Color

Wolfgang Heidrich

Course News

Assignment 3 (project)

- Due April 1

Quiz 2

- Wednesday (Mar 9)
- Topics: Rendering pipeline, but no transformations
- No procedural shaders etc. (Gordon Wetzstein lecture)
  - *But: this will be on the final*

Reading (this week)

- Chapter 20 (color)

Reading (this week & next)

- Chapter 10 (ray tracing)

Course Topics for the Rest of the Term

Color

- Today, Friday

Shadows, Ray-tracing & Global Illumination

- Next week

Parametric Curves/Surfaces

Color

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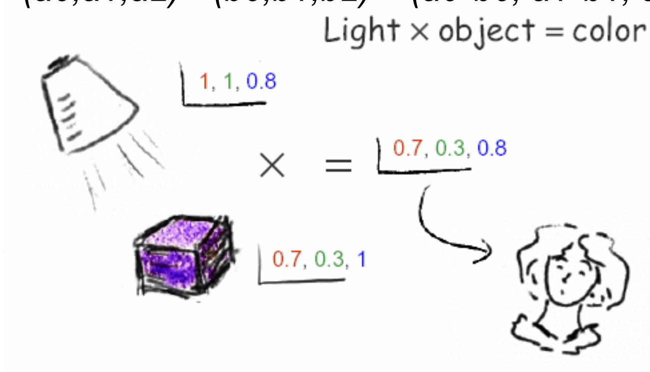
So far in this Course: Simple Model of Color

- Simple model based on RGB triples
- Component-wise multiplication of colors
  - *(a0,a1,a2) * (b0,b1,b2) = (a0*b0, a1*b1, a2*b2)*



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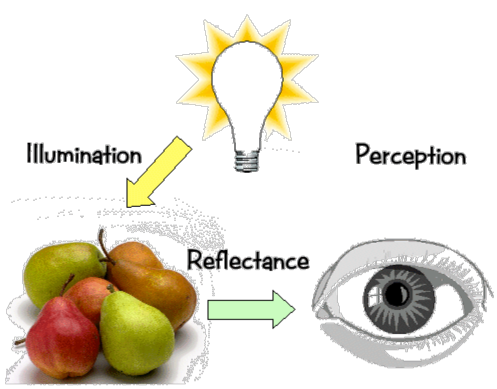
Basics Of Color

Elements of color:



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Basics of Color

Physics

- Illumination
  - *Electromagnetic spectra*
- Reflection
  - *Material properties*
  - *Surface geometry and microgeometry (i.e., polished versus matte versus brushed)*

Perception

- Physiology and neurophysiology
- Perceptual psychology

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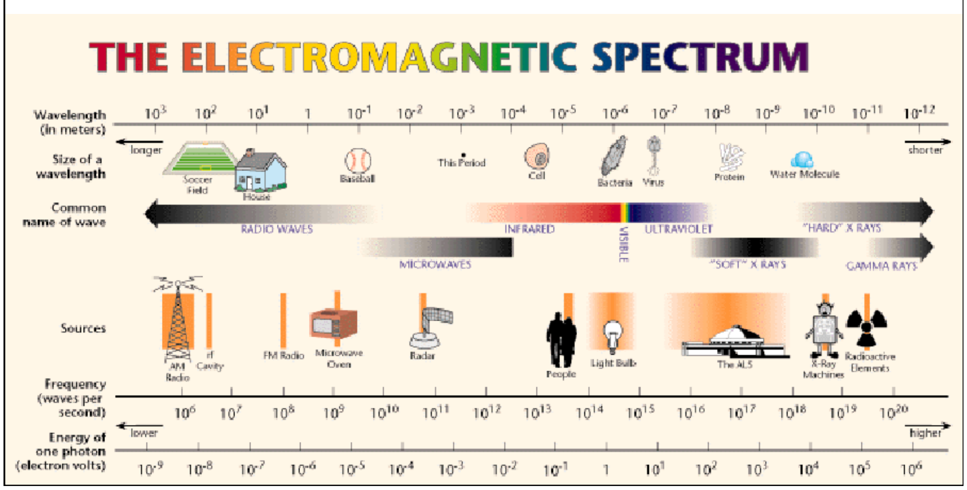
Electromagnetic Spectrum



