EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

FACULTY OF
SCIENCE
Computer Graphics

Computer Graphics (Graphische Datenverarbeitung)

- Color -

Hendrik Lensch

WS 2021/2022

Corona

- Regular random lookup of the 3G certificates

- Contact tracing: We need to know who is in the class room
  - New ILIAS group for every lecture slot
  - Register via ILIAS or this QR code (only if you are present in this room)

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

Dunkel-Grün

RGB: (63, 129, 80)

Hex: #3F8150

HSV: (135º 51.2%, 50.6%)

CMYK: (0.512, 0, 0.38, 0.494)

L*ab: (48.6812, -32.5923, 20.2798)

…

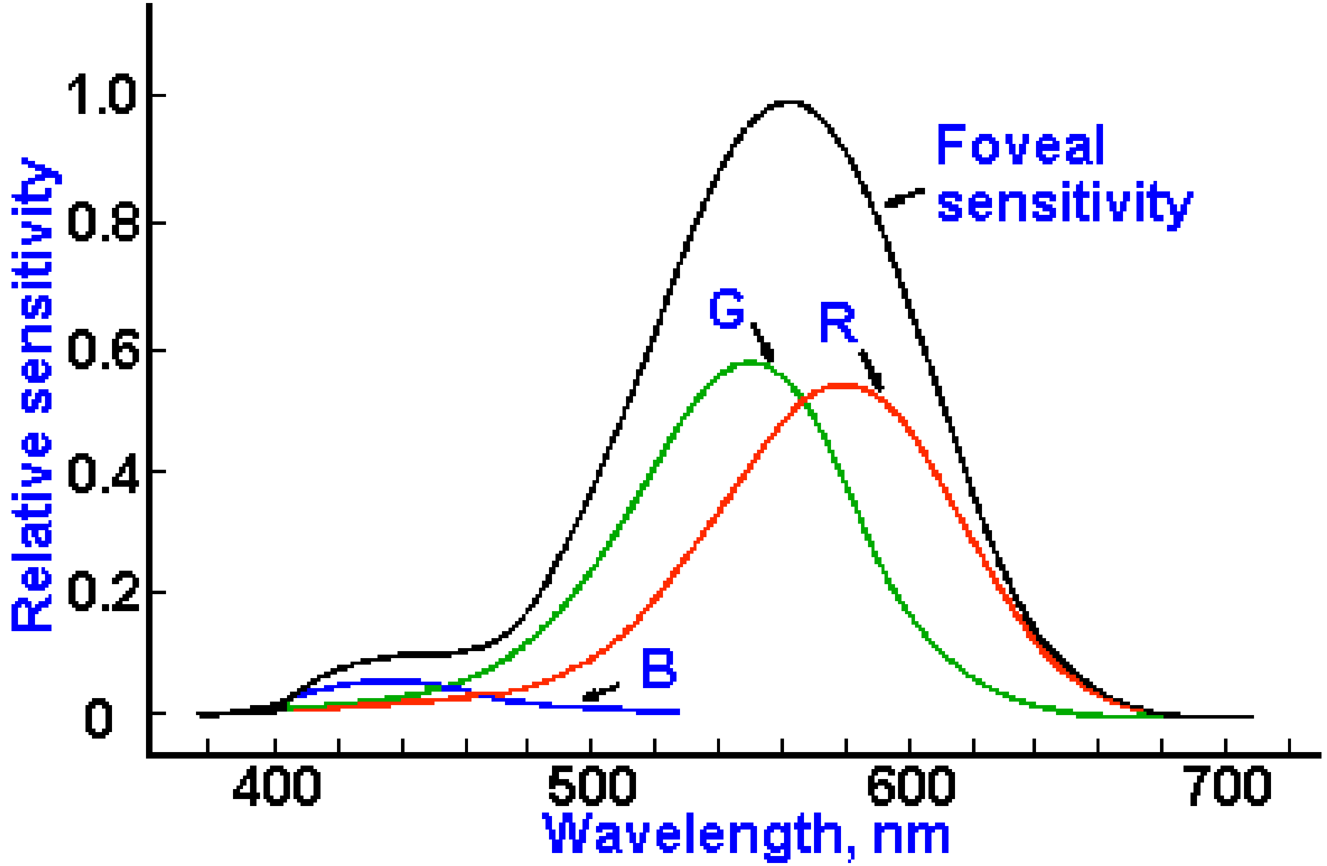
What is color?

- Color is a psychological property of our visual experiences when we look at objects and lights, not a physical property of those objects or lights. (S. Palmer, Vision Science: Photons to Phenomenology)
- Color is the result of interaction between physical light in the environment and our visual system

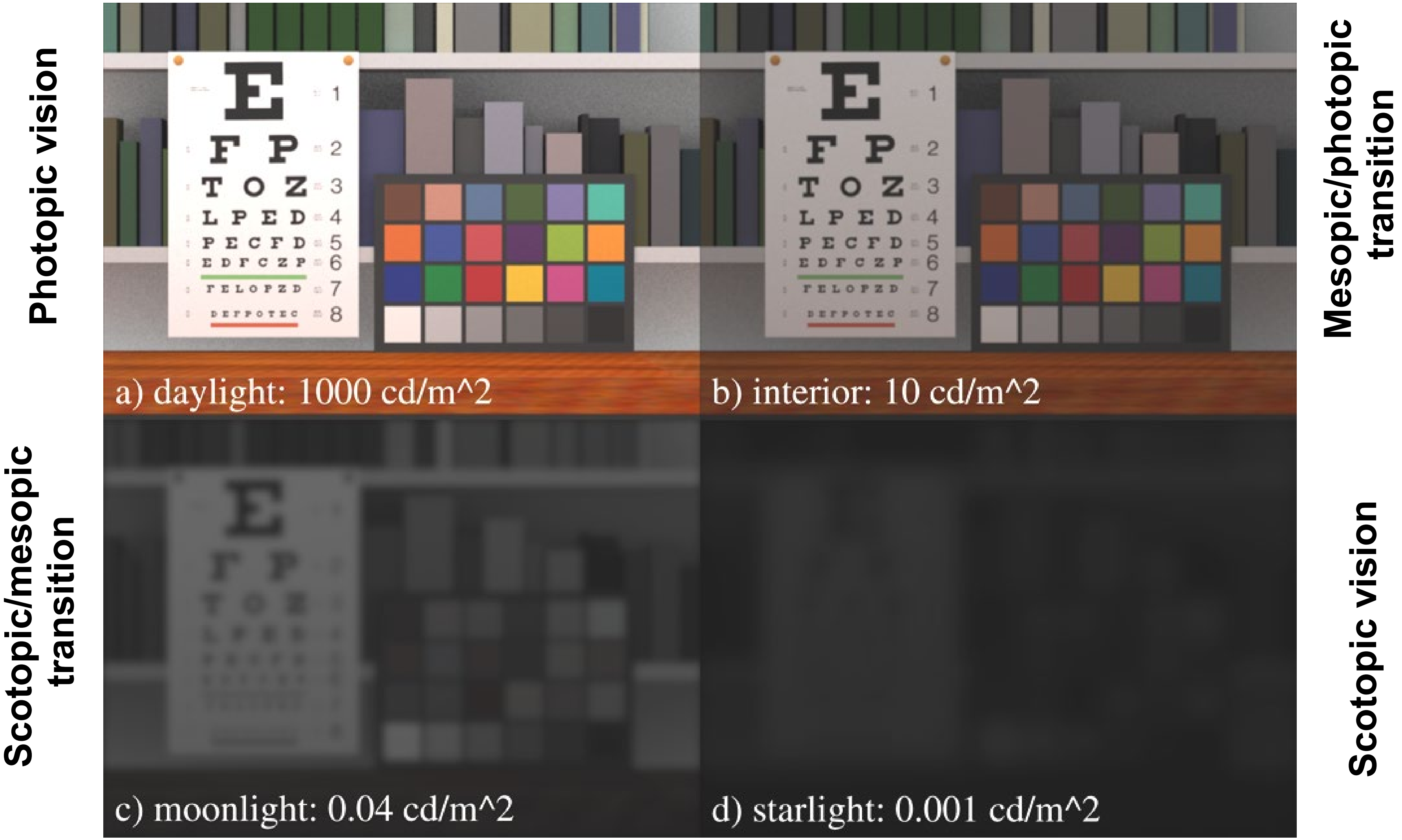
Wassily Kandinsky (1866-1944)
Murnau Street with Women, 1908

Eye as a Sensor

- Relative spectral sensitivity of human
  - Cone cells (Zapfen) S, M, L
  - Rod cells (Stäbchen)



Visual Acuity and Color Perception

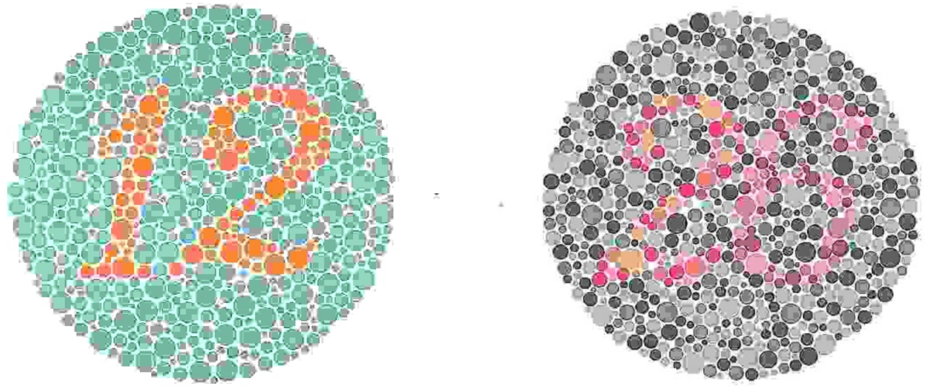


Color Perception

- Di-chromaticity (dogs, cats)
  - Yellow & blue-violet
  - Green, orange, red indistinguishable

- Tri-chromaticity (humans, monkeys)
  - Red, green, blue
  - Color-blindness
    - Most often men, green color-blindness

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



www.colorcube.com/illusions/clrblnd.html

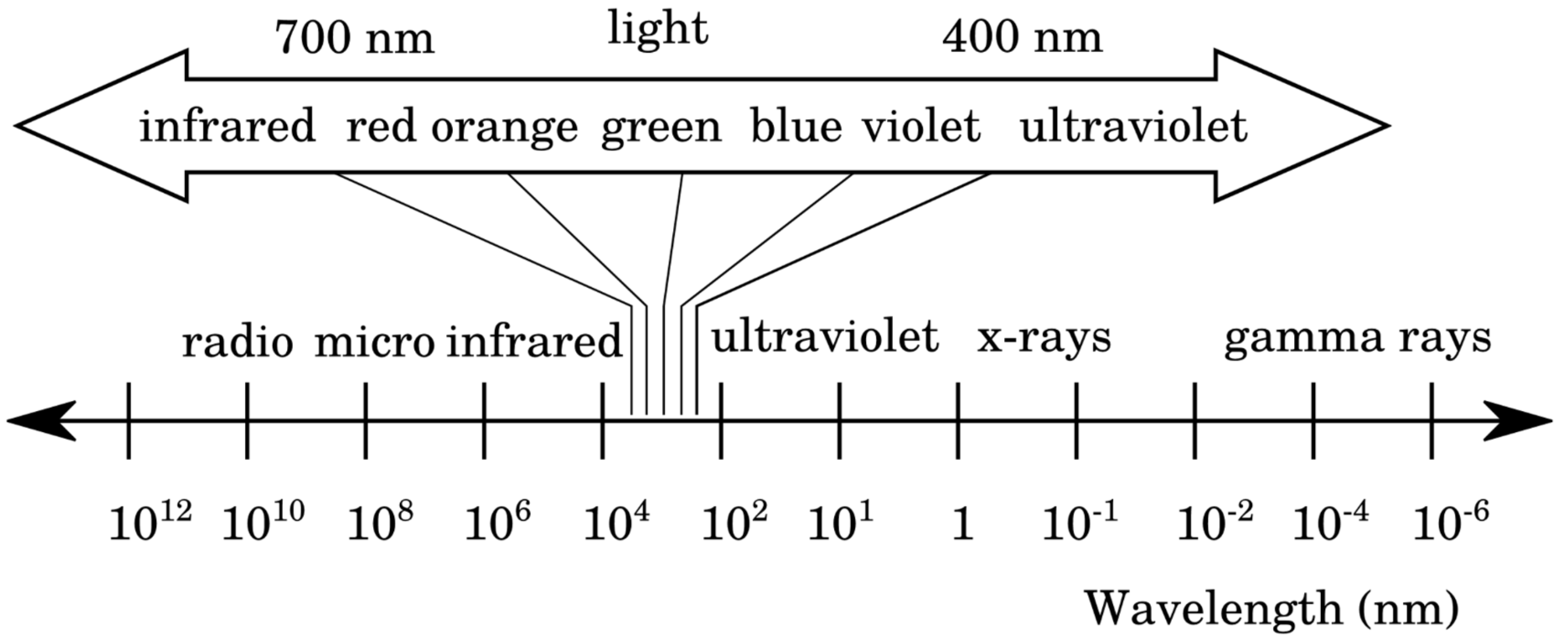
What you should learn

- Color as a joint product of illumination, reflectance and perception.
- Tri-Stimulus Color Models
  - RGB, HSV, …
  - Lab, La*b*
- ICC Profiles
- Understand the concept of color.
- Work with different color representations and how to transform between them.

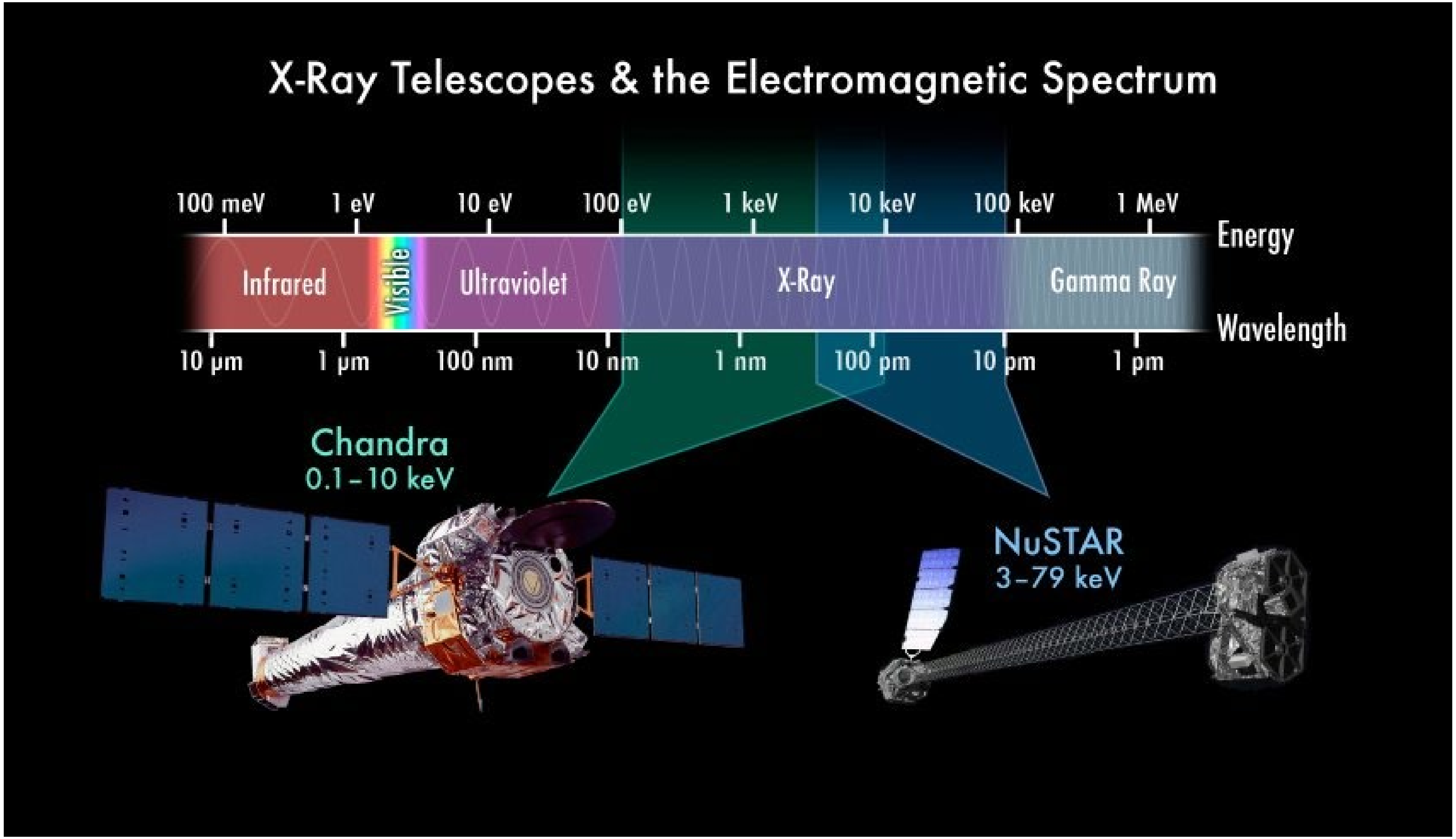
The Physics of Light / Color

Color Representation

- by the full spectrum
  - amplitude of each frequency

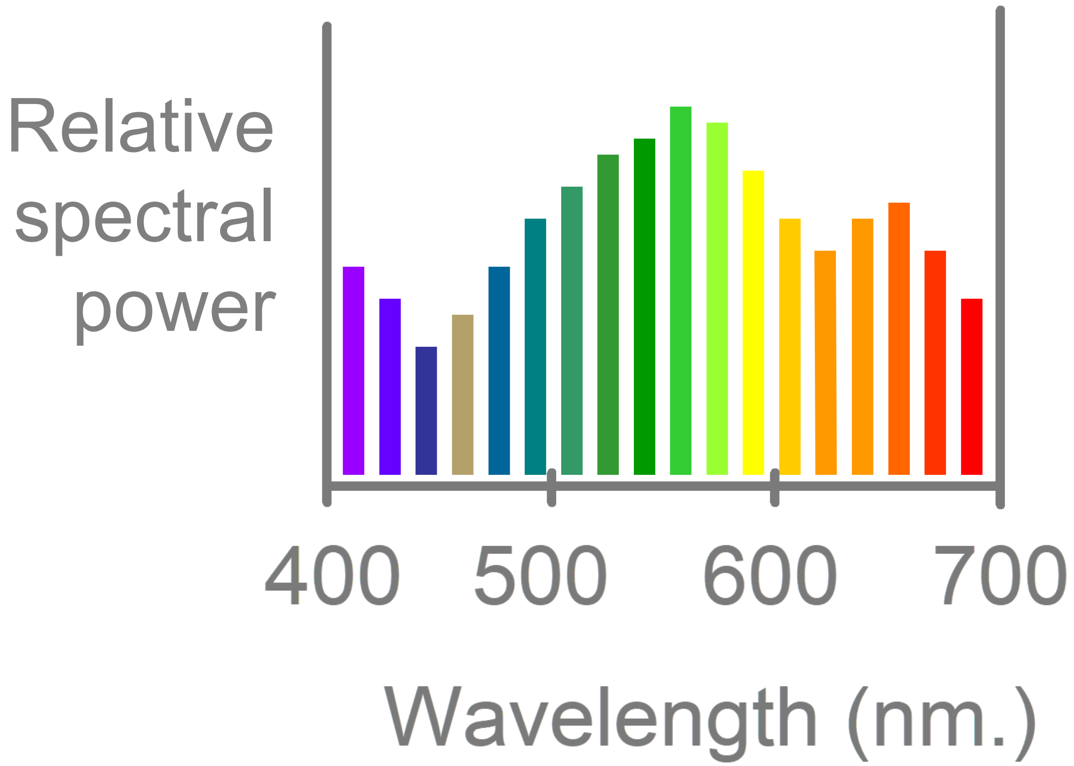


Visible Light in the Radiation Spectrum



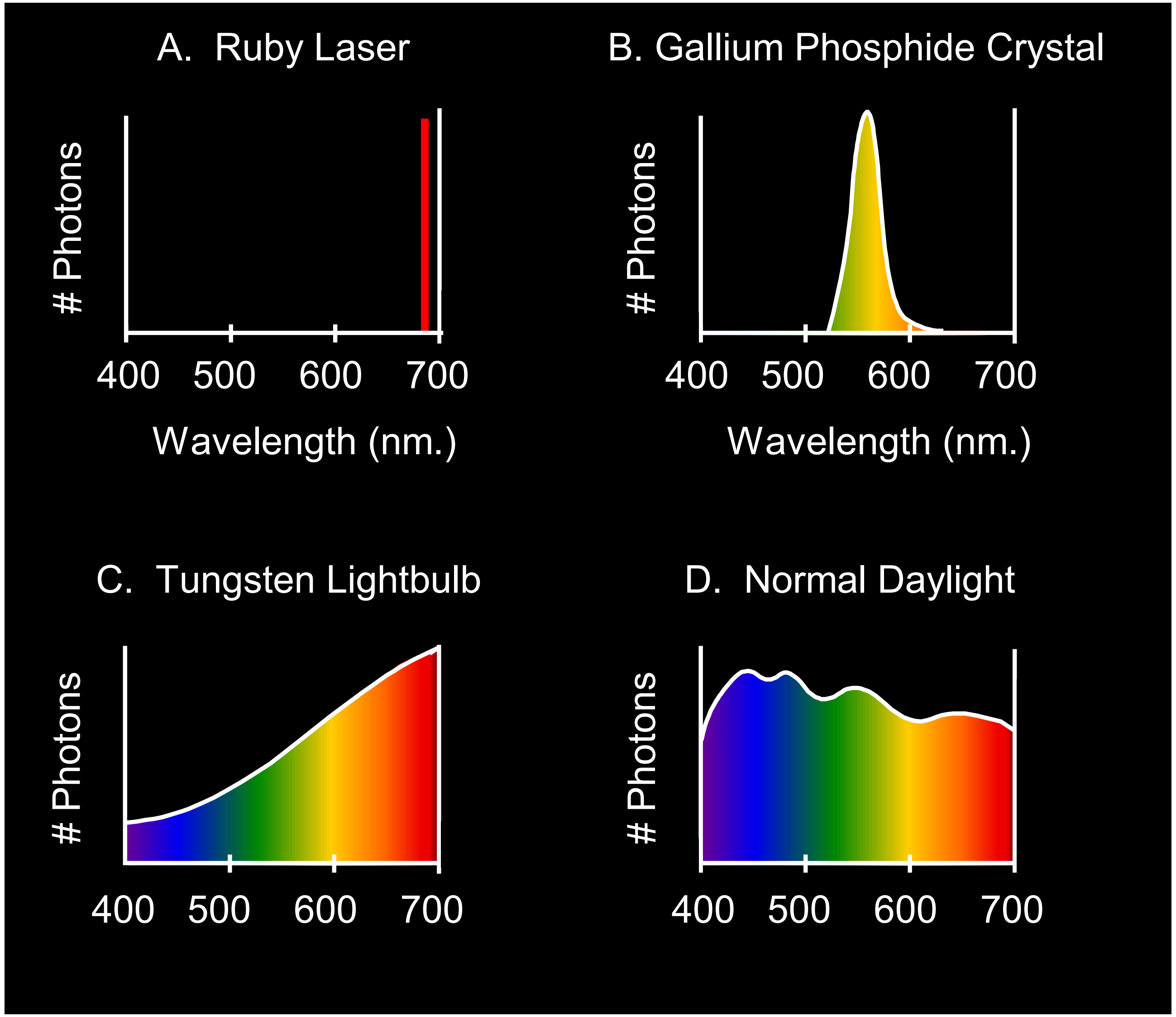
The Physics of Light

- Any source of light can be completely described physically by its spectrum:
  - The amount of energy emitted (per time unit) at each wavelength 400 - 700 nm.



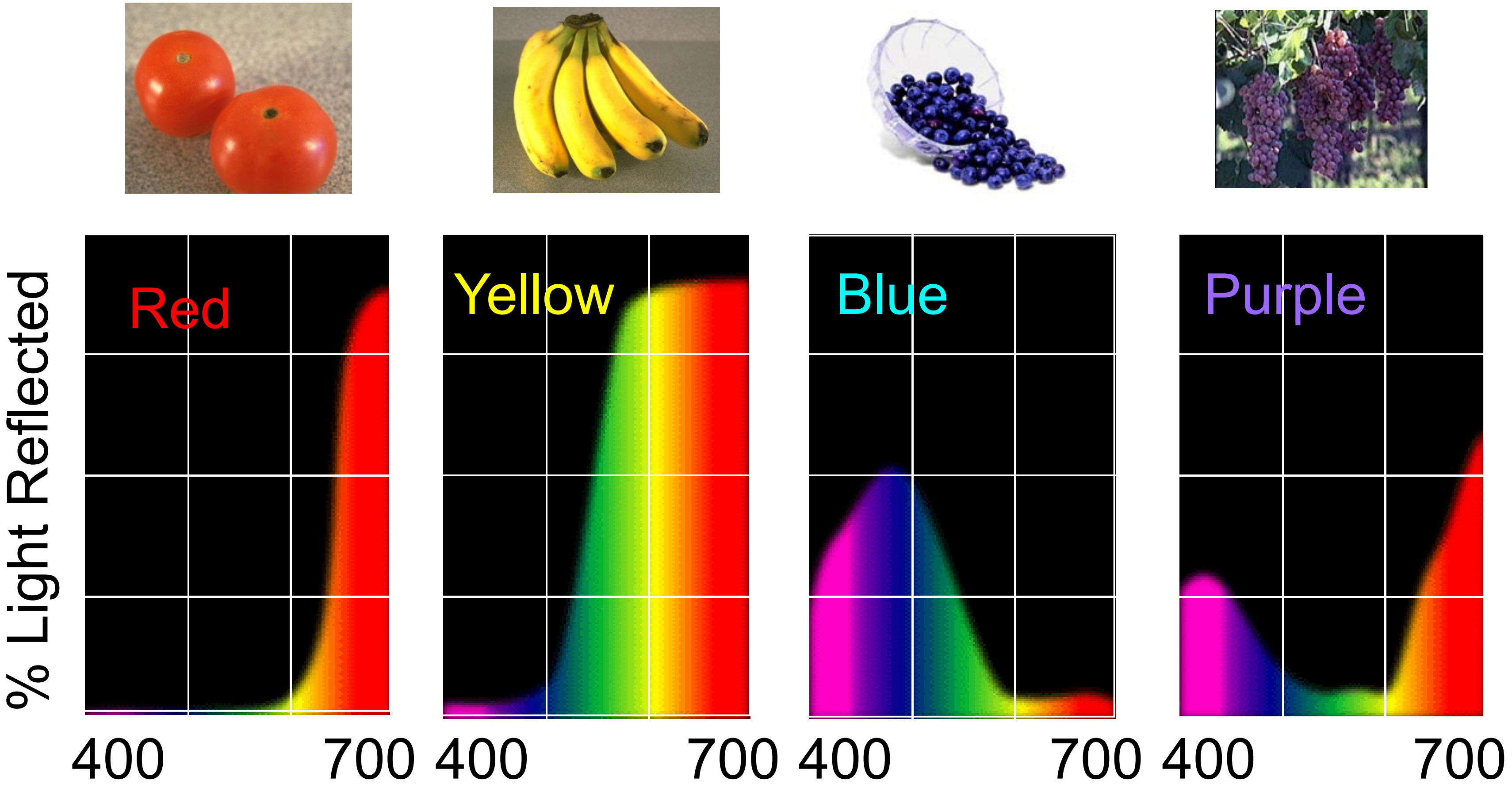
The Physics of Light

- Some examples of spectra of light sources



The Physics of Light

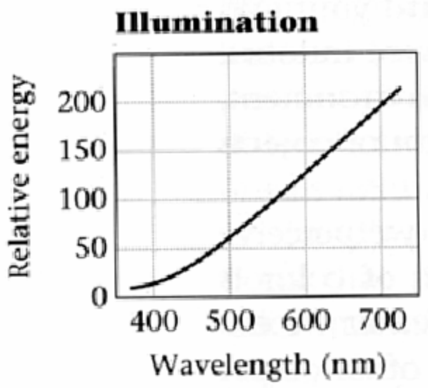
- Some examples of the reflectance spectra of surfaces



