

Computer Graphics

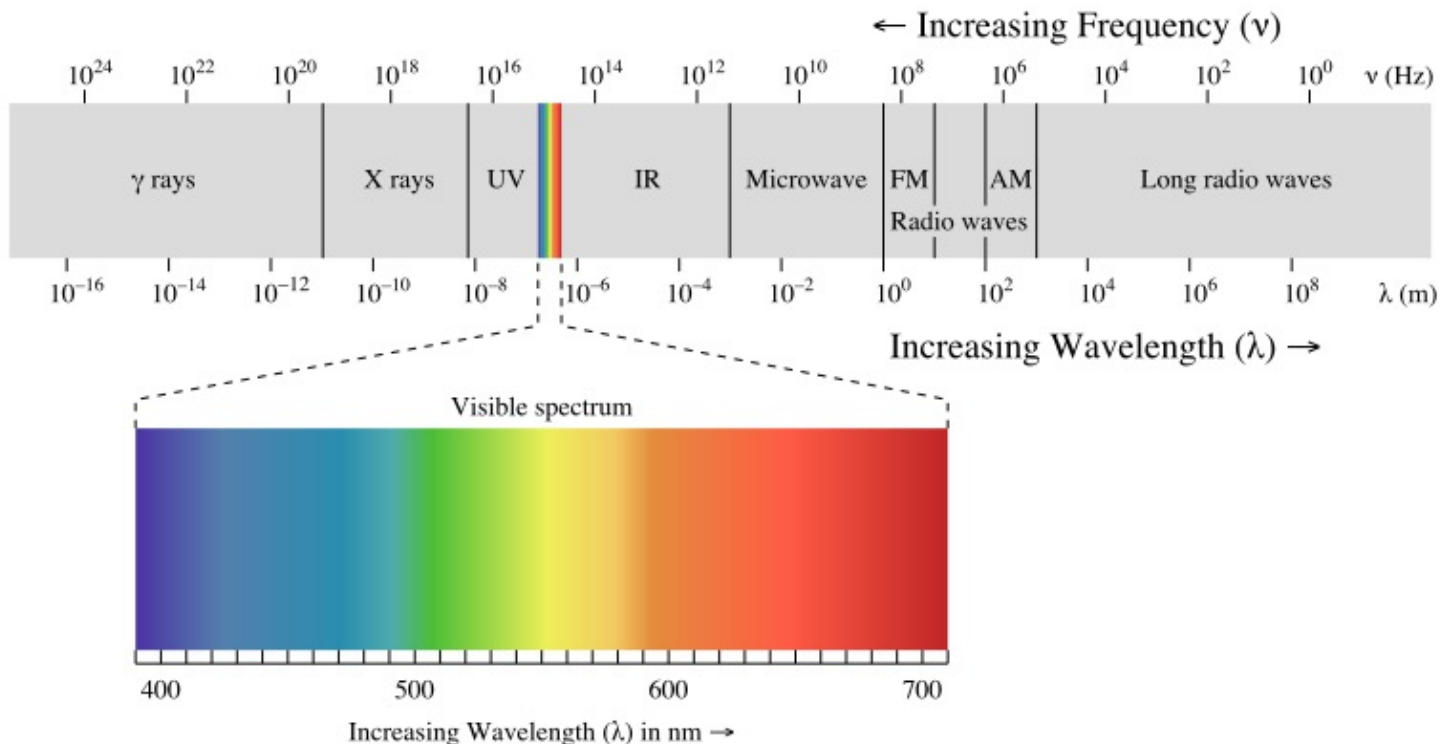
Color

Philipp Slusallek

Color Representation

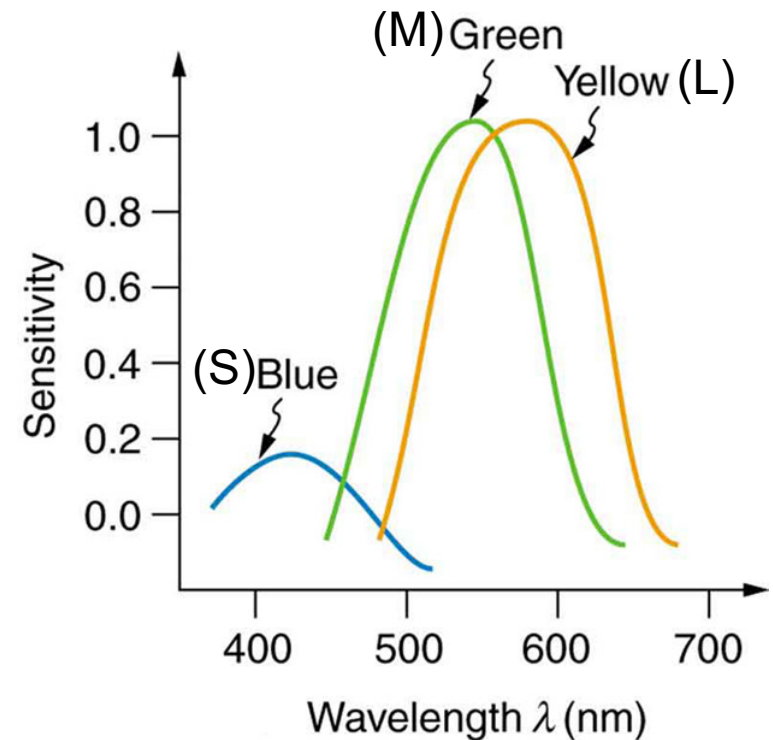
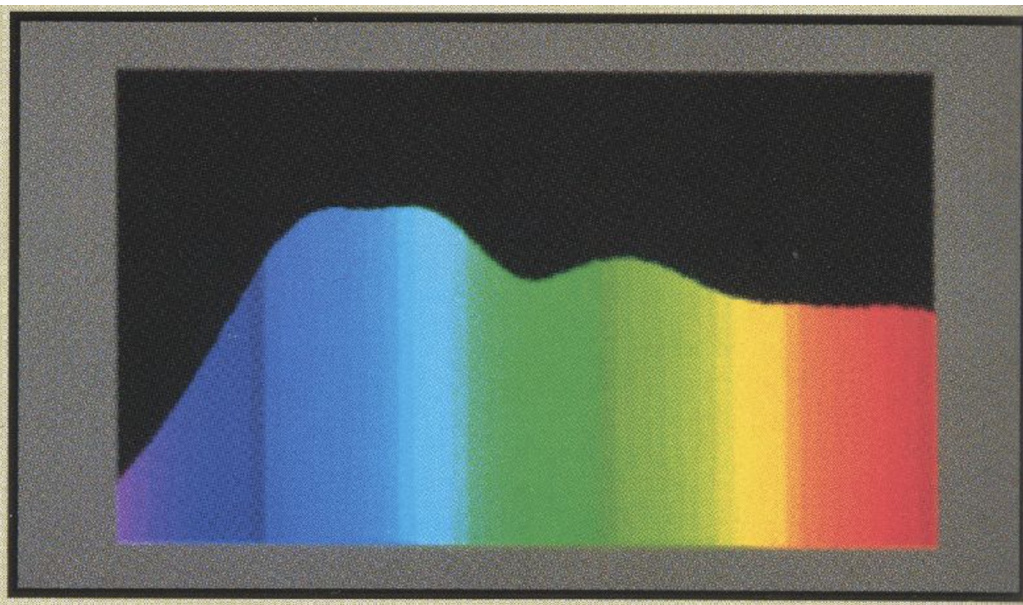
- **Physics: No notion of “color”**

- Light is simply a distribution of photons with different frequencies
- Specified as the “spectrum” of light
- No notion of “white”, “saturation”, “opposing color”, 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)

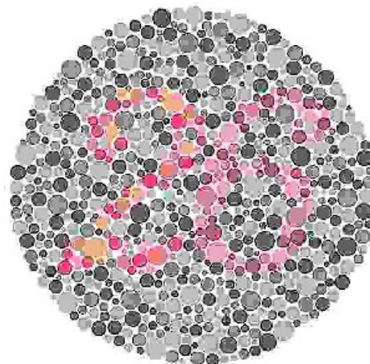
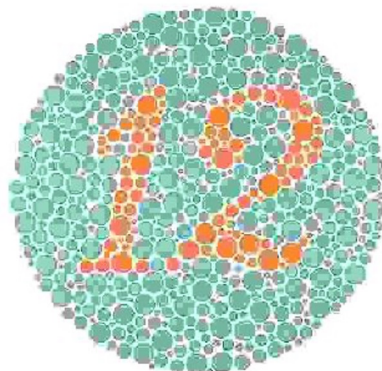


