University of British Columbia
CPSC 314 Computer Graphics
Jan-Apr 2007

Tamara Munzner

Vision/Color

Week 5, Mon Feb 5

http://www.ugrad.cs.ubc.ca/~cs314/Vjan2007

Reading for Today

- RB Chap Color
- FCG Sections 3.2-3.3
- FCG Chap 20 Color
- FCG Chap 21 Visual Perception

Reading for Next Time

-

Project 1 Grading News

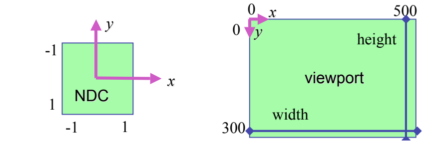
- don't forget to show up 10 min before your slot
  - see news item on top of course page for signup slot reminders
- signup snafu: 10-11 Wed overlaps with class
  - reschedule if possible

Midterm News

- midterm Friday Feb 9
  - closed book
  - no calculators
  - allowed to have one page of notes
    - handwritten, one side of 8.5x11" sheet
  - this room (DMP 301), 10-10:50
  - material covered
    - transformations, viewing/projection

Review: N2D Transformation

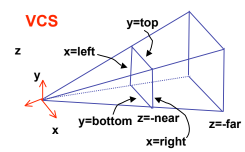
$$\begin{bmatrix}x_D\\y_D\\z_D\\1\end{bmatrix} = \begin{bmatrix}1&0&0&\frac{width}{2}-\frac{1}{2}\\0&1&0&\frac{height}{2}-\frac{1}{2}\\0&0&1&\frac{depth}{2}\\0&0&0&1\end{bmatrix}\begin{bmatrix}\frac{width}{2}&0&0&0\\0&\frac{height}{2}&0&0\\0&0&\frac{depth}{2}&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&-1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}x_N\\y_N\\z_N\\1\end{bmatrix} = \begin{bmatrix}\frac{width(x_N+1)-1}{2}\\\frac{height(-y_N+1)-1}{2}\\\frac{depth(z_N+1)}{2}\\1\end{bmatrix}$$

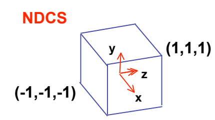


Review: Perspective Derivation

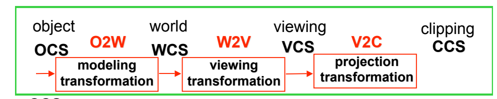
- shear
- scale
- projection-normalization

$$\begin{bmatrix}\frac{2n}{r-l}&0&\frac{r+l}{r-l}&0\\0&\frac{2n}{t-b}&\frac{t+b}{t-b}&0\\0&0&\frac{-(f+n)}{f-n}&\frac{-2fn}{f-n}\\0&0&-1&0\end{bmatrix}$$





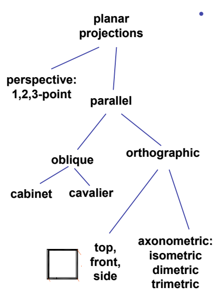
Review: OpenGL Example



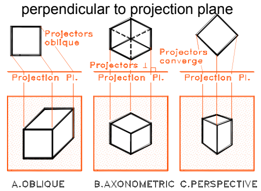

```
CCS   glMatrixMode( GL_PROJECTION );
      glLoadIdentity();
      gluPerspective( 45, 1.0, 0.1, 200.0 );
VCS   glMatrixMode( GL_MODELVIEW );
      glLoadIdentity();
      glTranslatef( 0.0, 0.0, -5.0 );
WCS   glPushMatrix()
      glTranslate( 4, 4, 0 );   W2O
OCS1  glutSolidTeapot(1);
      glPopMatrix();
      glTranslate( 2, 2, 0);    W2O
OCS2  glutSolidTeapot(1);
```

- transformations that are applied first are specified last

Review: Projection Taxonomy



- perspective: projectors converge
  - orthographic, axonometric: projectors parallel and perpendicular to projection plane
  - oblique: projectors parallel, but not perpendicular to projection plane

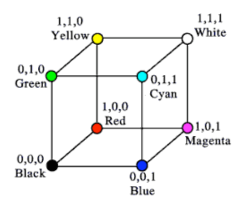


http://ceprofs.tamu.edu/tkramer/ENGR%20111/5.1/20

Vision/Color

RGB Color

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



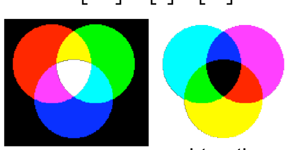
Alpha

- fourth component for transparency
  - (r,g,b,α)
- fraction we can see through
  - $c = \alpha c_f + (1-\alpha)c_b$
- more on compositing later

