Computer Graphics

- Color -

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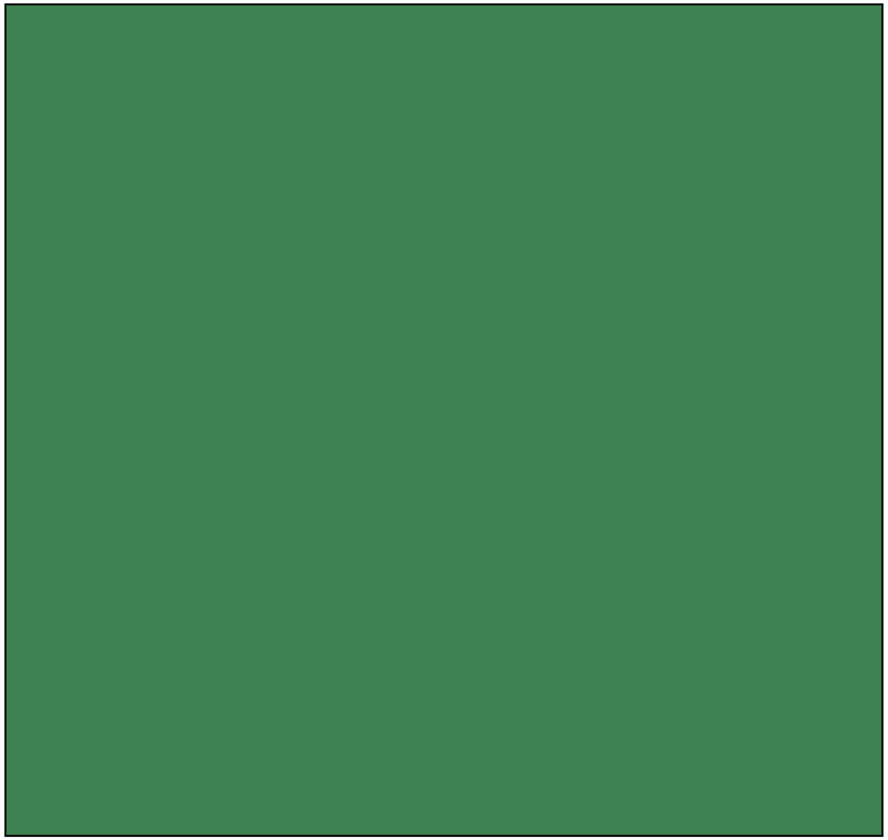
Overview

- **Last time**
  - The Human Visual System
  - The eye
  - Early vision
  - High-level analysis
  - Color perception

- **Today**
  - Gamma Correction
  - Color spaces
  - Transformations

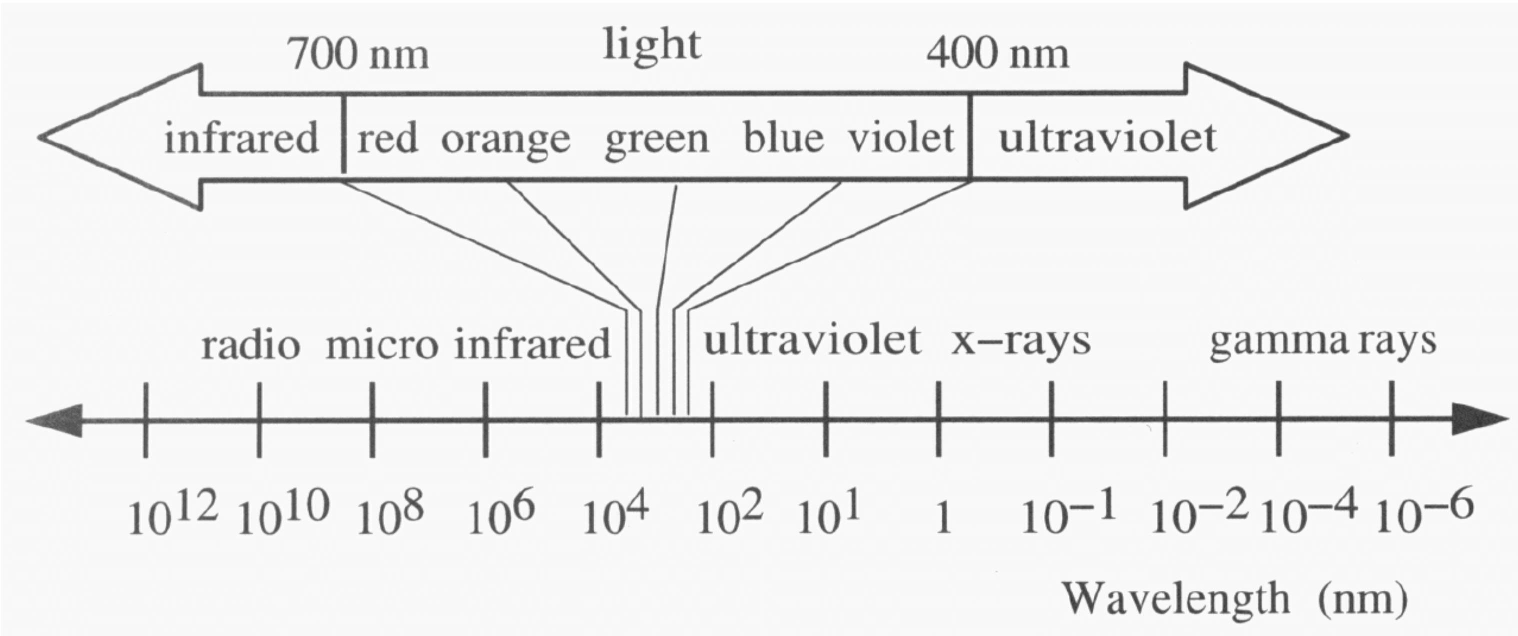
- **Next lecture**
  - Tone Mapping

Color Representation

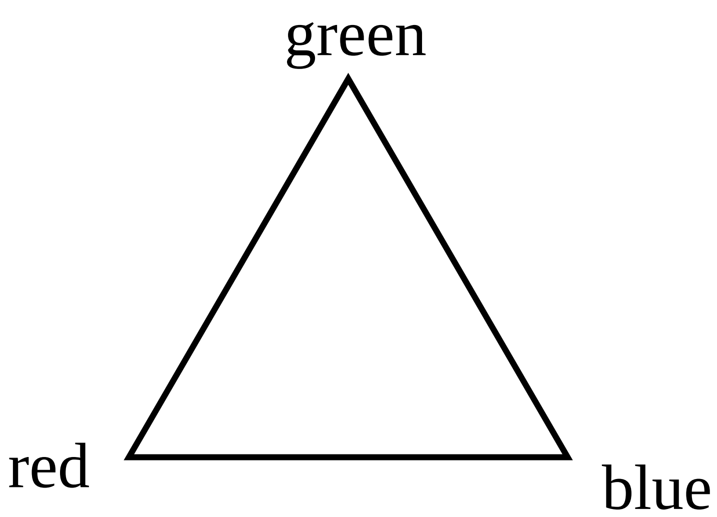


Color Representation

- **by the full spectrum**
  - amplitude of each frequency

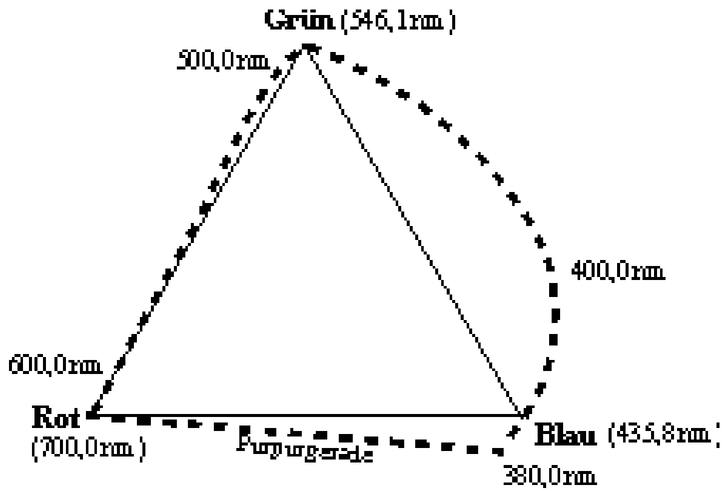


Tristimulus Color Representation



- **interpolation of primaries yields triangle of colors**
- **making use of the three cones and their weighting functions**

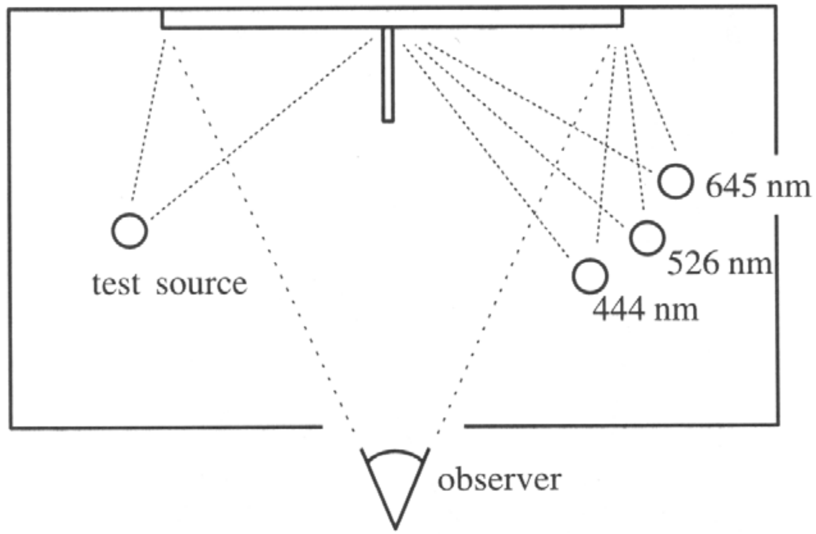
Tristimulus Color Representation

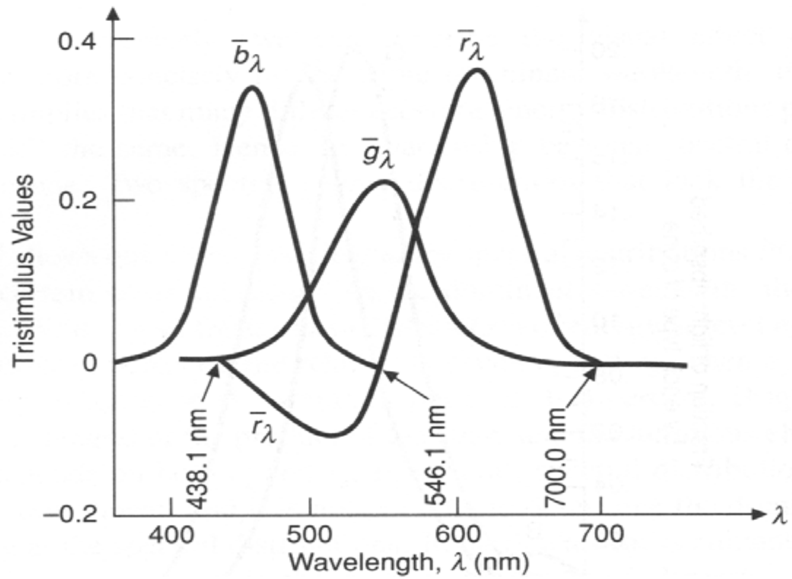


- **colors outside the range of primaries**
- **would require negative weights**
- **idea CIE-XYZ: define virtual colors**