Color Perception

- **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/



www.colorcube.com/illusions/clrblind.html

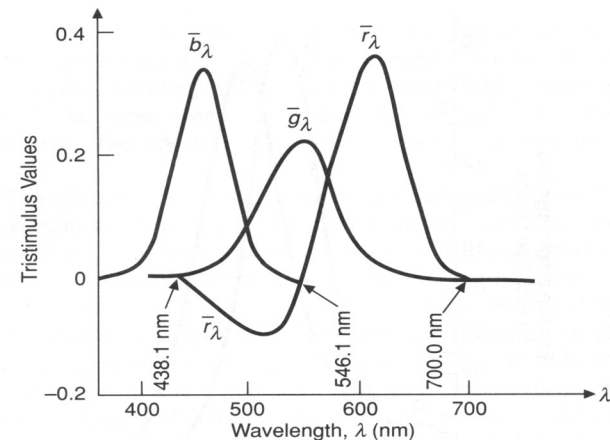
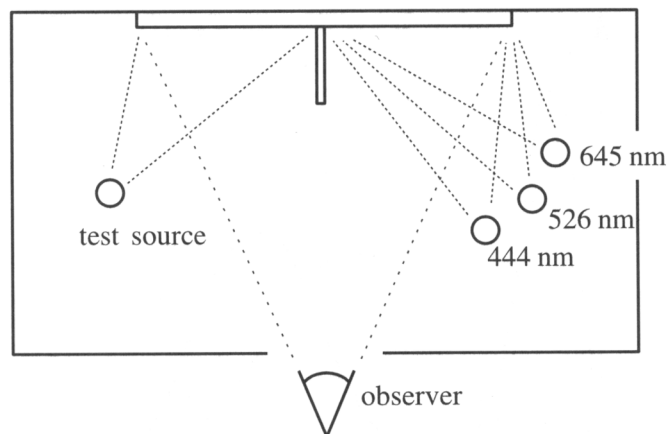
Tristimulus Color Representation

• Observation

- Any test 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 with a 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



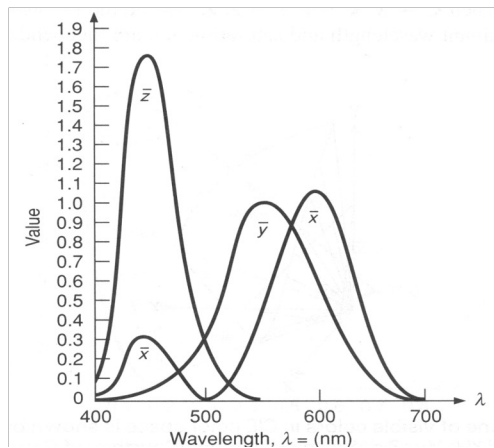
Standard Color Space CIE-XYZ

- **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
- **Definition of the CIE-XYZ color space**
 - CIE: Transformation to a set of *virtual primaries*
 - Transform in 3D color space, with virtual primaries as new basis
 - Goals:
 - Abstract from concrete primaries used in an experiment
 - All matching functions should be positive (all colors in one 3D octant)
 - One primary should be roughly proportionally to luminosity

Standard Color Space CIE-XYZ

- **Standardized imaginary primaries CIE XYZ (1931)**

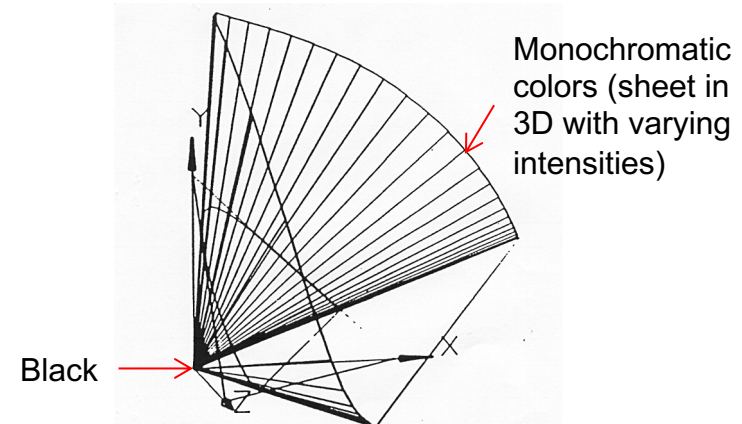
- Imaginary primaries “more saturated” than monochromatic lights
 - Together can match all physically realizable color stimuli
- Defined via spectral matching fct. for virtual CIE XYZ primaries
 - *Virtual* red (X), green (Y), blue (Z)
- Y is roughly equivalent to luminance
 - Shape similar to luminous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



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

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

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



CIE xy Chromaticity Diagram

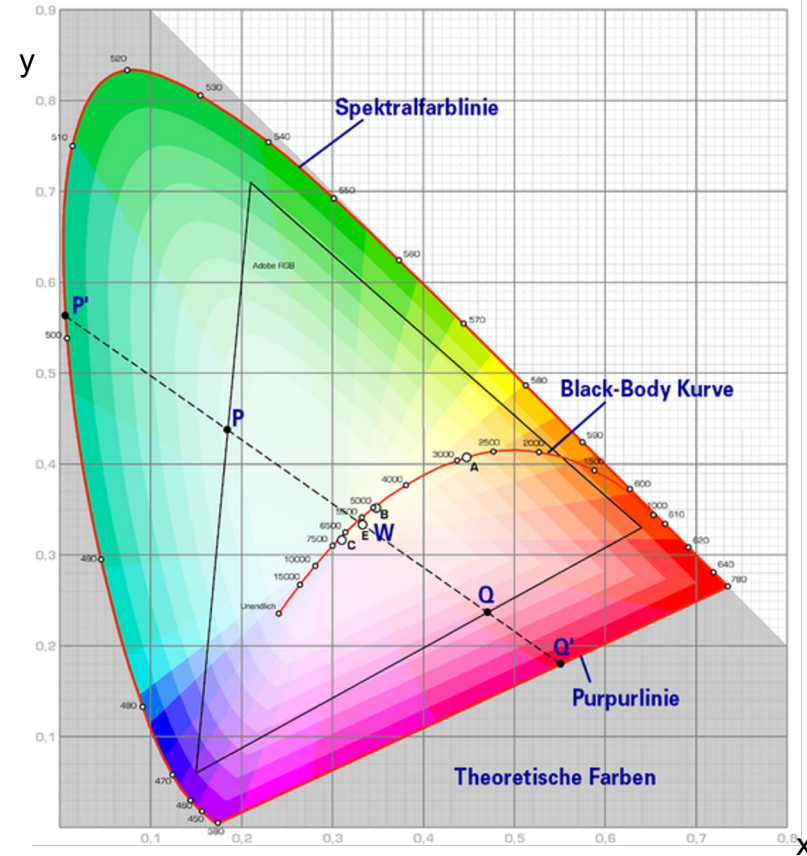
- **Concentrate on color, not light intensity**
 - Relative coordinates: projection on $X+Y+Z = 1$ plane (normalize)

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

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

$$z = 1 - x - y$$

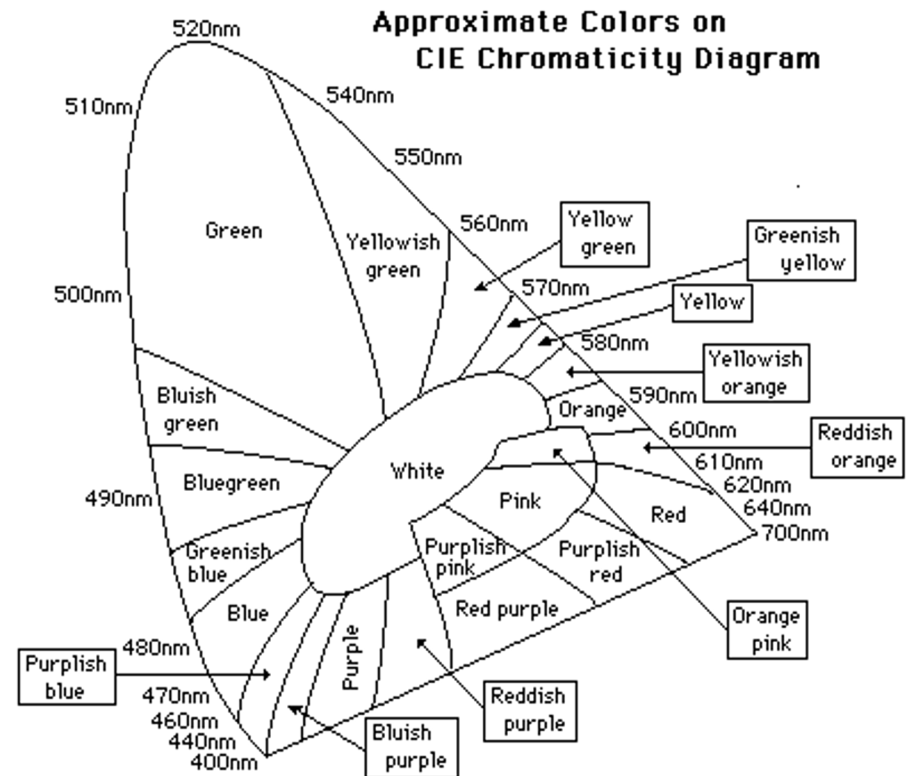
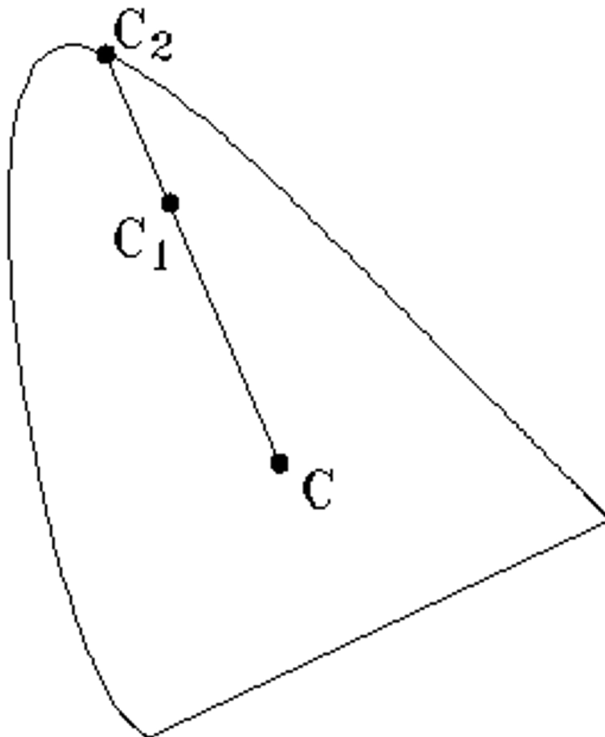
- Chromaticity diagram
 - 2D plot over x and y
 - 2D points called “color locations”
- **Locations of interest**
 - Pure spectral colors (red outline)
 - Purple line: interpolate red & violet
 - White point: $\sim(1/3, 1/3)$
 - Device dependent / eye adaptation
 - Black-body curve
- **Gamut:** Primaries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