Additive vs. Subtractive Colors

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

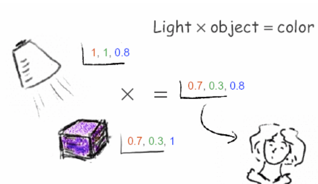
$$\begin{bmatrix}C\\M\\Y\end{bmatrix} = \begin{bmatrix}1\\1\\1\end{bmatrix} - \begin{bmatrix}R\\G\\B\end{bmatrix}$$



additive subtractive

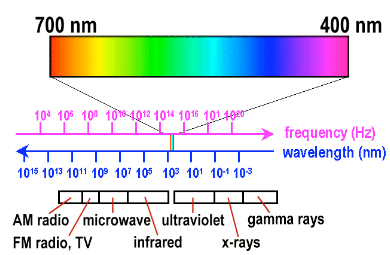
Component Color

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



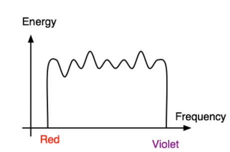
- why does this work?
  - must dive into light, human vision, color spaces

Electromagnetic Spectrum



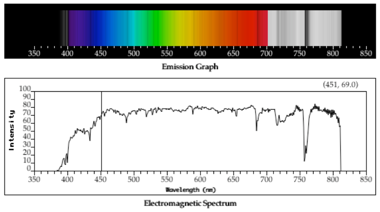
White Light

- 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



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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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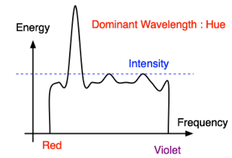
Hue

- 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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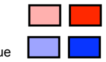
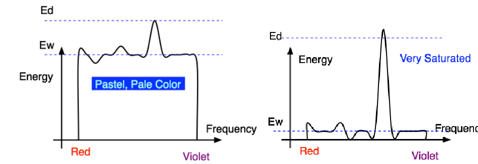
Saturation or Purity of Light

- 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





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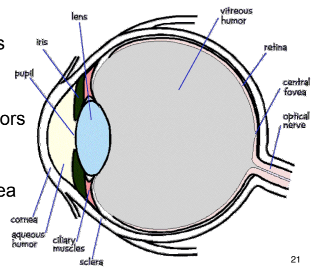
Physiology of Vision

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



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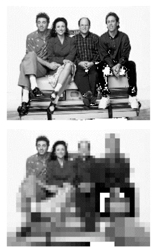
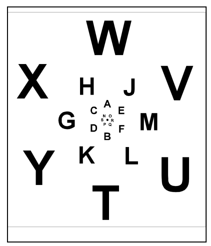
Foveal Vision

- hold out your thumb at arm's length





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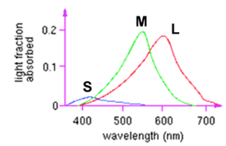
Trichromacy

- 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)

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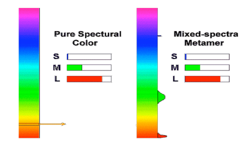
Metamers

- 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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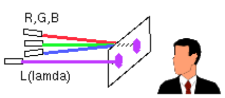
Color Spaces

- 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 (say R=700nm, G=546nm, and B=436nm)
  - adjust intensity of RGB until colors are identical
    - this works because of metamers!

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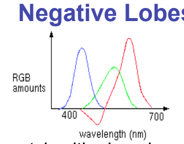
Negative Lobes



- exact target match with phosphors not possible
  - possible: point red light to shine on target
  - impossible: 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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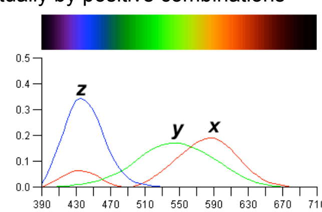
CIE Color Space

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

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



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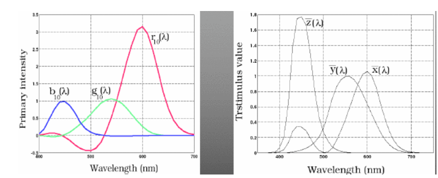
Measured vs. CIE Color Spaces



- 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

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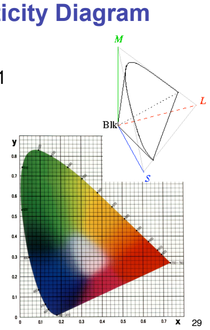
CIE and Chromaticity Diagram

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



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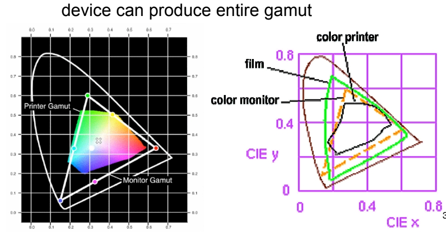
Device Color Gamuts

