



Color

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Course News

Assignment 3 (project)

- Due April 1

Homework 7

- Out today

Reading

- Chapter 10 (ray tracing)

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Course Topics for the Rest of the Term



Color

- Today, Friday

Shadows, Ray-tracing & Global Illumination

- Next week

Parametric Curves/Surfaces

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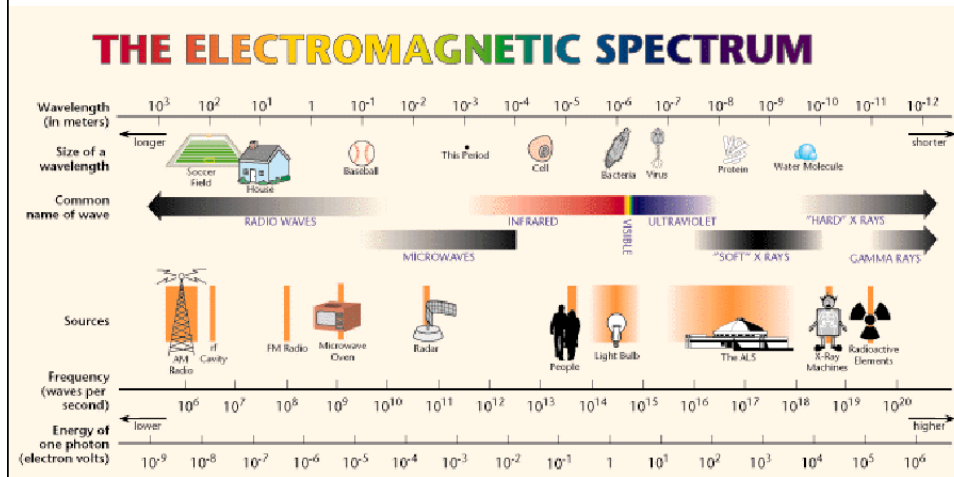
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Electromagnetic Spectrum



Blackbody Radiation

Black body

- Dark material, so that reflection can be neglected
- Spectrum of emitted light changes with temperature
 - This is the origin of the term “color temperature”
 - E.g. when setting a white point for your monitor
 - Cold: mostly infrared
 - Hot: redish
 - Very hot: bluish
- Demo:



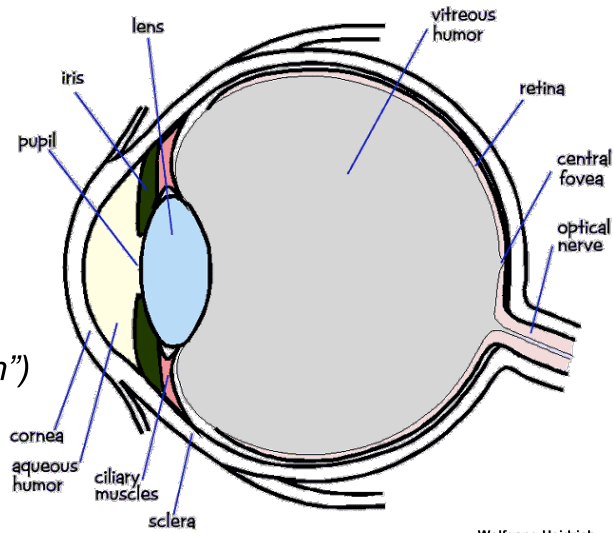
<http://www.mhhe.com/physci/astronomy/applets/Blackbody/frame.html>

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Physiology of Vision

The retina

- Rods
 - B/w, edges
- Cones
 - **Color!**
 - 3 types: S,M,L
 - Short (“blue”)
 - Medium (“green”)
 - Long (“red”)

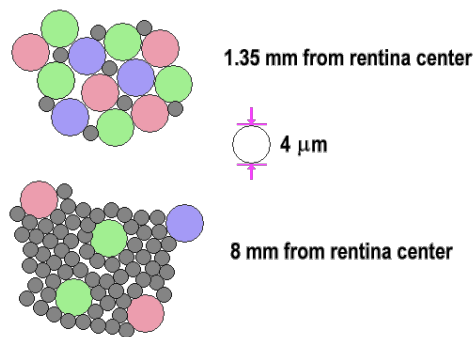


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Physiology of Vision

Center of retina is densely packed region called the fovea.