CIE Chromaticity Diagram

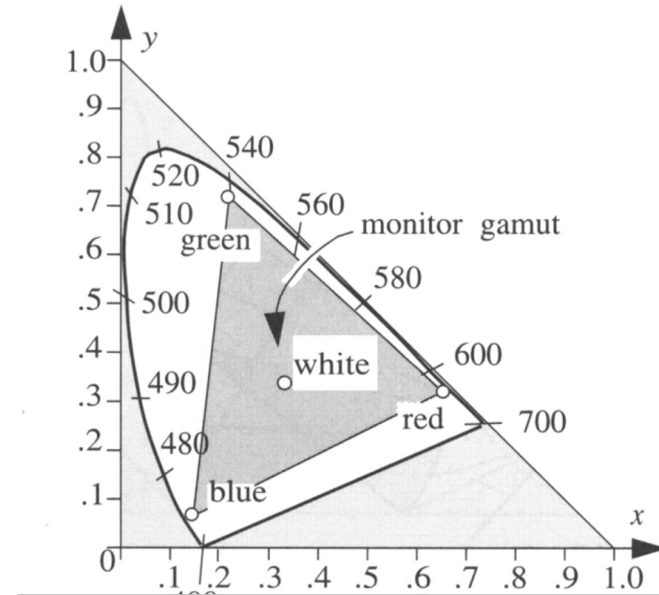
- **Specifying colors**

- **Saturation**: relative distance between pure color and white point
- **Complementary colors**: on other side of white point
- **Line of purples**: closes the color circle (mix of red & blue/violet)



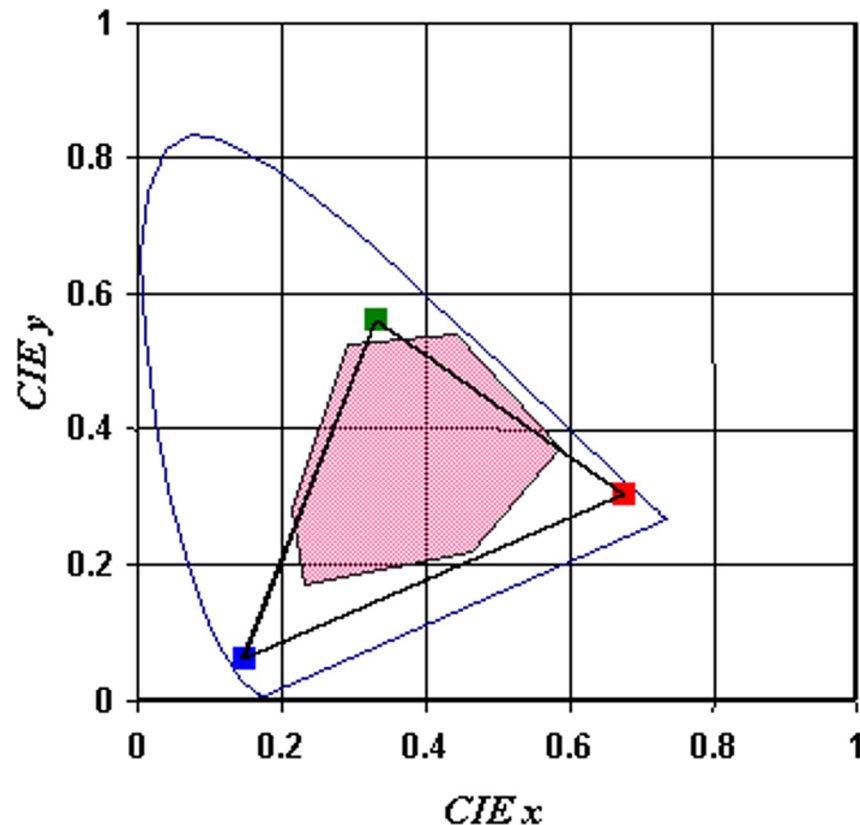
Color Gamut

- **Color gamut**
 - Set of representable colors
- **CIE XYZ gamut**
 - Device-independent
- **Device color gamut**
 - Set of color location reproducible on a device (typically a triangle)
 - Linear combinations of primary colors of the device (w/ additive mixture)
- **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

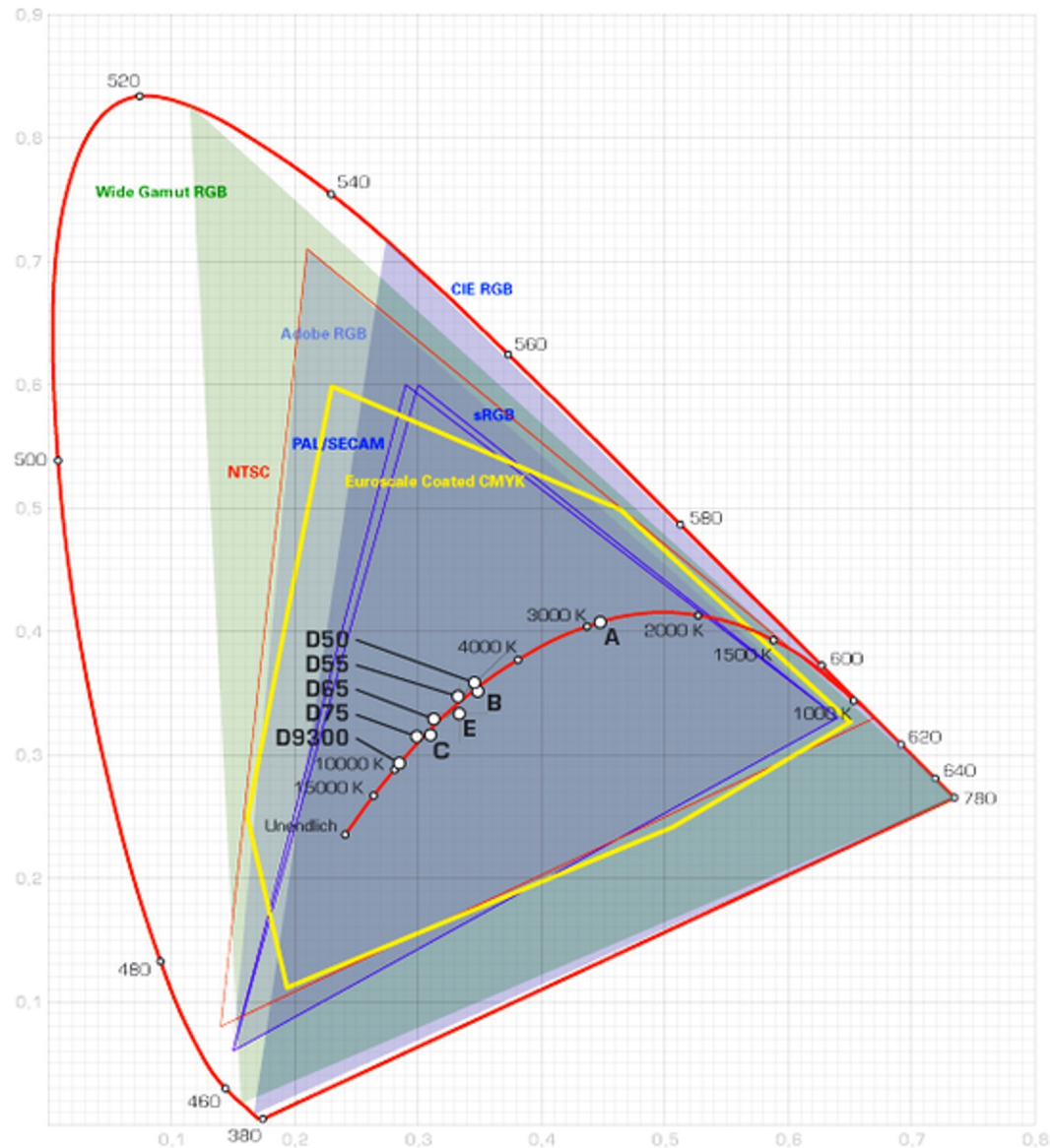
- Complex for printer due to subtractive color mixing
- Complex interactions between printed colors
- Depends on colors, printing technology, paper, ...