Interaction of light and surfaces

- Observed color is the result of interaction of light source spectrum with surface reflectance

- Spectral radiometry
  - All definitions and units are now “per unit wavelength”
  - All terms are now “spectral”



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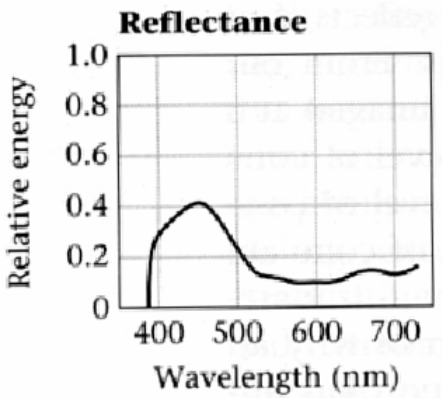

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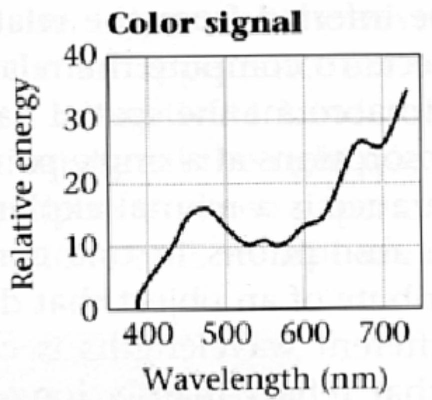
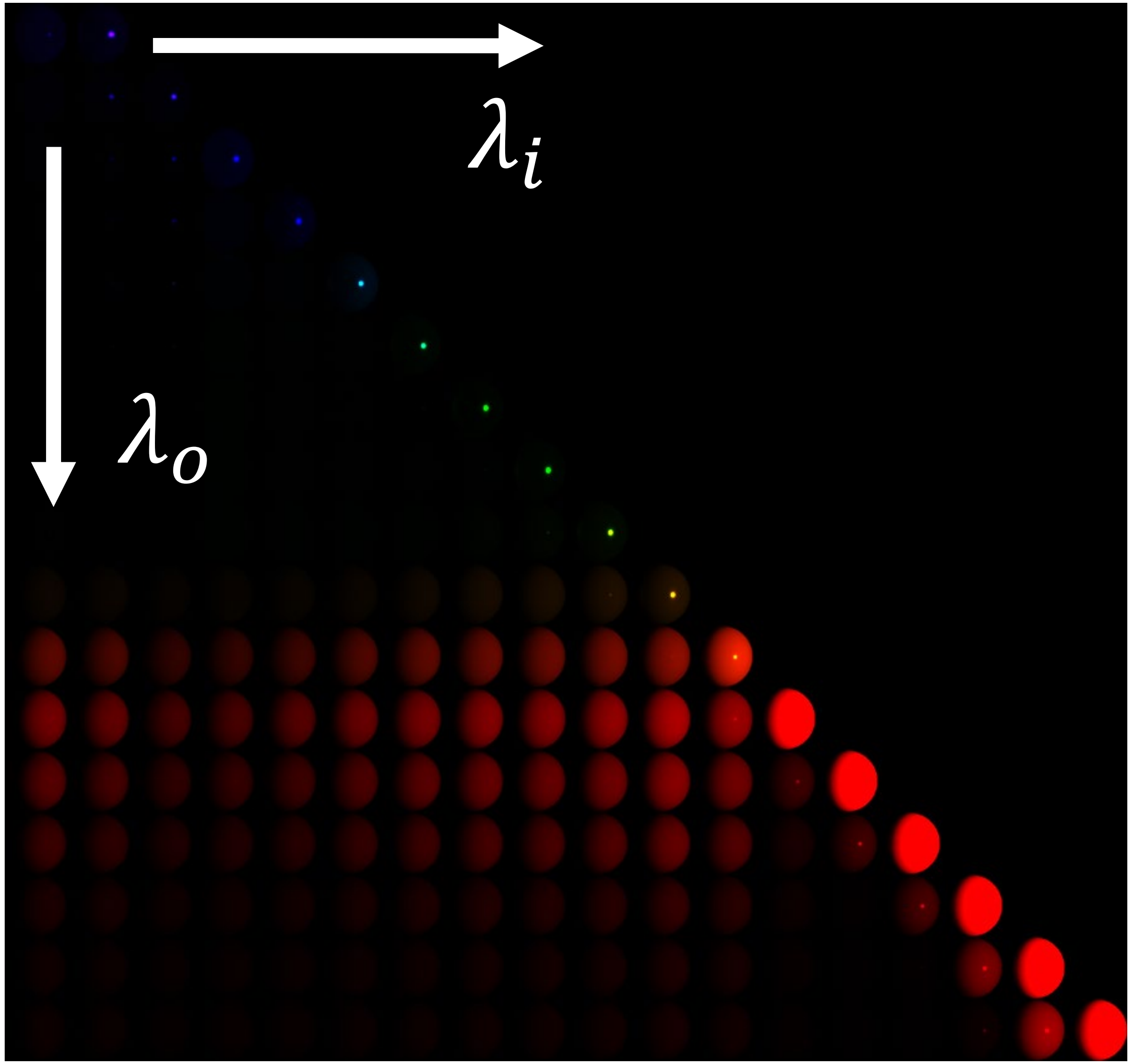
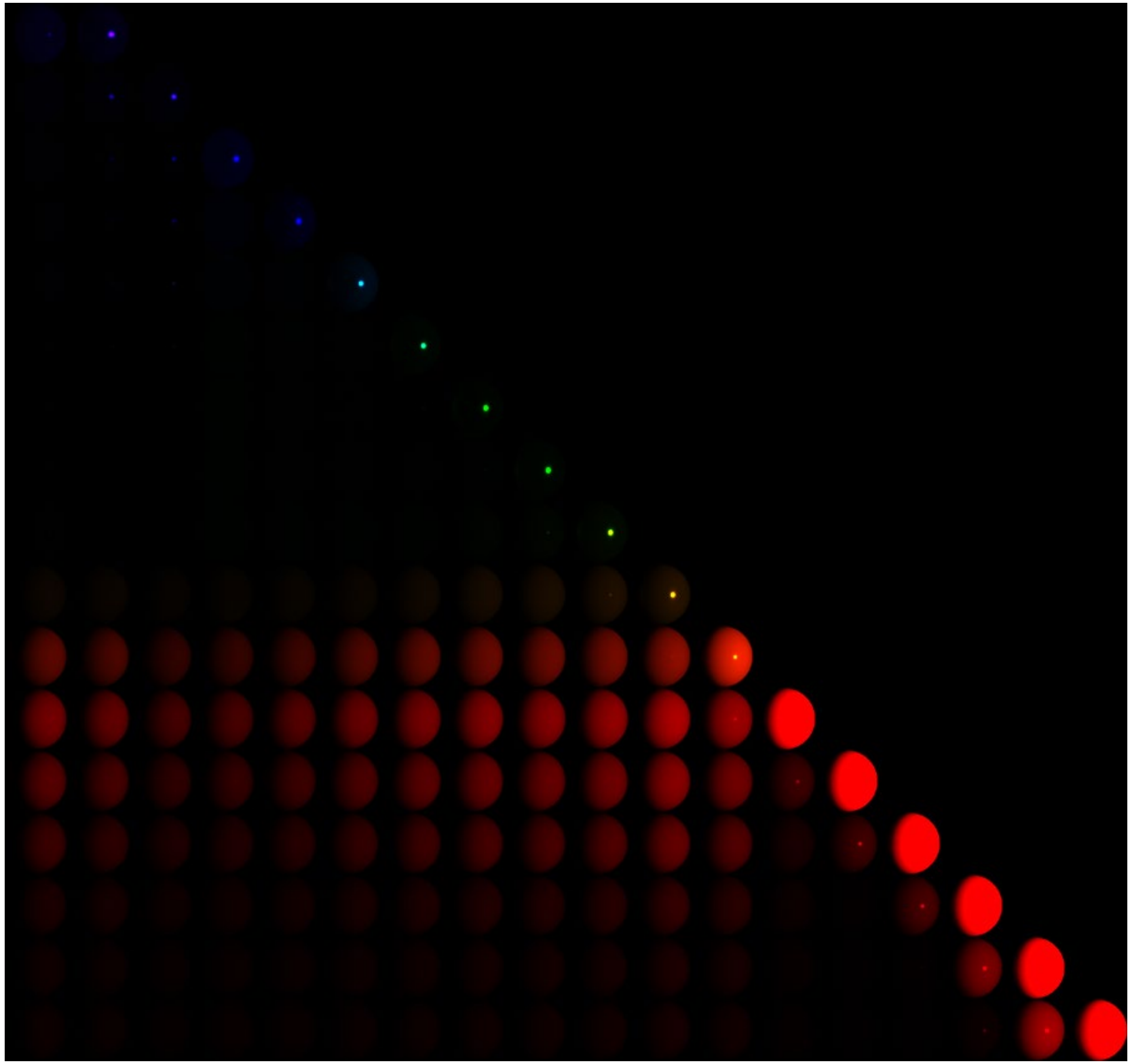


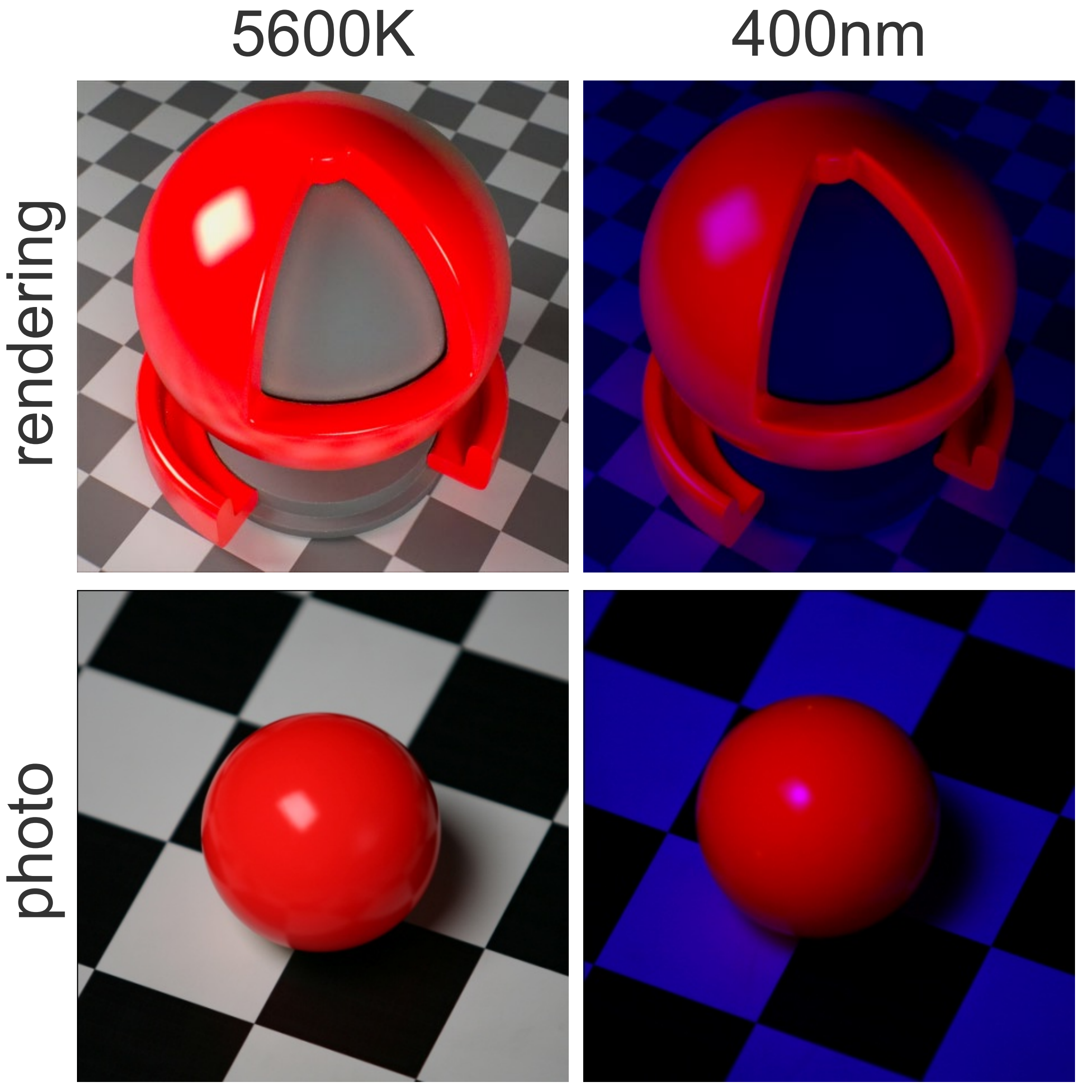
Bispectral BRRDF



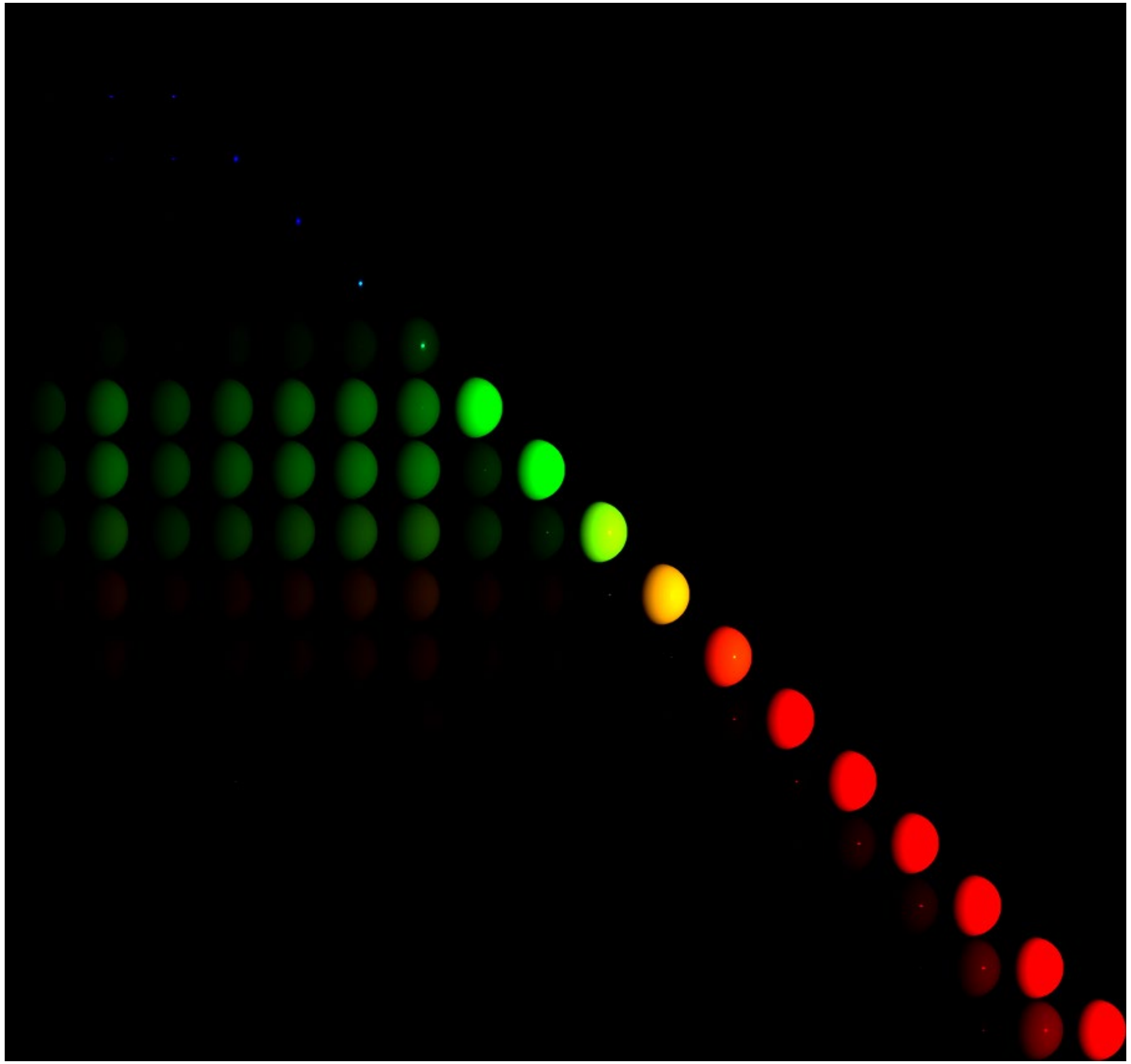
- Complete BRDF for each pair of wavelengths