Tristimulus Color Representation

- **Observation**
  - Any color can be matched using three linear independent reference colors
  - May require “negative” contribution to test color
  - *Matching curves* describe the value for matching mono-chromatic spectral colors of equal intensity
    - With respect to a certain set of primary colors



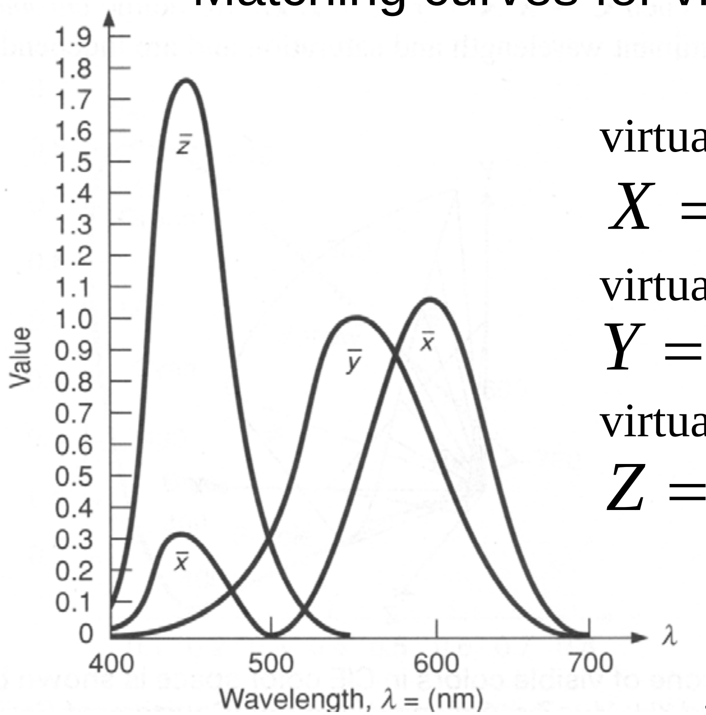


Standard Color Space CIE-*XYZ*

- **CIE Experiments [Guild and Wright, 1931]**
  - Color matching experiments
  - Group ~12 people with „normal“ color vision (from London area)
  - 2 degree visual field (fovea only)
  - Other Experiment in 1964
    - 10 degree visual field, ~50 people (with foreigners)
    - More appropriate for larger field of view but rarely used
- **CIE-XYZ Color Space**
  - Transformation to a set of **virtual primaries**
    - Simple basis transform in 3D color space
  - Goals
    - Abstract from concrete primaries used in experiment
    - All matching functions are positive
    - One primary is roughly proportionally to light intensity

Standard Color Space CIE-*XYZ*

- **Standardized imaginary primaries CIE *XYZ* (1931)**
  - Imaginary primaries more saturated than monochromatic lights
    - Could match all physically realizable color stimuli
  - ***Y*** is roughly equivalent to luminance
    - Shape similar to luminous efficiency curve
  - Monochromatic spectral colors form a curve in 3D XYZ-space
  - Matching curves for virtual CIE XYZ primaries



virtual red

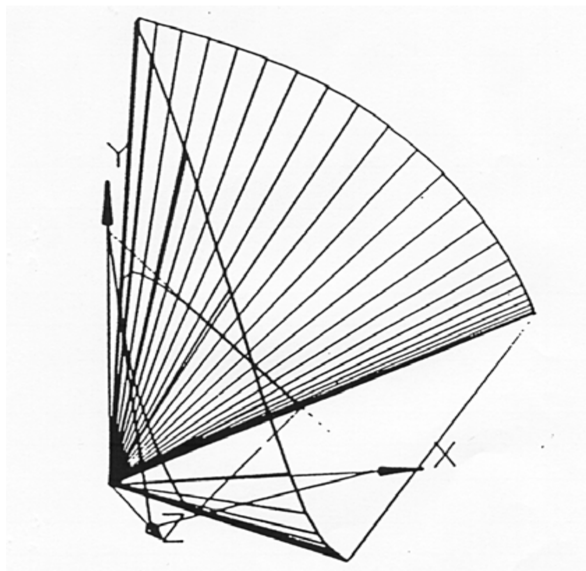
$$X = K_m \int L(\lambda)\bar{x}(\lambda)d\lambda,$$

virtual green

$$Y = K_m \int L(\lambda)\bar{y}(\lambda)d\lambda,$$

virtual blue

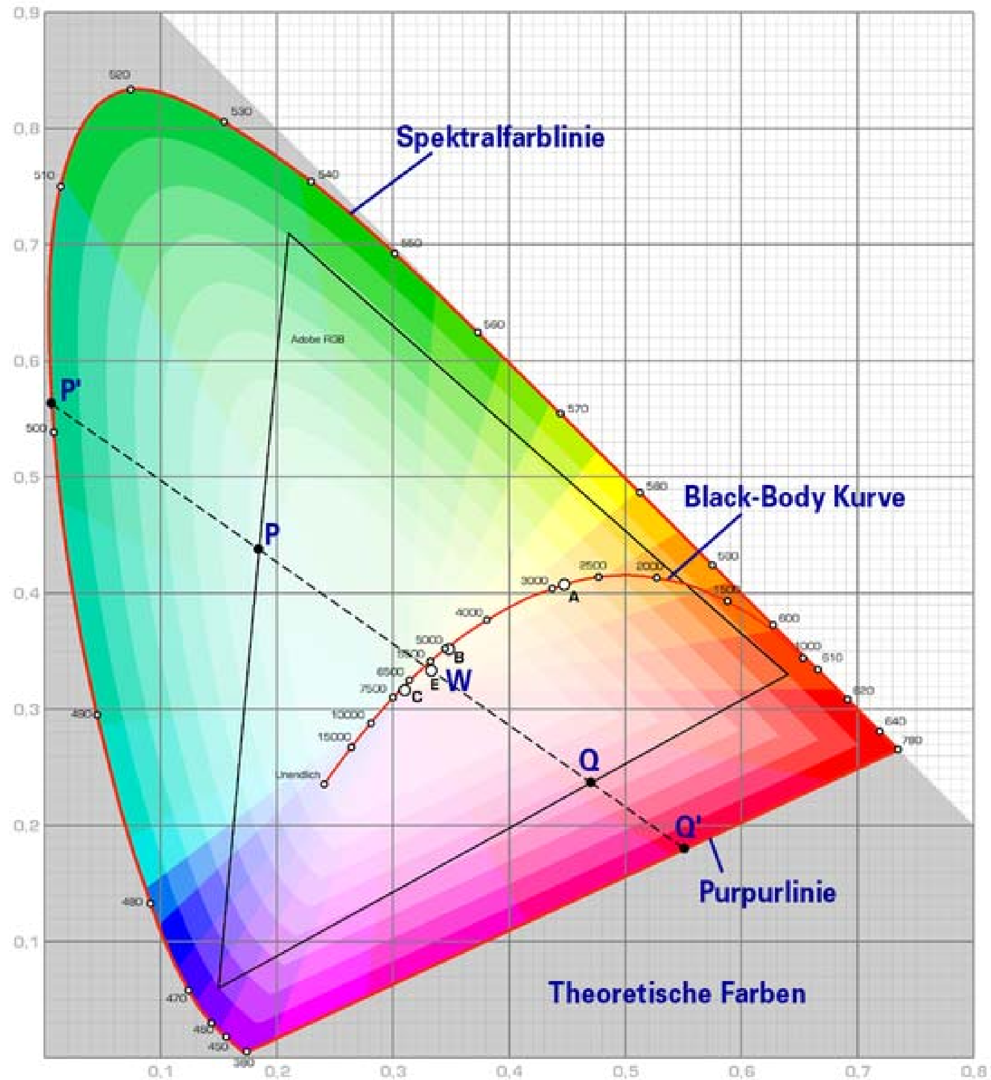
$$Z = K_m \int L(\lambda)\bar{z}(\lambda)d\lambda$$



CIE Chromaticity Diagram

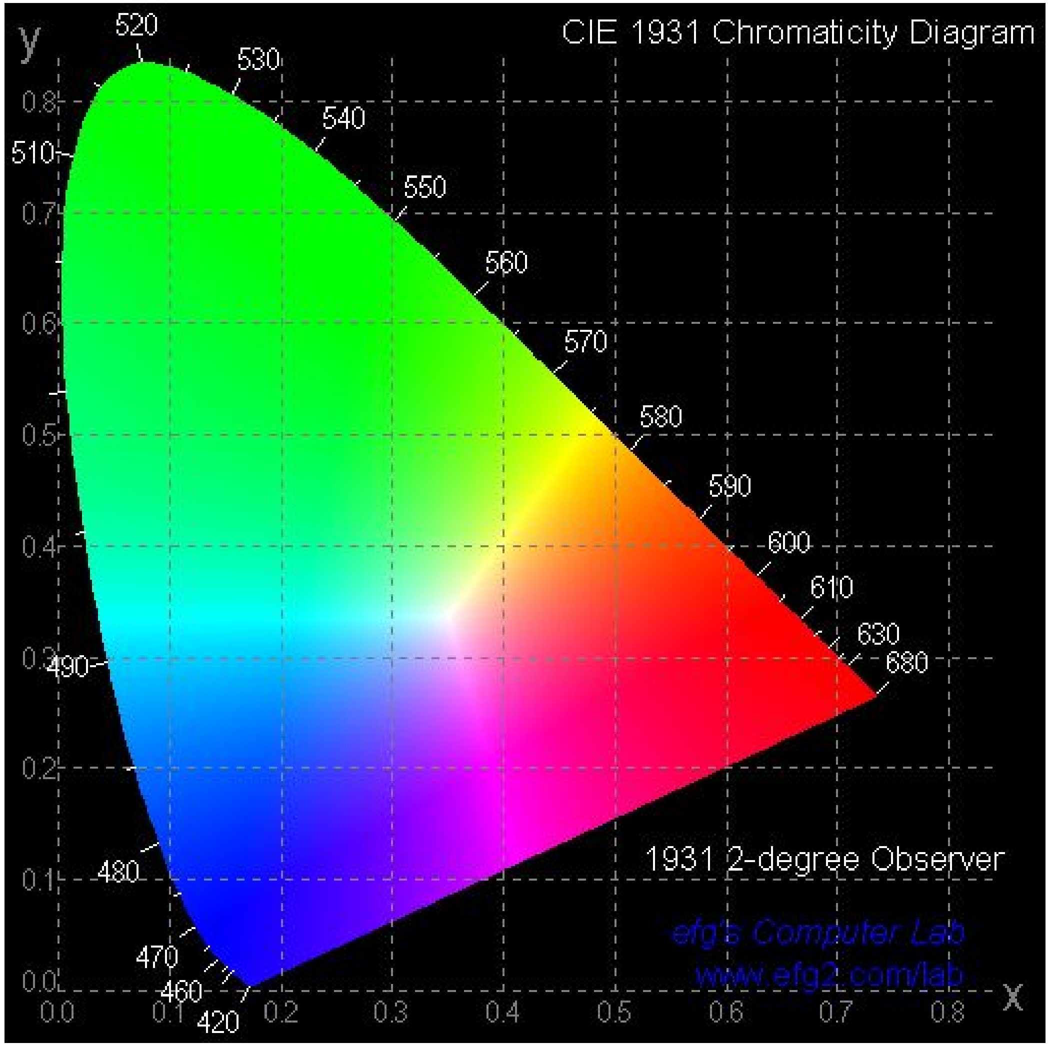
- **Normalization:**
  - Concentrate on color, not light intensity
  - Relative color coordinates
  - $x = \dfrac{X}{X+Y+Z}$ etc

