Computer Graphics

Color

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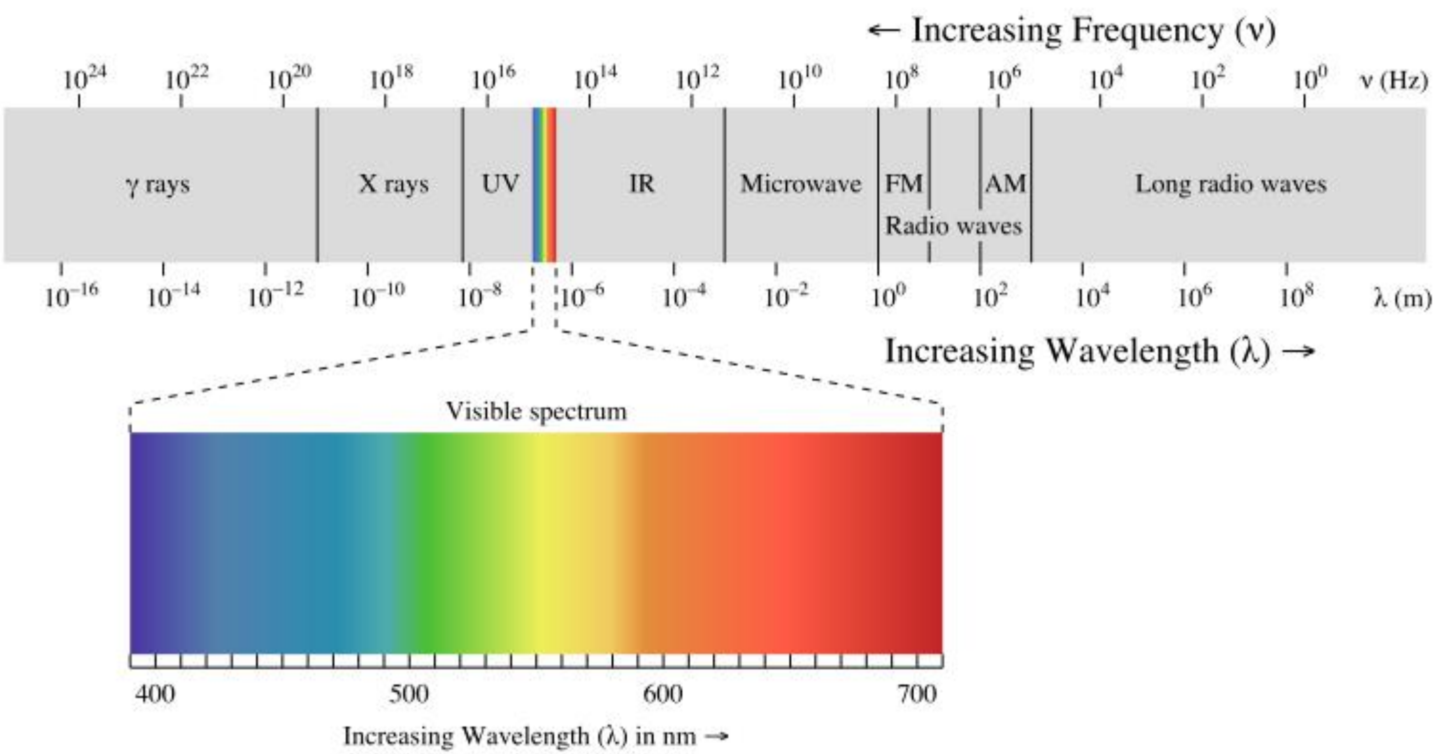
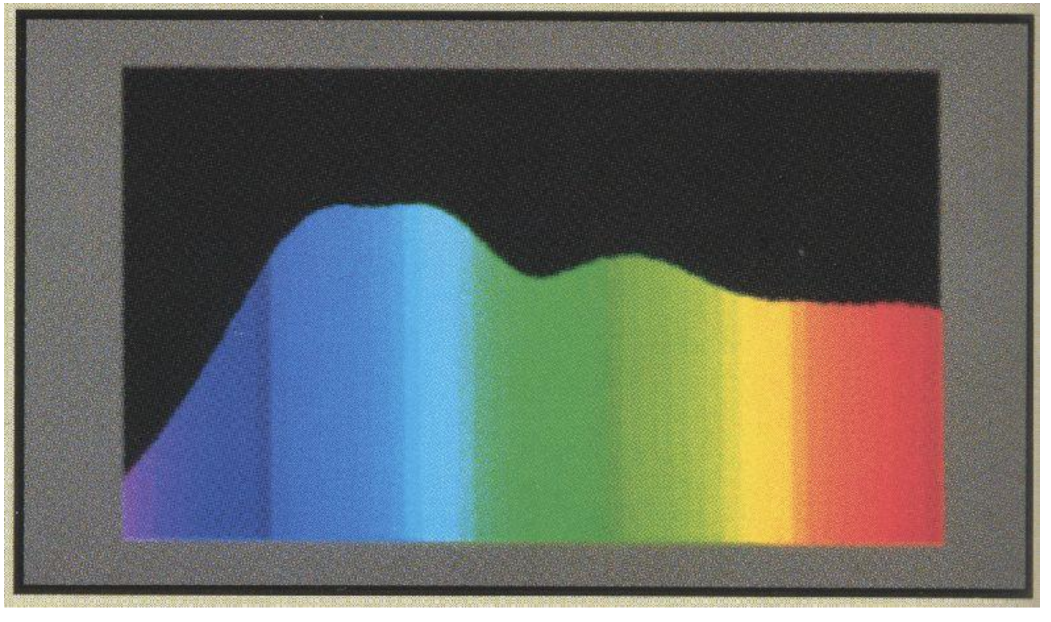
Color Representation

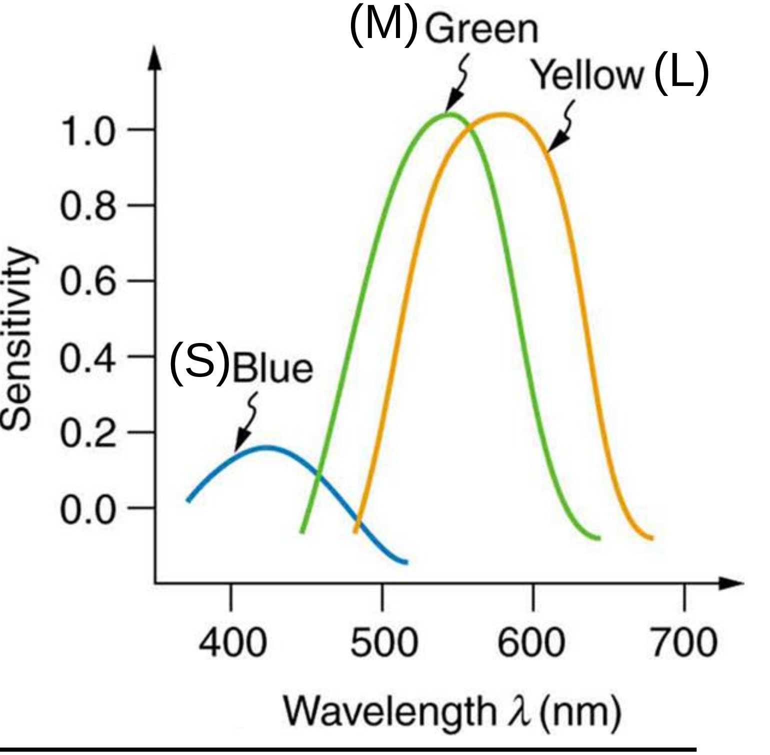
- **Physics: No notion of “color”**
  - Light is simply a distribution of photons with different frequencies
  - Specified as the “spectrum” of light
  - No notion of “opposing color”, “saturation”, etc.



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)

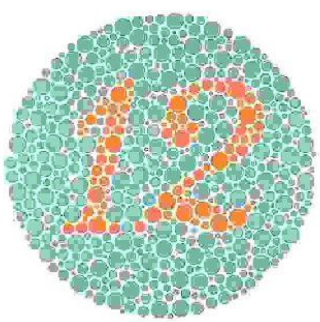


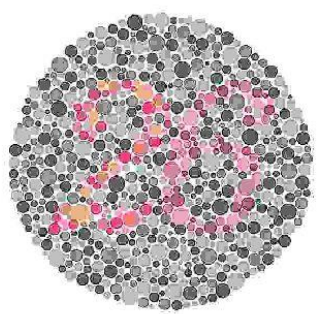


Color Perception

- **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)**
  - Some even have 5 types of cones
- **Penta-chromacy (some insects, pigeons)**

www.lam.mus.ca.us/cats/color/

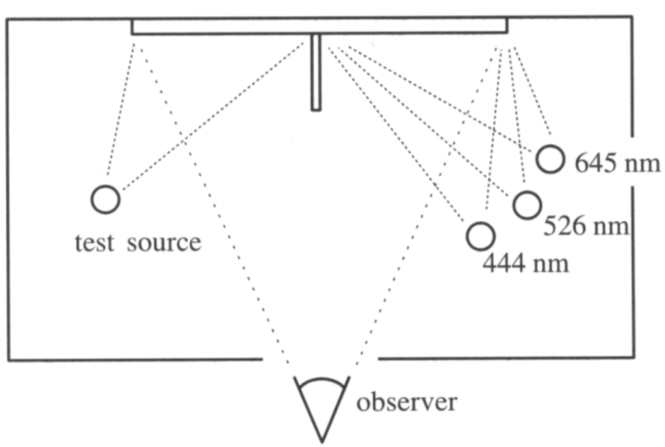


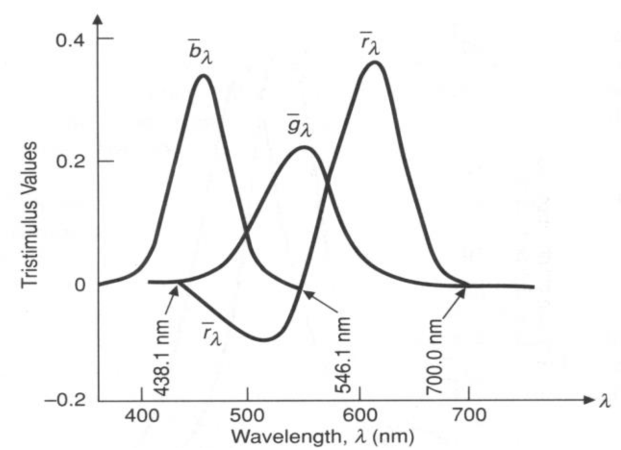


www.colorcube.com/illusions/clrblnd.html

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



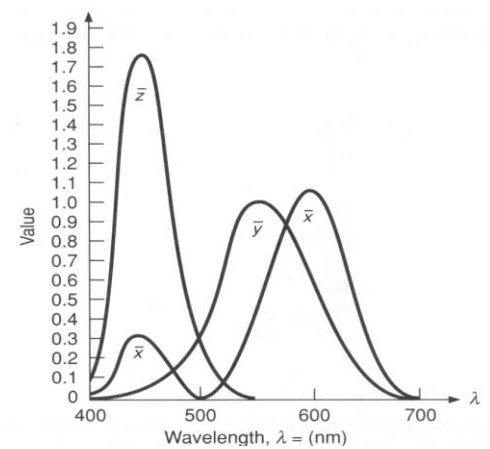


Standard Color Space CIE-XYZ

- **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**
  - 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