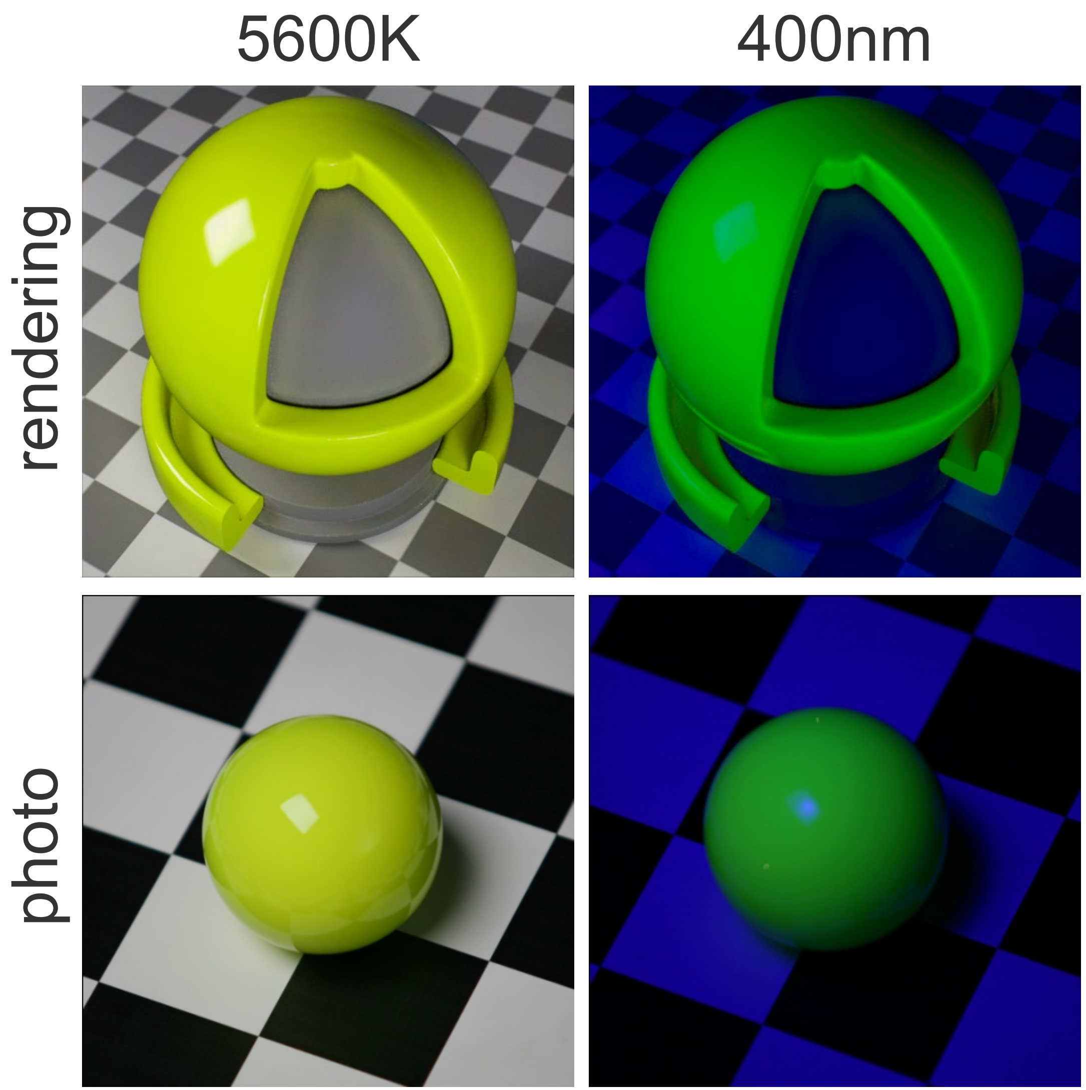
Result – Red no varnish



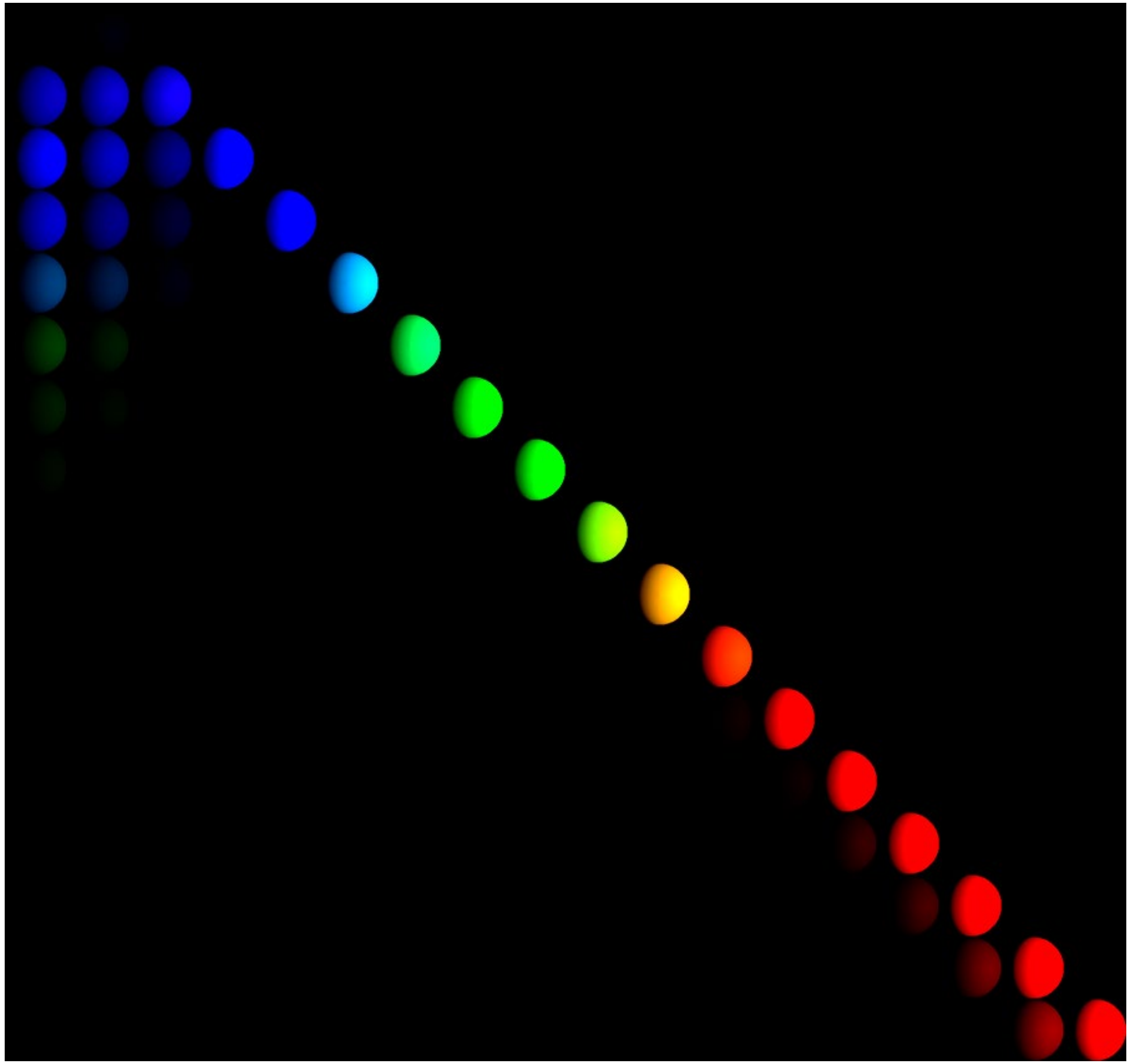


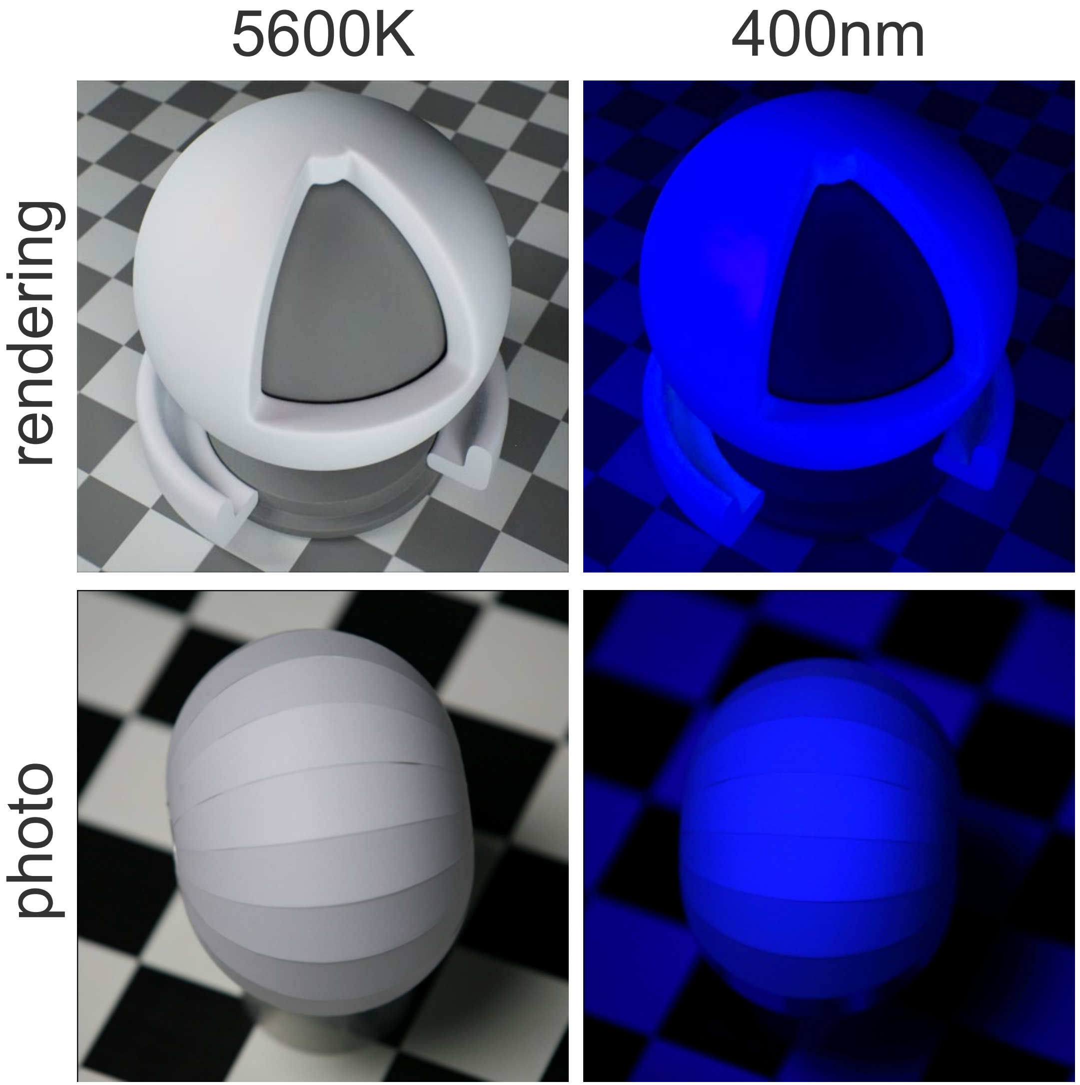
Result – Yellow



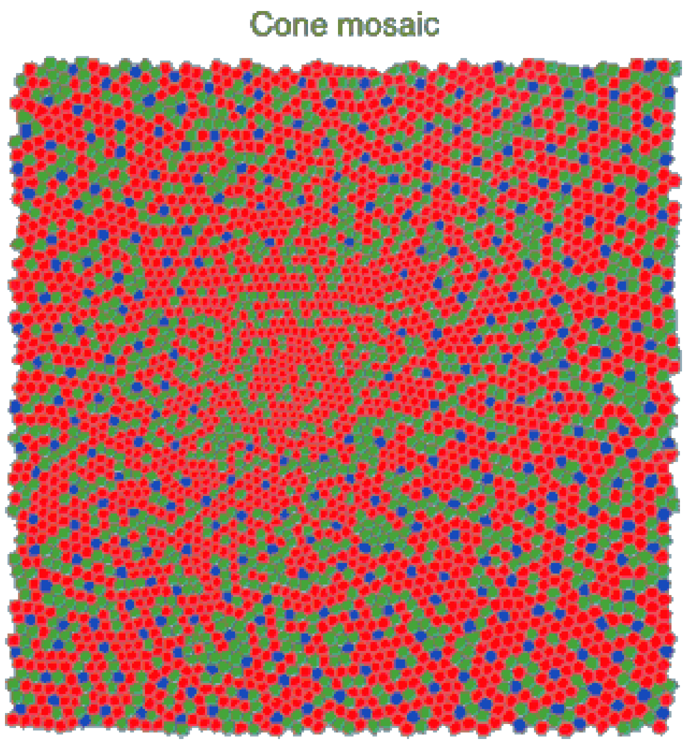


Result – Printing Paper

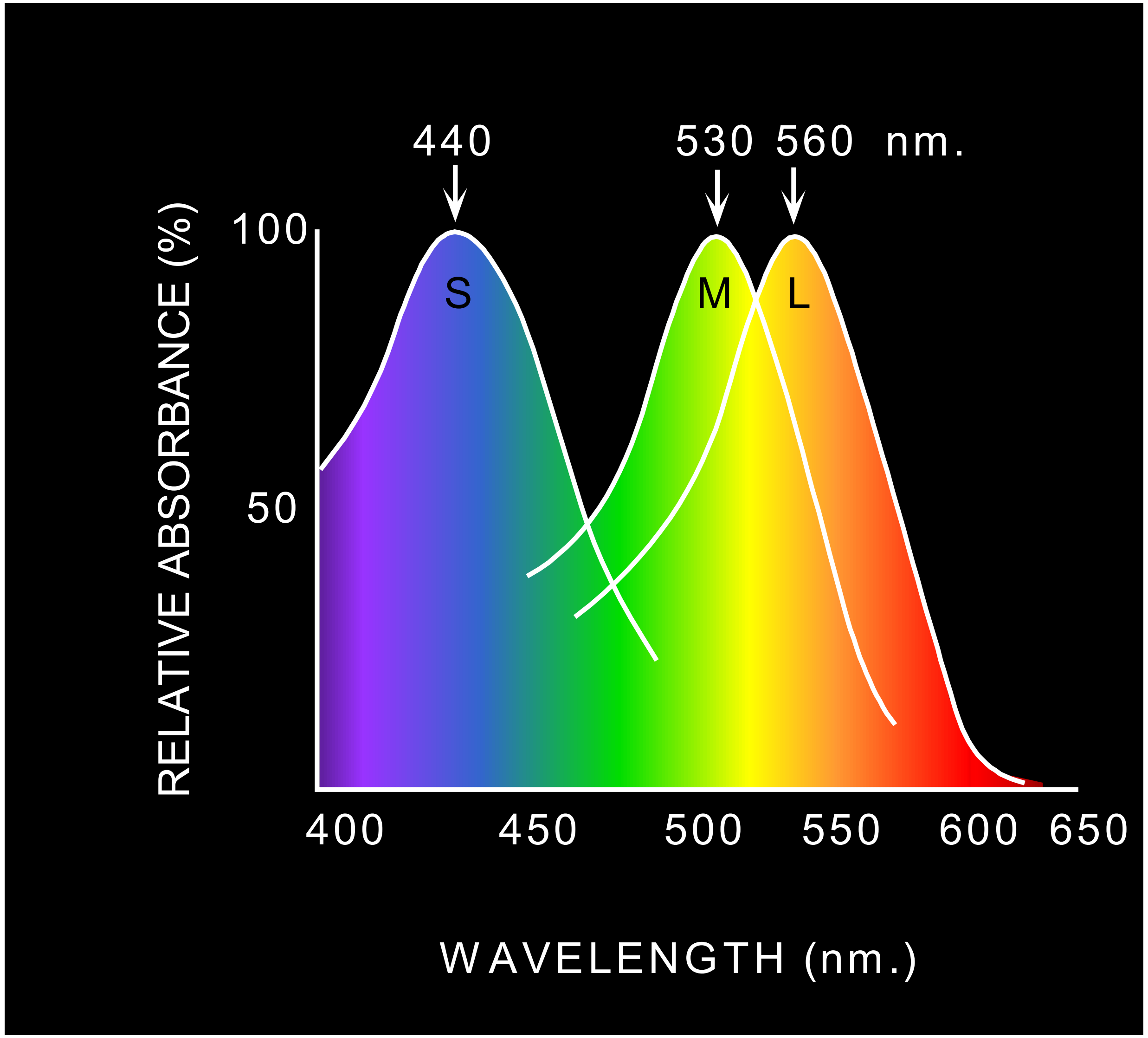




Physiology of Color Vision

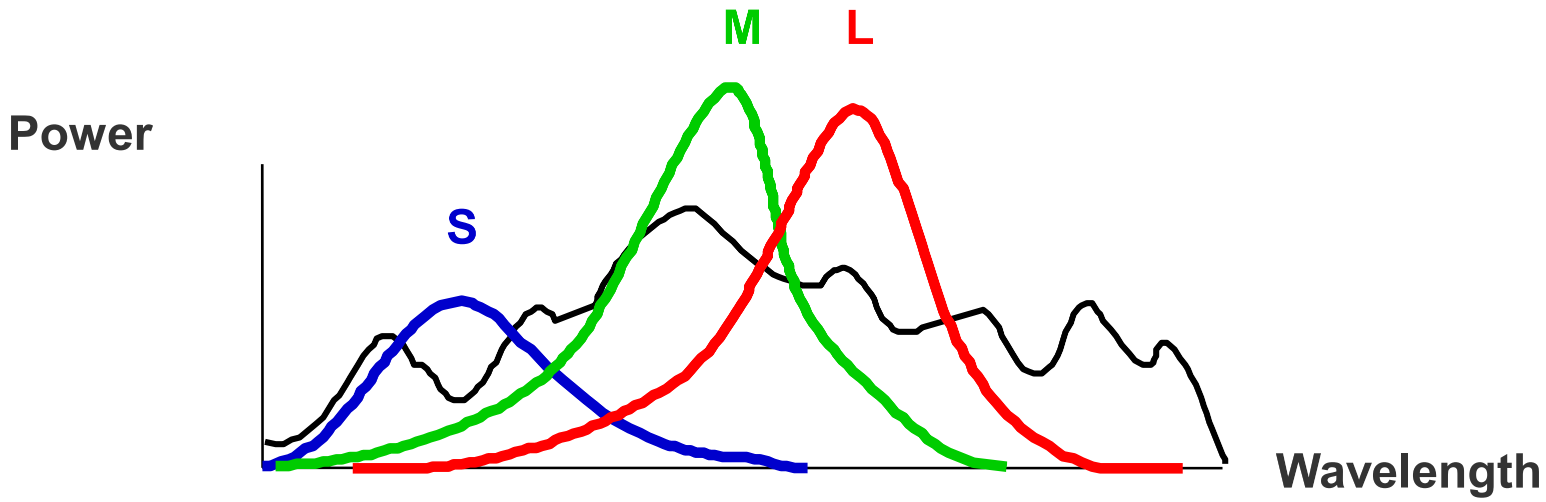


- Three kinds of cones:
- Ratio of L to M to S cones: ~ 10:5:1
- Almost no S cones in the center of the fovea



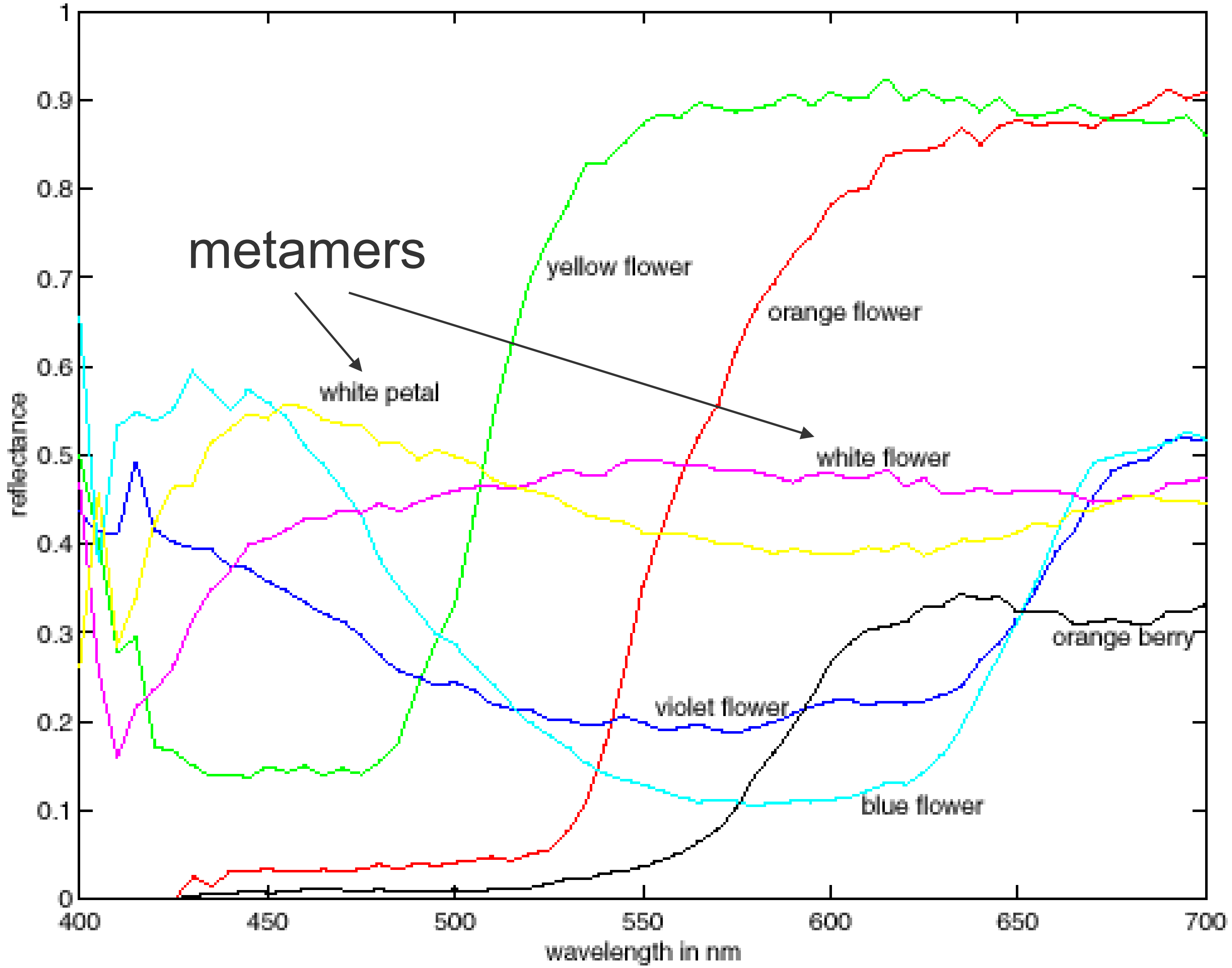
Color perception

- Rods and cones act as filters on the spectrum
  - To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
    - Each cone yields one number



- Q: How can we represent an entire spectrum with 3 numbers?
- A: We can't! Most of the information is lost.
  – As a result, two different spectra may appear indistinguishable
    » such spectra are known as **metamers**

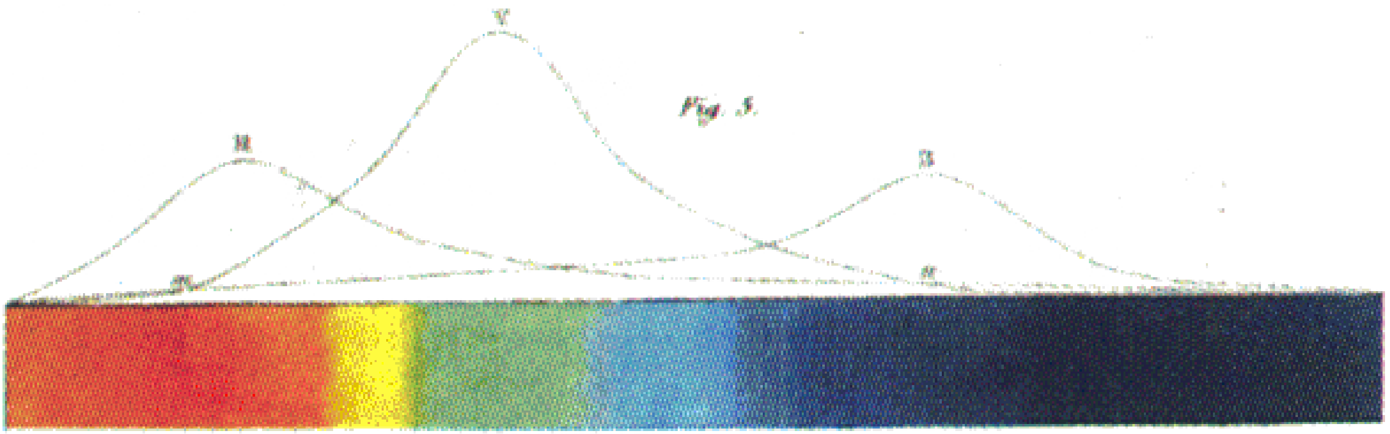
Spectra of some real-world surfaces



Tristimulus Color Representation

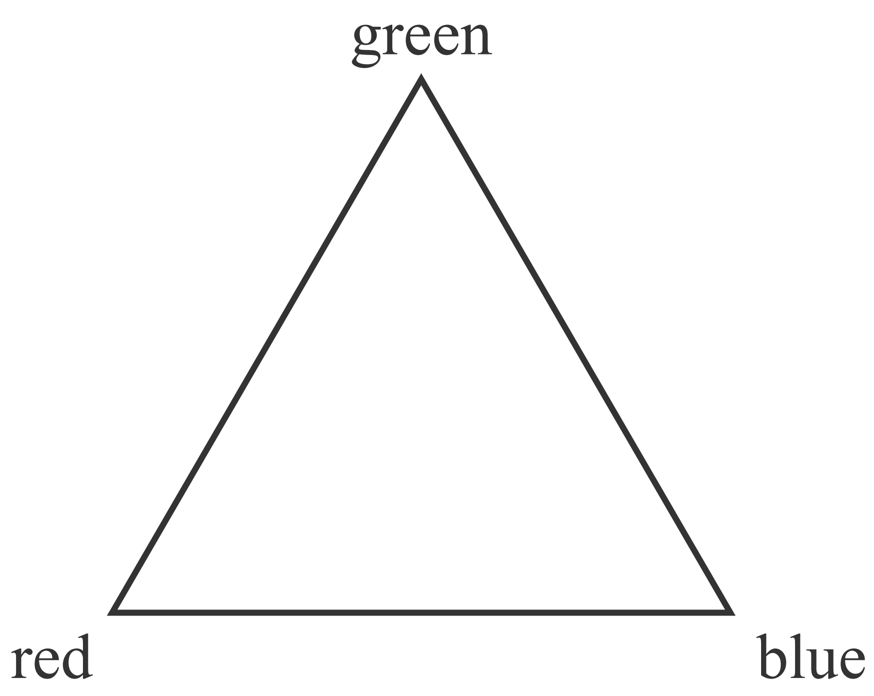
Brewster's Observation

- In the 19th century
- One can compose any color experience by mixing three colored light sources.



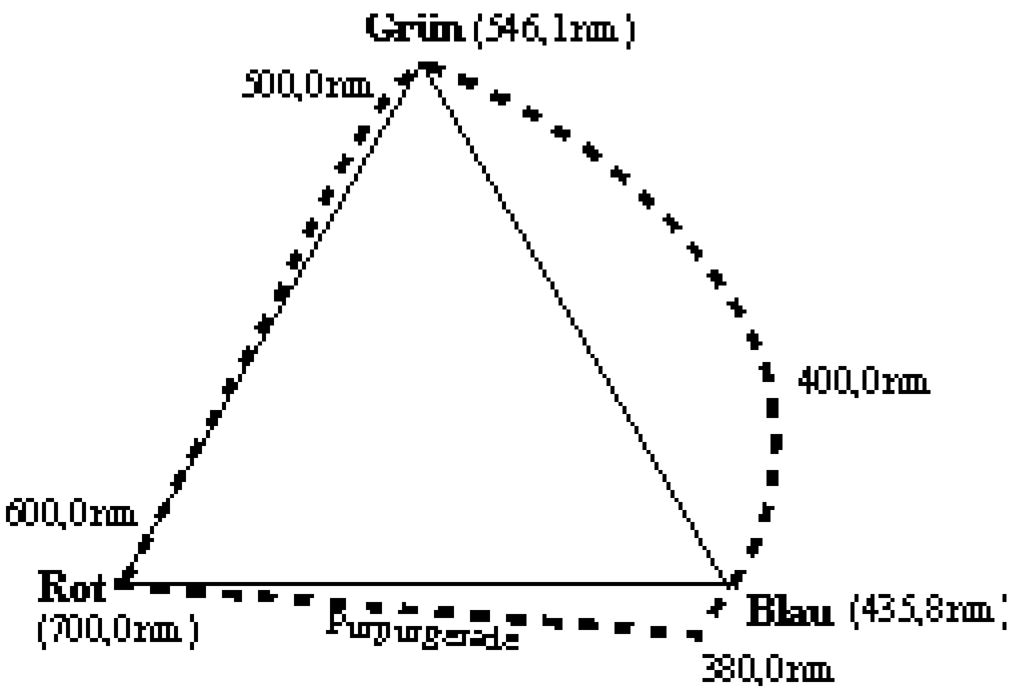
Brewster (1831)

Tristimulus Color Representation



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

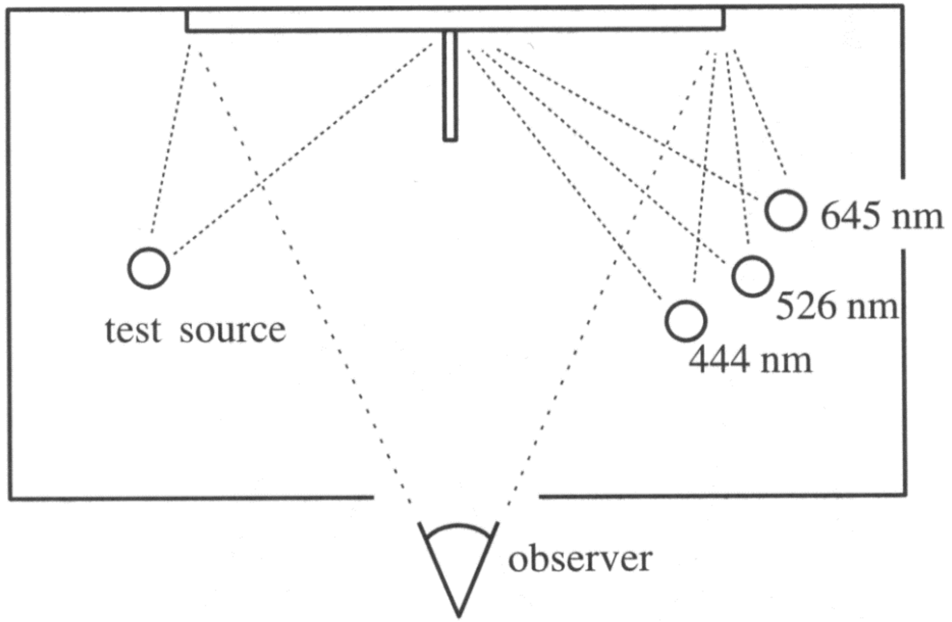
Tristimulus Color Representation

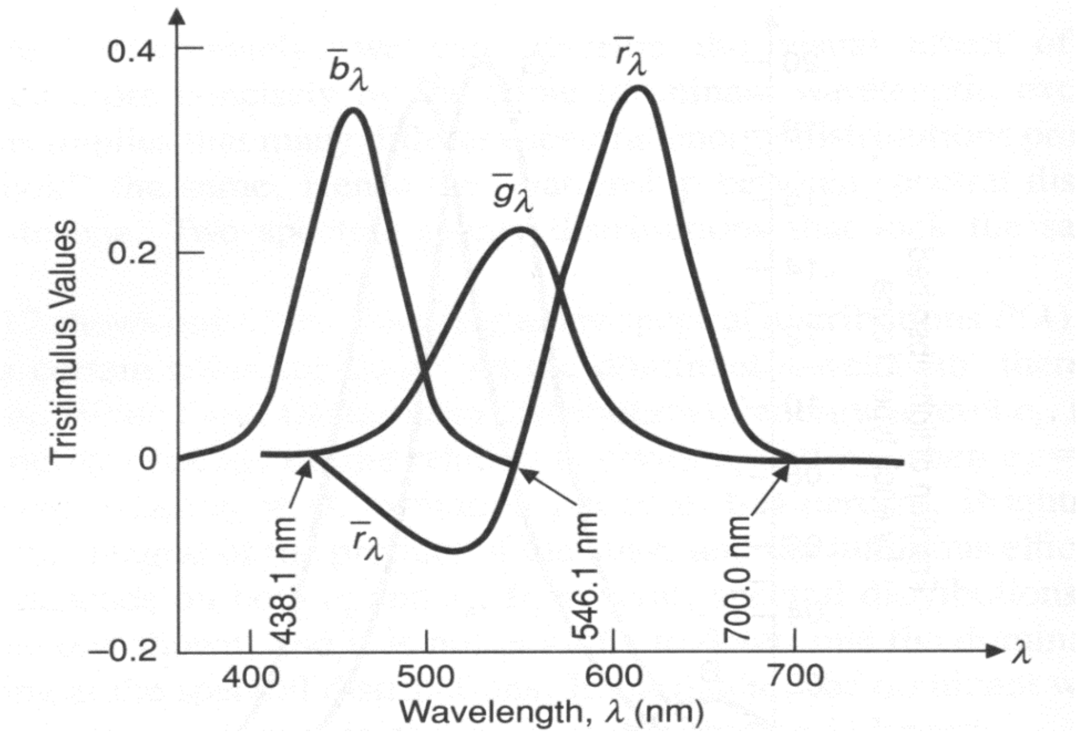


- colors outside the range of primaries
- would require negative weights
- idea CIE-XYZ: define virtual colors

Tristimulus Color Representation

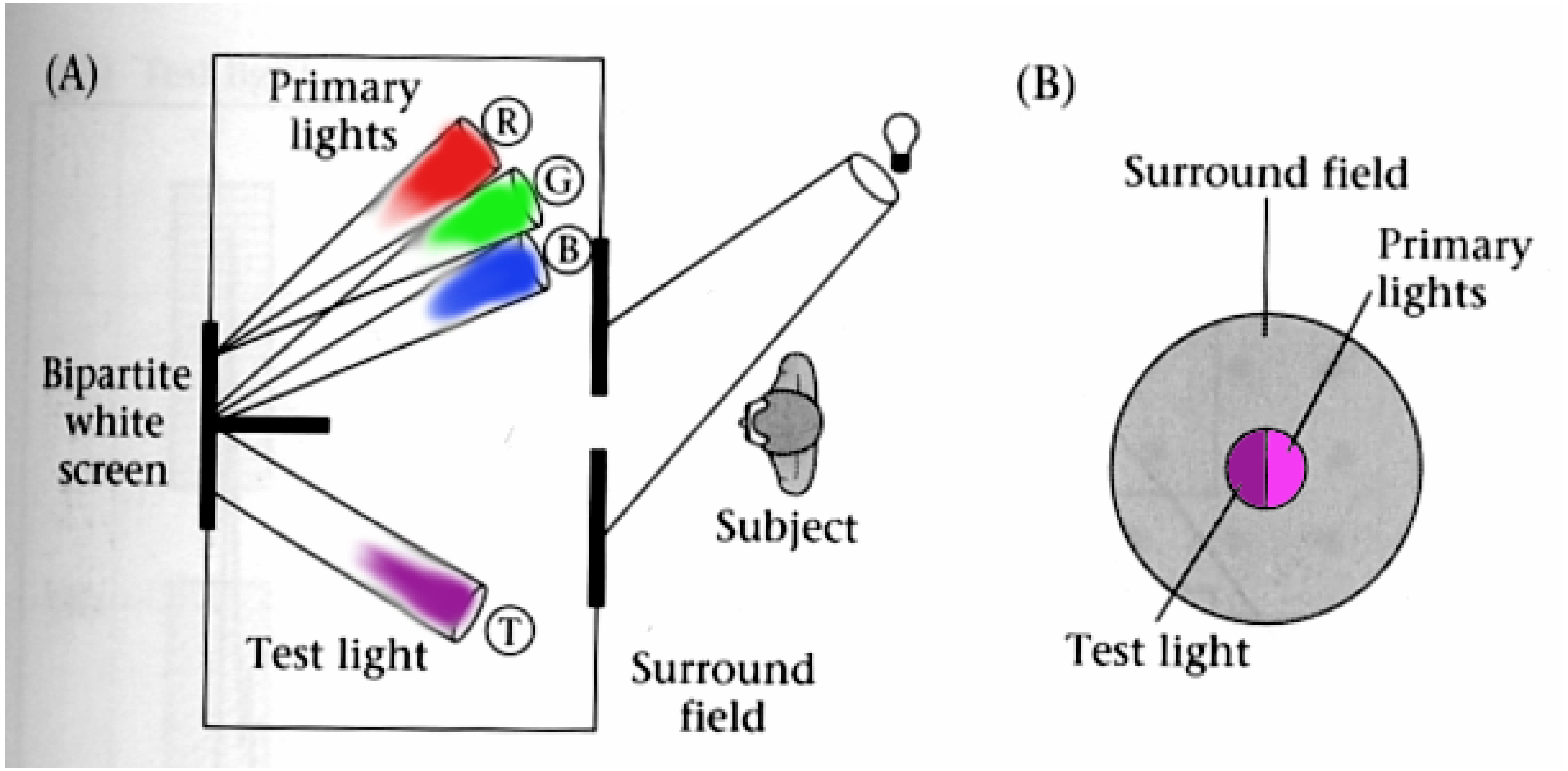
- Observation
  - Any color can be matched using three linear independent reference colors
  - May require “negative” contribution to test color
  - Curves describe the value for matching mono-chromatic spectral colors of equal intensity
    - With respect to a certain set of primary colors





