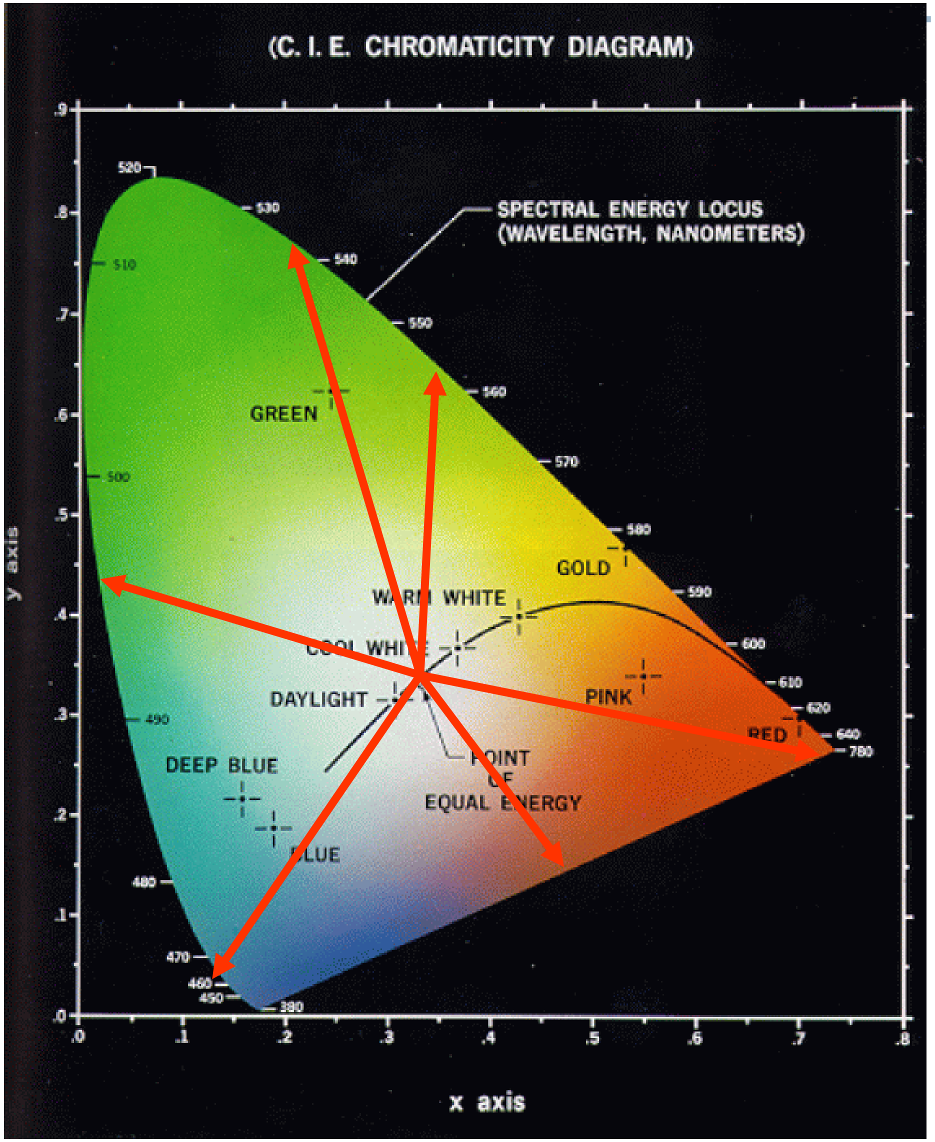


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Hue

- What's the dominant wavelength of this color?

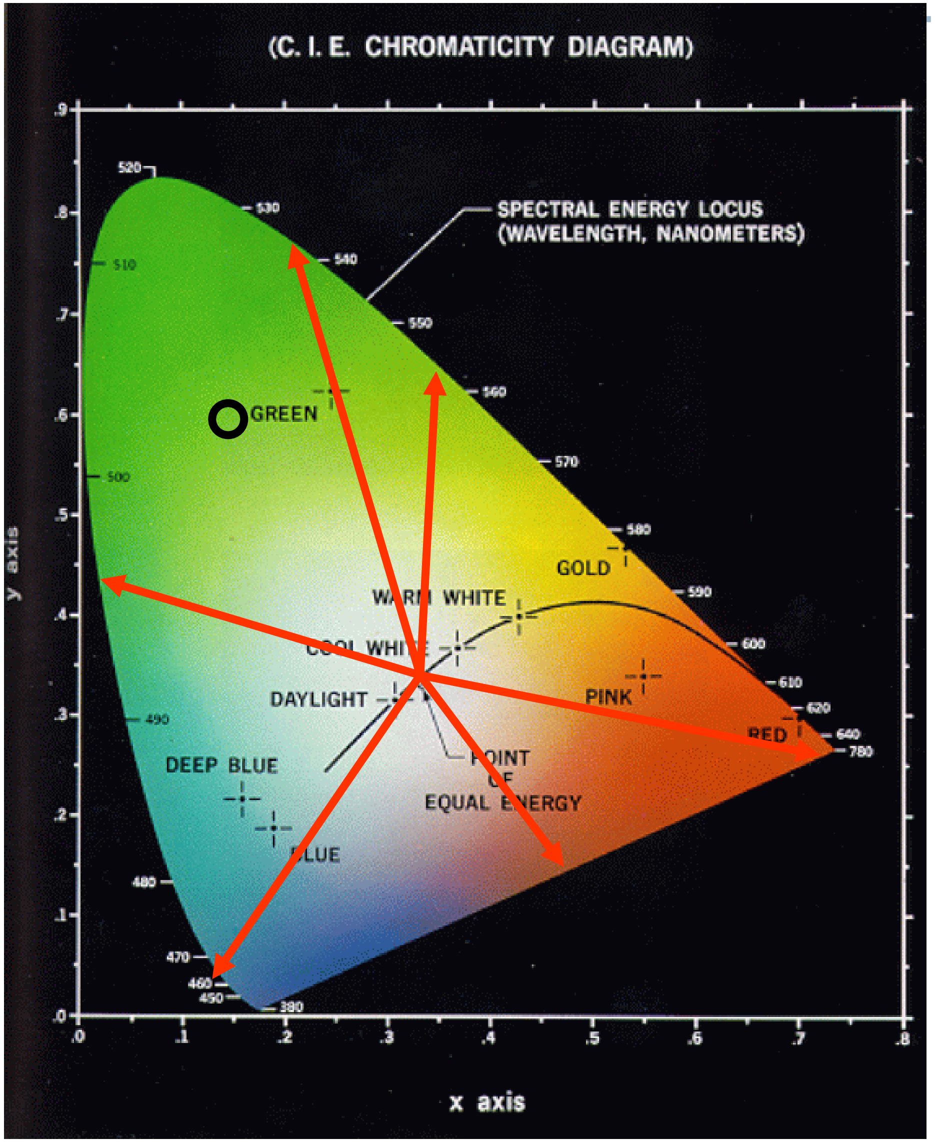


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Hue

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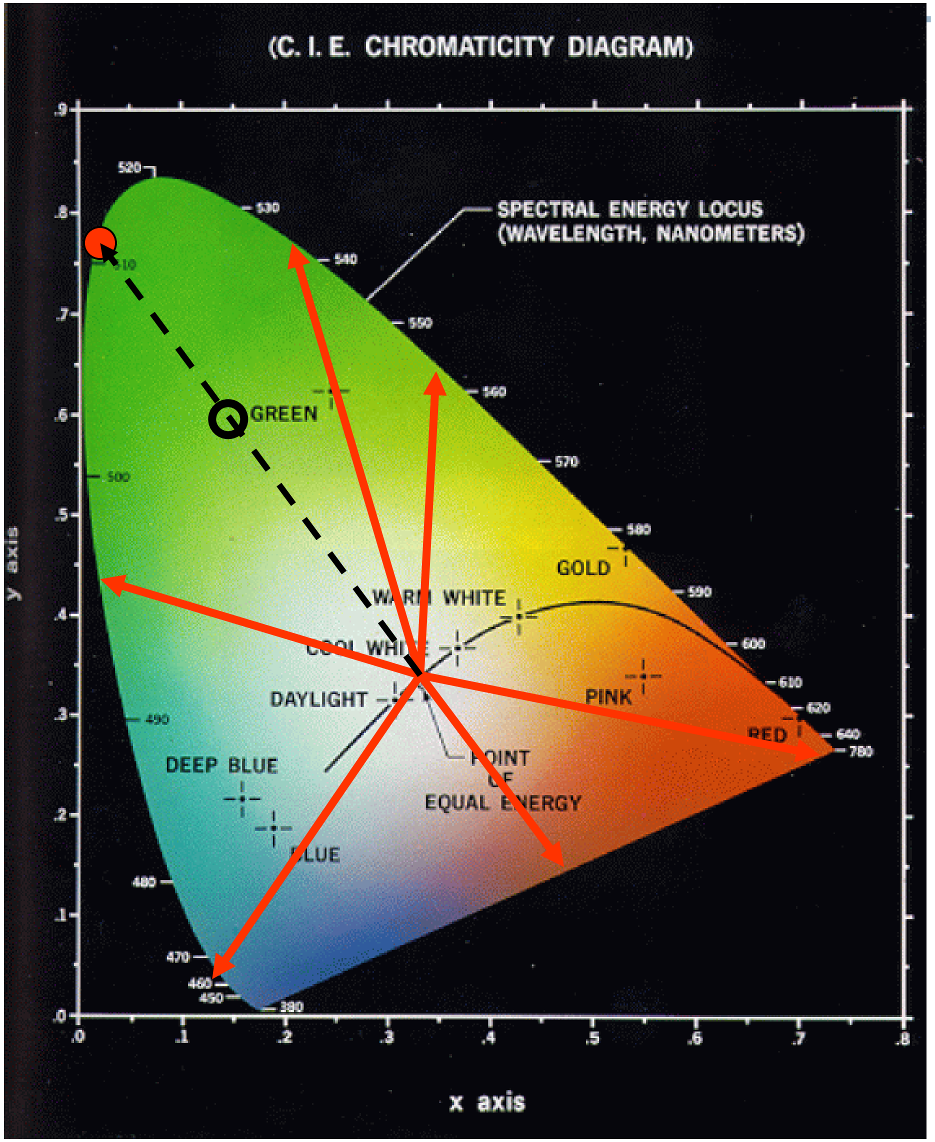

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Hue

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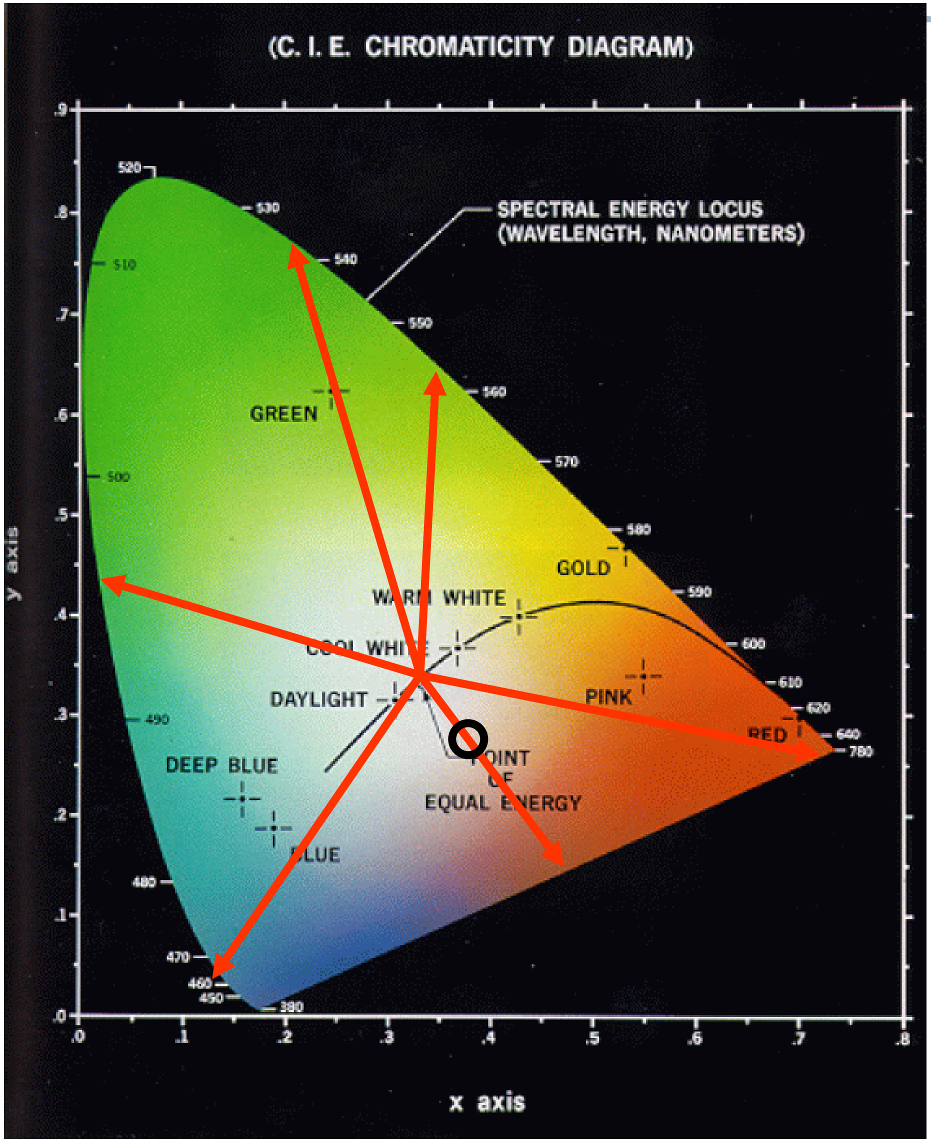