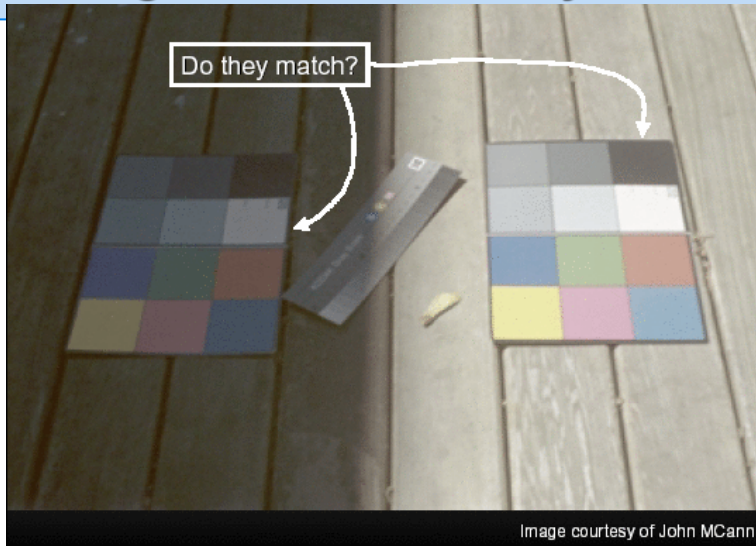
- Cones much denser here than the *periphery*



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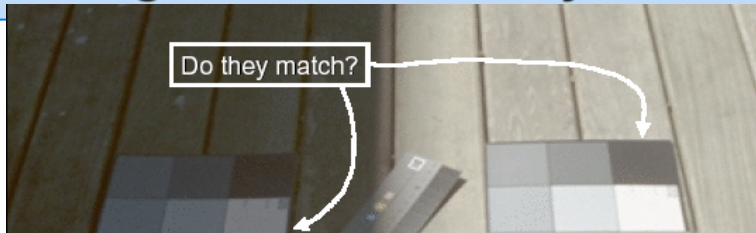
Color/Lightness Constancy



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Color/Lightness Constancy



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Color/Lightness Constancy



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Color/Lightness Constancy



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Color Constancy

- Automatic “white balance” from change in illumination
- Vast amount of processing behind the scenes!
- Colorimetry vs. perception



Tristimulus Theory of Color Vision



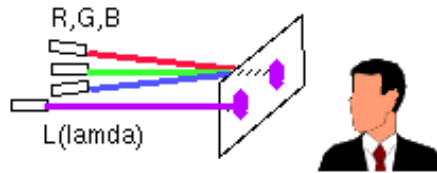
- Although light sources can have extremely complex spectra, it was empirically determined that colors could be described by only 3 **primaries**
- Colors that look the same but have different spectra are called **metamers**
- Metamer demo:
http://www.cs.brown.edu/exploratories/freeSoftware/catalogs/color_theory.html

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Color Matching Experiments

**Performed
in the 1930s**



Idea: perceptually based measurement

- Shine given wavelength (λ) on a screen
- User must control three pure lights producing three other wavelengths (say $R=700$ nm, $G=546$ nm, and $B=438$ nm)
- Adjust intensity of RGB until colors are identical

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Color Matching Experiment

Results

- It was found that any color $S(\lambda)$ could be matched with three suitable primaries $A(\lambda)$, $B(\lambda)$, and $C(\lambda)$
 - Used monochromatic light at 438, 546, and 700 nanometers

- Also found the space is linear, i.e. if

$$R(\lambda) \equiv S(\lambda)$$

then

$$R(\lambda) + M(\lambda) \equiv S(\lambda) + M(\lambda)$$

and

$$k \cdot R(\lambda) \equiv k \cdot S(\lambda)$$

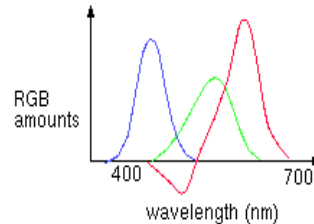
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Negative Lobes