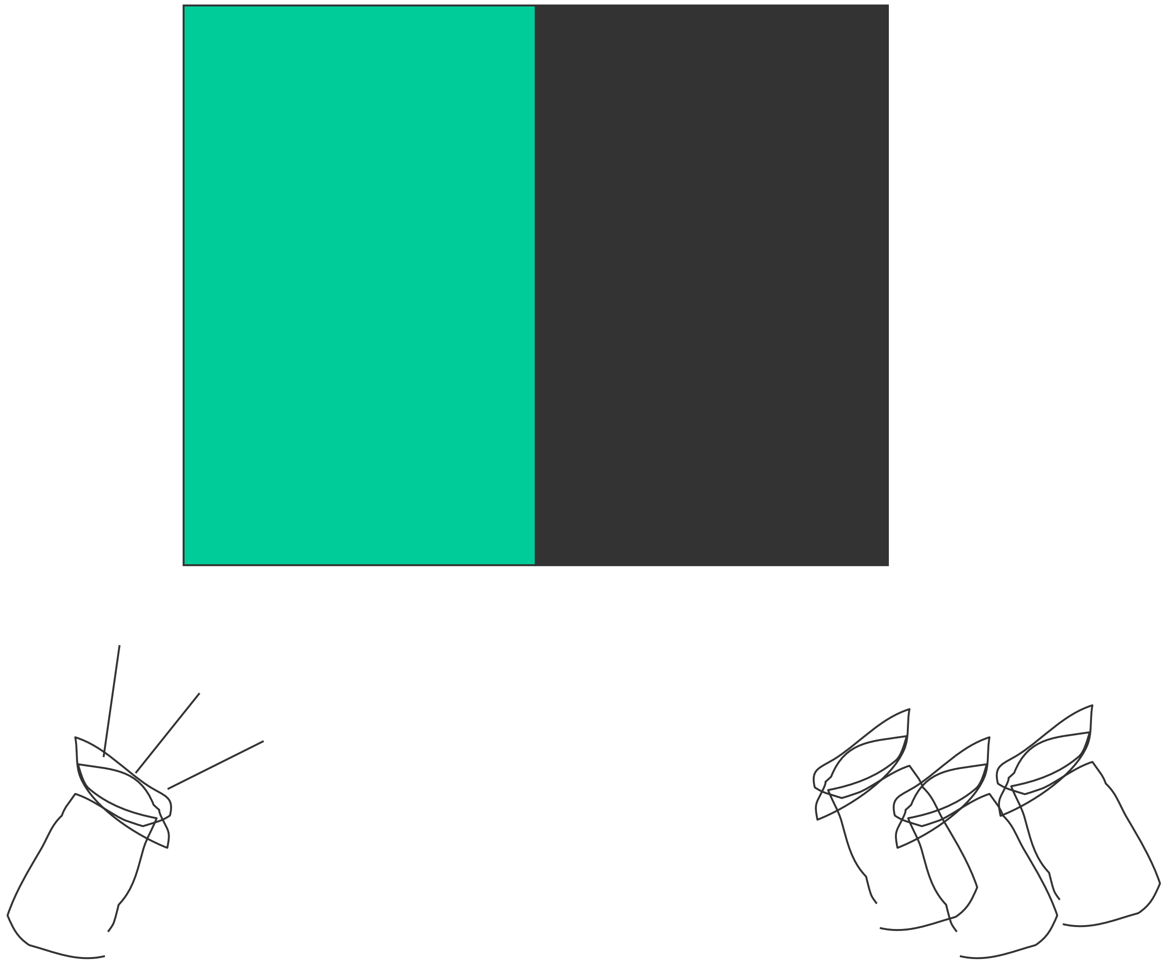
Standardizing color experience

- We would like to understand which spectra produce the same color sensation from people under similar viewing conditions
- Color matching experiments



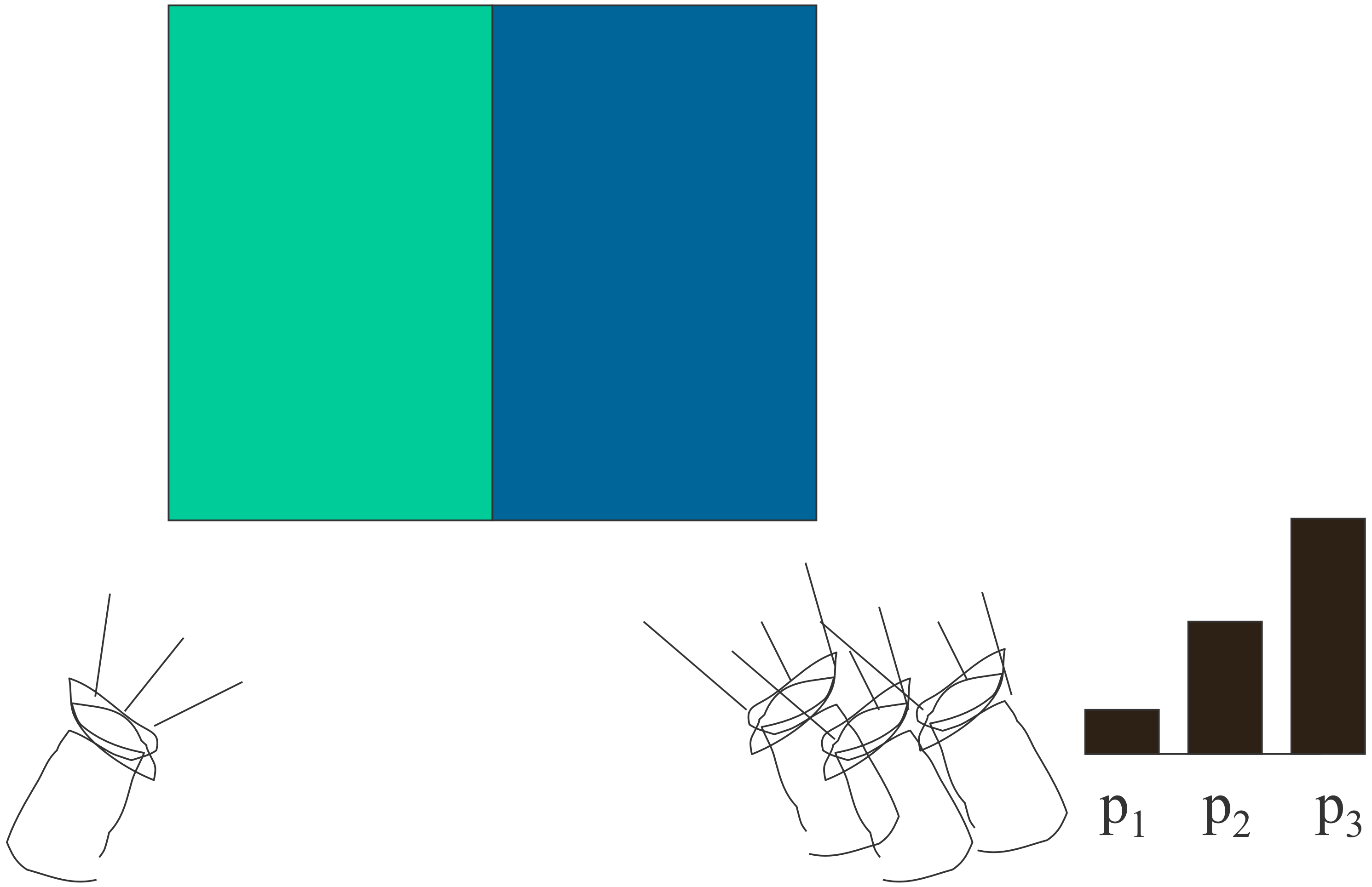
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Color matching experiment 1



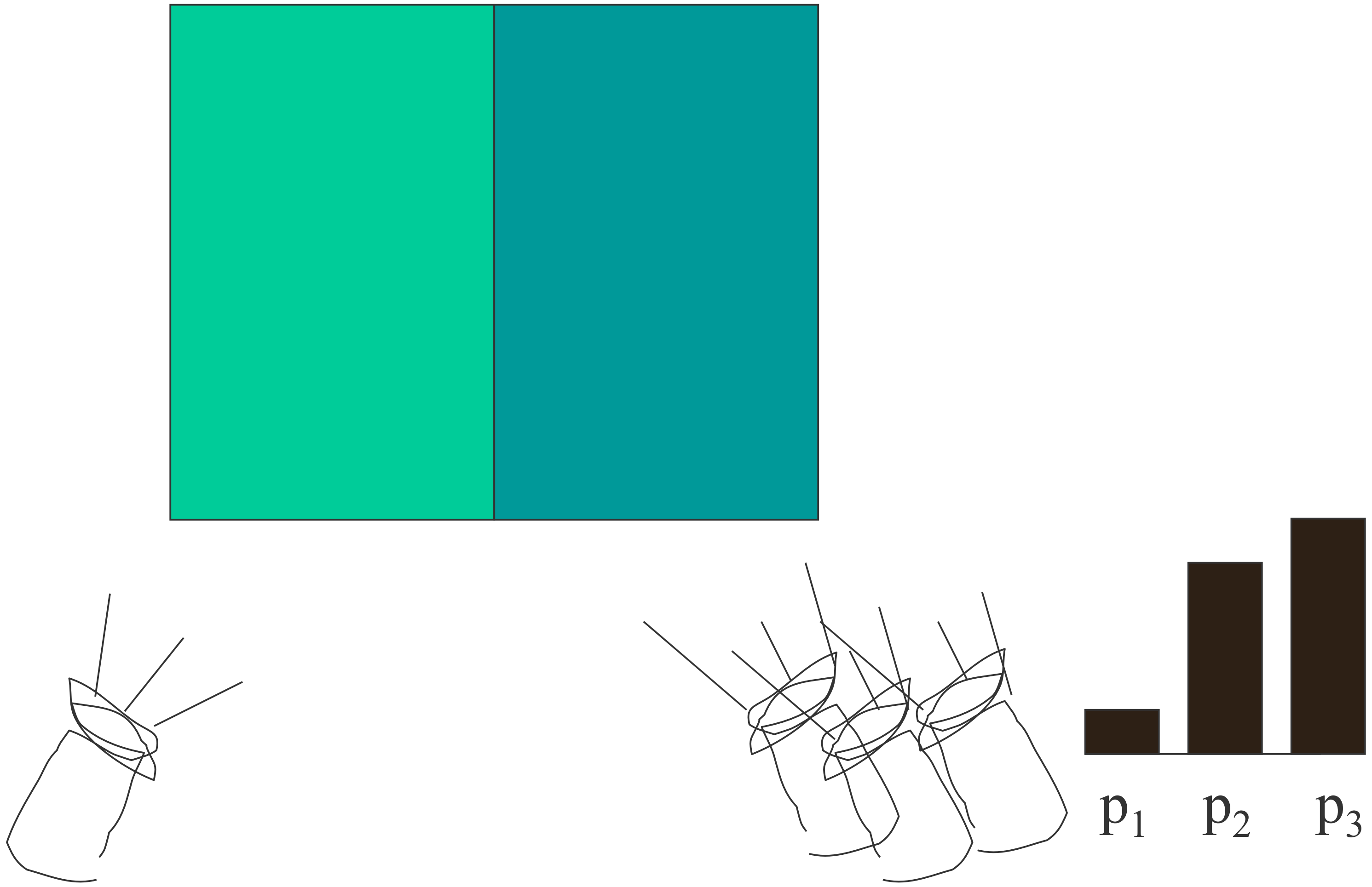
Source: W. Freeman

Color matching experiment 1



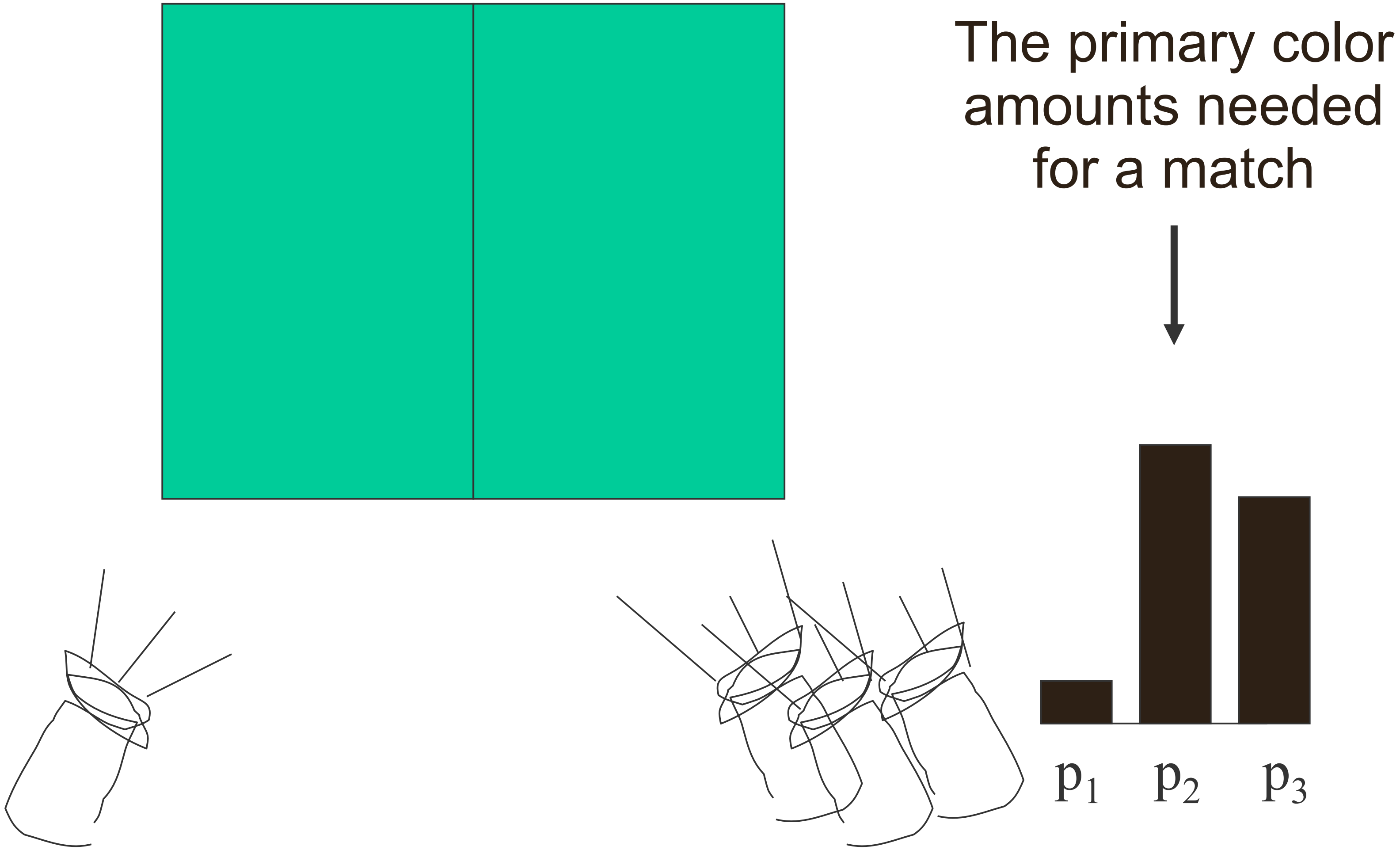
Source: W. Freeman

Color matching experiment 1



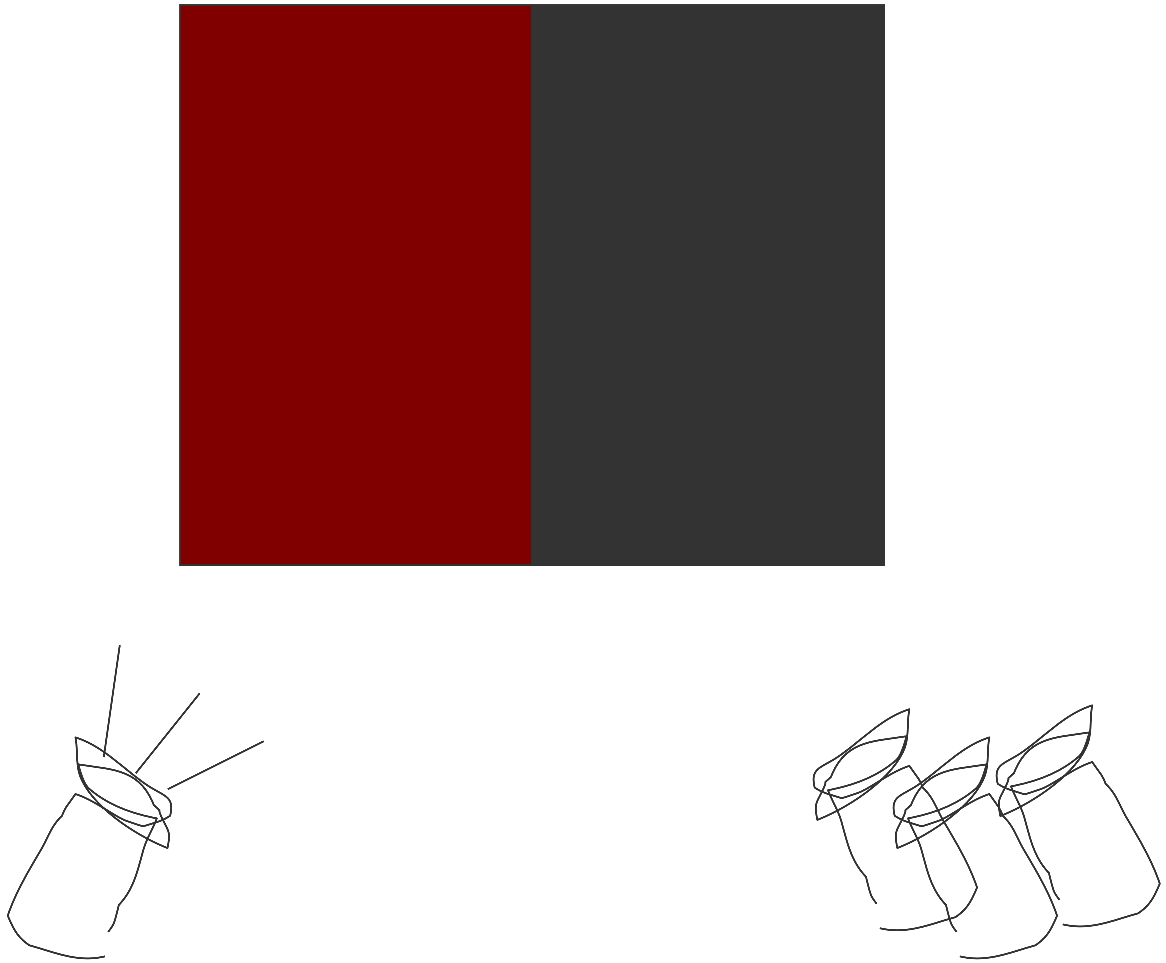
Source: W. Freeman

Color matching experiment 1



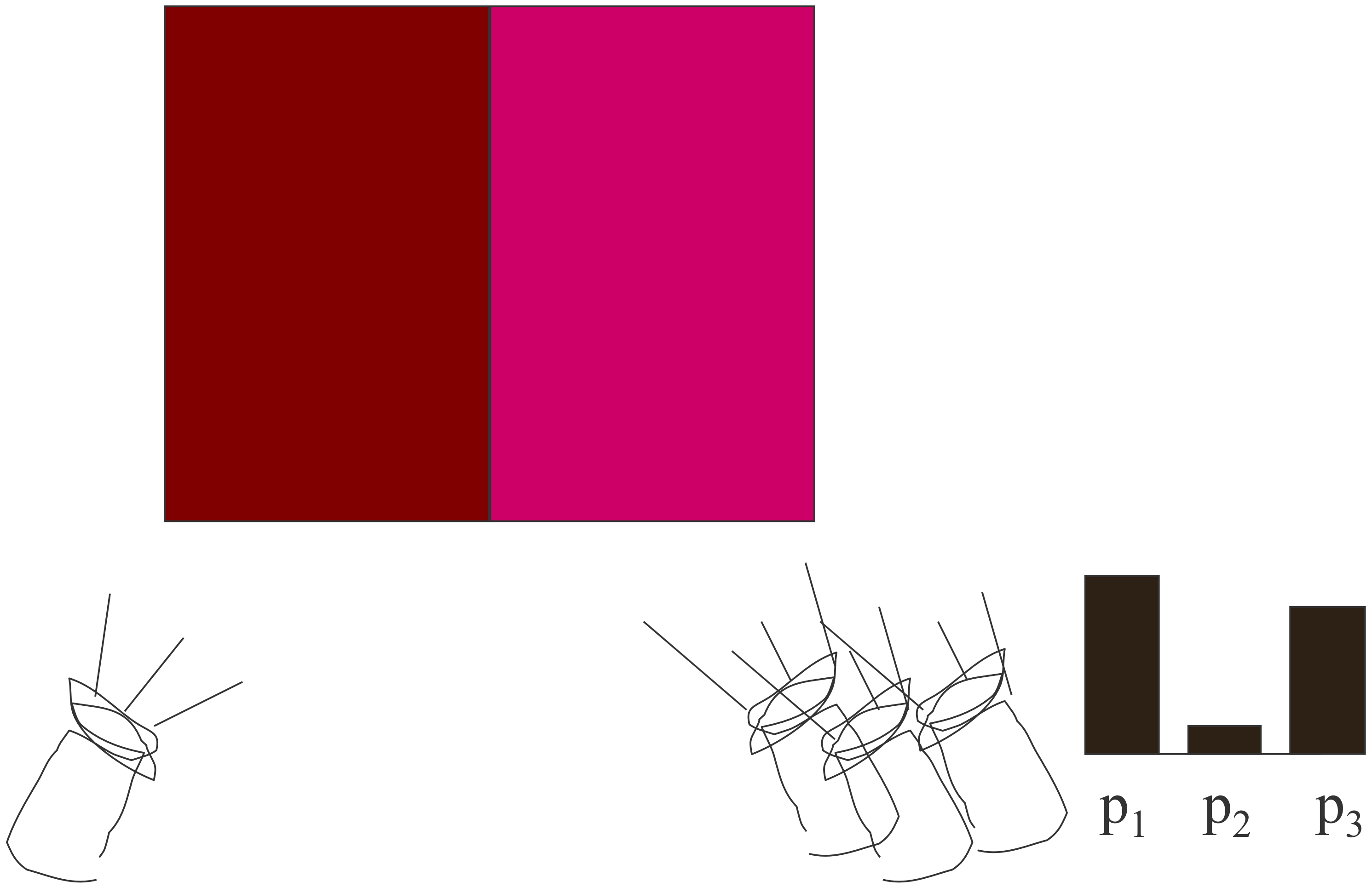
Source: W. Freeman

Color matching experiment 2



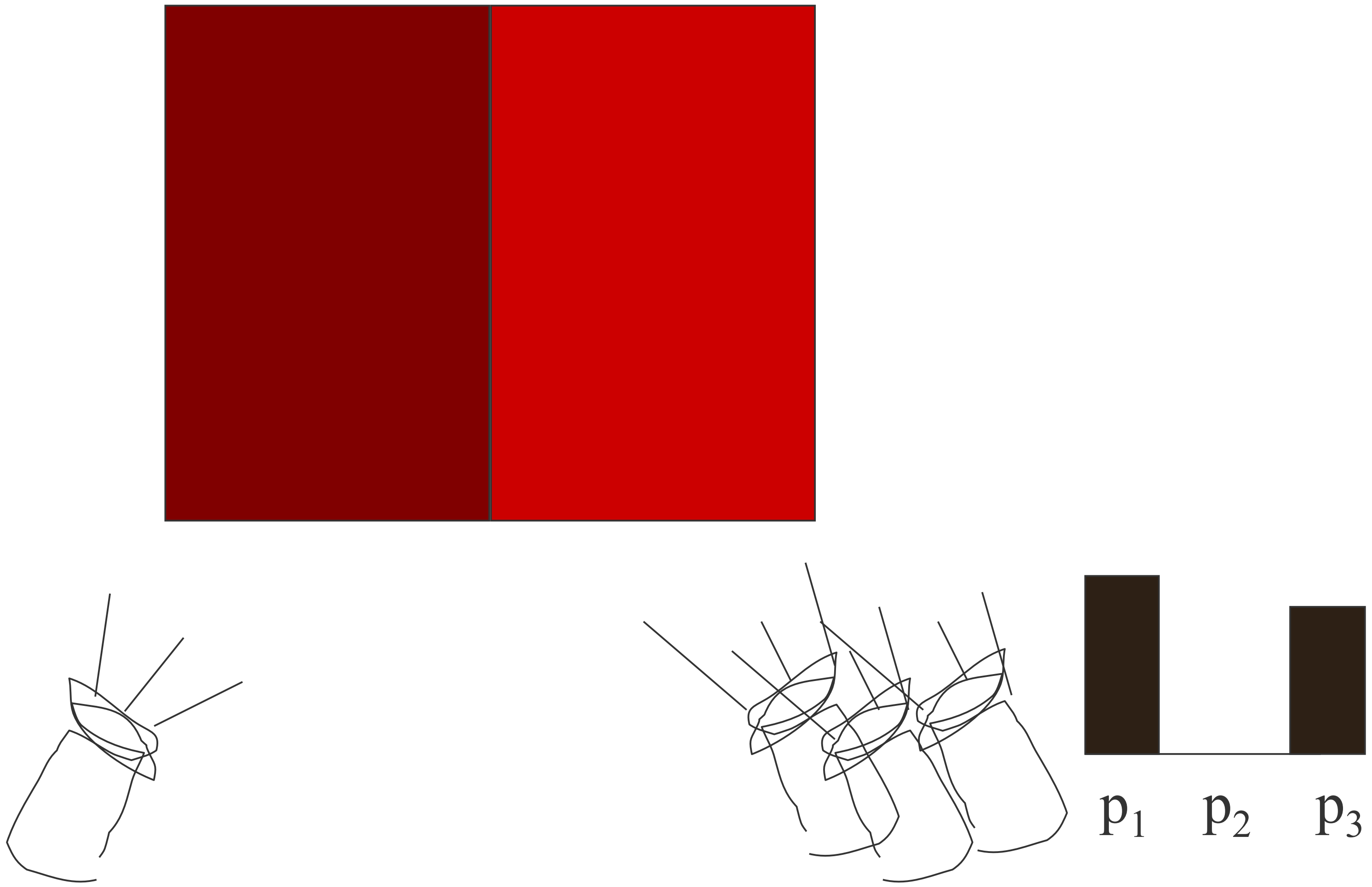
Source: W. Freeman

Color matching experiment 2



Source: W. Freeman

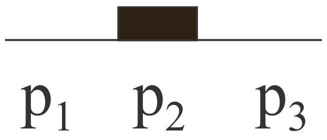
Color matching experiment 2

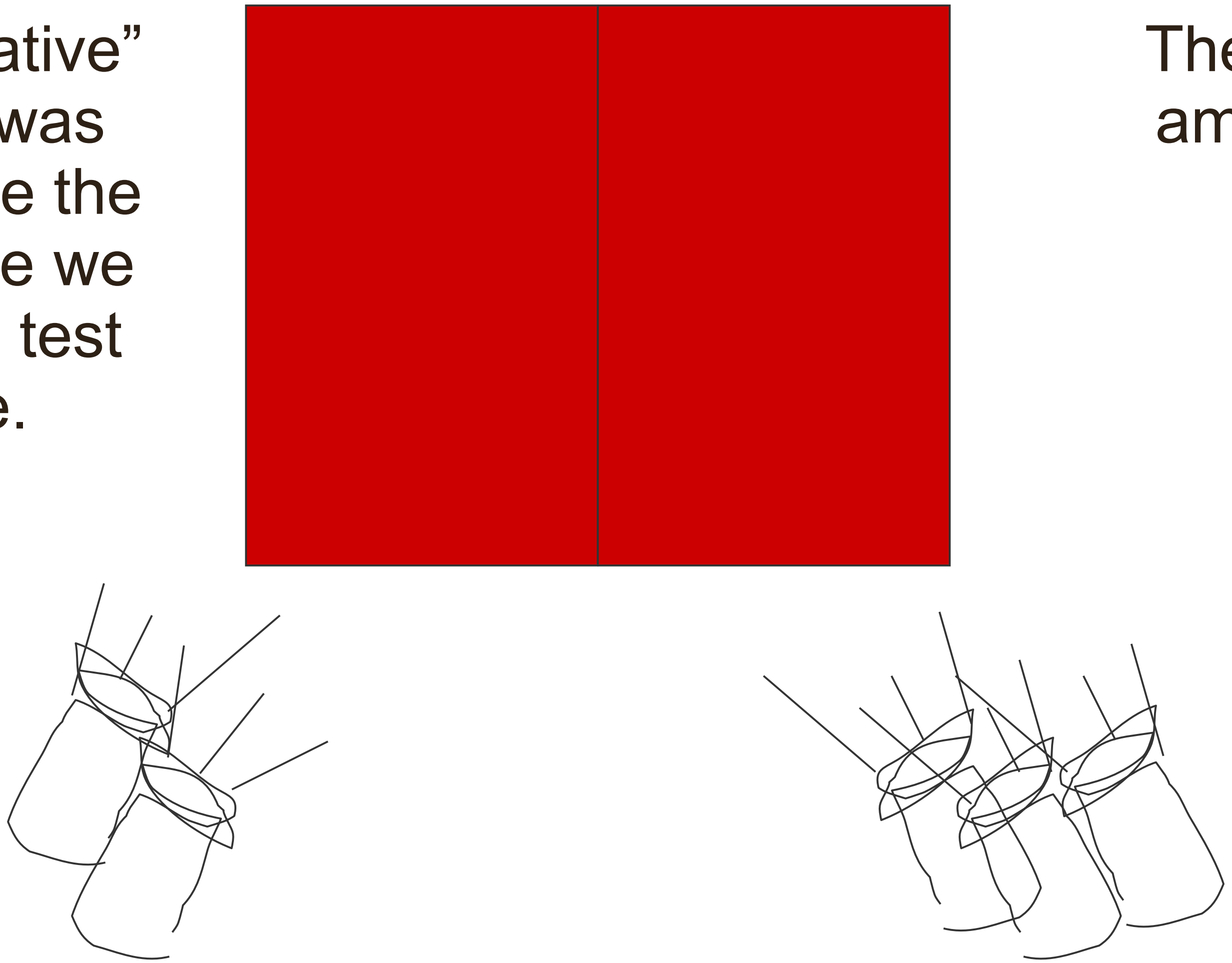


Source: W. Freeman

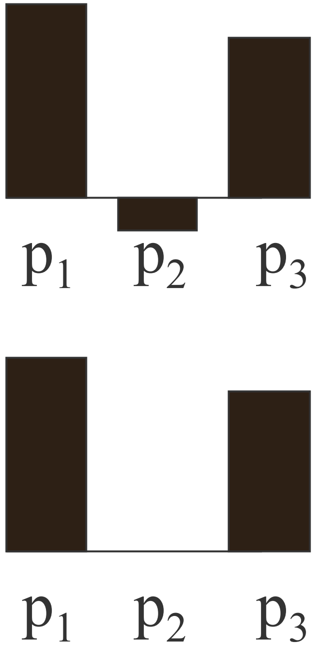
Color matching experiment 2

We say a “negative” amount of p_2 was needed to make the match, because we added it to the test color’s side.





