University of British Columbia
CPSC 314 Computer Graphics
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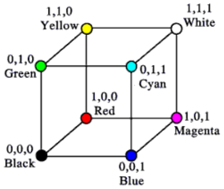
Color

http://www.ugrad.cs.ubc.ca/~cs314/Vjan2016

Vision/Color

RGB Color

- triple (r, g, b) represents colors with amount of red, green, and blue
  - hardware-centric
  - used by OpenGL



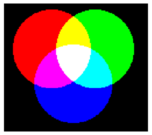
Alpha

- fourth component for transparency
  - (r,g,b,α)
- fraction we can see through
  - $c = \alpha c_f + (1-\alpha)c_b$
- as we saw in blending/compositing already

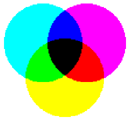
Additive vs. Subtractive Colors

- additive: light
  - monitors, LCDs
  - RGB model
- subtractive: pigment
  - printers
  - CMY model
  - dyes absorb light

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



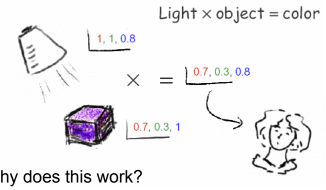
additive



subtractive

Component Color

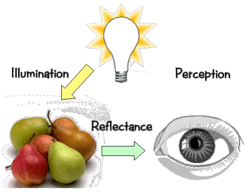
- component-wise multiplication of colors
  - (a0,a1,a2) * (b0,b1,b2) = (a0*b0, a1*b1, a2*b2)



  - why does this work?
    - must dive into light, human vision, color spaces

Basics Of Color

- elements of color:



Basics of Color

- physics
  - illumination
    - electromagnetic spectra
  - reflection
    - material properties
    - surface geometry and microgeometry
      - polished versus matte versus brushed
- perception
  - physiology and neurophysiology
  - perceptual psychology

Light Sources

- common light sources differ in 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

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: reddish
    - very hot: bluish
  - demo:

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

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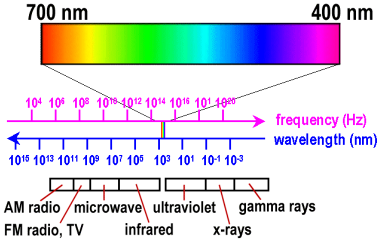
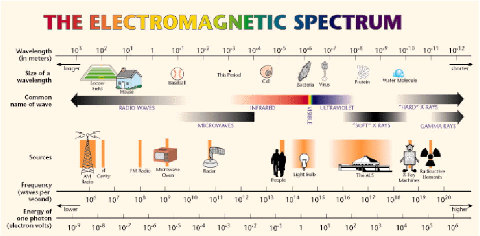
Electromagnetic Spectrum

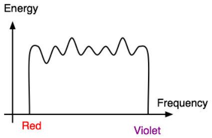


Electromagnetic Spectrum



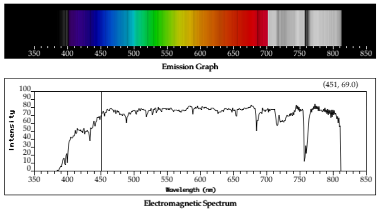
White Light

- sun or light bulbs emit all frequencies within visible range to produce what we perceive as "white light"



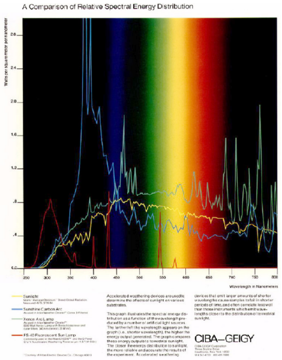
Sunlight Spectrum

- spectral distribution: power vs. wavelength



Continuous Spectrum

- sunlight
- various “daylight” lamps

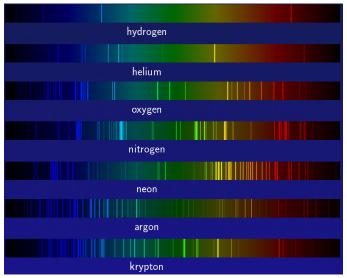


Accelerated weathering devices are used to determine the effects of sunlight on various substrates.

This graph illustrates the spectral energy distribution as a function of the wavelength produced by a number of artificial light sources. The farther left the wavelength appears on the graph (i.e., shorter wavelength), the higher the energy output generated. The graph compares these energy outputs to terrestrial sunlight. The closer the energy distribution to sunlight, the more reliable and accurate the results of the experiment. Accelerated weathering devices that emit larger amounts of shorter wavelengths cause samples to fail in shorter periods of time, and often correlate less well than those instruments which emit wavelengths closer to the distribution of terrestrial sunlight.