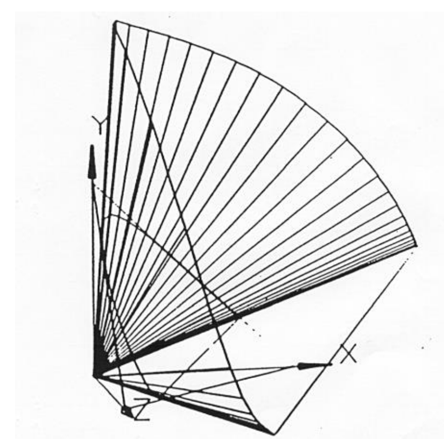
- **Standardized imaginary primaries CIE XYZ (1931)**
  - Imaginary primaries “more saturated” than monochromatic lights
    - Could match all physically realizable color stimuli
  - Defined via spectral matching for virtual CIE XYZ primaries
    - Virtual red (X), green (Y), blue (Z)
  - Y is roughly equivalent to luminance
    - Shape similar to luminous efficiency function V(λ)
  - Monochromatic spectral colors form a curve in 3D XYZ-space
    - Colors: combinations of monochromatic light ⇒ 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

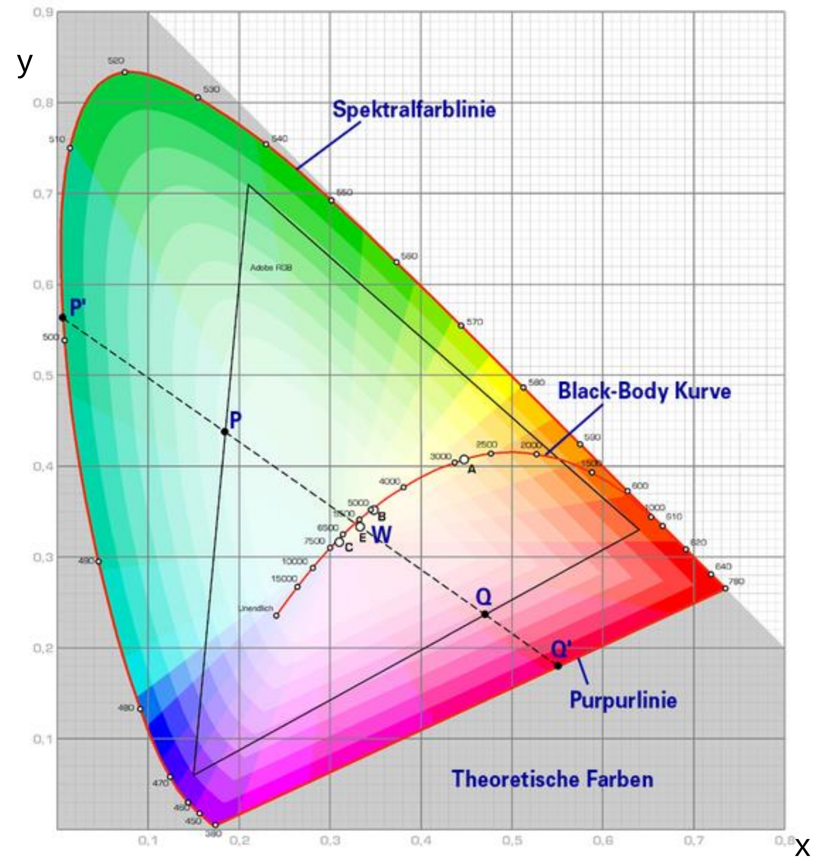
- **Concentrate on color, not light intensity**
  - Relative coordinates: projection on X+Y+Z = 1 plane (normalize)

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

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

$$z = 1 - x - y$$

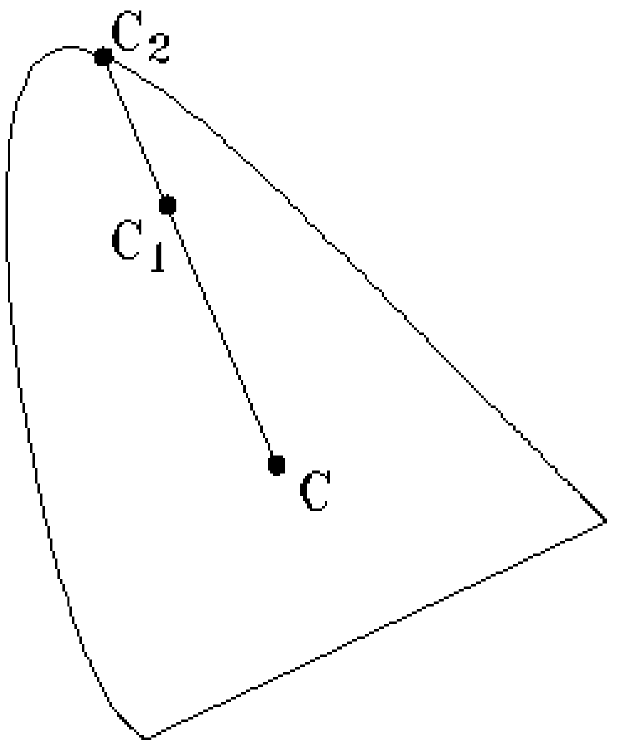
  - Chromaticity diagram
    - 2D plot over *x* and *y*
    - Points called “color locations”

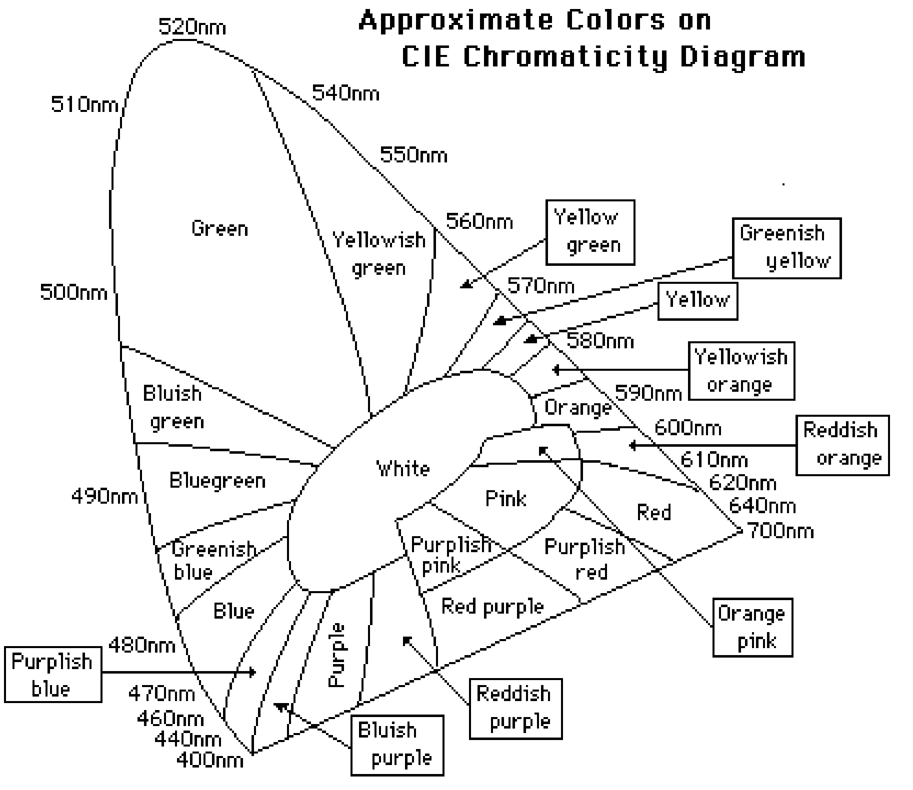


- **Locations of interest**
  - Pure spectral colors (red line)
  - Purple line: interpolate red & violet
  - White point: ~(1/3, 1/3)
    - Device dependent / eye adaptation
  - Black-body curve
- **Primaries of physical devices only allow subdomain**

CIE Chromaticity Diagram

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

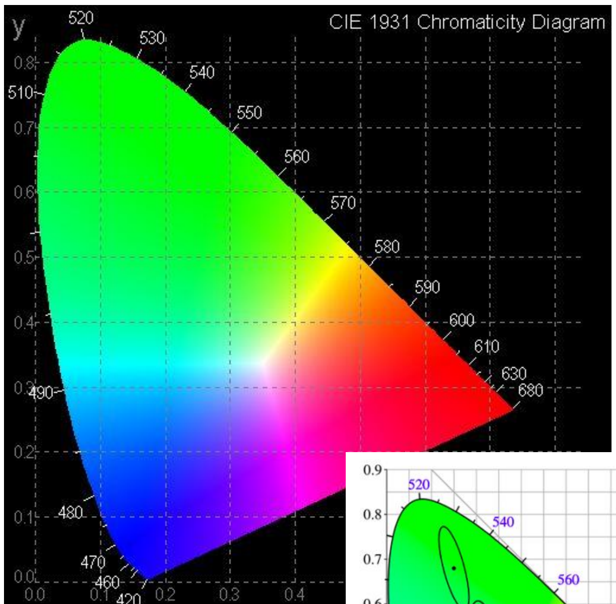




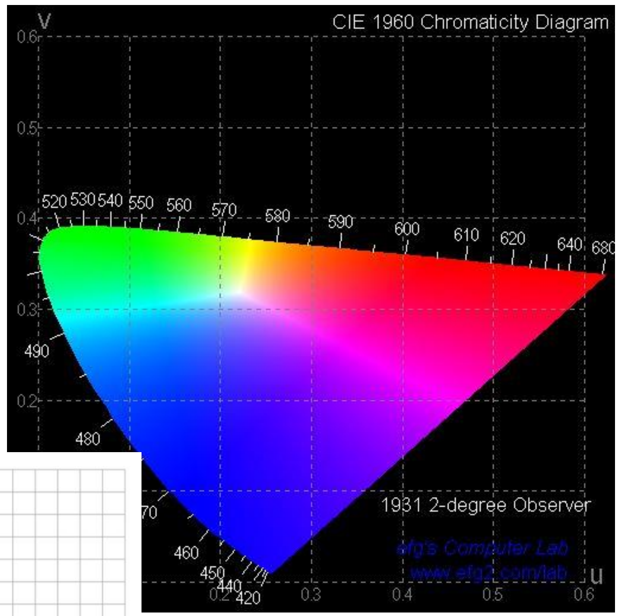
CIE Chromaticity Diagrams

- **Distance threshold until perceptible color difference**
  - Very inhomogeneous ⇒ alternate transformations