The primary color amounts needed for a match



Grassman's Laws

- Color matching appears to be *linear*

- If two test lights can be matched with the same weights, then they match each other:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = u_1 P_1 + u_2 P_2 + u_3 P_3$
  - Then $A = B$

- If we mix two test lights, then mixing the matches will match the result:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = v_1 P_1 + v_2 P_2 + v_3 P_3$
  - Then $A + B = (u_1 + v_1) P_1 + (u_2 + v_2) P_2 + (u_3 + v_3) P_3$

- If we scale the test light, then the matches get scaled by the same amount:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$
  - Then $\mathrm{k}A = (k u_1) P_1 + (k u_2) P_2 + (k u_3) P_3$

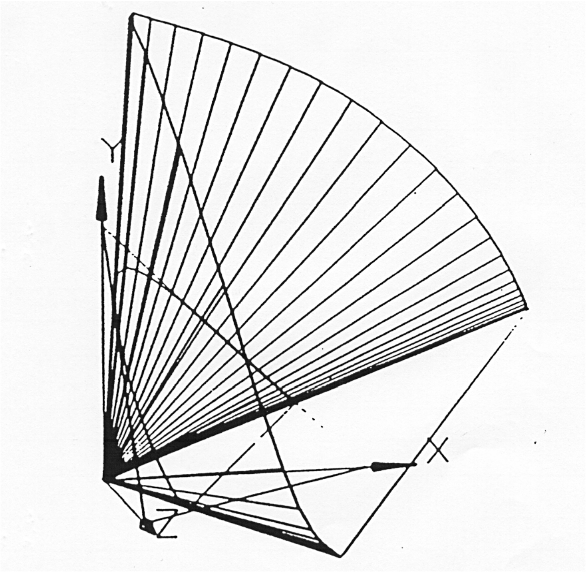
Standard Color Space CIE-XYZ

- CIE Experiments [Guild and Wright, 1931]
  - Color matching experiments
  - Group ~12 people with „normal“ color vision (from London area)
  - 2 degree visual field (fovea only)
  - Other Experiment in 1964
    - 10 degree visual field, ~50 people (with foreigners)
    - More appropriate for larger field of view but rarely used

- CIE-XYZ Color Space
  - Transformation to a set of virtual primaries
    - Simple basis transform in 3D color space
  - Goals
    - Abstract from concrete primaries used in experiment
    - All matching functions are positive
    - One primary is roughly proportionally to light intensity

Standard Color Space CIE-XYZ

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



virtual red

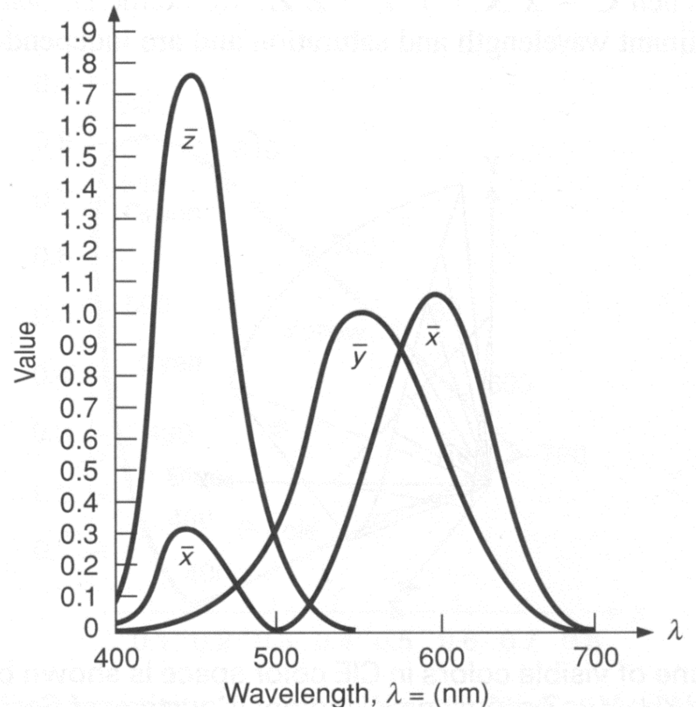
$$X = K_m \int L(\lambda)\, x(\lambda)\, d\lambda$$

virtual green

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

virtual blue

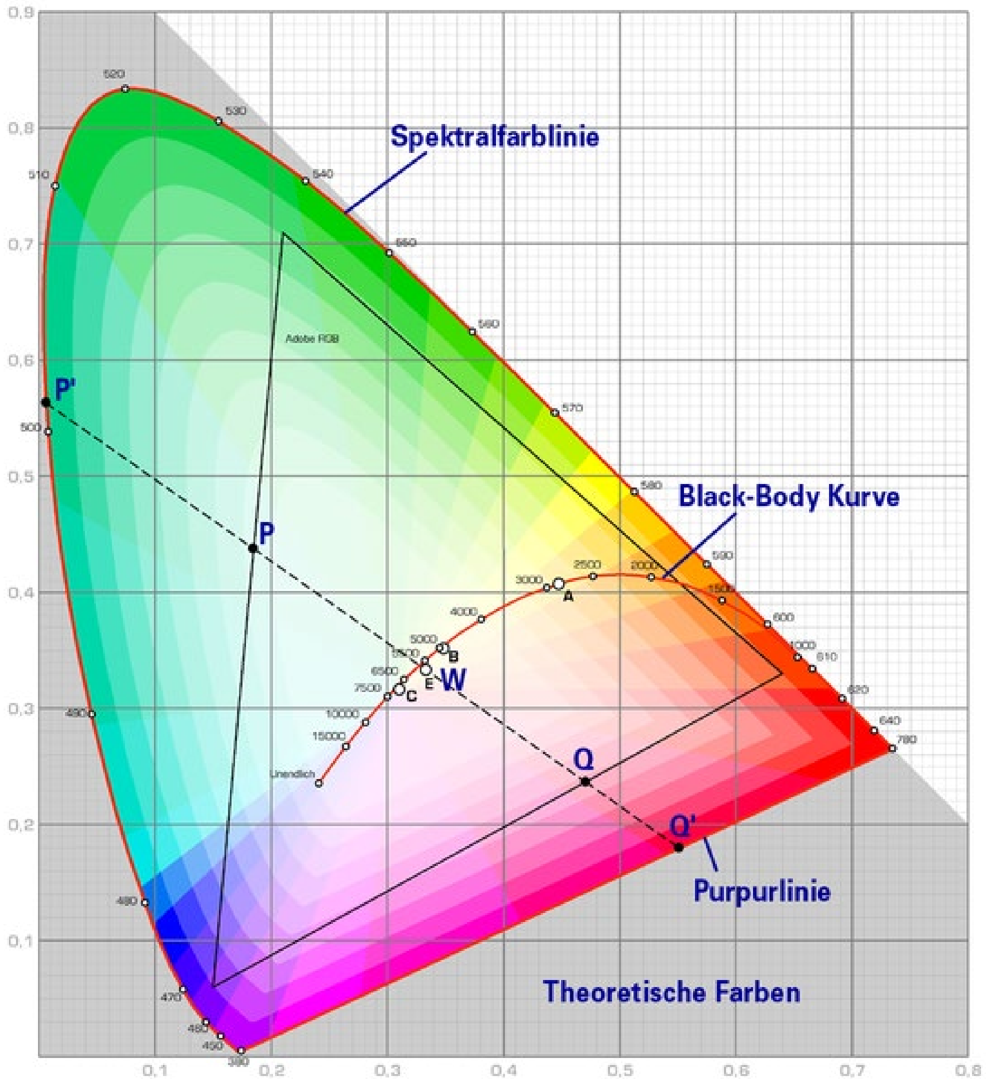
$$Z = K_m \int L(\lambda)\, z(\lambda)\, d\lambda$$



CIE Chromaticity Diagram

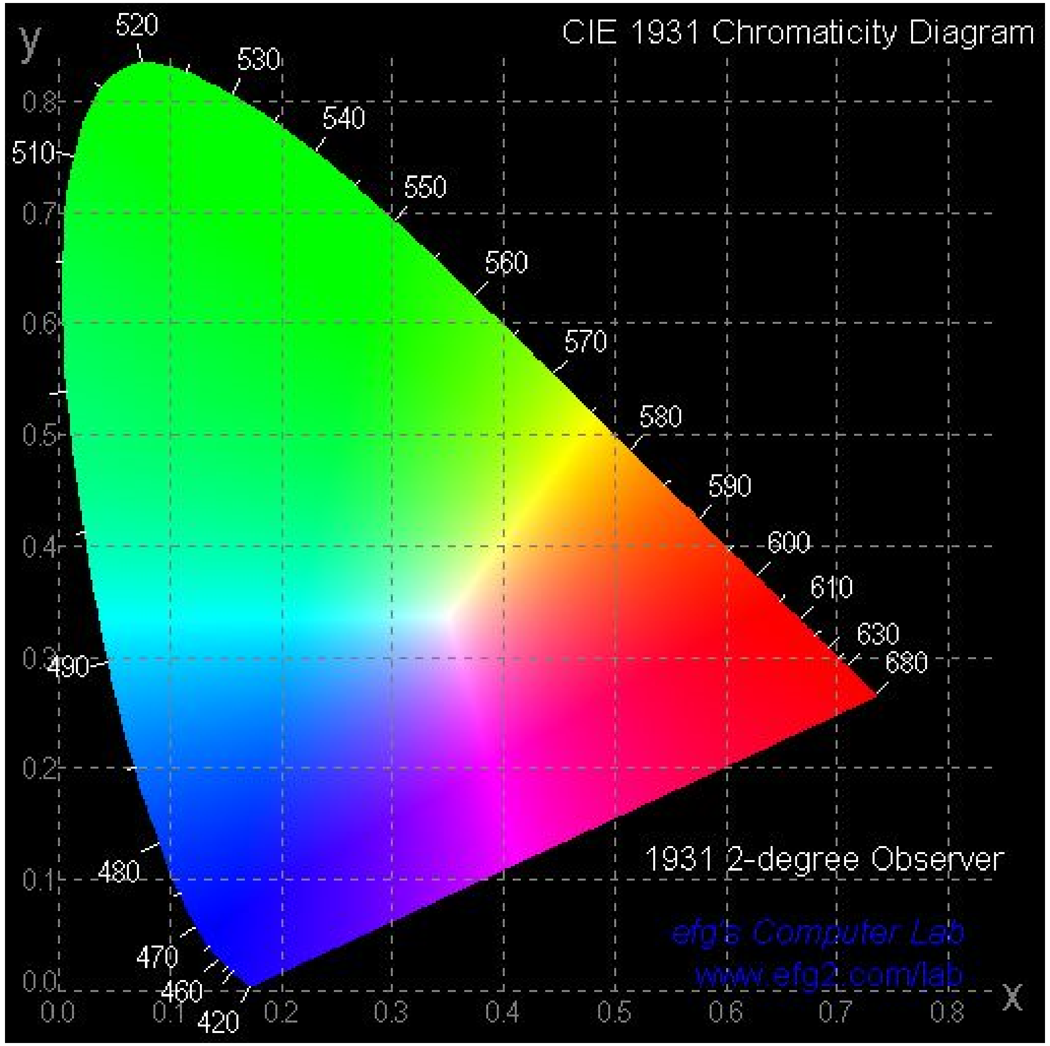
- Normalization:
  - Concentrate on color, not light intensity
  - Relative color coordinates
  - $x = \frac{X}{X+Y+Z}$ etc.

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

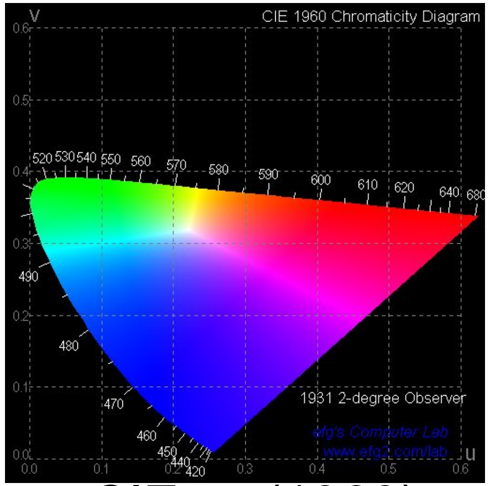


The CIE xy chromaticity diagram

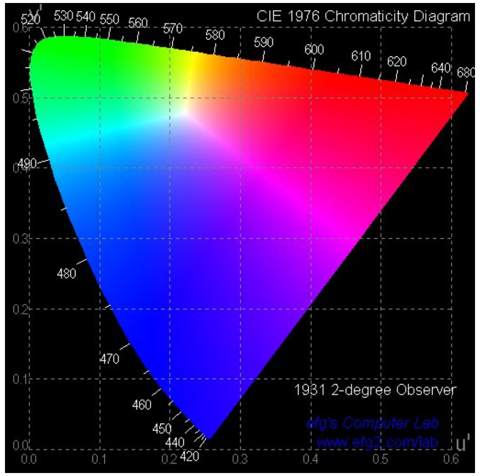
CIE Chromaticity Diagrams



1931 CIE-*xy*



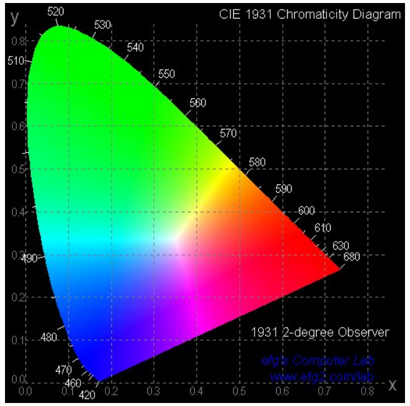
CIE-***uv*** (1960)

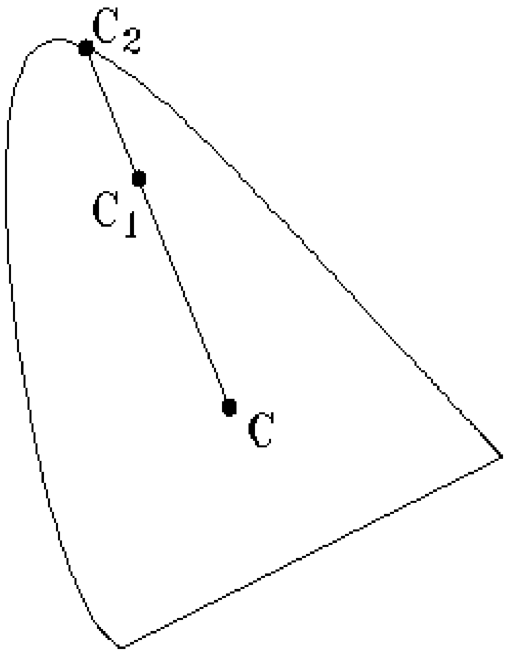


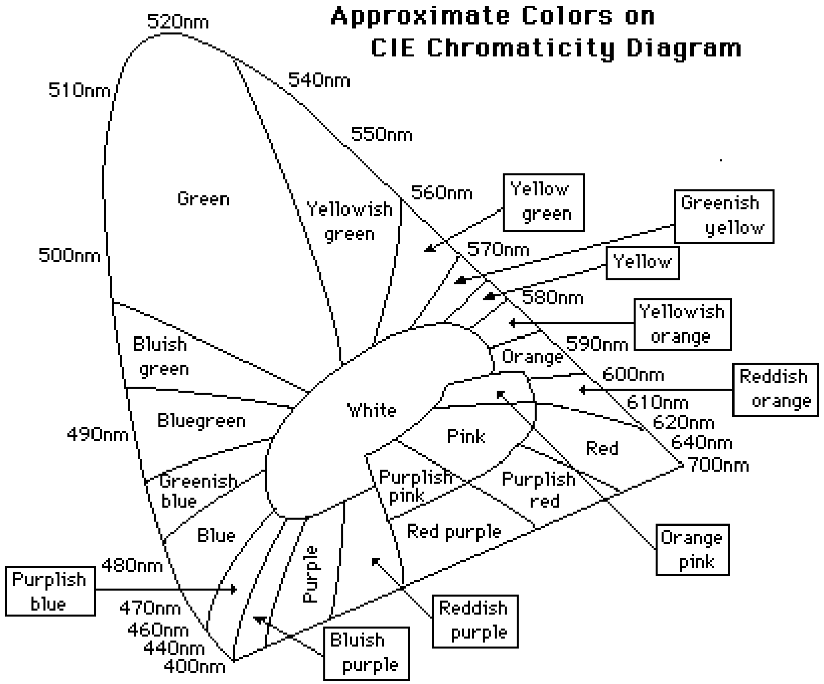
CIE-***u`v`*** (1976)

CIE Chromaticity Diagram

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

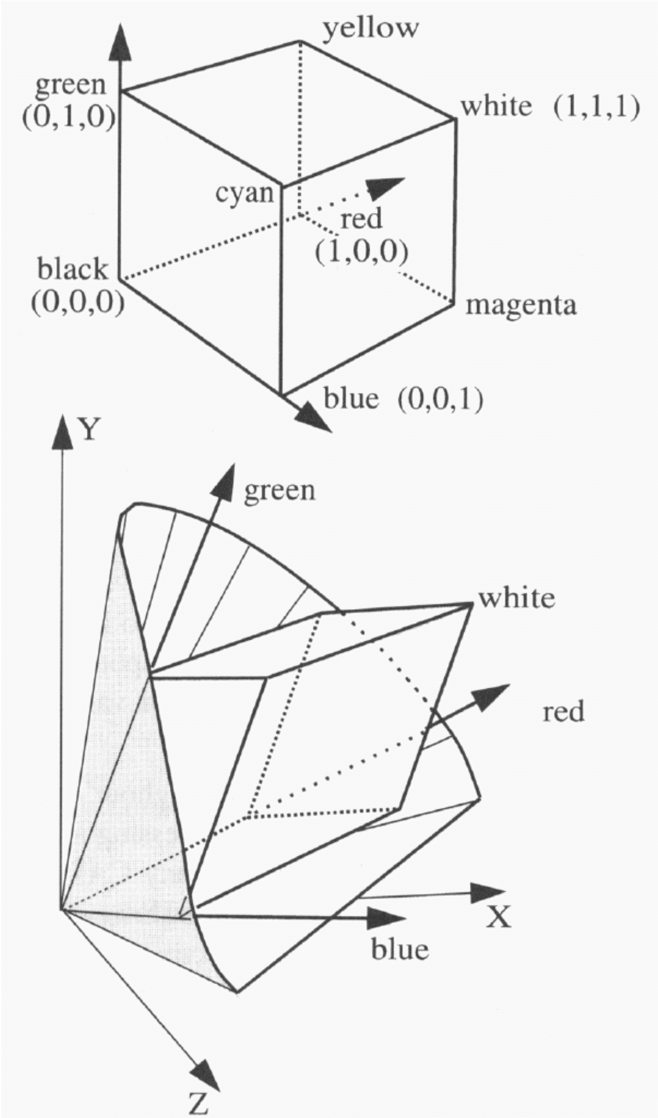




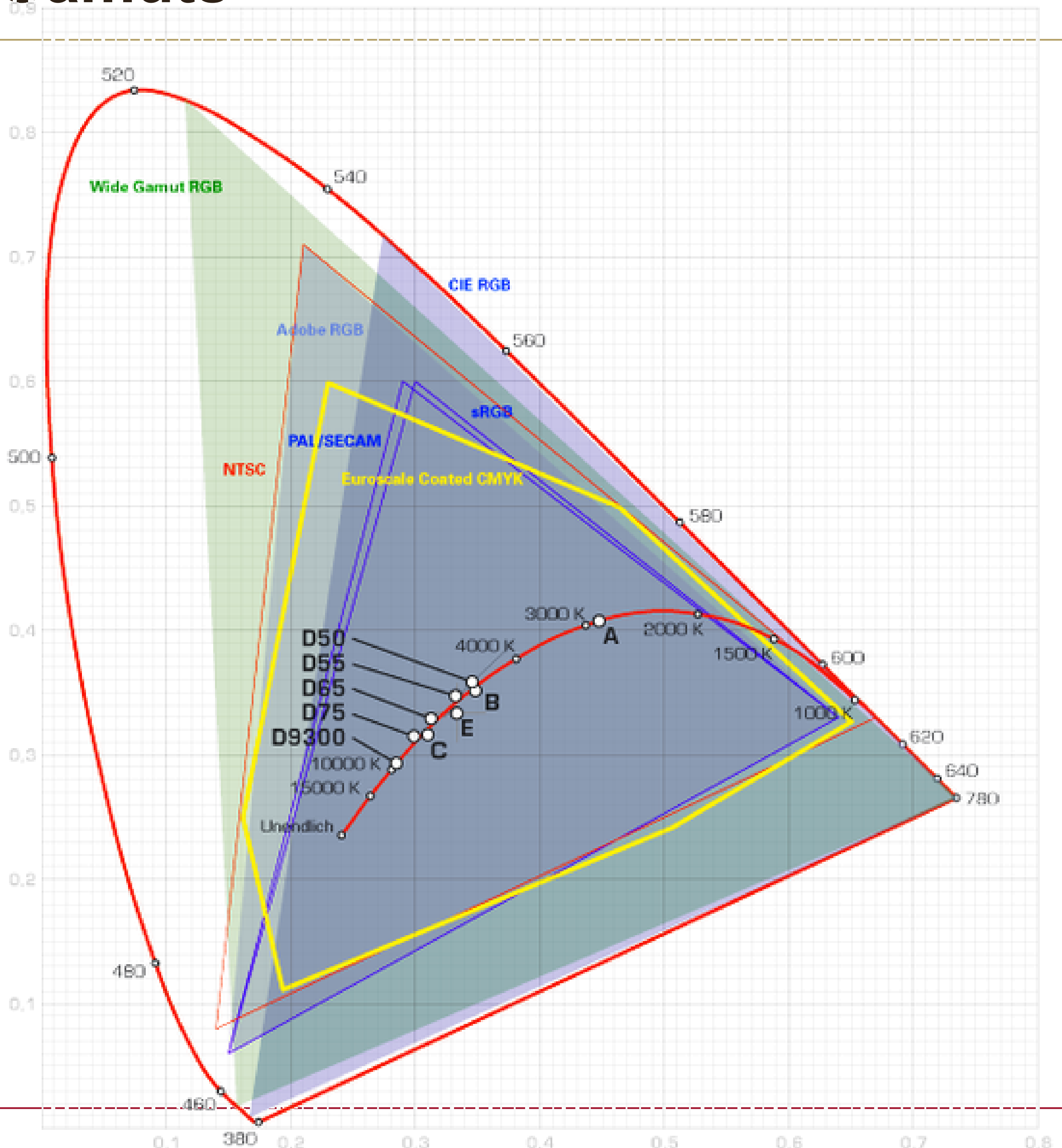


Monitor Color Gamut

- Gamut: subset of representable colors
- CIE XYZ gamut
  - Device-independent
- Device color gamut
  - Triangle inside color space with additive color blending



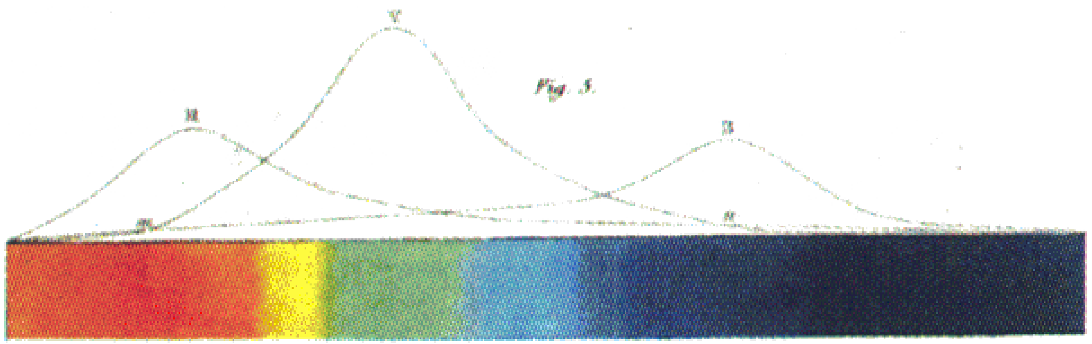
Different Color Gamuts

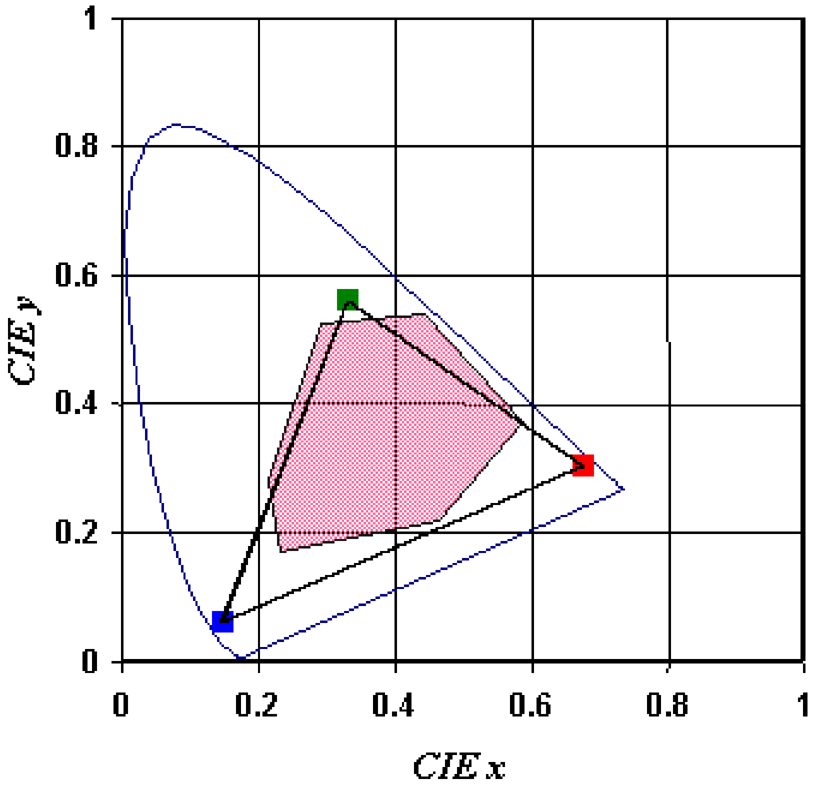


Printer Color Gamut

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

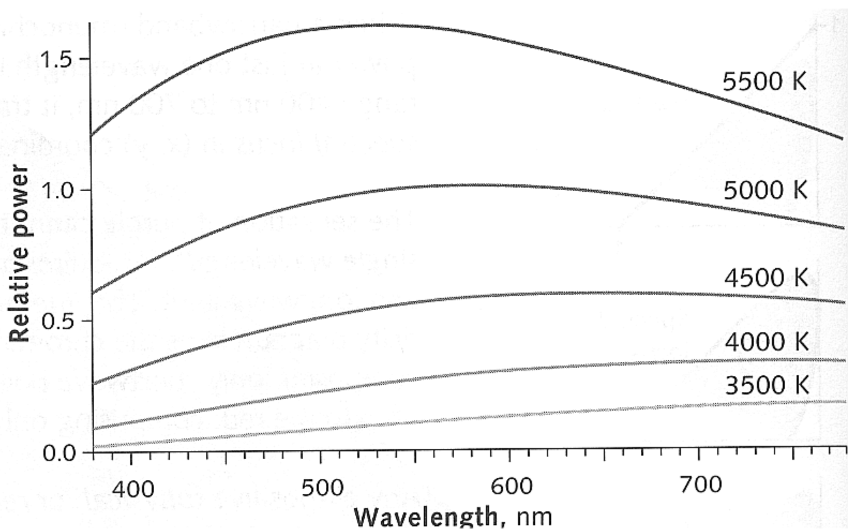
- Gamut compression
  - Each device should replace its out-off-gamut colors with the nearest approximate achievable colors
  - Possible significant color distortions in a
    - Printed → scanned → displayed image

