
Computer Graphics

- Color -

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Overview

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

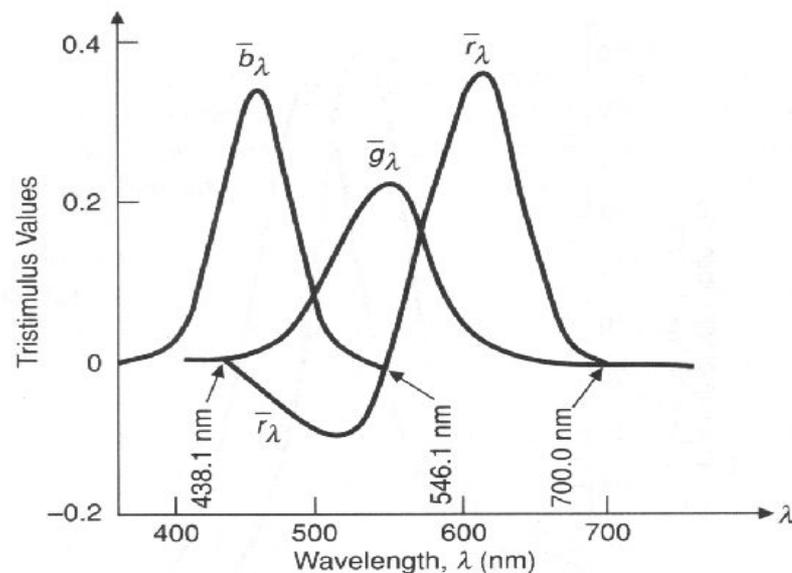
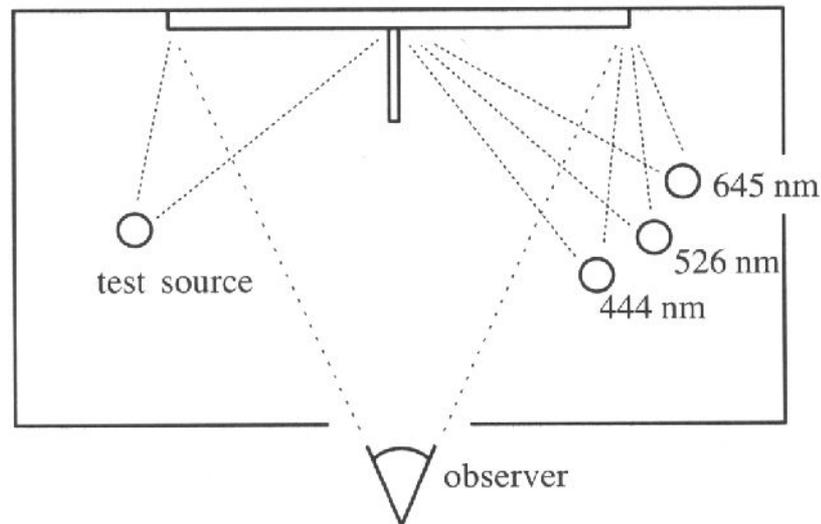
- **Today**
 - Gamma Correction
 - Color spaces
 - Transformations

- **Next lecture**
 - Tone Mapping

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 monochromatic spectral colors of equal intensity
 - With respect to a certain set of primary colors

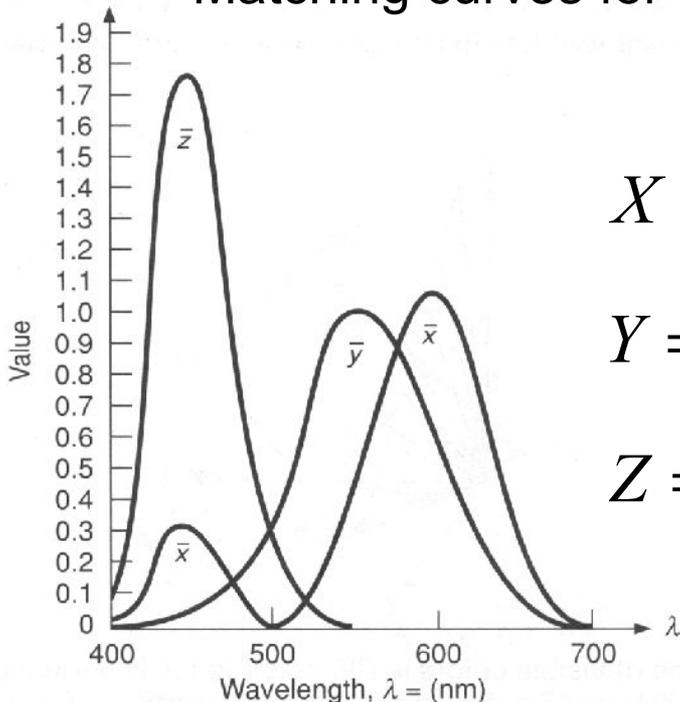


Standard Color Space CIE-XYZ

- **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

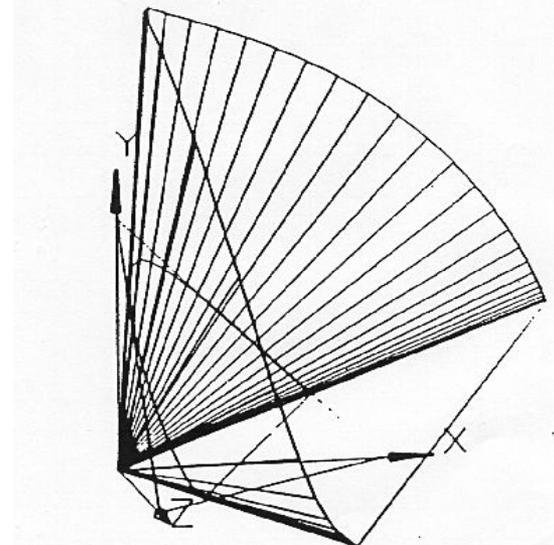
- **Standardized imaginary primaries CIE XYZ (1931)**
 - Imaginary primaries more saturated than monochromatic lights
 - Could match all physically realizable color stimuli
 - Y is roughly equivalent to luminance
 - Shape similar to luminous efficiency curve
 - Monochromatic spectral colors form a curve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