Different Color Gamuts

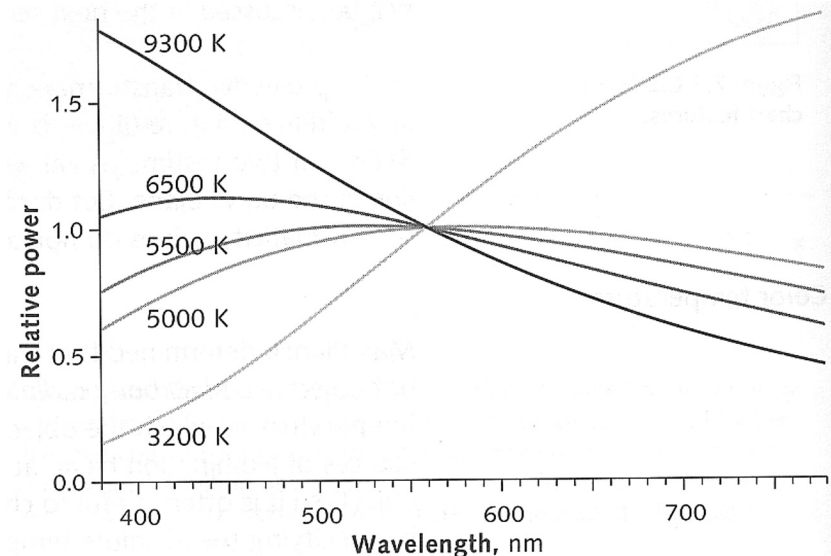
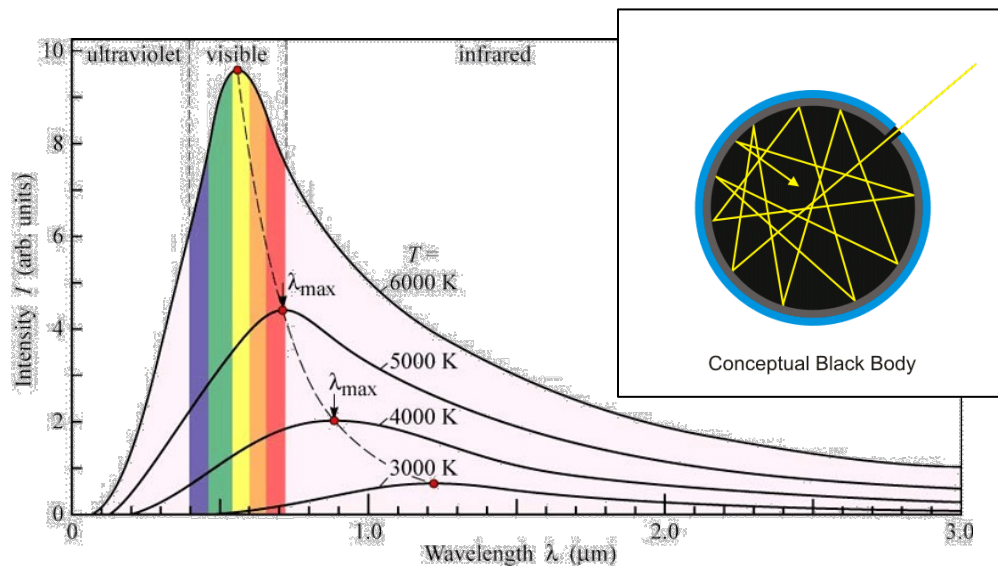
- **Gamut compression/mapping**
 - What to do if colors lie outside of the printable area?
 - Scaling, clamping, other non-linear mappings
 - Each device should replace its out-of-gamut colors with the nearest approximate achievable colors
 - Possible significant color distortions in a printed → scanned → 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
 - Fixed frequency spectrum independent of material (Planck's law)
 - Spectrum can be converted into CIE-xy color location
 - Normalizing the spectrum (at 550 nm)
 - Energy relatively shifts from longer (reddish) toward shorter wavelengths (blueish) as the temperature increases
 - Allows for white point specification through temperatures



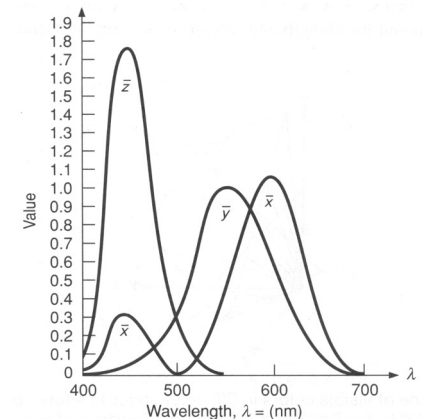
CIE Standard Illuminants

- **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 (e.g., sample every 5-10 nm)
 - Projecting from m D to 3D using matching curves (loss of information, reverse mapping is not unique!)

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



- **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.)

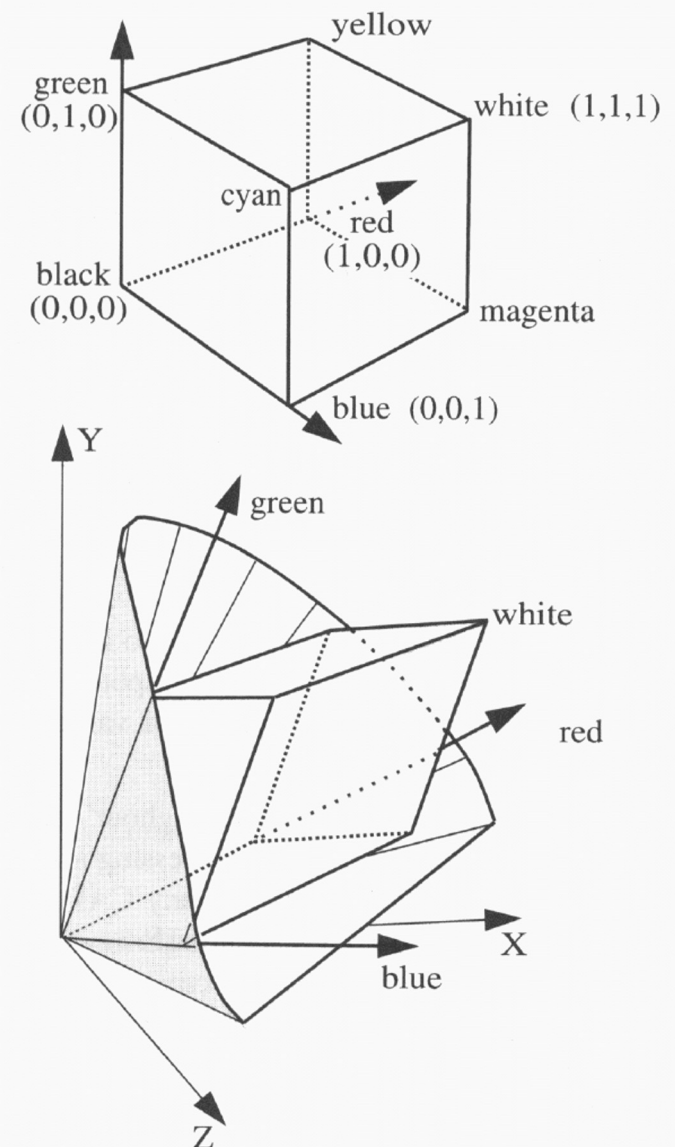
- **Computing the constants C_r , C_g , C_b**
 - Per definition the white point is given as $(R, G, B) = (1, 1, 1)$
 - $(X_w, Y_w, Z_w) = M * (1, 1, 1)$

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

- (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**
 - May result in out of gamut colors and require gamut mapping!

Geometric Interpretation

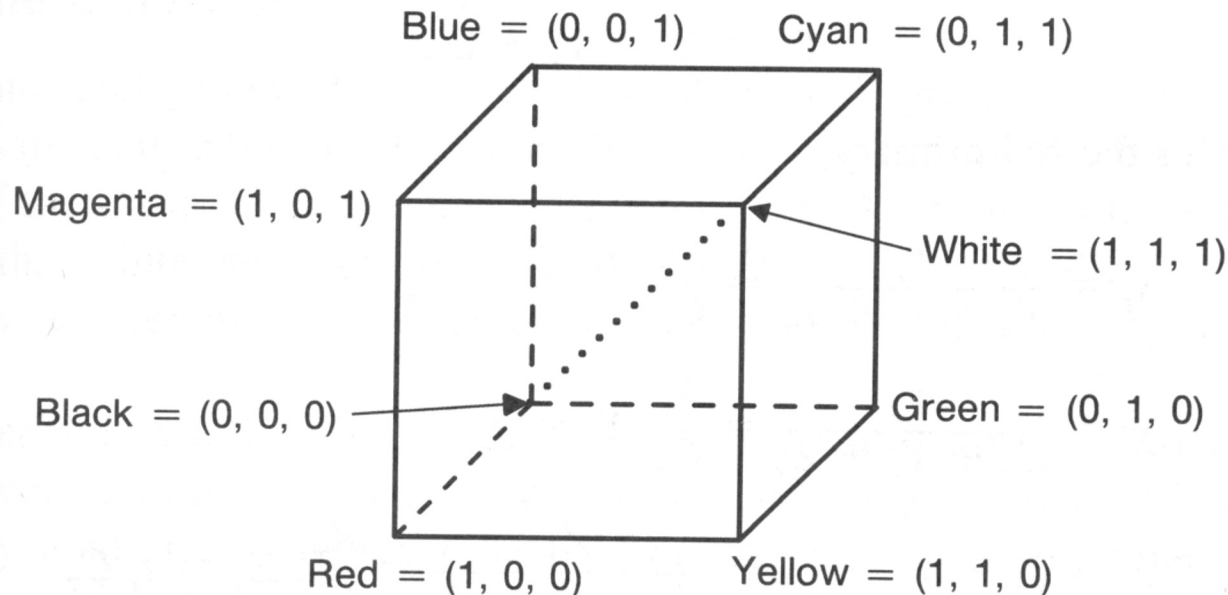
- RGB embedded in XYZ space
- Basis change bet. RGB spaces
- Possibly need to handle out-of-gamut colors
- Changes of color temperature/white point
 - Cannot change color locations of primaries (defined by material)
 - Changing intensities of primaries
 - Scales the length of the basis vectors
 - Moves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



