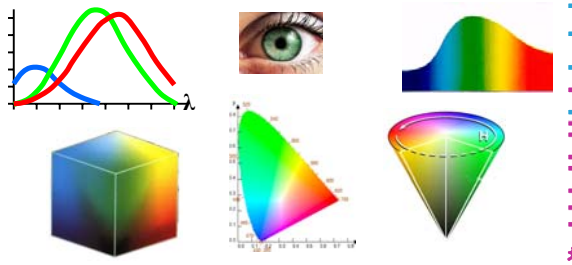
Color and Color Models

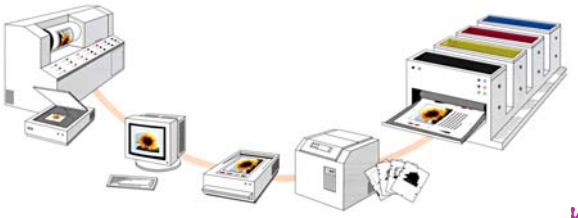


Color Models

- Problem Specification
- Light and Perception
- Colorimetry
- Device Color Systems
- Color Ordering Systems

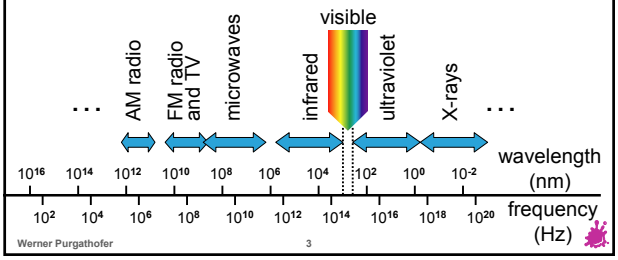
Color - Why Do We Care?

- Computer Graphics is all about the generation and the manipulation of color images
- proper understanding and handling of color is necessary at every step



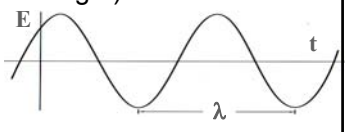
What is Light?

- "light" = narrow frequency band of electromagnetic spectrum
- red border: 380 GHz ≈ 780 nm
- violet border: 780 GHz ≈ 380 nm

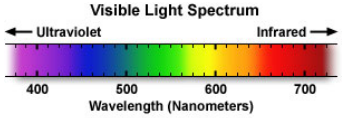


Light - An Electromagnetic Wave

- light is electromagnetic energy
- monochrome light can be described either by frequency f or wavelength λ
- c = λ f (c = speed of light)
- shorter wavelength equals higher frequency

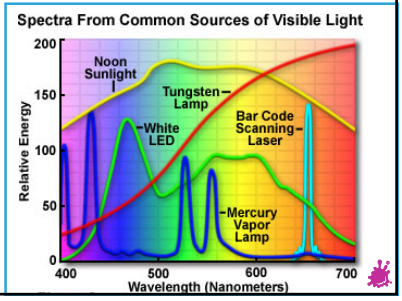


- red ≈ 700 nm
- violet ≈ 400 nm

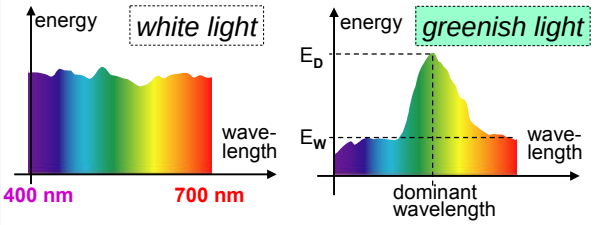


Light – Spectrum

- normally, a ray of light contains many different waves with individual frequencies
- the associated distribution of wavelength intensities per wavelength is referred to as the ***spectrum*** of a given ray or light source



