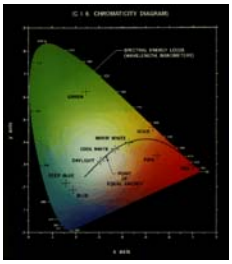
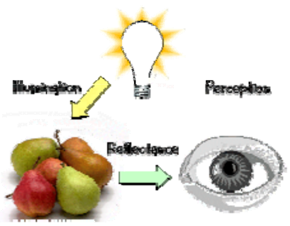


COLOR AND PERCEPTION:

- Physics & Physiology
- Grading
- Expectations

Acknowledgements: David Luebke, U of VA; Chris Hoffmann, Purdue

Elements of Color Perception

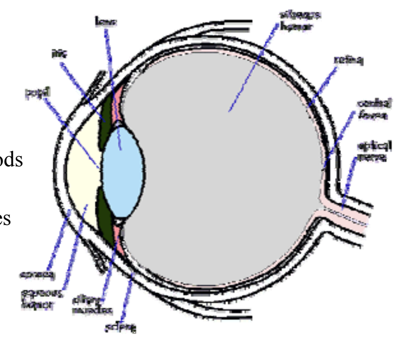


Elements of Color

- Physics:
  - Illumination
    - Electromagnetic spectra; approx. 350 – 720 nm
  - Reflection
    - Material properties (i.e., reflectance, transparency)
    - Surface geometry and micro geometry (i.e., polished versus matte versus brushed)
- Perception
  - Physiology and neurophysiology
  - Perceptual psychology

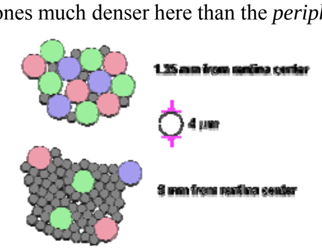
Physiology of the Eye

- The eye:
- The retina
  - 100 M Rods
    - B&W
  - 5 M Cones
    - Color



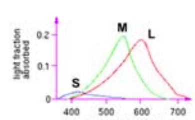
Physiology of the Retina

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



Types of Cones

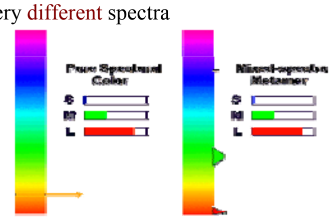
- Three types of cones:
  - **L** or **R**, most sensitive to red light (610 nm)
  - **M** or **G**, most sensitive to green light (560 nm)
  - **S** or **B**, most sensitive to blue light (430 nm)



  - Color blindness results from missing cone type(s)

Perception: 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



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Perception: Other Gotchas

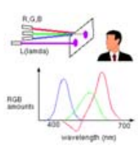
- Color perception is also difficult because:
  - It varies from person to person (thus *standard observers*)
  - It is affected by adaptation
  - It is affected by surrounding color
  - There is Mach-banding

Surround color

Mach banding

Color Spaces

- Three types of cones suggests color is a 3D quantity. How to define 3D color space?
- Idea: shine given wavelength (λ) on a screen, and mix three other wavelengths (R,G,B) on same screen. Have user adjust intensity of RGB until colors are identical:



- *How closely does this correspond to a color CRT?*
- Problem: sometimes need to "subtract" R to match λ

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Summary of Human Color Perception

- Subjectively, the human eye seems to perceive color by three conceptual dimensions:
  - hue,
  - brightness, and
  - saturation.
- This suggests a 3D color space.
- Hardware reproduction of color cannot match human perception perfectly.

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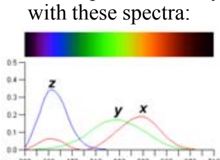
CIE Color Space

- The *CIE* (Commission Internationale d'Eclairage) came up with three hypothetical lights X, Y, and Z with these spectra:



- Approximately:
  X ~ R
  Y ~ G
  Z ~ B
- Idea: any wavelength λ can be matched perceptually by *positive* combinations of X,Y,Z