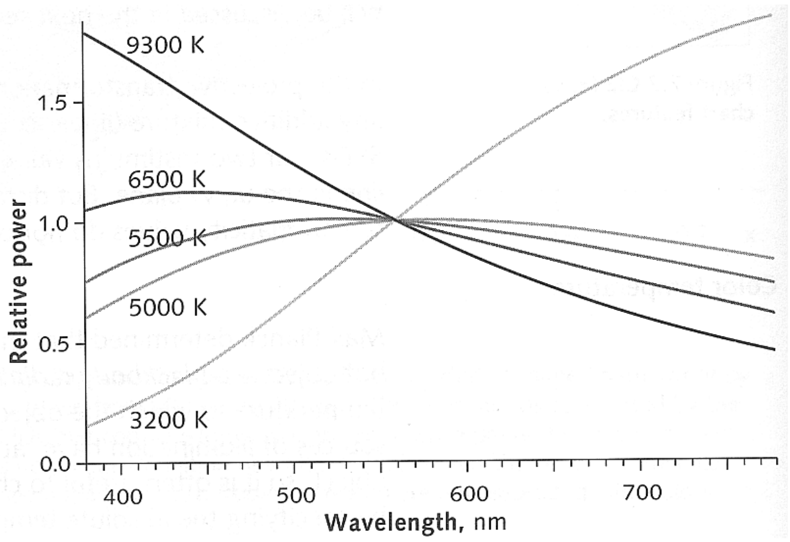




Color Temperature

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





CIE Standard Illuminants

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

- The spectral data of CIE Standard Illuminants are available and often used in the CG applications

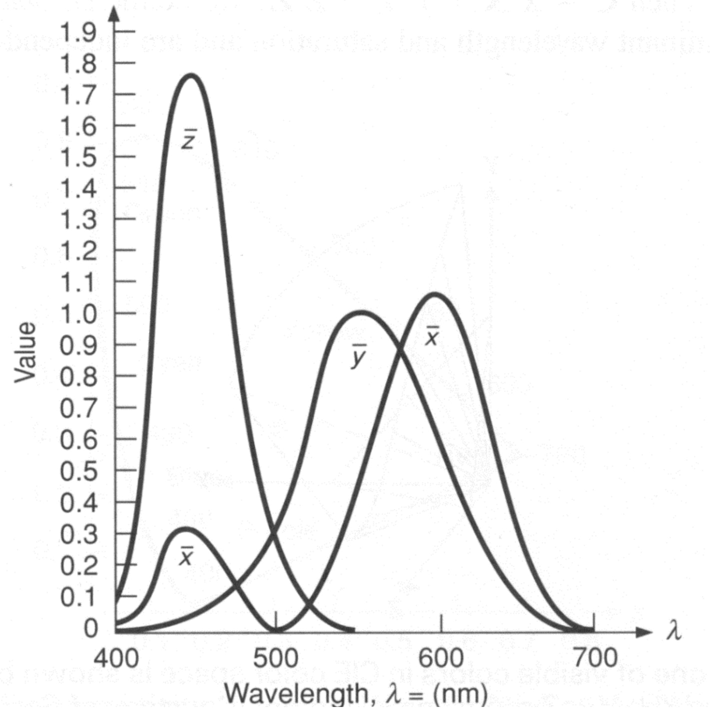
Color Transformation

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)

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

3x1 3 x m m x 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 RGB → XYZ

- Computing the transformation matrix M
  - Given that R,G,B are factors modulating the primaries $(0 \leq R, G, B \leq 1)$
  - 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, used on next slide
  - Assume $C_R = X_R + Y_R + Z_R$
  - $x_R = \frac{X_R}{X_R+Y_R+Z_R} = \frac{X_R}{C_R} \quad \rightarrow \quad X_R = x_R C_R \quad$ (analogous for X_G, X_B)
  - Inserting yields

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_R C_R & x_G C_G & x_B C_B \\ y_R C_R & y_G C_G & y_B C_B \\ (1 - x_R - y_R) C_R & (1 - x_G - y_G) C_G & (1 - x_B - y_B) C_B \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

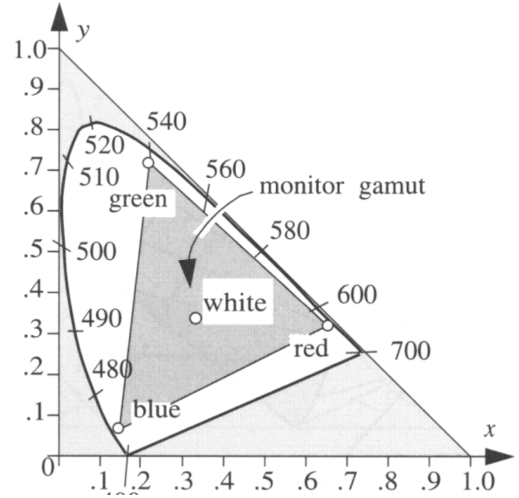
Color Transformations (Cont.)

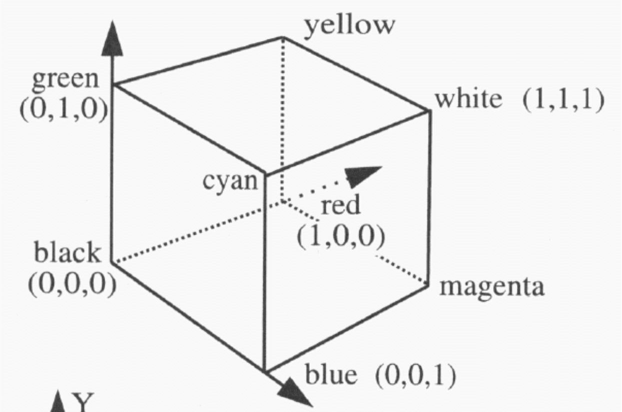
- Computing the constants C_X
  - Per definition the white point is given as
    - $(X_w, Y_w, Z_w) = M(1,1,1)$

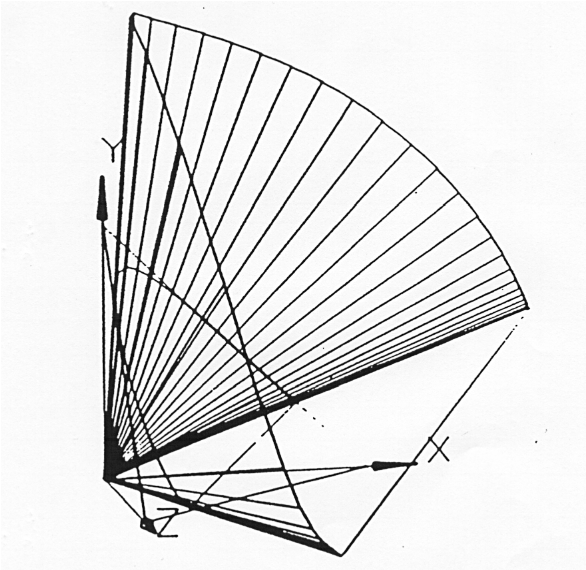
$$\begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = \begin{bmatrix} x_R C_R & x_G C_G & x_B C_B \\ y_R C_R & y_G C_G & y_B C_B \\ (1 - x_R - y_R) C_R & (1 - x_G - y_G) C_G & (1 - x_B - y_B) C_B \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

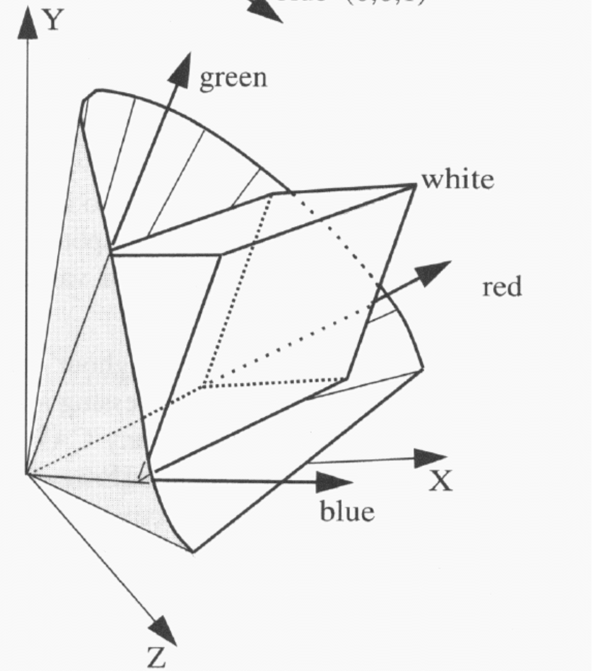
  - (X_w, Y_w, Z_w) can be computed using the normalization constant $Y_w = 1$

Geometric Interpretation



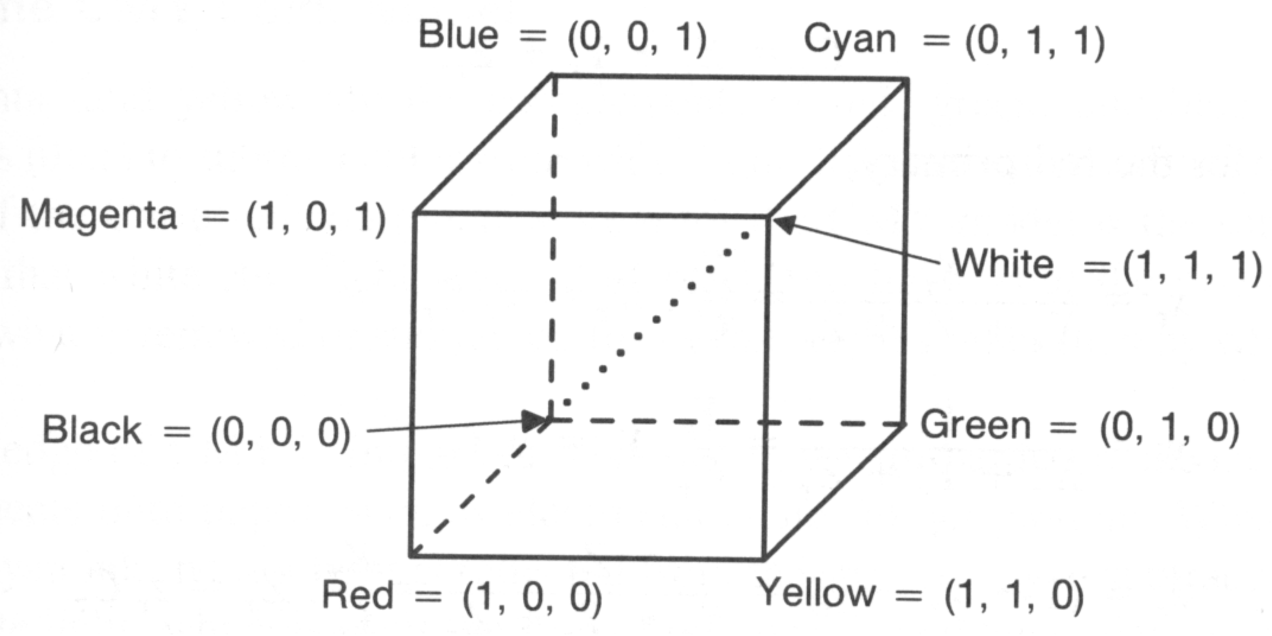


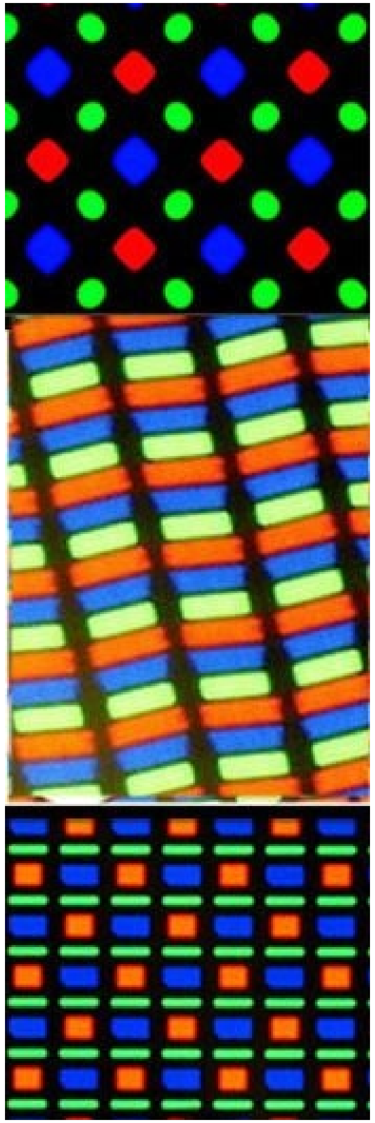




RGB Color Model

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





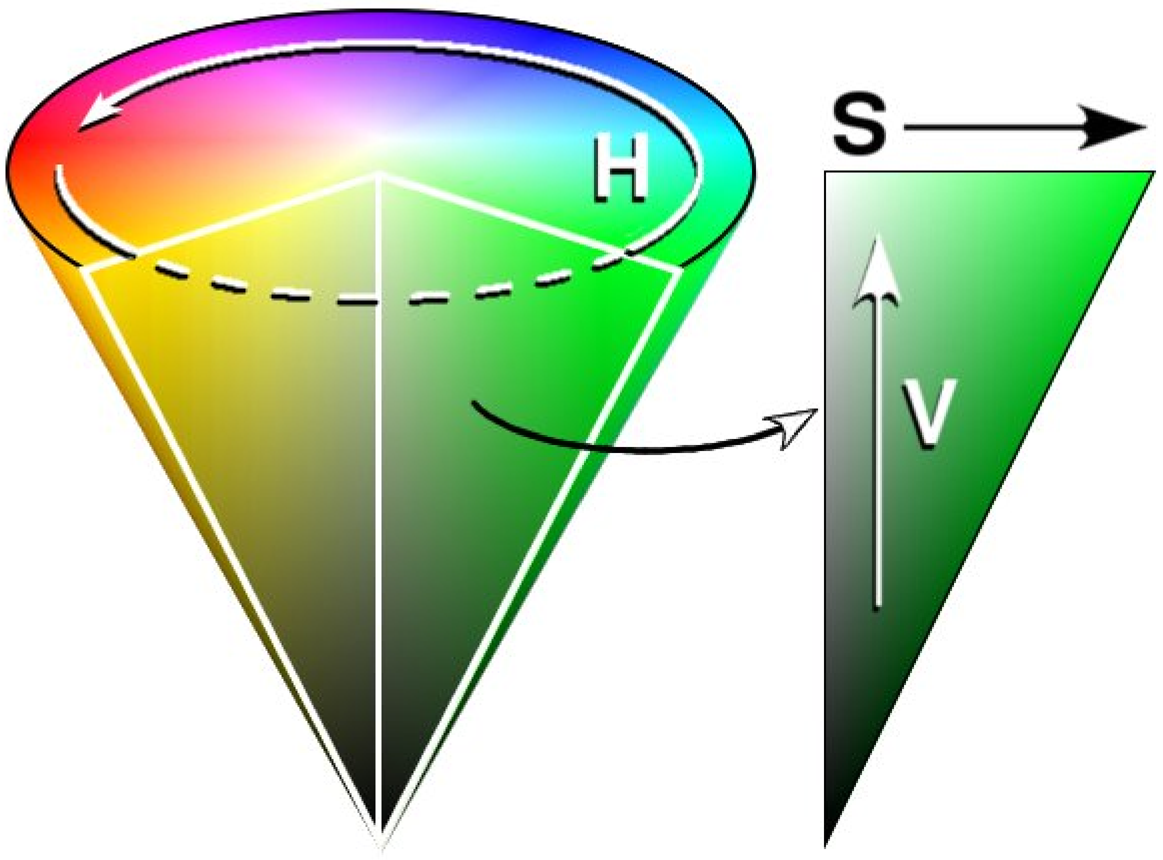
sRGB Color Space

- 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

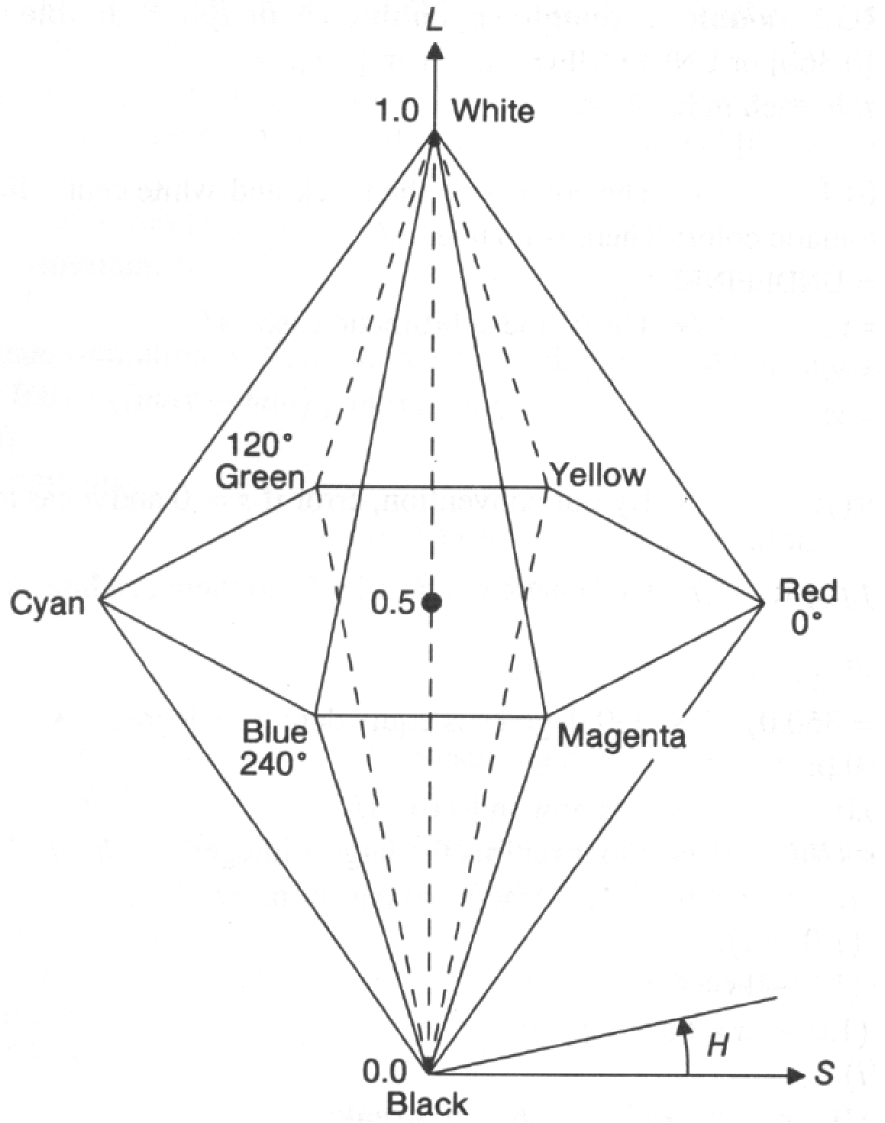
- HSV/HSB (Hue, Saturation, Value / Brightness)
  - Motivated from artistic use and intuition
  - H is equivalent to tone
  - S is equivalent to saturation
    - (H undefined for S == 0)
  - V/B is equivalent to the gray value
  - Pure tones for S == 1 and V == 1
  - Intuitive model for color blending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



HLS Model

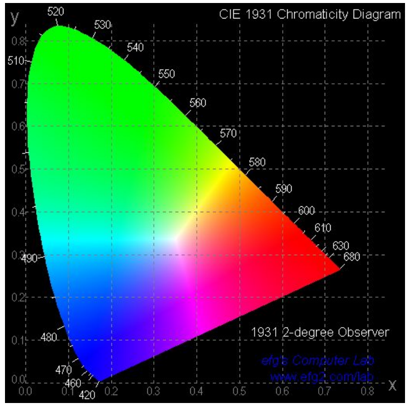
- HLS (Hue, Lightness, Saturation)
  - Similar to HSV/HSB
  - Slightly less intuitive

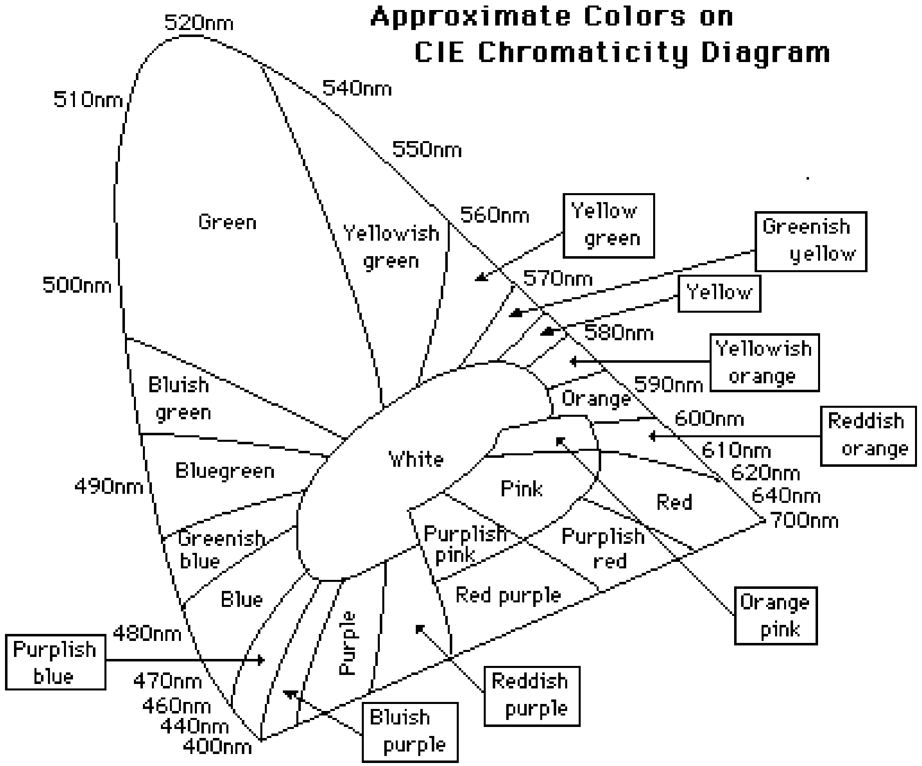
- Other color models
  - TekHVC
    - Developed by Tektronix
    - Perceptually uniform color space
  - Video-processing
    - YUV
    - Y´, B-Y, R-Y
    - Y´IQ
    - Y´PrPb
    - Y´CrCb
  - Non-linear color spaces



Color Model: In Practice

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

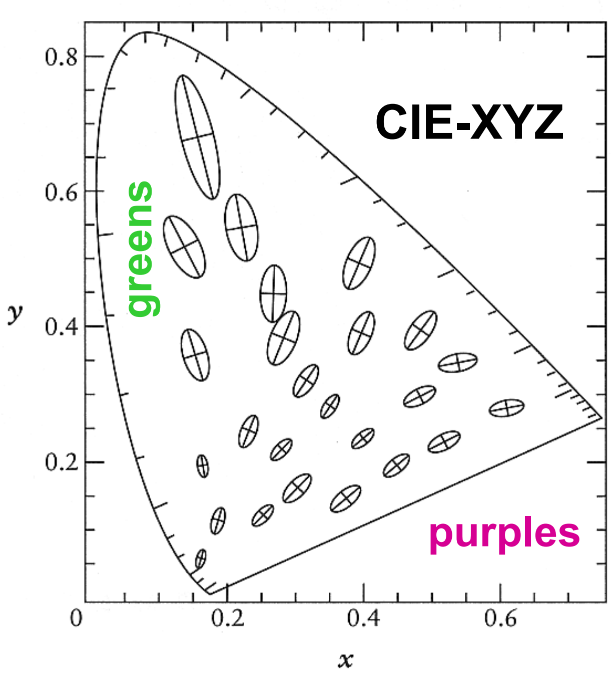


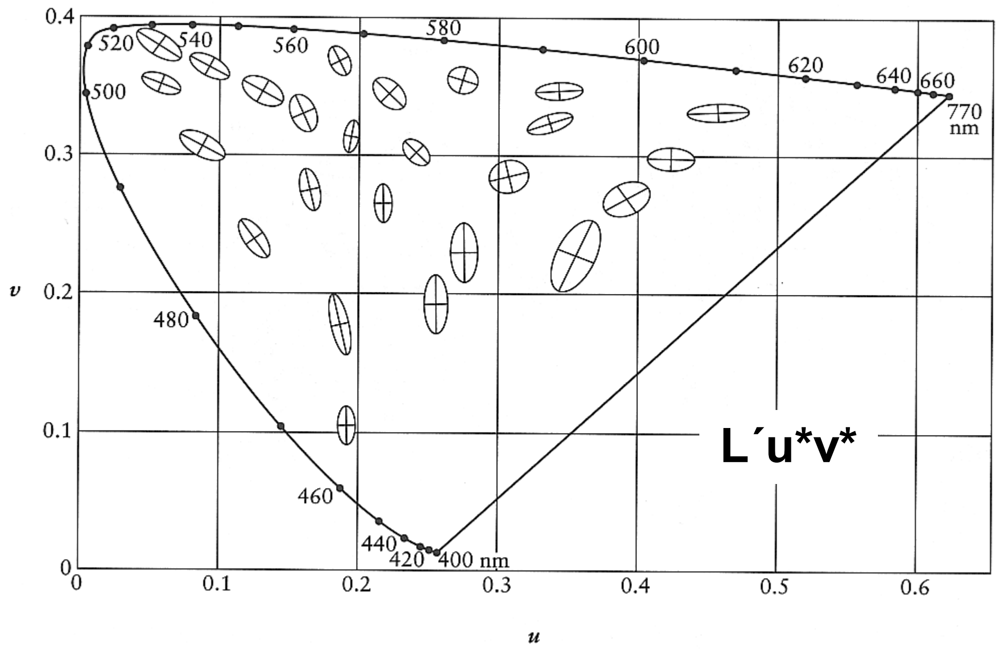


Color Perception Models

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*/Lαβ 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)
    (limited applicability to HDR)
  - $L^* \in \{0, \dots, 100\}$