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Hue

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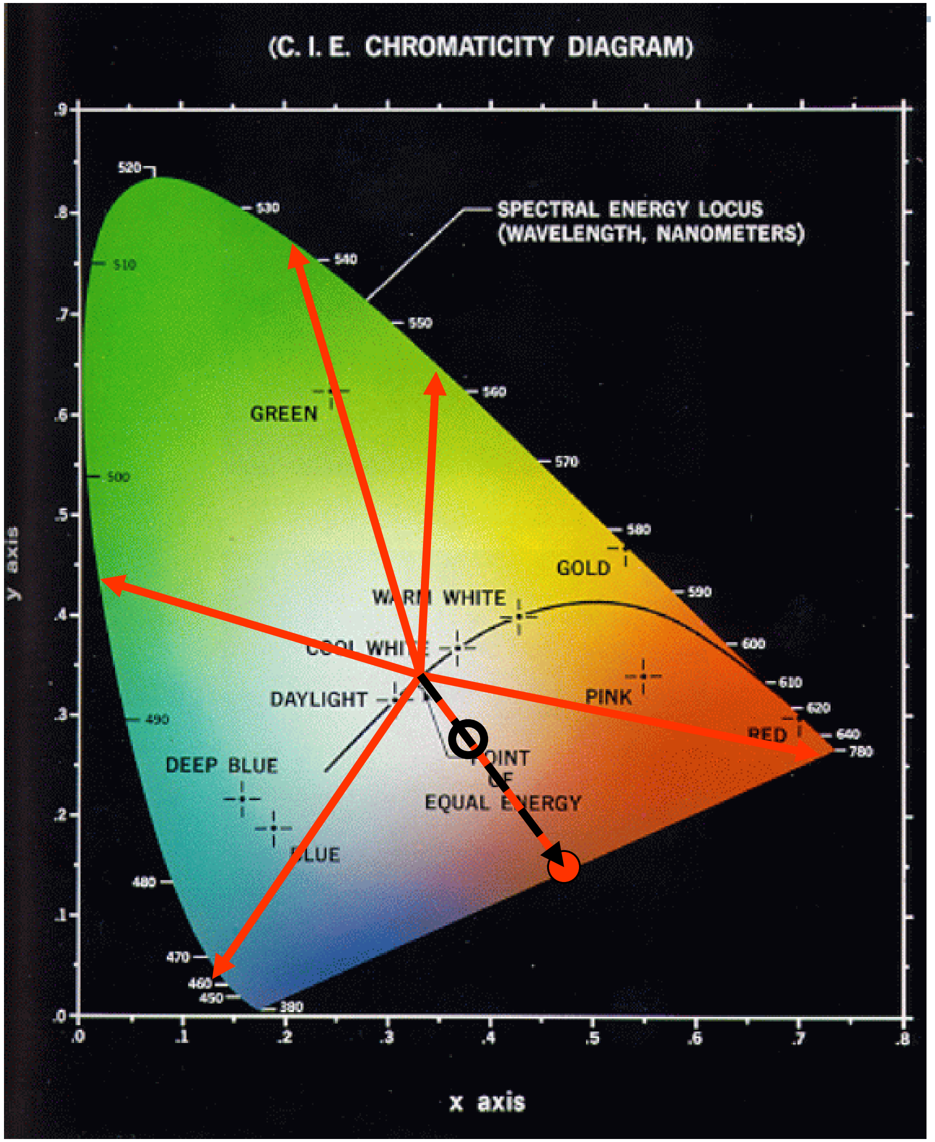


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Non-Spectral Colors

- Non-spectral colors: do not correspond to any wavelength of light.
  - i.e. not seen in rainbow
  - e.g. maroon, magenta

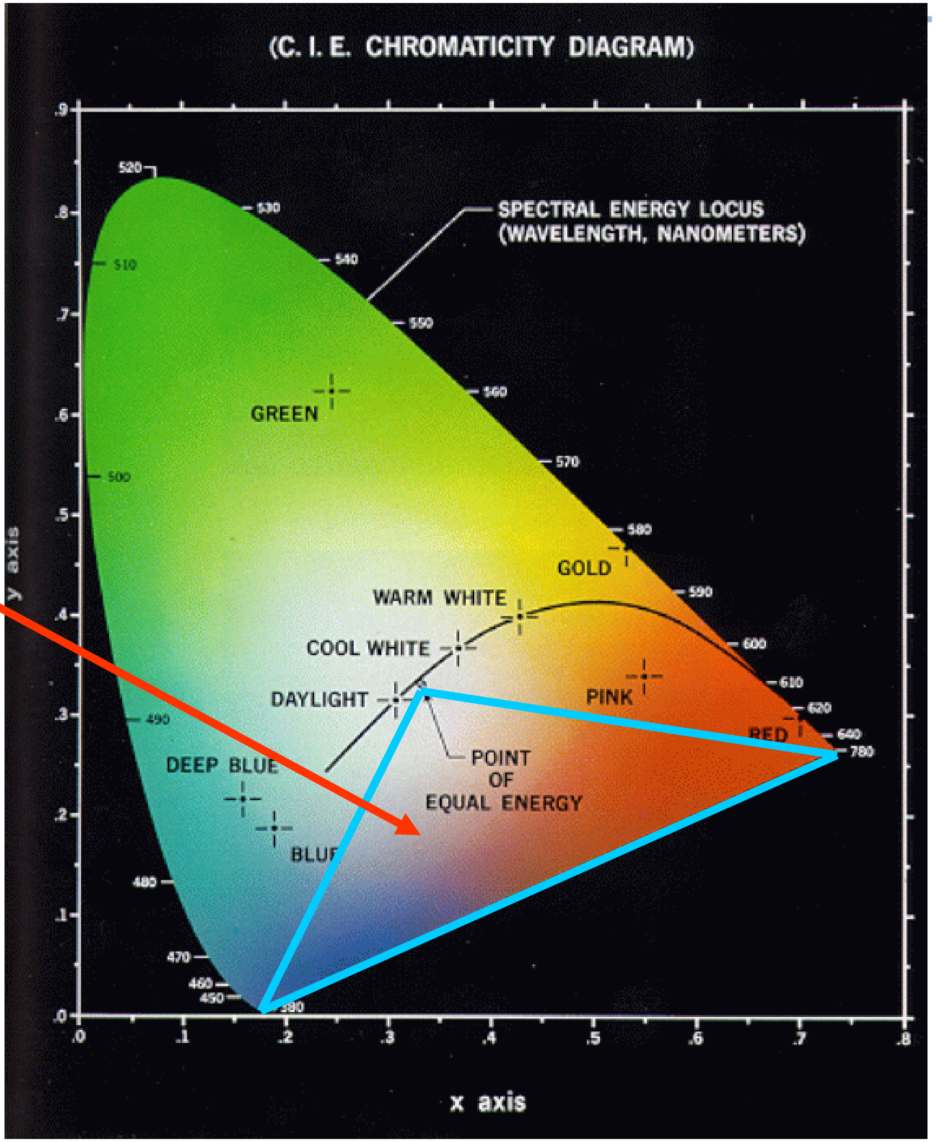


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Combining Two Colors

- If we have two colors, A and B, by varying the relative intensity, we can generate any color on the line between A and B.

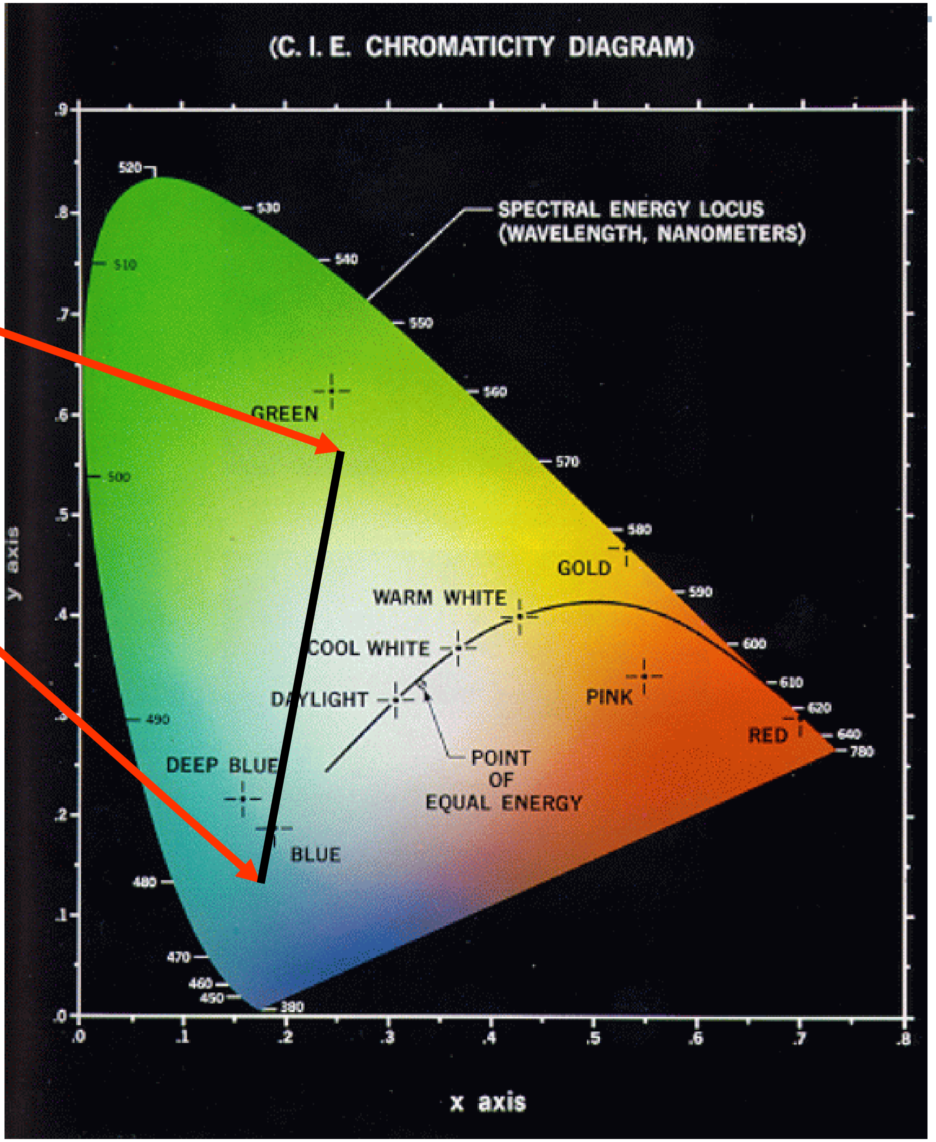
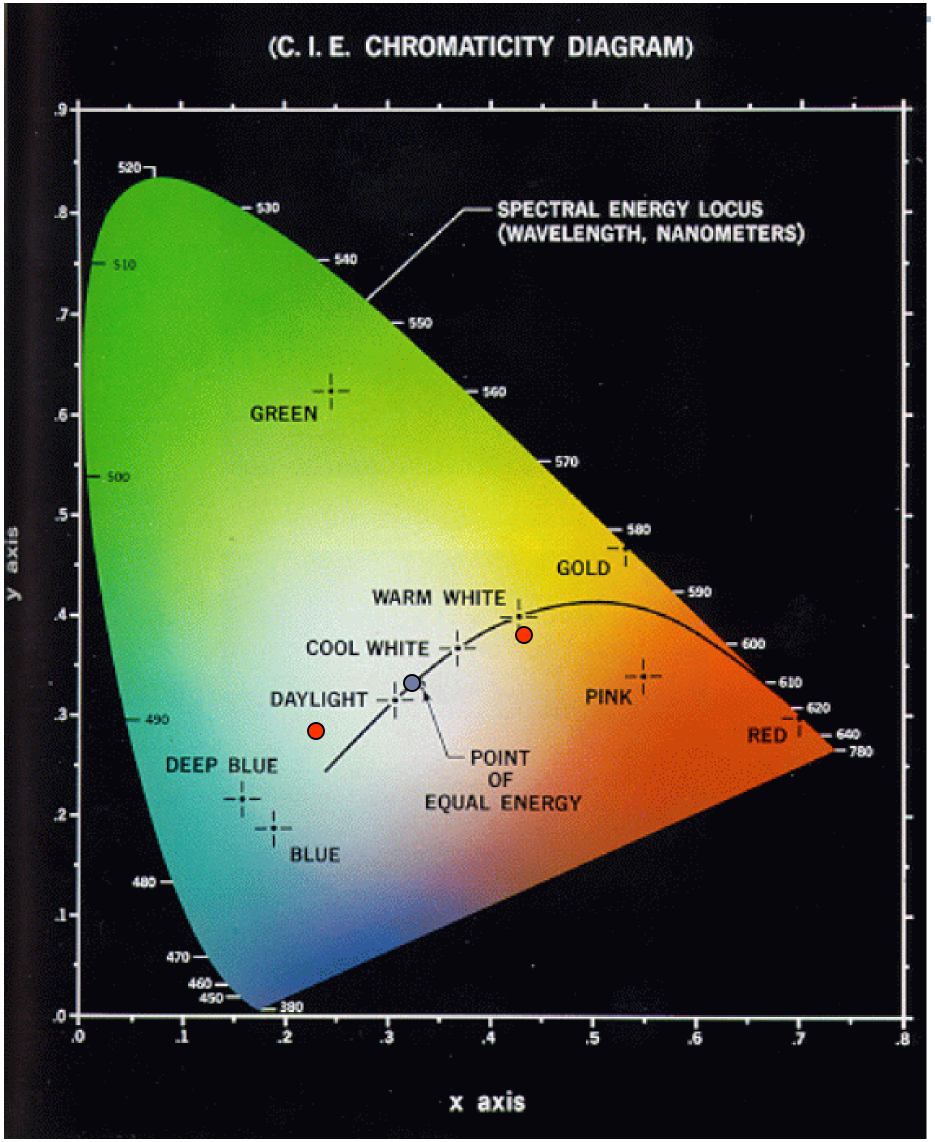


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Complementary Colors

- Complementary colors are those that will sum to white.
- That is, white is halfway between them.



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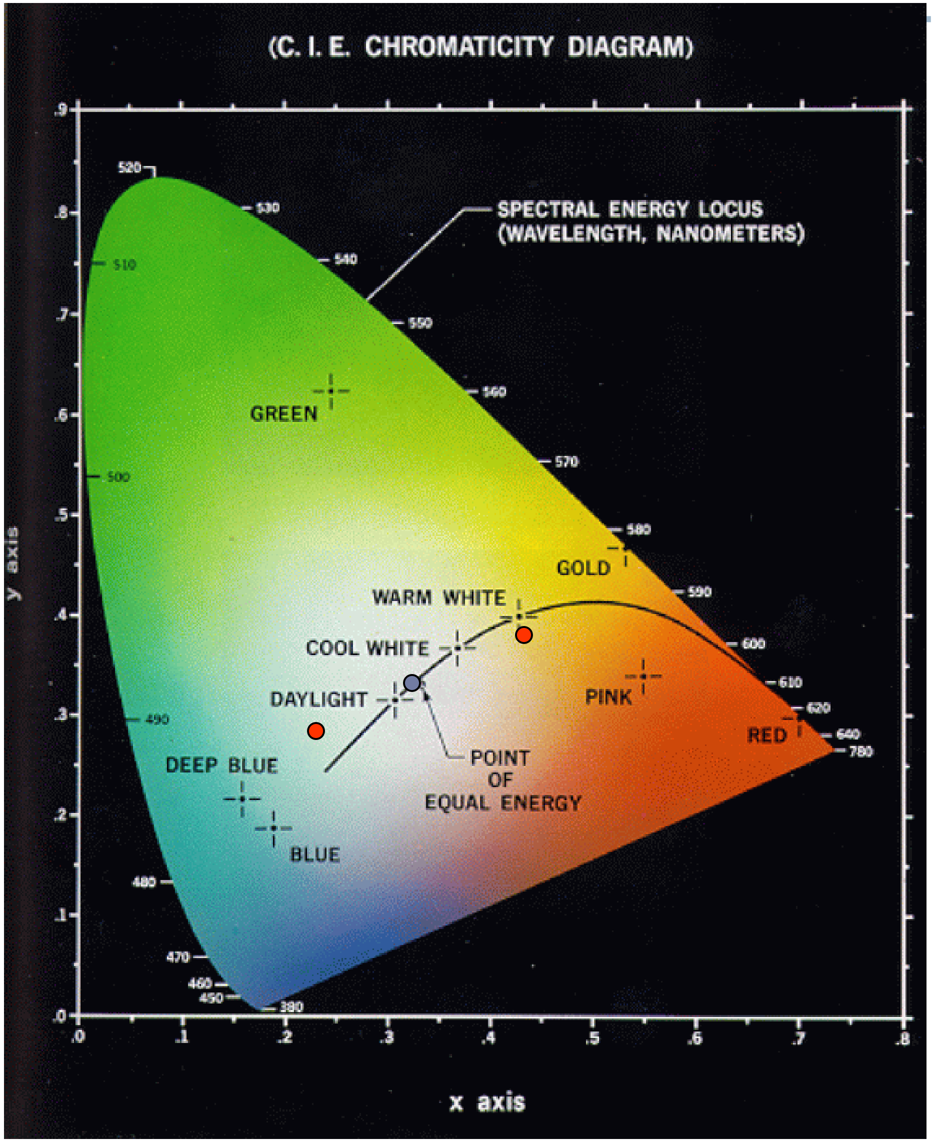


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Combining Three Colors

- If we have three colors, A, B, and C, by varying the relative intensity, we can generate any color in the triangle between them.