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

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

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



CIE Chromaticity Diagram

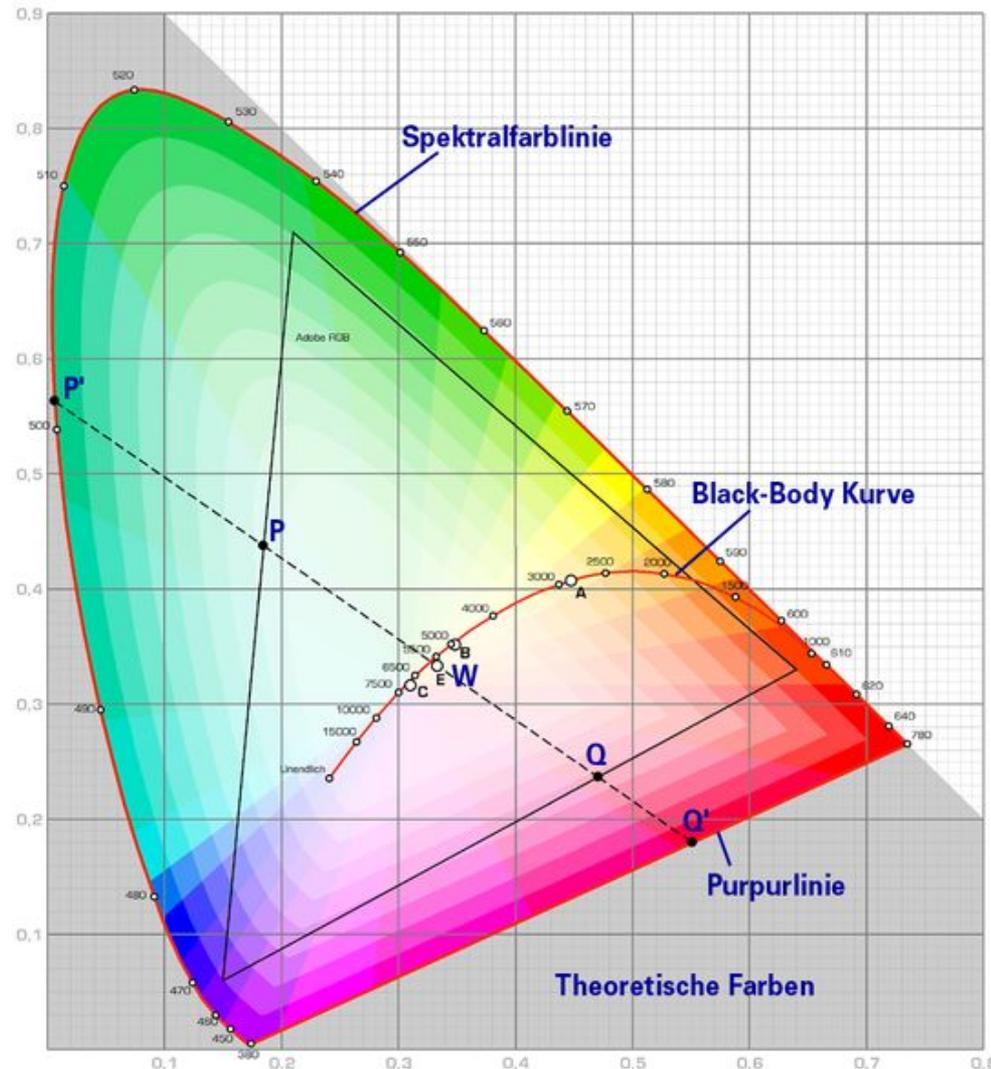
- **Normalization:**

- Concentrate on color, not light intensity
- Relative color coordinates

- $$x = \frac{X}{X + Y + Z} \text{ etc}$$

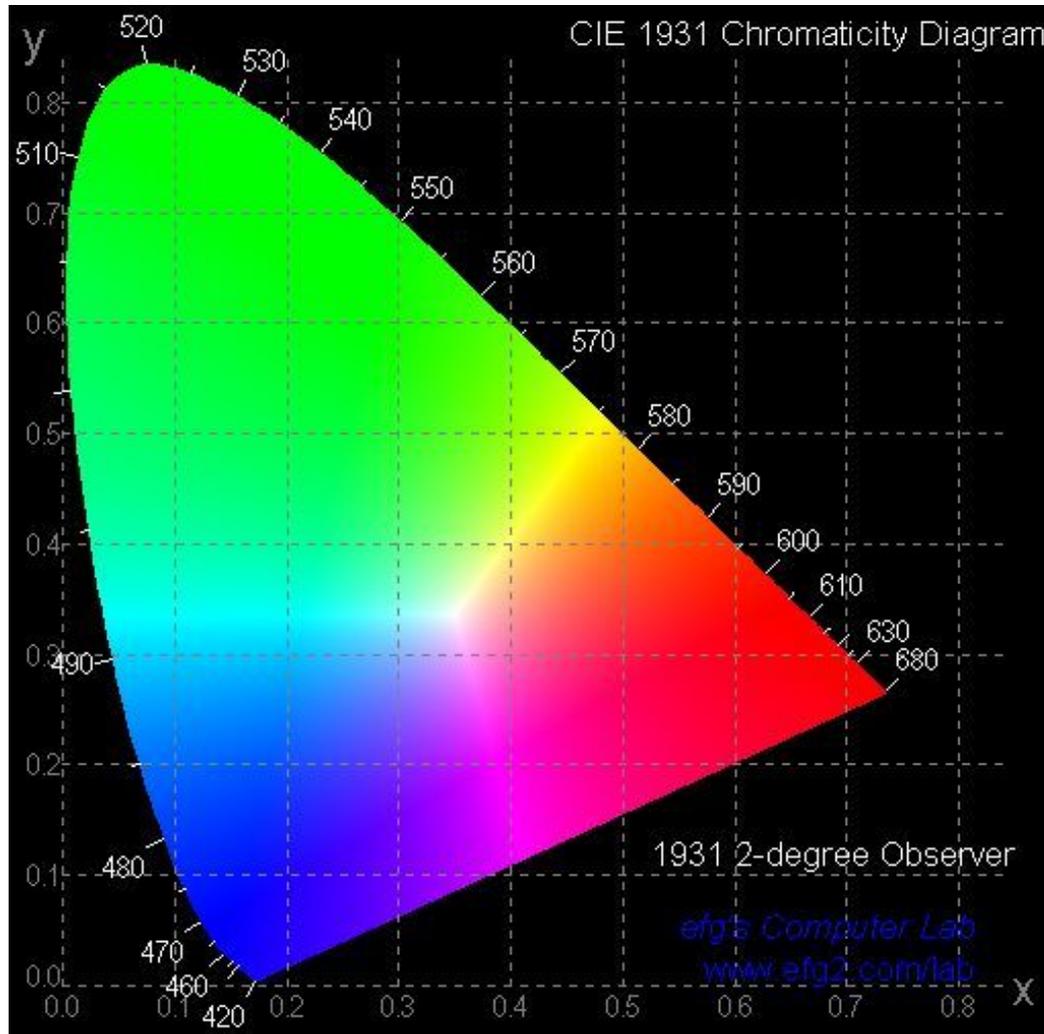
Projection on the plane of the „primary valences“

- $z = 1 - x - y$
- Chromaticity diagram: 2D-Plot over x and y
- Points in diagram are called „color locations“
- White point: $\sim(0.3, 0.3)$
 - Device dependent
 - Adaptation of the eye

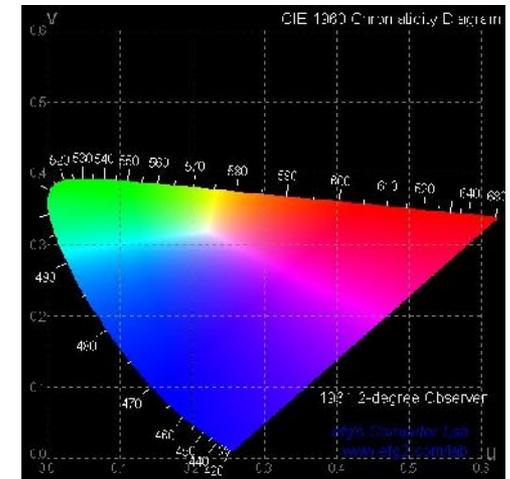


The CIE xy chromaticity diagram

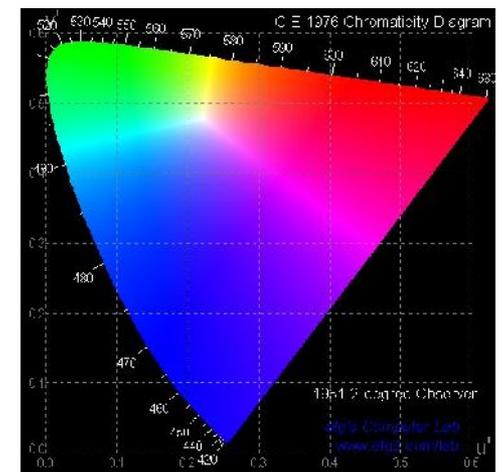
CIE Chromaticity Diagrams



1931 CIE-xy



CIE-uv (1960)