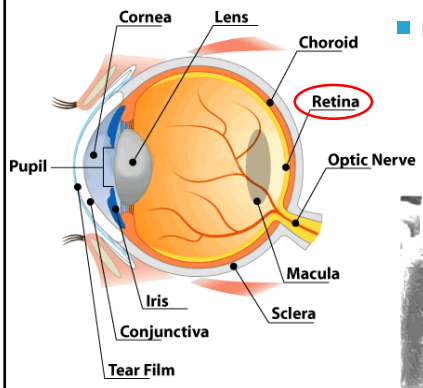
Dominant Wavelength | Frequency



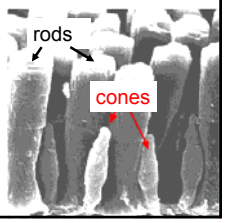
- dominant wavelength | frequency (hue, color)
- brightness (area under the curve)
- purity $\frac{E_D - E_W}{E_D}$

E_D...dominant energy density
E_W...white light energy density

The Human Eye

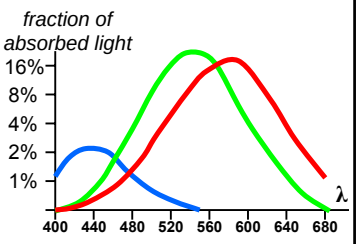


- retina contains
  - rods: b/w
  - cones: color



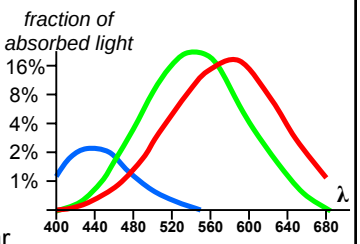
The Human Eye

- 3 types of cones
- different wavelength sensitivities:
  - red
  - green
  - blue

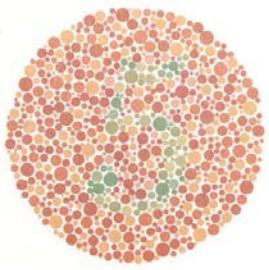


Color Blindness

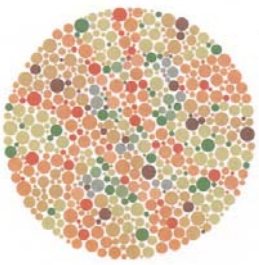
- red/green blindness
  - red & green cones too similar
- blue blindness
  - no blue cones
- other
  - cones missing
  - cones too similar



Color Blindness Tests

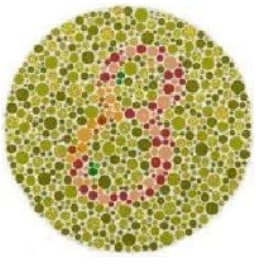


5 = normal
nothing = red/green blind

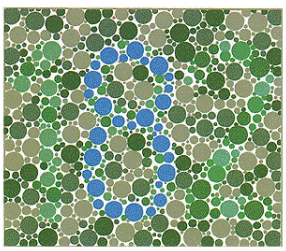


2 = red/green blind
nothing = normal

Color Blindness Tests



8 = normal
3 = red/green weak
nothing = r/g blind



8 = red/green blind
12 = blue/yellow blind
182 = normal

Color Blindness Example

red/green blindness

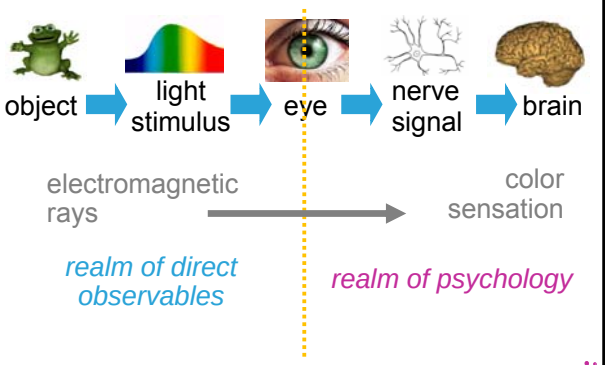
Color Spaces (CS)

- **Color Metric Spaces** (CIE XYZ, L*a*b*)
  - used to measure absolute values and differences - roots in colorimetry
- **Device Color Spaces** (RGB, CMY, CMYK)
  - used in conjunction with device
- **Color Ordering Spaces** (HSV, HLS)
  - used to find colors according to some criterion
- the distinction between them is somewhat obscured by the prevalence of multi-purpose RGB in computer graphics

What is our Goal?

