

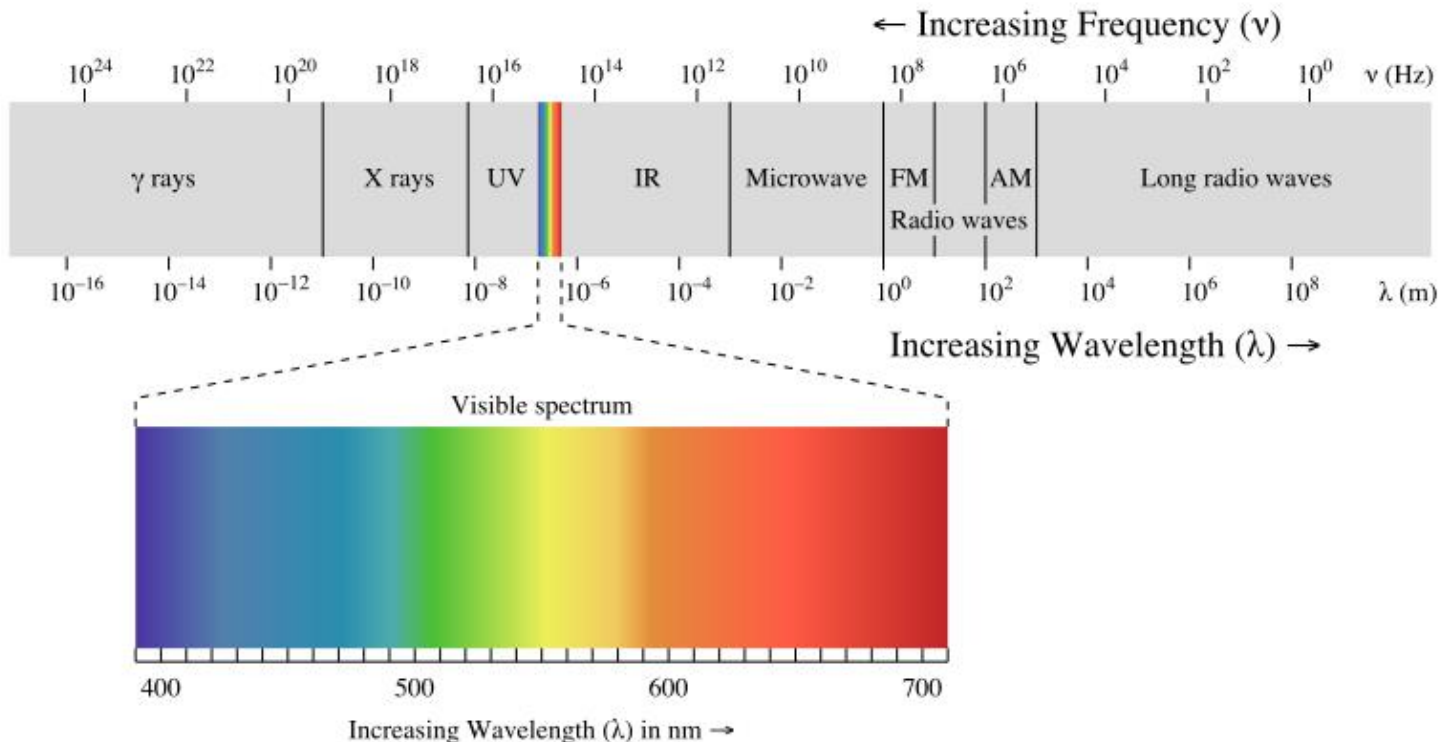
# Computer Graphics

## Color

**Philipp Slusallek**

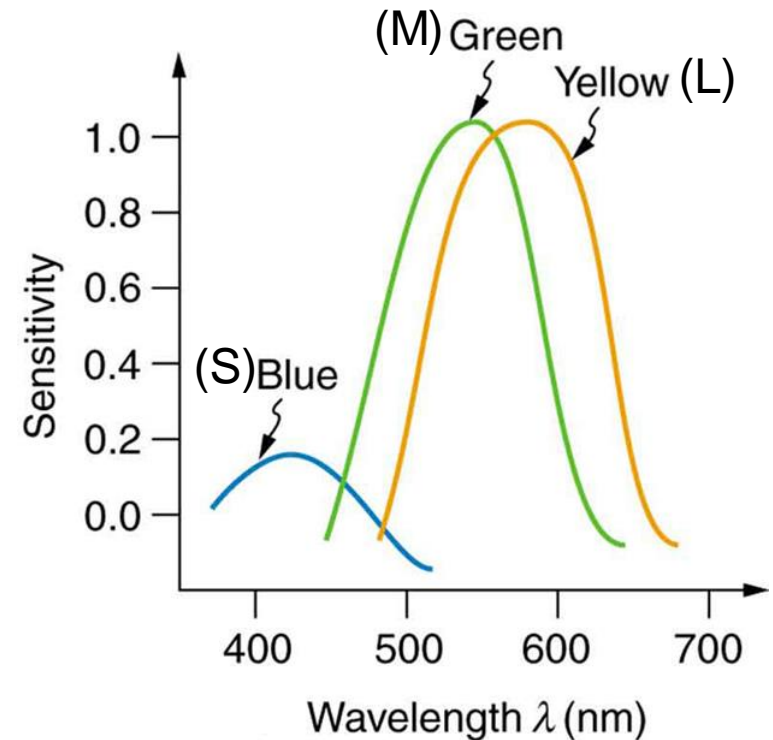
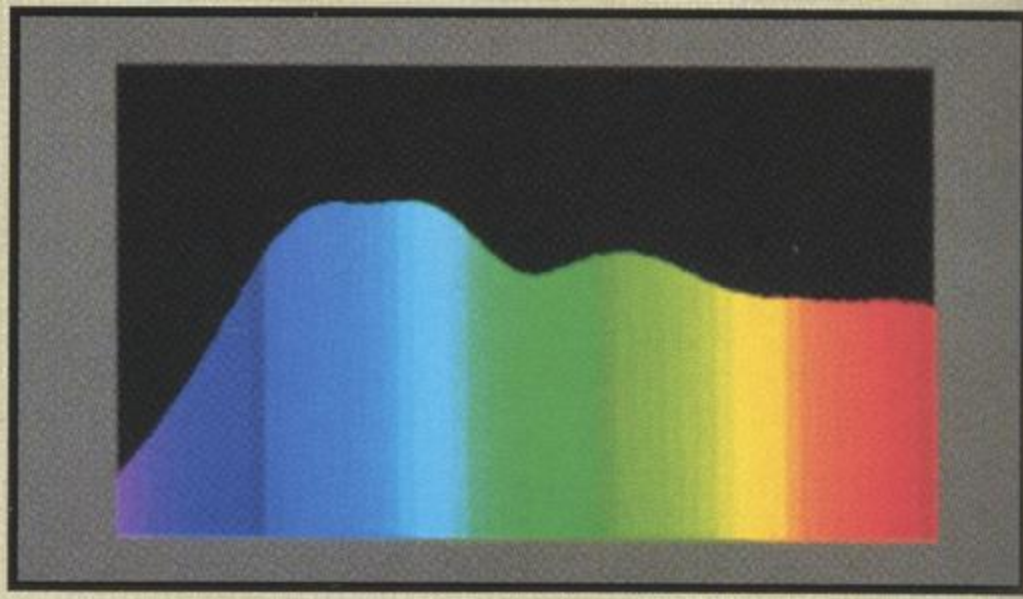
# Color Representation

- **Physics: No notion of “color”**
  - Light is simply a distribution of photons with different frequencies
  - Specified as the “spectrum” of light
  - No notion of “opposing color”, “saturation”, etc.



# Eye as a Sensor

- **Human color perception**
  - Cones in retina: 3 different types
  - Light spectrum is mapped to 3 different signal channels
- **Relative sensitivity of cones for different wavelengths**
  - Long (L, yellow/red), Medium (M, green), and Short (S, blue)

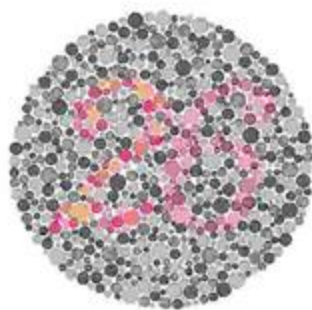
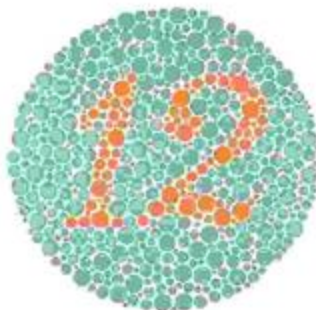


# Color Perception

- **Tri-chromacy (humans, monkeys)**
  - Red, green, blue
  - Color-blindness (most often red-green)
- **Di-chromacy (dogs, cats)**
  - Yellow & blue-violet
  - Green, orange, red indistinguishable
- **Tetra-chromacy (some birds, reptiles)**
- **Penta-chromacy (some insects, pigeons)**



[www.lam.mus.ca.us/cats/color/](http://www.lam.mus.ca.us/cats/color/)



[www.colorcube.com/illusions/clrblind.html](http://www.colorcube.com/illusions/clrblind.html)

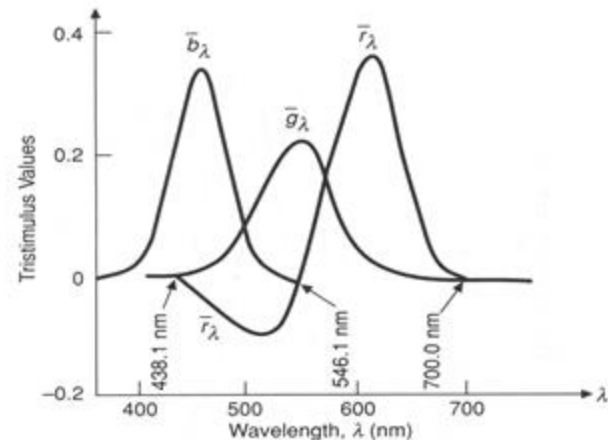
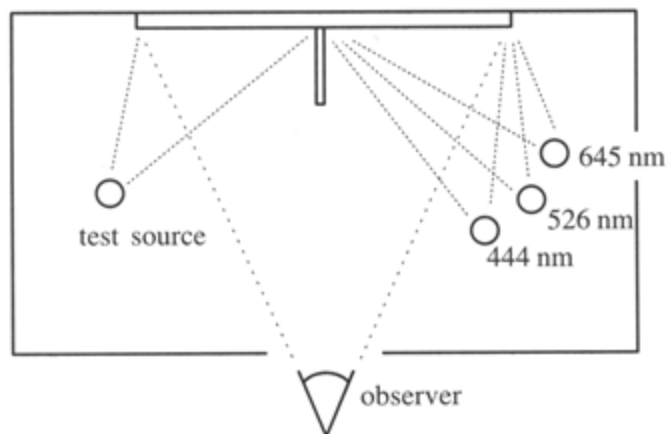
# Tristimulus Color Representation

