Color

Wolfgang Heidrich

Course News

Assignment 3 (project)

- Due April 1

Reading (this week)

- Chapter 20 (color)

Reading (this week & next)

- Chapter 10 (ray tracing)

Course Topics for the Rest of the Term

Color

- Monday, Today

Ray-tracing & Global Illumination

- Friday, next week

Parametric Curves/Surfaces

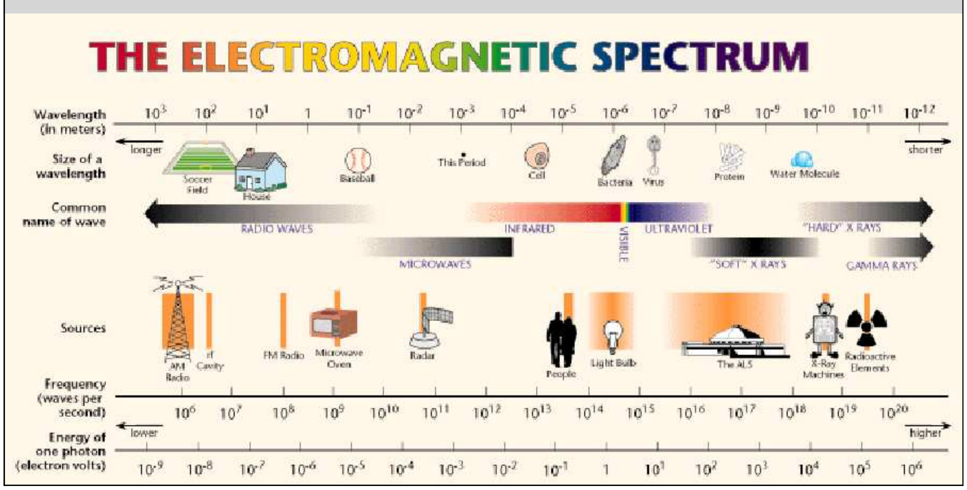
- March 30/April 1
- Taught by Robert Bridson - I will be at a conference

Overview of current research

- April 3/6 (Ivo Ihrke – I am still at conference)

April 8 – Final Q&A (I will be back for that)

Electromagnetic Spectrum



Light Sources

Common light sources differ in the kind of spectrum they emit:

- Continuous spectrum
  - *Energy is emitted at all wavelengths*
    - Blackbody radiation
    - Tungsten light bulbs
    - Certain fluorescent lights
    - Sunlight
    - Electrical arcs
- Line spectrum
  - *Energy is emitted at certain discrete frequencies*

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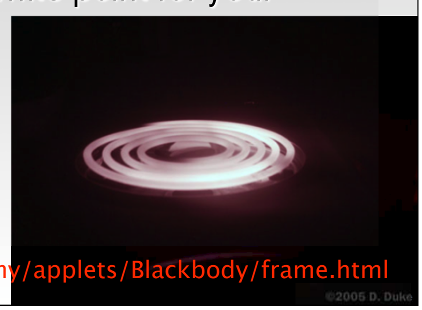
Blackbody Radiation

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:

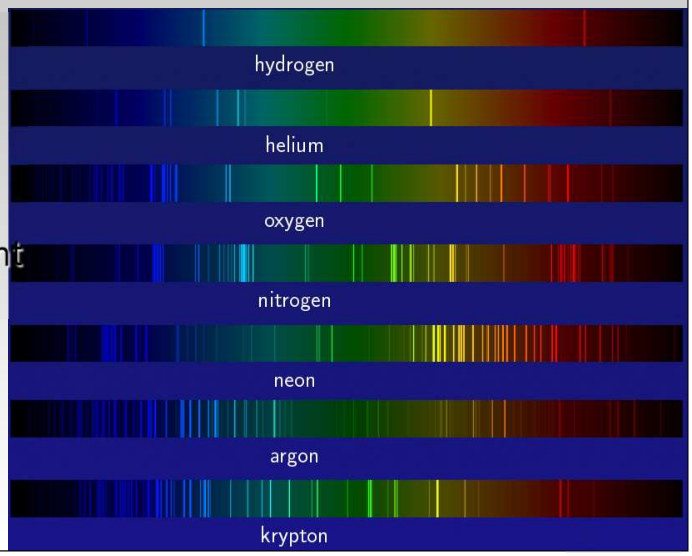


http://www.mhhe.com/physsci/astronomy/applets/Blackbody/frame.html

Line Spectrum

Examples:

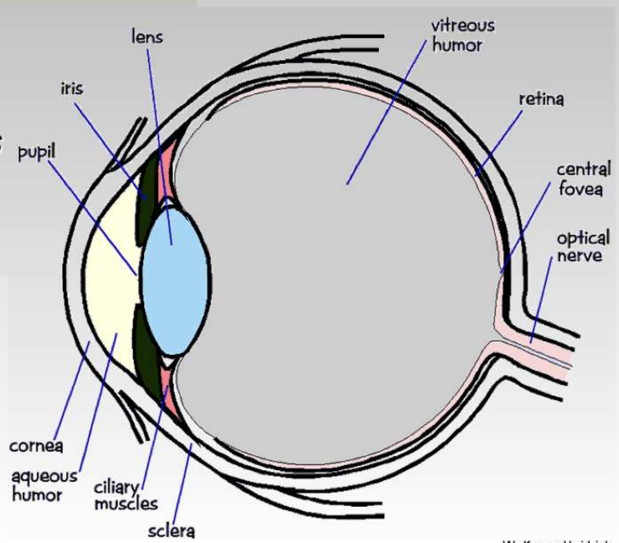
- Ionized gases
- Lasers
- Some fluorescent lamps



Physiology of Vision

The retina

- Rods
  - *B/w, edges*
- Cones
  - *Color!*



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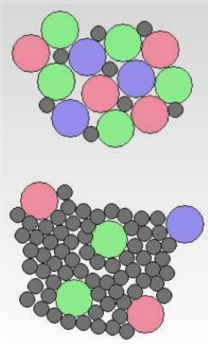
Physiology of Vision

Center of retina is densely packed region called the fovea.

- Cones much denser here than the *periphery*



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Color/Lightness Constancy

Image courtesy of John MCann

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Color/Lightness Constancy

Color Constancy

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

From Color Appearance Models, fig 8-1

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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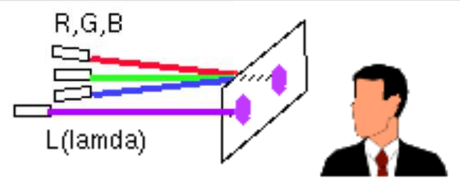
Color Matching Experiments

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(λ) could be matched with three suitable primaries A(λ), B(λ), and C(λ)
  - *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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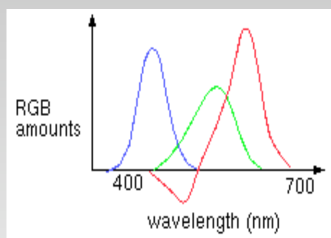
Negative Lobes

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!*
  - *Display primaries 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(λ), g (λ), b (λ)
  - *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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Determine Matching for Arbitrary Spectra

Given

- Some light spectrum s(λ)

How do we find R, G, B?

- Coefficients to describe color of s(λ) in **RGB** space
- i.e. as mixtures of the specific monochromatic colors mentioned!

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Determine Matching for Arbitrary Spectra

Given

- Some light spectrum s(λ)

How do we find R, G, B?

- Coefficients to describe color of s(λ) in **RGB** space

A: Integrate with color matching functions

- Treat spectra as vector space
- Dot product of s1, s2 defined as

$$\int s_1(\lambda)s_2(\lambda)d\lambda$$

$$R = \int s(\lambda)r(\lambda)d\lambda$$

$$G = \int s(\lambda)g(\lambda)d\lambda$$

$$B = \int s(\lambda)b(\lambda)d\lambda$$

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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(λ), y(λ), z(λ) are now positive everywhere
- But the primaries contain "negative" light contributions, and are therefore not physically realizable

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Negative Lobes

In general:

- It is not possible to find three color primaries (monochromatic or continuous spectrum) that can produce all visible colors with positive weights

Q: How can this be?