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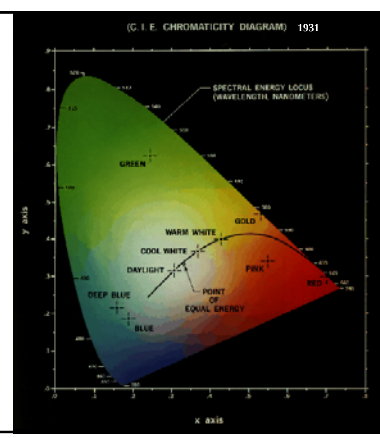

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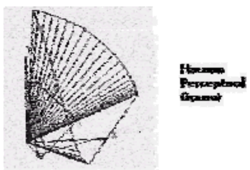
CIE Color Space

- The *gamut* of all colors perceivable is thus a three-dimensional shape in X,Y,Z:



- For simplicity, we often project to the 2D plane X+Y+Z=1

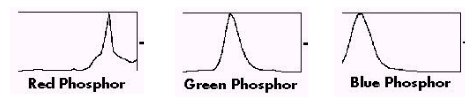
  X = X / (X+Y+Z)

  Y = Y / (X+Y+Z)

  Z = 1 - X - Y

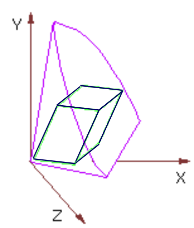
Device Color Gamuts

- X, Y, and Z are hypothetical light sources; no real device can produce the entire gamut of perceivable color
- Example: CRT monitor



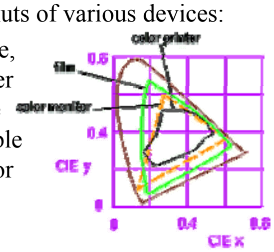
Device Color Gamuts

- The RGB color cube sits within CIE color space something like this:



Device Color Gamuts

- We can use the CIE chromaticity diagram to compare the gamuts of various devices:
- Note, for example, that a color printer cannot reproduce all shades available on a color monitor



Converting Within Color Space

- Simple matrix operation:

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- The transformation $\mathbf{C_2} = \mathbf{M^{-1}_2}\, \mathbf{M_1}\, \mathbf{C_1}$ yields RGB on monitor 2 that is equivalent to a given RGB on monitor 1
- Analogous to change of coordinate system.

Color Models

- Nominal spectral distributions
  - RGB, HSV, CIE, XYZ
- Colors expressed as mix of these *primary* colors

Converting Between Color Spaces

- Converting between color models can also be expressed as such a matrix transform:

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

- *YIQ* is the color model used for color TV in the US. *Y* is luminance, *I* & *Q* are color
  - Note: *Y* is the same as CIE's *Y*
  - Result: backwards compatibility with B/W TV!

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Gamma Correction

- We generally assume color brightness is linear
- But most display devices are inherently nonlinear
  - i.e., brightness(voltage) ≠ 2×brightness(voltage/2)
- Common solution: *gamma correction*
  - Post-transformation on RGB values to map them to linear range on display device:
  - Can have separate γ for R, G, B

$$y = x^{\frac{1}{\gamma}}$$

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RGB Space

- Customarily quantized in the range 0…255
- Full color = 3 bytes/pixel
- Web color specs in hex, as in

  <body bgcolor="#ffffcc">

  "browser safe" means multiples of 0x33

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The RGB Color Model

- The RGB colors can be arranged in a cube, in a space with the dimensions R, G, and B. The colors at the vertices of the RGB cube are then:

Color	R	G	B
black	0	0	0
white	255	255	255
red	255	0	0
green	0	255	0
blue	0	0	255
cyan	0	255	255
magenta	255	0	255
yellow	255	255	0

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RGB Cube Properties

- The main diagonal from black to white contains the gray scale.
- If a specific color is given as (R,G,B) and k is a number smaller than 1, then (kR, kG, kB) has approximately the same hue and is dimmer. So, we can model color intensity by
  – (kR, kG, kB), k < 1
  – Note that the brightness of (R,G,B) is not exceeded

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RGB Color Mixers

Naïve method

Adaptive method

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HSV (IHS) Color Model

- Based on RGB cube and on the observation that the hue of (*k*R,*k*G,*k*B) is perceived roughly the same as the hue of (R,G,B)
- Demos:

RGB color cube
IHS (HSV) mixer
RGB-IHS mixer

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