- **Observation**

- Any color (left-hand side test source) can be matched using 3 linear independent reference *primary colors* (right-hand side)
- May require “negative” contribution of primary colors  
⇔ positive contribution to test color
- “**Matching curves**” describe values for a certain set of primaries to match a mono-chromatic spectral test color of given intensity

- **Main results of key Color Matching Experiments**

- Color perception forms a linear 3-D vector space
- Superposition holds: Mixing two colors == mixing primaries



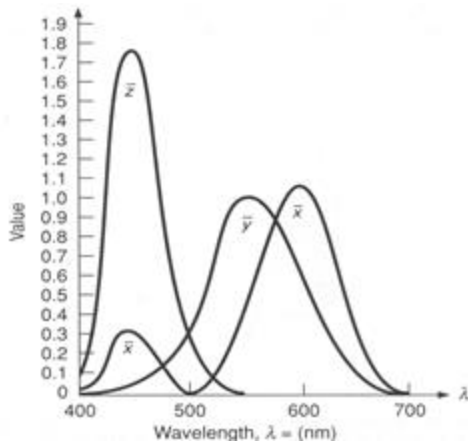
# Standard Color Space CIE-XYZ

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- **CIE color matching experiments**
  - First experiment [Guild and Wright, 1931]
    - Group of ~12 people with “normal” color vision (from London area)
    - 2-degree visual field (fovea only)
  - Other experiment in 1964
    - Group of ~50 people (with foreigners)
    - 10-degree visual field
    - More appropriate for larger field of view, but rarely used since similar
- **CIE-XYZ color space**
  - CIE selected: 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 should be positive
    - One primary should be roughly proportionally to light intensity

# Standard Color Space CIE-XYZ

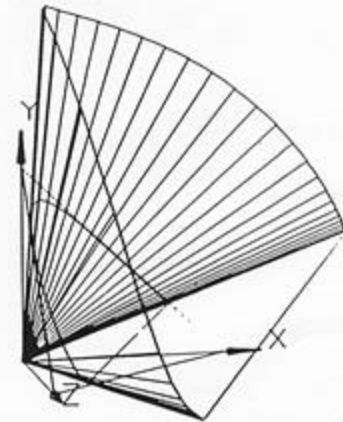
- **Standardized imaginary primaries CIE XYZ (1931)**
  - Imaginary primaries “more saturated” than monochromatic lights
    - Together can match all physically realizable color stimuli
  - Defined via spectral matching for virtual CIE XYZ primaries
    - Virtual red (X), green (Y), blue (Z)
  - Y is roughly equivalent to luminance
    - Shape similar to luminous efficiency function  $V(\lambda)$
  - Monochromatic spectral colors form a curve in 3D XYZ-space
    - Colors: combinations of monochromatic light  $\Rightarrow$  within the curve hull
    - Colors beyond visible limits typically ignored since not perceptible



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

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

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



# CIE xy Chromaticity Diagram

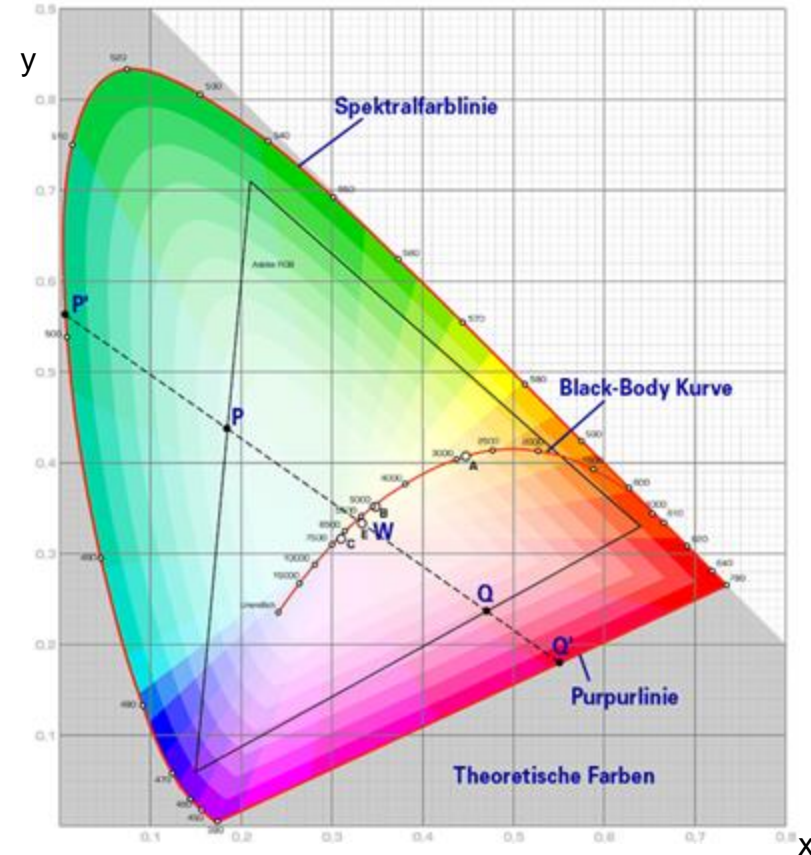
- **Concentrate on color, not light intensity**
  - Relative coordinates: projection on  $X+Y+Z = 1$  plane (normalize)

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

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

$$z = 1 - x - y$$

- Chromaticity diagram
  - 2D plot over  $x$  and  $y$
  - Points called “color locations”
- **Locations of interest**
  - Pure spectral colors (red line)
  - Purple line: interpolate red & violet
  - White point:  $\sim(1/3, 1/3)$ 
    - Device dependent/ eye adaptation
  - Black-body curve
- **Gamut:** Primaries of HW devices only allow for subset

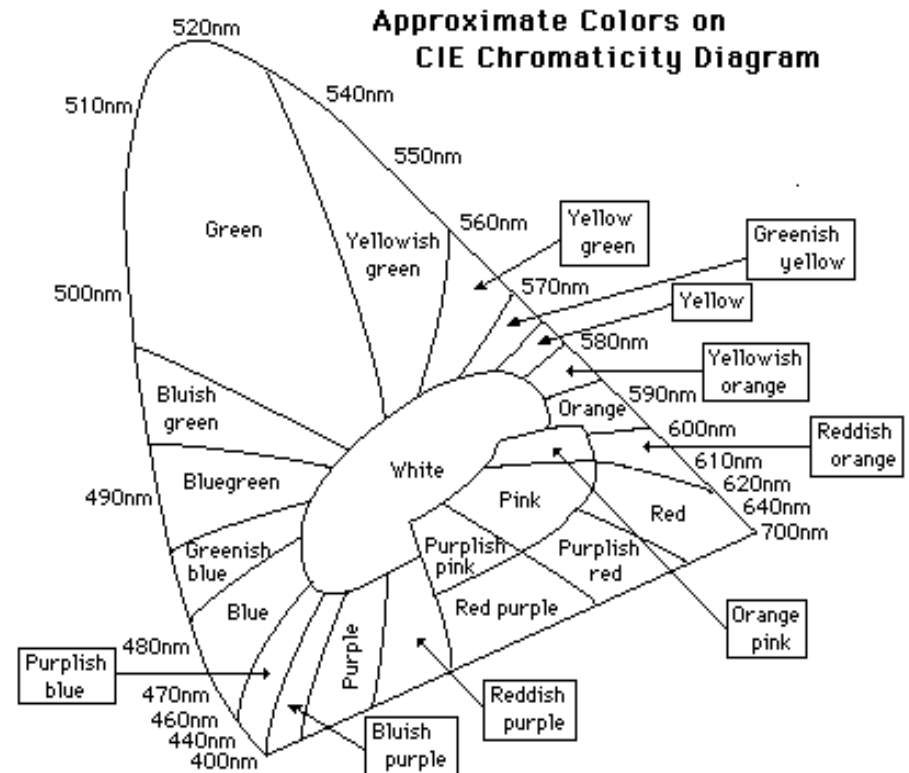
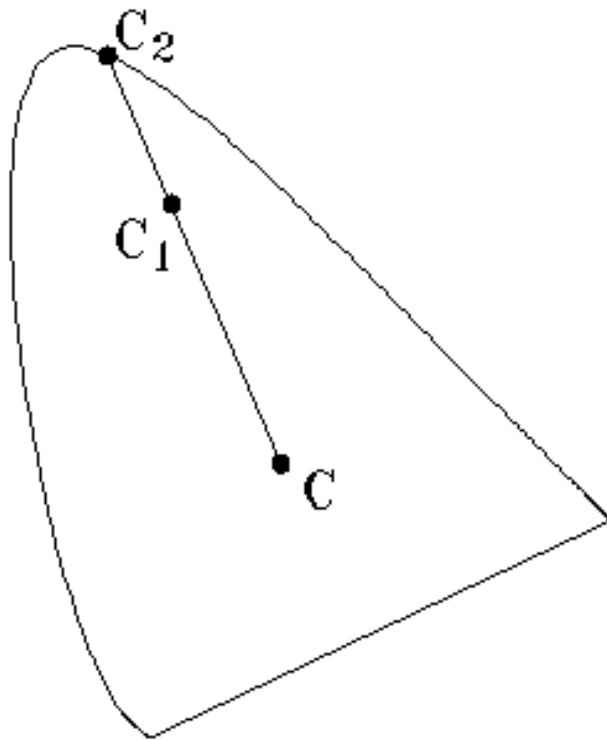




# CIE Chromaticity Diagram

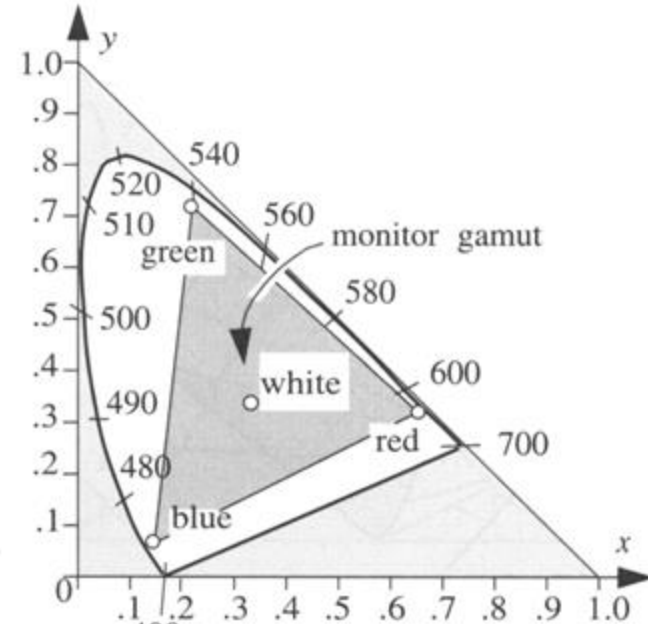
- **Specifying colors**

- **Saturation**: relative distance between pure color and white point
- **Complementary colors**: on other side of white point