Actually:

- Exact target match possible sometimes requires “negative light”



- Some red has to be added to target color to permit exact match using “knobs” on RGB intensity output
- Equivalent mathematically to removing red from RGB output

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Notation

Don't confuse:

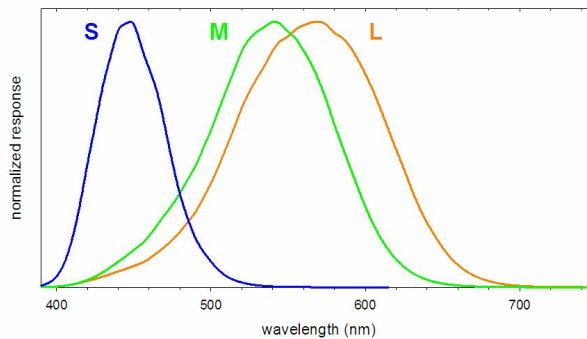
- Primaries: the spectra of the three different light sources: **R, G, B**
 - For the matching experiments, these were **monochromatic** (i.e. single wavelength) light!
 - Primaries for displays usually have a wider spectrum
- Coefficients R, G, B
 - Specify how much of **R, G, B** is in a given color
- Color matching functions: $r(\lambda), g(\lambda), b(\lambda)$
 - Specify how much of **R, G, B** is needed to produce a color that is a metamer for pure monochromatic light of wavelength λ

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Cone Response Functions

Cone Response

- For every type of cone (short, medium, long), one can also measure how much it responds to illumination at a given wavelength



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Color Matching and Cone Response

Linear Algebra View:

- Space of spectra is infinite-dimensional vector space
 - Dot product between two spectra, S_1 , S_2 :

$$(S_1 \cdot S_2) = \int_{\lambda} S_1(\lambda) S_2(\lambda) d\lambda$$

- Cone responses form a 3D subspace
- Matching functions form **the same** 3D subspace
- Cone resp. and matching fns are **dual bases**
- Consequence: if the cone resp. overlap and are positive everywhere, they are **not** an orthonormal basis
 - The dual basis (matching functions) then **must** be negative for some wavelenqths

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Negative Lobes

So:

- Can't generate **all** other wavelengths with **any** set of three **positive** monochromatic lights!

Solution:

- Convert to new synthetic "primaries" to make the color matching easy

$$\begin{pmatrix} \mathbf{X} \\ \mathbf{Y} \\ \mathbf{Z} \end{pmatrix} = \begin{pmatrix} 2.36460 & -0.51515 & 0.00520 \\ -0.89653 & 1.42640 & -0.01441 \\ -0.46807 & 0.08875 & 1.00921 \end{pmatrix} \begin{pmatrix} \mathbf{R} \\ \mathbf{G} \\ \mathbf{B} \end{pmatrix}$$

Note:

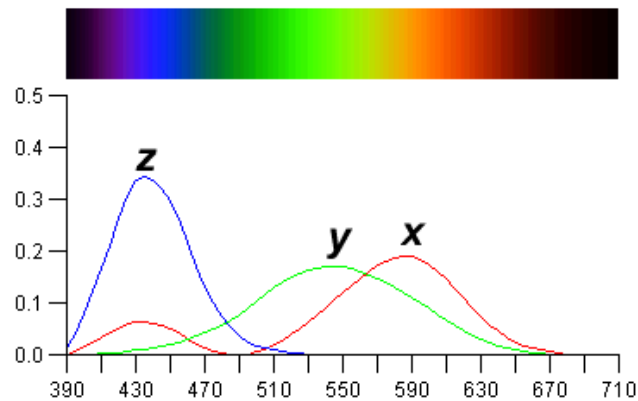
- **R, G, B** are the same monochromatic primaries as before
- The corresponding matching functions $x(\lambda)$, $y(\lambda)$, $z(\lambda)$ are now positive everywhere
- But the primaries contain "negative" light contributions, and are therefore not physically realizable