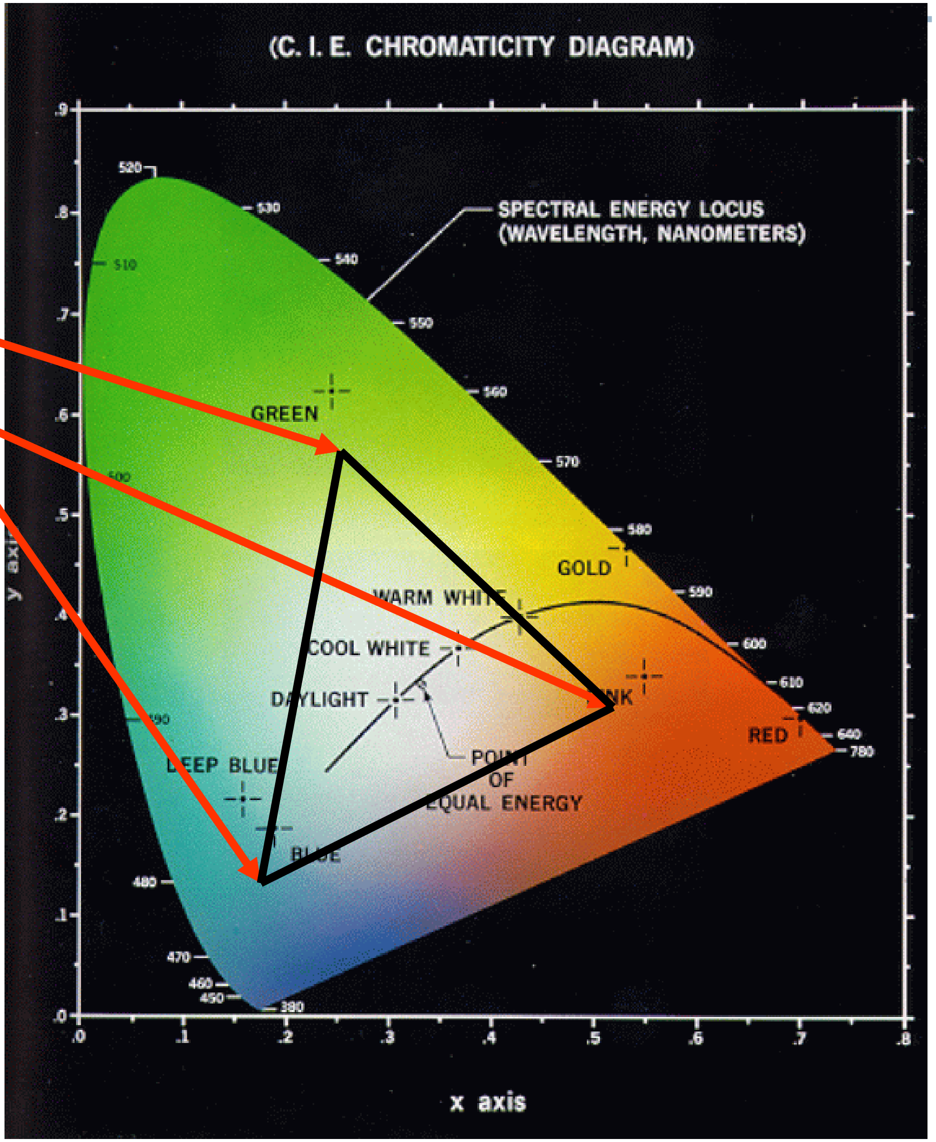


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Gamut (Γκάμα)

- Display devices generally have 3 colors (a few have more).
  - e.g. RGB in monitor
- The display can therefore display any color created from a combination of those 3.
- This range of displayable colors is called the **gamut** of the device.

Differing Gamuts

- Different devices have different gamuts
  - e.g. differing phosphors
- So, RGB on one monitor is **not** the same as RGB on another

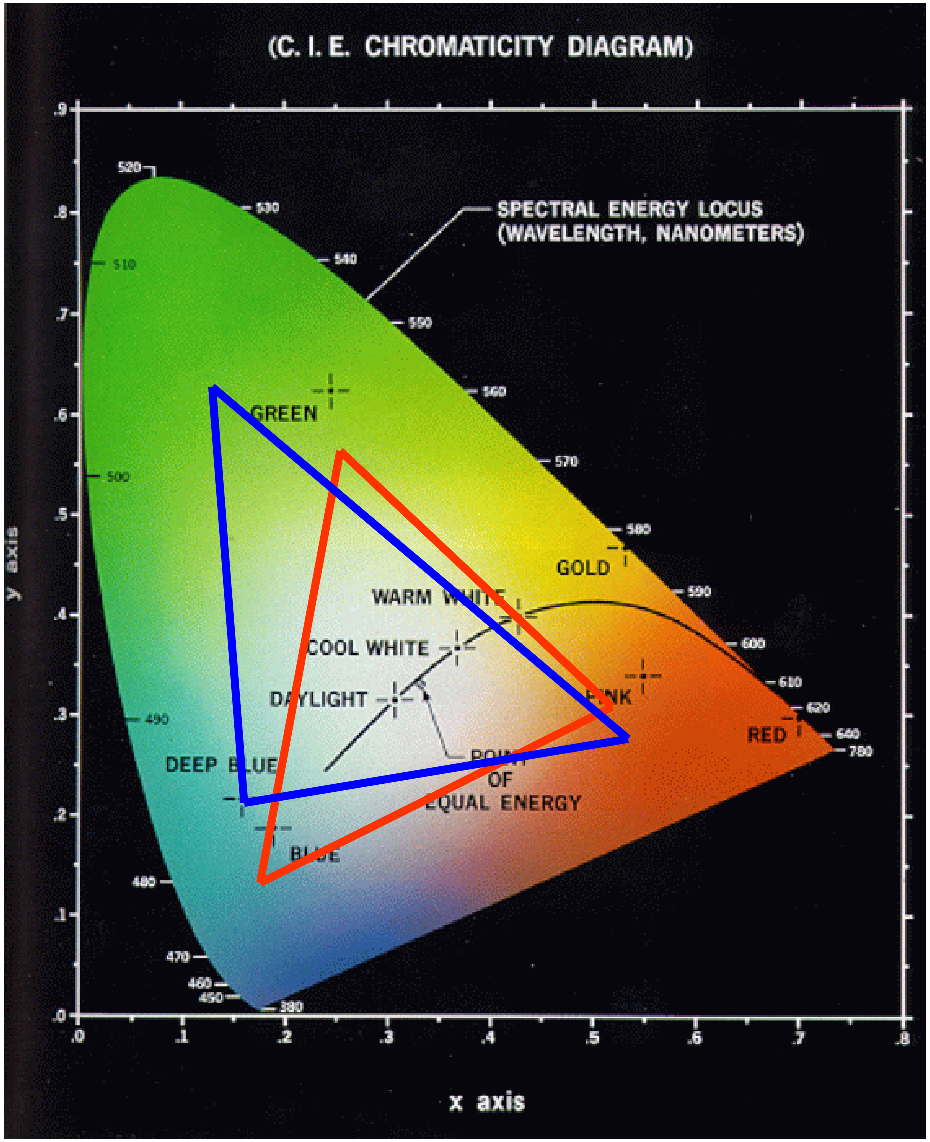
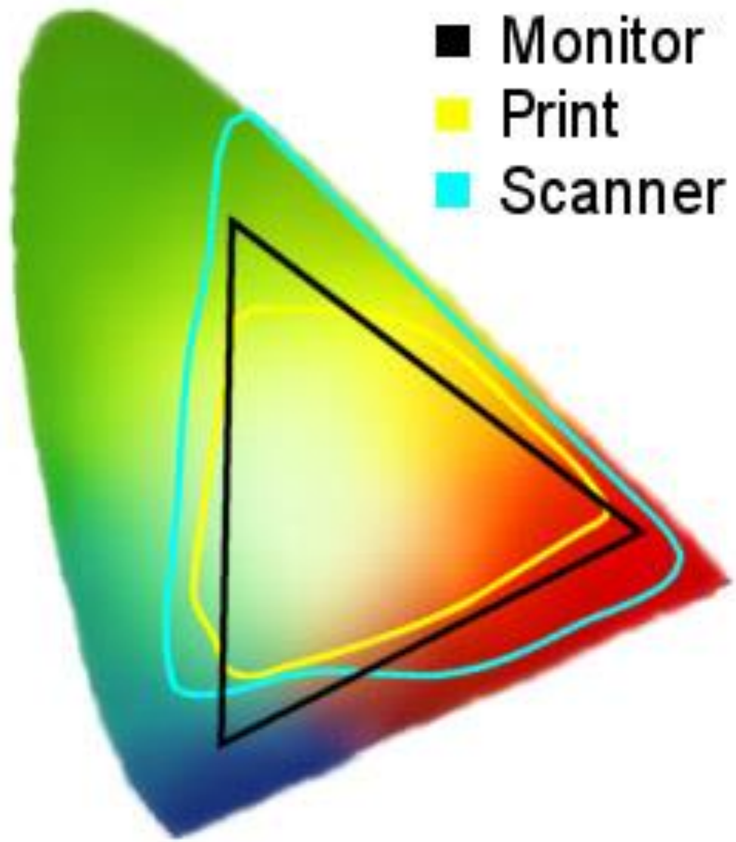


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Monitor/Print/Scanner Gamut



Device Gamuts

- For monitors, typically have colors in the Red, Green, Blue areas
  - Helps cover lots of visible spectrum
- But, not all (in fact, nowhere close to all) of the visible spectrum is ever represented
- Since all 3 colors are visible, can't possibly encompass full visible spectrum!

Gamuts

- Red: typical monitor gamut
- Blue: maximum gamut with 3 phosphors

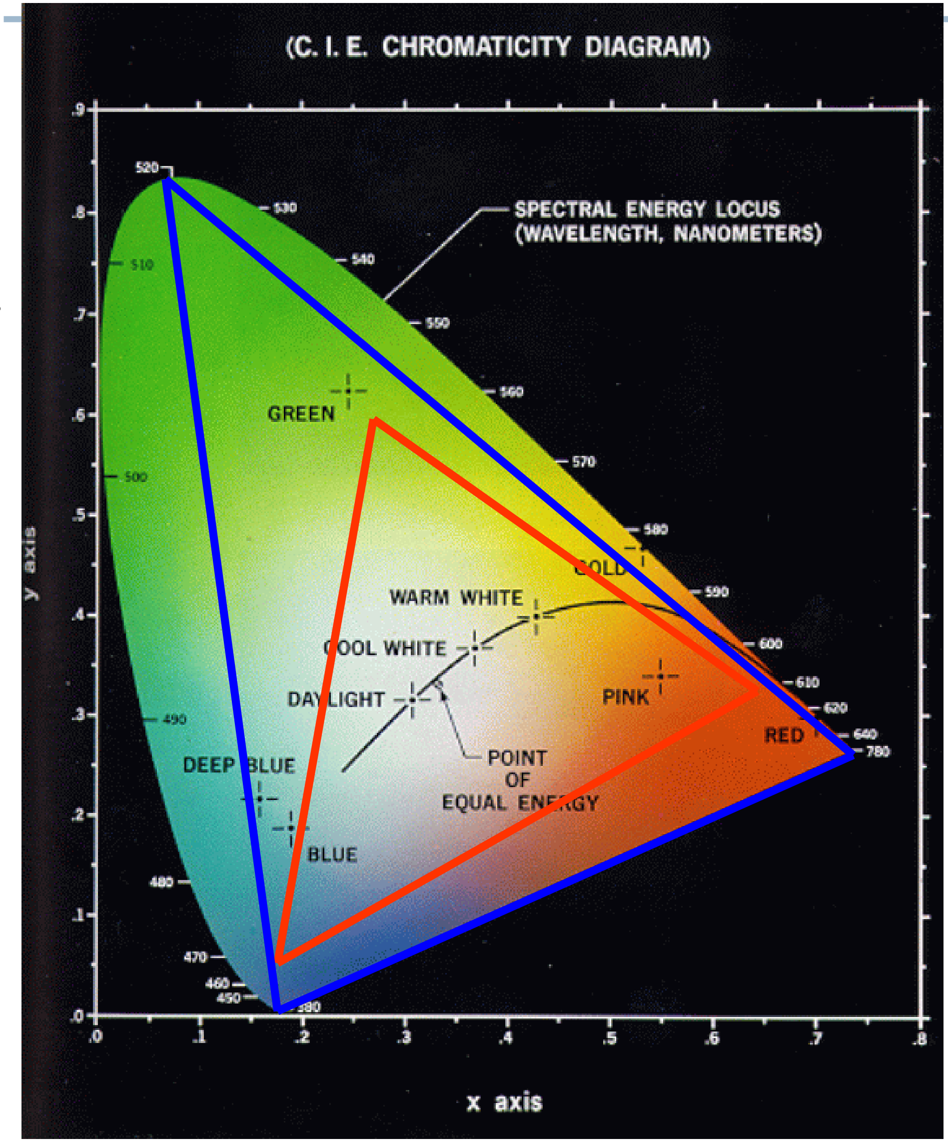


Image taken from http://fourier.eng.hmc.edu/e180/handouts/color1/node27.html

Color Models

Color Models

- CIE's XYZ system is a standard, but not very intuitive.
- As we saw with saturation and hue, there's more than one way to specify a color.
- A variety of color models have been developed to help with some specifications.