# Color Gamut

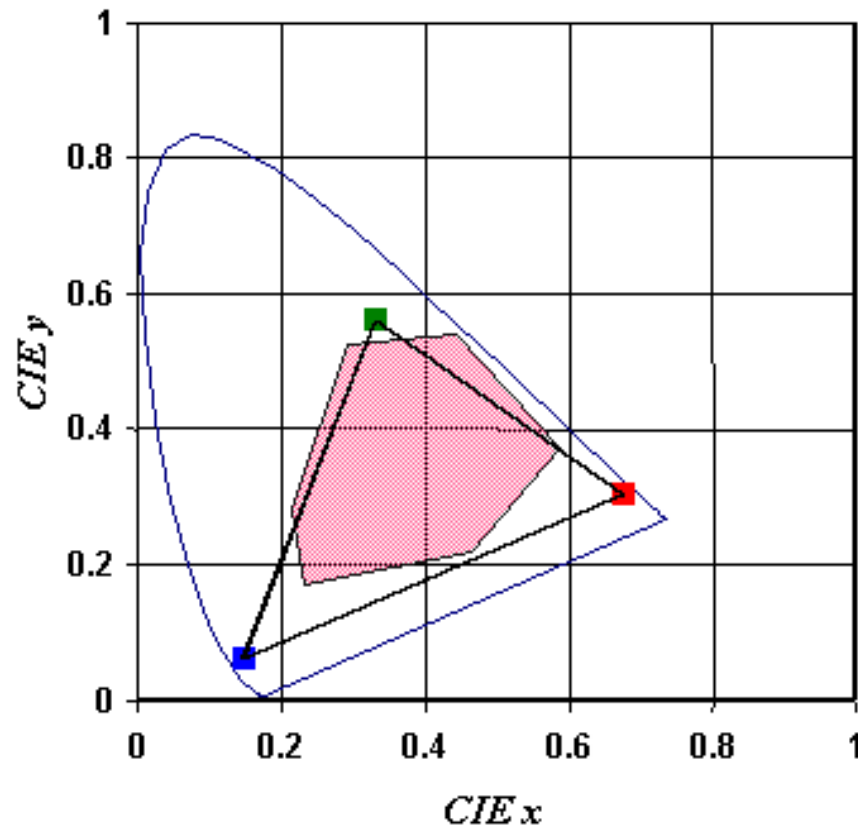
- **Color gamut**
  - Set of representable colors
- **CIE XYZ gamut**
  - Device-independent
- **Device color gamut**
  - Triangle inside color space defined by additive color blending
- **RGB colors**
  - Colors defined as linear combinations of primary colors of the device
- **RGB space gamut**
  - **Device (monitor/projector) dependent (!!!)**
    - Choice of primaries used (lamps, LEDs)
    - Weighting/intensity of primaries (filters)
  - White-point/temperature adjustment
    - Moves white point and thus all other colors *within* the gamut



# Printer Color Gamut

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- **Complex for printer due to subtractive color blending**
- **Complex interactions bet. printed colors (mixing)**
- **Depends on colors, printing technology, paper, ...**

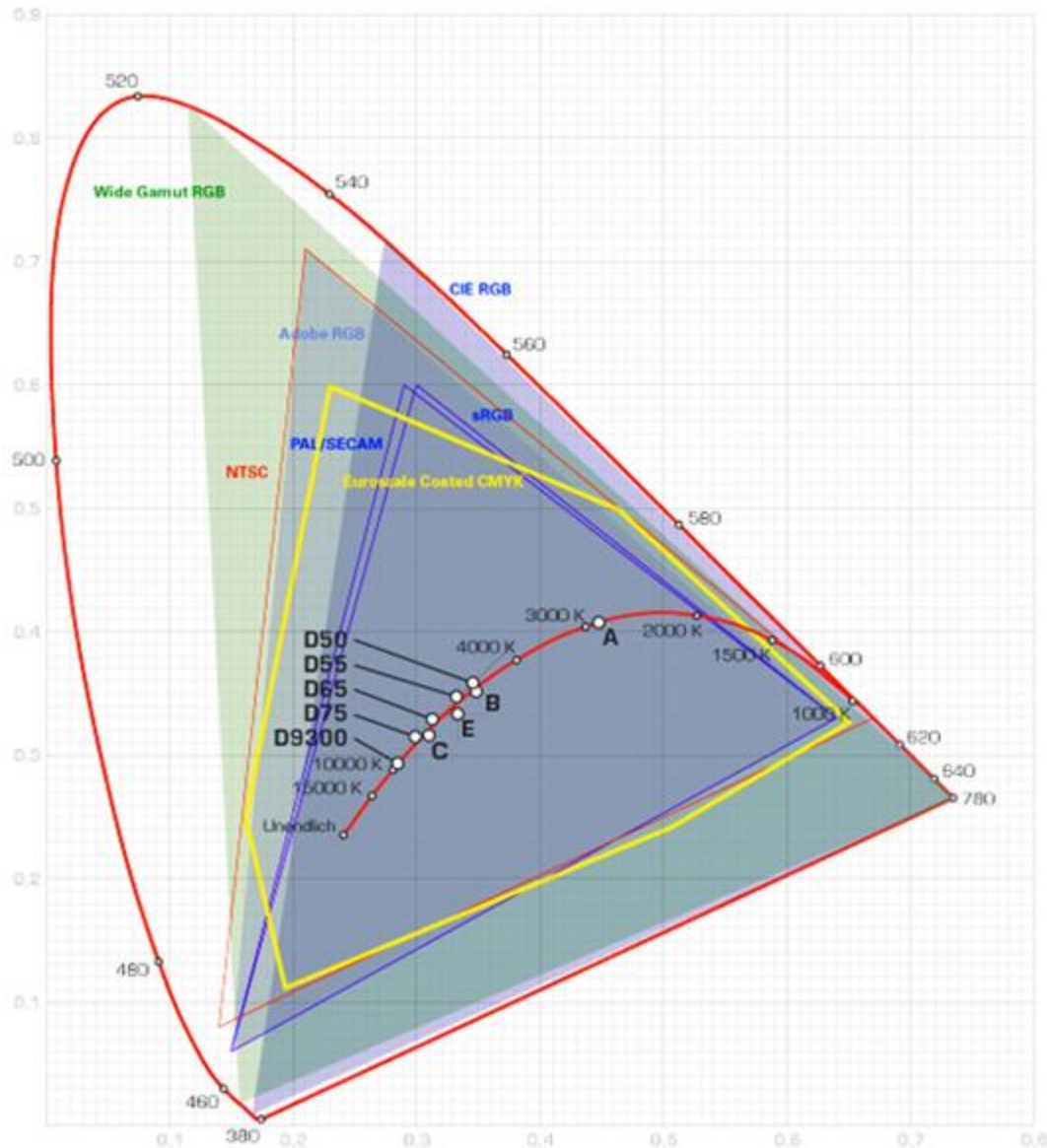


# Different Color Gamuts

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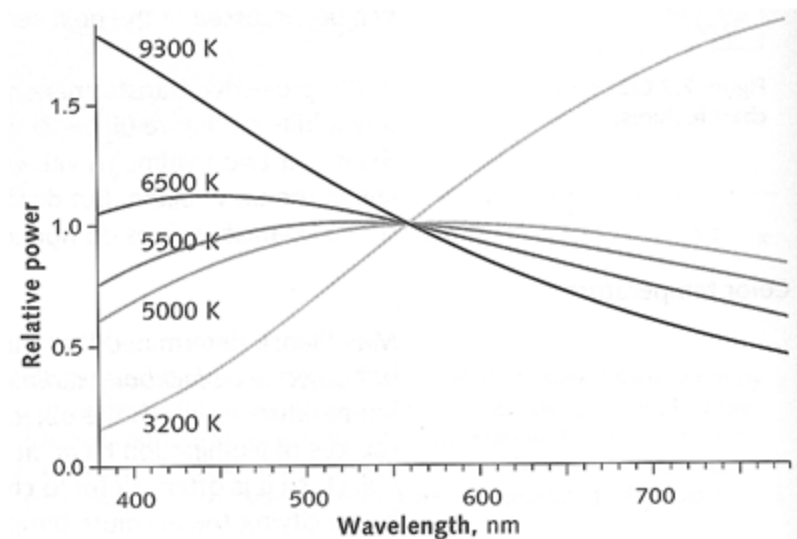
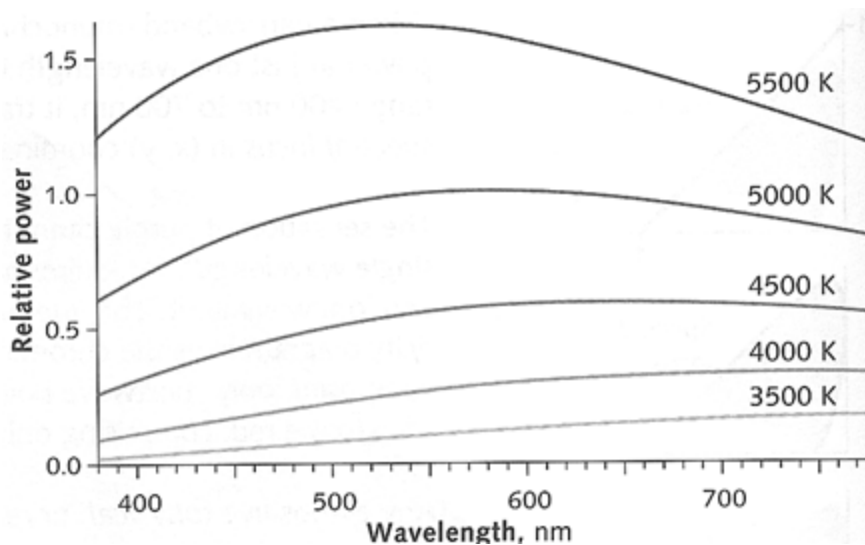
- **Gamut compression/mapping**
  - What to do if colors lie outside of the printable area?
    - Scaling, clamping, other non-linear mappings
  - Each device should replace its out-of-gamut colors with the nearest approximate achievable colors
  - Possible significant color distortions in a printed → scanned → displayed image
- **See color management later**