- to be able to ***quantify*** color in a meaningful, expressive, consistent and reproducible way.
- problem: color is a ***perceived quantity***, not a direct, physical observable

Color - A Visual Sensation



Colorimetry (CM)

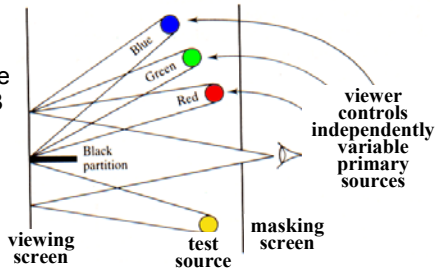
- CM is the branch of color science concerned with *numerically specifying* the color of a physically defined visual stimulus in such manner that
  - stimuli with the same specification look alike under the same viewing conditions
  - stimuli that look alike have the same specification
  - the numbers used are continuous functions of the physical parameters

Colorimetry Properties

- Colorimetry only considers the ***visual discriminability*** of physical beams of radiation
- for the purposes of CM „colors“ are an equivalence class of mutually ***indiscriminable beams***
- colors in this sense cannot be said to be “red”, “green” or any other “color name”
- discriminability is decided before the brain comes into action - CM is not psychology

Color Matching Experiments (CME)

- observers had to match a test light by combining three fixed primaries
- goal: find the unique RGB coordinates for each stimulus



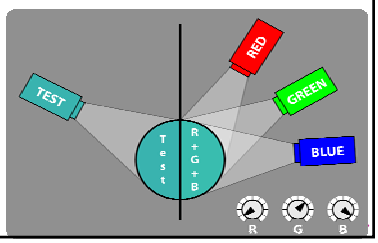
Tristimulus Values

- the values R_Q, G_Q and B_Q for a stimulus Q that fulfill

$$Q = R_Q \cdot R + G_Q \cdot G + B_Q \cdot B$$

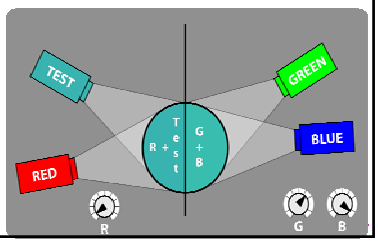
are called the ***tristimulus values*** of Q

- R = 700.0 nm
- G = 546.1 nm
- B = 435.8 nm

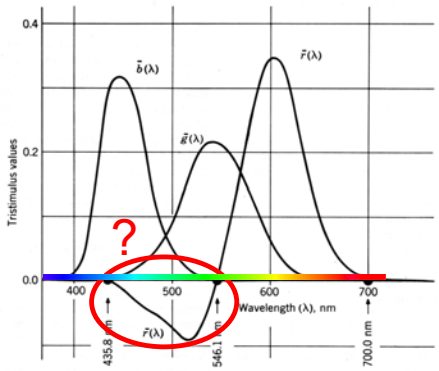


"Negative" Light in a CME

- if a match using only positive RGB values proved impossible, observers could simulate a *subtraction* of red from the match side *by adding it to the test side*

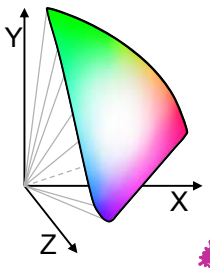


CIE RGB Color Matching Functions



CIE XYZ

- problem solution: ***XYZ color system***
- tristimulus system derived from RGB
- based on 3 *imaginary* primaries
- all 3 primaries are outside the human visual gamut
- only positive XYZ values can occur!
- 1931 by CIE (**C**ommission **I**nternationale de l'**E**clairage)