- We only have 3 types of cones, after all?

Negative Lobes

In general:

- It is not possible to find three color primaries (monochromatic or continuous spectrum) that can produce all visible colors with positive weights

Q: How can this be?

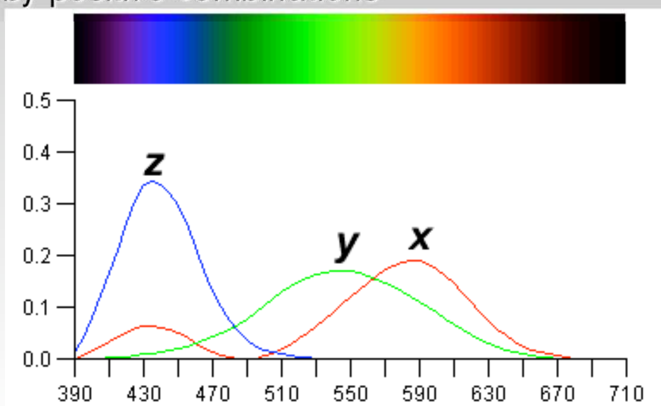
- We only have 3 types of cones, after all?

A: the spectral sensitivity curves of cones overlap

- i.e. the cones span a linear color (vector) space , but this space is not orthonormal!
- Orthonormalization introduces negative weights…

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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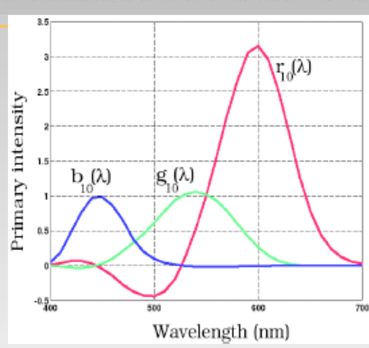
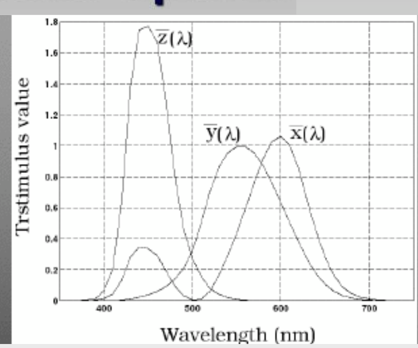
Matching Functions - Measured vs. CIE Color Spaces





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(λ), y(λ), z(λ)
  - *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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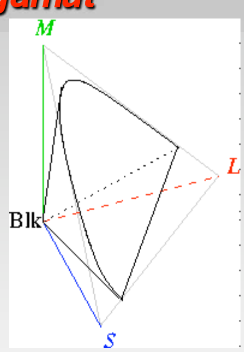
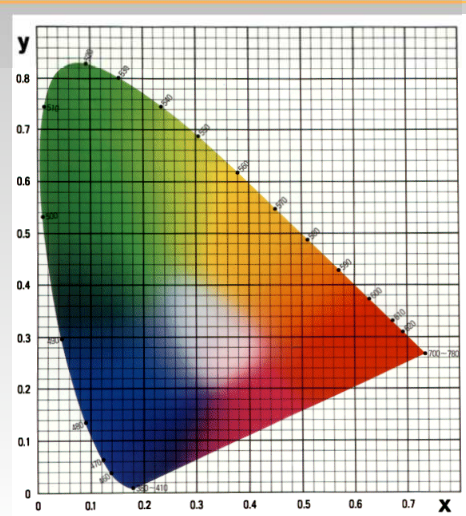
CIE Gamut and λ Chromaticity Diagram