# Different Color Gamuts



# Color Temperature

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



# CIE Standard Illuminants

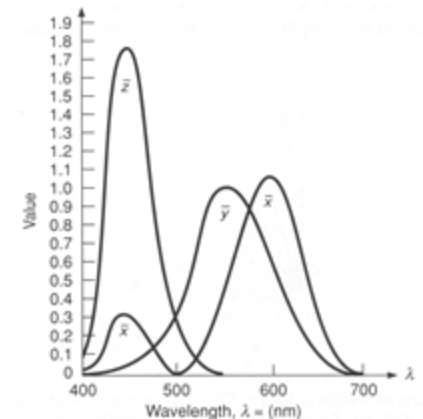
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- **Properties of illuminant (light sources)**
  - Important in many applications
  - Scenes look different under different (real or virtual) illumination
- **Set of standardized light sources**
  - Illuminant A – incandescent lighting conditions with 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
- **Practical use**
  - Spectral data of CIE standard illuminants available on the web
  - Frequently used in the CG applications to compare against well-defined real-world lighting conditions

# Color and Linear Operations

- **Additive color blending is a linear operation**
  - Can represent the operations as a matrix
- **Calculating primary components of a color**
  - Measure the spectral distribution (e.g. sample every 5-10 nm)
  - Projecting from  $m$ D to 3D using sampled matching curves (loss of information)

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



- **Transformation between color spaces**

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



# Color Transformations

---

- **Computing the transformation matrix M**

- Given (e.g. from monitor manufacturer or measured)

- Primary colors  $(x_r, y_r), (x_g, y_g), (x_b, y_b)$
- White point  $(x_w, y_w)$  for given color temperature (R=G=B=1)

- Setting

$$\begin{aligned}z_r &= 1 - x_r - y_r \\C_r &= X_r + Y_r + Z_r \\x_r &= \frac{X_r}{X_r + Y_r + Z_r} = \frac{X_r}{C_r} \rightarrow X_r = x_r C_r\end{aligned}$$

- Analogous for  $x_g, x_b$

- R,G,B are factors modulating the primaries  $(X_{rgb}, Y_{rgb}, Z_{rgb})$

$$M = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} = \begin{bmatrix} x_r C_r & x_g C_g & x_b C_b \\ y_r C_r & y_g C_g & y_b C_b \\ z_r C_r & z_g C_g & z_b C_b \end{bmatrix}$$

# Color Transformations (Cont.)

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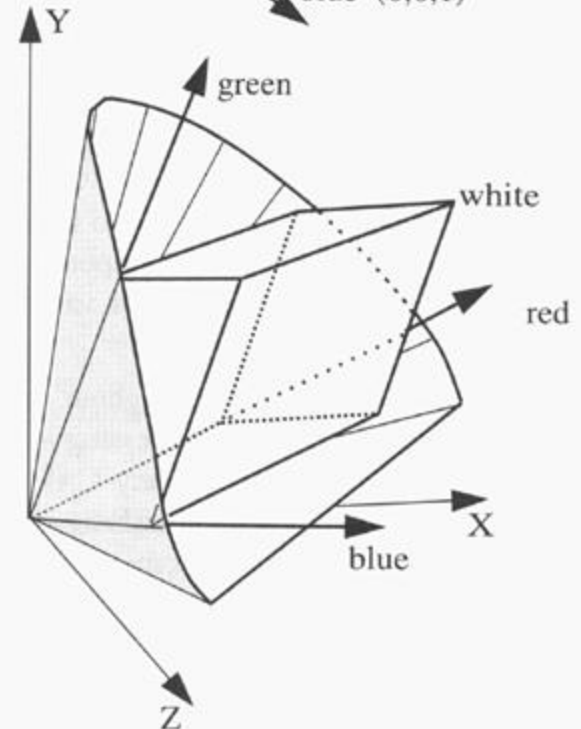
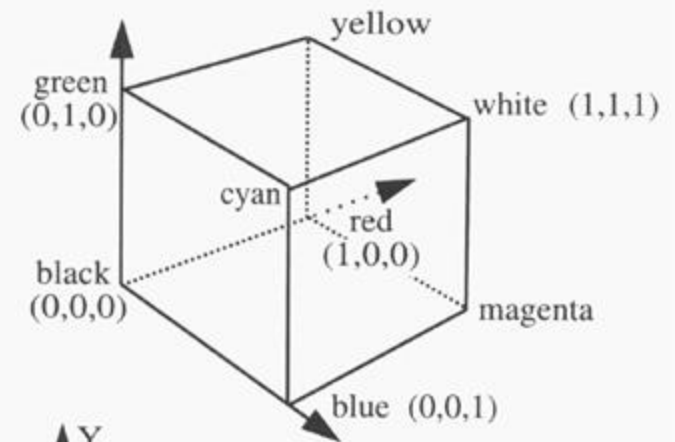
- **Computing the constants  $C_r$ ,  $C_g$ ,  $C_b$** 
  - Per definition the white point is given as  $(R, G, B) = (1, 1, 1)$ 
    - $(X_w, Y_w, Z_w) = M * (1, 1, 1)$

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

- $(X_w, Y_w, Z_w)$  can be computed from  $(x_x, y_x)$ 
    - Unspecified brightness
    - Use the normalization constant  $Y_w = 1$
- **Can now compute conversion between any two linear color spaces of different devices by intermediate mapping to CIE XYZ**

# Geometric Interpretation

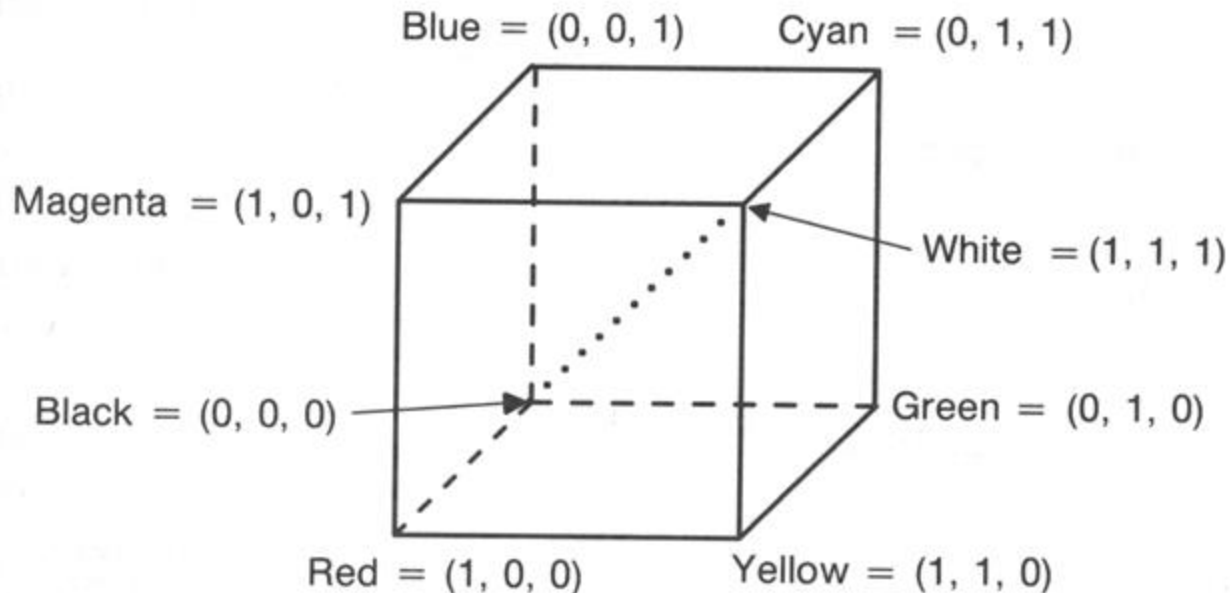
- RGB embedded in XYZ space
- Basis change bet. RGB spaces
- Possibly need to handle out-of-gamut colors
- Changes of color temperature/  
white point
  - Cannot change color locations of primaries (defined by material)
  - Changing intensities of primaries
  - Scales the length of the basis vectors
  - Moves the tip of the cube



# RGB Color Model

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- **RGB:**
  - Simplest model for computer graphics
    - Defined by primary colors of the device
  - Natural for additive devices (e.g. monitors)
  - **Device dependent (!!!)**
    - **Most display applications *still* do not correct for it!!!!**
  - Many image formats don't allow primaries to be specified



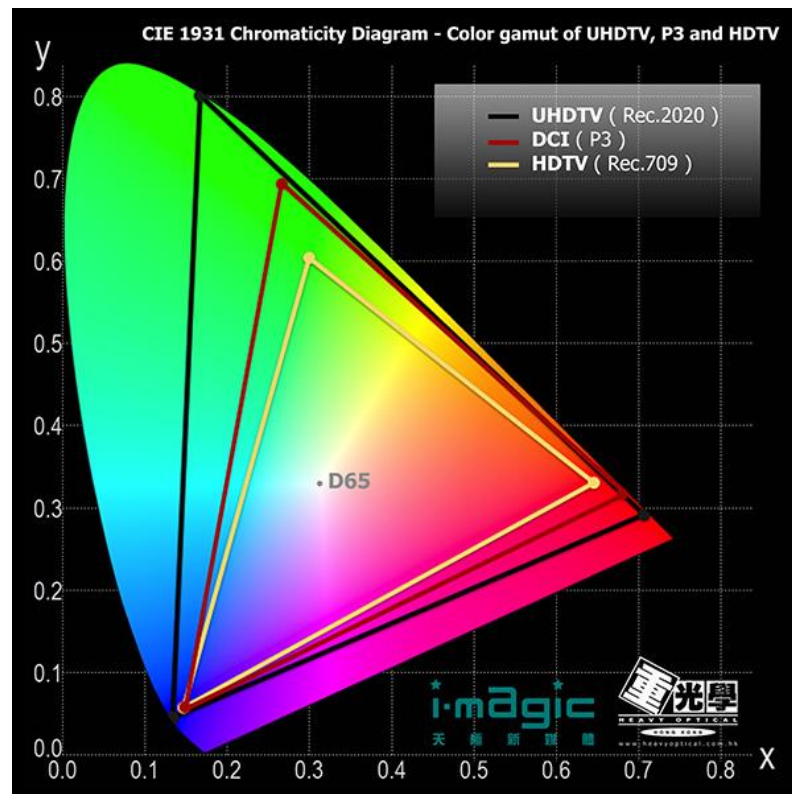
# sRGB Color Space

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- **Standardized RGB color space**
  - RGB for standardized primaries and white point (and gamma)
  - 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 Int. Color Consortium
  - Assume all image data without ICC profile implicitly lie in sRGB
    - Generating: ICC-Profile or writing sRGB
    - Reading/output: using ICC-Profile or assume sRGB