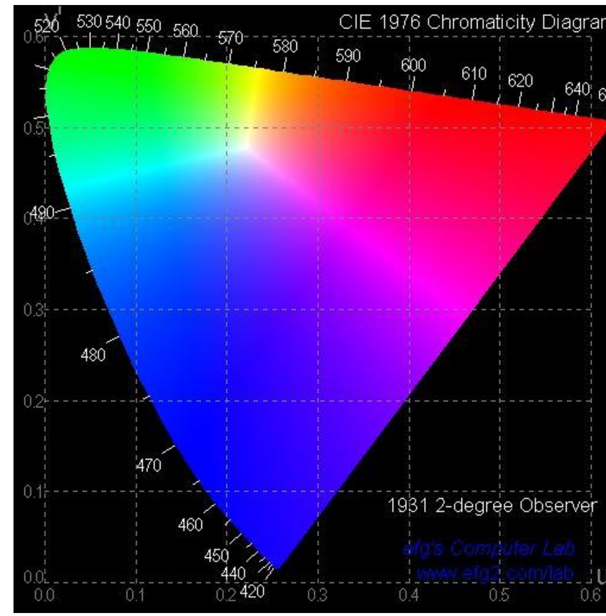
CIE-xy (1931)

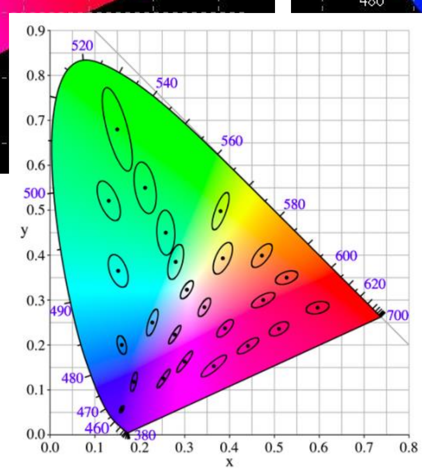


CIE-uv (1960)



CIE-u‘v‘ (1976)

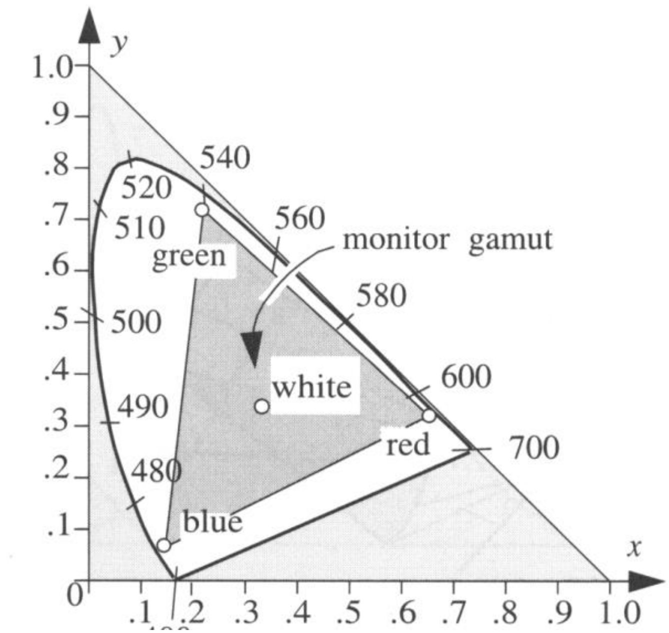




MacAdams ellipses: Same difference threshold

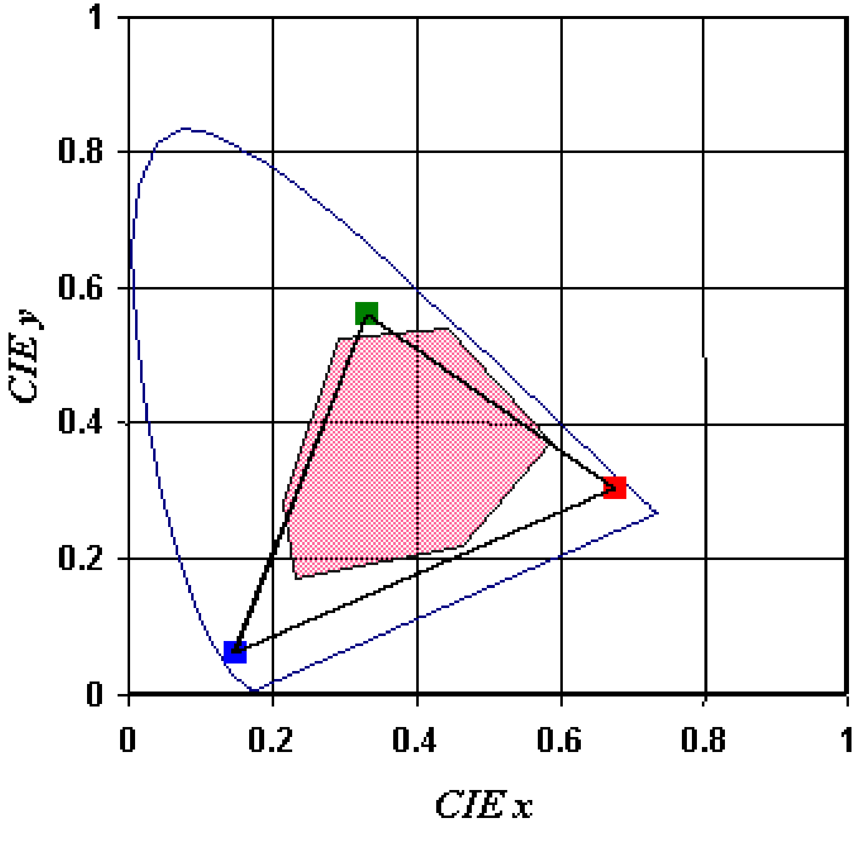
Color Gamut

- **Gamut**
  - Set of representable colors
- **CIE XYZ gamut**
  - Device-independent
- **Device color gamut**
  - Triangle inside color space defined by ad
- **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 of primaries (filters)
  - White-point/temperature adjustment
    - Virtually moves colors *within* the gamut



Printer Color Gamut

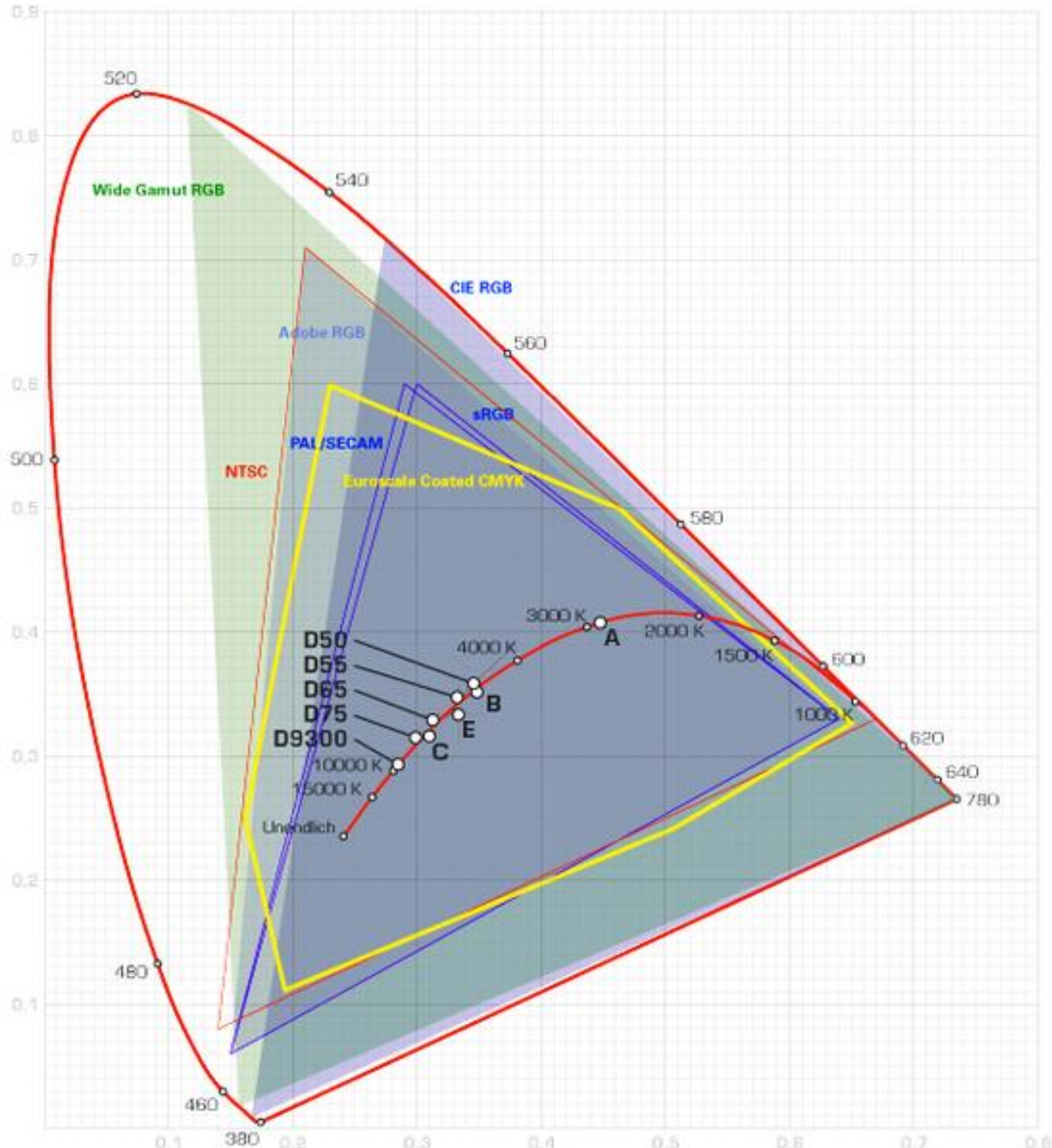
- **Complex for printer due to subtractive color blending**
- **Complex interactions bet. printed color pts (mixing)**
- **Depends on printer colors and printer technique**