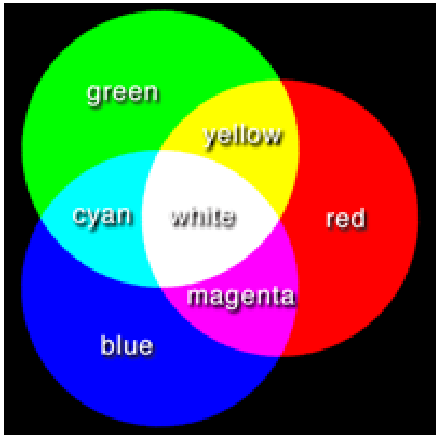
RGB

- Red, Green, Blue

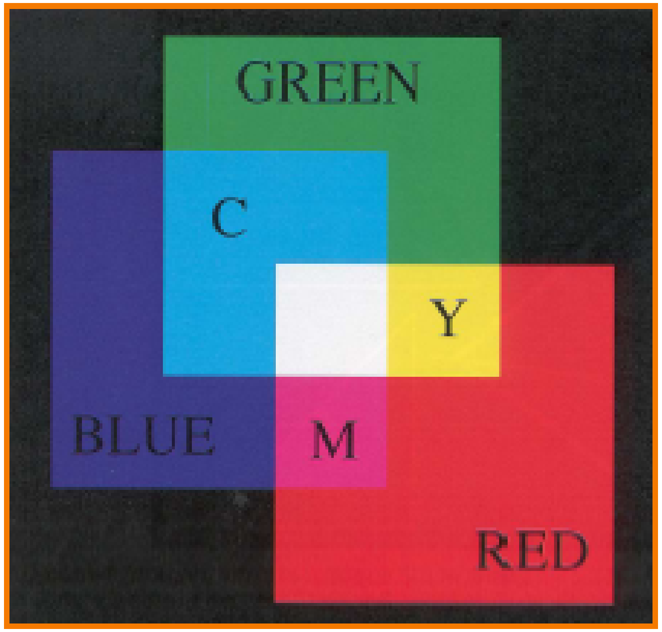
- Common specifications for most monitors
  - Tells how much intensity to use for pixels

- Note: Not standard – RGB means different things for different monitors

- Generally used in an *additive* system
  - Each adds additional light (e.g. phosphor)
  - Combine all three colors to get white



RGB color model

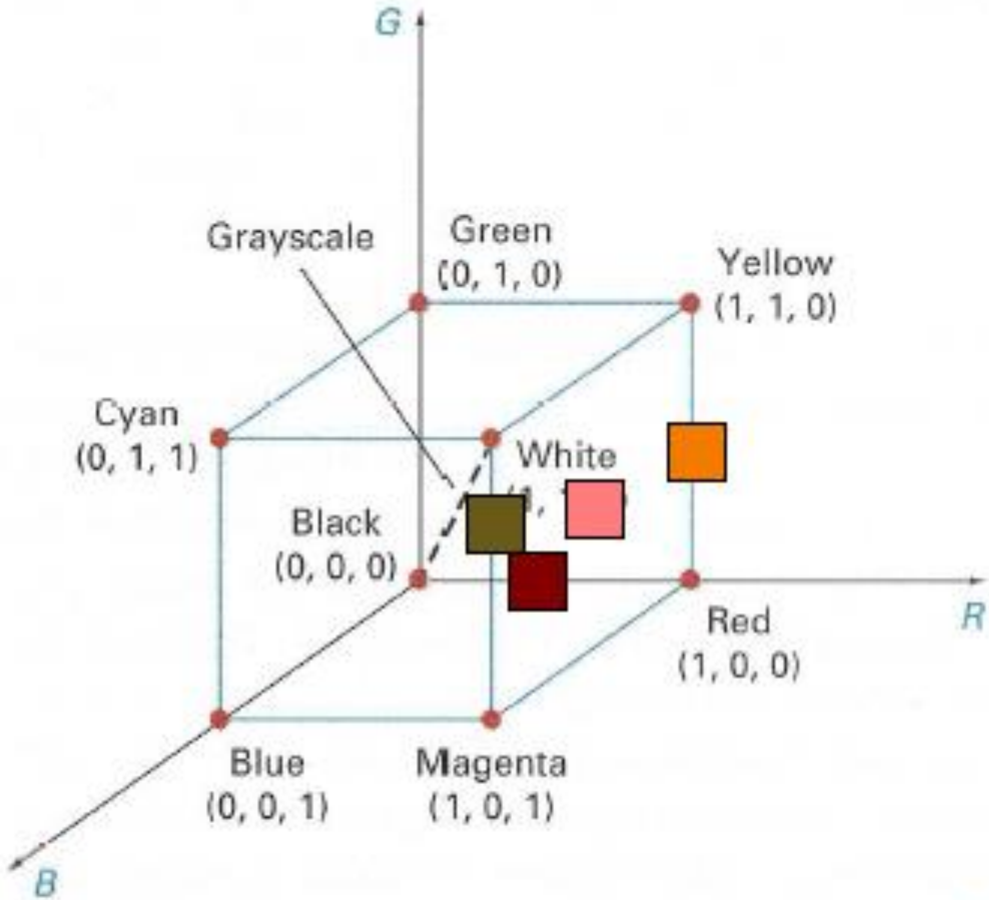


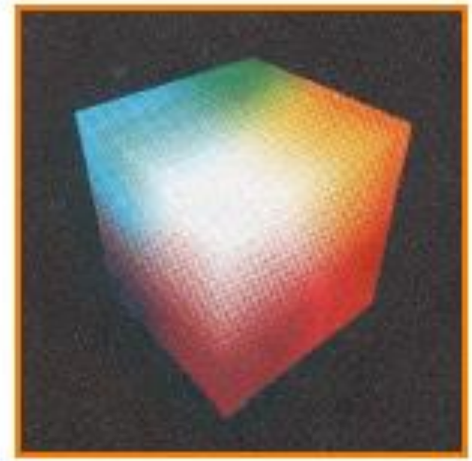
Colors are additive

R	G	B	Color
0.0	0.0	0.0	Black
1.0	0.0	0.0	Red
0.0	1.0	0.0	Green
0.0	0.0	1.0	Blue
1.0	1.0	0.0	Yellow
1.0	0.0	1.0	Magenta
0.0	1.0	1.0	Cyan
1.0	1.0	1.0	White
0.5	0.0	0.0	?
1.0	0.5	0.5	?
1.0	0.5	0.0	?
0.5	0.3	0.1	?

Plate II.3 from FvDFH

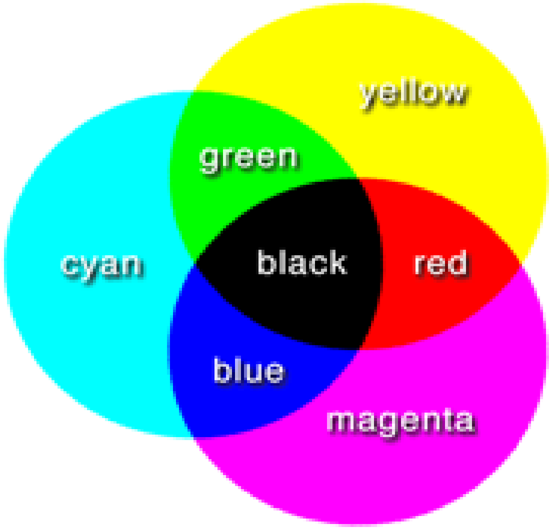
RGB Color Cube





Figures 15.11&15.12 from H&B

CMY



- Cyan, Magenta, Yellow
- Commonly used in printing
- Generally used in a *subtractive* system:
  - Each removes color from *reflected* light
  - Combine all three colors to get black
- Conceptually, [C M Y] = [1 1 1] – [R G B]
  - Complimentary colors to RGB

CMYK

- Cyan, Magenta, Yellow, Black
- Comes from printing process – since CMY combine to form black, can replace equal amounts of CMY with Black, saving ink.
- $K = \min(C, M, Y)$

  $C = C-K$

  $M = M-K$

  $Y = Y-K$

YIQ / YUV

- NTSC, PAL standards for broadcast TV
- Backward compatible to Black and White TV
- Y is luminance – only part picked up by Black and White Televisions
- Y is given most bandwith in signal
- I, Q channels (or U,V) contain chromaticity information

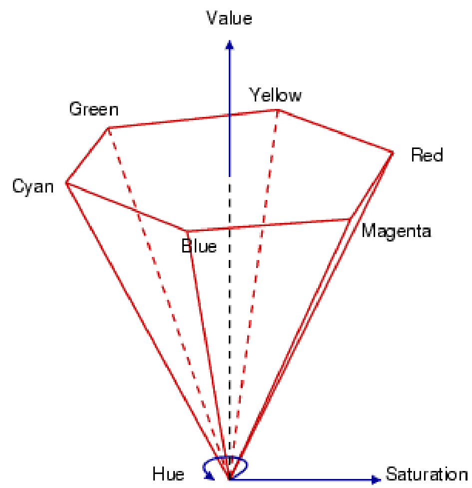
HSV Color Model

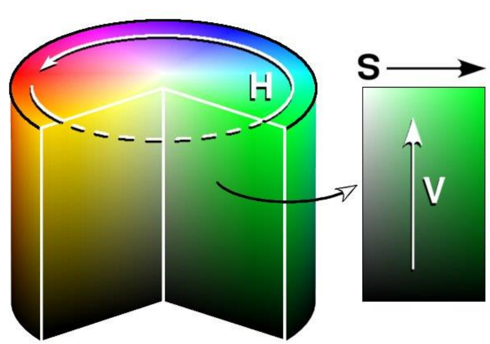
Perceptually appropriate:

- Hue: the color type (0-360 deg); angle from the cone
- Saturation: the purity of the color (0-100%); how far from the center
- Value (luminance): the brightness of color (0-100%); how high up cone

Nonlinear transform between the HSV and RGB space

- see section 12.7.3 in H&B





HLS

- Hue, Lightness, Saturation

  απόχρωση, φωτεινότητα, κορεσμός
- A variation on HSV, but with a double cone
- Lightness: black at base (0), white at top (1)

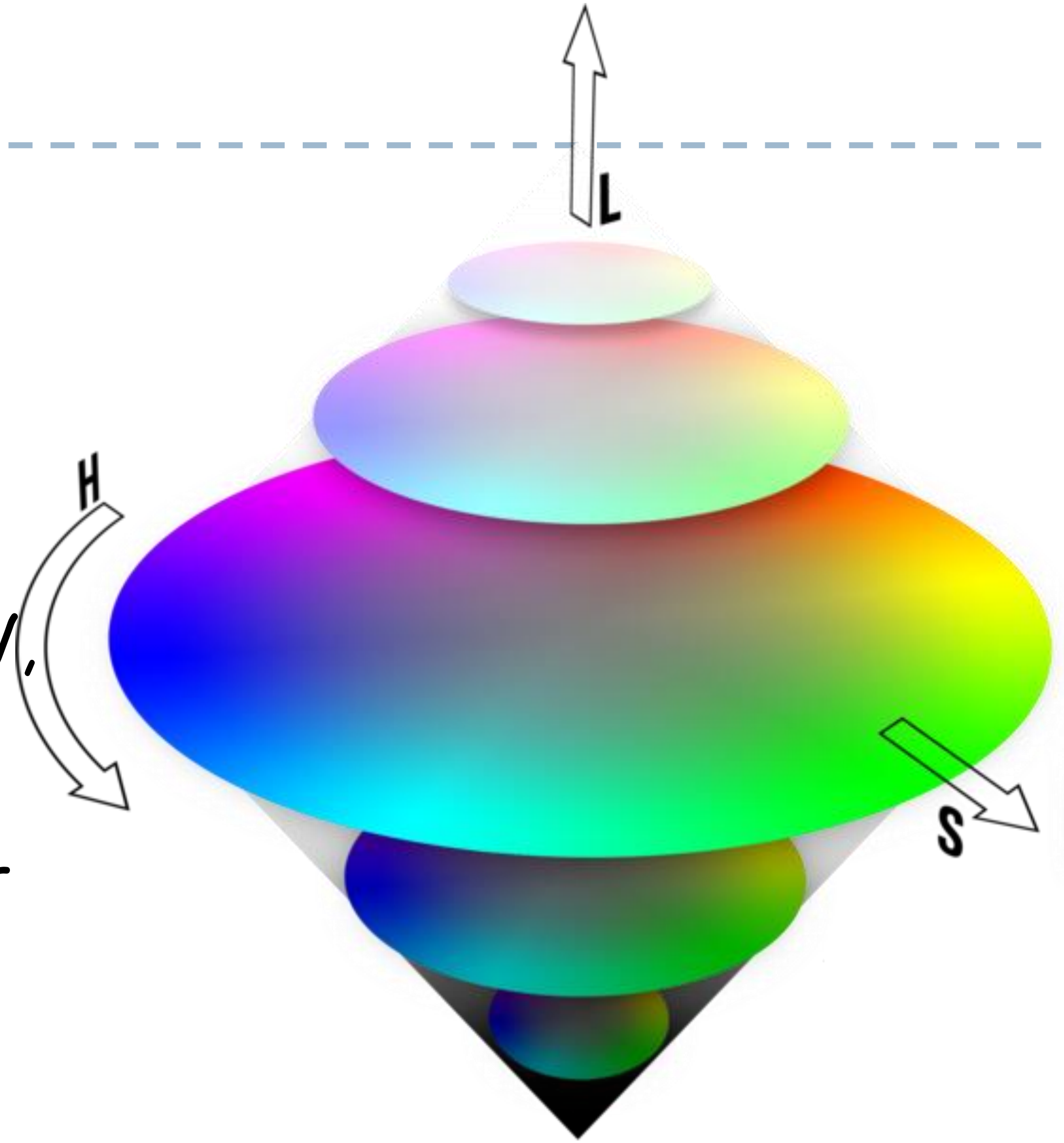


Image taken from http://en.wikipedia.org/wiki/Image:Color_cones.png

CIE LUV

- Perceptually-based color spaces (CIE standards)
- Idea: want the distance between colors in the color space to correspond to intuitive notion of how "similar" colors are perceptually
- Not perfect, but much better than XYZ or RGB color spaces.