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

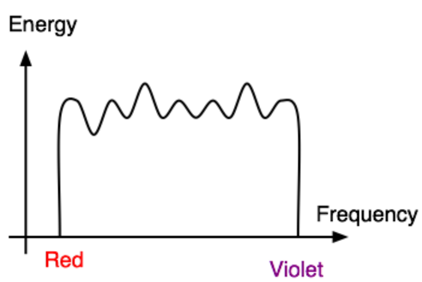
Black body

- 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:

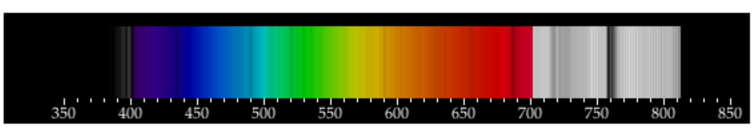
http://www.mhhe.com/physsci/astronomy/applets/Blackbody/frame.html

White Light

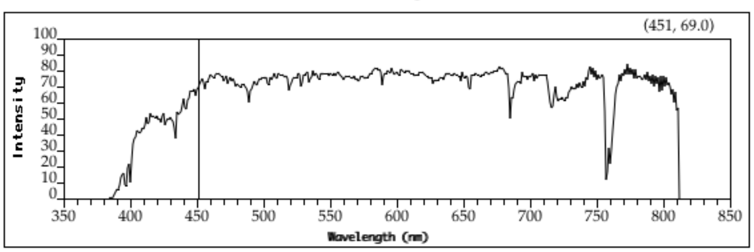
- Sun or light bulbs emit all frequencies within the visible range to produce what we perceive as the "white light”
- But the exact tone depends on the emitted spectrum



Sunlight Spectrum



Emission Graph

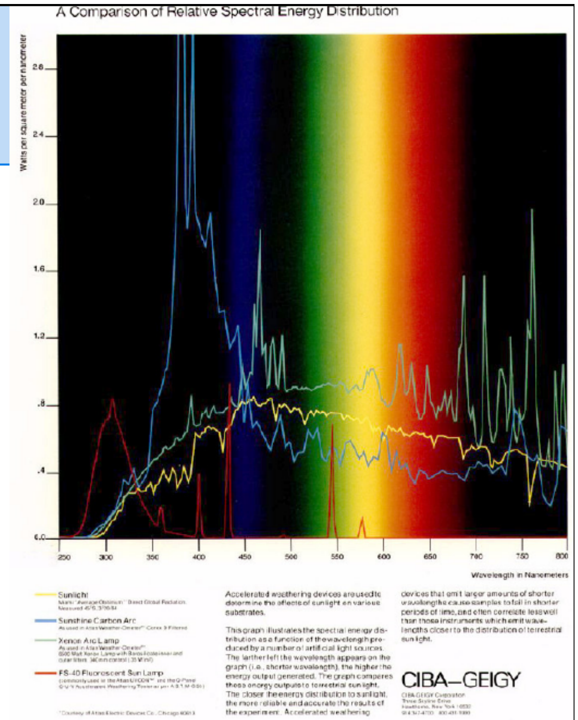


Electromagnetic Spectrum

Continuous Spectrum

Example:

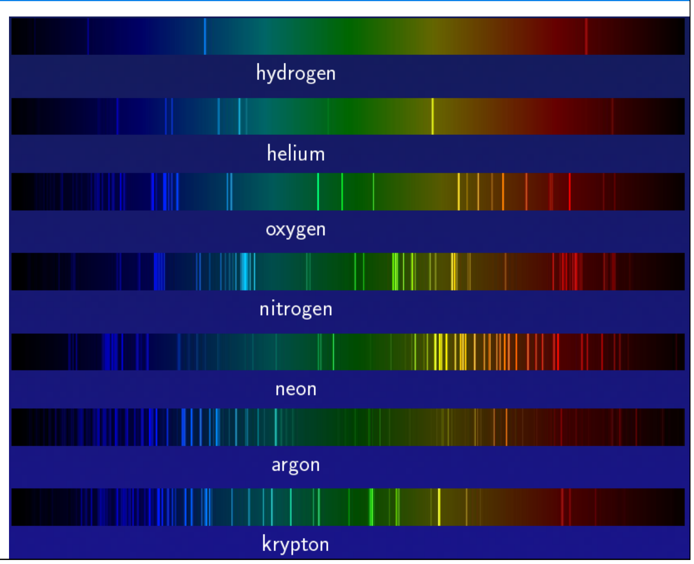
- Sunlight
- Various “daylight” lamps



Line Spectrum

Examples:

- Ionized gases
- Lasers
- Some fluorescent lamps



White Light and Color

- When white light is incident upon an object, some frequencies are reflected and some are absorbed by the object
  - *But generally, the wavelength of reflected photons remains the same*
  - *Exceptions: fluorescense, phosphorescense…*
- Combination of frequencies present in the reflected light that determines what we perceive as the color of the object

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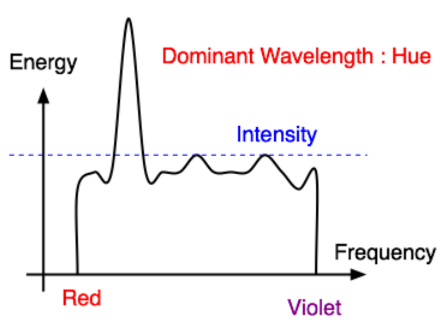
Hue

- Hue (or simply, "color") is dominant wavelength/ frequency



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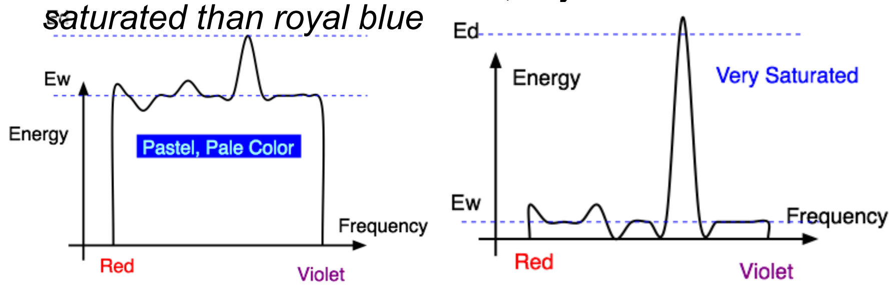
Saturation or Purity of Light

How washed out or how pure the color of the light appears

- Contribution of dominant light vs. other frequencies producing white light
- Saturation: how far is color from grey
  - *Pink is less saturated than red, sky blue is less saturated than royal blue*



Intensity vs. Brightness

Intensity: physical term

- Measured radiant energy emitted per unit of time, per unit solid angle, and per unit projected area of the source (related to the luminance of the source)

Lightness/brightness: perceived intensity of light

- Nonlinear

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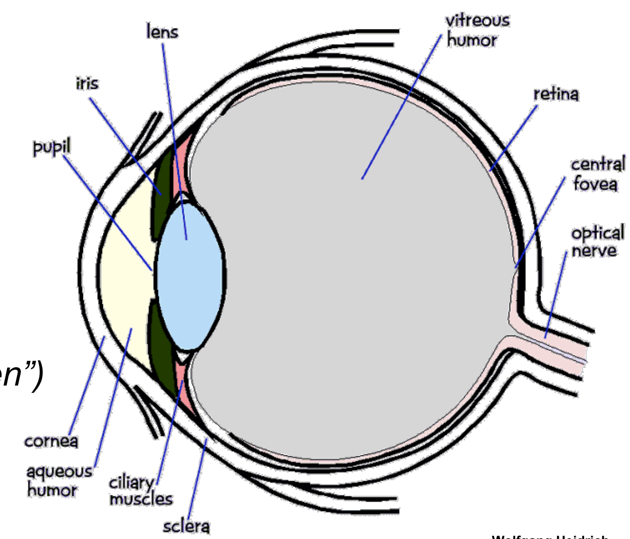
Physiology of Vision

The retina

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



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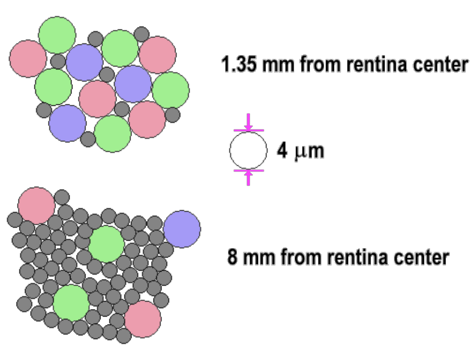
Physiology of Vision

Center of retina is densely packed region called the fovea.