Different Color Gamuts

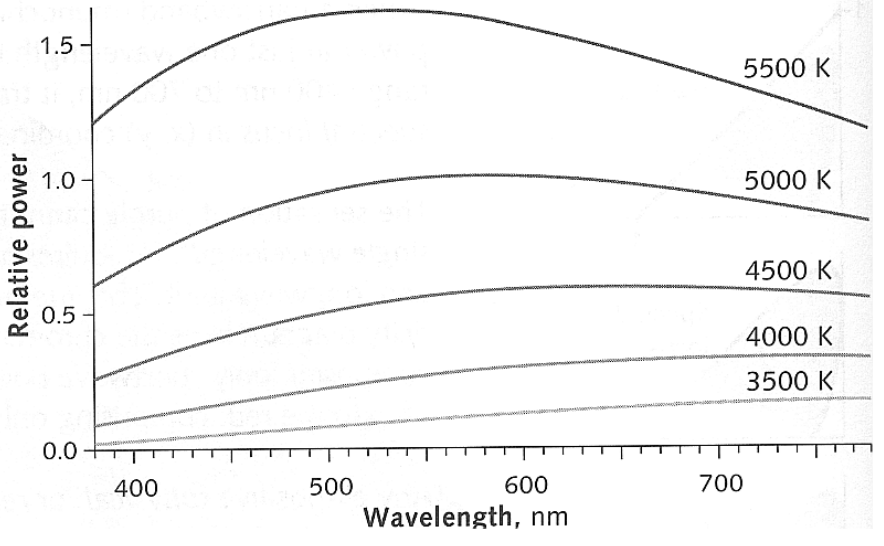
- **Gamut compression/mapping**
  - What to do if colors lay outside of the printable area?
    - Scaling, clamping, other non-linear mappings
  - Each device should replace its out-of-gamut colors with the nearest approximate achievable colors
  - Possible significant color distortions in a printed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

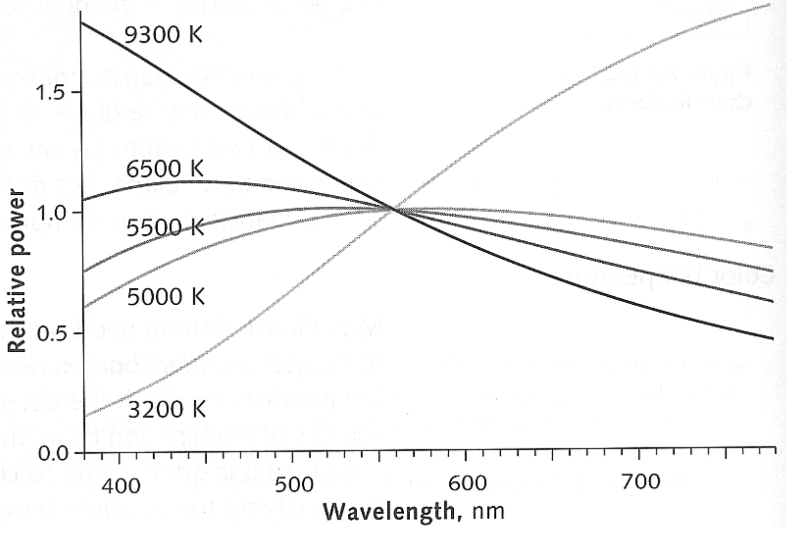
Different Color Gamuts



Color Temperature

- **Theoretical light source: A black body radiator**
  - Perfect emitter: whole energy emitted by thermal excitation only
  - Has a fixed frequency spectrum ρ = ρ(λ, 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





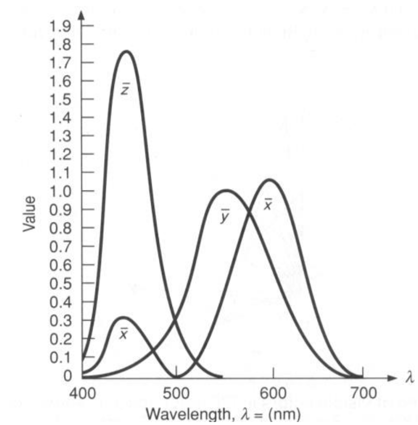
CIE Standard Illuminants

- **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 (samples every 5-10 nm)
  - Projecting from *m*D to 3D using sampled matching curves (loss of information)

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



- **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

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

    - 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.)

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

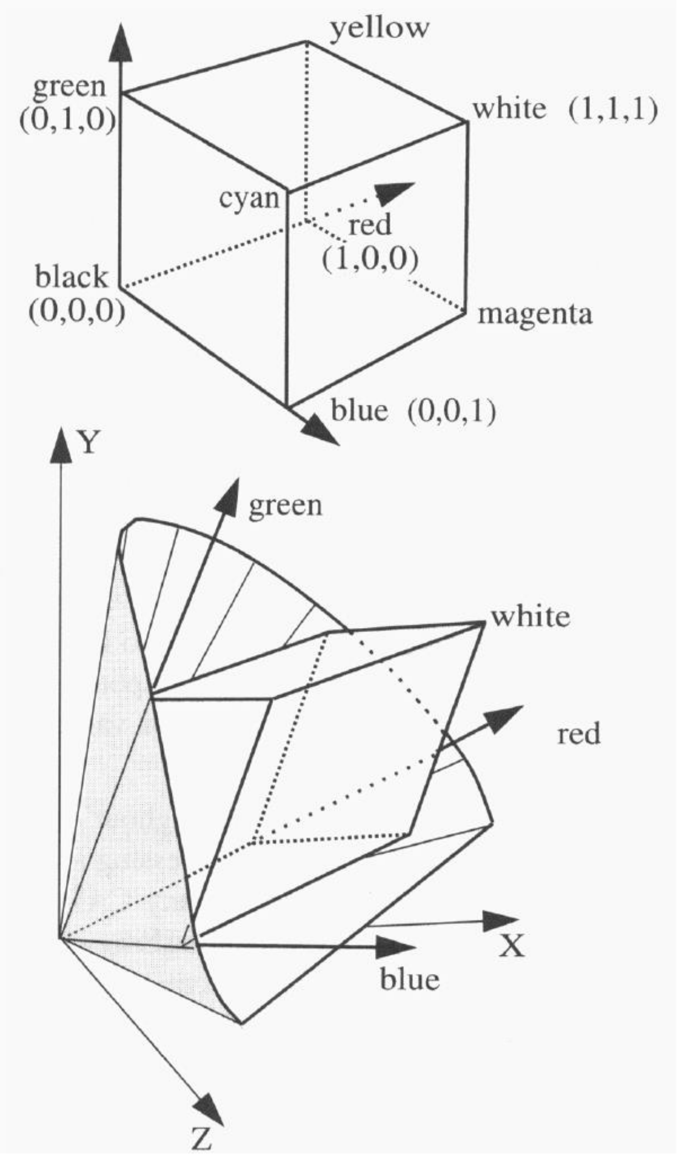
$$\begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = \begin{bmatrix} x_r C_r & x_g C_g & x_b C_b \\ y_r C_r & y_g C_g & y_b C_b \\ (1 - x_r - y_r) C_r & \left(1 - x_g - y_g\right) C_g & (1 - x_b - y_b) C_b \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

  - (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 color spaces of different devices by intermediate mapping to XYZ**

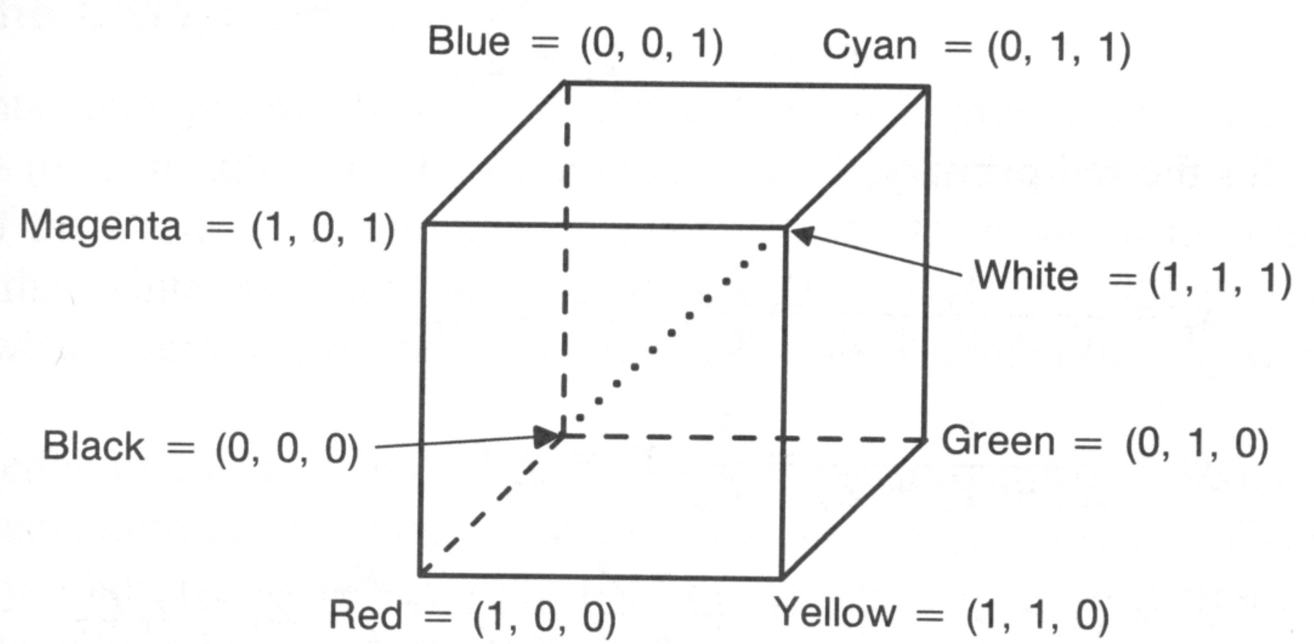
Geometric Interpretation

- **RGB embedded in XYZ space**
- **Basis change bet. RGB spaces**
- **Possibly need to handle out-of-gamut colors**