Representing Color

- Generally, store 3 color channels in equal bits
  - Not necessary, though, e.g. YIQ
  - Can sometimes get better mapping of color space for an application by adjusting bits
    - e.g. 10 bits R, 8 bits G, 6 bits B, totally 24 bits
- Color indexing: give each color a numerical identifier, then use that as reference
  - Good for specifying with a limited palette

Image representation

Image Representation

An image is a 2D rectilinear array of Pixels

- A width X height array where each entry of the array stores a single pixel

Image Representation

A pixel stores color information

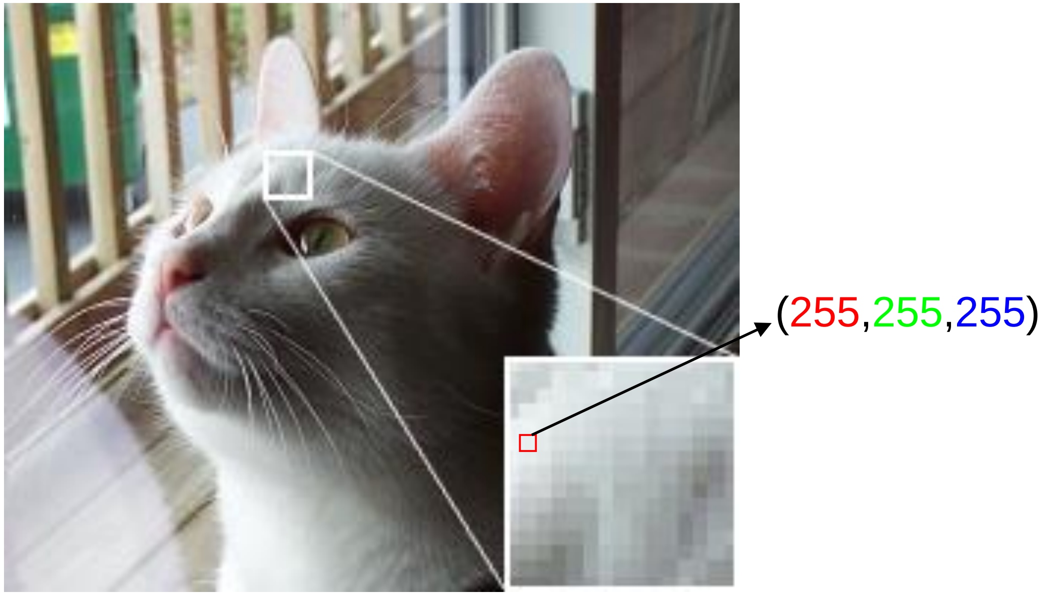
Luminance pixels
- gray-scale images (intensity images)
- 0-1.0 or 0-255
- 8 bits per pixel

Red, green, blue pixels (RGB)
- Color images
- Each channel: 0-1.0 or 0-255
- 24 bits per pixel

Image Representation

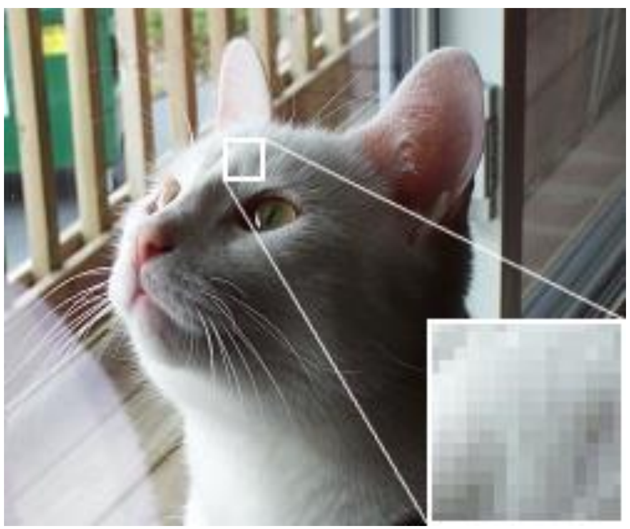
An image is a 2D rectilinear array of Pixels

- A W width X height array where each entry of the array stores a single pixel
- Each pixel stores color information

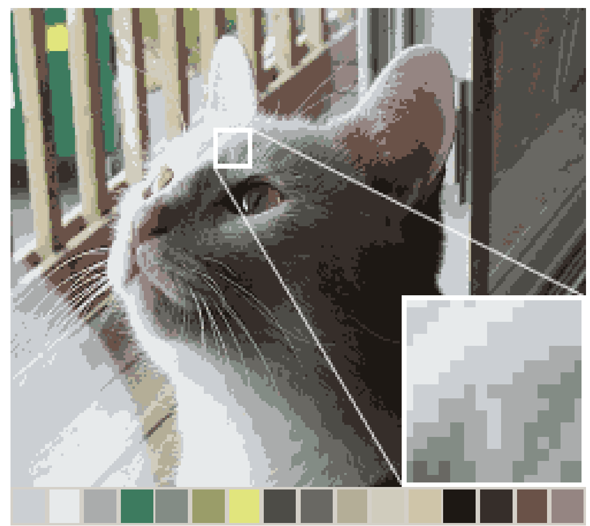


Color Quantization

Reduce the number of bits to encode color information



24 bits/pixel



4 bits/pixel

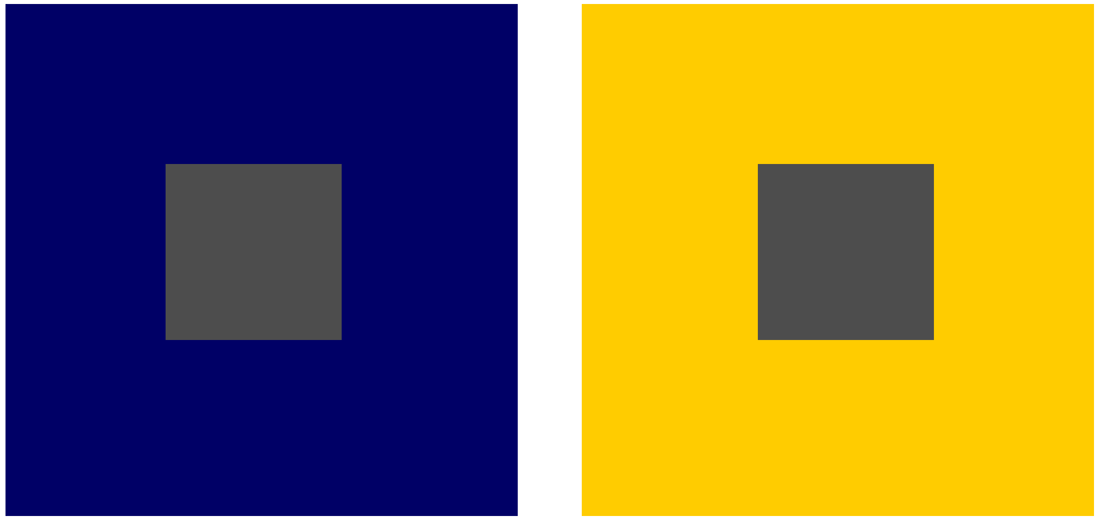
Psychophysics

- Tint, shade, and tone: subjective. Depend on observer's judgment, lighting, sample size, context…
- Colorimetry: quantitative; measurement via spectroradiometer (measures reflected/radiated light), colorimeter (measures primary colors), etc.

Perceptual term	Colorimetry term
Hue	Dominant wavelength
Saturation	Excitation purity
Lightness (reflecting objects)	Luminance
Brightness (self-luminous objects)	Luminance

- Physiology of vision, theories of perception still active research areas
- **Note**: our auditory and visual processing are very different!
  - both are forms of signal processing
  - visual processing integrates/much more affected by context
  - more than half of our cortex devoted to vision
  - vision probably dominant sense, though it is apparently harder to be deaf than blind

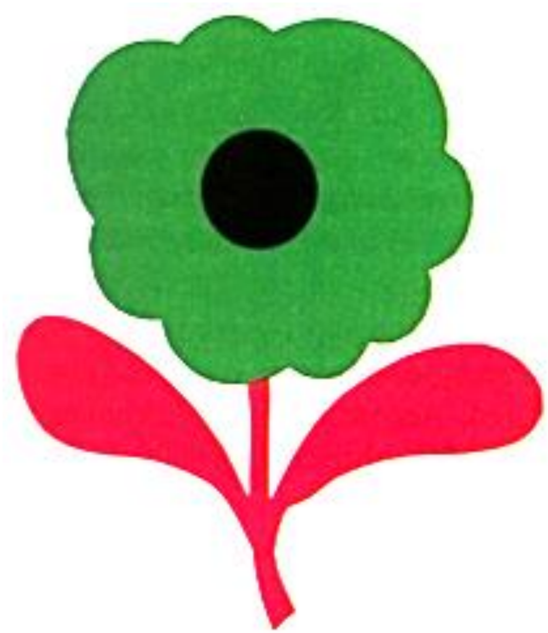
Color Contrast



- Gray patches on blue and yellow backgrounds are physically identical, look different
- Difference in perceived brightness: patch on blue looks brighter than on yellow, result of brightness contrast.
- Also a difference in perceived hue. Patch on blue looks yellowish, while patch on yellow looks bluish. This is color contrast: hues tend to induce their complementary colors in neighboring areas.

To explores, click any Albers Plate link on:
http://www.cs.brown.edu/courses/cs092/VA10/HTML/start.html

Negative Afterimage

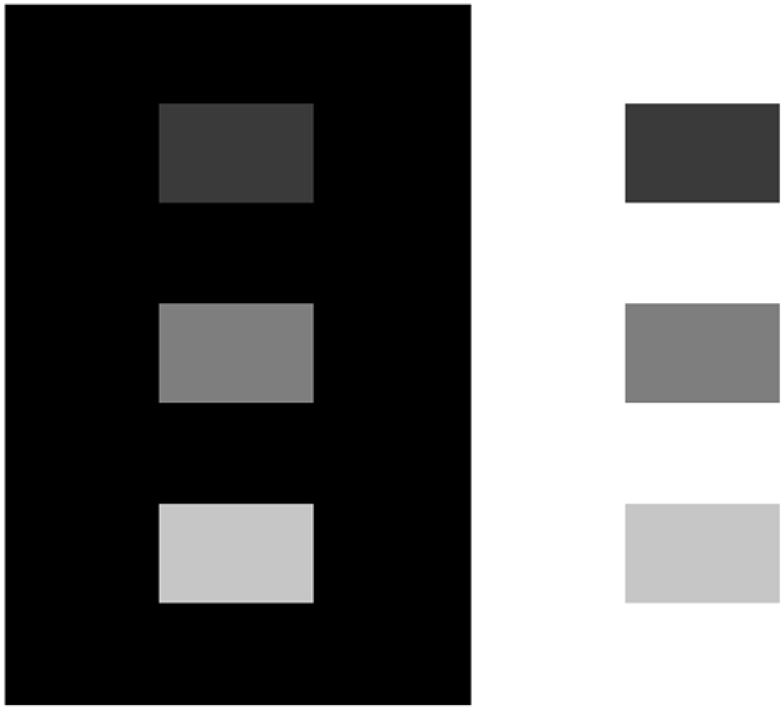


- Stare at center of figure for about a minute or two, then look at a blank white screen or a white piece of paper
- Blink once or twice; negative afterimage will appear within a few seconds showing the rose in its “correct” colors (red petals and green leaves)

Bonus Color Space: CIECAM02 Color Appearance Model

- http://scanline.ca/ciecam02/
- Even perceptually developed spaces (like Munsell) don't take into account color interactions
- Example: the surround effect, shown left

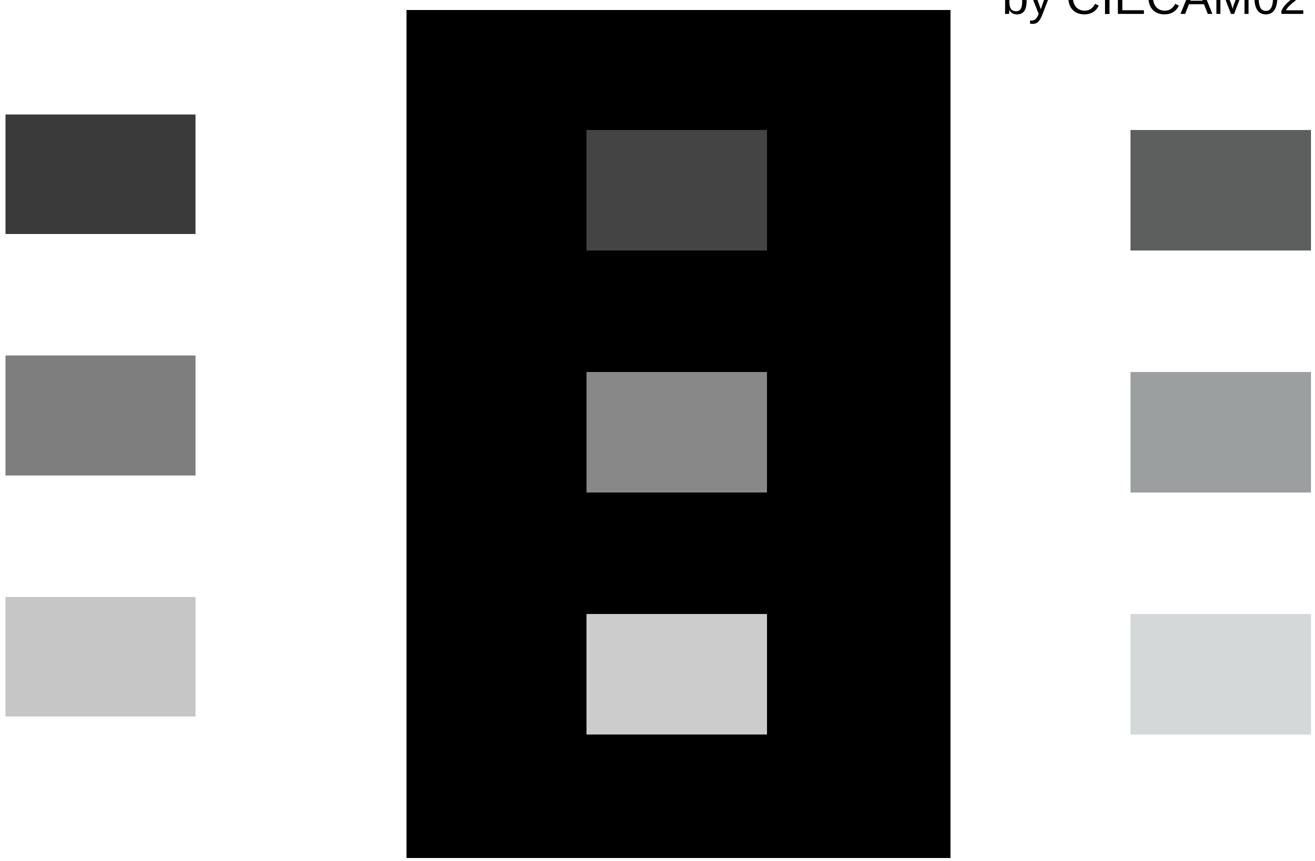
These rectangles have the same pixel values.