RGB Color Model

- **RGB:**

- Simplest model for computer graphics
 - Defined by primary colors of the device
- Natural for devices additively mixing colors (e.g., monitors)
- **Device dependent (!!!), due to different choices of primaries**
 - **Most display applications *still* do not correct for it!!!!**
- Many image formats do not allow color space to be specified



sRGB Color Space

- **Standardized RGB color space**

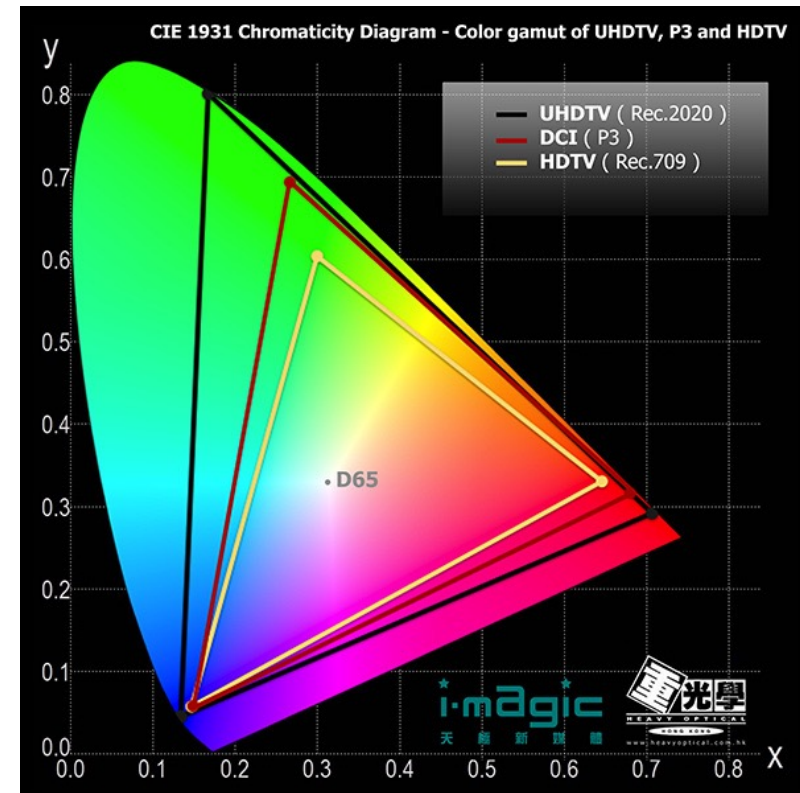
- RGB for standardized primaries and white point (and gamma)
- Specification of default CIE-XYZ values for monitors
 - Red: 0.6400, 0.3300
 - Green: 0.3000, 0.6000
 - Blue: 0.1500, 0.0600
 - White: 0.3127, 0.3290 (D65)
 - Gamma: 2.2
- Same values as HDTV and digital video (ITU-R 709)
- <http://www.color.org>

- **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

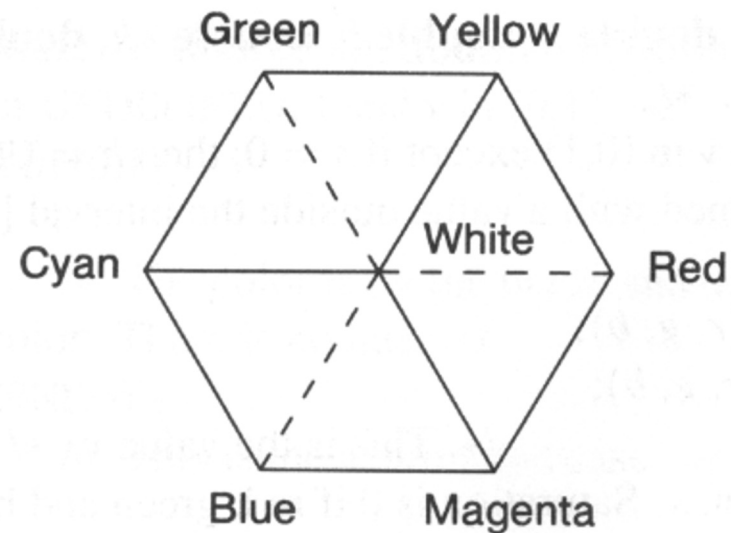
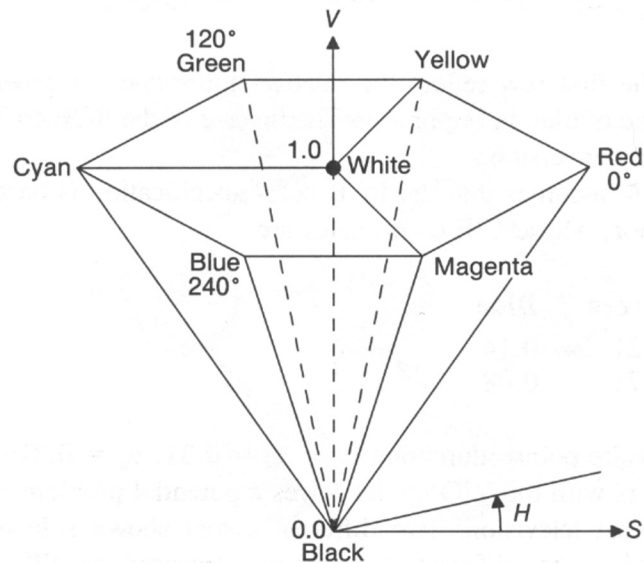
ITU Rec.-2020 / BT-2020