    Projection on the plane of the „primary valences"
  - z= 1-x-y
  - Chromaticity diagram: 2D-Plot over x and y
  - Points in diagram are called „color locations"
  - White point: ~(0.3, 0.3)
    - Device dependent
    - Adaptation of the eye

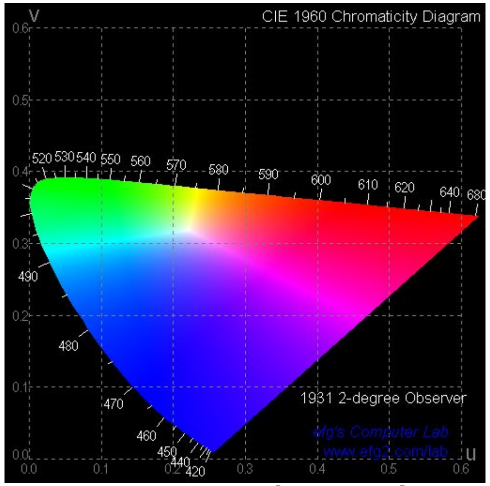


The CIE xy chromaticity diagram

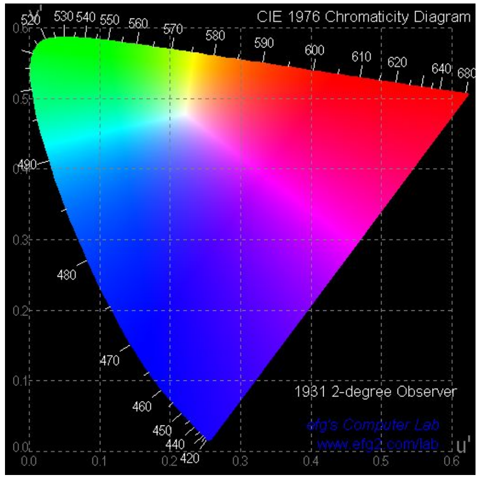
CIE Chromaticity Diagrams



1931 CIE-***xy***



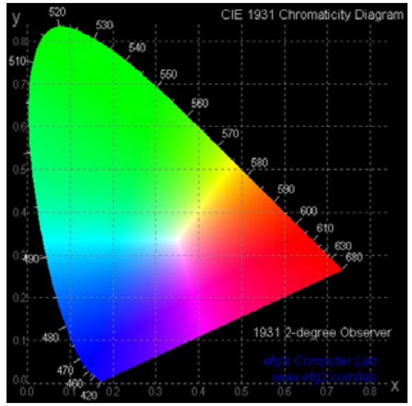
CIE-***uv*** (1960)

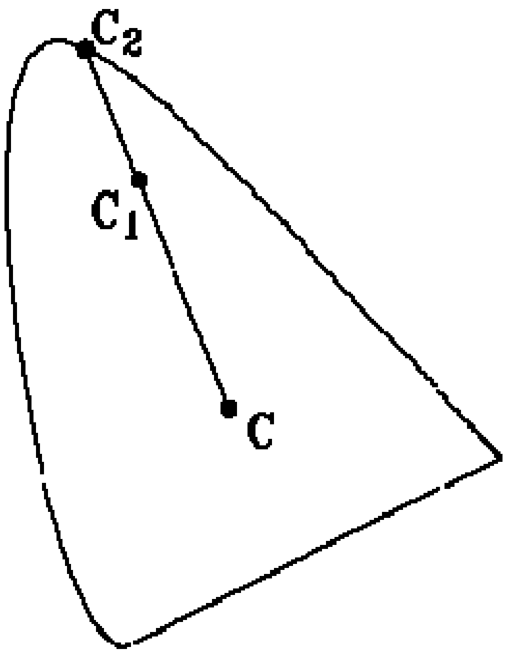


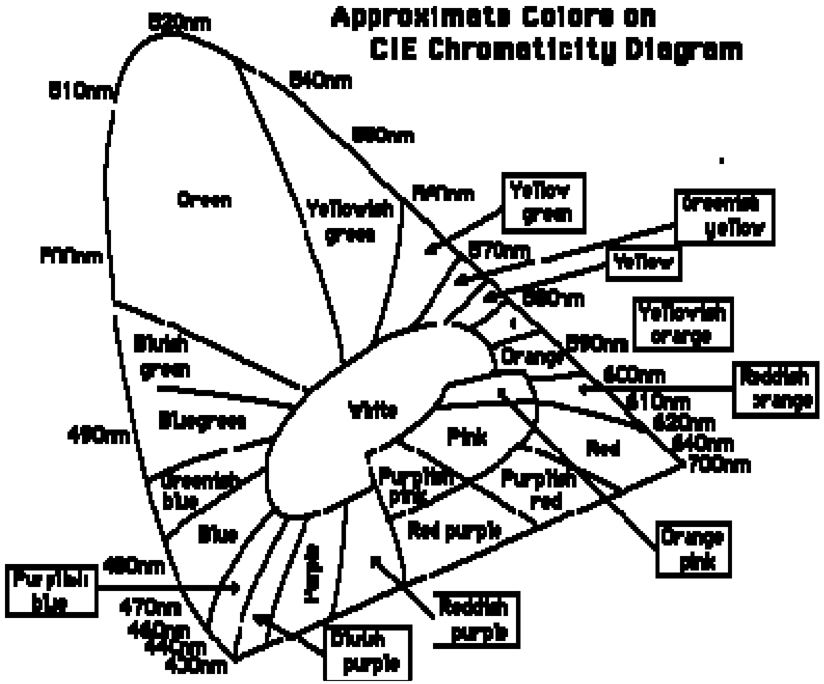
CIE-***u`v`*** (1976)

CIE Chromaticity Diagram

- **Specifying Colors**
  - Saturation: relative distance to the white point
  - Complementary colors: on other side of white point

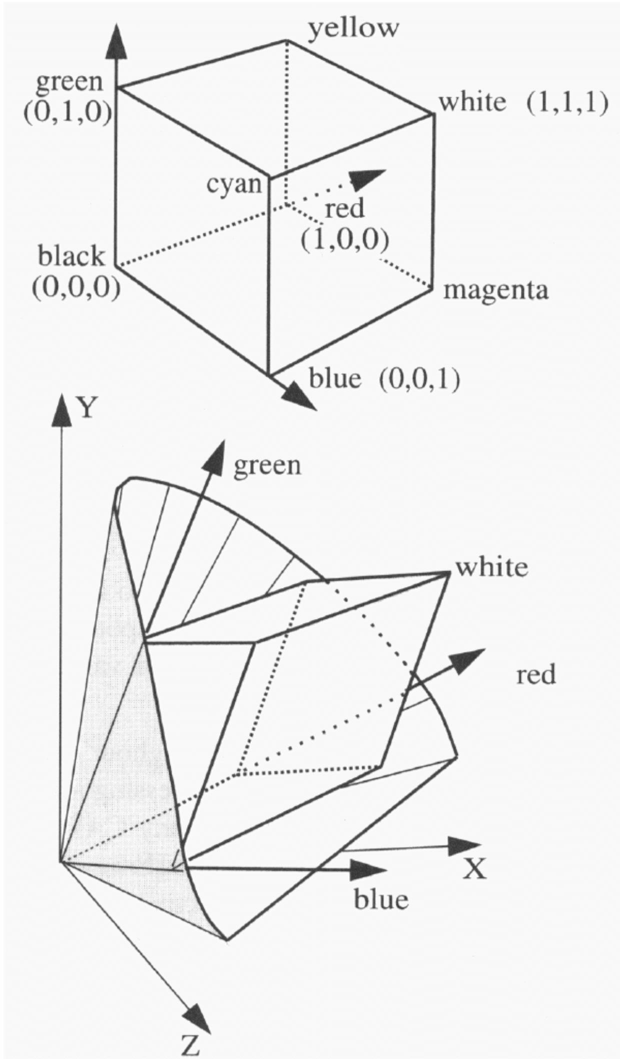




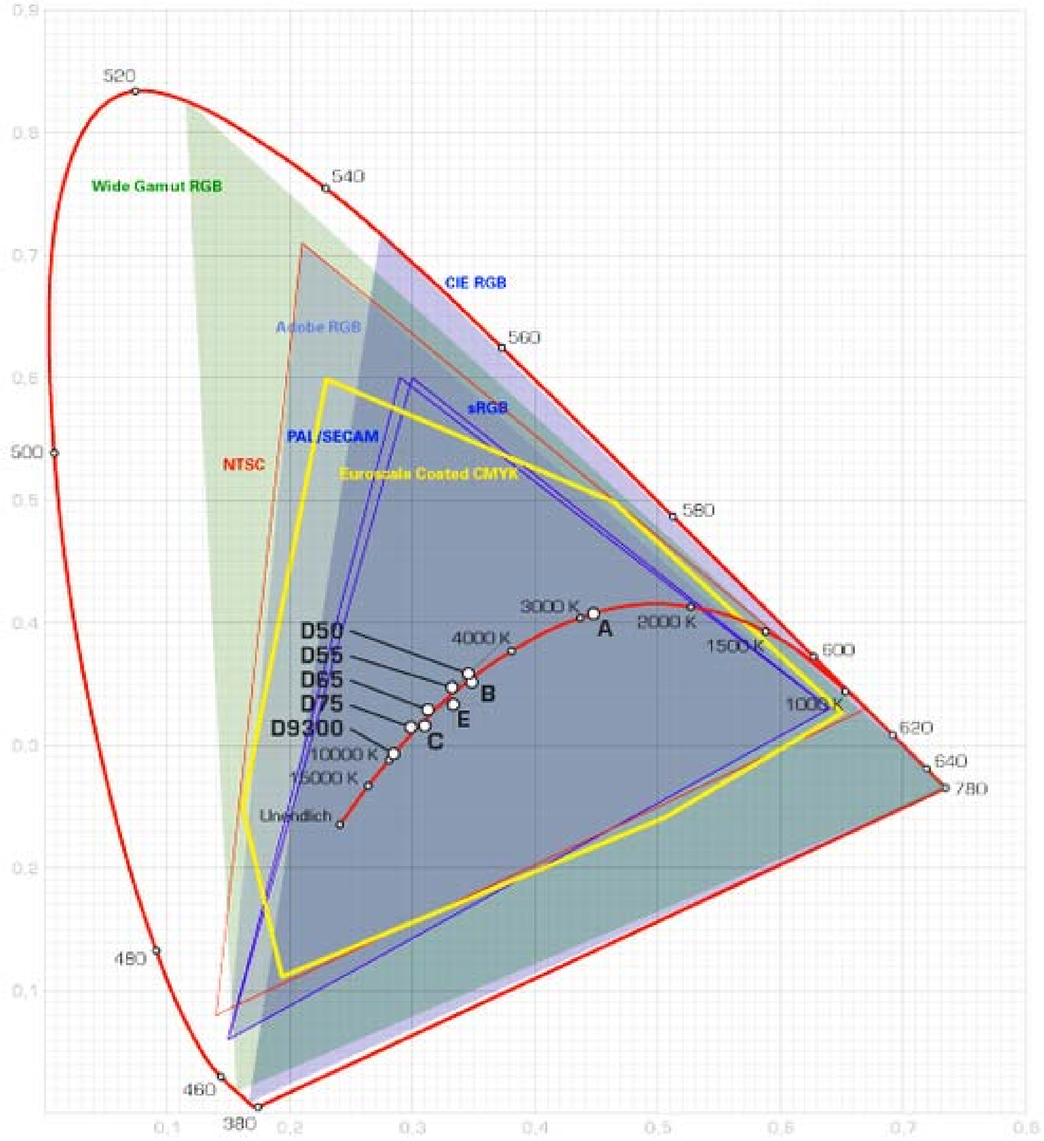


Monitor Color Gamut

- **CIE XYZ gamut**
  - Device-independent
- **Device color gamut**
  - Triangle inside color space with additive color blending