- Cones much denser here than the *periphery*



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Perceptual vs. Colorimetric Terms

Perceptual	*Colorimetric*
• Hue	• Dominant wavelength
• Saturation	• Excitation purity
• Lightness – *Reflecting objects*	• Luminance
• Brightness – *Light sources*	• Luminance

Color/Lightness Constancy

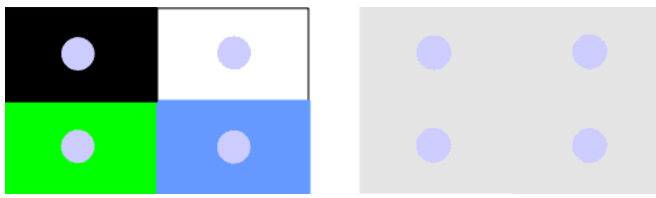
Color perception also depends on surrounding

- Colors in close proximity
- Illumination under which the scene is viewed

Adaptation, Surrounding Color

Color perception is also affected by

- Adaptation (move from sunlight to dark room)
- Surrounding color/intensity:
  - *Simultaneous contrast effect*



Color/Lightness Constancy

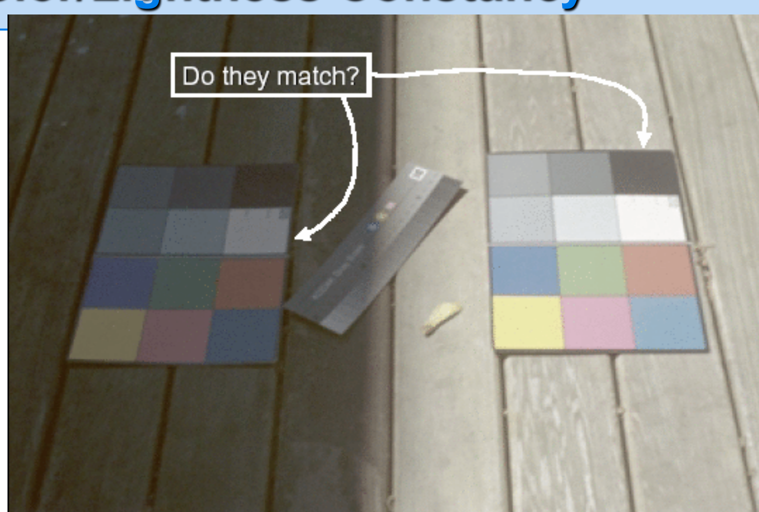
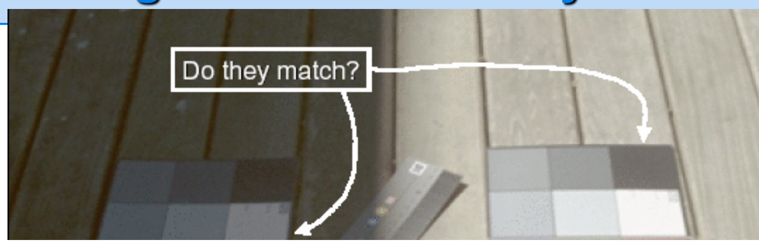


Image courtesy of John MCann

Color/Lightness Constancy



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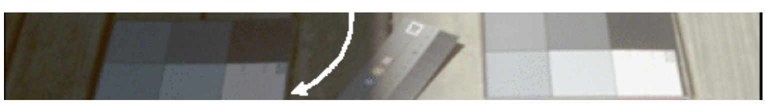
Color/Lightness Constancy



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Color/Lightness Constancy

Color/Lightness Constancy

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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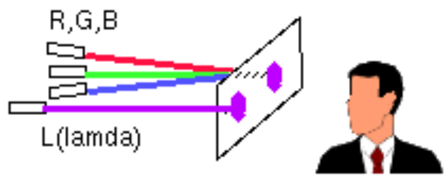
Color Matching Experiments