- **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



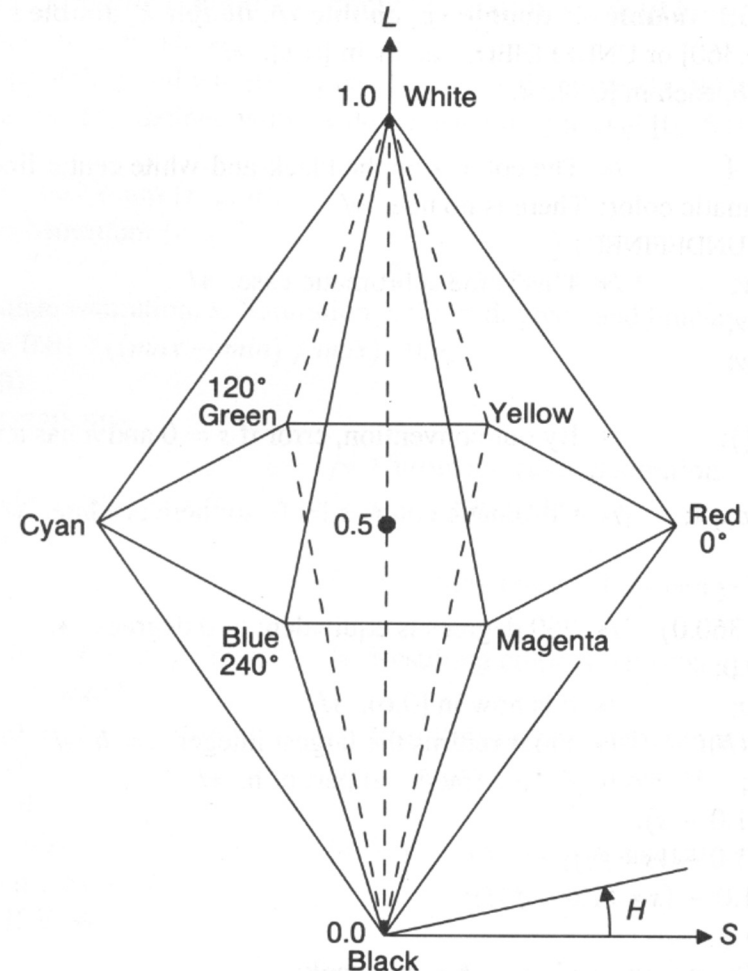
HLS Model

- **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

- **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

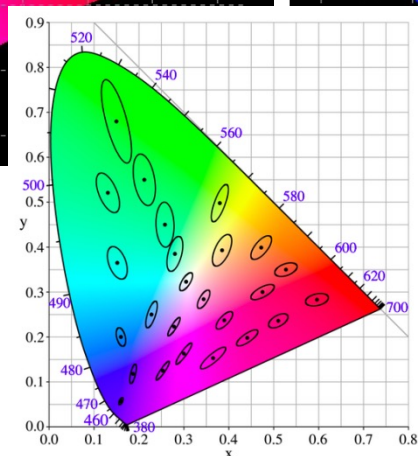
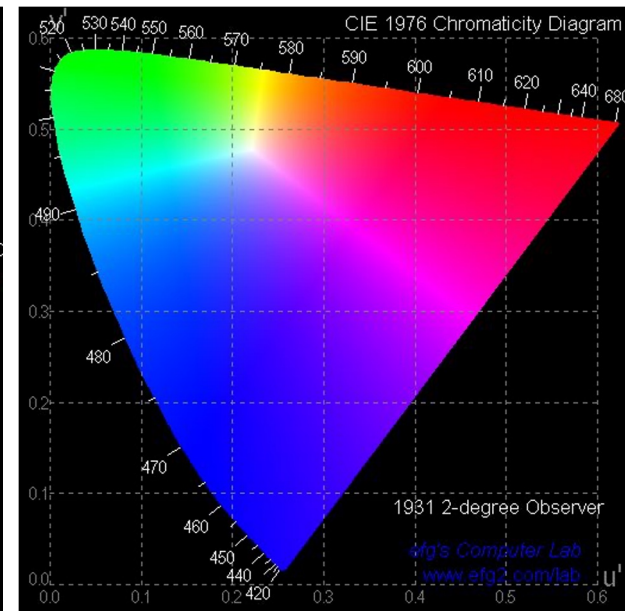
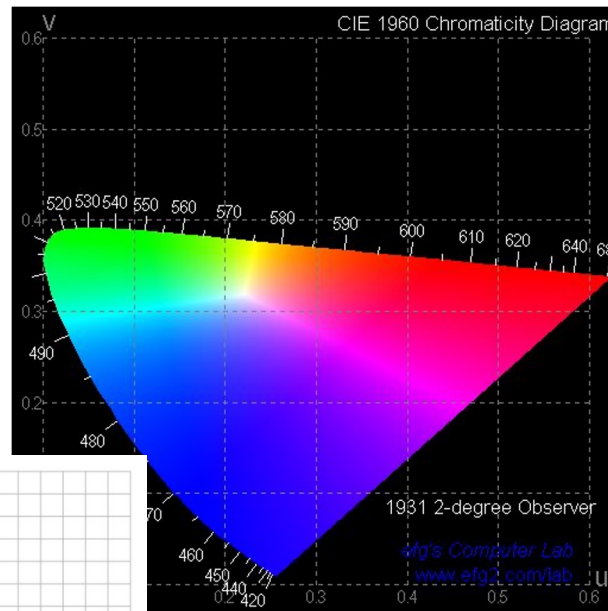
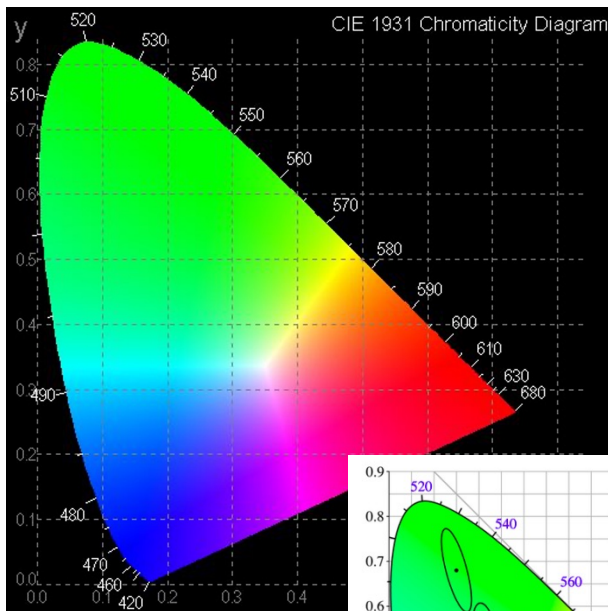
- **Distance threshold until perceptible color difference**

- Very inhomogeneous \Rightarrow alternate transformations

CIE-xy (1931)

CIE-uv (1960)

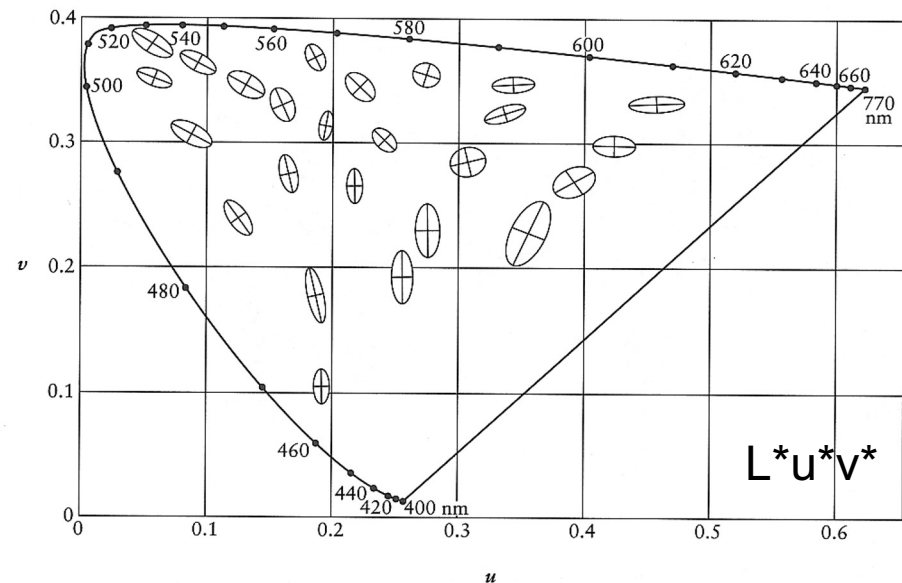
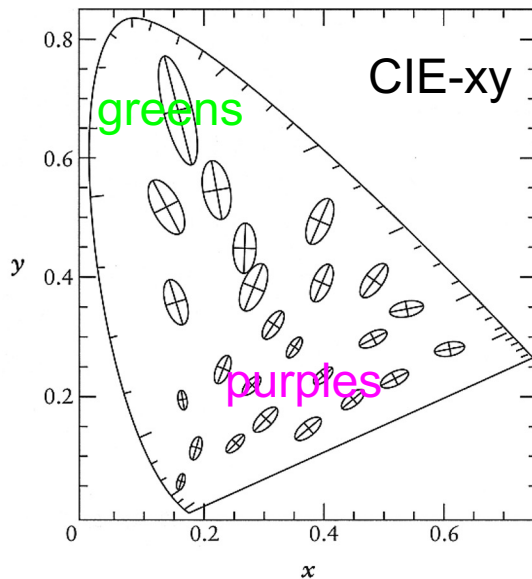
CIE-u'v' (1976)



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

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

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

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

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

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

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

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

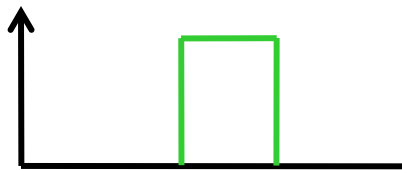
- Limited applicability to HDR

“Subtractive” Color Blending

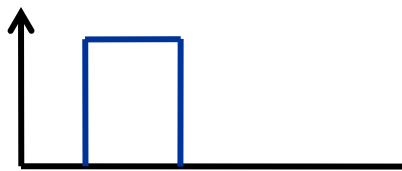
- Corresponds to stacked color filters (idealized)



+



+



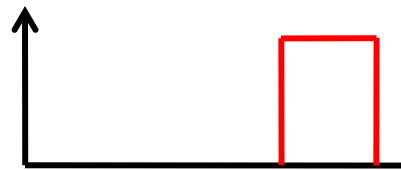
=



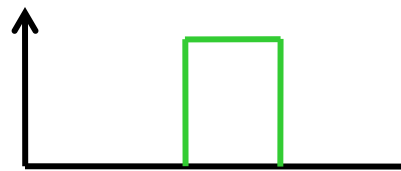
Additive blending



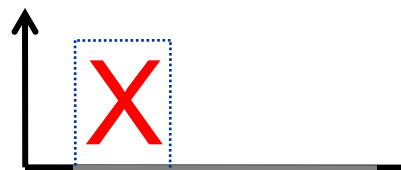
x



x



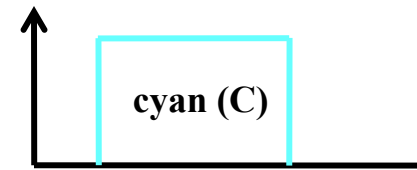
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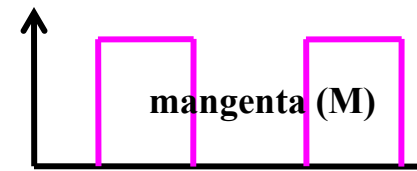
„Subtractive“ blending
Multiply by primary filters: wrong !



x



x



=



„Subtractive“ blending
Multiply by inverse primaries

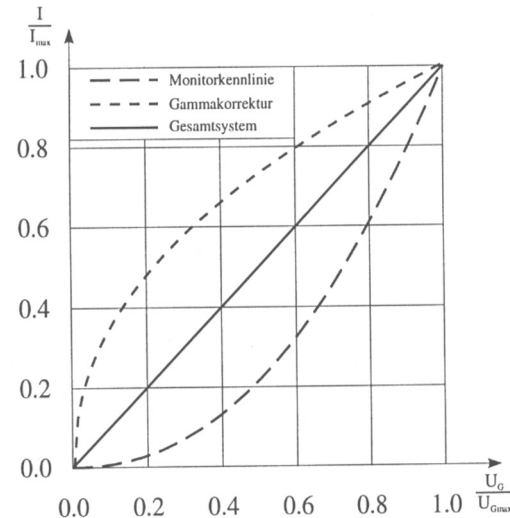
“Subtractive” Color Blending

- **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 during printing
 - Covering and/or blending between semitransparent layers
 - 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 Testing Chart