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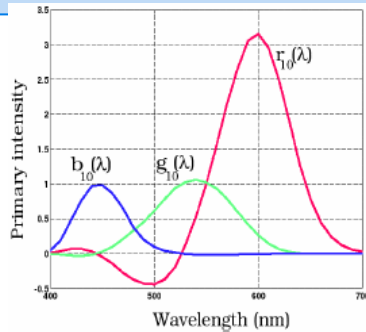
Matching Functions - CIE Color Space

- CIE defined three "imaginary" lights X, Y, and Z, any wavelength λ can be matched perceptually by positive combinations



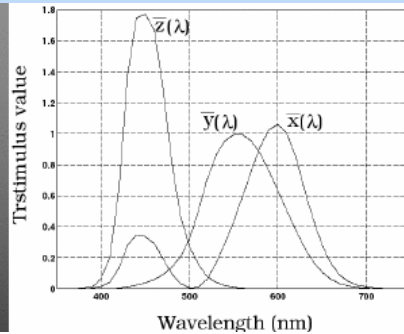
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Matching Functions - Measured vs. CIE Color Spaces



Measured basis

- Monochromatic lights
- Physical observations
- Negative lobes



Transformed basis

- “imaginary” lights
- All positive, unit area matching functions
- Y is luminance, no hue
- X,Z no luminance

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Notation



Don't confuse:

- Synthetic primaries **X, Y, Z**
 - Contain negative frequencies
 - Do not correspond to visible colors
- Color matching functions $x(\lambda), y(\lambda), z(\lambda)$
 - Are non-negative everywhere
- Coefficients X, Y, Z
- Normalized **chromaticity values**

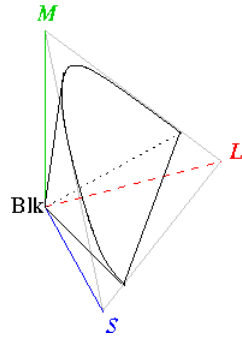
$$x = \frac{X}{X+Y+Z}, y = \frac{Y}{X+Y+Z}, z = \frac{Z}{X+Y+Z}$$

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CIE Gamut and λ Chromaticity Diagram

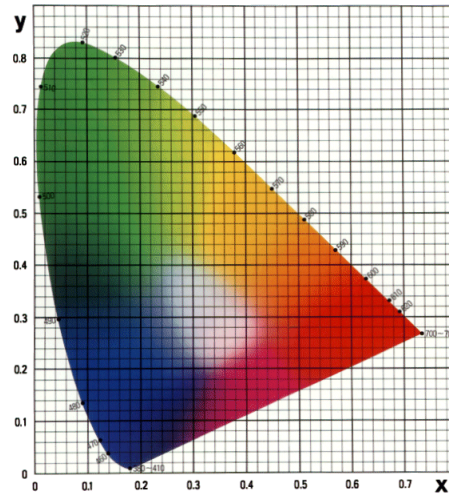


3D gamut



Chromaticity diagram

- Hue only, no intensity



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Facts about the CIE “Horseshoe” Diagram



- All visible colors lie inside the horseshoe
 - Result from color matching experiments
- Spectral (monochromatic) colors lie around the border
 - The straight line between blue and red contains the purple tones
- Colors combine linearly (i.e. along lines), since the xy-plane is a plane from a linear space

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Facts about the CIE “Horseshoe” Diagram (cont.)