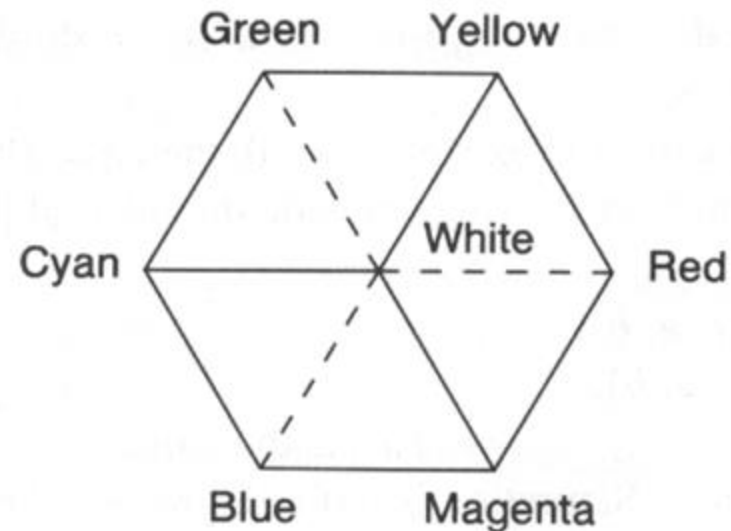
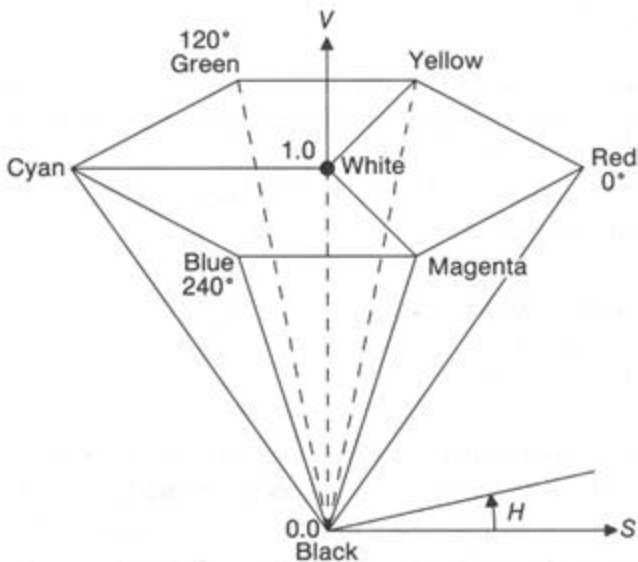
# ITU Rec.-2020 / BT-2020

- **Standardization of 4K and 8K video format**
  - Resolution, frequency, digital representation
  - Color gamut, gamma
- **Specification of default CIE-xy values (Wide Gamut)**
  - Primaries are monochromatic!
  - Red: 0.708, 0.292
  - Green: 0.170, 0.797
  - Blue: 0.131, 0.046
  - White: 0.3127, 0.3290 (D65)
  - Gamma similar to sRGB but more accurate depending on bit-depth



# HSV/HSB Model

- **HSV/HSB (Hue, Saturation, Value/Brightness)**
  - Motivated from artistic use and intuitive color definition (vs. RGB)
    - 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



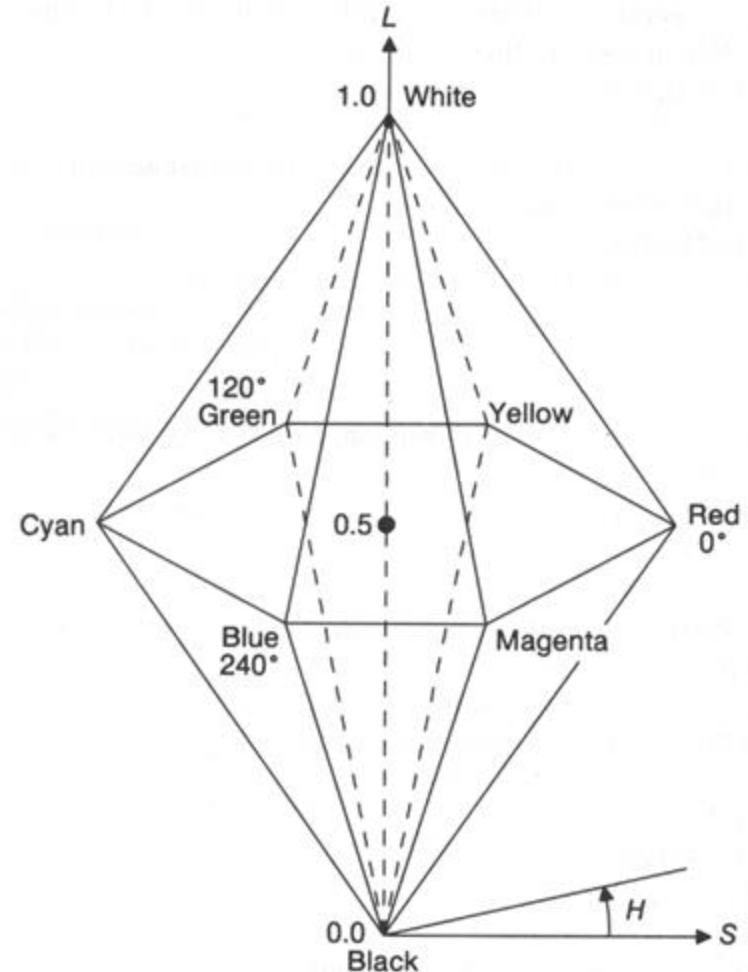
# HLS Model

- **HLS (Hue, Lightness, Saturation)**

- Similar to HSV/HSB
- Slightly less intuitive

- **Many 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

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- **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  
 $0.5*(0^\circ,1,1) + 0.5*(120^\circ,1,1) = (60^\circ,1,1)$
- **Interpretation**
  - Interpolation in RGB
    - Physical interpretation: linear mapping → interpolation in XYZ space
  - Interpolation in HSV
    - Intuitive color interpretation: “yellow lies between red and green”

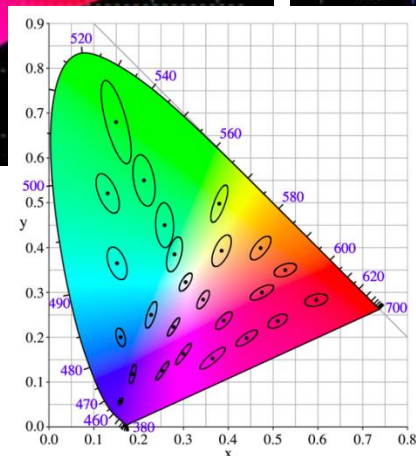
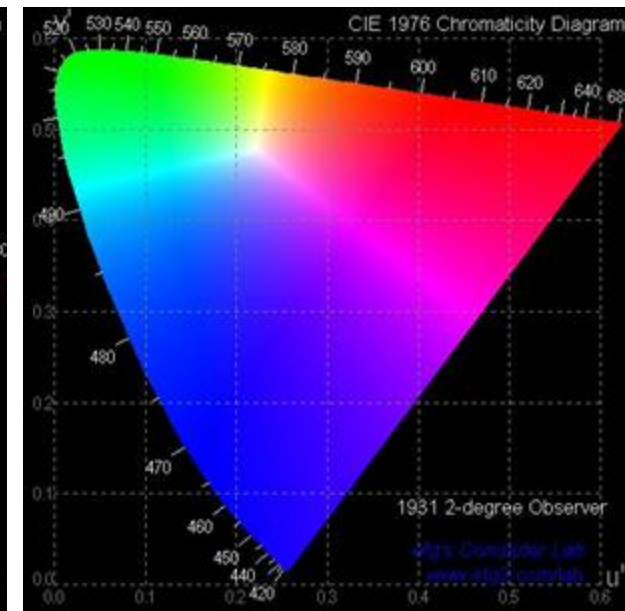
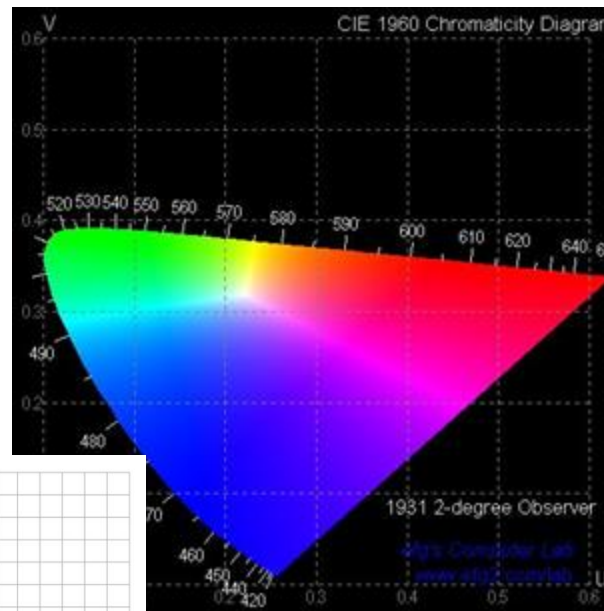
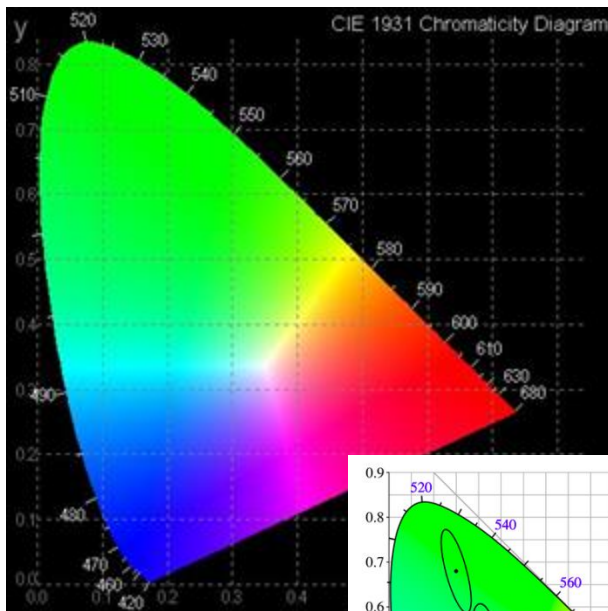
# Color Differences

- **Distance threshold until perceptible color difference**
  - Very inhomogeneous  $\Rightarrow$  alternate transformations

CIE-xy (1931)

CIE-uv (1960)