RGB Color Model

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

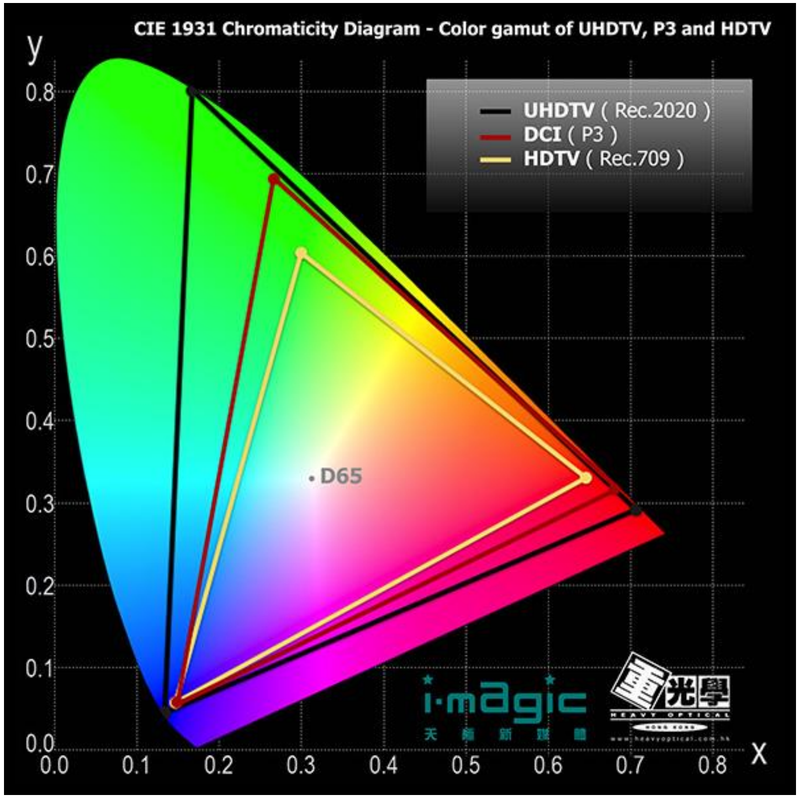


sRGB Color Space

- **Standardization of RGB**
  - 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's without ICC profile implicitly lie in sRGB
    - Generating: ICC-Profile or writing sRGB
    - Reading/output : using ICC-Profile or assume sRGB

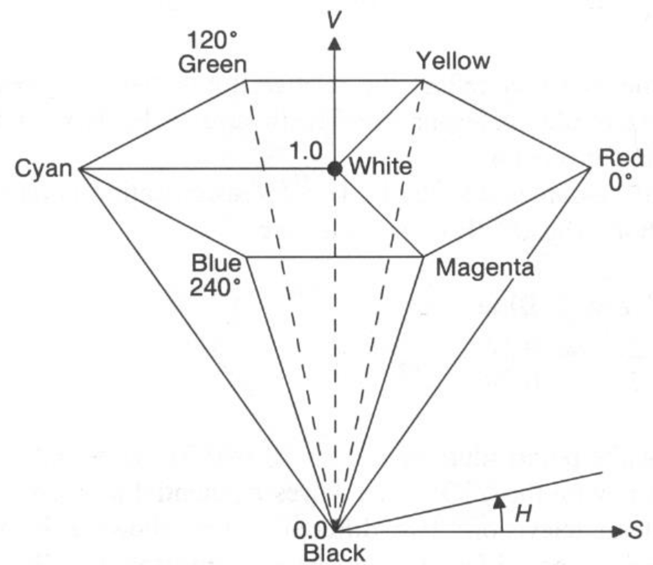
ITU Rec.-2020 / BT-2020

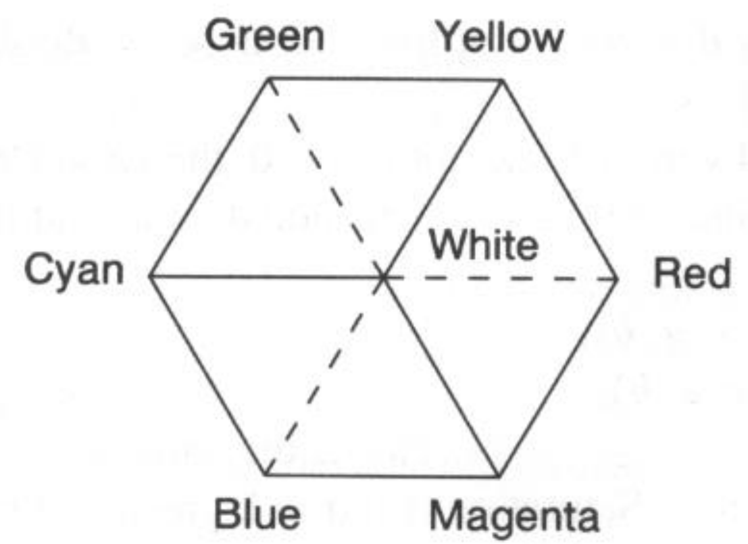
- **Standardization of 4K and 8K video format**
  - Resolution, frequency, digital representation
  - Color gamut, gamma
- **Specification of default CIE-xy values (Wide Gamut)**
  - Primaries are monogromatic!
  - Red: 0.708, 0.292
  - Green: 0.170, 0.797
  - Blue: 0.131, 0.046
  - White: 0.3127, 0.3290 (D65)
  - Gamma 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

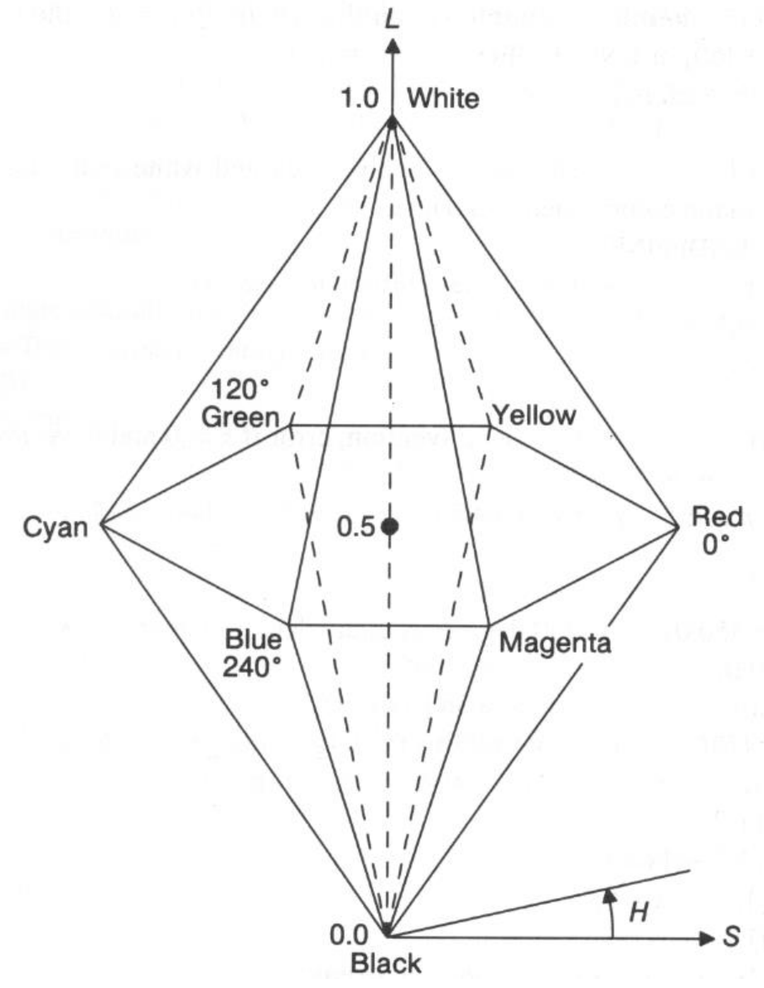




HLS Model

- **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

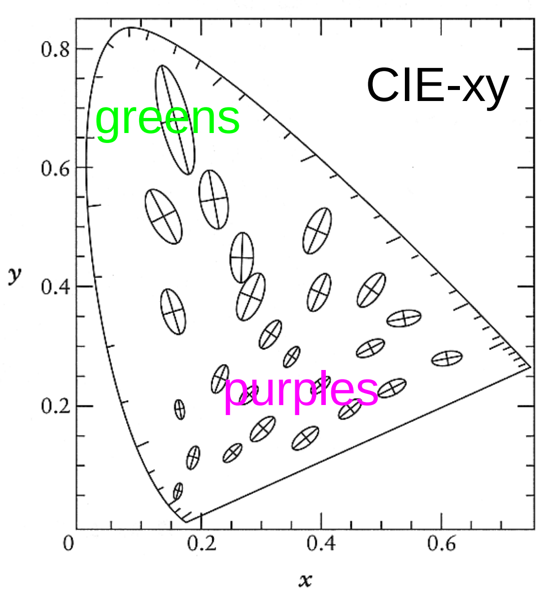


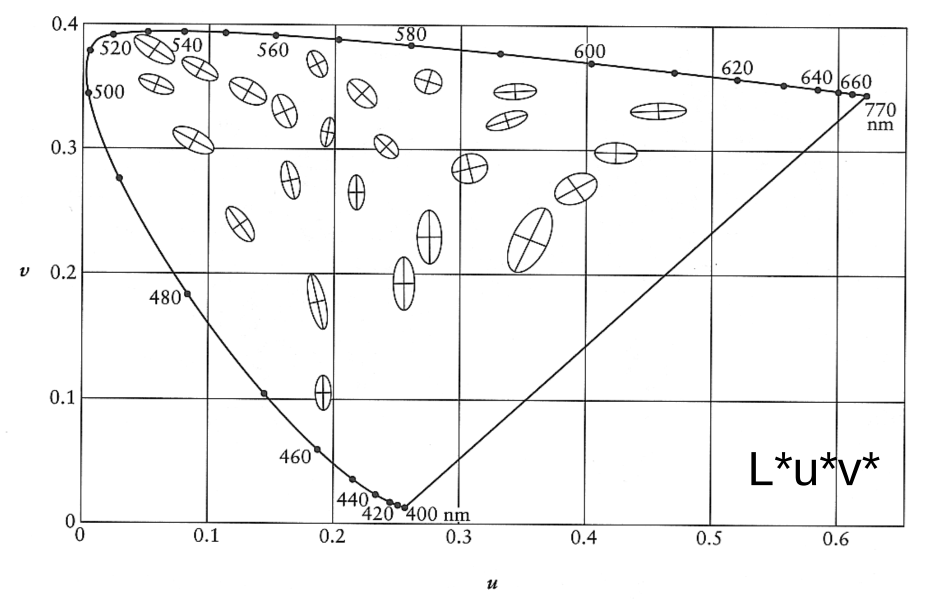
Color Model: In Practice

- **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 $\rightarrow$ interpolation in XYZ space
  - 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 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)