  - Transformation of color differences

$$u' = \frac{4X}{X + 15Y + 3Z}$$

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

$$v' = \frac{9Y}{X + 15Y + 3Z}$$

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

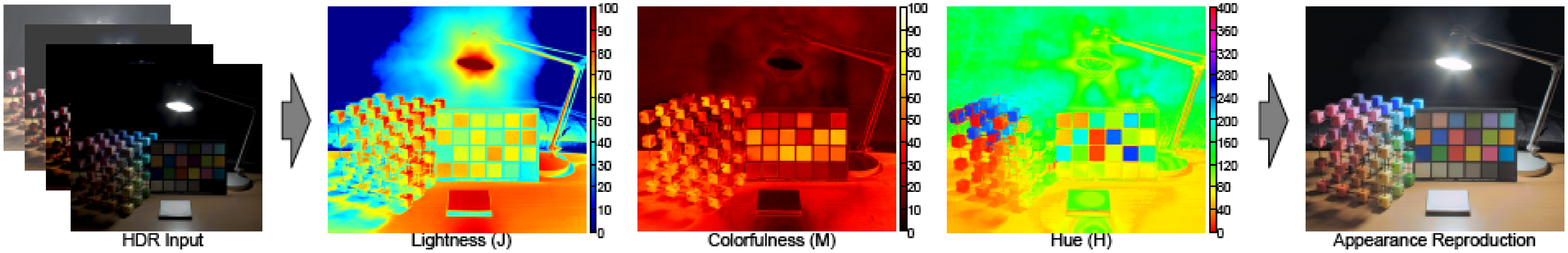
$$L^* = 116 \cdot f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{X}{Y_n}\right)\right]$$

$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right]$$

$$f(t) = \begin{cases} t > \delta^3: & x^{1/3} \\ x \leq \delta^3: & \frac{t}{3\delta^3} + \frac{4}{29} \end{cases}, \qquad \delta = \frac{4}{29}$$

Color Perception under Extended Luminance Levels

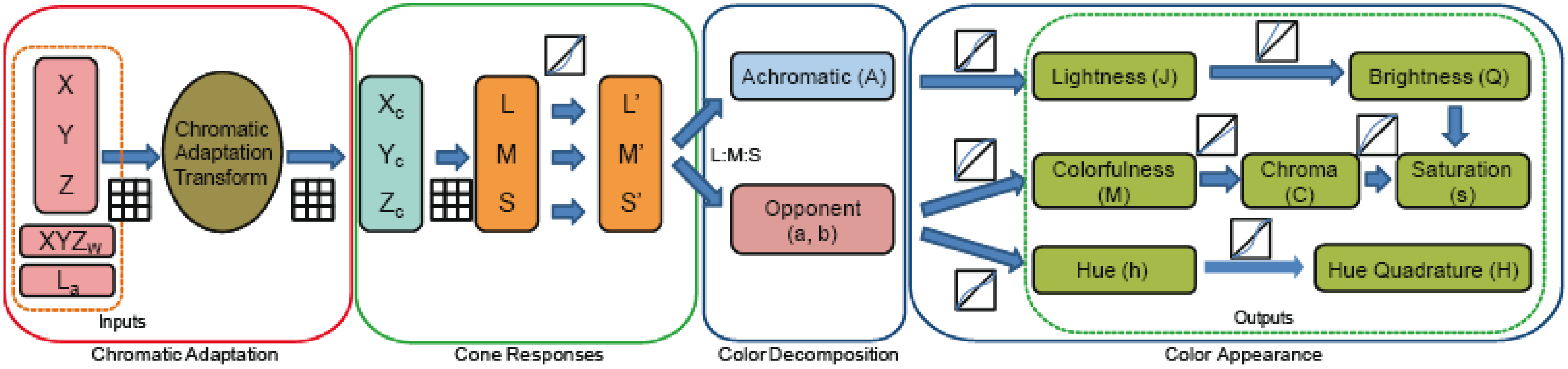


- Human color perception can be specified by the three modes
  - Lightness
  - Colorfulness
  - Hue

- Their composition depends on
  - Incoming luminance
  - Adaptation
  - Surrounding illumination

[Kim et al. SIGGRAPH2009]

Color Appearance Models

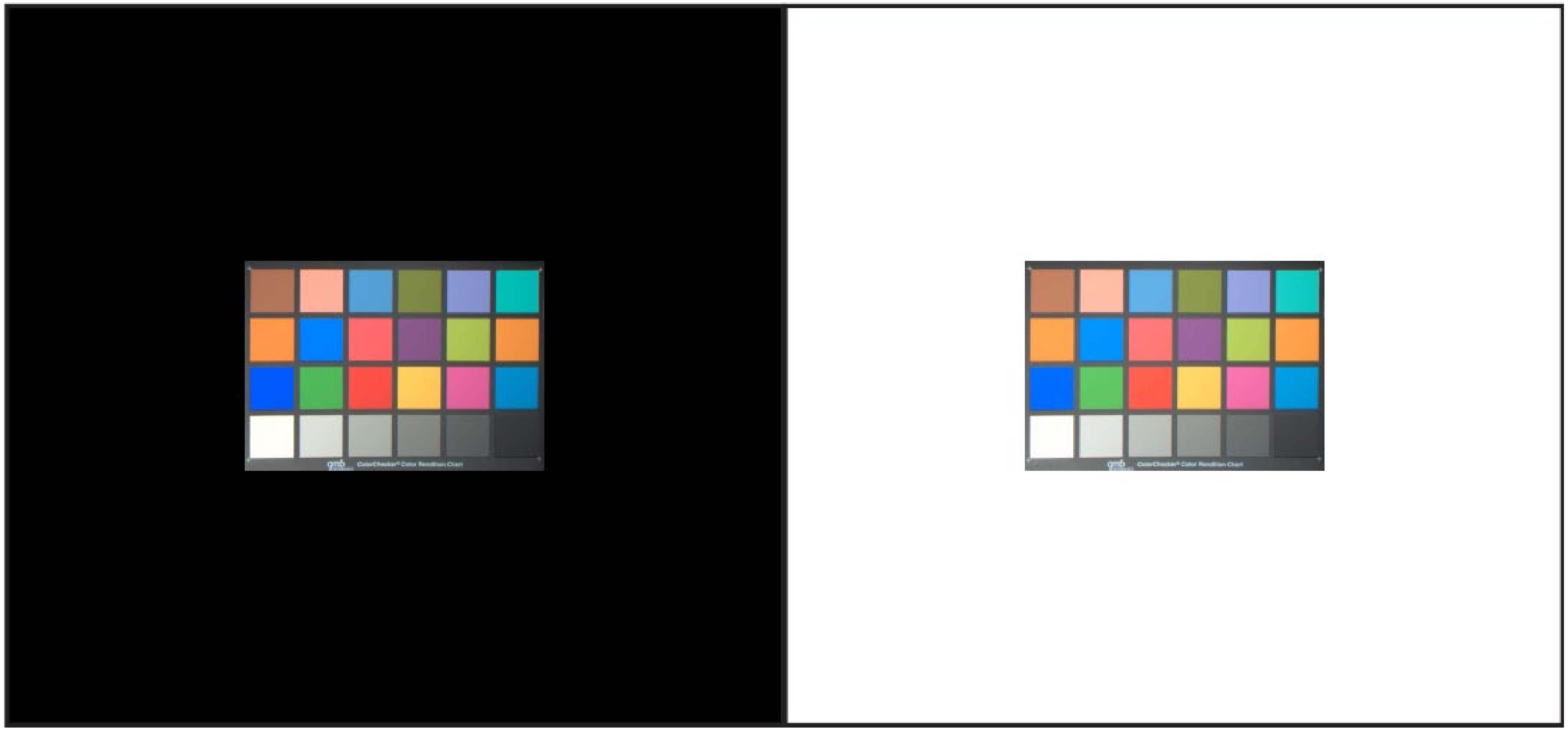


- Curves and parameters estimated by user study

- See paper for details:
  - Modeling Human Color Perception under Extended Luminance Levels

Applied Color Appearance Model

• Color perception should be the same for different background



Applied Color Appearance Model

- Color perception should be the same for different background
- Required to display different colors

White balance

- When looking at a picture on screen or print, we adapt to the illuminant of the room, not to that of the scene in the picture

- When the white balance is not correct, the picture will have an unnatural color “cast”

incorrect white balance

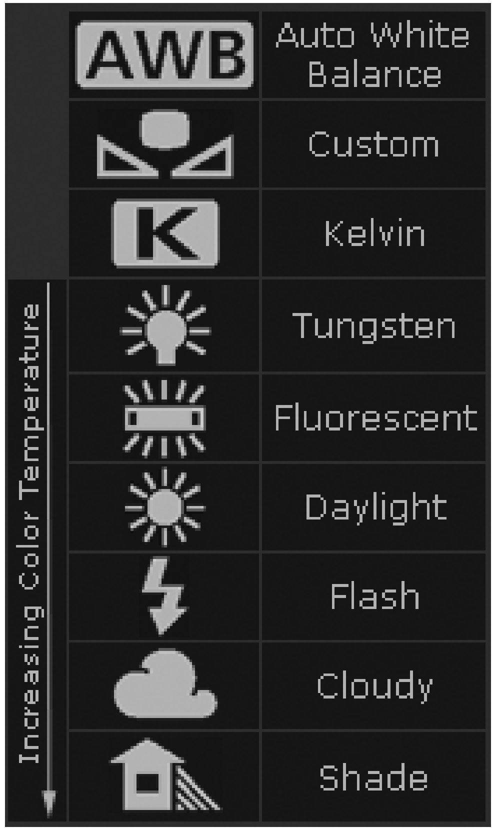
correct white balance

http://www.cambridgeincolour.com/tutorials/white-balance.htm

White balance

- Film cameras:
  - Different types of film or different filters for different illumination conditions

- Digital cameras:
  - Automatic white balance
  - White balance settings corresponding to several common illuminants
  - Custom white balance using a reference object



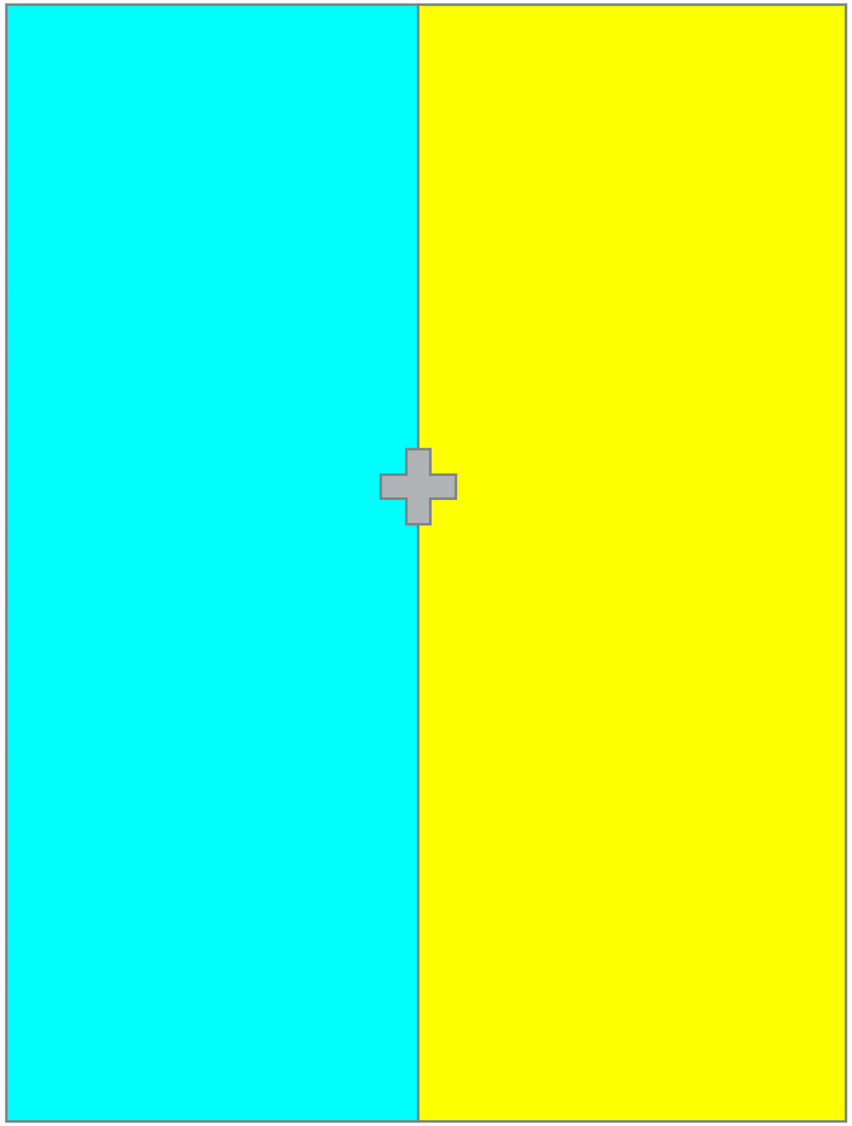
White balance

- Von Kries adaptation
  - Multiply each channel by a gain factor
  - The light source could have a more complex effect, corresponding to an arbitrary 3x3 matrix

- Best way: gray card
  - Take a picture of a neutral object (white or gray)
  - Deduce the weight of each channel
    - If the object is recoded as r_w, g_w, b_w use weights $1/r_w$, $1/g_w$, $1/b_w$

Chromatic adaptation

Chromatic adaptation



Chromatic adaptation

Chromatic adaptation

- The visual system changes its sensitivity depending on the luminances prevailing in the visual field
  - The exact mechanism is poorly understood

- Adapting to different brightness levels
  - Changing the size of the iris opening (i.e., the aperture) changes the amount of light that can enter the eye
  - Think of walking into a building from full sunshine

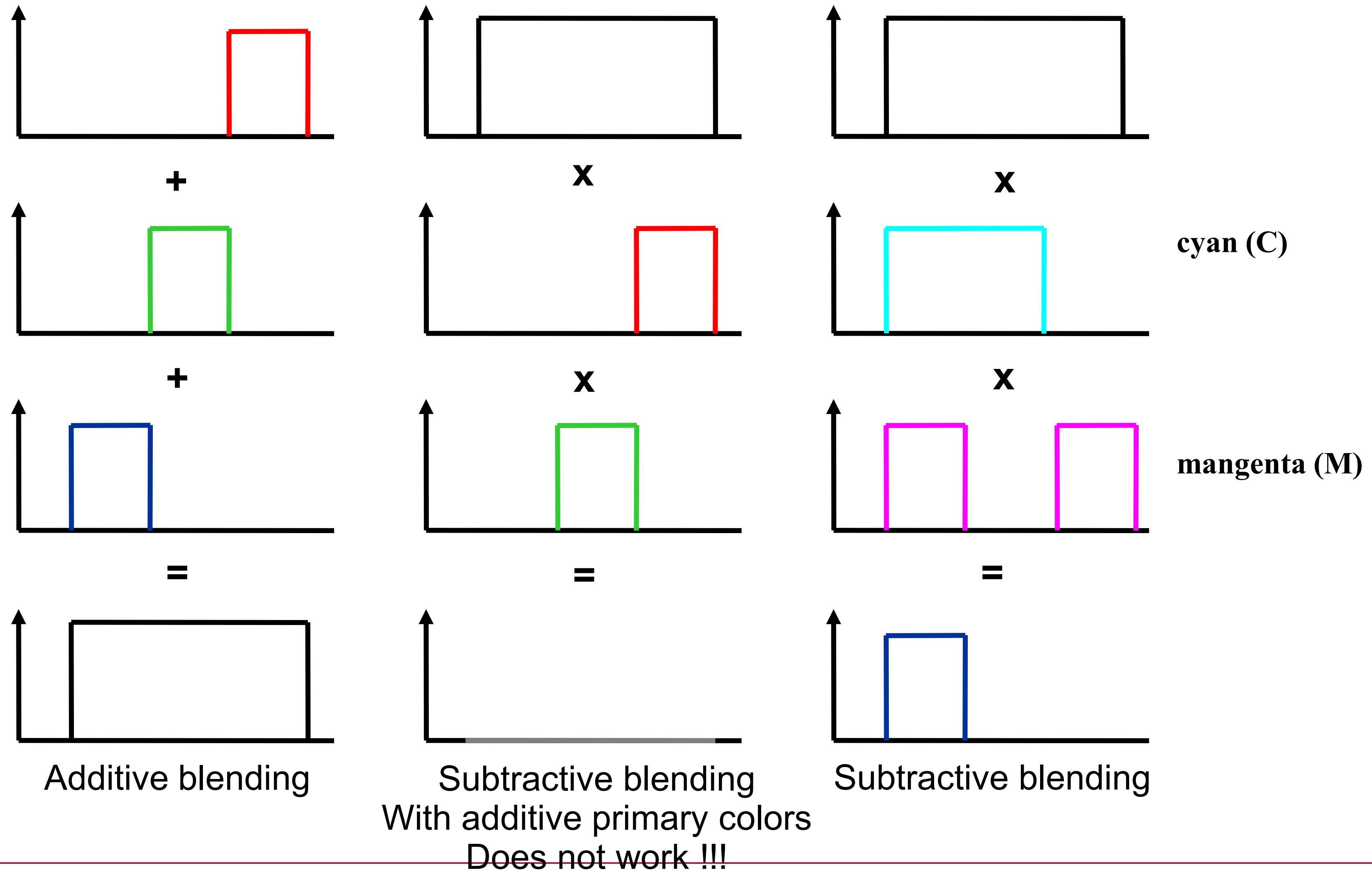
- Adapting to different color temperature
  - The receptive cells on the retina change their sensitivity
  - For example: if there is an increased amount of red light, the cells receptive to red decrease their sensitivity until the scene looks white again
  - We actually adapt better in brighter scenes: This is why candlelit scenes still look yellow

http://www.schorsch.com/kbase/glossary/adaptation.html

Printer Color Spaces

Subtractive Color blending

- Corresponds to stacked color filters

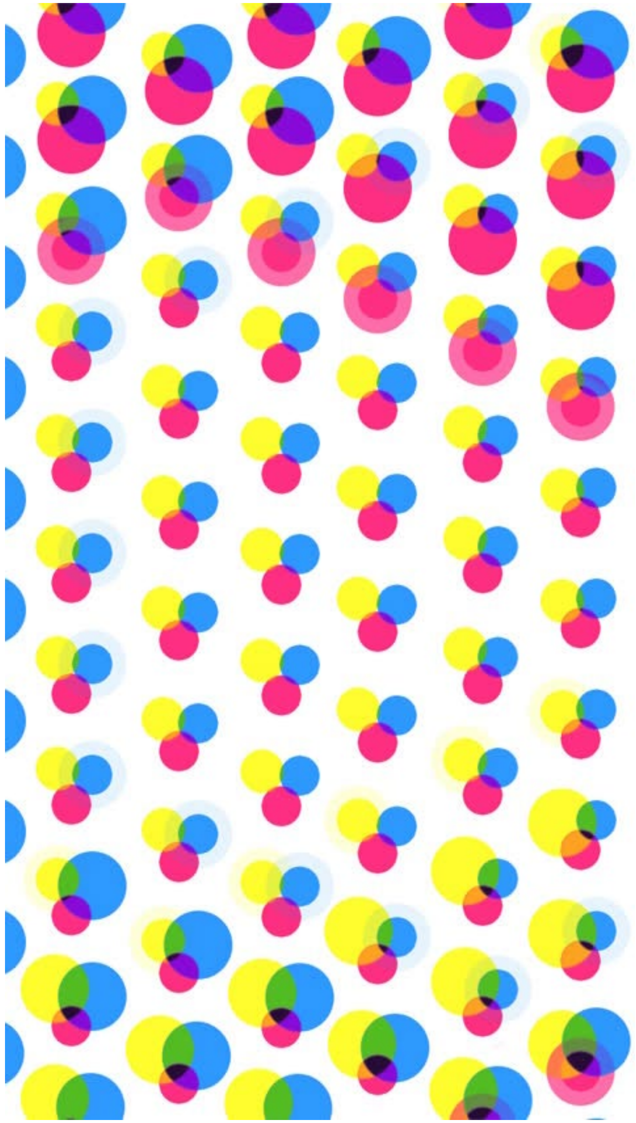


Subtractive Color Blending

- e.g. for printers

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

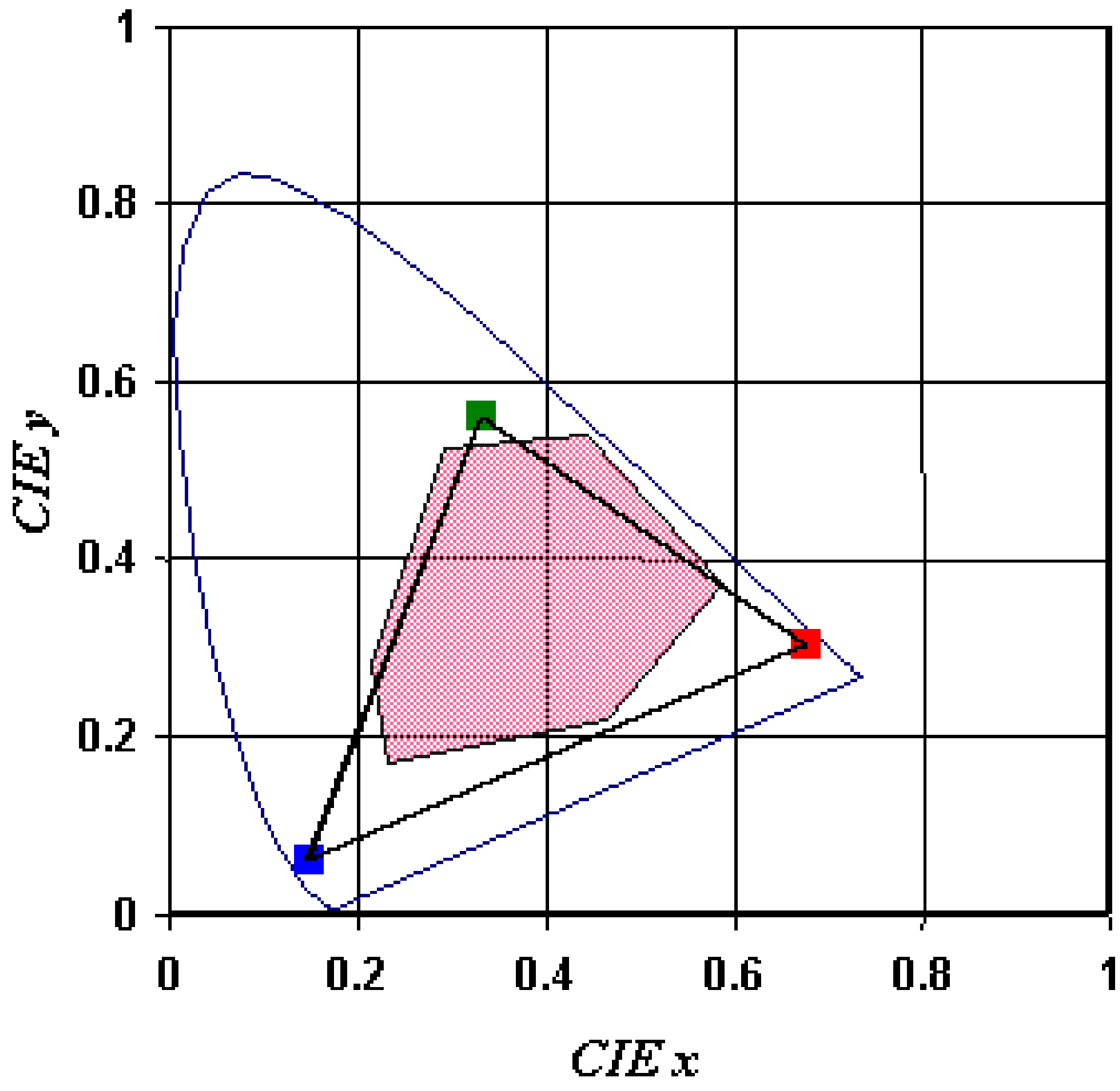
  - In practice: profoundly non-linear transformation
    - Other primary colors
    - Interaction of the color pigments among each other
    - Covering
    - Etc, etc.