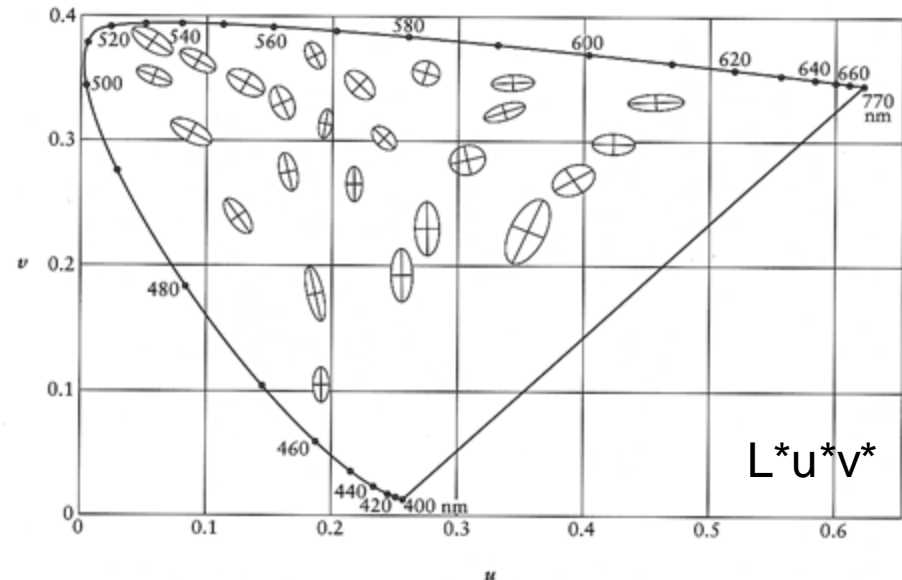
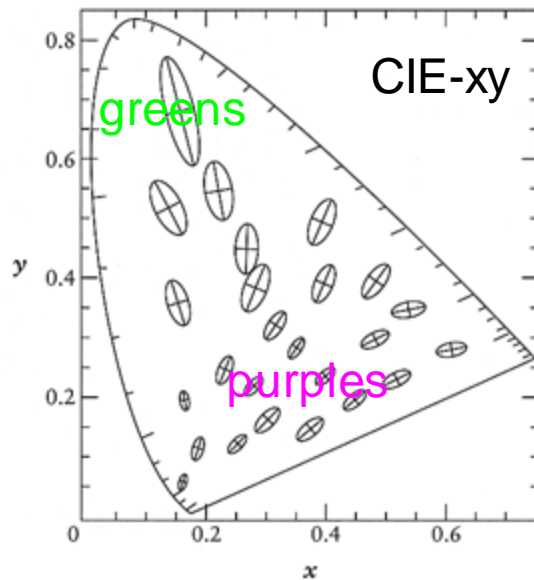
CIE-u'v' (1976)



MacAdams ellipses: Same difference threshold

# $L^*u^*v^*$ / $L^*a^*b^*$ - Color Spaces

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



# 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

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

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

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

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

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

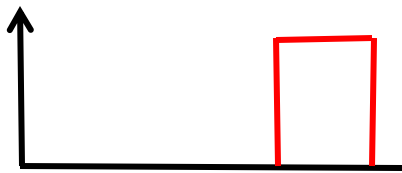
$$b^* = 500L * [f(Y/Y_n) - f(Z/Z_n)]$$

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

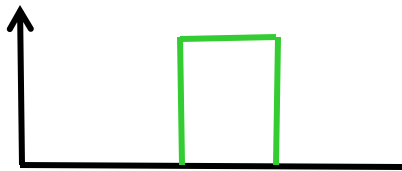
- Limited applicability to HDR

# Subtractive Color Blending

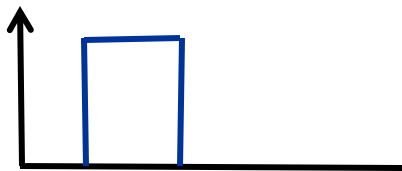
- Corresponds to stacked color filters



+



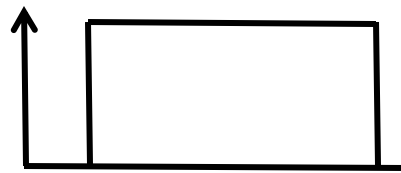
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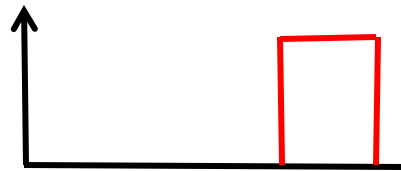
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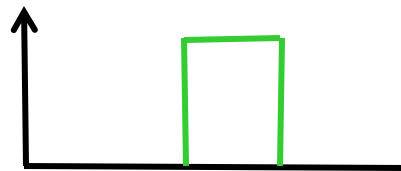
Additive blending



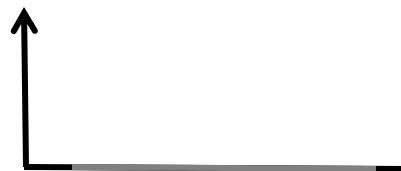
x



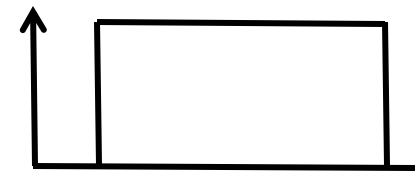
x



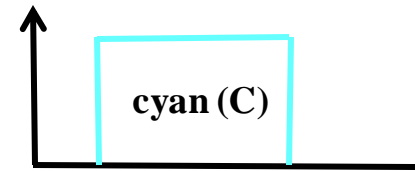
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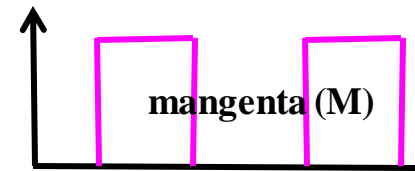
Subtractive blending  
Multiply by primaries: wrong !



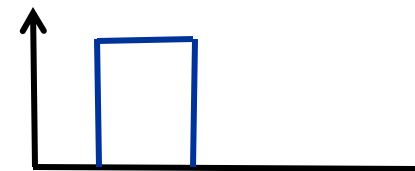
x



x



=



Subtractive blending  
Multiply by inverse primaries

# Subtractive Color Blending

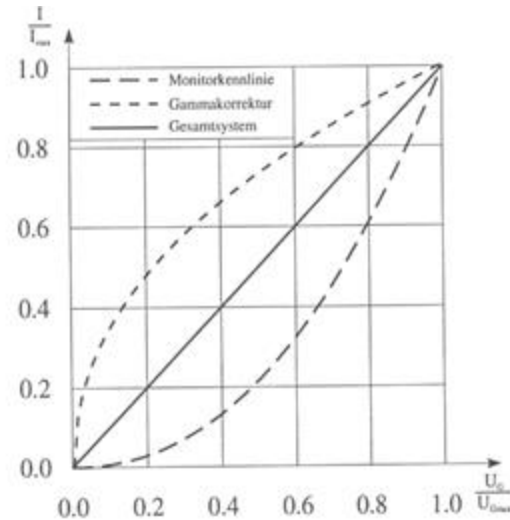
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- **Primarily used for printers**
- **CMYK (Cyan, Magenta, Yellow, Black)**
  - In theory:
    - $(C, M, Y) = 1 - (R, G, B)$  // Hence “subtractive” color space
    - $K = \min(C, M, Y)$  // Black (B already used for blue!)
    - $(C, M, Y, K) = (C-K, M-K, Y-K, K)$
  - In practice: profoundly non-linear transformation
    - Other primary colors
    - Interaction of the color pigments among each other
    - Covering
    - Etc, etc...
- **Subtractive 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 in CRT monitors is non-linear with respect to the applied voltage  $U$
- Best described as power law:  $L = U^\gamma$
- Gamma-Factor  $\gamma = \sim 2.5$  due to physics of CRT monitor (e-beam)
- For *compatibility* also in other displays (LCD, OLED, etc.)



- **Gamma correction**

- Pre-correct values with inverse to achieve a linear curve overall
- Quantization loss if value represented with  $<12$  bits
  - Hardly ever implemented this way in apps and HW

$\gamma=2$

$\gamma=1$  (original)

$\gamma=1/2$

$\gamma=1/3$

$\gamma=1/4$

# Gamma Testing Chart

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- **Gamma of monitors not always correct**
- **Testing:**
  - 50% intensity should give 50% grey (half black-white)
  - Match actual gray with true black/white average  $\rightarrow \gamma$





**3 . 0**

**2 . 8**

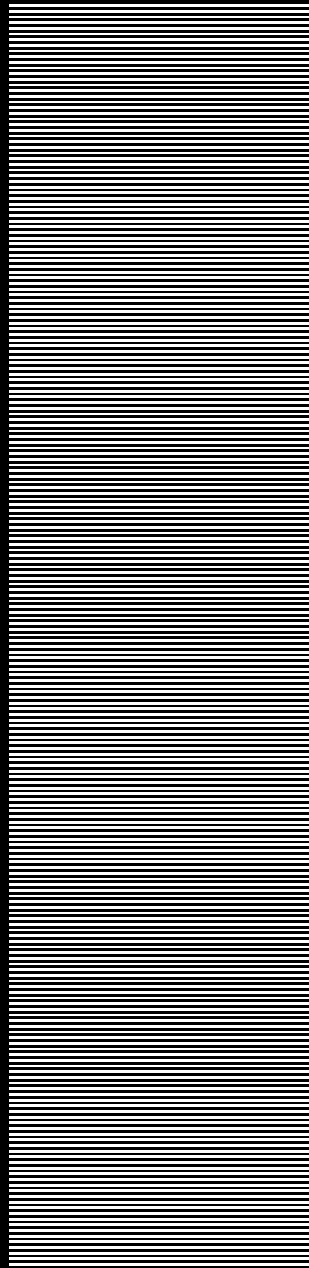
**2 . 6**

**2 . 4**

**2 . 2**

**2 . 0**

**1 . 8**



**1 . 8**

**1 . 6**

**1 . 4**

**1 . 2**

**1 . 0**

**0 . 8**

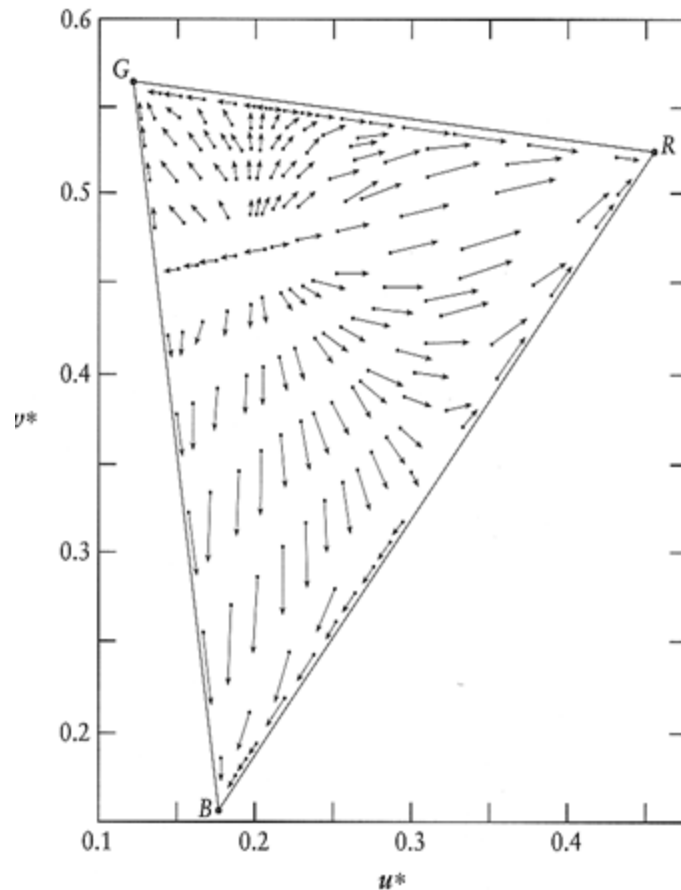
**0 . 6**

# Gamma Correction

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- **Problem:**

- Non-linear operator: RGB components not uniformly scaled by a constant factor  $\Rightarrow$  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