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

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

  - Transformation of color differences

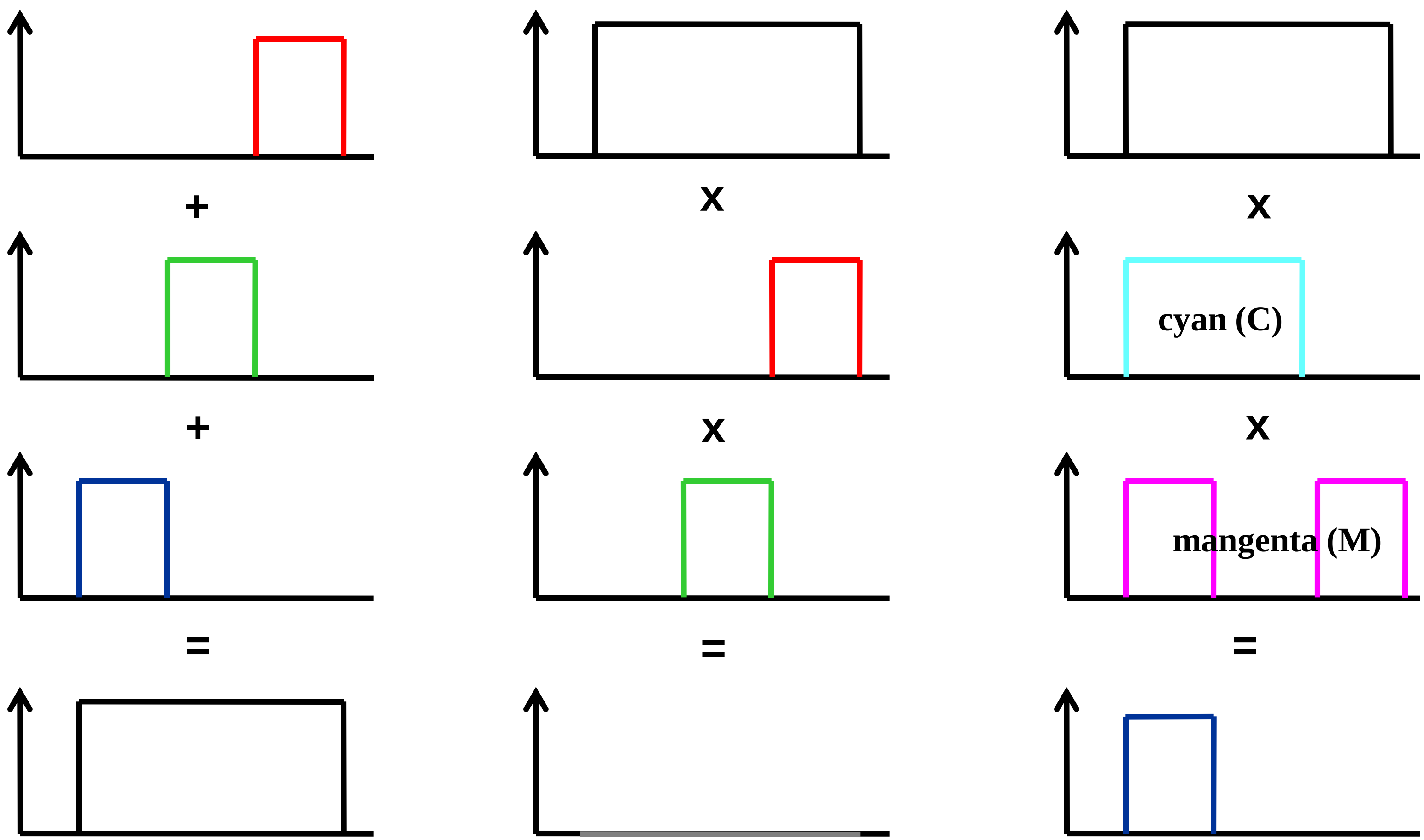
$$u' = 4X/(X + 15Y + 3Z)$$
$$v' = 9Y/(X + 15Y + 3Z)$$
$$u^* = 13L * (u' - u'_n)$$
$$v^* = 13L * (v' - v'_n)$$

$$a^* = 500L * [f(X/X_n) - f(Y/Y_n)]$$
$$b^* = 500L * [f(Y/Y_n) - f(Z/Z_n)]$$
$$f(x) = \begin{cases} x \geq 0.008856 & x^{1/3} \\ x < 0.008856 & 7.787x + 16/116 \end{cases}$$

  - Limited applicability to HDR

Subtractive Color Blending

- **Corresponds to stacked color filters**



Additive blending

Subtractive blending
Multiply by primaries: wrong !

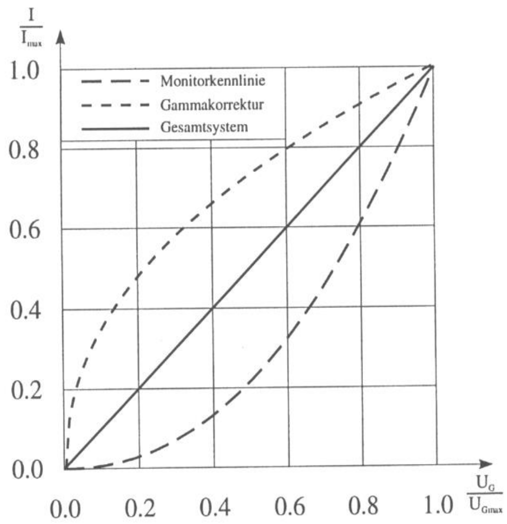
Subtractive blending
Multiply by inverse primaries

Subtractive Color Blending

- **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

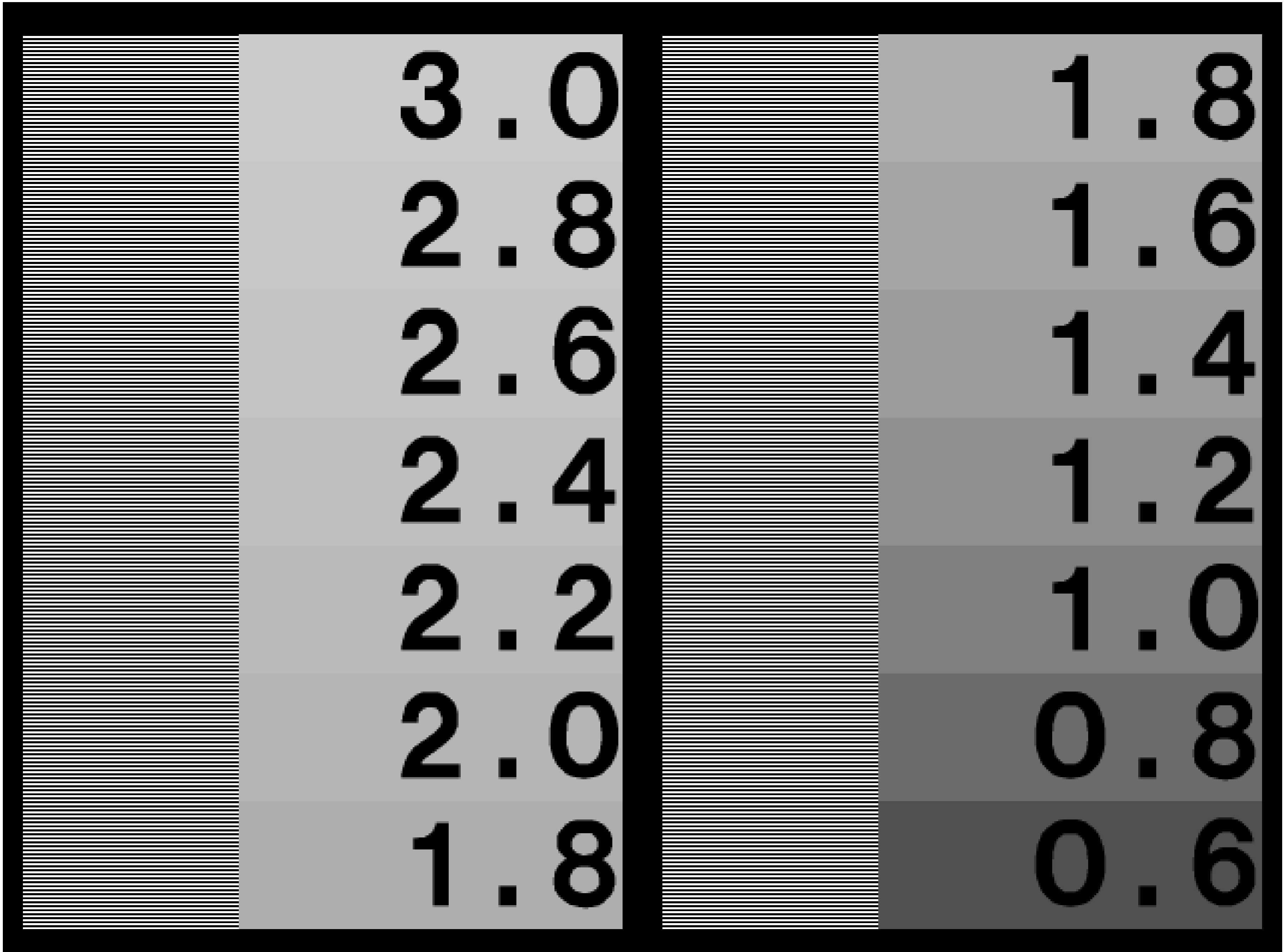
- **Display-Gamma**
  - Intensity *I* of electron beam in CRT monitors is non-linear with respect to the applied voltage *U*
  - Best described as power law: $L = U^{\gamma}$
  - Gamma-Factor γ = ~ 2.5 due to physics of CRT monitor (e-beam)
  - For *compatibility* also in other displays (LCD, OLED, etc.)