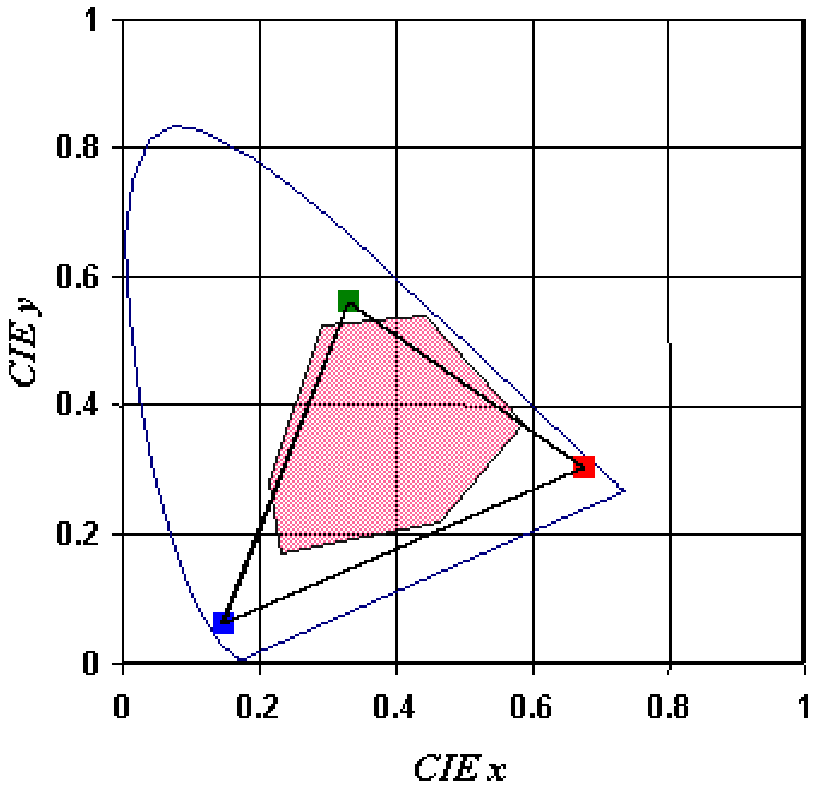


Different Color Gamuts



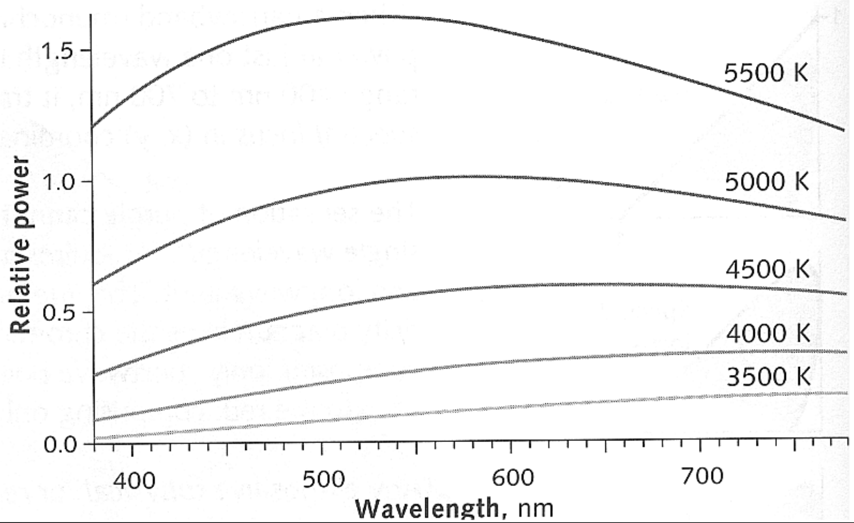
Printer Color Gamut

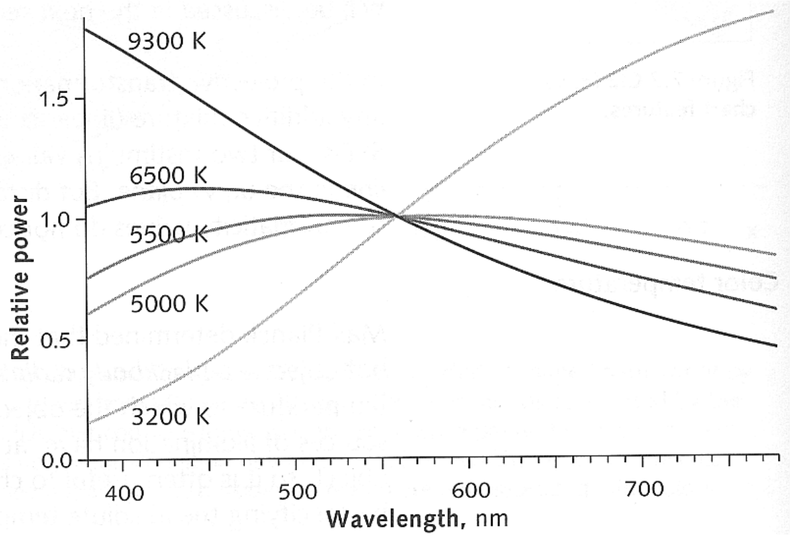
- **Color Gamut**
  - Complex for printer, because of subtractive color blend
  - Complex interactions between printed color points
  - Depends on printer colors and printer technique
- **Gamut compression**
  - Each device should replace of-gamut colors with the nearest approximate achievable colors
  - Possible significant color distortions in a printed ➔ scanned ➔ displayed image



Color Temperature

- **Theoretical light source: A black body radiator**
  - Perfect emitter of energy, the whole energy emitted due to thermal excitation only
  - Has a fixed frequency spectrum $\rho = \rho(\lambda, T)$ (Planck's law)
  - Spectrum can be converted into color location
    - Energy shifts toward shorter wavelengths as the temperature of the black body increases
    - Normalizing of the spectrum (at 550 nm)
  - Allows for white point specification through temperatures





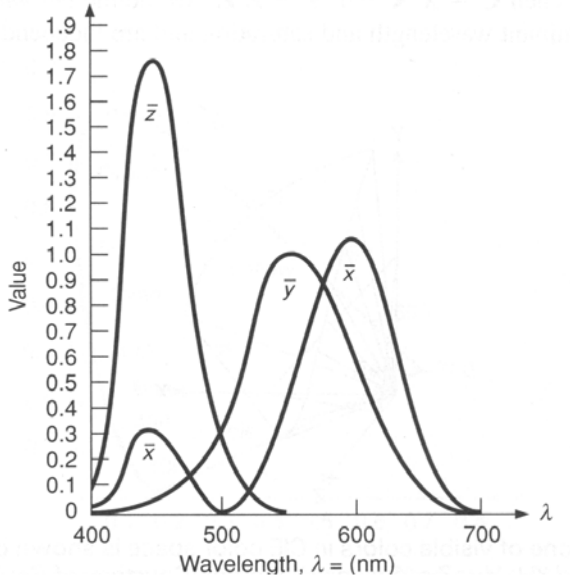
CIE Standard Illuminants

- **Defining the properties of illuminant is important to describe color in many applications**
  - **Illuminant A – incandescent lighting conditions with a color temperature of about 2856°K**
  - **Illuminant B – direct sunlight at about 4874°K**
  - **Illuminant C – indirect sunlight at about 6774°K**
  - **Illuminants D_{50} and D_{65} – different daylight conditions at color temperatures 5000°K and 6500°K, respectively**
- **The spectral data of CIE Standard Illuminants are available and often used in the CG applications**

Color and Linear Operations

- **Additive color blending is a linear operation**
  - Represented as a matrix
- **Calculating components of the primary colors**
  - Measure the spectral distribution (samples every 5-10 nm)
  - Projecting from mD to 3D using matching curves (loss of information)

$$\underset{3\times 1}{\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}} = \mathbf{PL} = \begin{bmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{bmatrix} L_e(\lambda) = \underset{3\times m}{\begin{bmatrix} [x_1, x_2, x_3, .., x_m] \\ [y_1, y_2, y_3, .., y_m] \\ [z_1, z_2, z_3, .., z_m] \end{bmatrix}} \underset{m\times 1}{\begin{bmatrix} l_1 \\ l_2 \\ \dots \\ l_m \end{bmatrix}}$$



- **Transformation between color spaces**

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Color Transformations

- **Computing the transformation matrix M**
  - Given primary colors (x_r, y_r), (x_g, y_g), (x_b, y_b) and white point (x_w, y_w)
    - Must be given or measured
  - Set $C_r = X_r + Y_r + Z_r$
  - $x_r = X_r/(X_r+Y_r+Z_r) = X_r/C_r \Rightarrow X_r = x_r C_r$ (analogous for x_g, x_b)
  - Given that R,G,B are factors modulating the primaries
    - $(0 <= R, G, B <= 1)$
  - Inserting yields

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_r C_r & x_g C_g & x_b C_b \\ y_r C_r & y_g C_g & y_b C_b \\ (1 - x_r - y_r) C_r & (1 - x_g - y_g) C_g & (1 - x_b - y_b) C_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

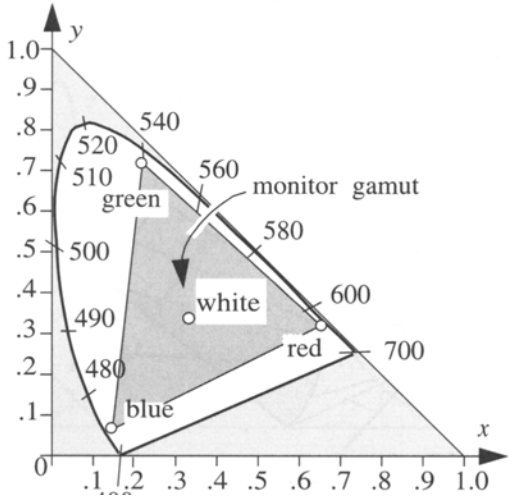
Color Transformations (Cont.)