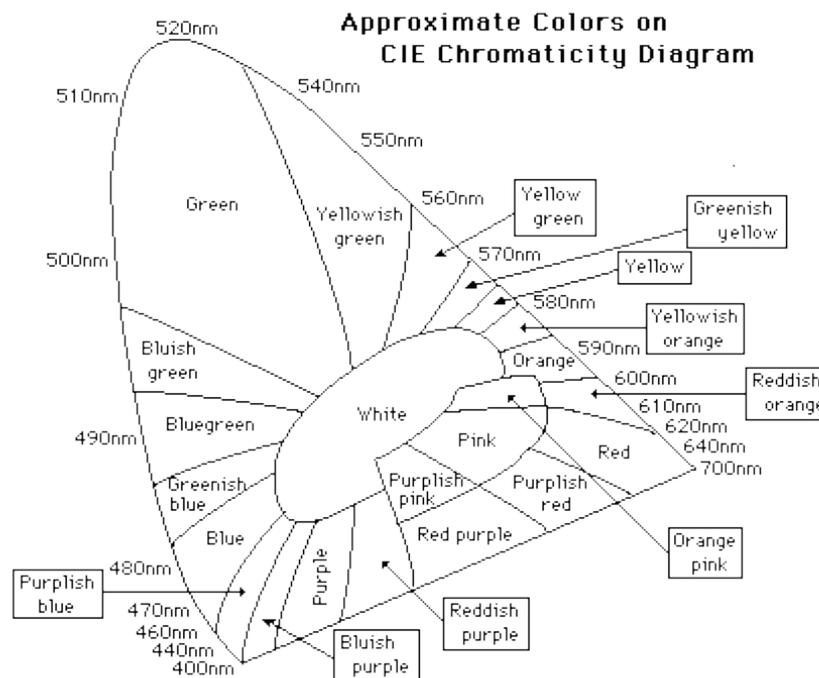
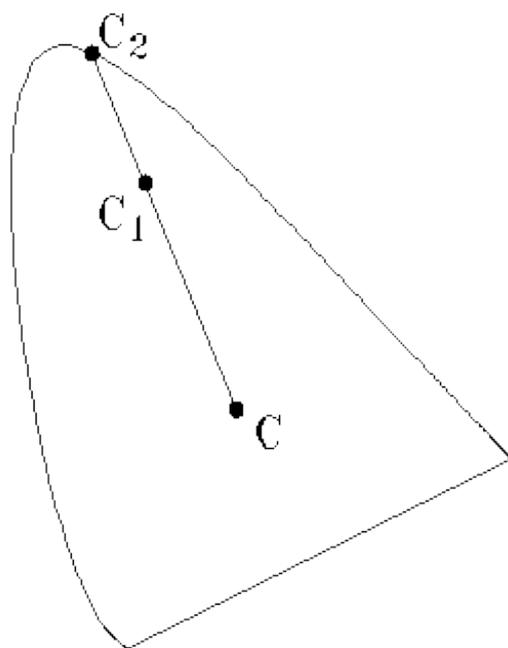
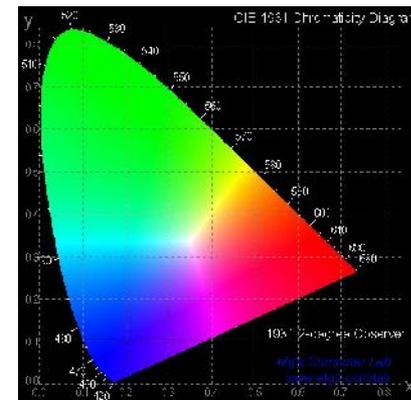


CIE-u'v' (1976)