Line Spectrum

- 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
- combination of frequencies present in the reflected light that determines what we perceive as the color of the object

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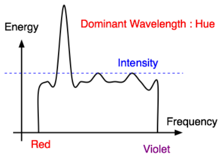
Hue

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



- integration of energy for all visible wavelengths is proportional to intensity of color

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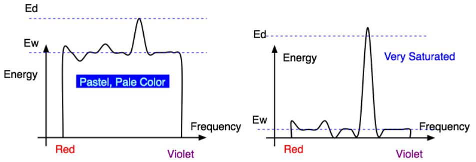
Saturation or Purity of Light

- 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

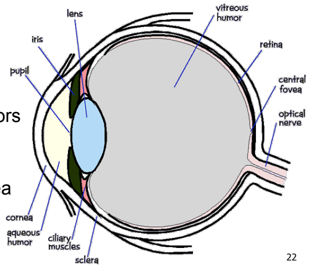
- intensity : physical term
  - measured radiant energy emitted per unit of time, per unit solid angle, and per unit projected area of the source (related to the luminance of the source)
- lightness/brightness: perceived intensity of light
  - nonlinear

Perceptual vs. Colorimetric Terms

Perceptual	Colorimetric
Hue	Dominant wavelength
Saturation	Excitation purity
Lightness *reflecting objects*	Luminance
Brightness *light sources*	Luminance

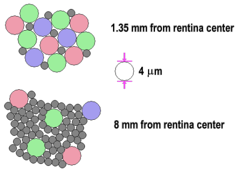
Physiology of Vision

- the retina
  - rods
    - b/w, edges
  - cones
    - 3 types
    - color sensors
  - uneven distribution
    - dense fovea



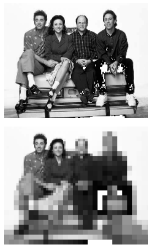
Physiology of Vision

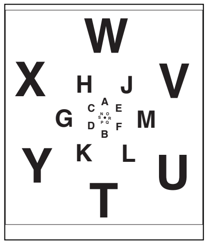
- Center of retina is densely packed region called the *fovea*.
  - Cones much denser here than the *periphery*



Foveal Vision

- hold out your thumb at arm's length





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

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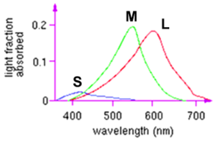
Trichromacy

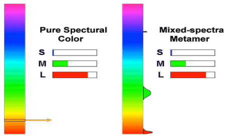
- three types of cones
  - L or R, most sensitive to red light (610 nm)
  - M or G, most sensitive to green light (560 nm)
  - S or B, most sensitive to blue light (430 nm)



- color blindness results from missing cone type(s)

Metamers

- a given perceptual sensation of color derives from the stimulus of all three cone types



- identical perceptions of color can thus be caused by very different spectra
- demo

http://www.cs.brown.edu/exploratories/freeSoftware/catalogs/color_theory.html

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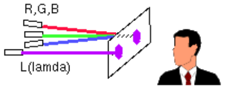
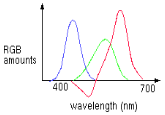
Color Spaces

- three types of cones suggests color is a 3D quantity. how to define 3D color space?



- idea: perceptually based measurement
  - shine given wavelength (λ) on a screen
  - user must control three pure lights producing three other wavelengths
    - used R=700nm, G=546nm, and B=436nm
  - adjust intensity of RGB until colors are identical
    - this works because of metamers!
    - experiments performed in 1930s

Negative Lobes



- sometimes need to point red light to shine on target in order to match colors
  - equivalent mathematically to "removing red"
    - but physically impossible to remove red from CRT phosphors
- can't generate all other wavelenths with any set of three positive monochromatic lights!
- solution: convert to new synthetic coordinate system to make the job easy

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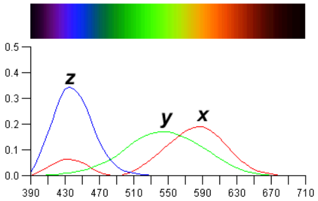
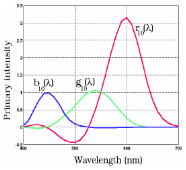
CIE Color Space

- CIE defined 3 "imaginary" lights X, Y, Z
  - any wavelength λ can be matched perceptually by positive combinations

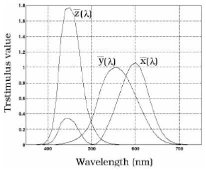
Note that:
X ~ R
Y ~ G
Z ~ B



Measured vs. CIE Color Spaces



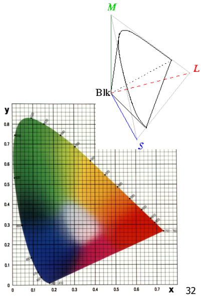
- measured basis
  - monochromatic lights
  - physical observations
  - negative lobes