Transformation CIE RGB → XYZ

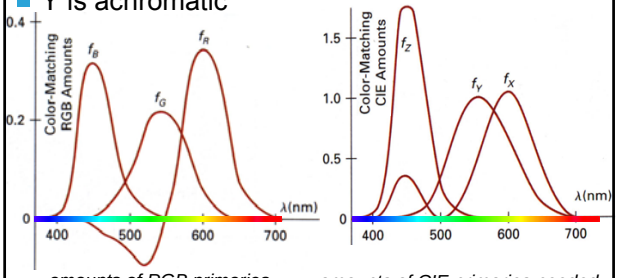
- projective transformation specifically designed so that Y = V (luminous efficiency function)

$$X = 0.723R + 0.273G + 0.166B$$
$$Y = 0.265R + 0.717G + 0.008B$$
$$Z = 0.000R + 0.008G + 0.824B$$

- XYZ → CIE RGB uses inverse matrix
- XYZ → any RGB matrix is device dependent

RGB vs. XYZ

- negative component disappears
- Y is achromatic



amounts of RGB primaries needed to display spectral colors

amounts of CIE primaries needed to display spectral colors

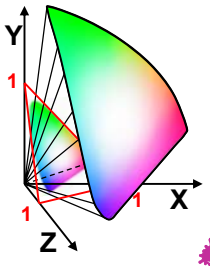
CIE Color Model Formulas

- **XYZ** color model $C(\lambda) = X\mathbf{X} + Y\mathbf{Y} + Z\mathbf{Z}$ (**X, Y, Z** are primaries)
- normalized *chromaticity values* x, y

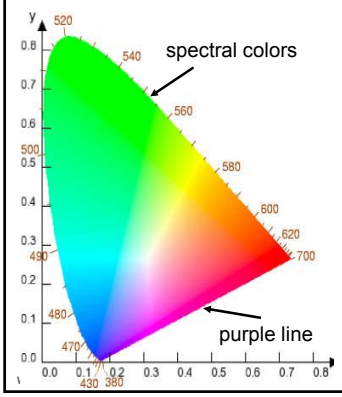
$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z}$$

$$(z = 1 - x - y)$$

- complete description of color: x, y, Y



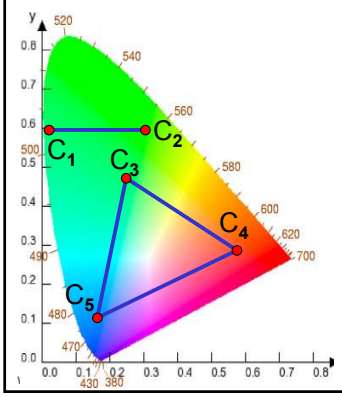
CIE Chromaticity Diagram



- comparing color gamuts
- identifying complementary colors
- determining dominant wavelength, purity

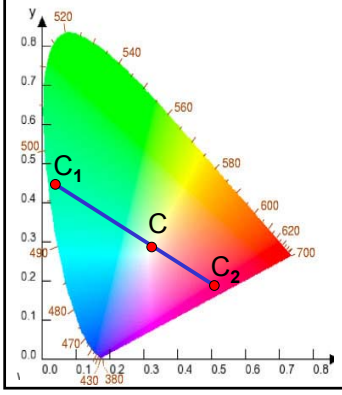
spectral color positions are along the boundary curve

Properties of CIE Diagram (1)



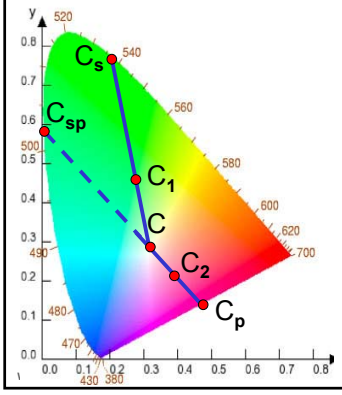
color gamuts defined for a two-color and a three-color system of primaries