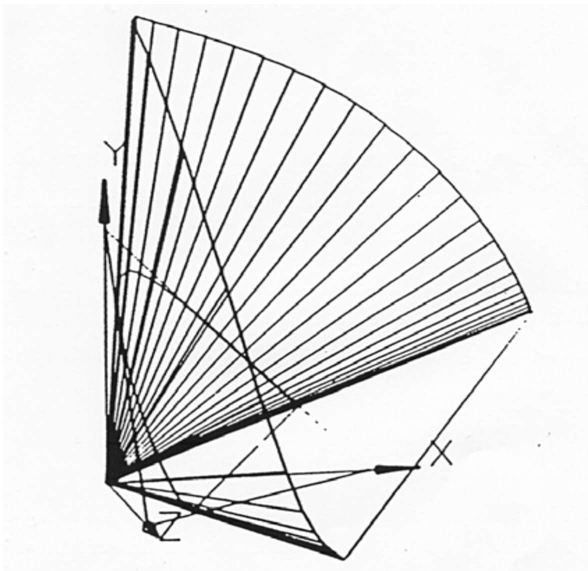
- **Computing the constants C_X**
  - Per definition the white point is given as
    - $(X_w, Y_w, Z_w) = M*(1,1,1)$

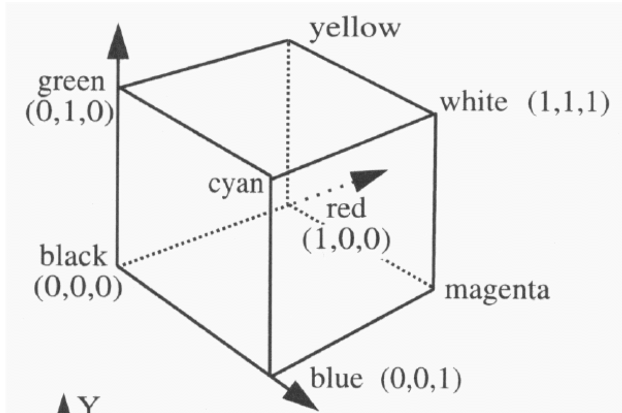
$$\begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = \begin{bmatrix} x_r C_r & x_g C_g & x_b C_b \\ y_r C_r & y_g C_g & y_b C_b \\ (1 - x_r - y_r) C_r & (1 - x_g - y_g) C_g & (1 - x_b - y_b) C_b \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

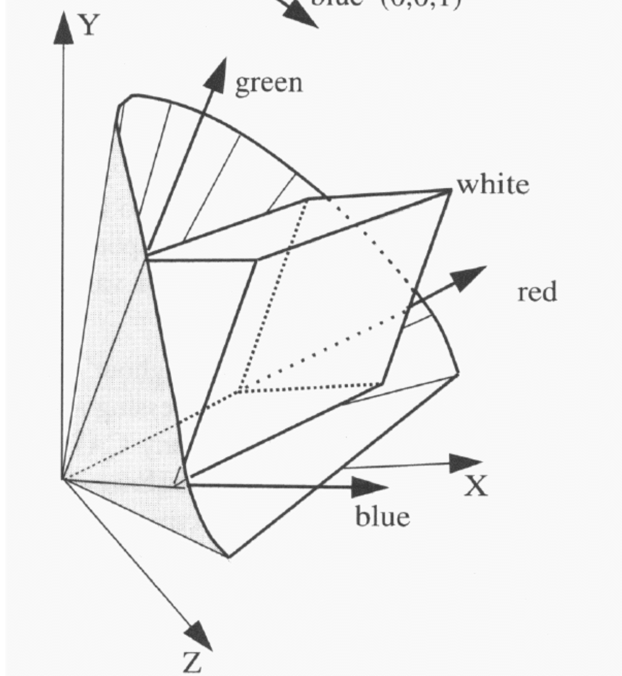
  - (X_w, Y_w, Z_w) can be computed using the normalization constant
    - $Y_w = 1$

Geometric Interpretation



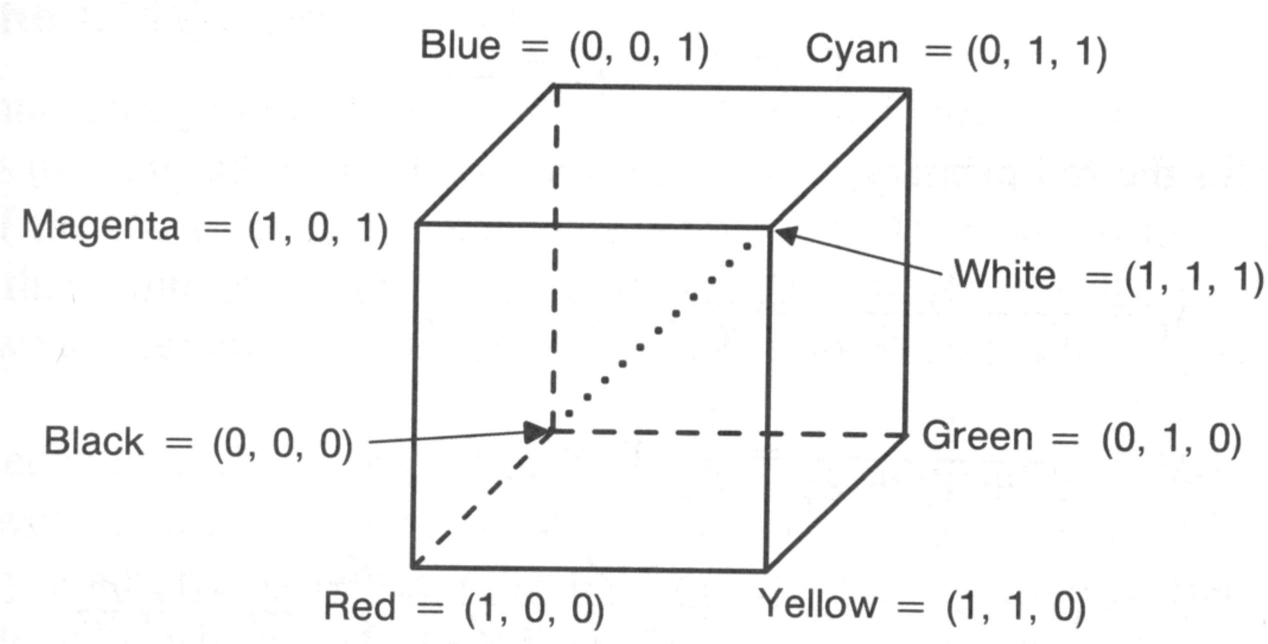






RGB Color Model

- **RGB:**
  - Simplest model for computer graphics
  - Natural for additive devices (e.g. monitors)
  - Device dependent !!!!
  - Definition of standard-RGB (sRGB)

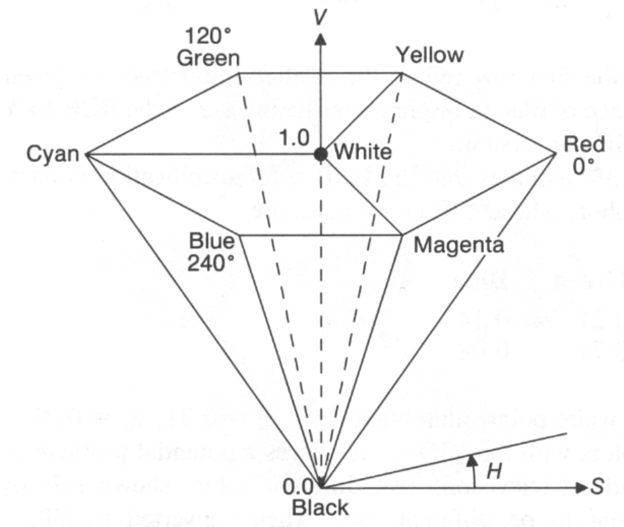


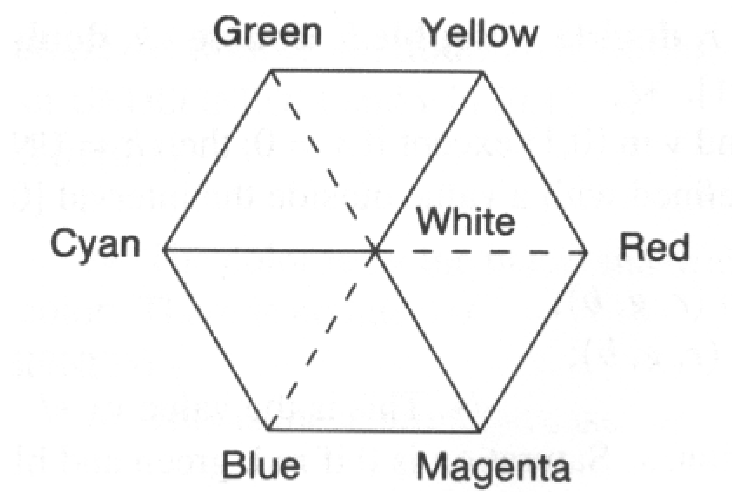
sRGB Color Space

- **Standardization of RGB**
  - Specification of default CIE-XYZ values for monitors
    - Red: 0.6400, 0.3300
    - Green: 0.3000, 0.6000
    - Blue: 0.1500, 0.0600
    - White: 0.3127, 0.3290 (D65)
    - Gamma: 2.2
  - Same values as HDTV and digital video (ITU-R 709)
  - http://www.color.org
- **Utilization:**
  - sRGB is a standard-replacement profile of ICC
  - All image data's without ICC profile *implicit* lie in sRGB
  - Generating: ICC-Profile or writing sRGB
  - Reading: using ICC-Profile or assume sRGB
  - Output: using ICC-Profile or assume sRGB

HSV/HSB Model

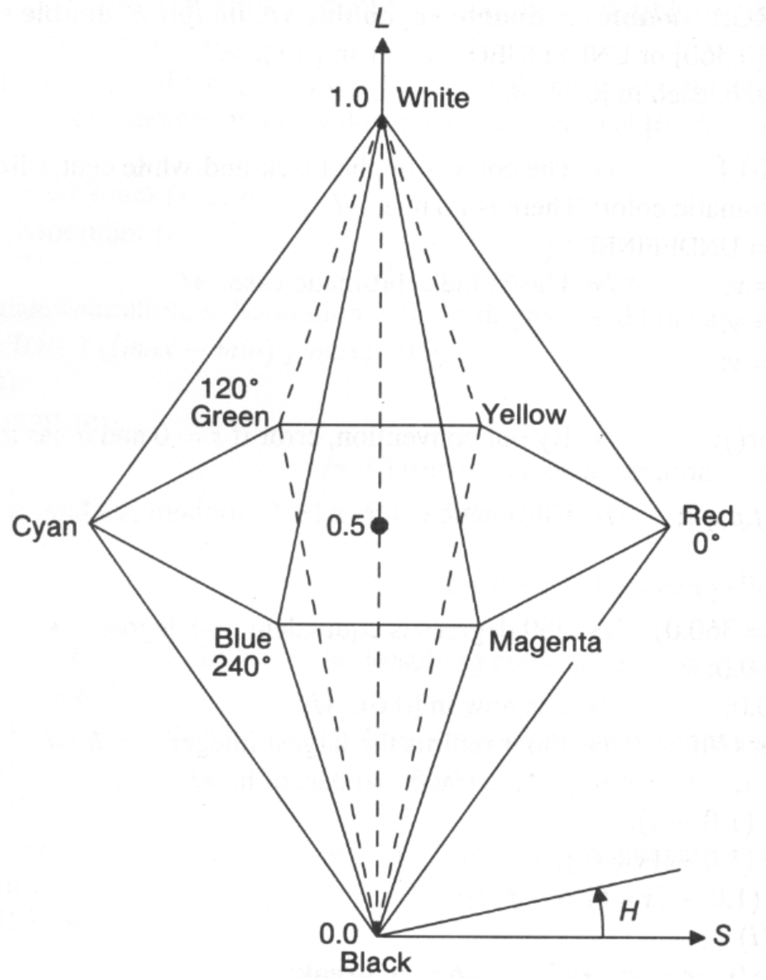
- **HSV/HSB (Hue, Saturation, Value /Brightness)**
  - Motivated from artistic use and intuition
  - H is equivalent to tone
  - S is equivalent to saturation (H undefined for S == 0)
  - V/B is equivalent to the gray value
  - Pure tones for S == 1 and V == 1
  - Intuitive model for color blending
  - Builds on RGB