- **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

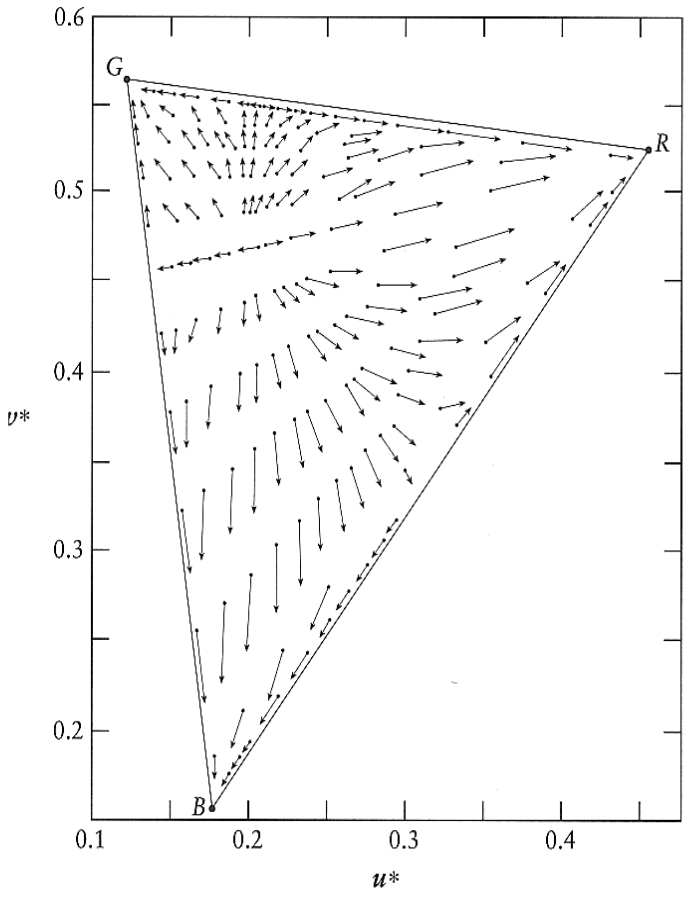
Gamma Testing Chart

- **Gamma of monitors not always 2.2**
- **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

- **Problem:**
  - Non-linear operator: RGB components not uniformly scaled by a constant factor ⇒ strong color corruptions



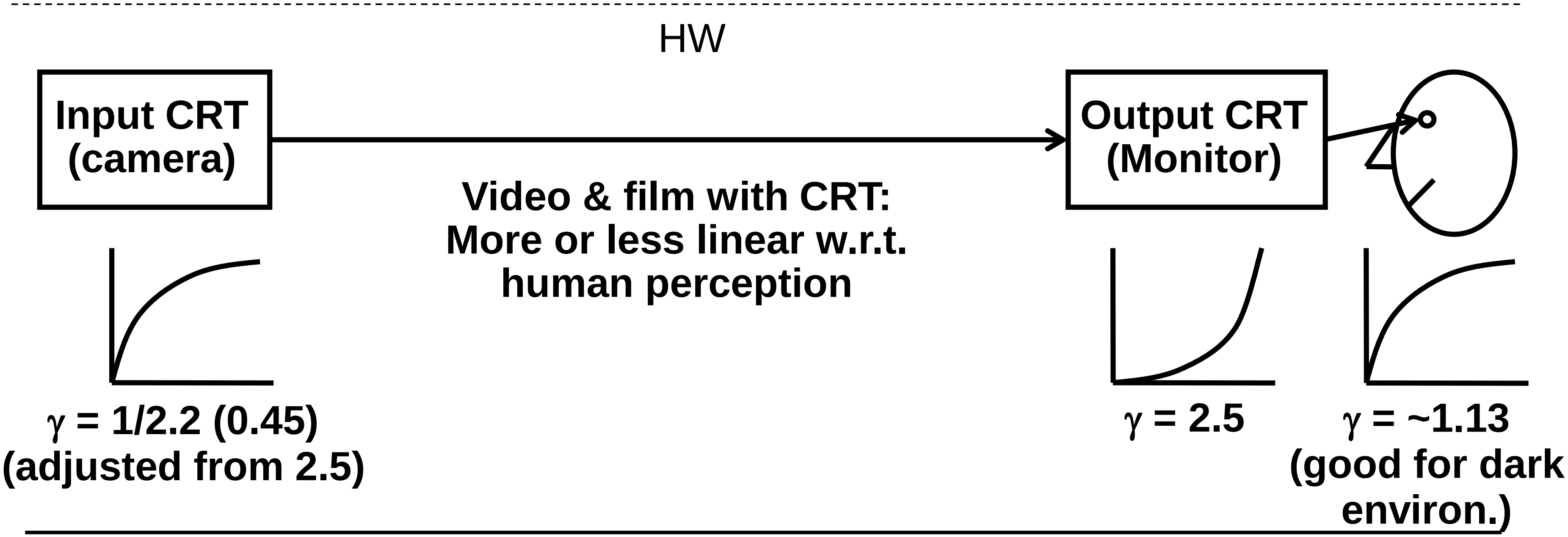
Shifts in reproduced chromaticities resulting from uncompensated gamma of 1.273 (such a gamma is desirable to compensate the contrast lowering in the dim surround).

Gamma

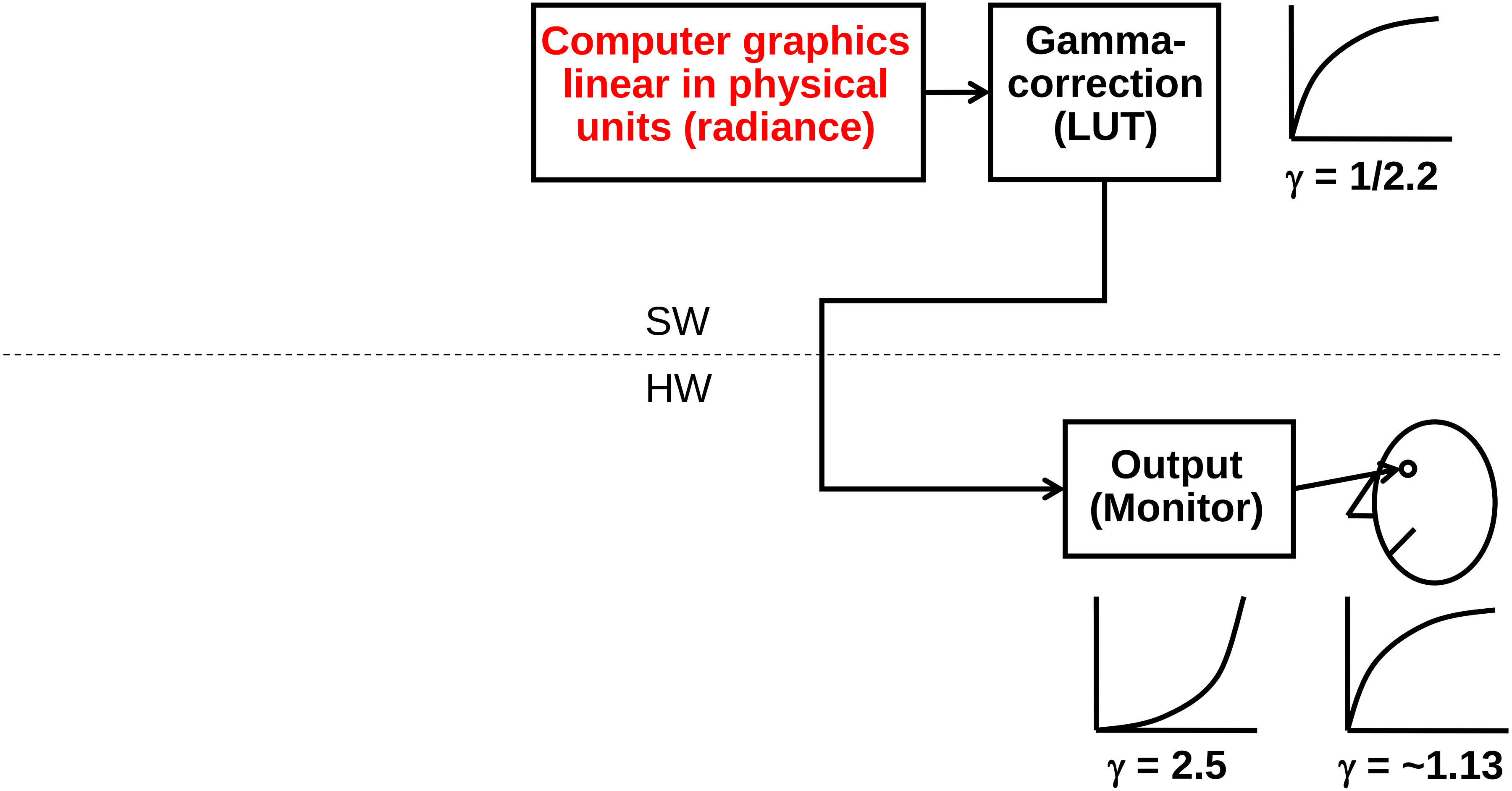
- **Camera-gamma**
  - Old cameras (electron tube) also had a gamma
  - Essentially the inverse of the monitor gamma (due to physics) → Display did correct for the camera
  - For better brightness perception in dark environments cameras are corrected to gamma of 1/2.2 for a total gamma of ~1.13