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- **Camera-gamma**

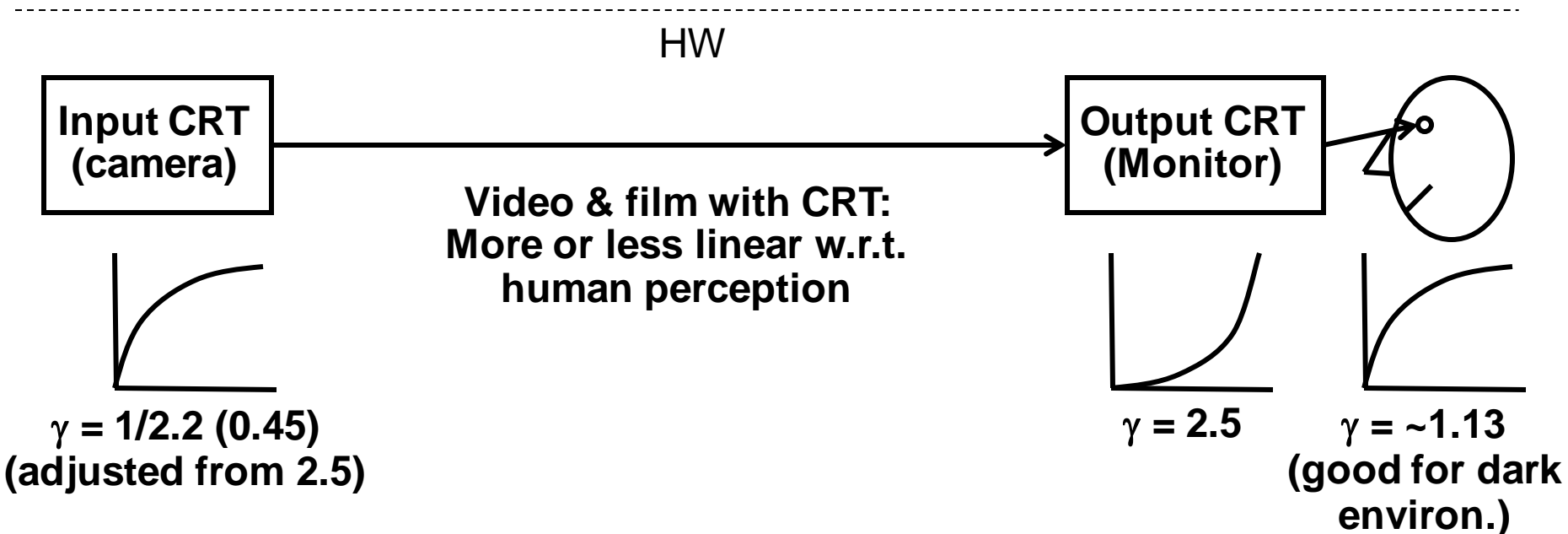
- Old cameras (electron tube) also had a gamma
- Essentially the inverse of the monitor gamma (due to physics) → Display did correct for the camera
- For better brightness perception in dark environments cameras are corrected to gamma of  $1/2.2$  for a total gamma of  $\sim 1.13$

- **“Human-gamma”**

- Human brightness perception exhibits a *log* response
- Roughly follows a gamma of  $\sim 1/3$  (formula) to  $\sim 0.45$
- Old cameras encoded light in a perceptually uniform way
  - Optimal for compression and transmission
- New cameras generate the same output for *compatibility* reasons (!)

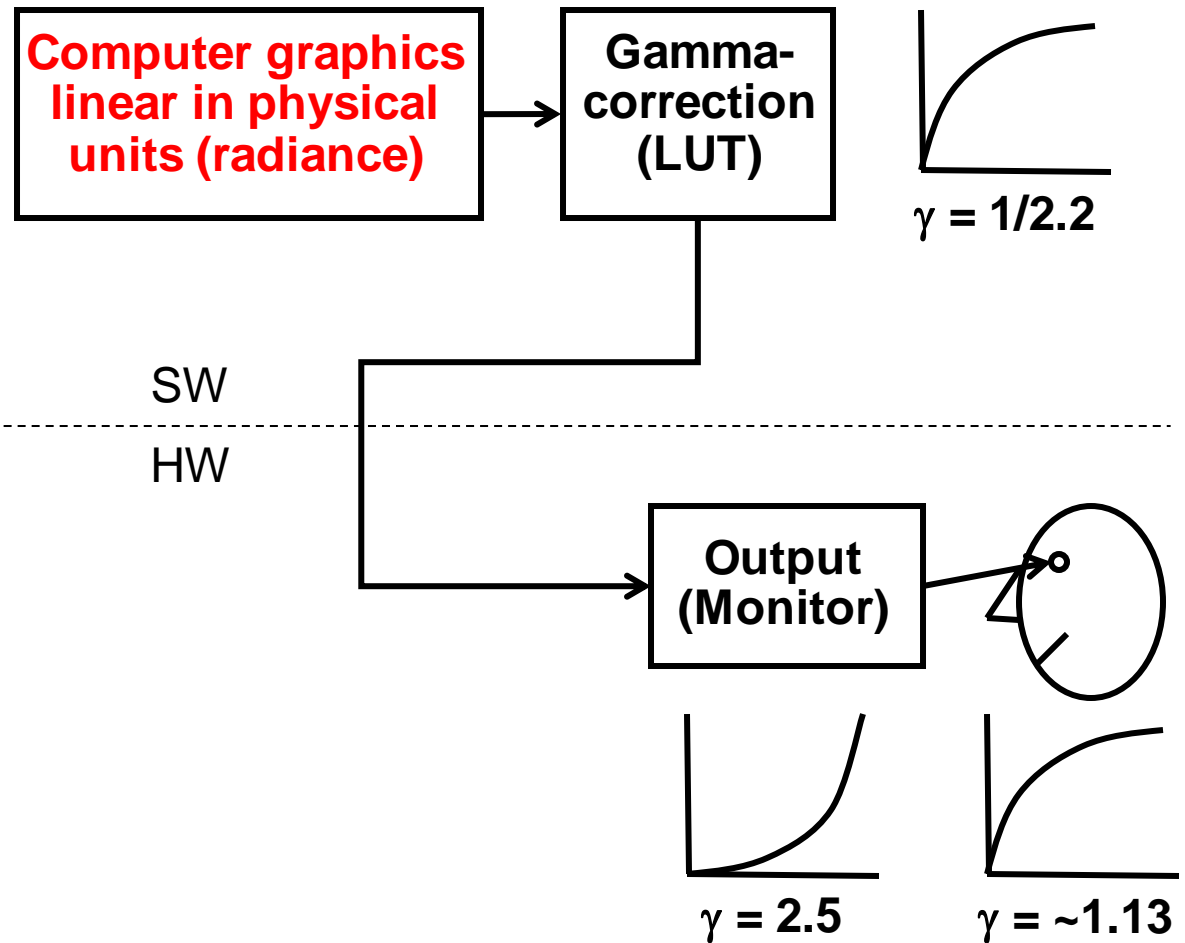
# Color from Beginning to End

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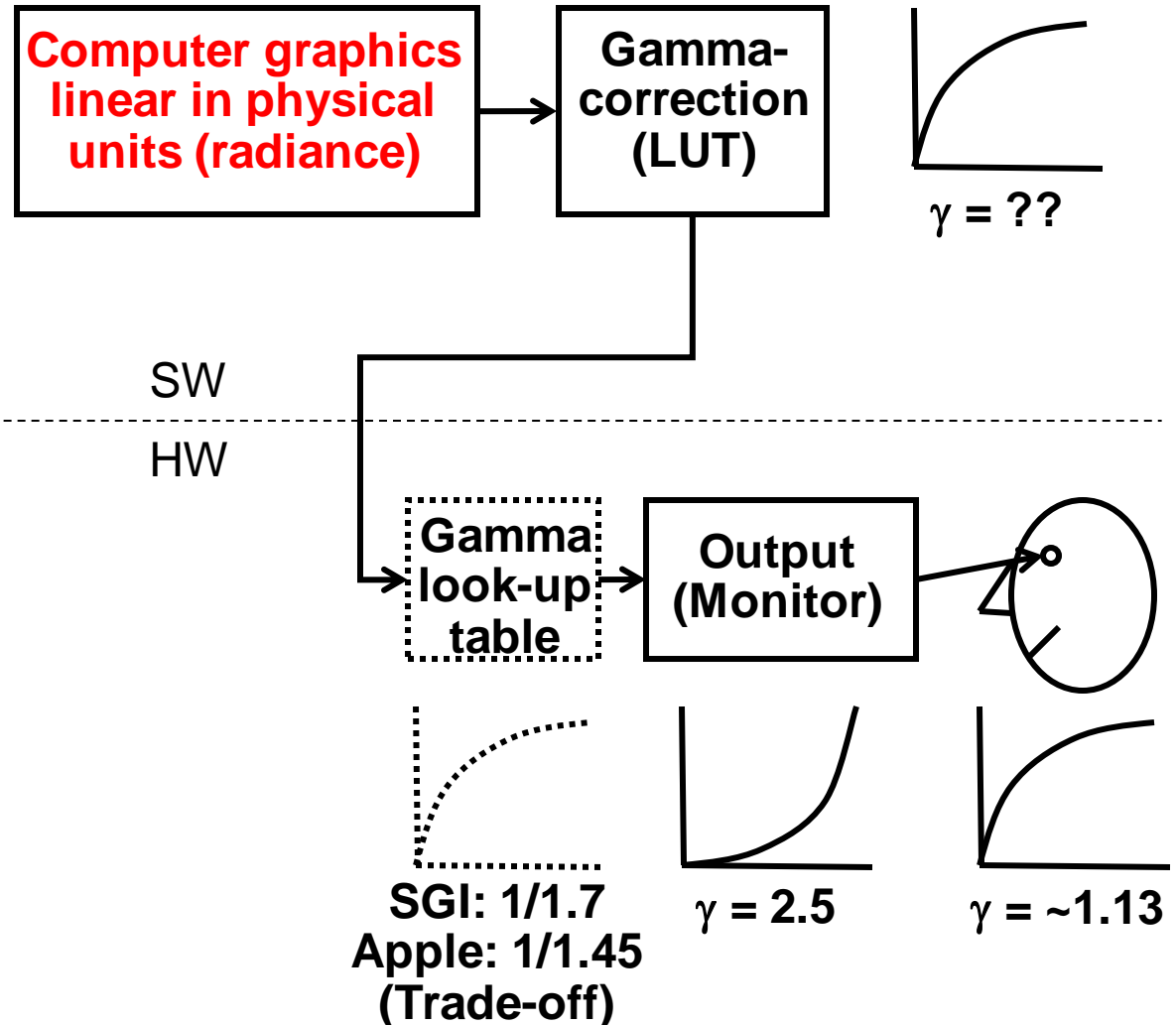