CIE Chromaticity Diagram

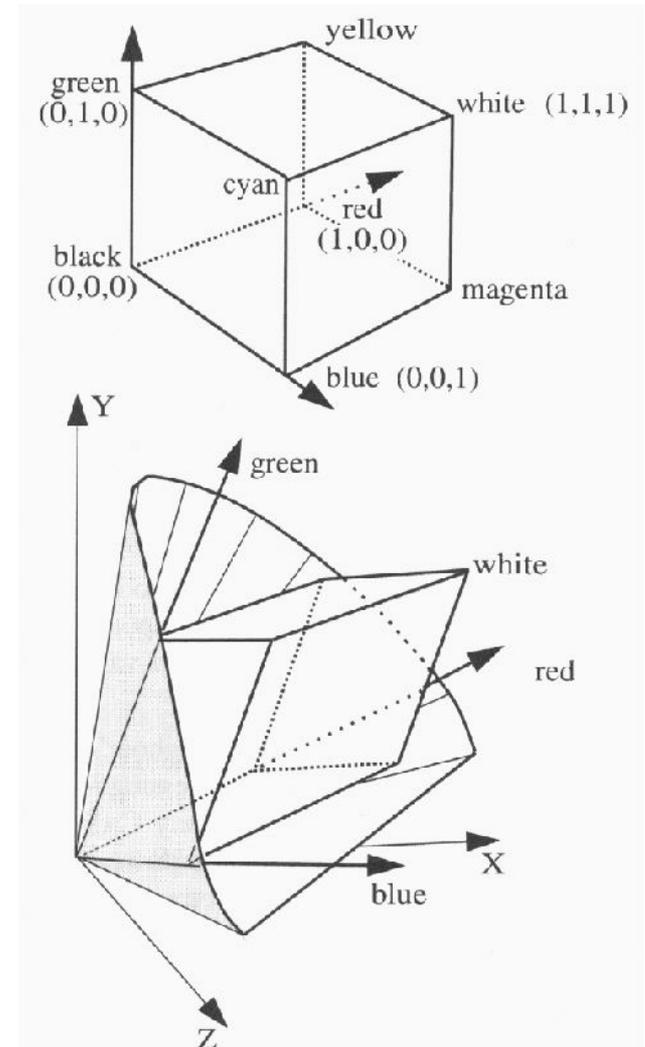
- **Specifying Colors**

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

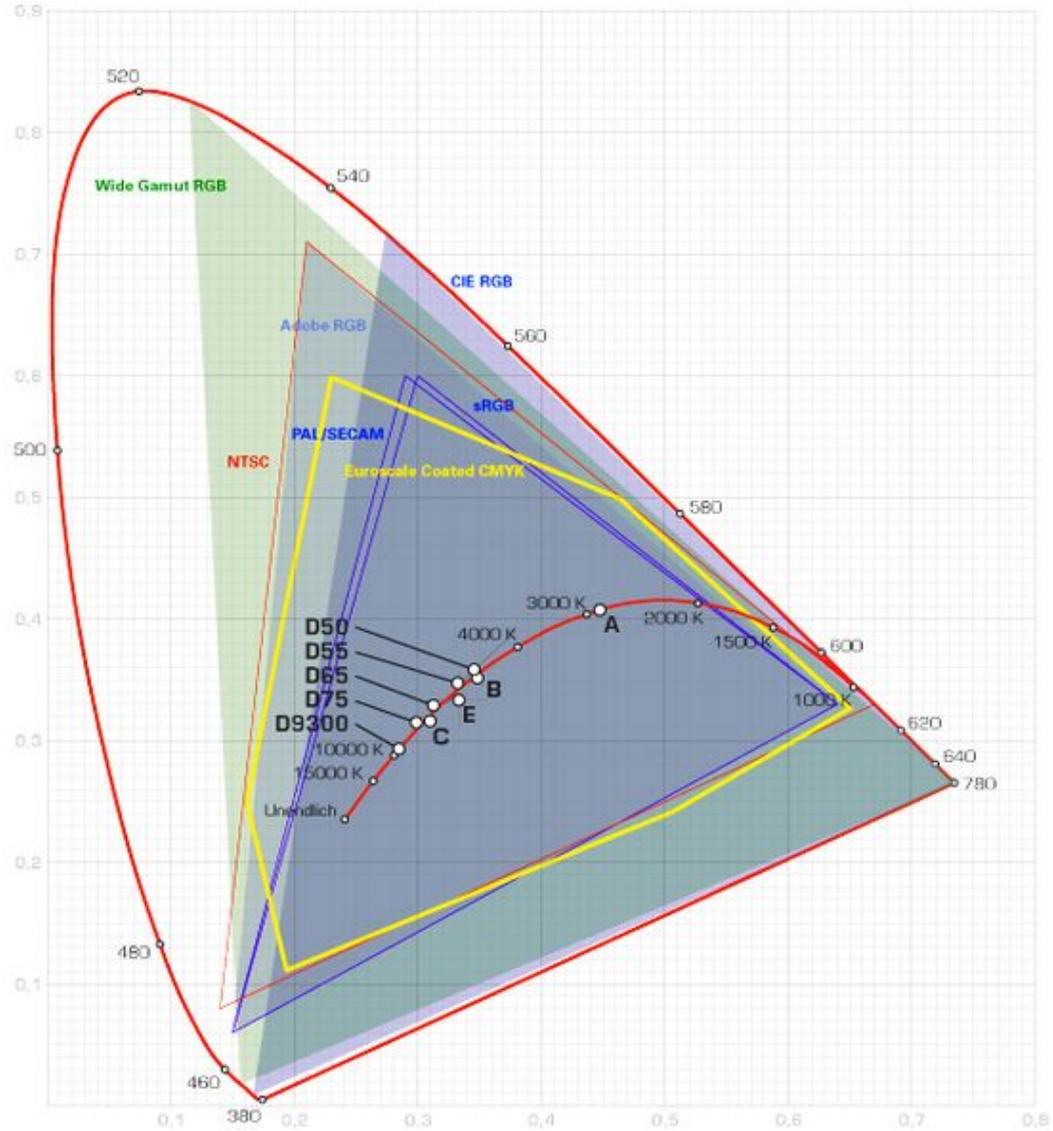


Monitor Color Gamut

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



Different Color Gamuts



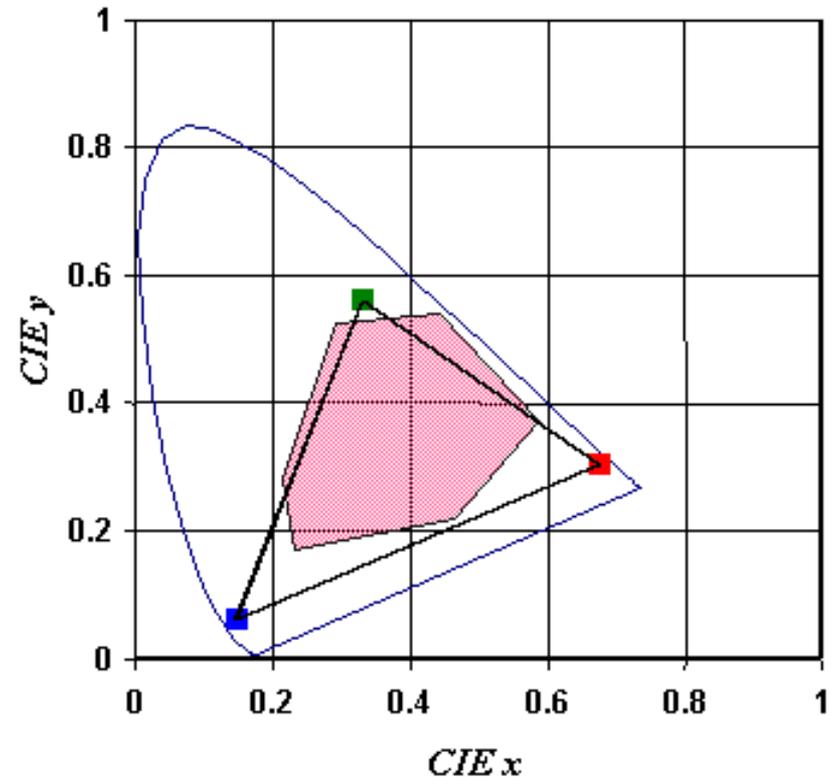
Printer Color Gamut

- **Color Gamut**

- Complex for printer, because of subtractive color blend
- Complex interactions between printed color points
- Depends on printer colors and printer technique

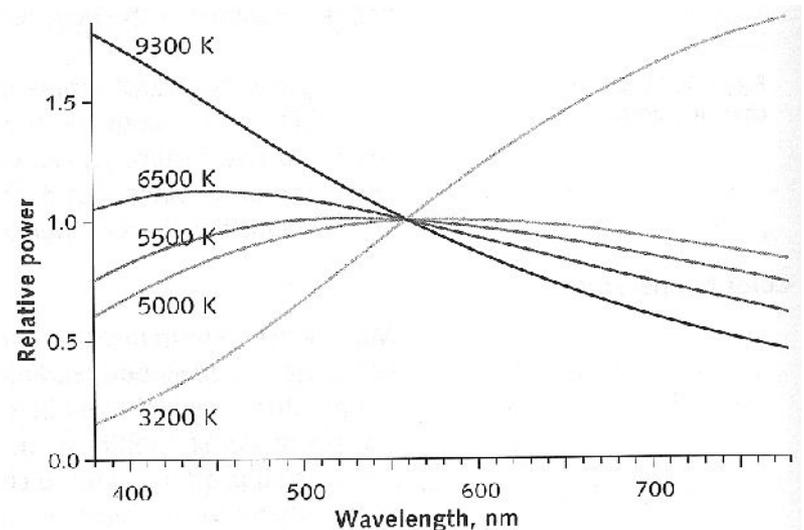
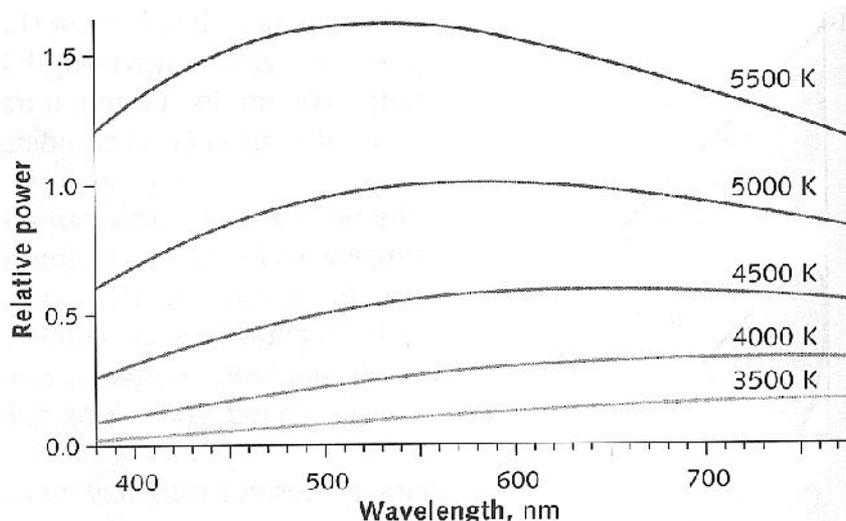
- **Gamut compression**

- 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 D₅₀** and **D₆₅** – 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

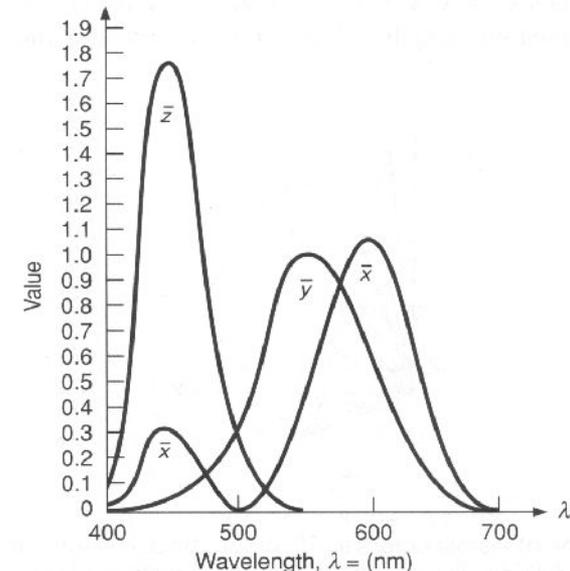
Color and Linear Operations

- **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)

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

- **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
 - $(0 \leq R, G, B \leq 1)$
 - 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