- transformed basis
  - "imaginary" lights
  - all positive, unit area
  - Y is luminance, no hue
  - X,Z no luminance

CIE and Chromaticity Diagram

- X, Y, Z form 3D shape
- project X, Y, Z on X+Y+Z=1 plane for 2D color space
  - chromaticity diagram
    - separate color from brightness
    - x = X / (X+Y+Z)
    - y = Y / (X+Y+Z)



CIE “Horseshoe” Diagram Facts

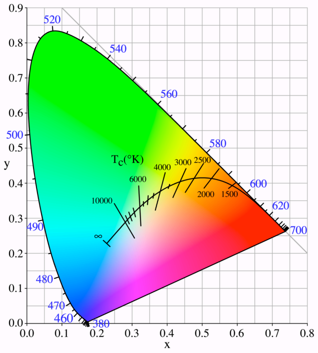
- all visible colors lie inside the horseshoe
  - result from color matching experiments
- spectral (monochromatic) colors lie around the border
  - straight line between blue and red contains purple tones
- colors combine linearly (i.e. along lines), since the xy-plane is a plane from a linear space

CIE “Horseshoe” Diagram Facts

- can choose a point C for a white point
  - corresponds to an illuminant
  - usually on curve swept out by black body radiation spectra for different temperatures

Blackbody Curve

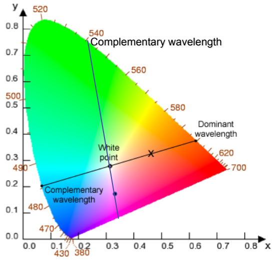
- illumination:
  - candle 2000K
  - A: Light bulb 3000K
  - sunset/ sunrise 3200K
  - D: daylight 6500K
  - overcast day 7000K
  - lightning >20,000K



CIE “Horseshoe” Diagram Facts

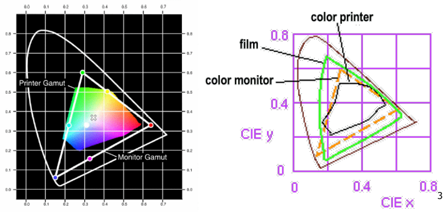
- can choose a point C for a white point
  - corresponds to an illuminant
  - usually on curve swept out by black body radiation spectra for different temperatures
  - two colors are complementary relative to C when are
    - located on opposite sides of line segment through C
      - so C is an affine combination of the two colors
  - find dominant wavelength of a color:
    - extend line from C through color to edge of diagram
    - some colors (i.e. purples) do not have a dominant wavelength, but their complementary color does

Color Interpolation, Dominant & Opponent Wavelength

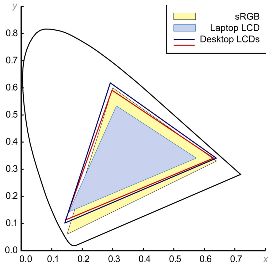


Device Color Gamuts

- gamut is polygon, device primaries at corners
  - defines reproducible color range
  - X, Y, and Z are hypothetical light sources, no device can produce entire gamut

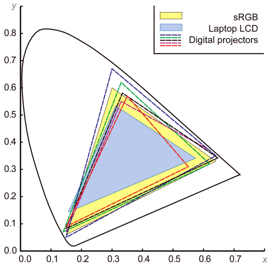


Display Gamuts



From *A Field Guide to Digital Color*, © A.K. Peters, 2003

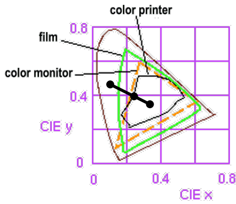
Projector Gamuts



From *A Field Guide to Digital Color*, © A.K. Peters, 2003

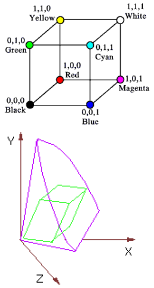
Gamut Mapping

- how to handle colors outside gamut?
  - one way: construct ray to white point, find closest displayable point within gamut



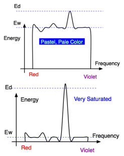
RGB Color Space (Color Cube)

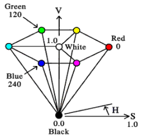
- define colors with (r, g, b) amounts of red, green, and blue
  - used by OpenGL
  - hardware-centric
- RGB color cube sits within CIE color space
  - subset of perceivable colors
  - scale, rotate, shear cube