Perceptual Effect Corrected For…

Same pixel values

Pixel values adjusted by CIECAM02



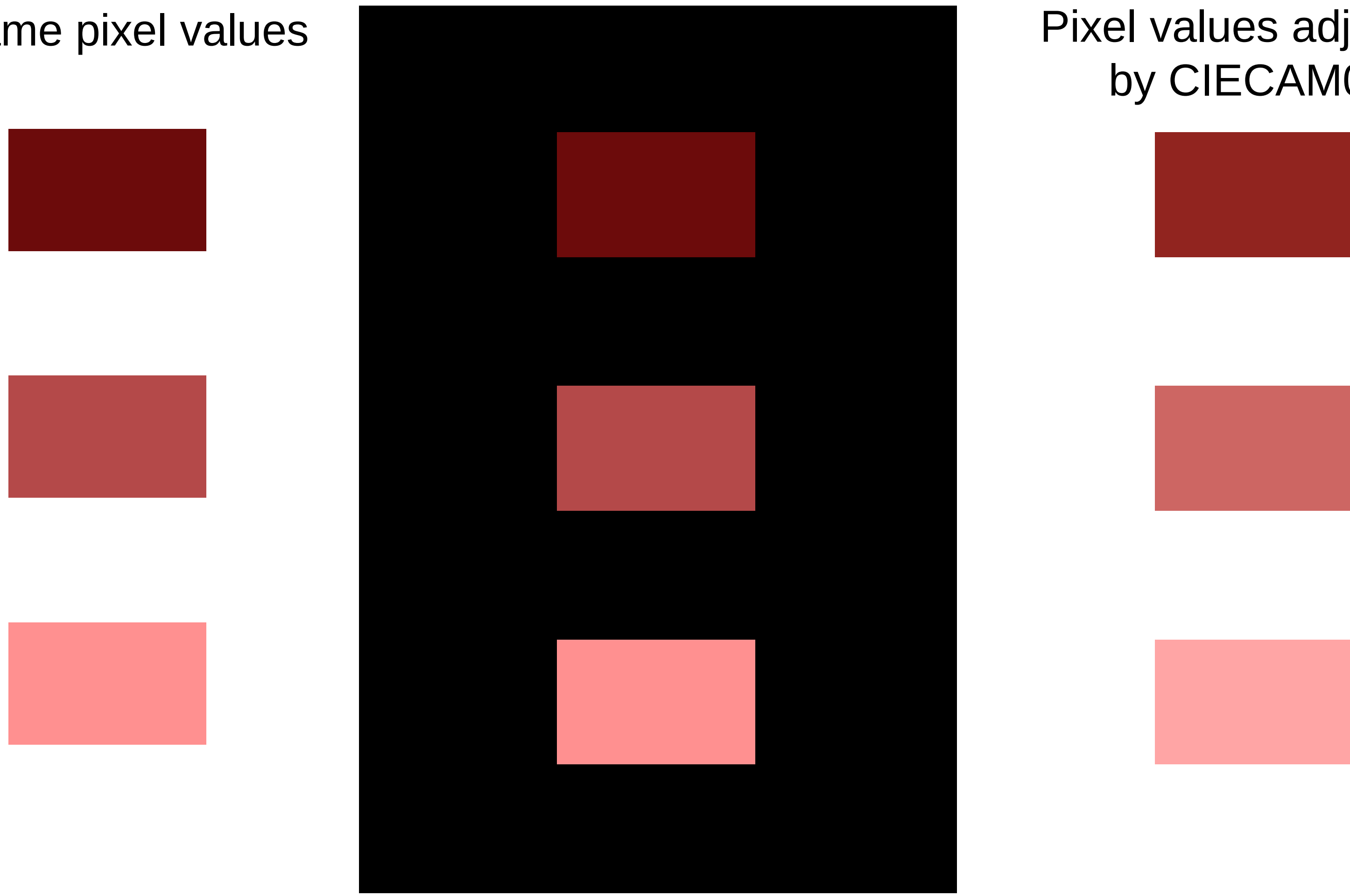
One More Time... with Color 1/2

- Same pixel values

One More Time… with Color 2/2

Same pixel values

Pixel values adjusted by CIECAM02



Color Model Pros and Cons (1/2)

- RGB

  + Cartesian coordinate system

  + linear

  + hardware-based (easy to transform to video)

  + tri-stimulus-based

  - hard to use to pick and name colors

  - doesn't cover gamut of perceivable colors

  - non-uniform: equal geometric distance => unequal perceptual distance

- HSV

  + easy to convert to RGB

  + easy to specify colors/intuitive

  - nonlinear

  - doesn't cover gamut of perceivable colors

  - non-uniform

Color Model Pros and Cons (2/2)

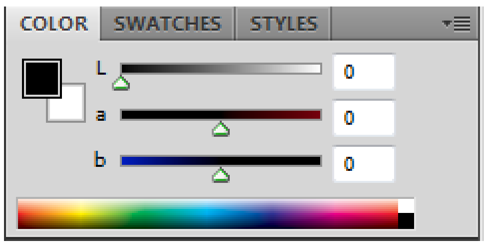
- CIE
  + covers gamut of perceived colors
  + based on human perception (matching experiments)
  + linear
  + contains all other spaces

  - non-uniform (but variations such as CIE Lab are closer to Munsell, which is uniform)
  - xy-plot of chromaticity horseshoe diagram doesn't show luminance

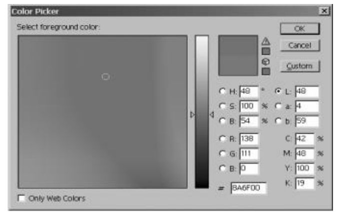
- CIE Lab space
  + perceptually uniform
  + based on psychological colors (y-b, r-g, w-b)

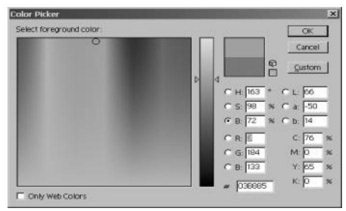
  - terrible interface in Photoshop
  - sliders used for a curved surface
  - surface changes when L value changes
  - no visualization of the color space
  - very difficult to determine what values mean if you are unfamiliar with the space
  - primarily used as an internal space to convert between RGB and CMYK

CIELab in Photoshop

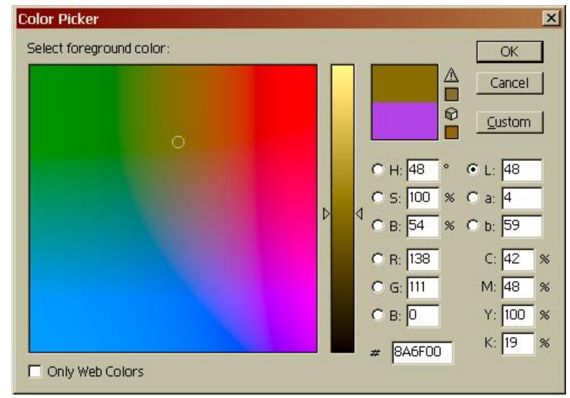


Lab slides

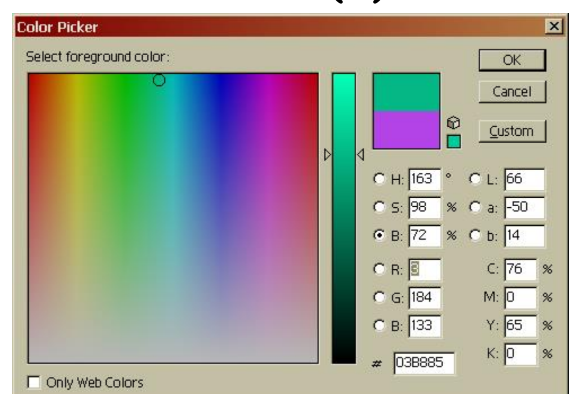




Lab color space slice—constant value (L)

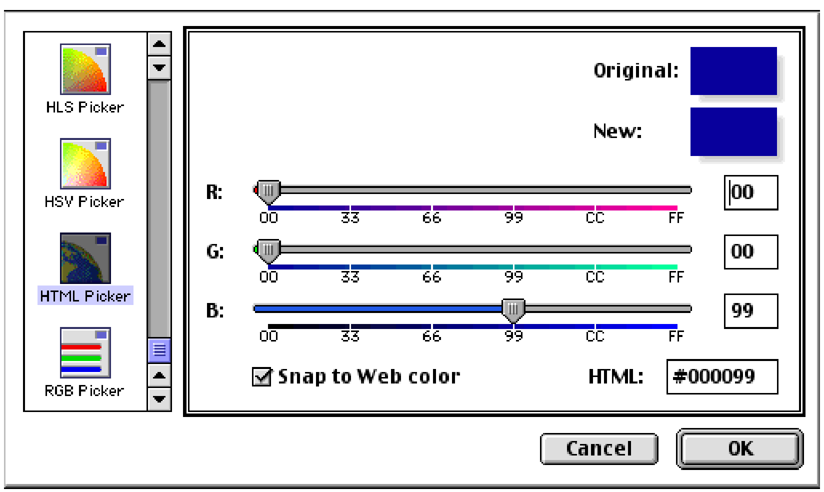


HSB color space slice—constant value (B)

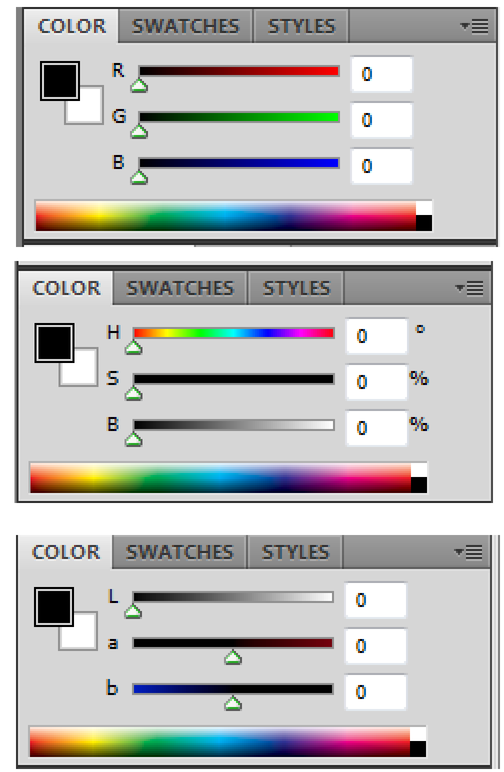


Interactive Specification of Color, 1/3 Sliders

- English-language names are ambiguous and subjective
- Most programs use numeric coordinates in color space with slide dials:

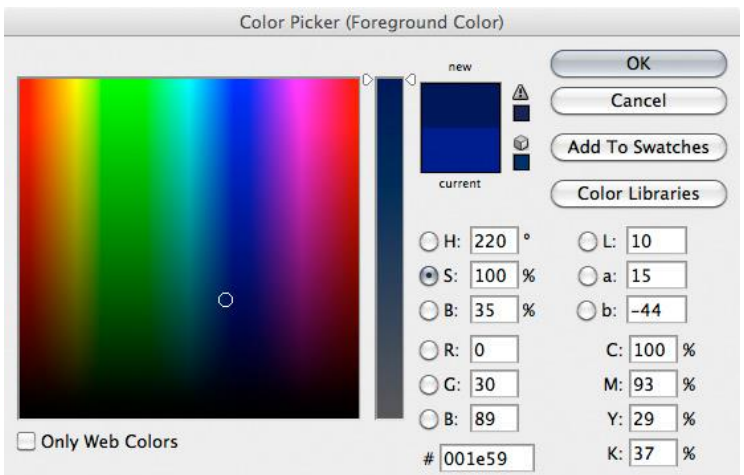


- Adobe Photoshop

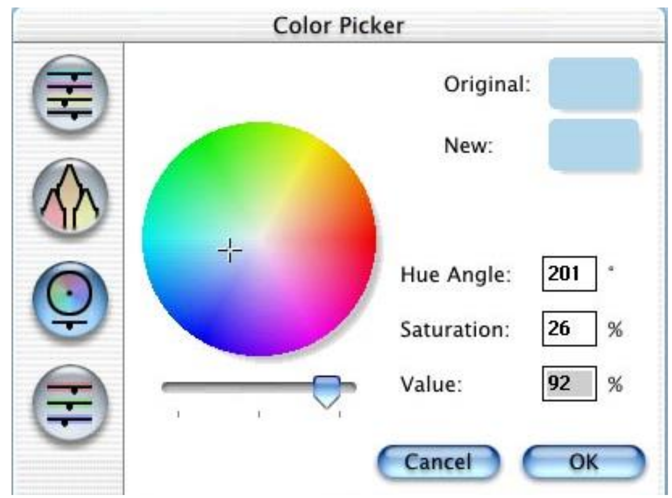


Interactive Specification of Color, 2/3 : Geometric Views

- Interact with visual representation of the color space
- Important for user to see actual display with new color
- Beware of ***surround effect***!