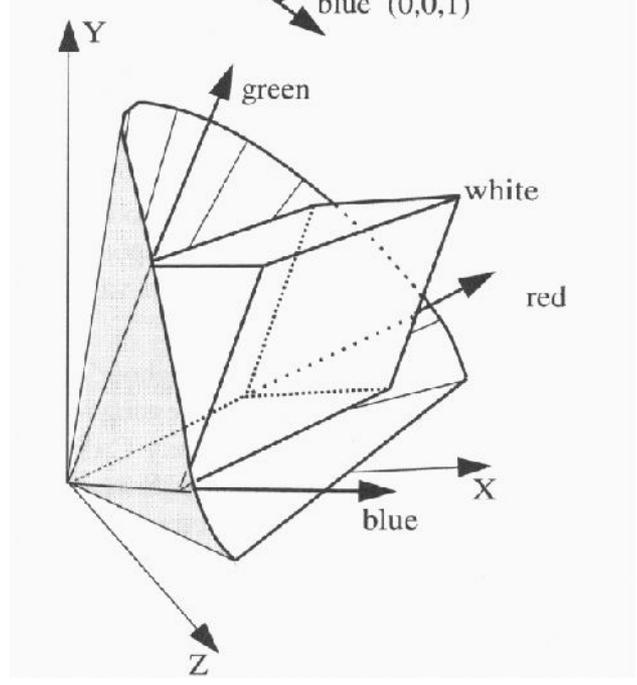
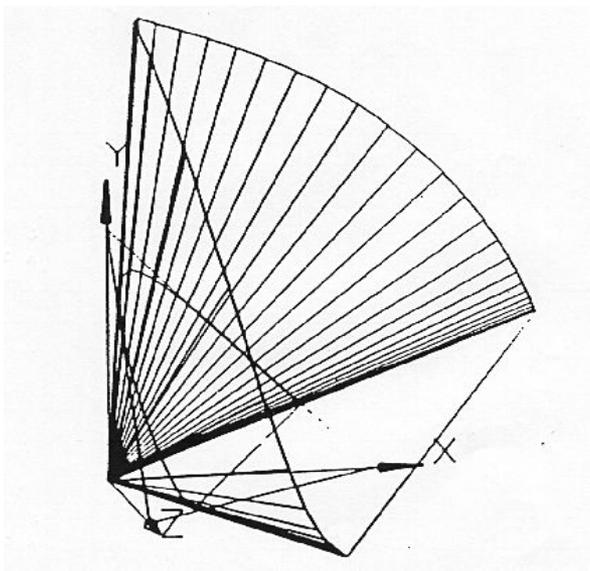
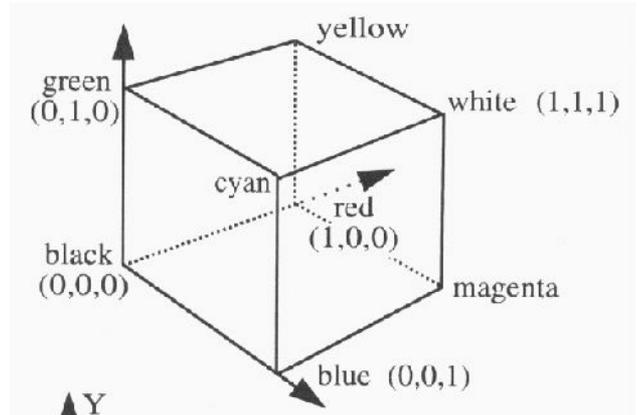
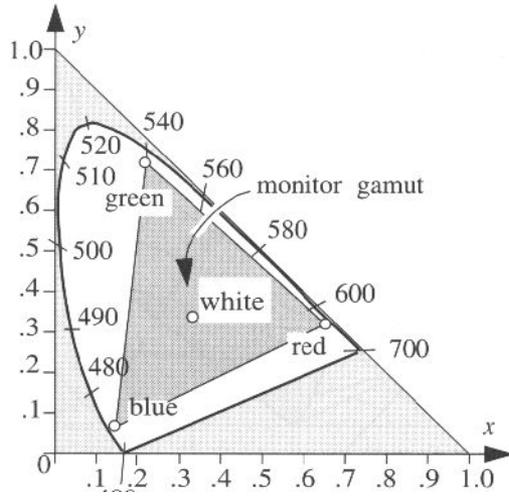
- $(X_w, Y_w, Z_w) = M^*(1, 1, 1)$

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

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

- $Y_w = 1$

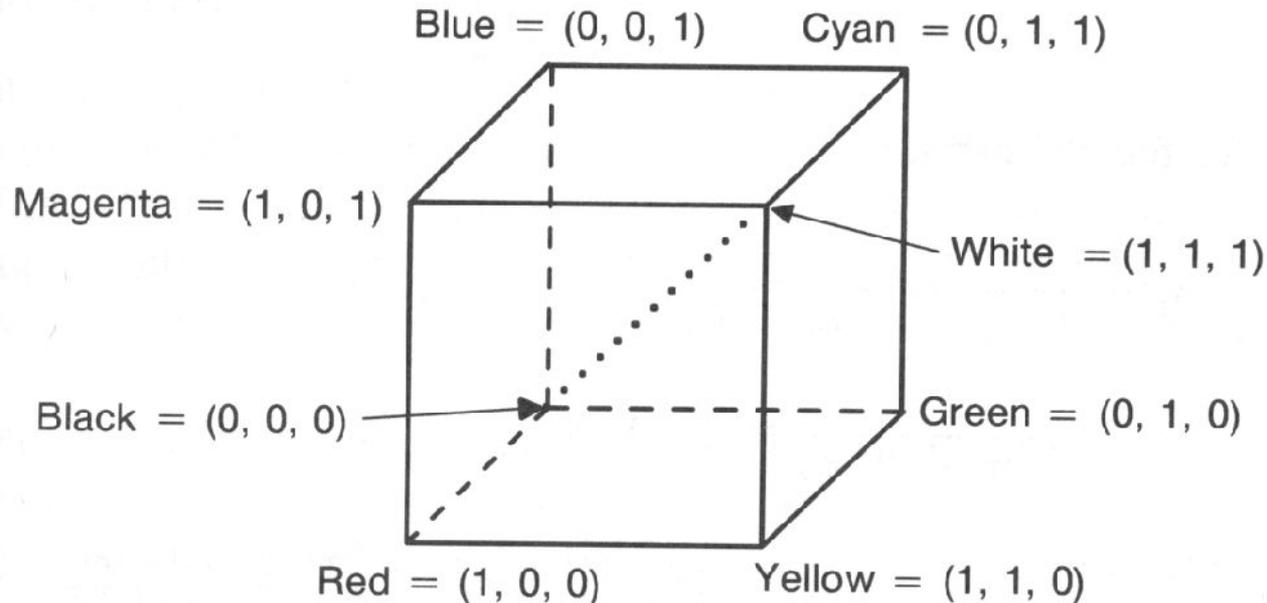
Geometric Interpretation



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

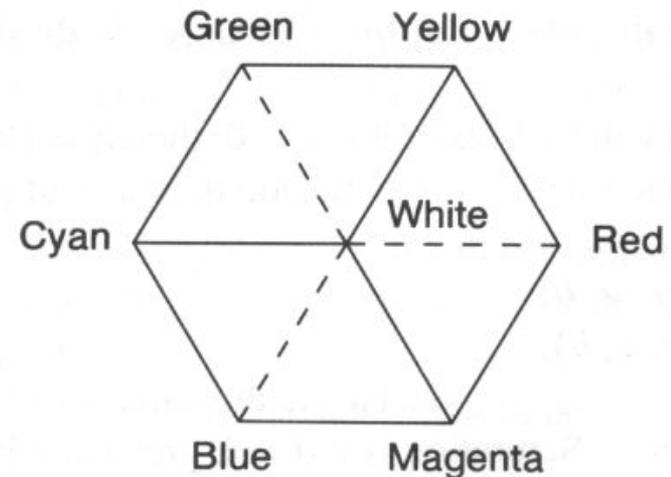
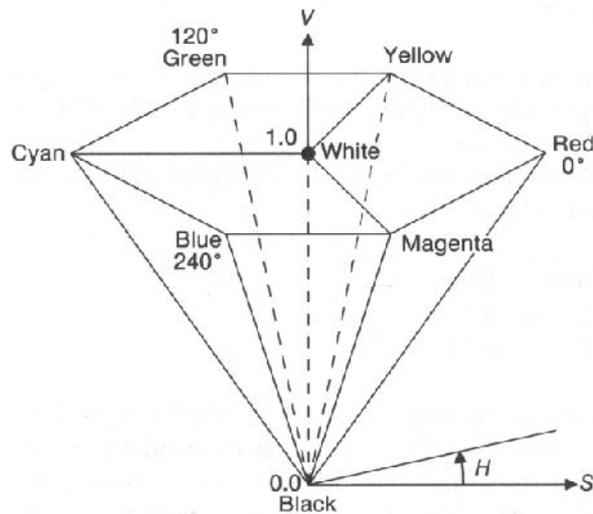
- Generating: ICC-Profile or writing sRGB