Properties of CIE Diagram (2)



representing complementary colors on the chromaticity diagram

Properties of CIE Diagram (3)



determining dominant wavelength and purity with the chromaticity diagram

$C_1 \rightarrow C_s$

$C_2 \rightarrow C_p$?
→ *complement* C_{sp}

Color Spaces (CS)

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  - used to measure absolute values and differences - roots in colorimetry
- **Color Models** (RGB, CMY, CMYK)
  - used in conjunction with device
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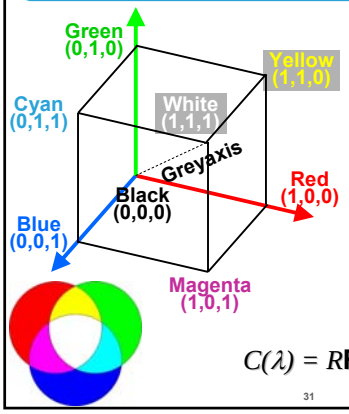
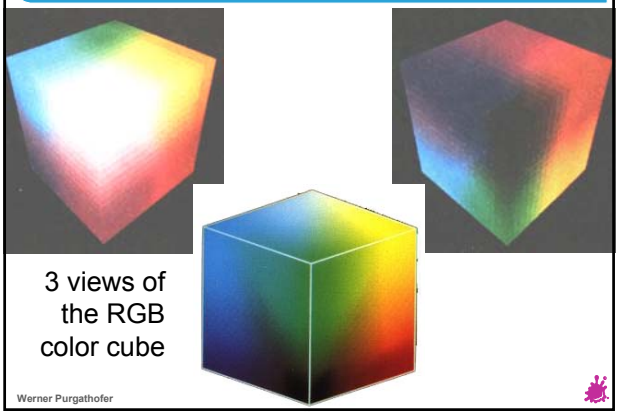
RGB Color Model



- tristimulus theory, peak sensitivity
  - 630nm (red)
  - 530nm (green)
  - 450nm (blue)
- additive color model (*monitors*)

$$C(\lambda) = R\mathbf{R} + G\mathbf{G} + B\mathbf{B}$$

RGB Color Model Images

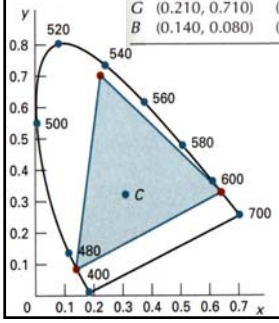


3 views of the RGB color cube

RGB Color Model Gamut

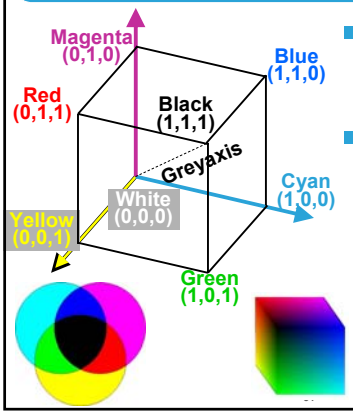
RGB (X,Y) CHROMATICITY COORDINATES

	NTSC Standard	CIE Model	Approx. Color Monitor Values
R	(0.670,0.330)	(0.735, 0.265)	(0.628, 0.346)
G	(0.210, 0.710)	(0.274, 0.717)	(0.268, 0.588)
B	(0.140, 0.080)	(0.167, 0.009)	(0.150, 0.070)



RGB color gamut

CMY Color Model



- primary colors cyan, magenta, yellow
- subtractive color model (*hardcopy devices*)
  - C=G+B, using C "subtracts" R