- 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



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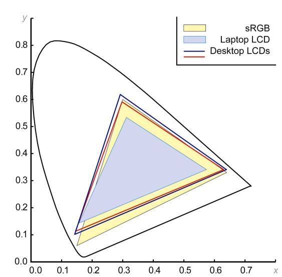
Display Gamuts



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

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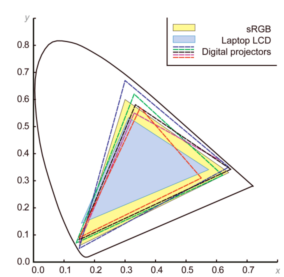
Projector Gamuts



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

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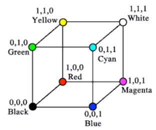
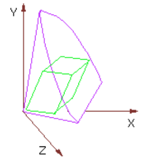
RGB Color Space (Color Cube)

- define colors with (r, g, b) amounts of red, green, and blue
  - used by OpenGL
  - hardware-centric

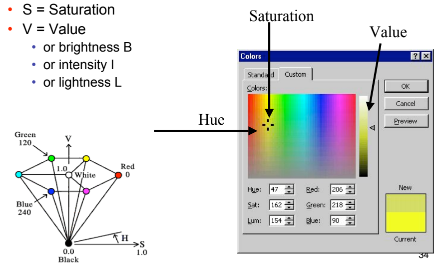


- RGB color cube sits within CIE color space
  - subset of perceivable colors
  - scale, rotate, shear cube



HSV Color Space

- more intuitive color space for people
  - H = Hue
  - S = Saturation
  - V = Value
    - or brightness B
    - or intensity I
    - or lightness L



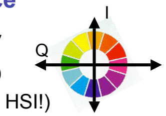
HSV and RGB

- HSV/HSI conversion from RGB
  - not expressible in matrix

$$I = \frac{R+G+B}{3} \qquad S = 1 - \frac{\min(R+G+B)}{I}$$

$$H = \cos^{-1}\left[\frac{\frac{1}{2}[(R-G)+(R-B)]}{\sqrt{(R-G)^2+(R-B)(G-B)}}\right]$$

YIQ Color Space



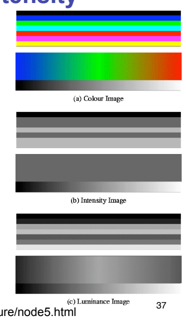
- color model used for color TV
  - Y is luminance (same as CIE)
  - I & Q are color (not same I as HSI!)
  - using Y backwards compatible for B/W TVs
  - conversion from RGB is linear

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

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

Luminance vs. Intensity

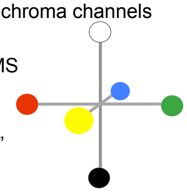
- luminance
  - Y of YIQ
  - 0.299R + 0.587G + 0.114B
- intensity/brightness
  - I/V/B of HSI/HSV/HSB
  - 0.333R + 0.333G + 0.333B



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

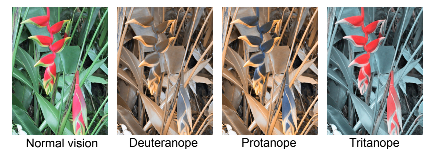
Opponent Color

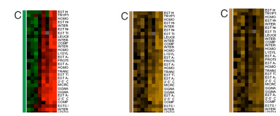
- definition
  - achromatic axis
  - R-G and Y-B axis
  - separate lightness from chroma channels
- first level encoding
  - linear combination of LMS
  - before optic nerve
  - basis for perception
  - defines "color blindness"



vischeck.com

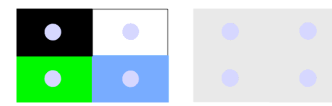
- simulates color vision deficiencies





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

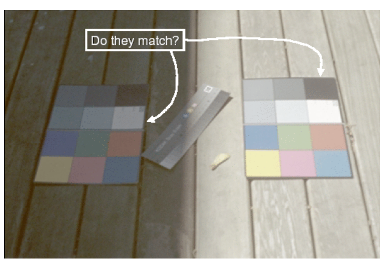


Image courtesy of John McCann

Color/Lightness Constancy

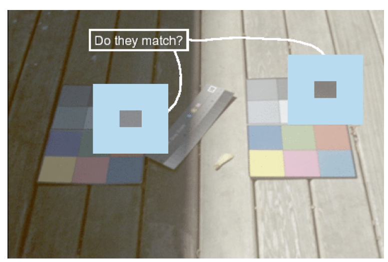


Image courtesy of John McCann

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