- Reading: using ICC-Profile or assume sRGB

- Output: using ICC-Profile or assume sRGB

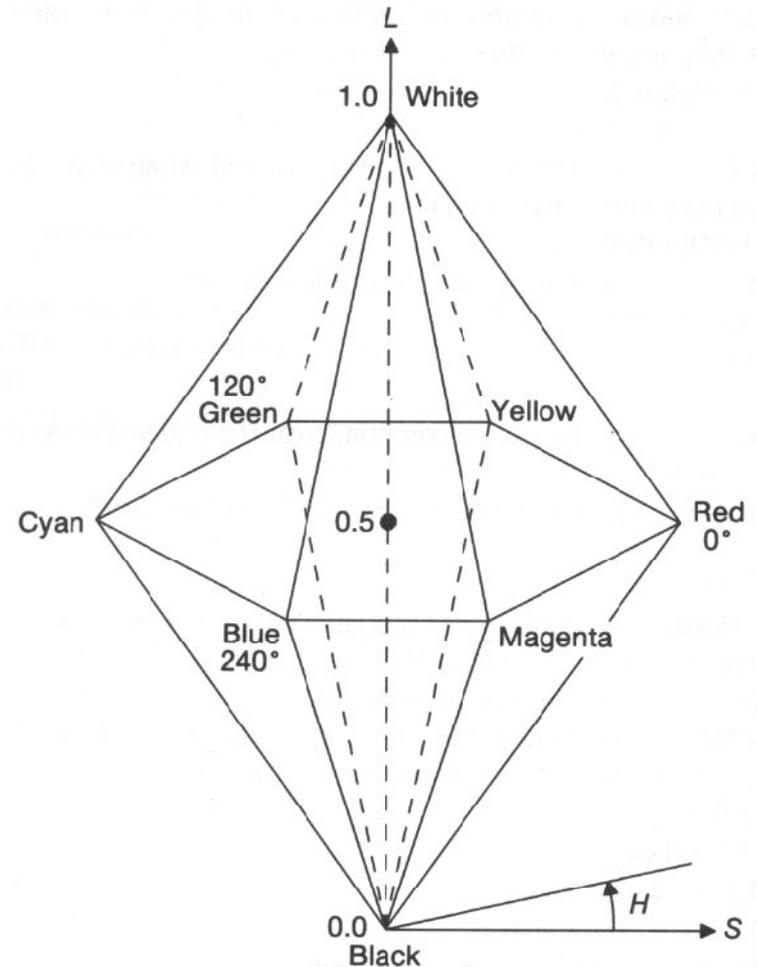
HSV/HSB Model

- **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

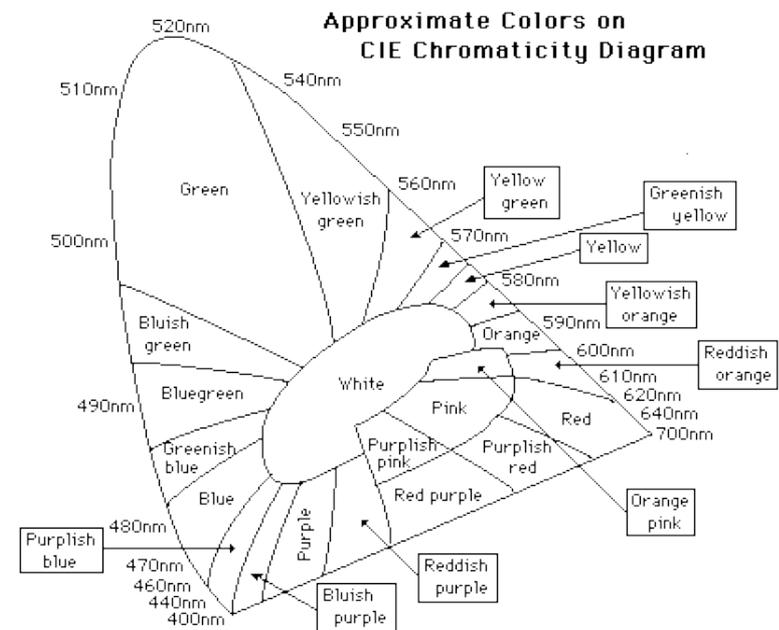
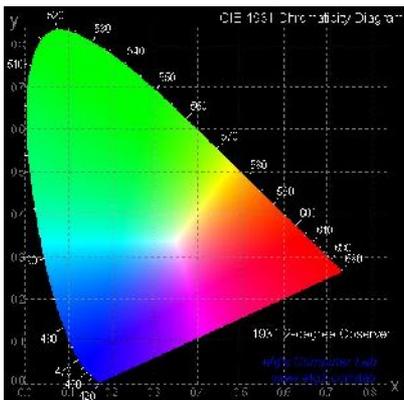
- **HLS (Hue, Lightness, Saturation)**
 - Similar to HSV/HSB
 - Slightly less intuitive
- **Other color models**
 - TekHVC
 - Developed by Tektronix
 - Perceptually uniform color space
 - Video-processing
 - Y', B-Y, R-Y
 - Y'IQ
 - Y'PrPb
 - Y'CrCb
 - Non-linear color spaces



Color Model: In Practice

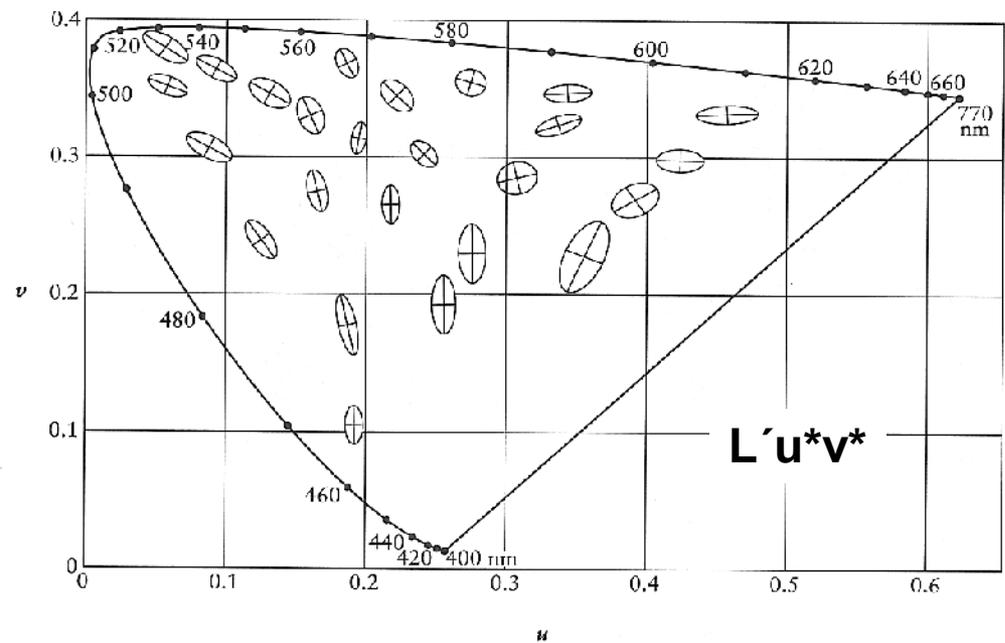
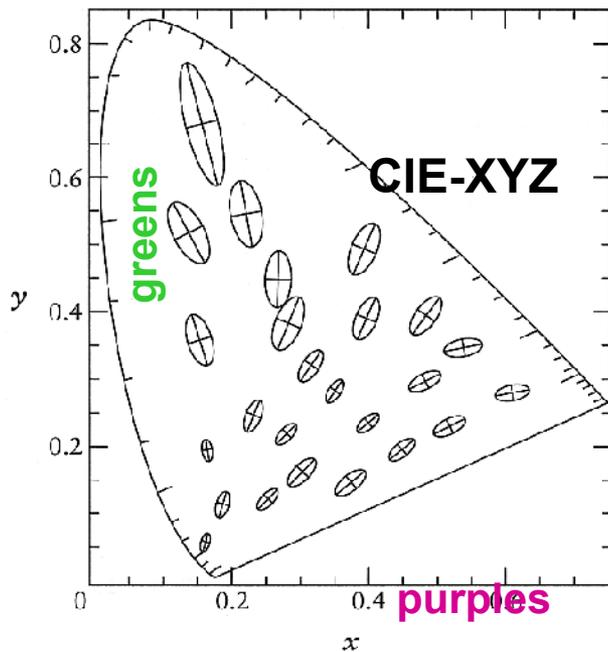
- **Interpolation (shading, anti-aliasing, blending)**

- RGB: $0.5 \text{ red} + 0.5 \text{ green} = \text{dark yellow}$
 $0.5*(1,0,0)+0.5*(0,1,0)= (0.5,0.5,0)$
- HSV: $0.5 \text{ red} + 0.5 \text{ green} = \text{pure yellow}$
 $0.5*(0^\circ,1,1)+0.5*(120^\circ,1,1)= (60^\circ,1,1)$
- 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)