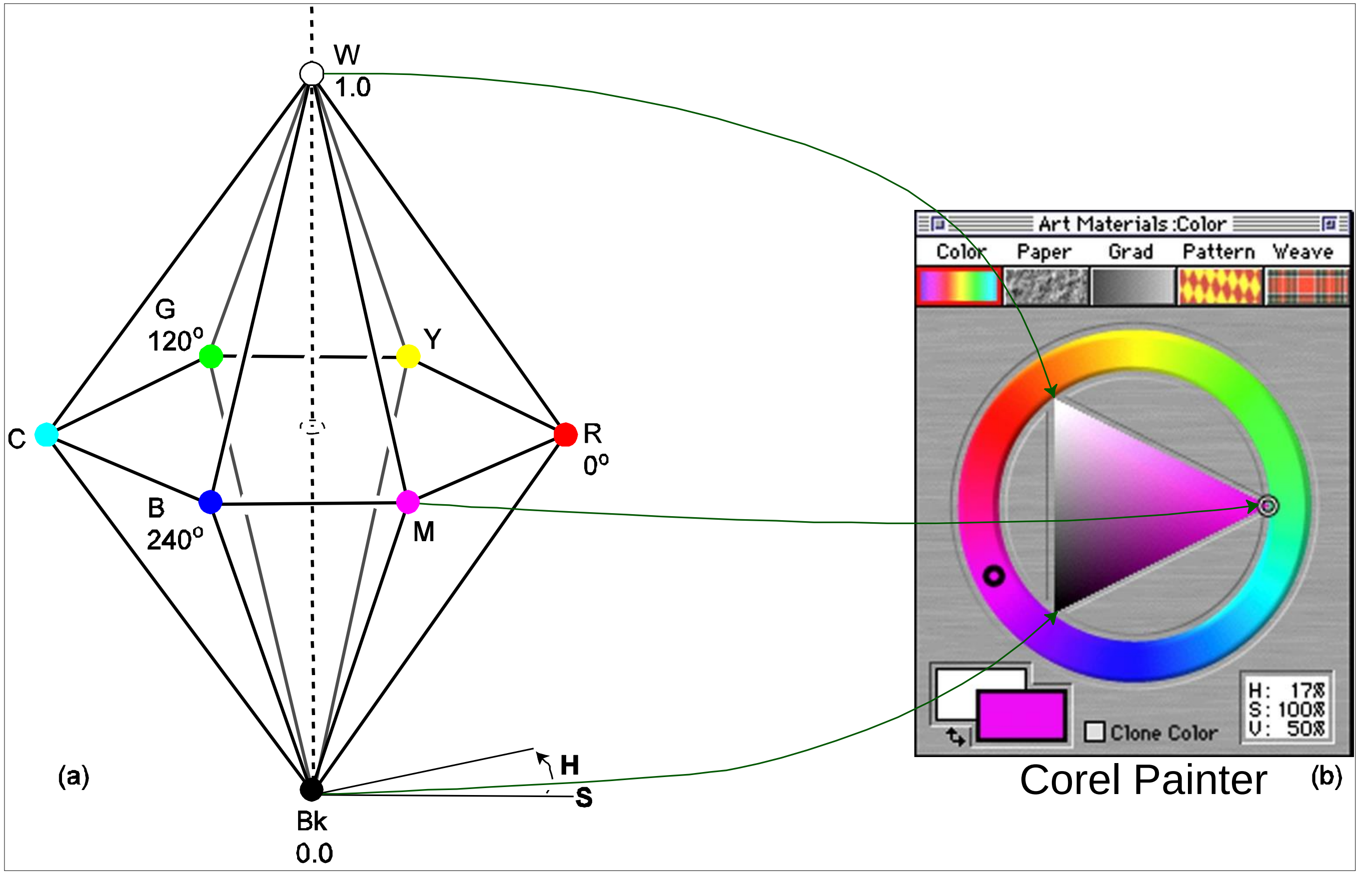


HSB color picker from Adobe Photoshop

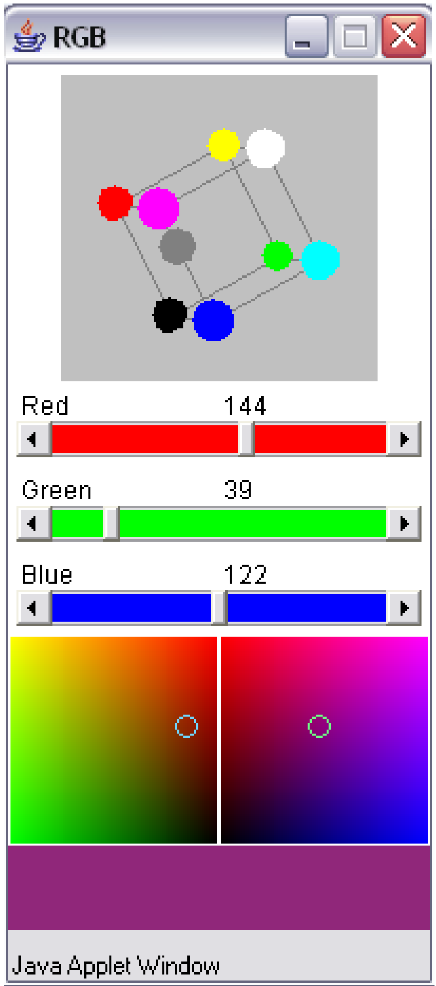


HSV color picker from Mac OS X's Finder

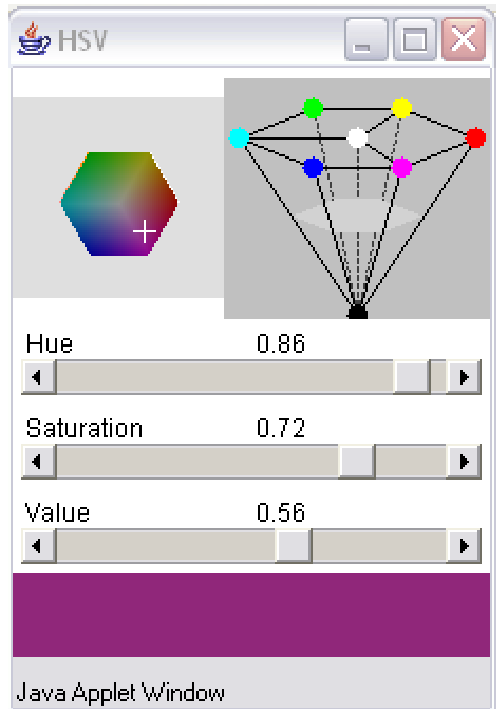
Interactive Specification of Color, 3/3
Geometric Views, cont.

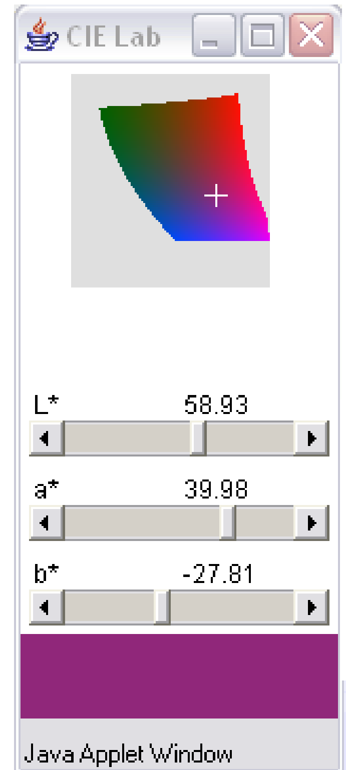


3D Color Pickers



3D spaces applet

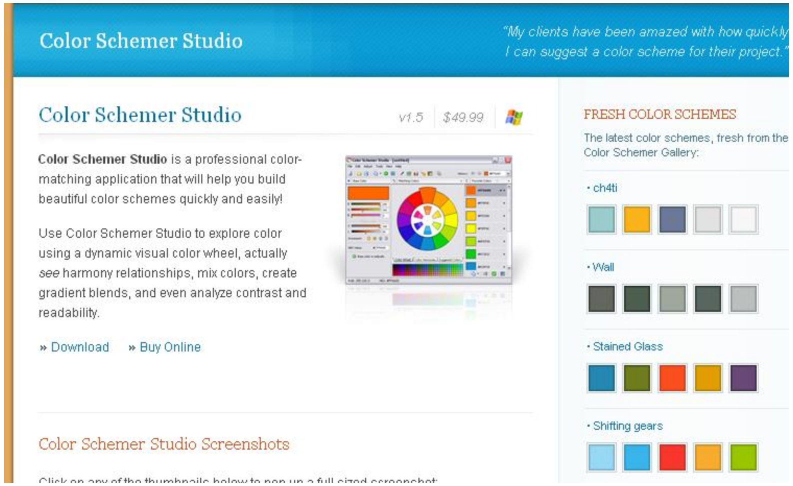




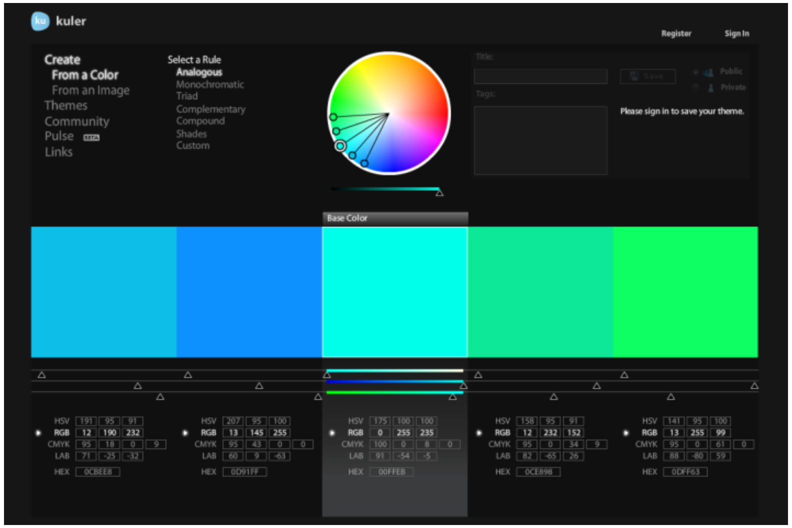
http://www.cs.rit.edu/~ncs/color/a_spaces.html

Some Commercial Alternative Pickers

- From the Behr paint company: great for interior decoration (related to rendering spaces!) http://www.behr.com/behrx/workbook/index.jsp
- A color wheel-based palette creator,
  based on a perceptual color space: http://www.colorschemer.com/



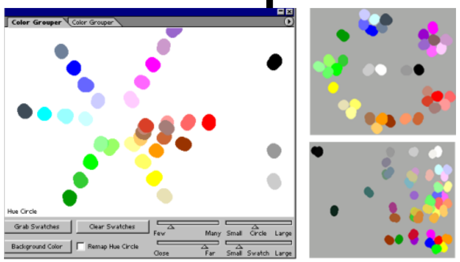
- A relational palette creator, with HSV,
  RGB, CMYK, LAB, and HEX color pickers: http://kuler.adobe.com/



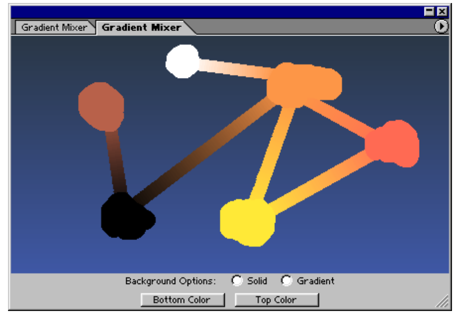
Interactive Palette Tools

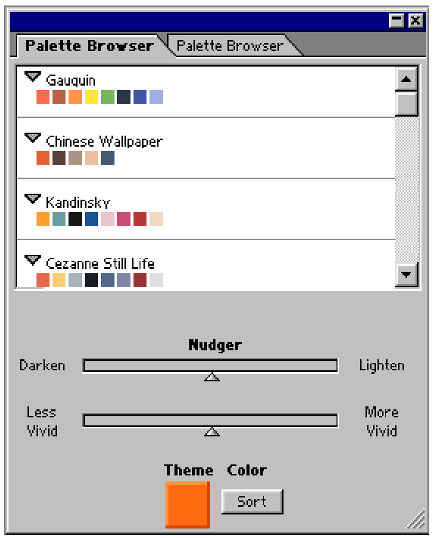
Adobe Kuler

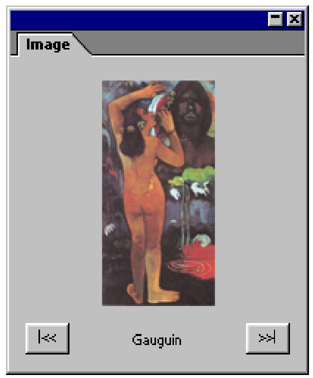
Color Grouper



Gradient Mixer

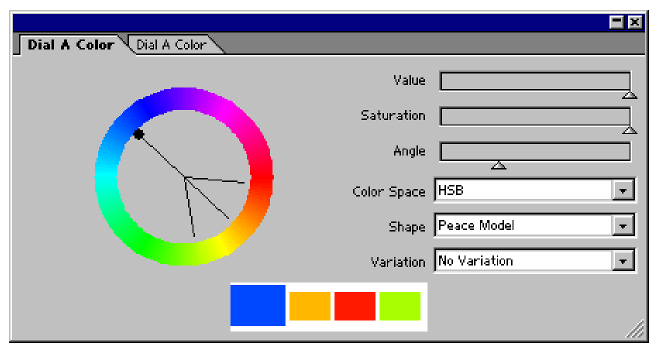






Palette Browser

Barb Meier, Anne Spalter, David Karelitz, CG&A Vol24, No 3, 2004 (sponsored by Adobe)

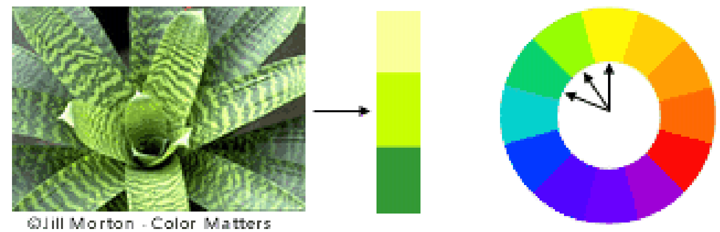


Dial-a-Color

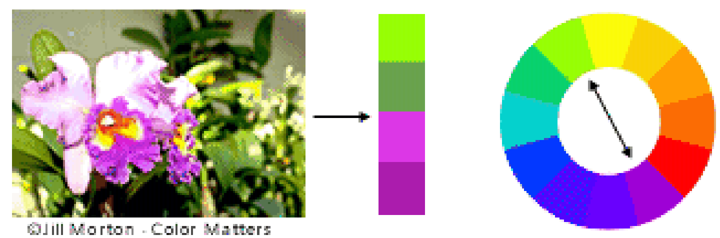
Choose Palette or Scheme

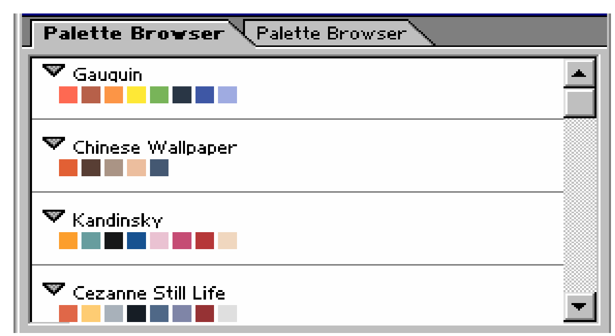
- Color harmony:
  - choose a theme color
  - complementary colors for objects that should have a dynamic relationship with theme-colored objects
  - analogous (close together) colors close together to model light (shading) and for coloring objects close to each other
  - contrasting colors (especially value contrast) for text and background
  - Color circles can help with these choices
- Expert palettes

A color scheme based on analogous colors

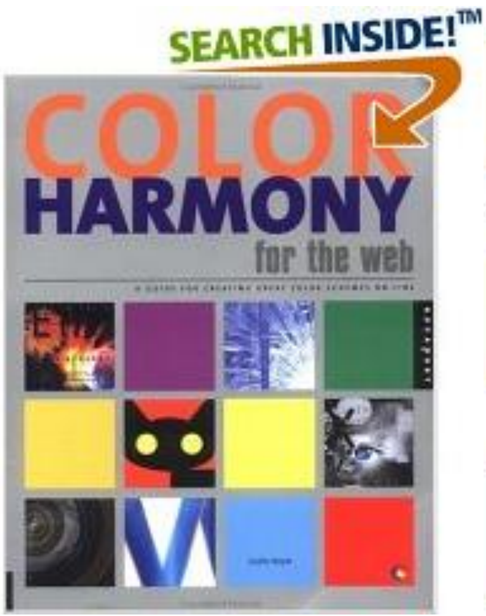


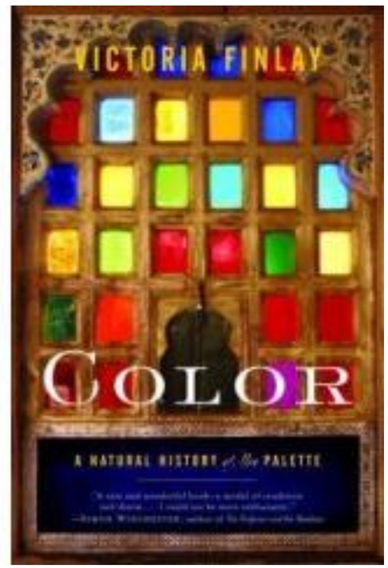
A color scheme based on complementary colors