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

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  - used in conjunction with device
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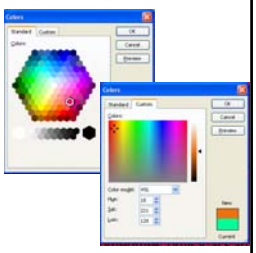
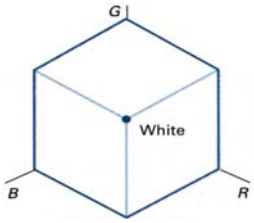
Colour Ordering Systems (COS)



- **primary aim:** enable the user to intuitively choose colour values according to certain criteria
- choice can yield single or multiple colour values
- **examples:** HSV, HLS, Munsell, NCS, RAL Design, Coloroid
- used in bottom-up parts of a design process
- sometimes physical samples are provided

HSV Color Model

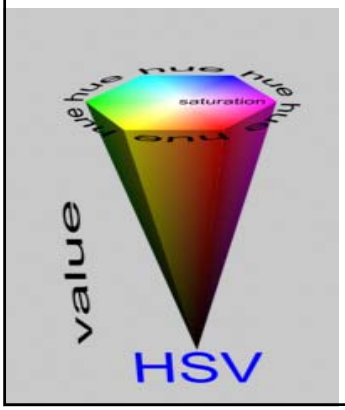
- more *intuitive* color specification
- derived from the RGB color model:
  - when the RGB color cube is viewed along the diagonal from white to black, the color cube outline is a hexagon



RGB Color Cube

Color Hexagon

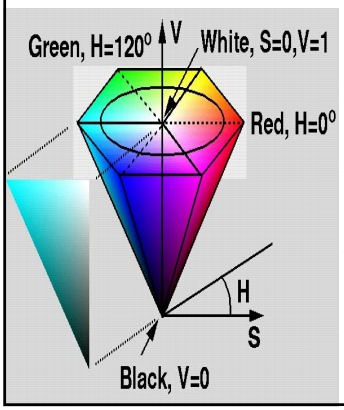
HSV Color Model Hexcone



- color components:
  - hue (H) ∈ [0°, 360°]
  - saturation (S) ∈ [0, 1]
  - value (V) ∈ [0, 1]

HSV hexcone

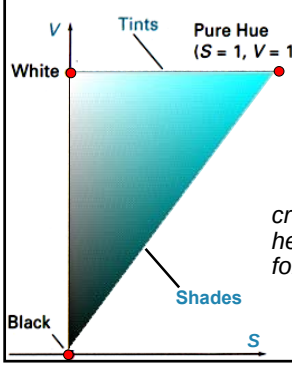
HSV Color Model Hexcone



- color components:
  - hue (H) ∈ [0°, 360°]
  - saturation (S) ∈ [0, 1]
  - value (V) ∈ [0, 1]

HSV hexcone

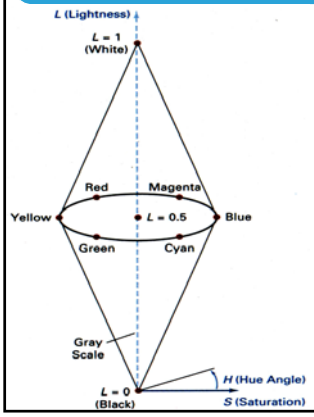
HSV Color Definition



- color definition
  - select hue, S=1, V=1
  - add black pigments, i.e., decrease V
  - add white pigments, i.e., decrease S

cross section of the HSV hexcone showing regions for shades, tints, and tones

HLS Color Model



- color components:
  - hue (H) ∈ [0°, 360°]
  - lightness (L) ∈ [0, 1]
  - saturation (S) ∈ [0, 1]

HLS double cone

Color Model Summary

- **Colorimetry**:
  - **CIE XYZ**: contains all visible colours

- **Device Color Systems**:
  - **RGB**: *additive* device color space (monitors)
  - **CMY(K)**: *subtractive* device color space (printers)
  - **YIQ**: television (NTSC) (Y=luminance, I=R-Y, Q=B-Y)

- **Color Ordering Systems**:
  - **HSV**, **HLS**: for user interfaces