# Color from Beginning to End

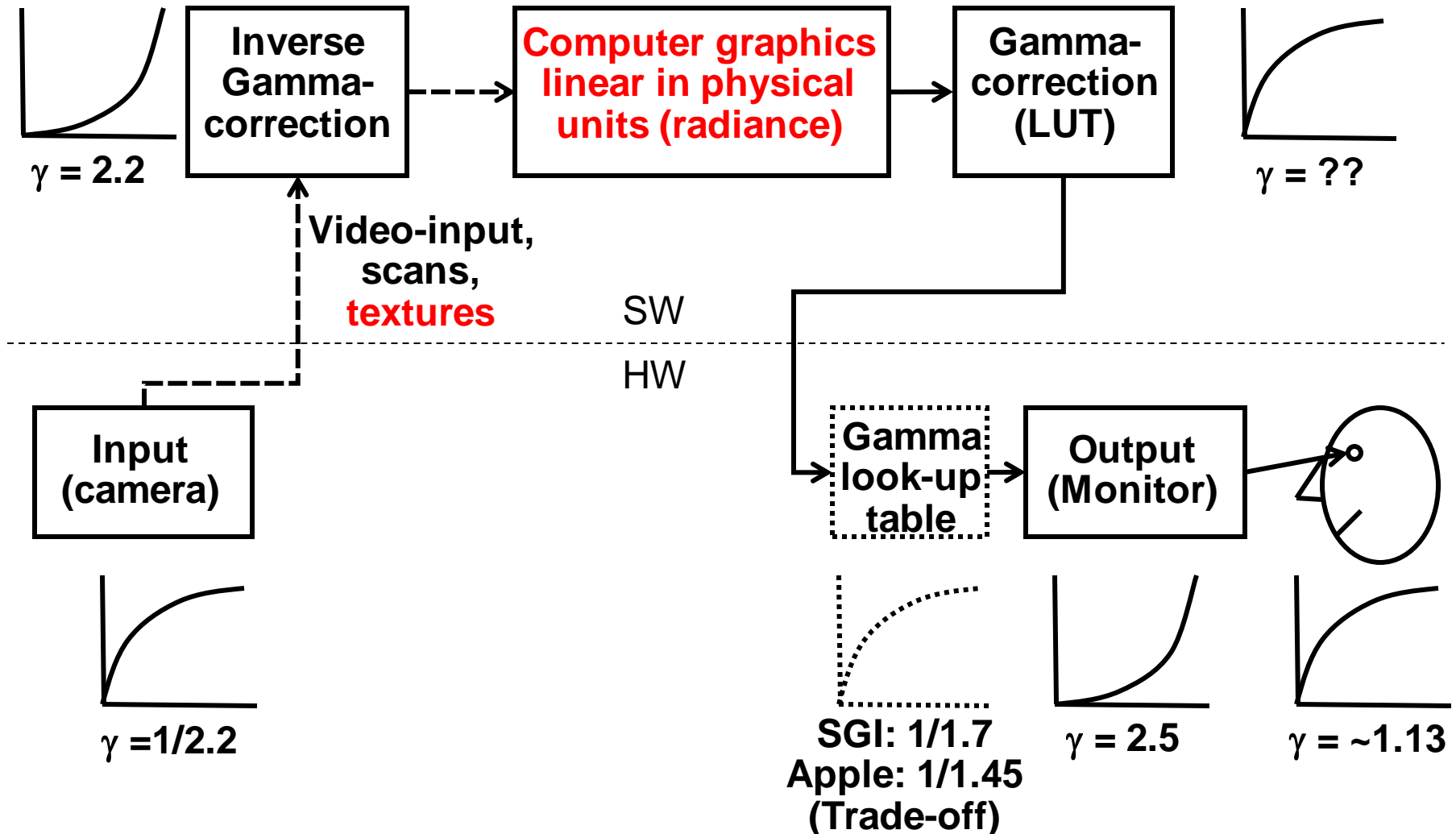
---



# Color from Beginning to End



# Color from Beginning to End



# Color from Beginning to End

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- **Problems**

- Color coordinate system often unknown
  - No support in image formats
  - Assume sRGB!
- Multiple color-space transformations
  - Loosing accuracy through quantization
    - Unless floats or many bits are used
- Gamma-correction depends on application
  - Non-linear:
    - Video-/image editing (but not all operations!)
  - Linear:
    - Image syntheses, interpolation, color blending, rendering, ...



# ICC Profiles

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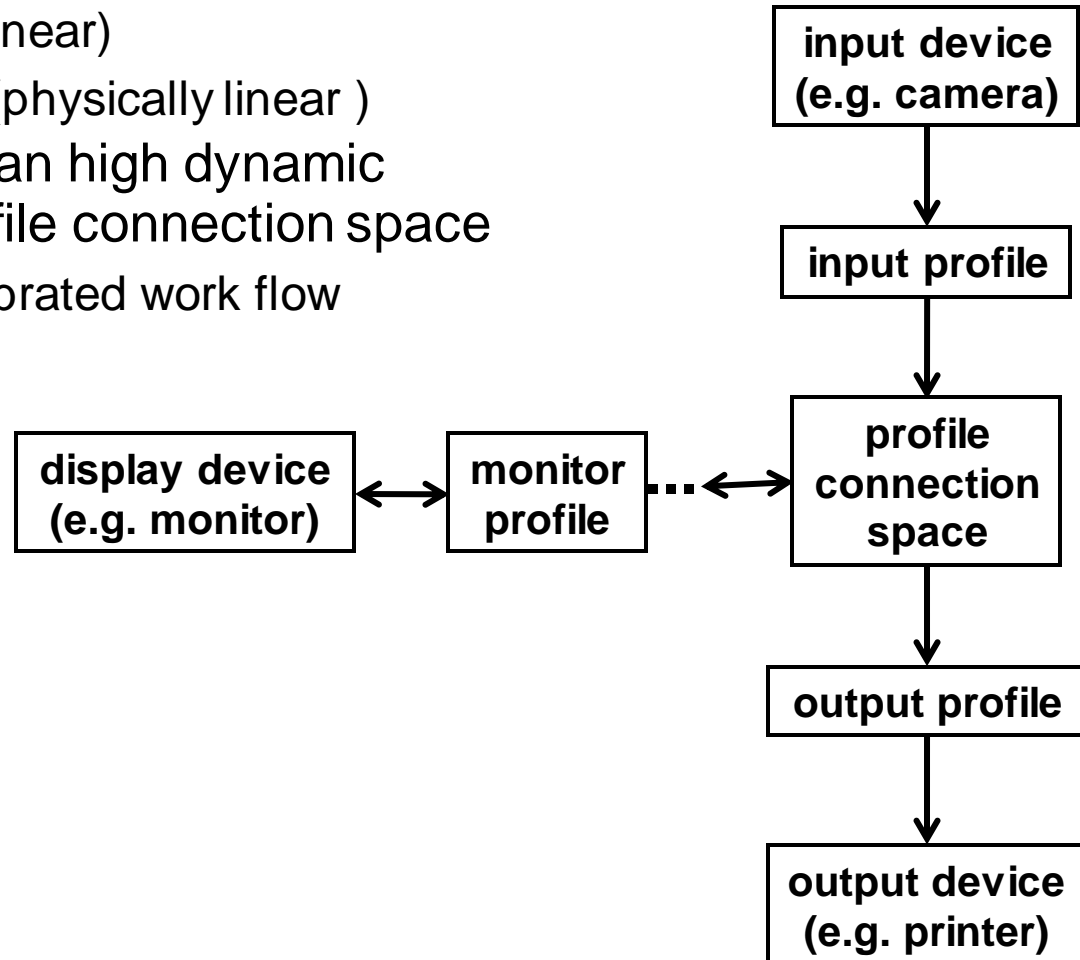
- **International Color Consortium**
  - Standardized specification of color spaces
  - Profile Connection Space (PCS) – intermediate, device-independent color space (CIELAB and CIEXYZ supported)
  - ColorDevice #1 → PCS → ColorDevice #2
- **ICC profile**
  - A file with data describing the color characteristics 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, but no standard-API
- **Problems**
  - Inaccurate specifications, interoperability
  - Profiles difficult to generate

# ICC Profiles and HDR Images

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- **ICC processing**

- Typical profile connection spaces
  - CIELAB (perceptual linear)
  - CIEXYZ color space (physically linear )
- Can be used to create an high dynamic range image in the profile connection space
  - Allows for a color calibrated work flow



# Issues: HDR Image Formats

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- **History**

- Usually little *user data*, mostly data curated professionally
- Color issues with Web images due to different color displays
  - “Solved” by sRGB color space and better monitors (LCD/OLED)

- **Big confusion: HDR Format (HDR10(+)) vs. Dolby Vision)**

- Quantization (10 vs. 12 bit/sample)
  - Color spaces (DCI-P3 vs. Rec. 2020)
  - Maximum brightness (1 000 vs. 10 000 nits)
  - Transfer functions (Perceptual Quantizer vs. Hybrid Log Gamma)
  - Frame rate (!)
  - Issue of “best” reconstruction filter during rendering
  - Little support for still images (e.g. OpenEXR, JPEG-XR)
  - Varying support in consumer displays, cameras
  - No good support for interactive applications (yet)
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# Issues: HDR Image Formats

- **Need for tone and gamut mapping**
  - Because each display may be different
- **What's the expected behavior? What about reverse?**