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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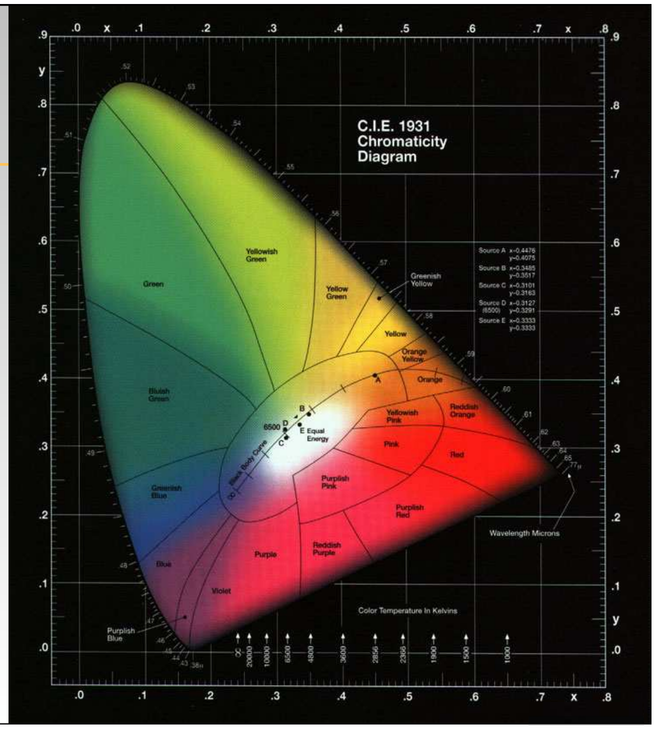
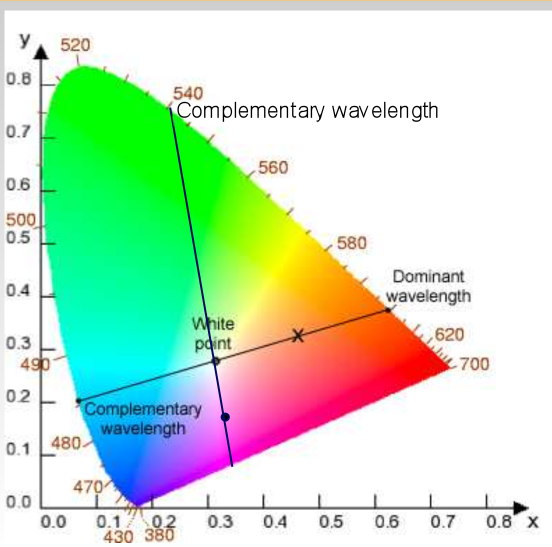
CIE Diagram

- 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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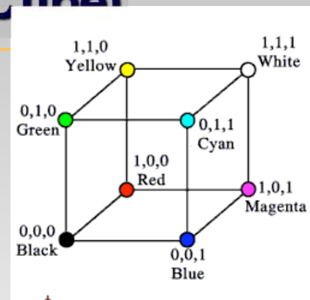
RGB Color Space (Color Cube)

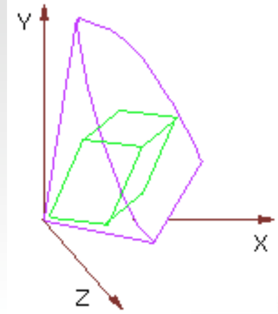
Define colors with (r, g, b) amounts of red, green, and blue