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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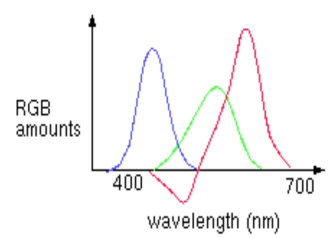
Negative Lobes

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

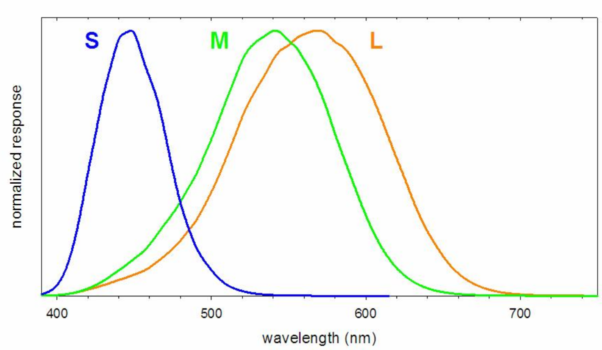
Don't confuse:

- Primaries: the spectra of the three different light sources: **R**, **G**, **B**
  - *For the matching experiments, these were monochromatic (I.e. single wavelength) light!*
  - *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(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

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



Color Matching and Cone Response

Linear Algebra View:

- Space of spectra is infinite-dimensional vector space
  - *Dot product between two spectra, S1, S2:*

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

- 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 wavelengths*

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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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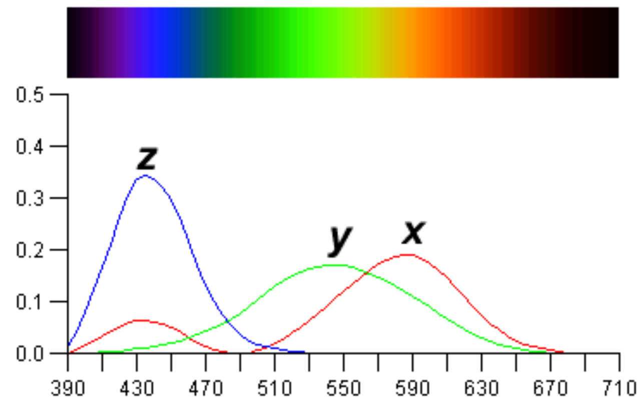
Matching Functions - CIE Color Space

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



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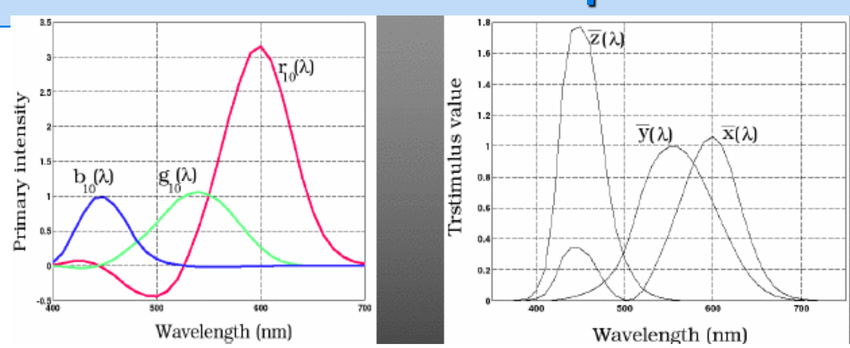
Matching Functions - Measured vs. CIE Color Spaces



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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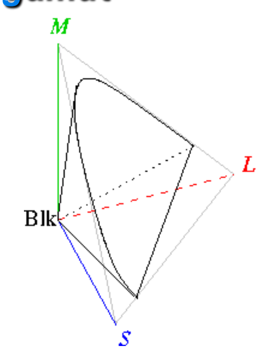
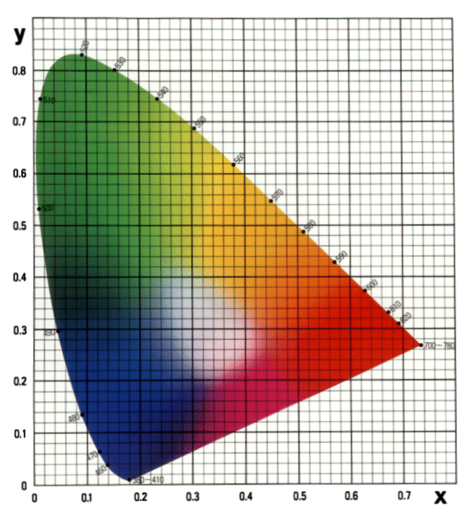
CIE Gamut and λ Chromaticity Diagram