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

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

- Transformation of color differences

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

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

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

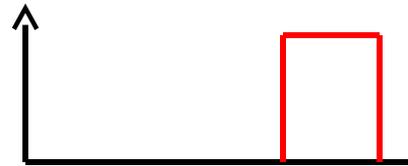
$$b^* = 500L^* [f(Y/Y_n) - f(Z/Z_n)]$$

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

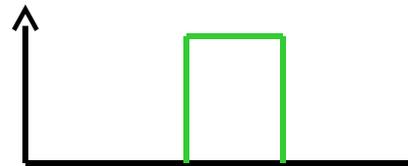
$$v^* = 13L^* (v' - v'_n)$$

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

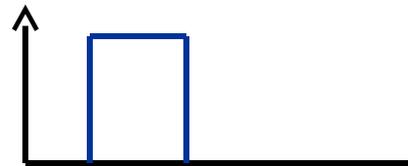
Subtractive color blending



+



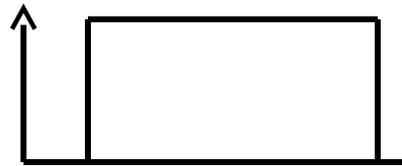
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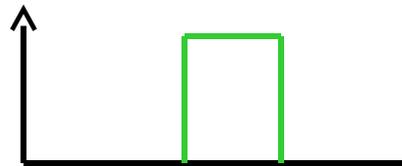
Additive blending



x



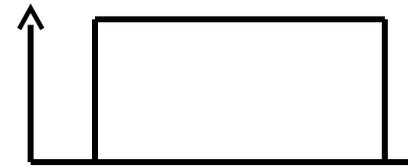
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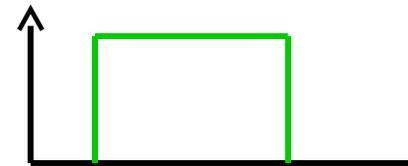
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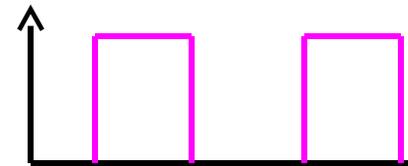
Subtractive blending
With additive primary colors
WRONG !!!



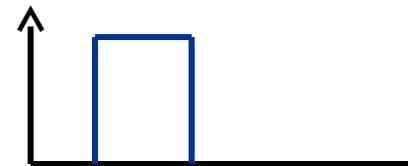
x



x



=



Subtractive blending

cyan (C)

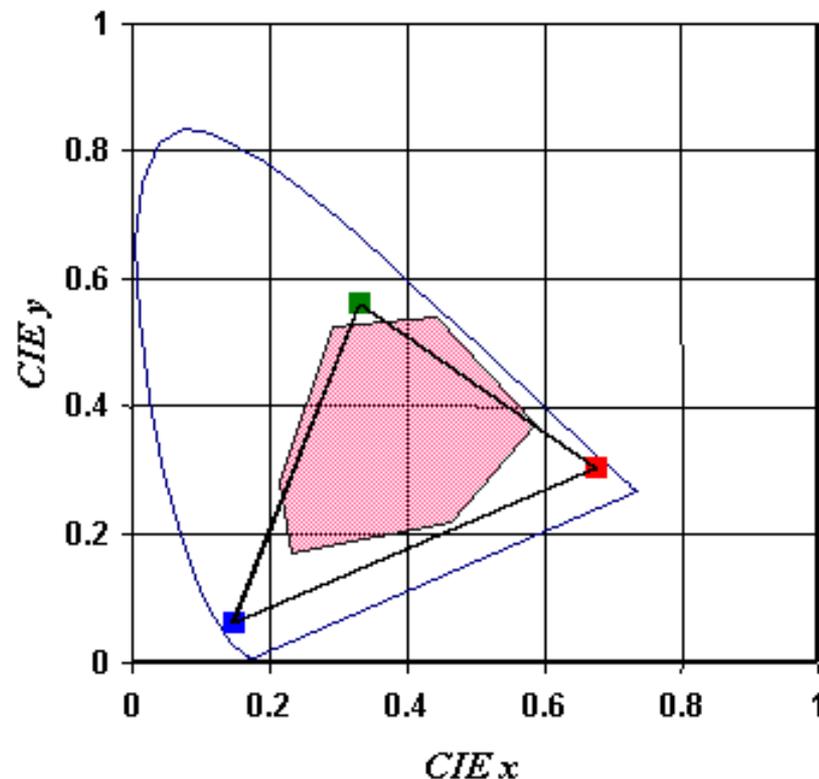
magenta (M)

Subtractive Color Blending

- **CMYK (Cyan, Magenta, Yellow, Black)**
 - Subtractive color blending
 - In the 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 $(CMY) = 1 - (RGB)$



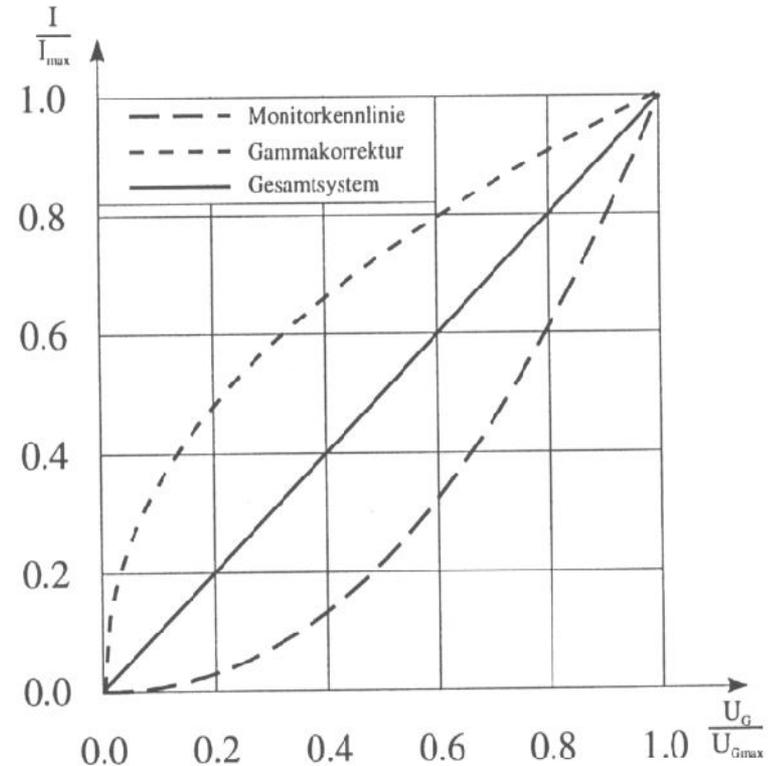
Gamma

- **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 $\gamma = \sim 2.2$ due to physical reasons

- **Gamma correction**

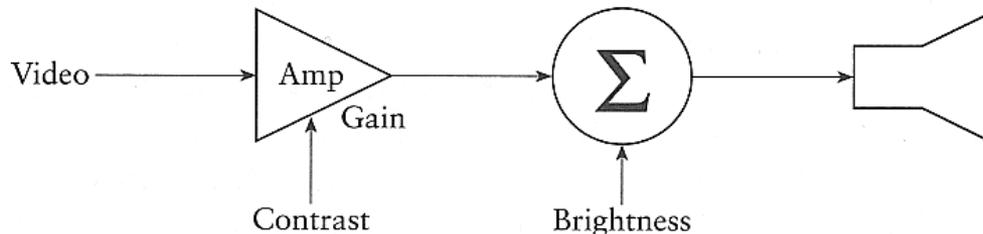
- Pre-correct output values to achieve overall linear curve
- Quantization loss if value represented with less than 12 Bit



Gamma Correction

- **Monitor calibration (for dummies):**

- Correctly: you would need a colorimeter, spectrophotometer
- The procedure:



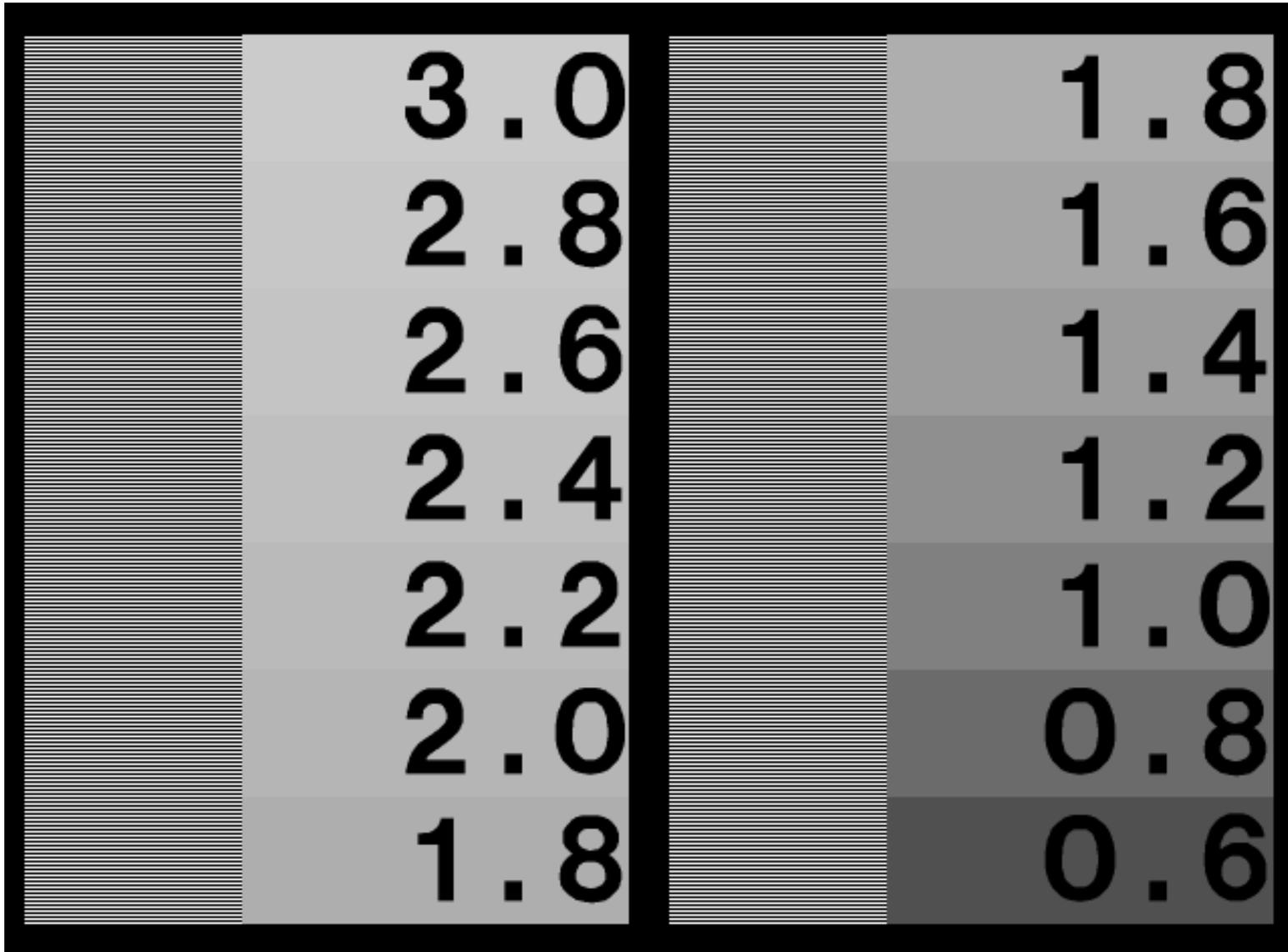
- “Brightness” \leftrightarrow “Contrast”

- 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:

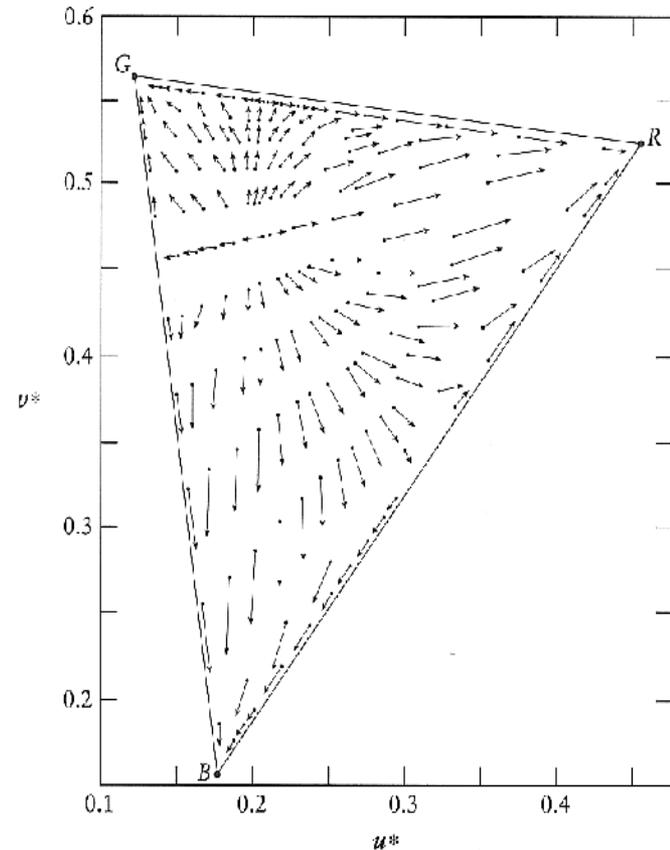


Gamma Testing Chart



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“**

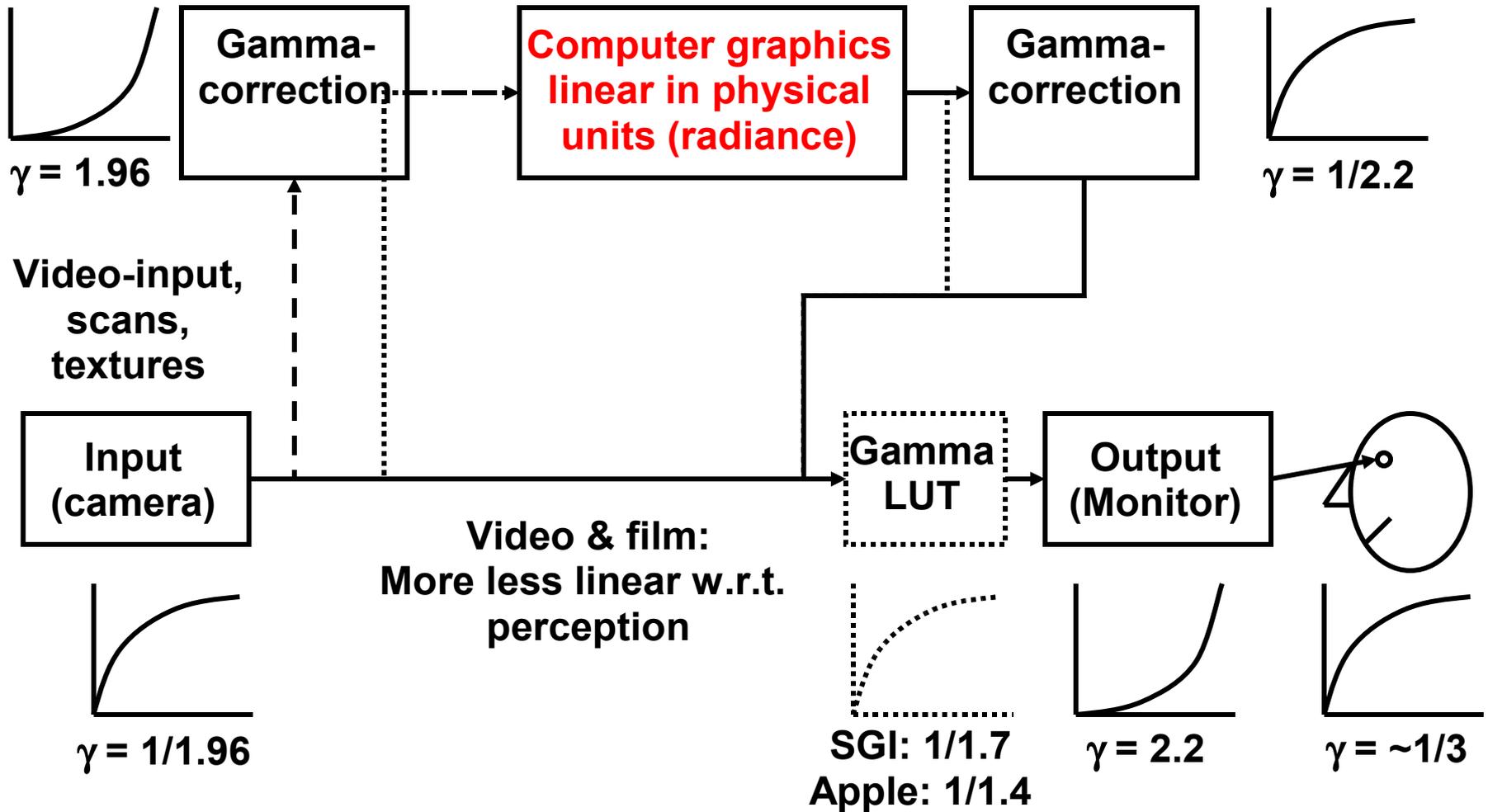
- Human brightness perception roughly follow the gamma curve
 - Really a log-curve, but close

→ **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