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

RGB color cube sits within CIE color space

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

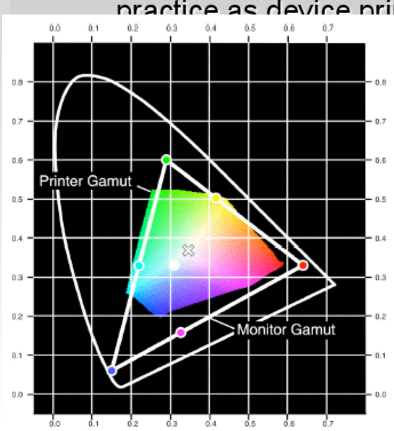


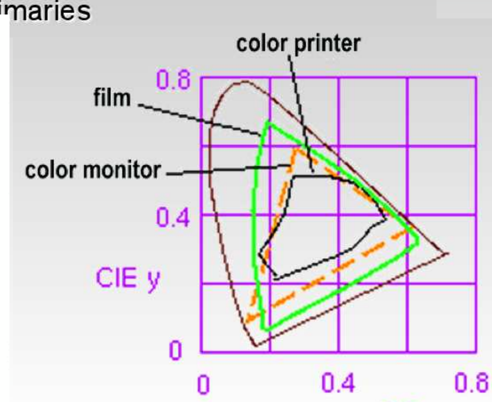


Device Color Gamuts

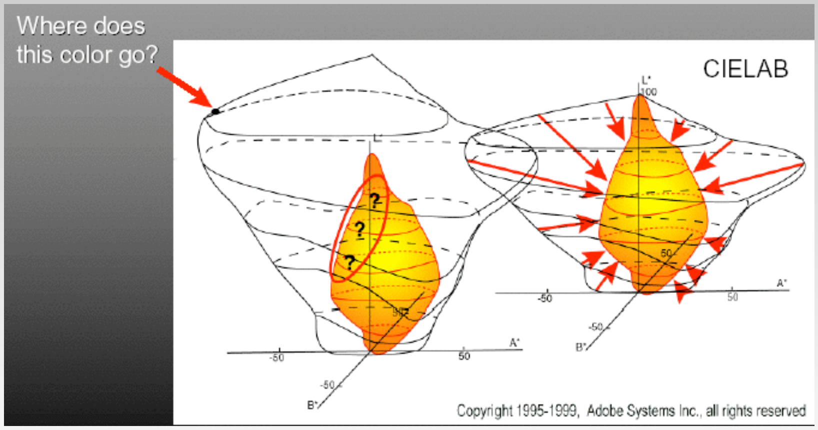
Use CIE chromaticity diagram to compare the gamuts of various devices

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





Gamut Mapping



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Additive vs. Subtractive Colors

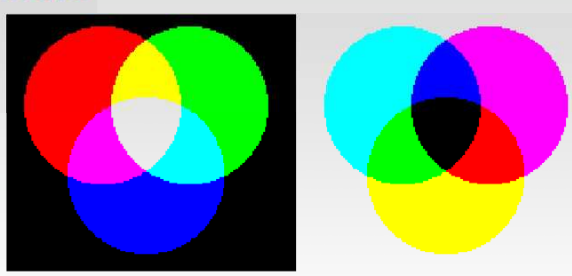
Additive: light

- 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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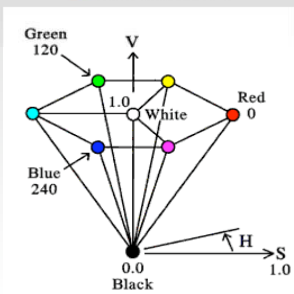
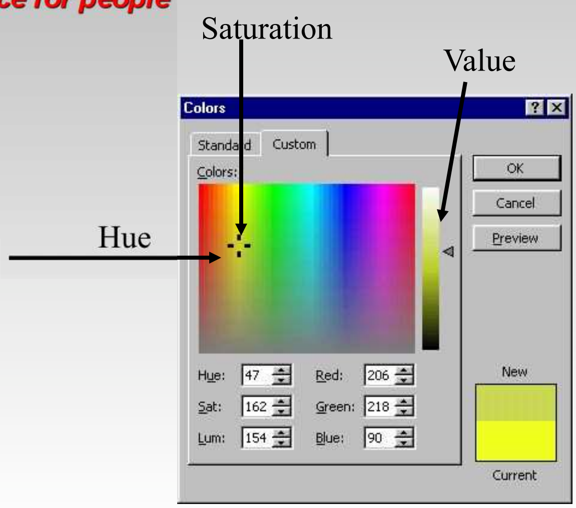
HSV Color Space

More intuitive color space for people

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





Monitors

Monitors have nonlinear response to input

- Characterize by gamma
  - *displayedIntensity = a^{γ} (maxIntensity)*

Gamma correction

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

  = a (maxIntensity)

Gamma for CRTs:

- Around 2.4

Coming Up...

Friday, next week:

- Ray-tracing

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