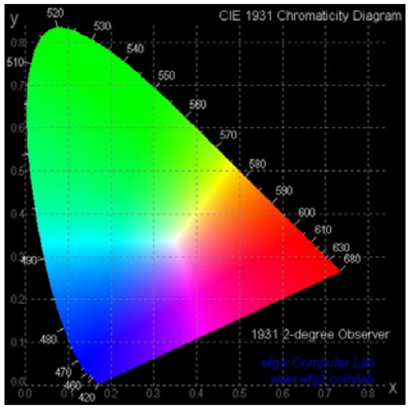
HLS Model

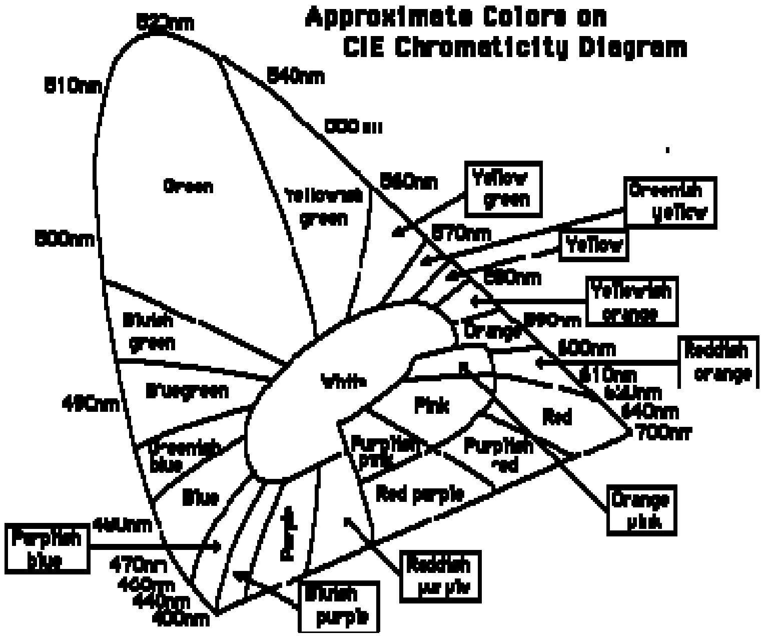
- **HLS (Hue, Lightness, Saturation)**
  - Similar to HSV/HSB
  - Slightly less intuitive
- **Other color models**
  - TekHVC
    - Developed by Tektronix
    - Perceptually uniform color space
  - Video-processing
    - Y´, B-Y, R-Y
    - Y´IQ
    - Y´PrPb
    - Y´CrCb
  - Non-linear color spaces



Color Model: In Practice

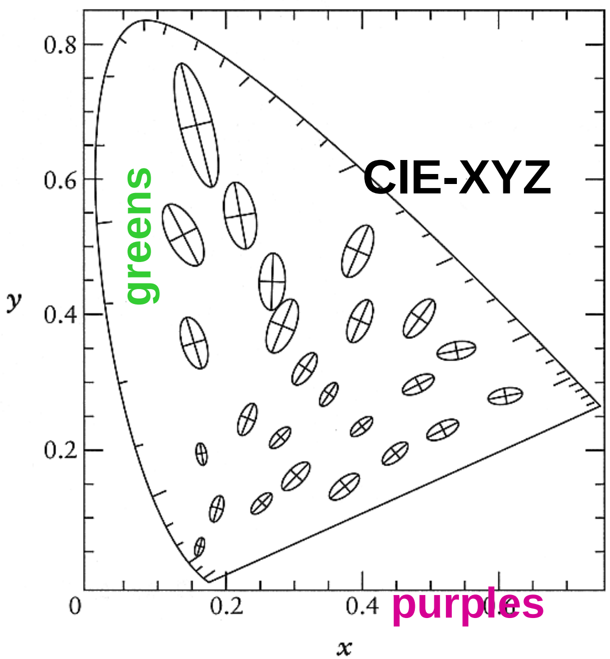
- **Interpolation (shading, anti-aliasing, blending)**
  - RGB: 0.5 red + 0.5 green = dark yellow
    0.5*(1,0,0)+0.5*(0,1,0)= (0.5,0.5,0)
  - HSV: 0.5 red + 0.5 green = pure yellow
    0.5*(0º,1,1)+0.5*(120º,1,1)= (60º,1,1)
  - Interpolation in RGB
    - Physical interpretation
  - Interpolation in HSV
    - Intuitive color interpretation
      „yellow lies between red and green“

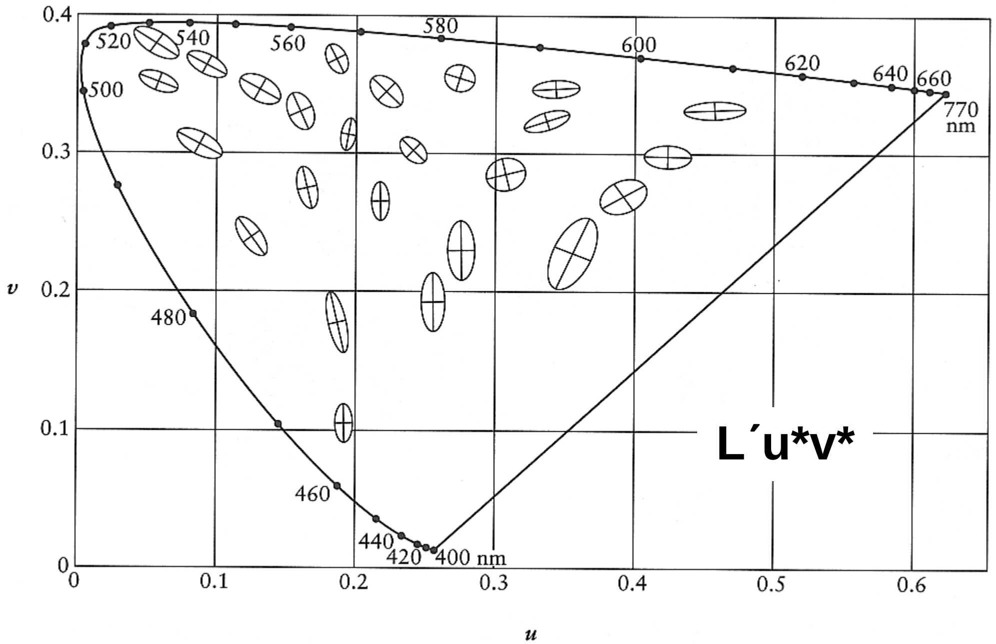




L*u*v* / L*a*b*- Color Spaces

- **CIE-XYZ is perceptually non-uniform**
  - Same differences of xy lead to very different perceived differences (purples tightly packed, greens stretched out)
  - Transforming in uniform color space (similarly to gamma)
  - Measure color difference there
- **L*u*v* / L*a*b* are device-independent color spaces**





L*u*v* / L*a*b*- color spaces

- **Transformation:**
  - Converting to XYZ (Y incidental luminance)
  - Non-linear transformation on Y
    (Y_n is Y of the white point)

$$L^* = \begin{cases} Y/Y_n \geq 0.008856: & 116(Y/Y_n)^{1/3} - 16 \\ Y/Y_n < 0.008856: & 903.3(Y/Y_n) \end{cases}$$

$$L^* \in \{0,\ldots,100\}$$

(limited applicability to HDR)

  - Transformation of color differences

$$u' = 4X/(X + 15Y + 3Z)$$

$$v' = 9Y/(X + 15Y + 3Z)$$

$$u^* = 13L^*(u' - u'_n)$$

$$v^* = 13L^*(v' - v'_n)$$

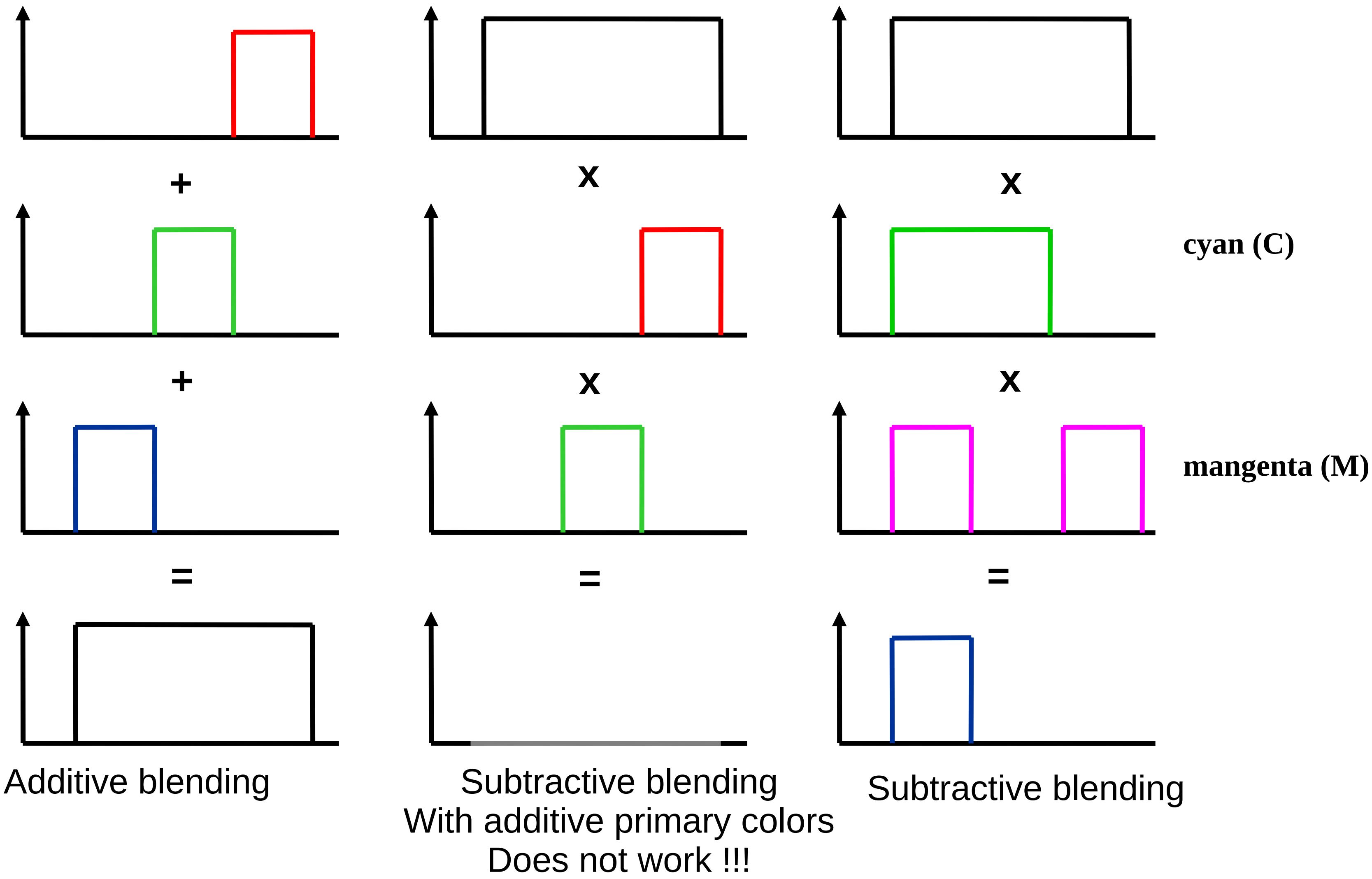
$$a^* = 500L^*[f(X/X_n) - f(Y/Y_n)]$$

$$b^* = 500L^*[f(Y/Y_n) - f(Z/Z_n)]$$

$$f(x) = \begin{cases} x \geq 0.008856 & x^{1/3} \\ x < 0.008856 & 7.787x + 16/116 \end{cases}$$