- **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

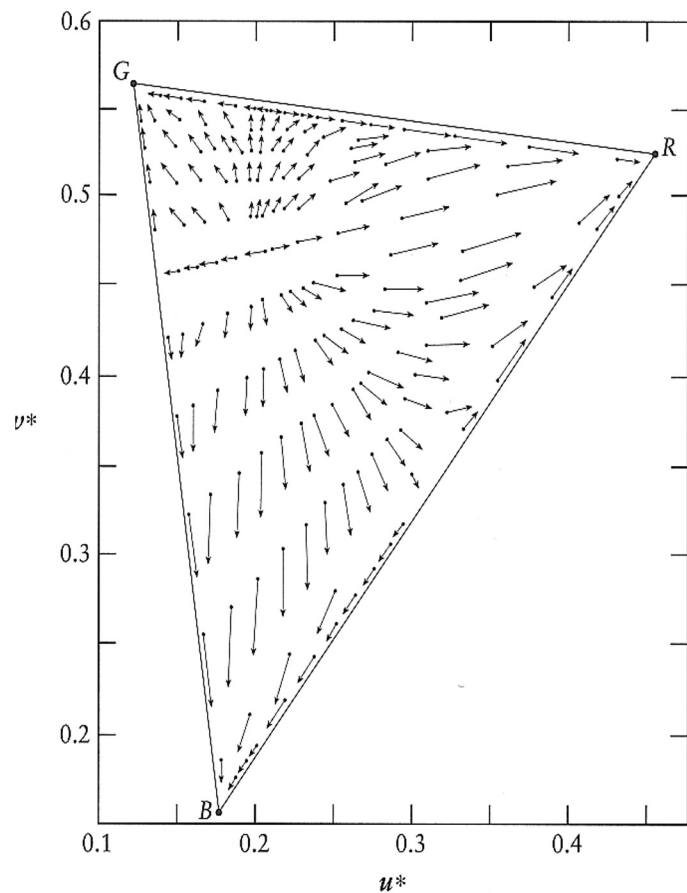
0 . 8

0 . 6

Gamma Correction

- **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

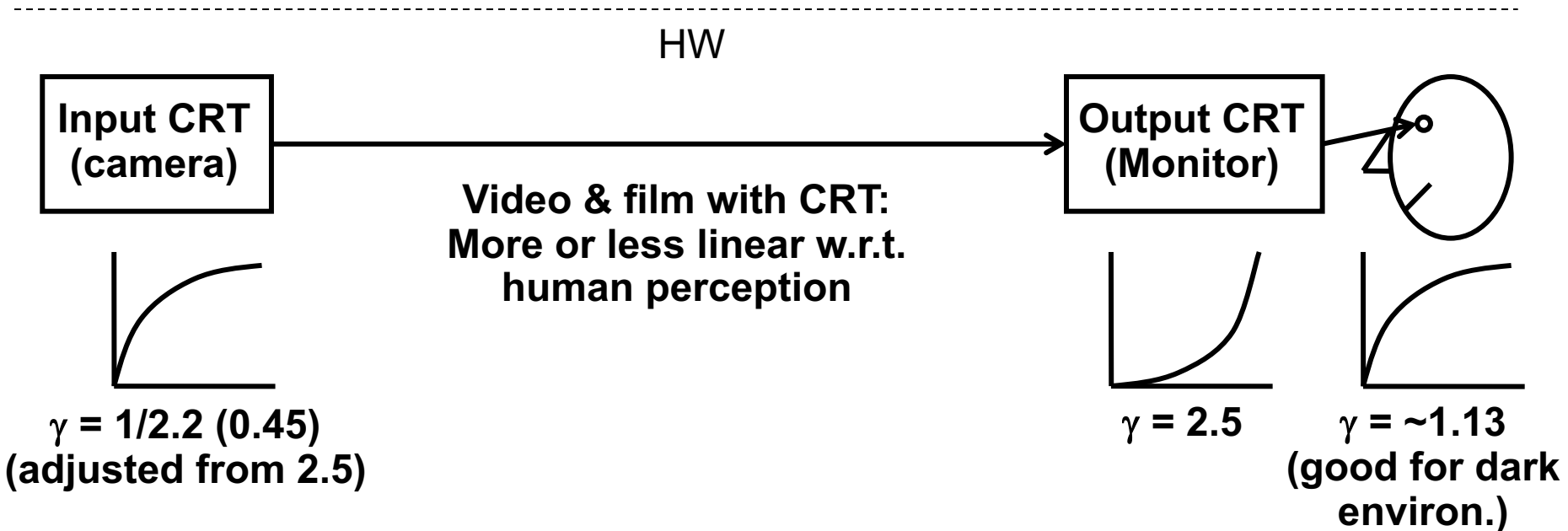
- **Camera-gamma**

- 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 typically corrected to gamma of $1/2.2$ for a total gamma of ~ 1.13