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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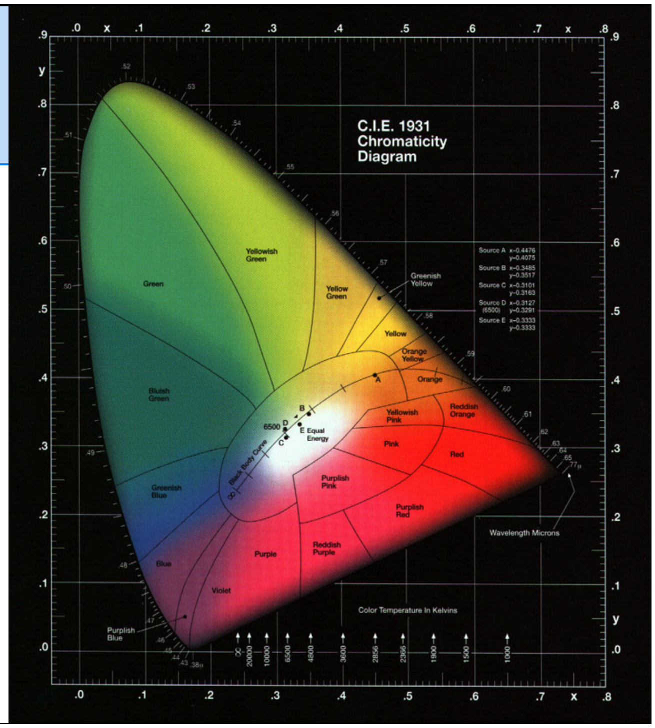
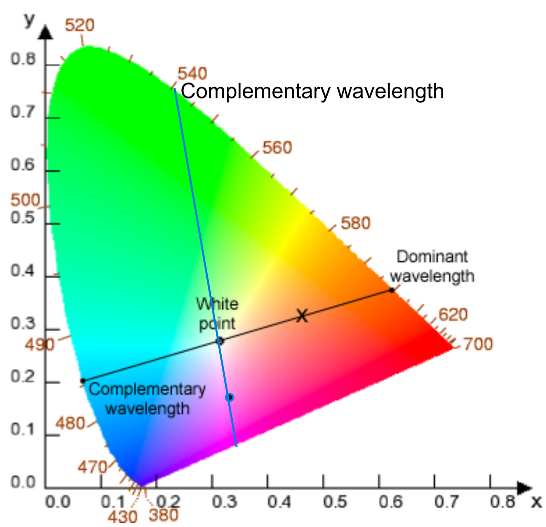
CIE Diagram

- 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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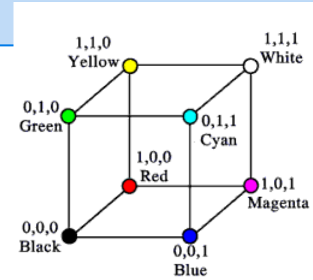
RGB Color Space (Color Cube)

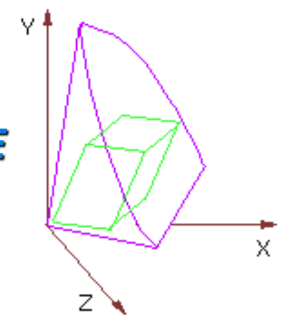
Define colors with (r, g, b) amounts of red, green, and blue