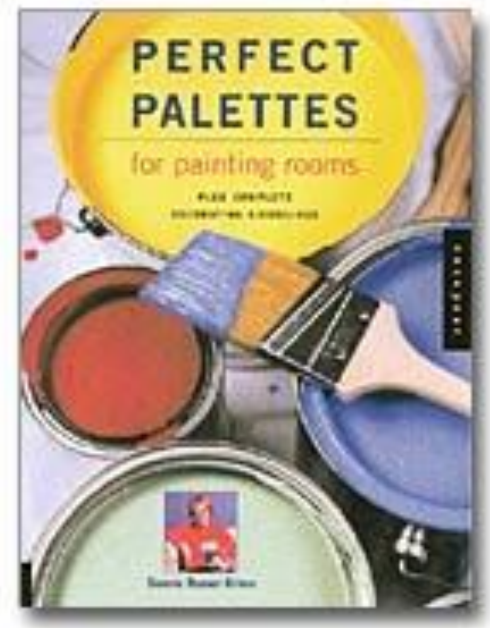




Color palette books…

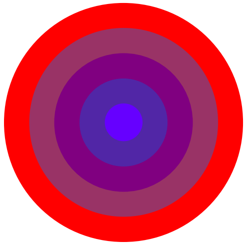






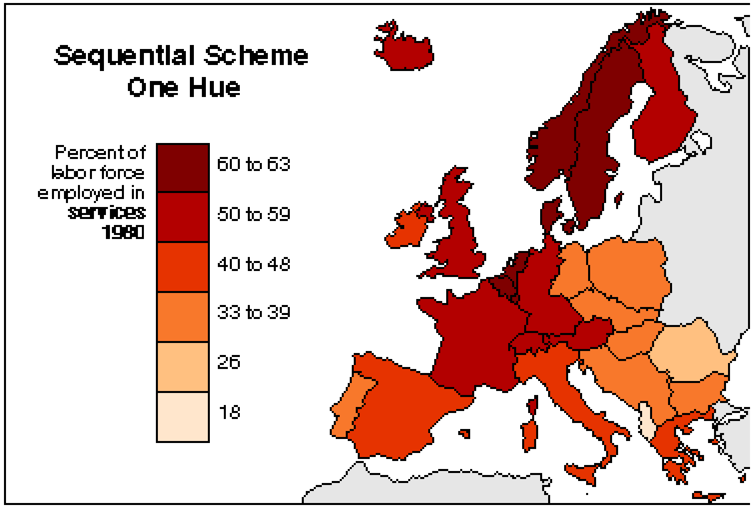
Assign Colors for Ease of Use/Reading/Viewing

- Don't use more colors than necessary (when in doubt use less color)
- Ensure contrast of color between text and background (especially of value)
- All else being equal, areas of saturated color will draw attention
  - Don't use highly saturated colors of background
  - Large areas of intense color can lead to eye strain
- Use colors that have greatest contrast with the background for most important items
- If using several colors of foreground object, use a neutral background
- Blue-family colors tend to recede while warmer red-family colors come forward



Color Coding 1/2

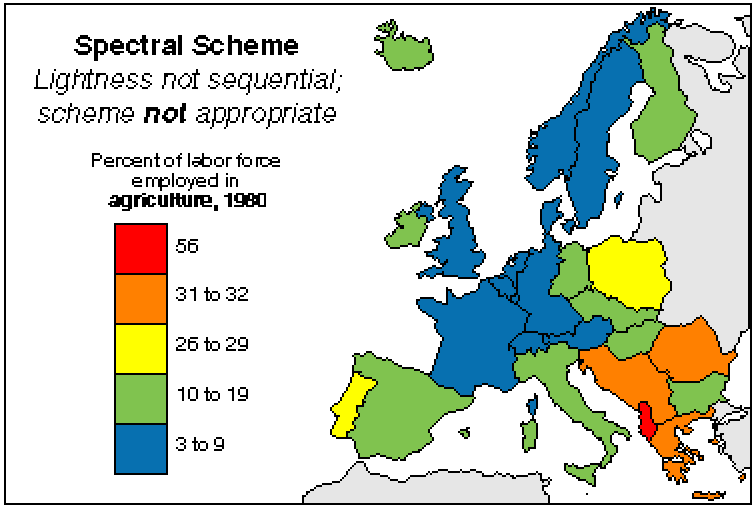
- Do
  - Use families of color to code related items
  - Use a progression of values to code an ordered set (don't use more than 5 steps if values need to be remembered)
  - Color code for accepted use in specific industry: red often means stop, but in power industry means go (electricity flowing), In finance means money being lost…
  - Supply a legend



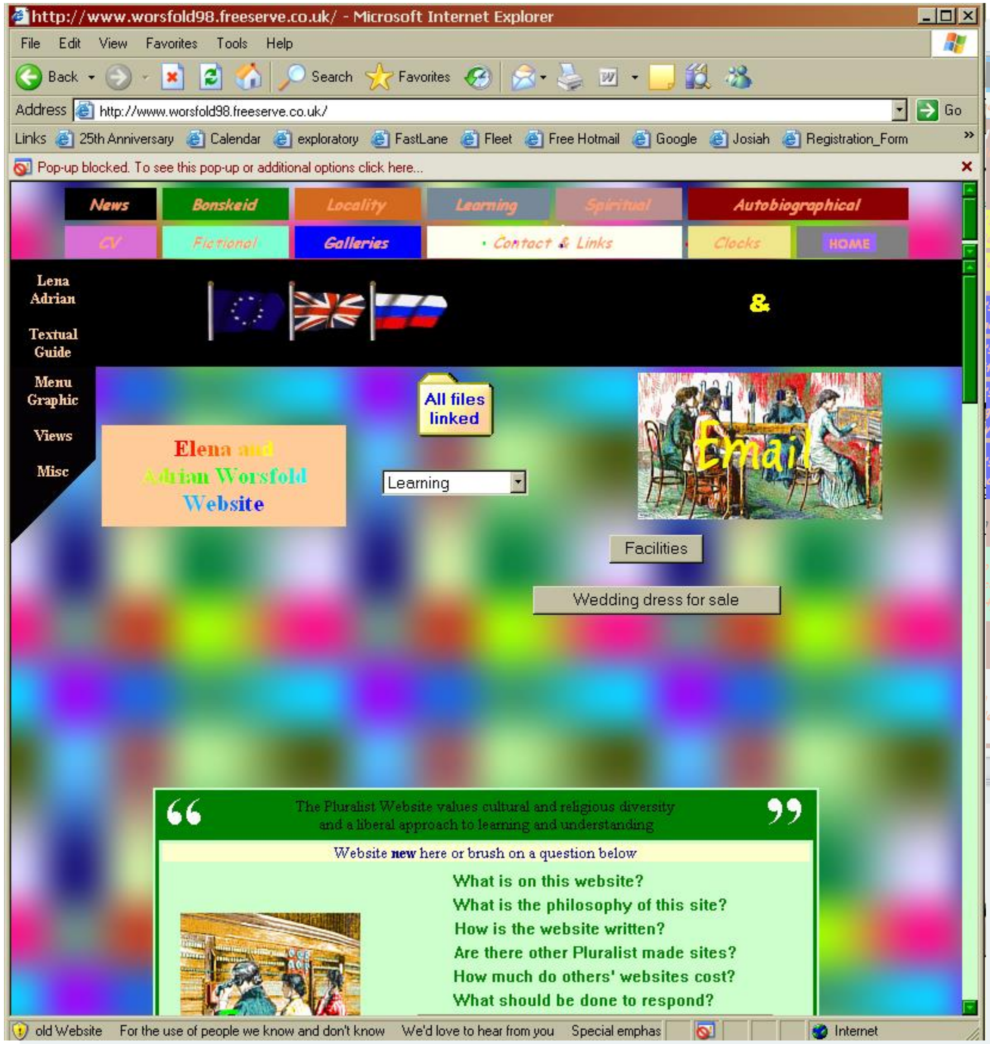
http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/SchHTMLs/CBColorSeq.html

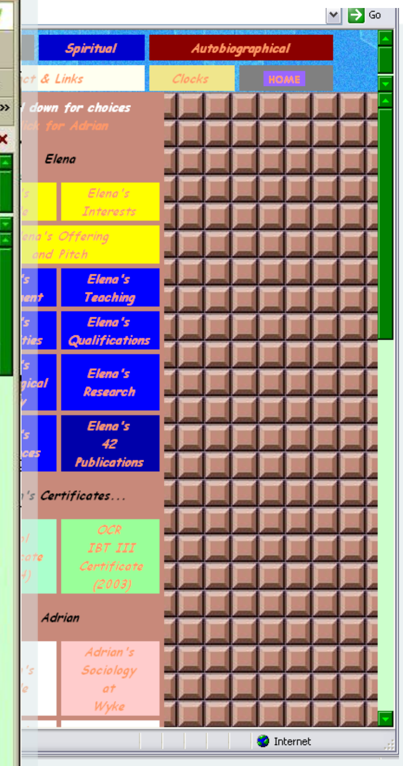
Color Coding 2/2

- Don't
  - Use red and green for important color coding. Many people (10% men) red-green colorblind.
  - Use similar shades of green and blue for key differentiation. Often confused by viewers
  - Use adjacent small patches of different colors: they will just blend into each other
  - Use rainbow/spectral scale for ordinal coding: we have no sense of whether green is more or less than red…



Too Much Diversity?

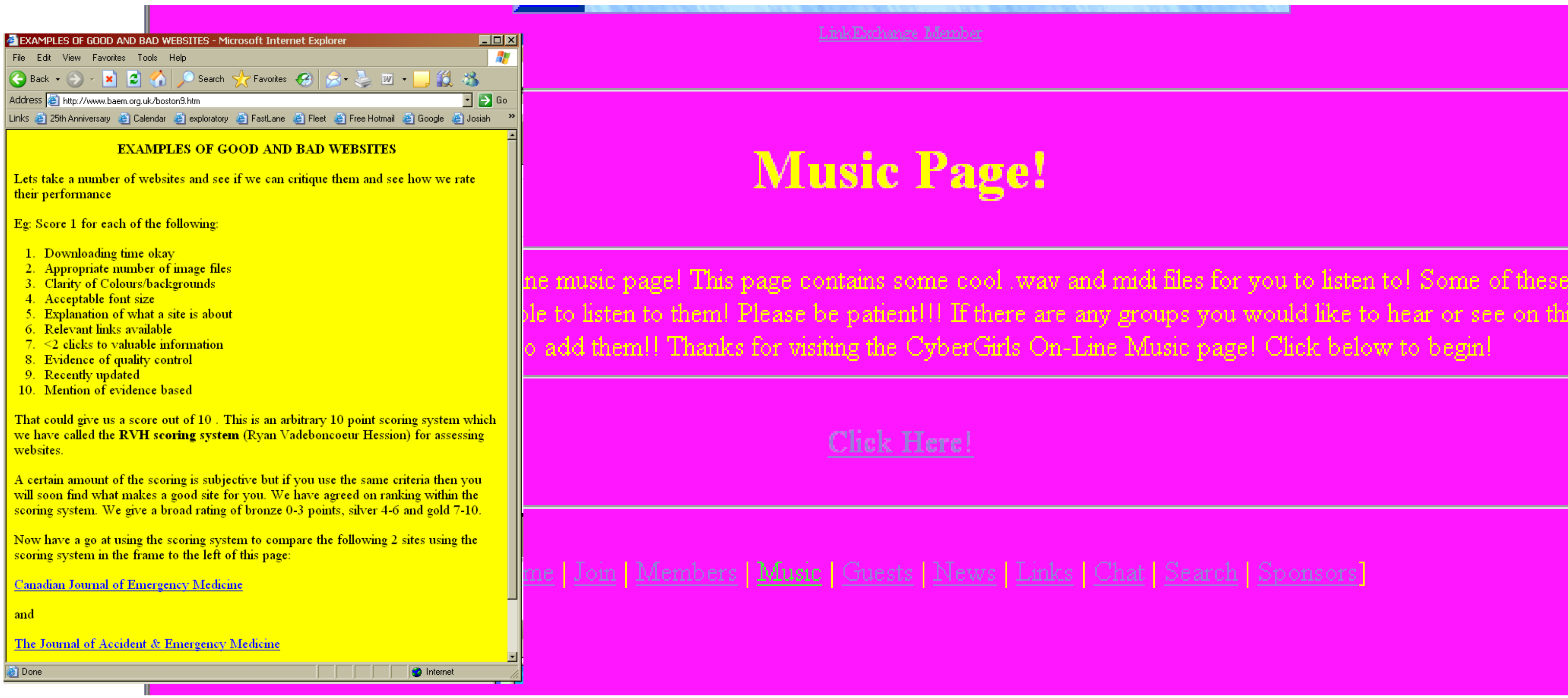




- http://www.pluralist.co.uk/

Saturation—Not Easiest Choice for a Background…

http://www.baem.org.uk/boston9.htm

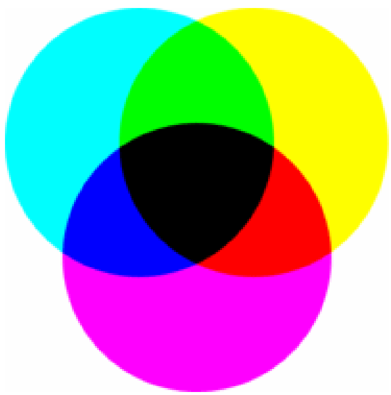


Also

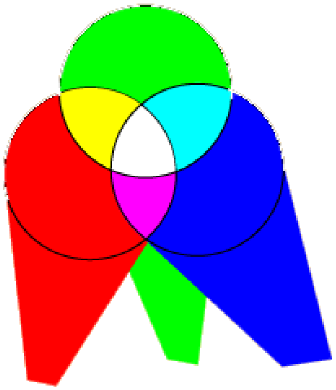
http://www.angelfire.com/or/cybergirls/music.html

Color Mixture Applets

A



B



The effect of (A) passing light through several filters (subtractive mixture), and (B) throwing different lights upon the same spot (additive mixture)

Color Mixing Applets

Additive Mixing Applet:

http://www.cs.brown.edu/exploratories/freeSoftware/repository/edu/brown/cs/exploratories/applets/colorMixing/additive_color_mixing_guide.html

Combined Mixing Applet:

http://www.cs.brown.edu/exploratories/freeSoftware/repository/edu/brown/cs/exploratories/applets/combinedColorMixing/combined_color_mixing_guide.html

Ερωτήσεις

- Ιστοσελίδα μαθήματος (ενεργοποιημένη) :
  http://support.inf.uth.gr/courses/CE416/

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  ce416@inf-server.inf.uth.gr

- Π. Τσομπανοπούλου, Ε3-12, yota@uth.gr