Subtractive color blending

- Gamut-Mapping:
  - What to do if colors lay outside of the printable area?
  - Clamp, Scale

- Subtractive primary colors:
  - Product of all primary colors must be black
  - Any number of colors
    - (CMY, CMYK, 6-color-print, etc.)
  - It does not need to obtain
    - (CMY)= 1-(RGB)



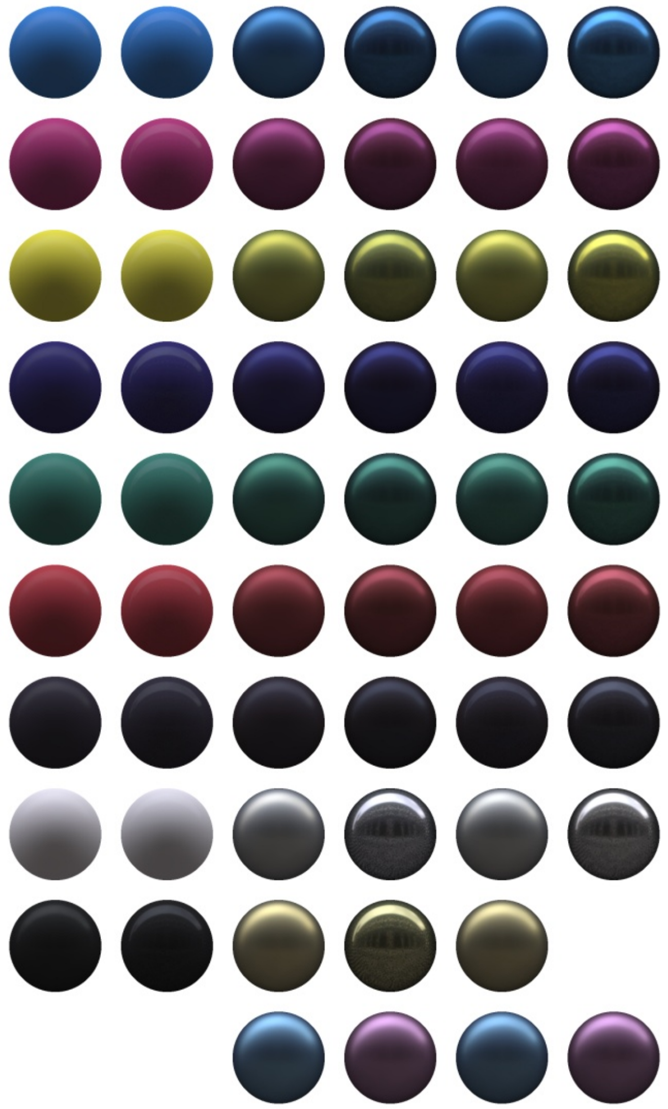
Printing Arbitrary BRDFs

- Color printing so far only varies color
- No control over directional dependent effects
  - High gloss paper
  - finisher

- Special Ink Printer
  ALPS MD-5000

Primary BRDFs

- 12 distinct inks
  - Color, finisher
    Gold- u. Silverfoil
- Deposited in mulitple layers
  - Measuring the BRDF for each combination
- Arbitrary BRDF with the Gamut (spatial dithering)



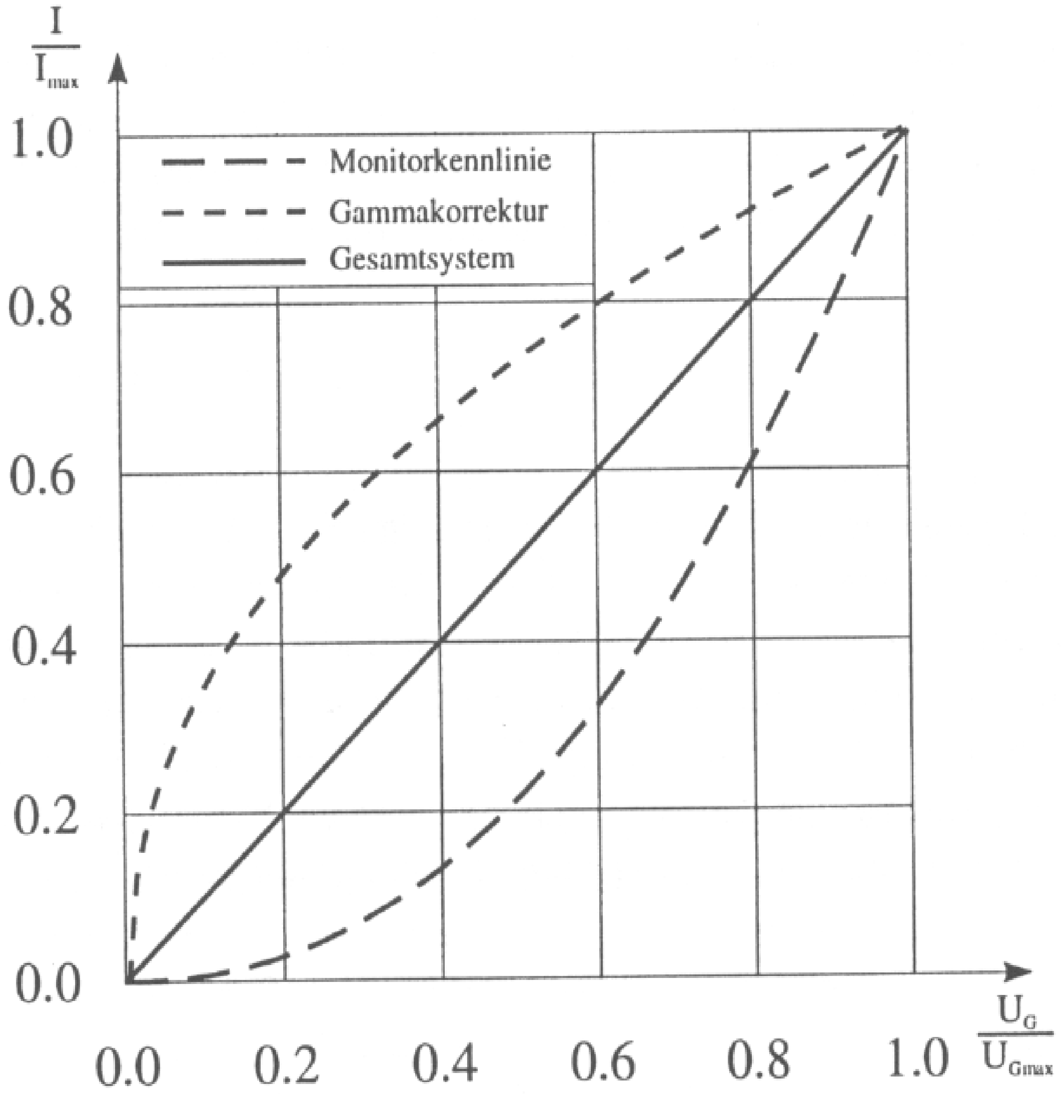
ICC Profiles

Gamma

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

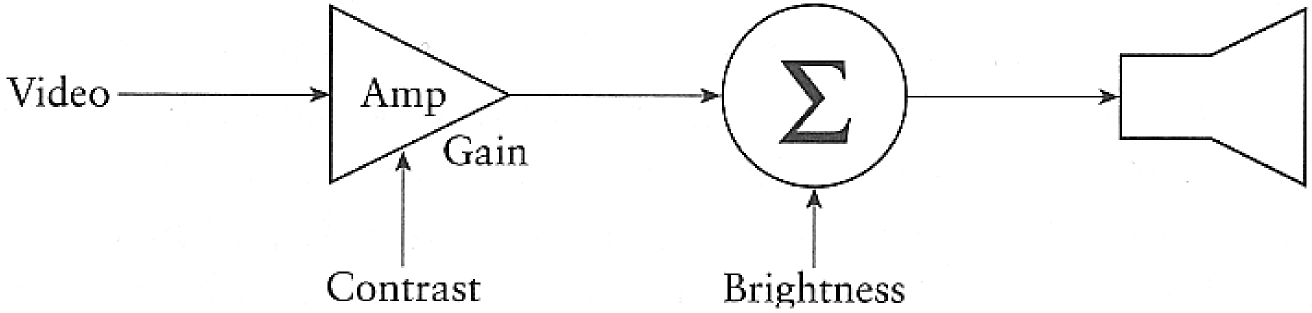
      →Gamma-Factor γ = ~2.2 due to physical reasons

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

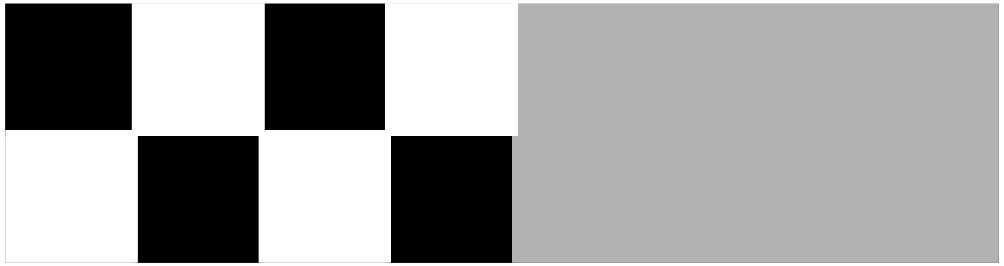


Gamma Correction

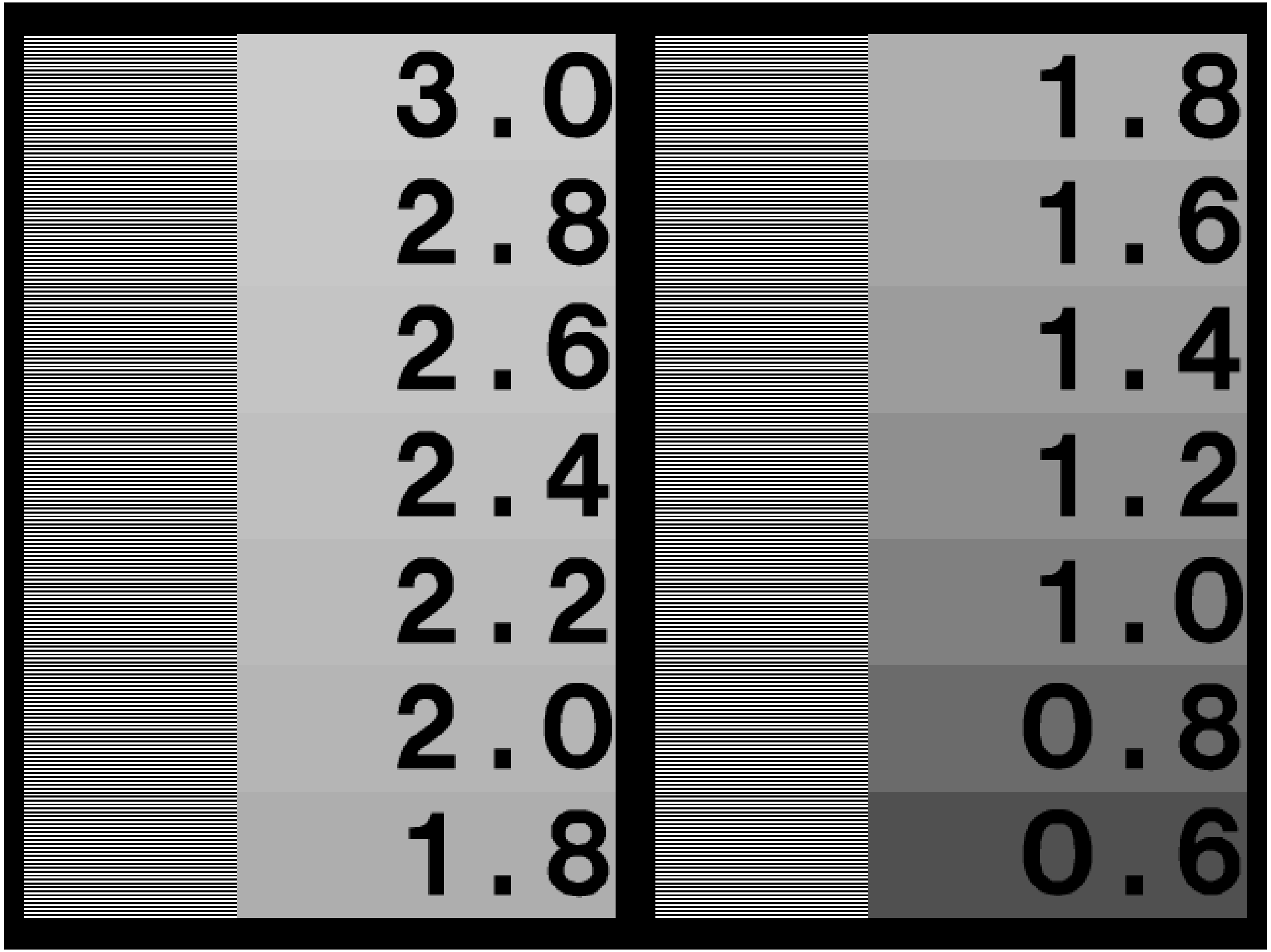
- Monitor calibration (for dummies):
  - Correctly: you would need a colorimeter, spectrophotometer
  - The procedure:



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

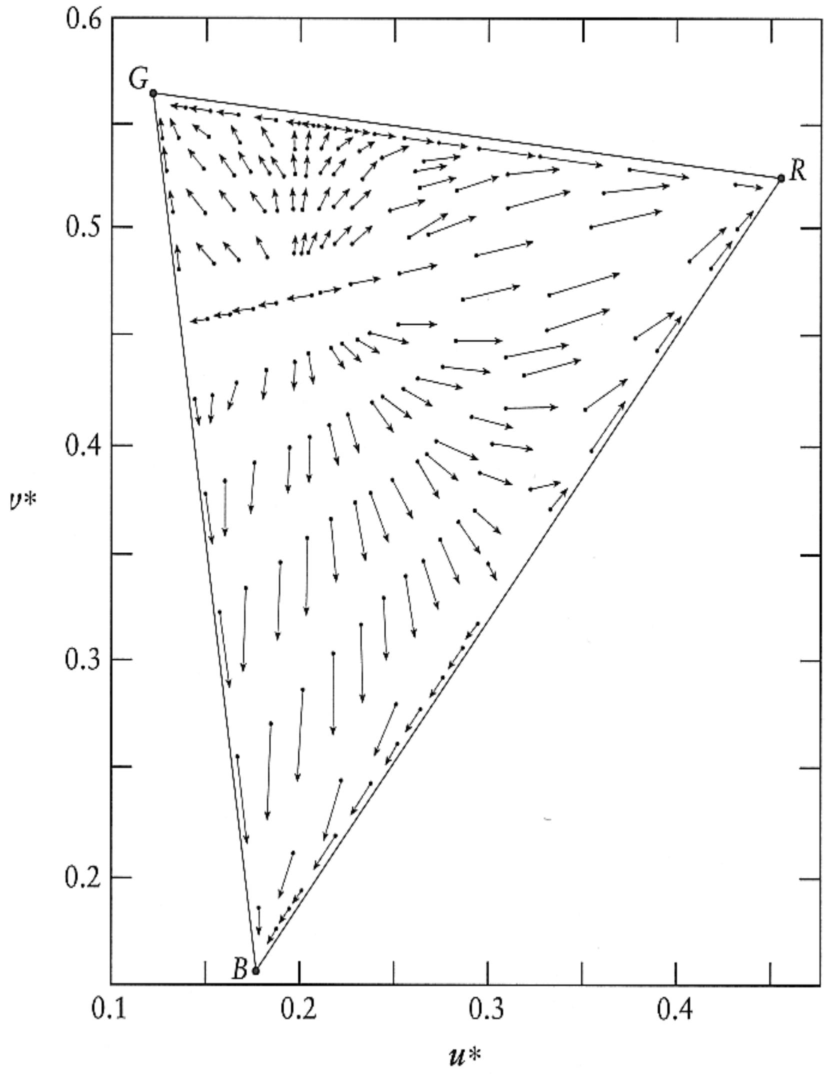


Gamma Testing Chart



Gamma Correction

- Problem:
  - Strong color corruptions



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

Gamma

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

➔Display corrected the camera

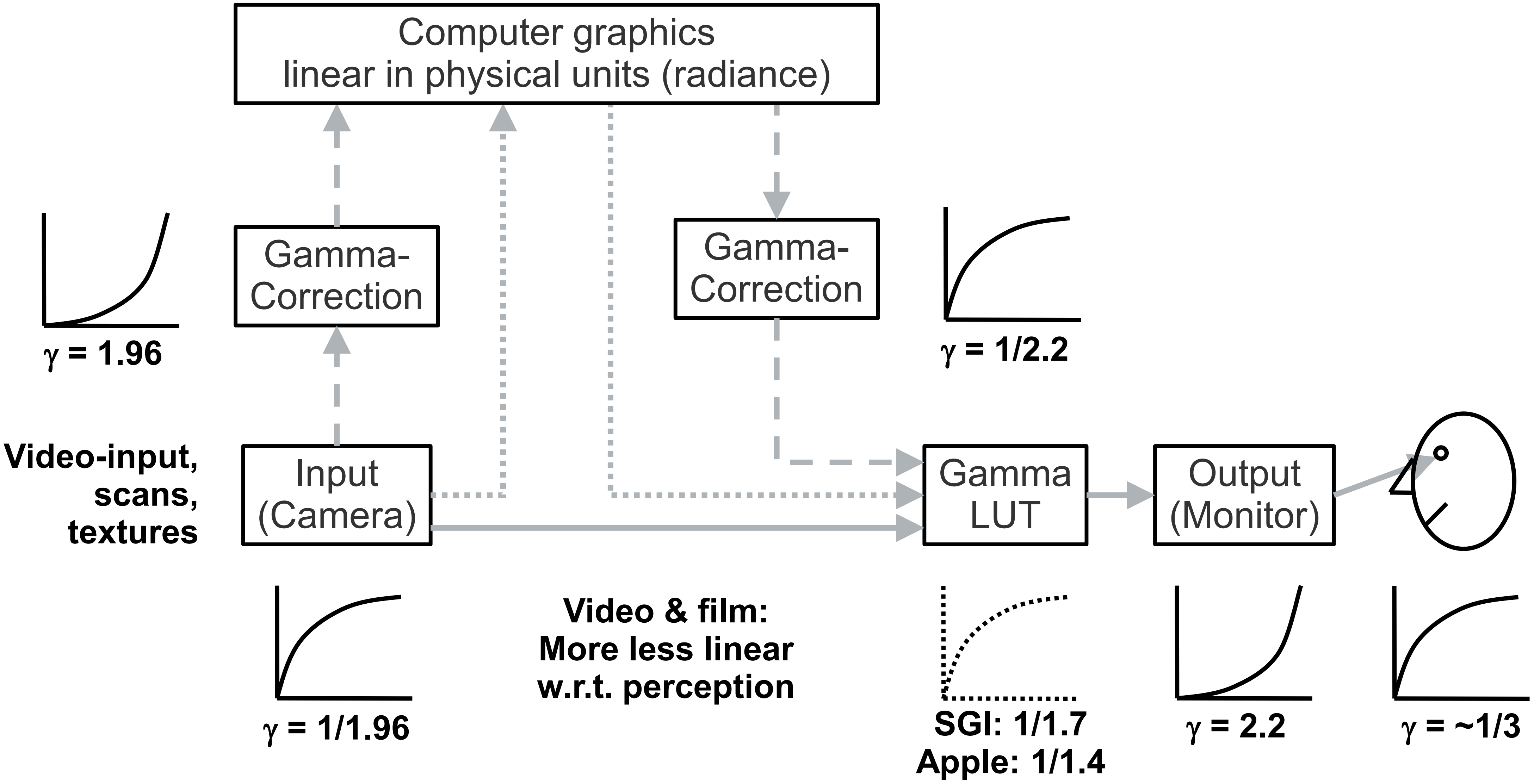
- „Human-Gamma“
  - Human brightness perception roughly follow the gamma curve
    - Really a log-curve, but close

➔Old camera encode light perceptually uniform

- Optimal coding for transmitted values

➔New cameras specifically generate the same output for compatibility reasons

Color from beginning to end



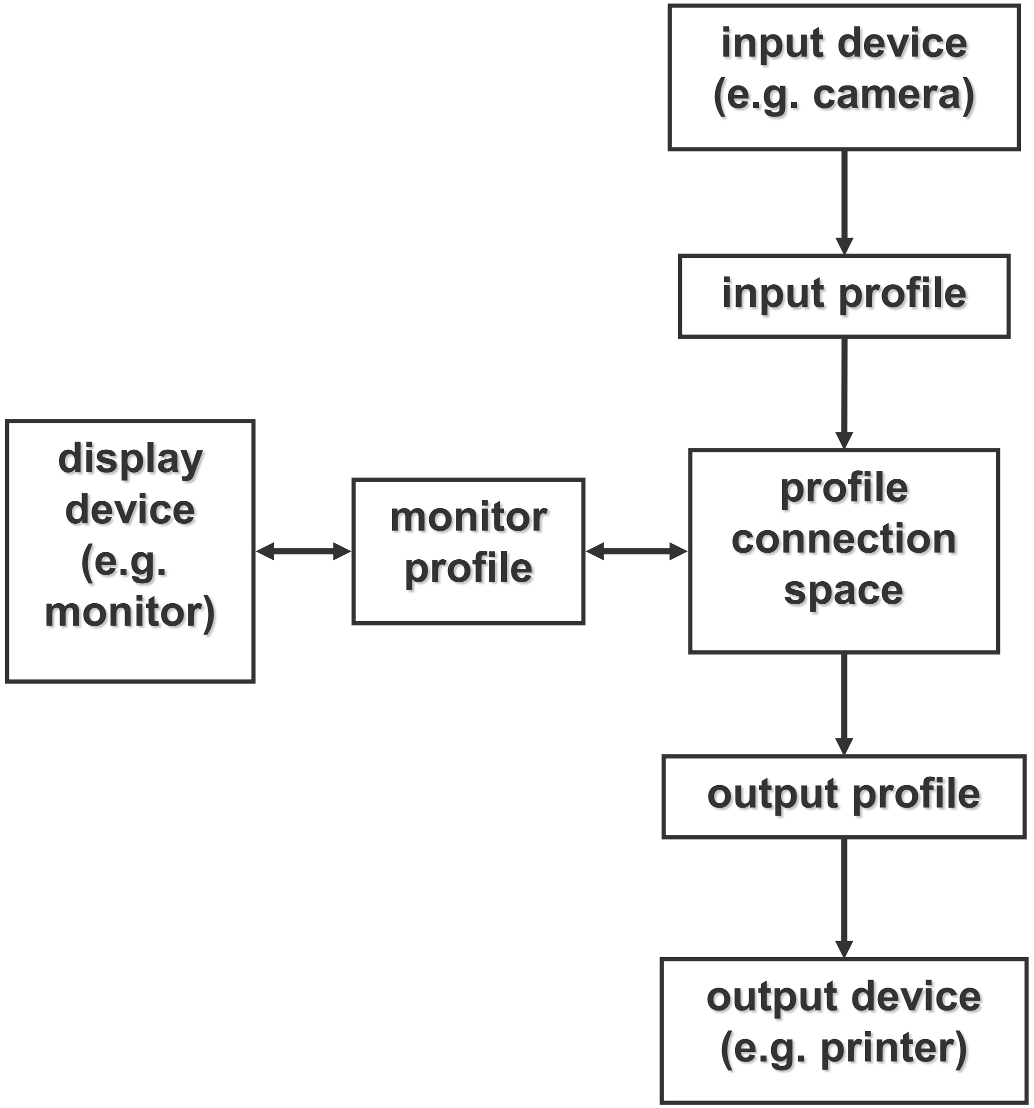
Color from beginning to end

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

ICC Profiles

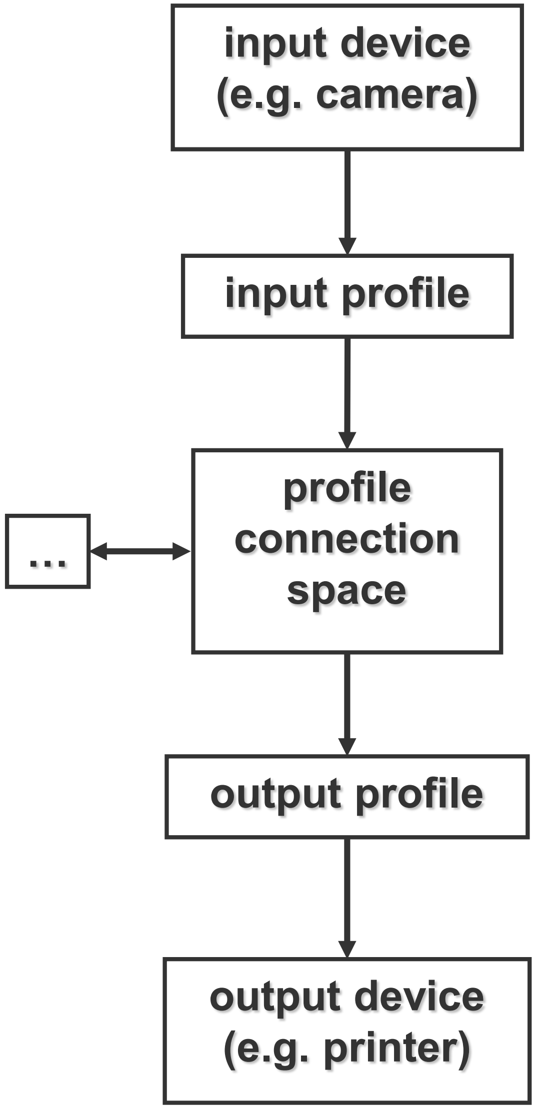
- International Color Consortium
  - Standardized specification of color spaces
  - Profile Connection Space (PCS) – intermediate, device-independent color space (CIELAB and CIEXYZ supported)
  - ColorDevice #1 → PCS → ColorDevice #2
- ICC profile
  - A file with data describing the color characteristics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

ICC Profiles



ICC Profiles and HDR Image Generation

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



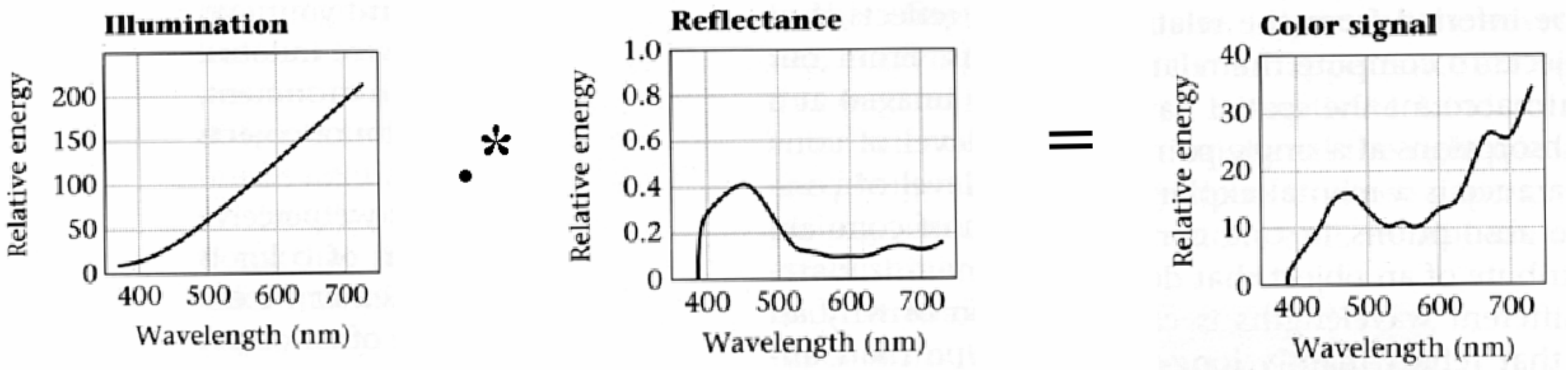
Device-independent Color Representation

- reproduce the same appearance or at least the best possible approximation on arbitrary output devices

Wrap-UP

Interaction of light and surfaces

- Observed color is the result of interaction of light source spectrum with surface reflectance
- Spectral radiometry
  - All definitions and units are now “per unit wavelength”
  - All terms are now “spectral”



CIE Chromaticity Diagram

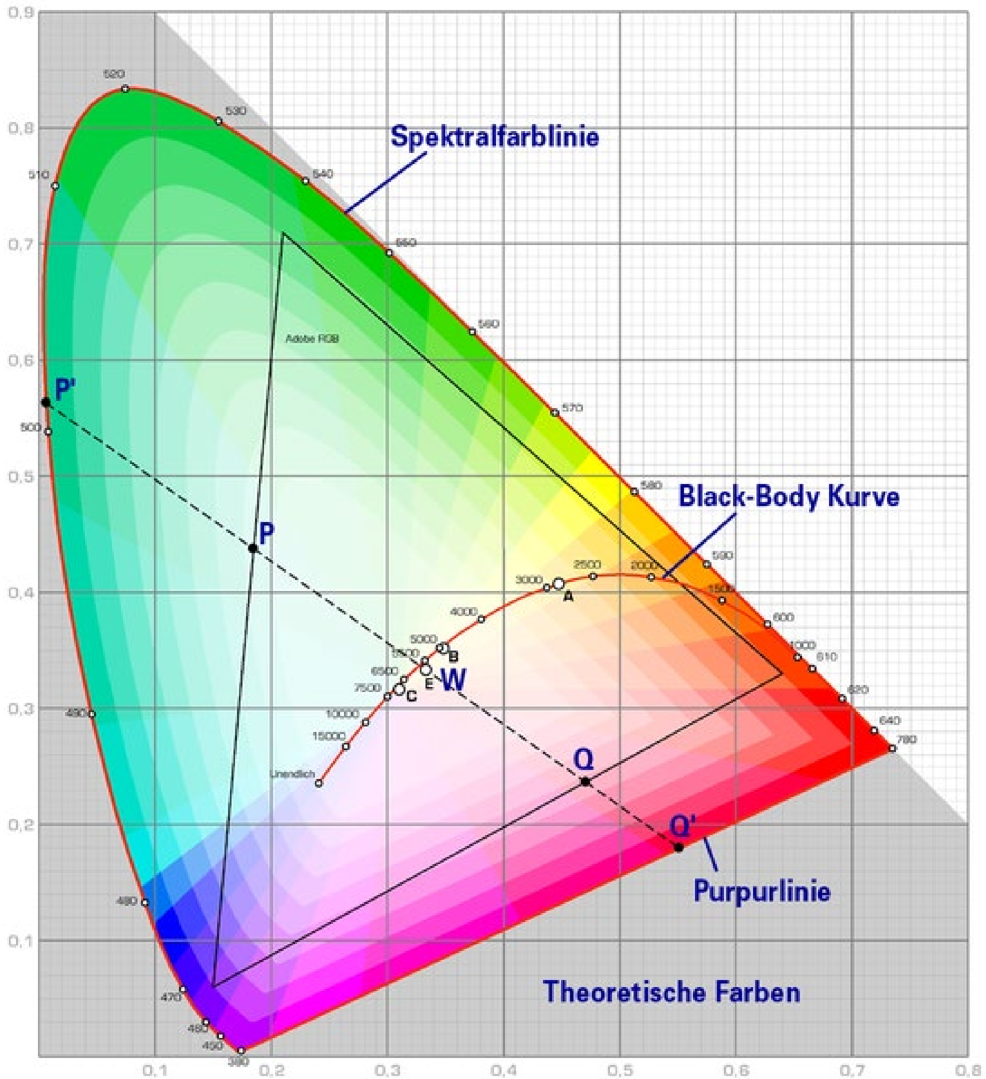
- Normalization:
  - Concentrate on color, not light intensity
  - Relative color coordinates
  - $x = \frac{X}{X+Y+Z}$ etc.

    Projection on the plane of the „primary valences“
  - $z = 1 - x - y$

  - Chromaticity diagram:
    - 2D-Plot over x and y

  - Points in diagram are called „color locations“

  - White point: ~(0.3, 0.3)
    - Device dependent
    - Adaptation of the eye



The CIE xy chromaticity diagram

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