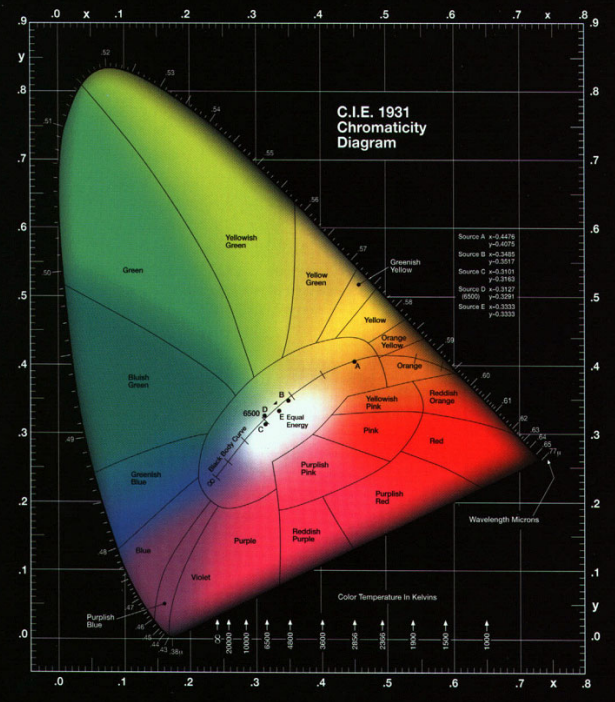
A point C can be chosen as a white point corresponding to an illuminant

- Usually this point is of the curve swept out by the black body radiation spectra for different temperatures
- Relative to C, two colors are called complementary if they are located along a line segment through C, but on opposite sides (I.e C is an affine combination of the two colors)
- The dominant wavelength of the color is found by extending the line from C through the color to the edge of the diagram
- Some colors (I.e. purples) do not have a dominant wavelength, but their complementary color does

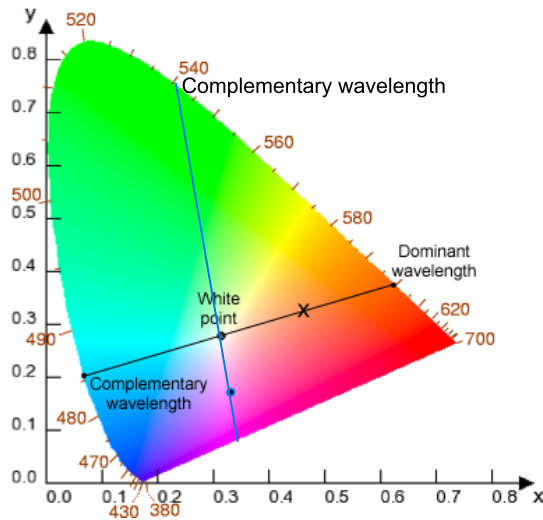
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CIE Diagram

- Blackbody curve
- Illumination:
 - Candle 2000K
 - Light bulb 3000K (A)
 - Sunset/sunrise 3200K
 - Day light 6500K (D)
 - Overcast day 7000K
 - Lightning >20,000K



Color Interpolation, Dominant & Opponent Wavelength



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RGB Color Space (Color Cube)

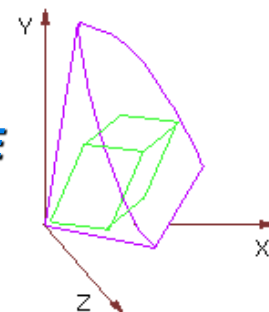
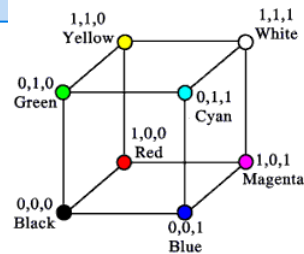


Define colors with (r, g, b) amounts of red, green, and blue

- Used by OpenGL
- Hardware-centric
- Describes the colors that can be generated with specific RGB light sources

RGB color cube sits within CIE

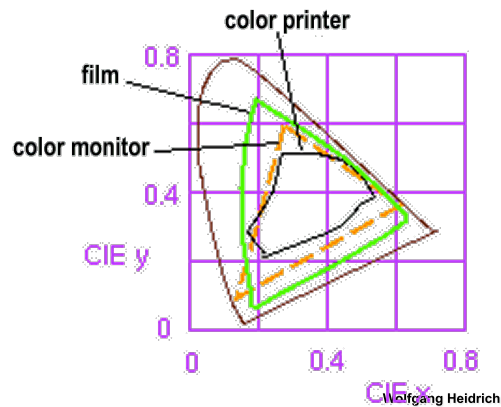
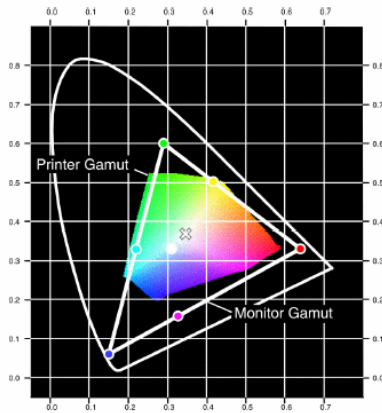
- Subset of perceivable colors
- Scaled, rotated, sheared cube