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

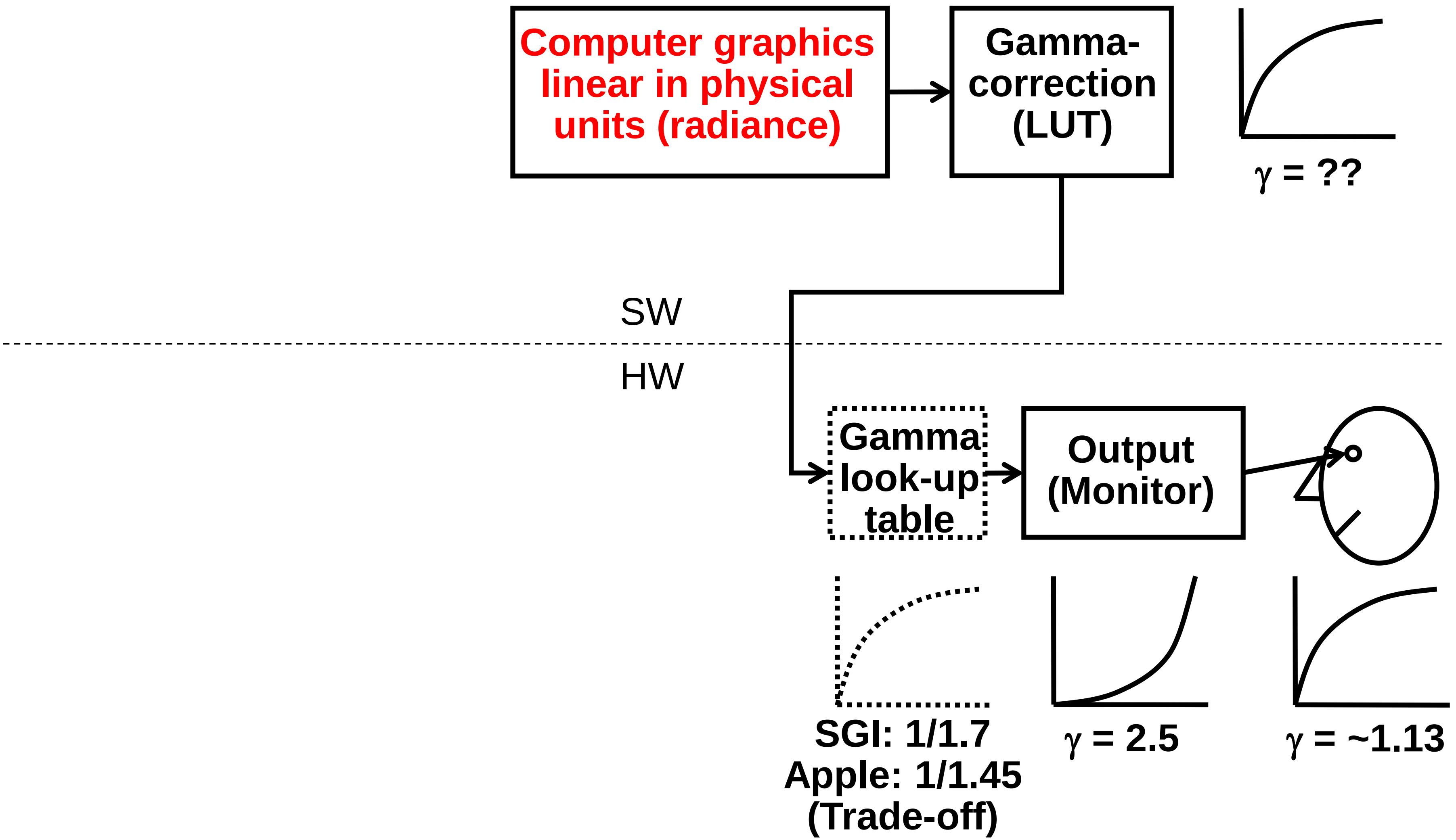
Color from Beginning to End



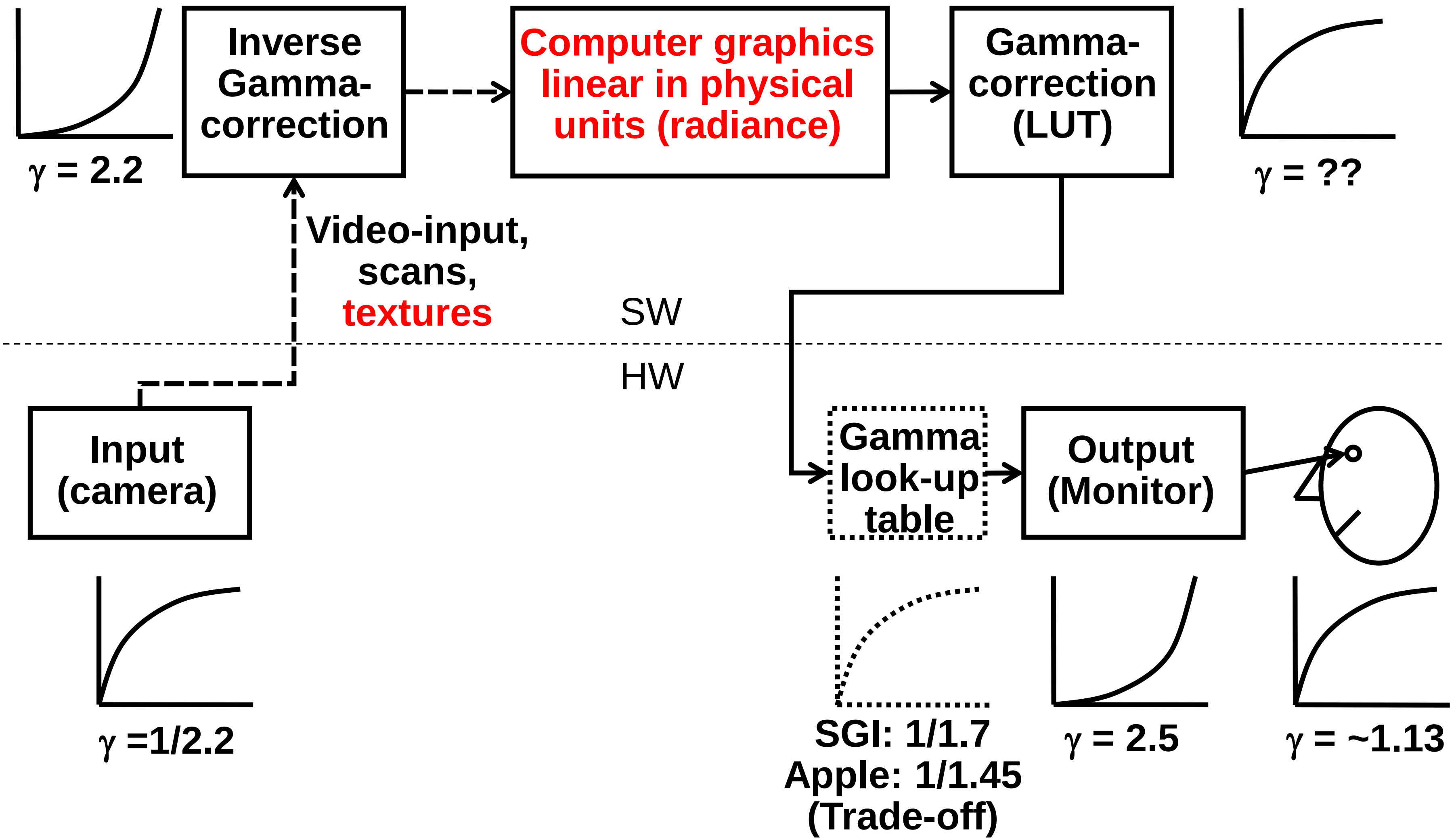
Color from Beginning to End



Color from Beginning to End



Color from Beginning to End



Color from Beginning to End

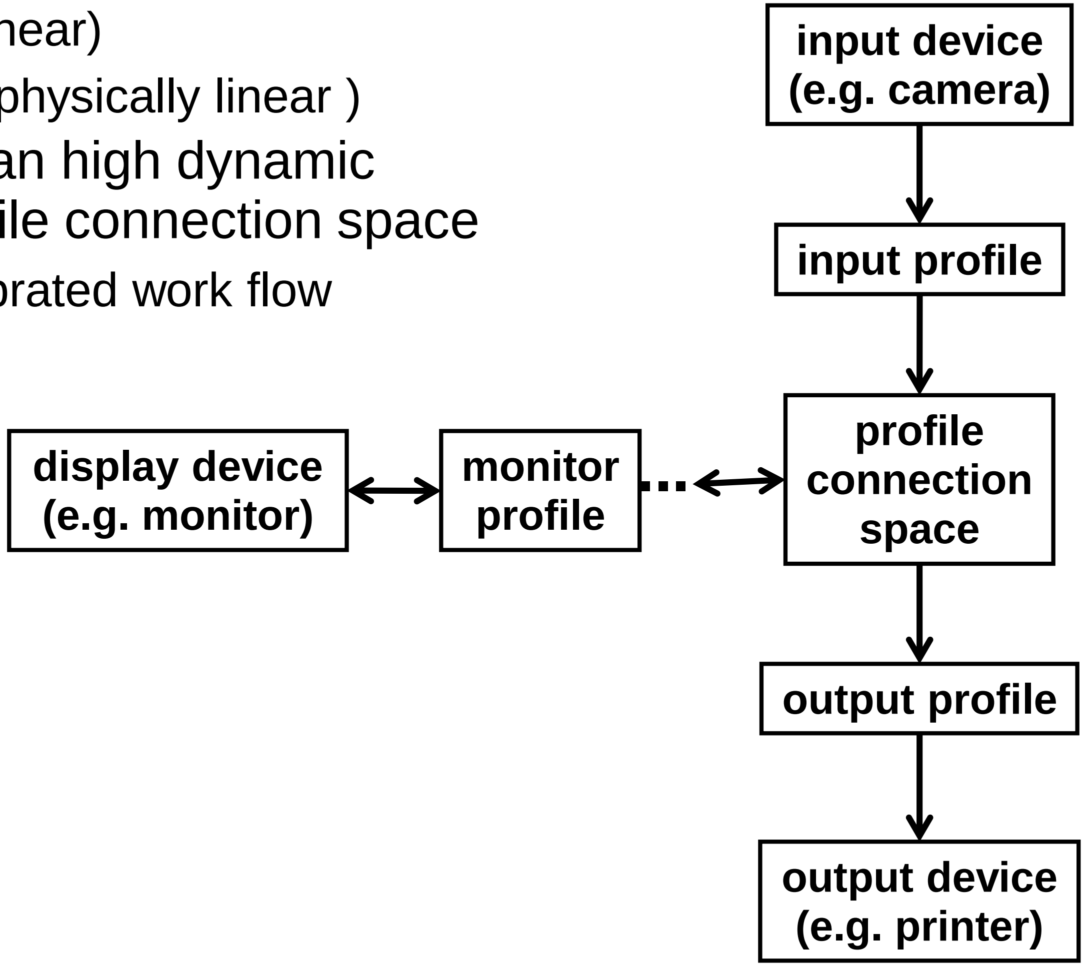
- **Problems**
  - Color coordinate system often unknown
    - No support in image formats
    - Assume sRGB!
  - Multiple color-space transformations
    - Loosing accuracy through quantization
      - Unless floats or many bits are used
  - Gamma-correction depends on application
    - Non-linear: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

ICC Profiles

- **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

- **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

- **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, no cameras yet
  - No good support for interactive applications (yet)

Issues: HDR Image Formats

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