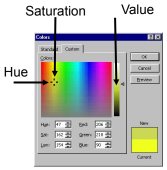


HSV Color Space

- more intuitive color space for people
  - H = Hue
    - dominant wavelength, “color”
  - S = Saturation
    - how far from grey/white
  - V = Value
    - how far from black/white
    - also: brightness B, intensity I, lightness L







HSI/HSV and RGB

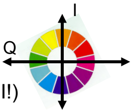
- HSV/HSI conversion from RGB not expressible in matrix
  - H=hue same in both
  - V=value is max, I=intensity is average

$$H = \cos^{-1}\left[\frac{\frac{1}{2}\left[(R-G)+(R-B)\right]}{\sqrt{(R-G)^2+(R-B)(G-B)}}\right] \quad \begin{array}{l}\text{if (B > G),}\\ H = 360 - H\end{array}$$

$$\text{HSI:}\quad S = 1 - \frac{\min(R,G,B)}{I} \qquad I = \frac{R+G+B}{3}$$

$$\text{HSV:}\quad S = 1 - \frac{\min(R,G,B)}{V} \qquad V = \max(R,G,B)$$

YIQ Color Space



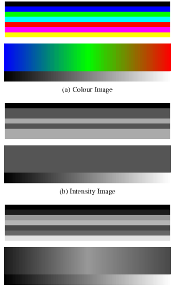
- color model used for color TV
  - Y is luminance (same as CIE)
  - I & Q are color (not same I as HSI!)
  - using Y backwards compatible for B/W TVs
  - conversion from RGB is linear
    - expressible with matrix multiply

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.11 \\ 0.60 & -0.28 & -0.32 \\ 0.21 & -0.52 & 0.31 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

    - green is much lighter than red, and red lighter than blue

Luminance vs. Intensity

- luminance
  - Y of YIQ
  - 0.299R + 0.587G + 0.114B
  - captures important factor
- intensity/brightness
  - I/V/B of HSI/HSV/HSB
  - 0.333R + 0.333G + 0.333B
  - not perceptually based



(a) Colour Image

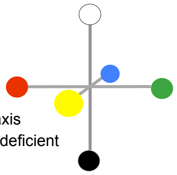
(b) Intensity Image

(c) Luminance Image

www.csse.uwa.edu.au/~robyn/Visioncourse/colour/lecture/node5.html

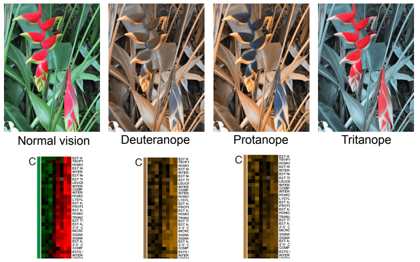
Opponent Color

- definition
  - achromatic axis
  - R-G and Y-B axis
  - separate lightness from chroma channels
- first level encoding
  - linear combination of LMS
  - before optic nerve
  - basis for perception
  - “color blind” = color deficient
    - degraded/no acuity on one axis
    - 8%-10% men are red/green deficient



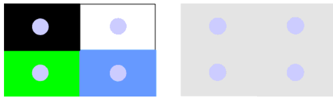
rehue.net

- simulates color vision deficiencies



Color/Lightness Constancy

- color perception depends on surrounding
  - colors in close proximity
    - simultaneous contrast effect



  - illumination under which the scene is viewed

Color/Lightness Constancy

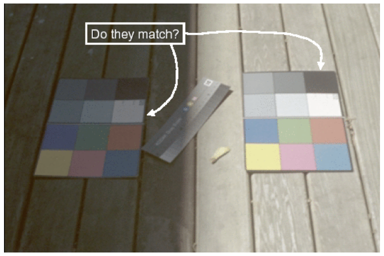


Image courtesy of John McCann

Color/Lightness Constancy

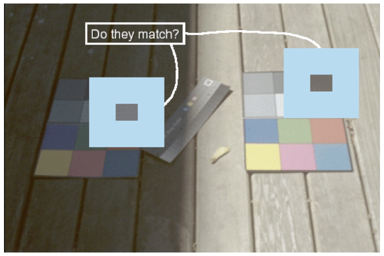
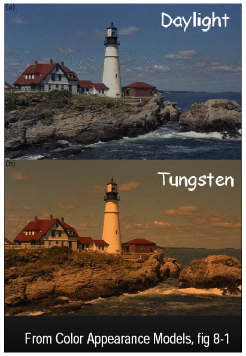


Image courtesy of John McCann

Color Constancy



From Color Appearance Models, fig 8-1

- automatic “white balance” from change in illumination
- vast amount of processing behind the scenes!
- colorimetry vs. perception

Stroop Effect

- **red**
- **blue**
- **orange**
- **purple**
- **green**

Stroop Effect

- **blue**
- **green**
- **purple**
- **red**
- **orange**

- interplay between cognition and perception