Device Color Gamuts

Use CIE chromaticity diagram to compare the gamuts of various devices

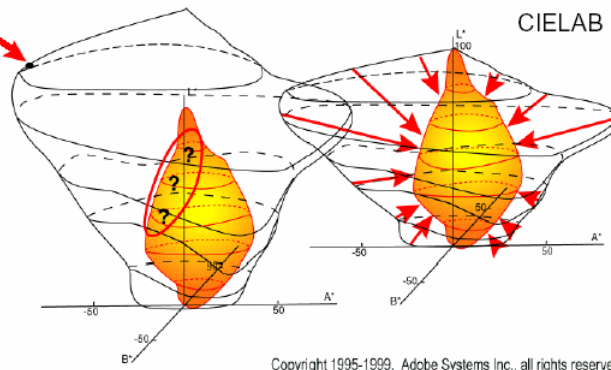
- X, Y, and Z are hypothetical light sources, not used in practice as device primaries



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Gamut Mapping

Where does this color go?



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Additive vs. Subtractive Colors

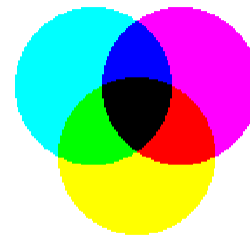
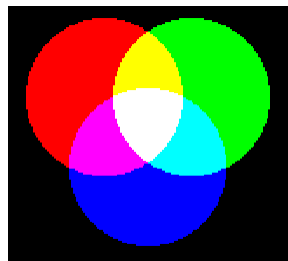
Additive: light

- Monitors, LCDs
- RGB model

Subtractive: pigment

- Printers
- CMY(K) model

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



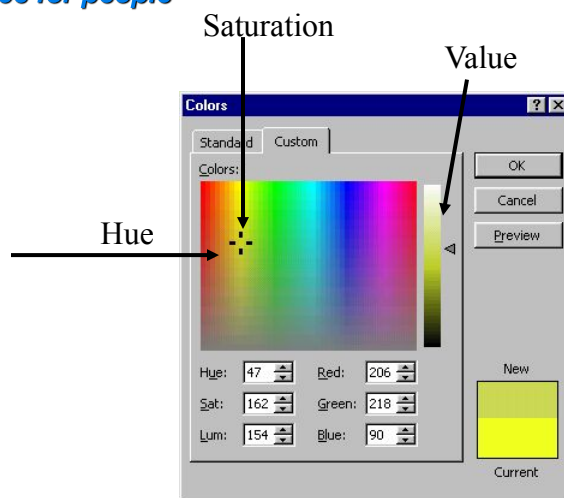
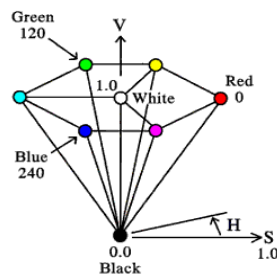
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HSV Color Space

More intuitive color space for people

- H = Hue
- S = Saturation
- V = Value
 - Or brightness B
 - Or intensity I



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Monitors

Monitors have nonlinear response to input

- Characterize by **gamma**
 - $displayedIntensity = a^\gamma (maxIntensity)$

Gamma correction

- $displayedIntensity = \left(a^{1/\gamma} (maxIntensity)\right)^\gamma$
= $a (maxIntensity)$

Gamma for CRTs:

- Around 2.4

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Coming Up...

Wednesday

- Shadows

Friday:

- Ray-tracing

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