Subtractive color blending

- **corresponds to stacked color filters**



Subtractive Color Blending

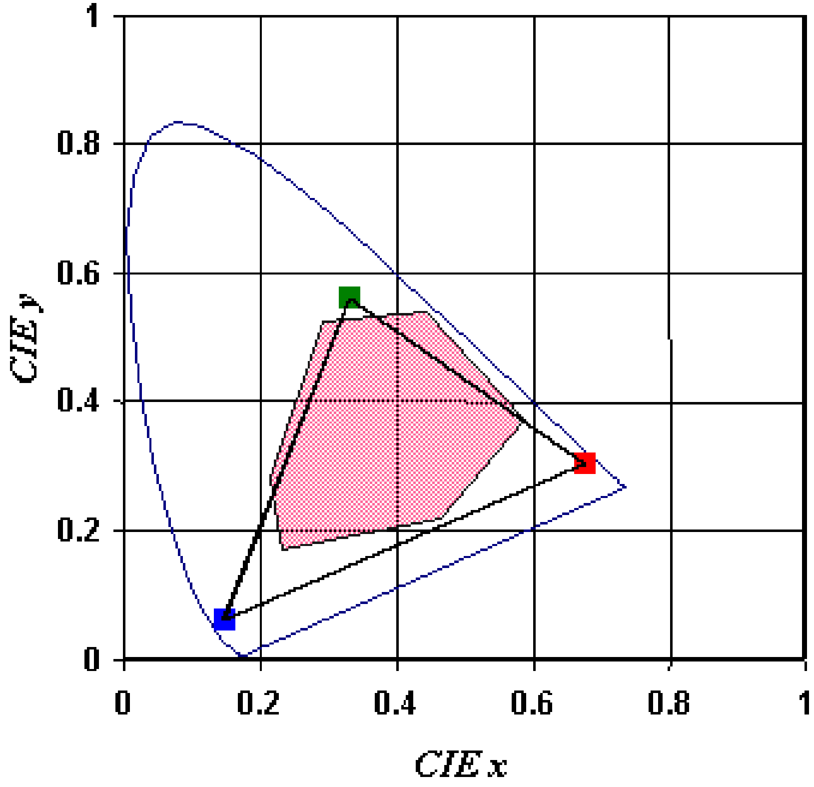
- **e.g. for printers**

- **CMYK (Cyan, Magenta, Yellow, Black)**
  - Subtractive color blending
  - In theory:
    - (C, M, Y)= 1 – (R, G, B)
    - K= min(C, M, Y)   // Black
    - (C, M, Y, K)= (C-K, M-K, Y-K, K)

  - In practice: profoundly non-linear transformation
    - Other primary colors
    - Interaction of the color pigments among each other
    - Covering
    - Etc, etc.

Subtractive color blending

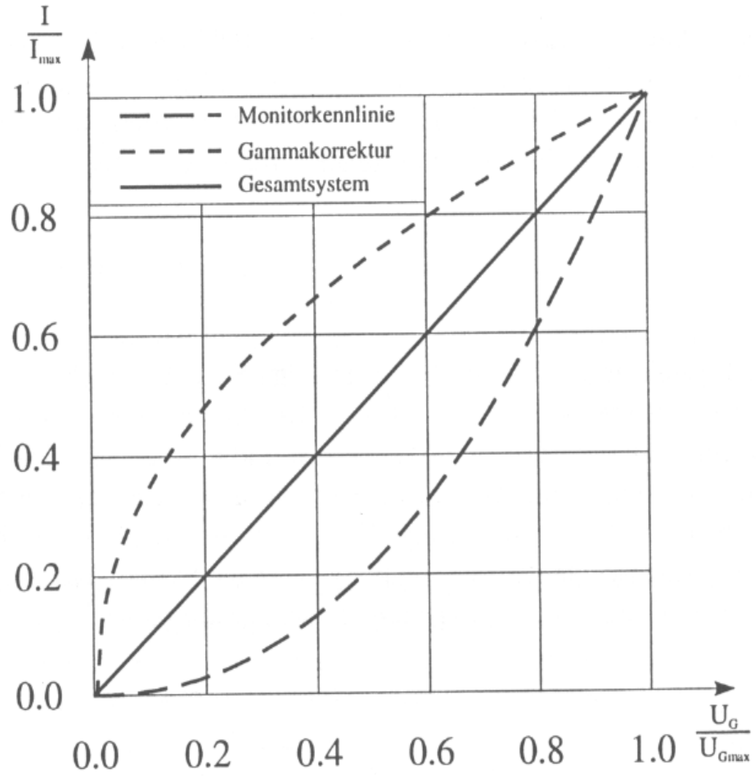
- **Gamut-Mapping:**
  - What to do if colors lay outside of the printable area?
  - Clamp, Scale
- **Subtractive primary colors:**
  - Product of all primary colors must be black
  - Any number of colors (CMY, CMYK, 6-color-print, etc.)
  - It does not need to obtain (CMY)= 1-(RGB)



Gamma

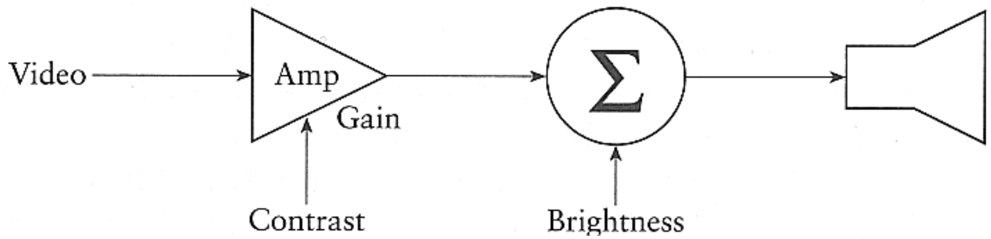
- **Display-Gamma**
  - Intensity I of electron beam is non-linear with respect to the applied voltage U
  - Best described as power law
    - $I = U^{\gamma}$

    ➔Gamma-Factor γ = ~2.2 due to physical reasons
- **Gamma correction**
  - Pre-correct output values to achieve overall linear curve
  - Quantization loss if value represented with less than 12 Bit

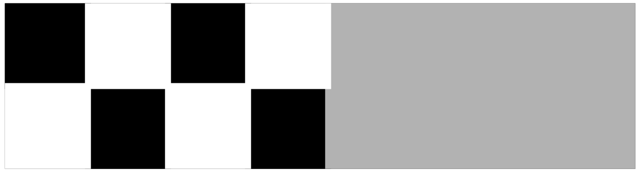


Gamma Correction

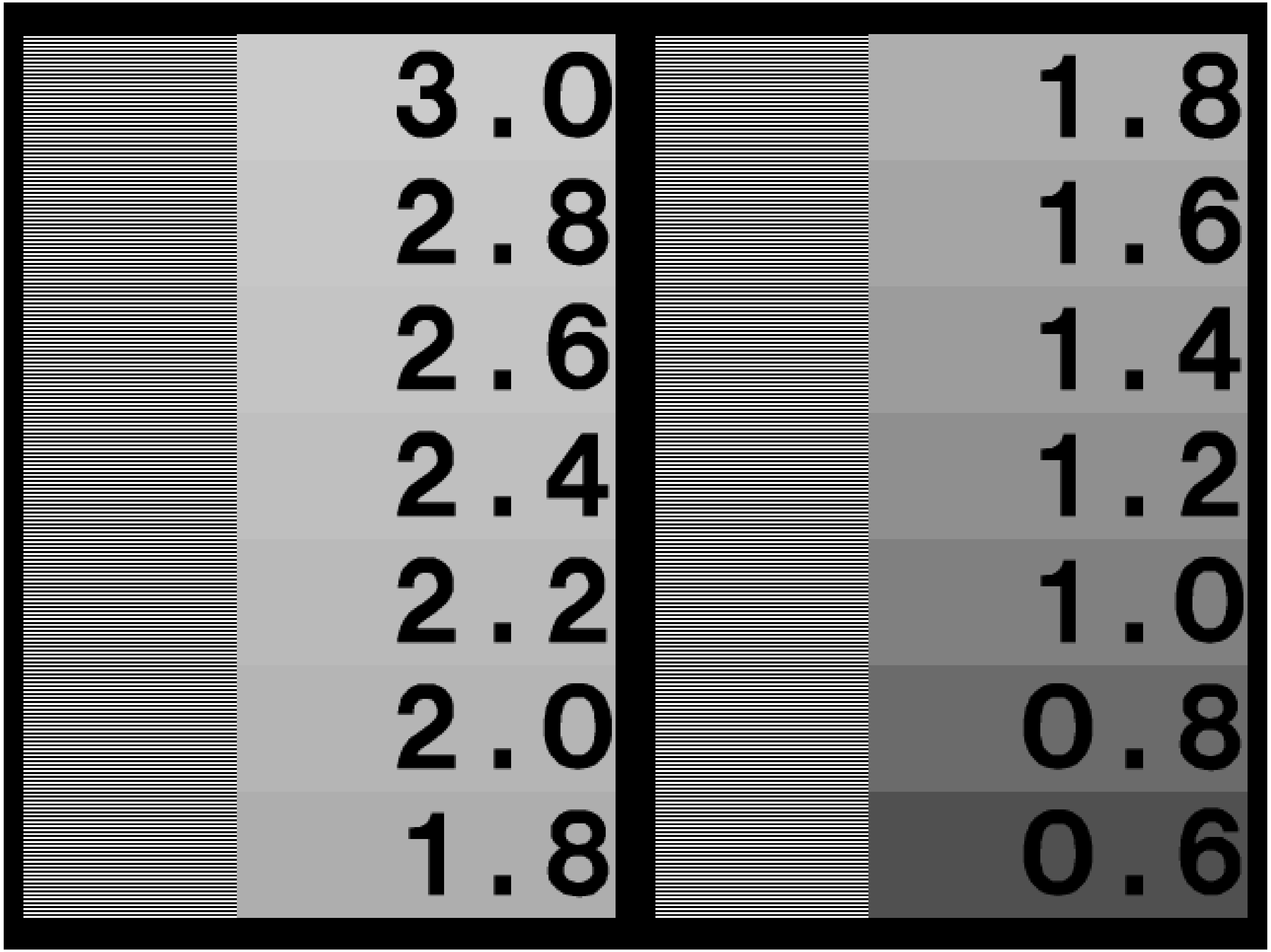
- **Monitor calibration (for dummies):**
  - Correctly: you would need a colorimeter, spectrophotometer
  - The procedure:



- "Brightness" ←→ "Contrast"
  - Change „Brightness" so that (0,0,0) just has no light emission
  - Change „Contrast" so that (1,1,1) is bright as possible – without blurring
  - Iterate
- Then gamma correct through comparison with average brightness: 0.5 - grey

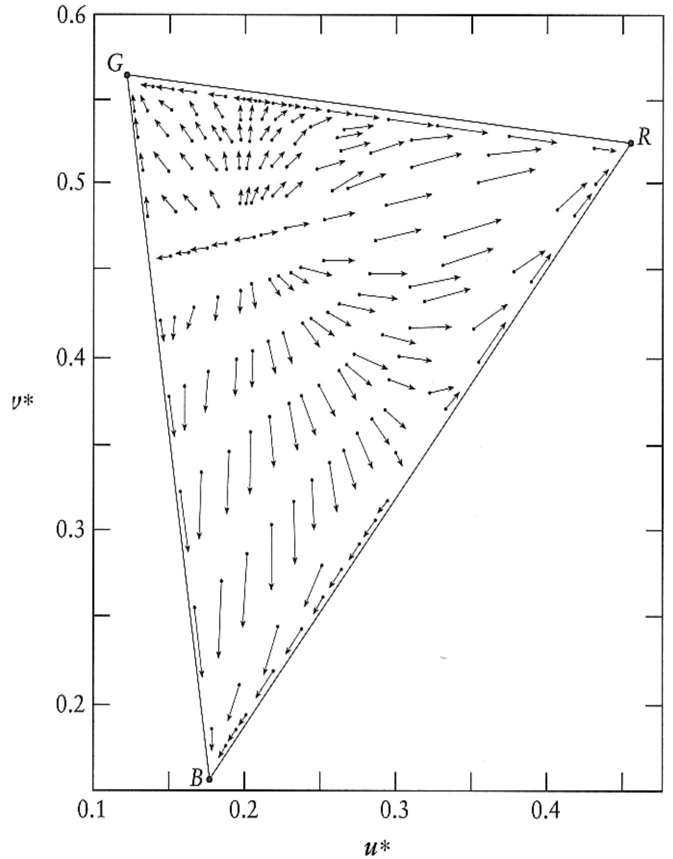


Gamma Testing Chart



Gamma Correction

- **Problem:**
  - Strong color corruptions



Shifts in reproduced chromaticities resulting from uncompensated gamma of 1.273 (such a gamma is desirable to compensate the contrast lowering in the dim surround).

Gamma

- **Camera-Gamma**
  - Old cameras (electron tube) also had a Gamma factor
  - Essentially the inverse of the monitor gamma (due to Physics)

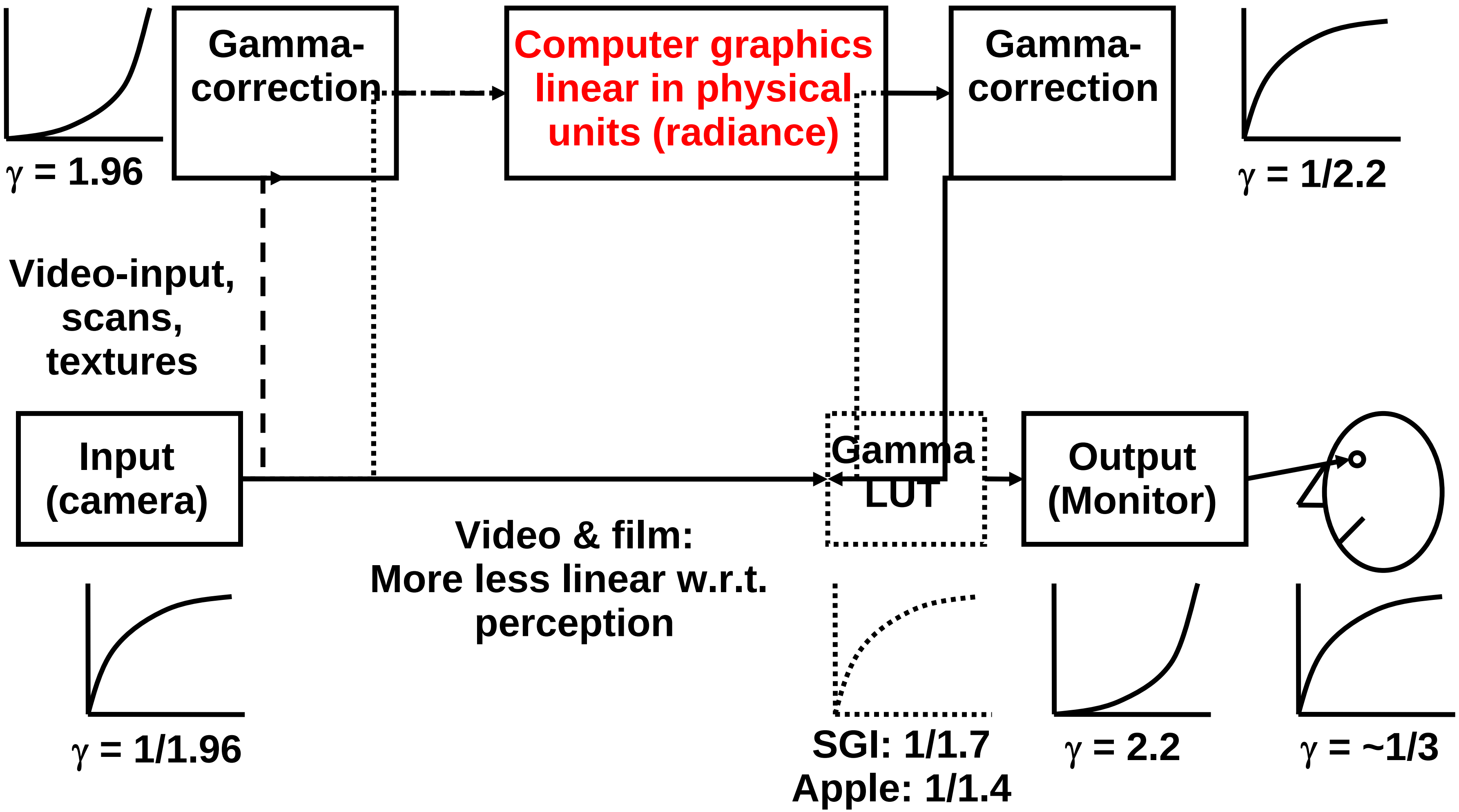
➔ **Display corrected the camera**

- **„Human-Gamma"**
  - Human brightness perception roughly follow the gamma curve
    - Really a log-curve, but close

➔ **Old camera encode light perceptually uniform**
  - Optimal coding for transmitted values

➔ **New cameras specifically generate the same output for compatibility reasons**

Color from beginning to end



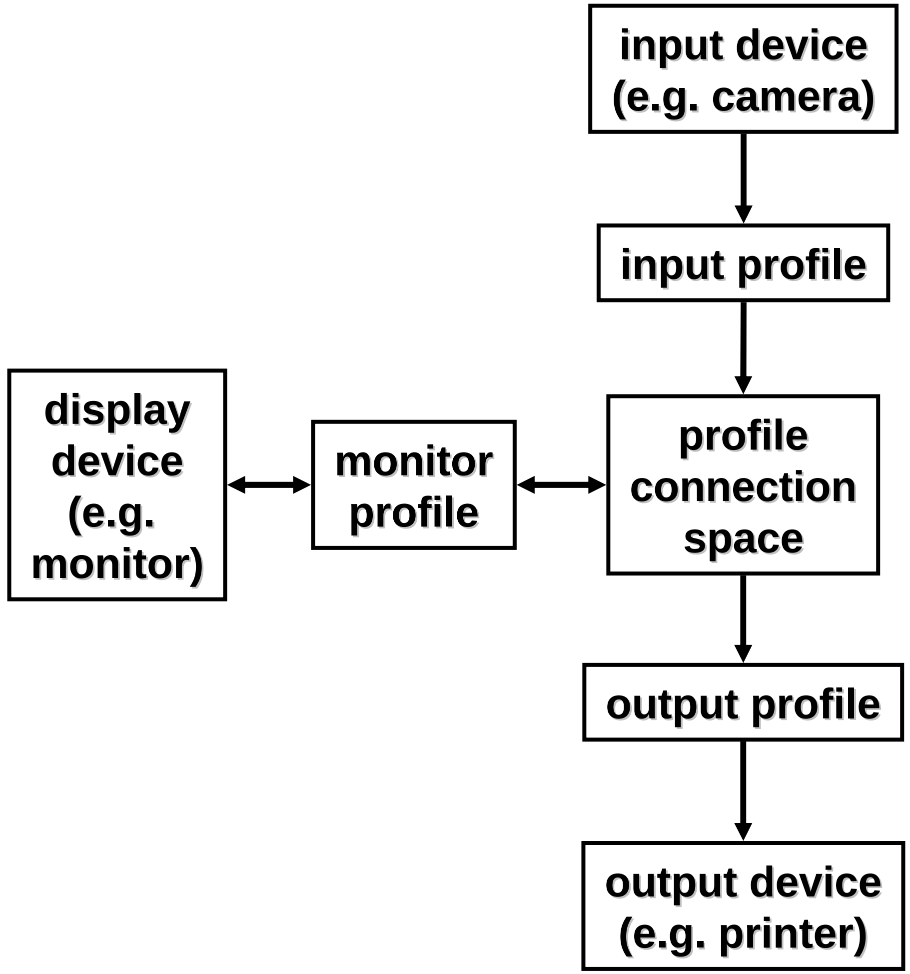
Color from beginning to end

- **Problems**
  - Color coordinate system often unknown
    - No support in image formats
  - Multiple transformations
    - Loosing accuracy through quantization
  - Gamma-correction depends on application
    - Non-linear:
      - Video-/image editing
    - Linear:
      - Image syntheses, interpolation, color blending, rendering, ...

ICC Profiles

- **International Color Consortium**
  - Standardized specification of color spaces
  - Profile Connection Space (PCS) – intermediate, device-independent color space (CIELAB and CIEXYZ supported)
  - ColorDevice #1 ➔ PCS ➔ ColorDevice #2
- **ICC profile**
  - A file with data describing the color characteristics of a device (such as a scanner, printer, monitor) or an image
  - Simple matrices
  - Transformation formulas (if necessary proprietary)
  - Conversion tables
- **ICC library**
  - Using profiles for color transformations
  - Optimizes profile-sequences transformations
  - No standard-API
- **Problems**
  - Inaccurate specifications
  - Interoperability
  - Difficult to generate profiles

ICC Profiles



ICC Profiles and HDR Image Generation

- profile connection spaces
  - CIELAB (perceptual linear)
  - linear CIEXYZ color space
- can be used to create an high dynamic range image in the profile connection space
- allows for a color calibrated workflow