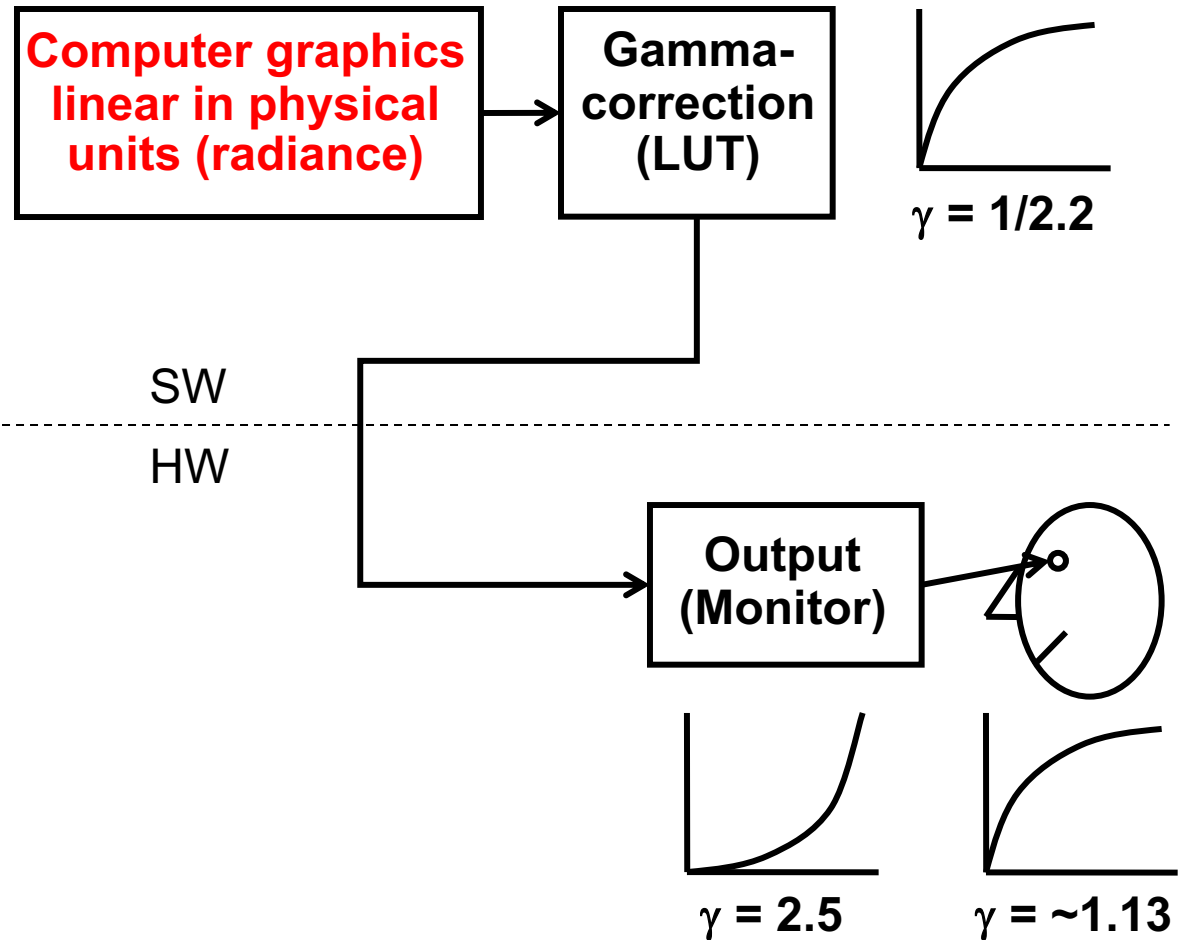
- **“Human-gamma”**

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

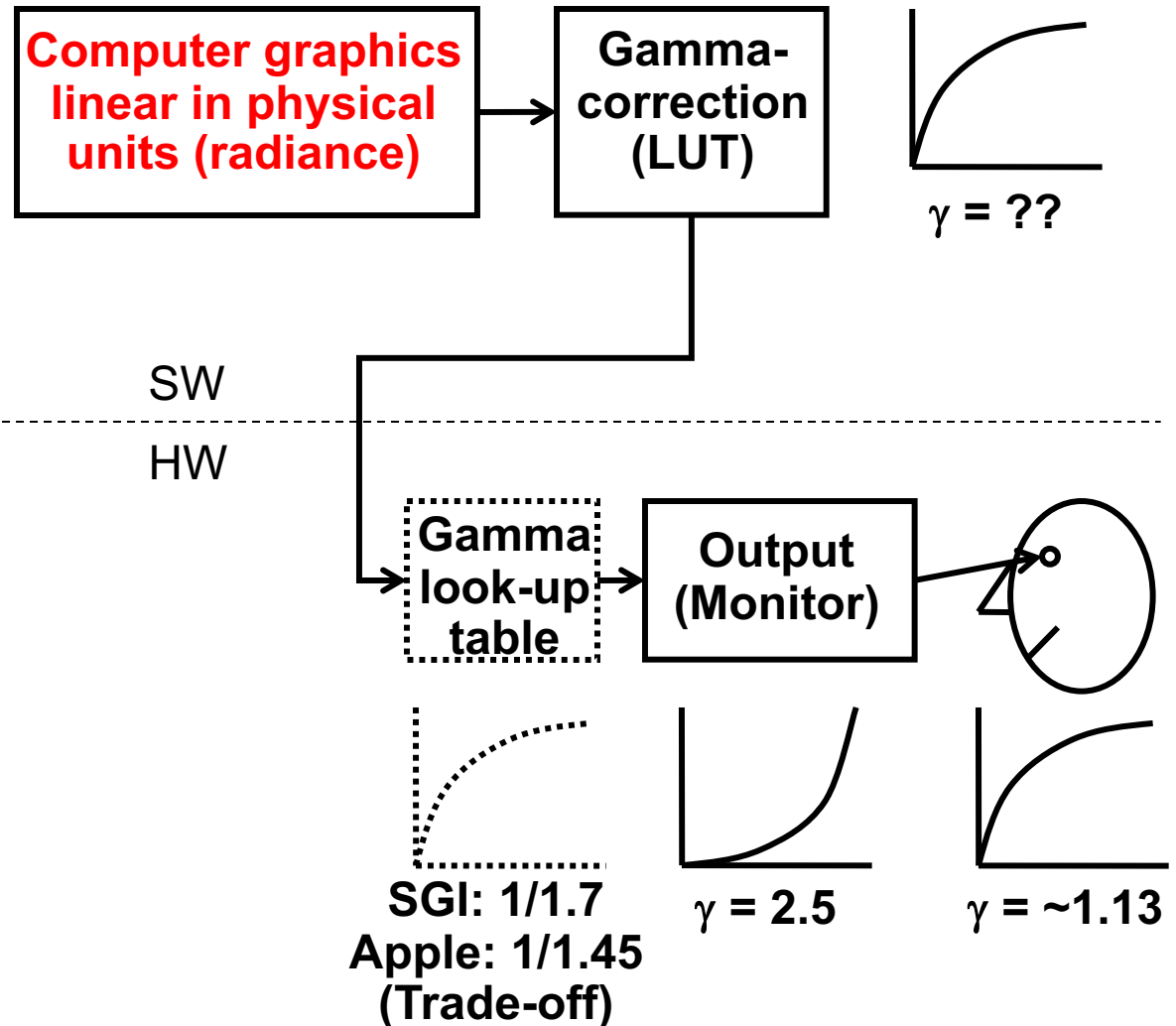
Color from Beginning to End



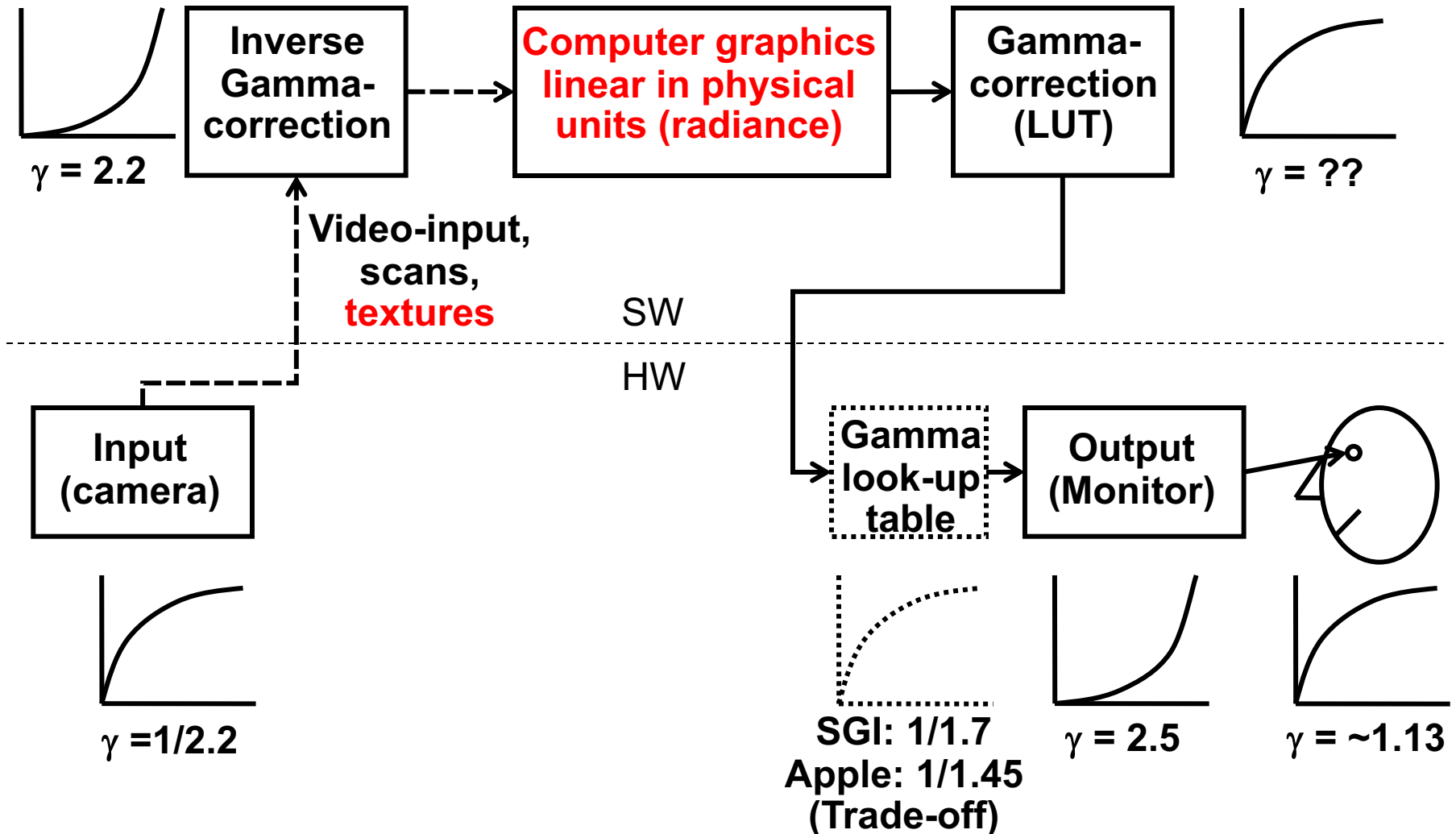
Color from Beginning to End



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, ...

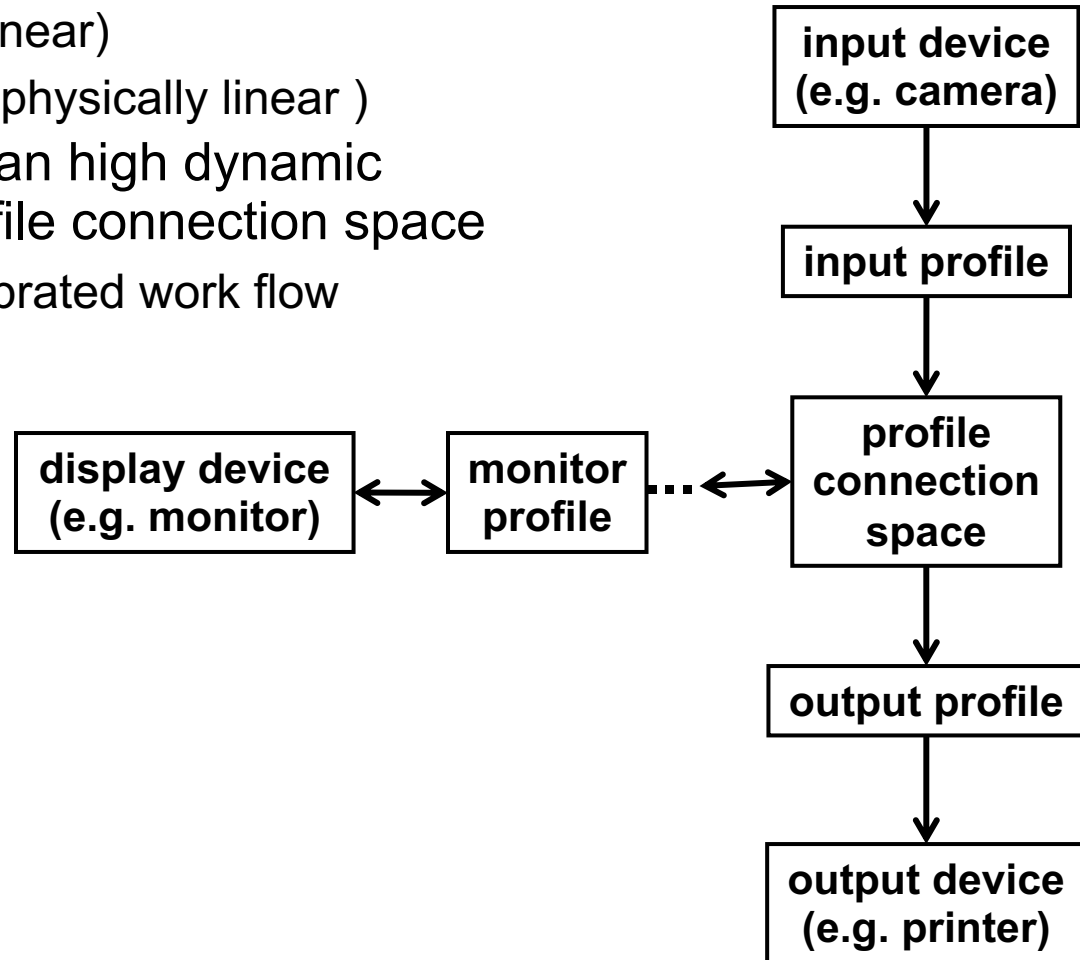
ICC Profiles

- **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, cameras
 - 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?**