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

RGB color cube sits within CIE

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

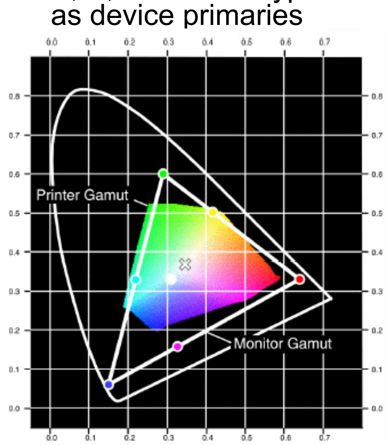


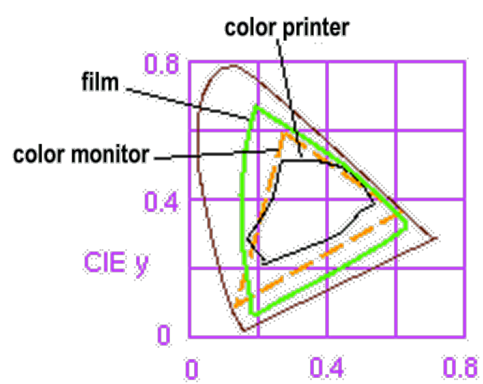


Device Color Gamuts

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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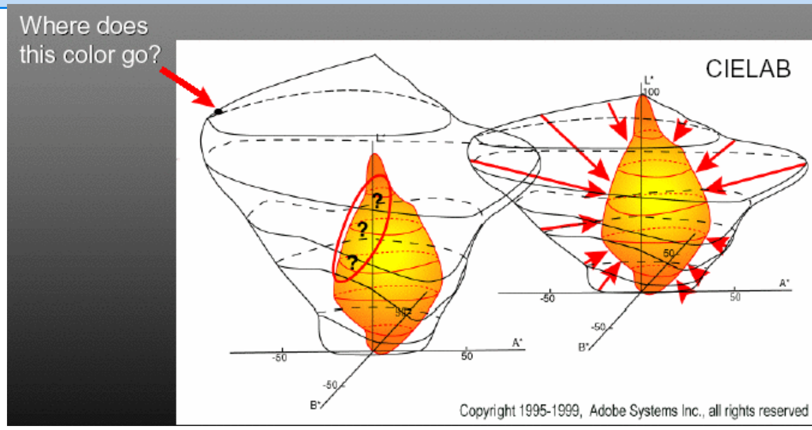
Gamut Mapping



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Additive vs. Subtractive Colors

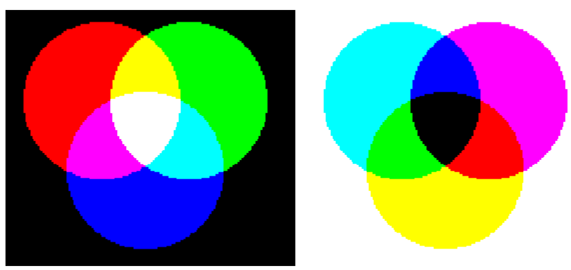
Additive: light

- 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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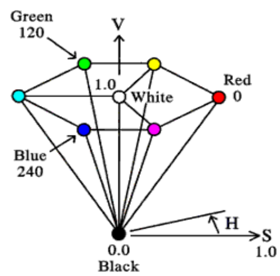
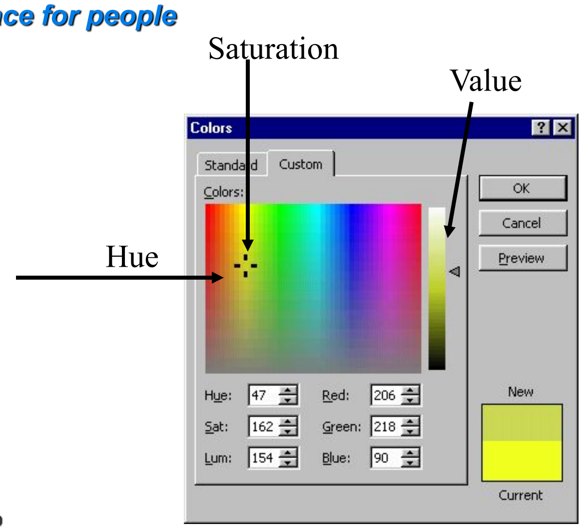
HSV Color Space

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

  = a (maxIntensity)

Gamma for CRTs:

- Around 2.4

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Coming Up…

Wednesday:

- More color, ray-tracing

Friday:

- Ray-tracing

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