Light and colour

Advanced Graphics

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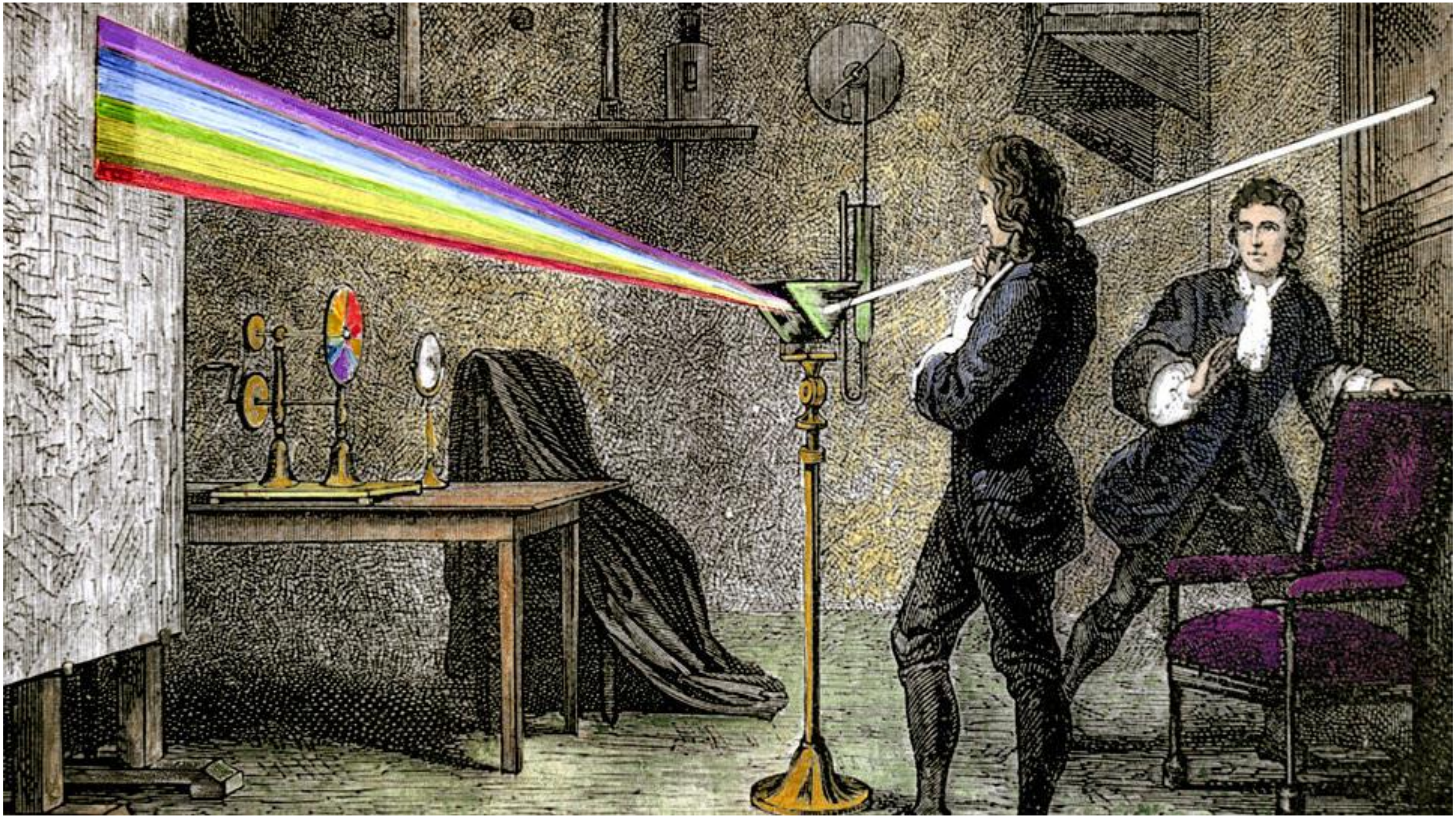
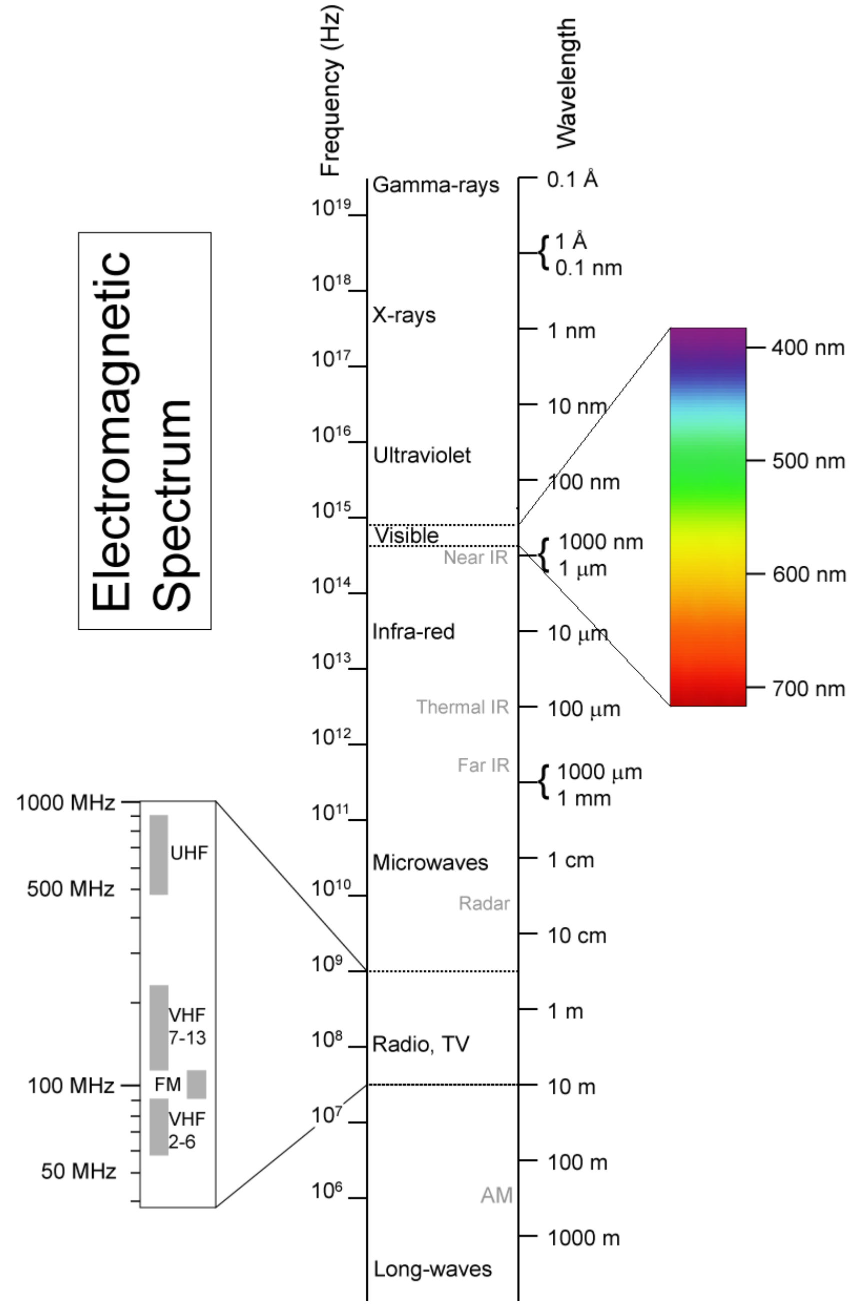
From light to colour spaces



Electromagnetic spectrum

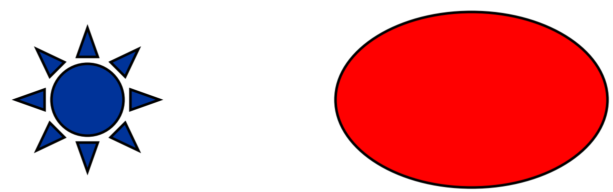
- Visible light
  - Electromagnetic waves of wavelength in the range 380nm to 730nm
  - Earth's atmosphere lets through a lot of light in this wavelength band
  - Higher in energy than thermal infrared, so heat does not interfere with vision



Colour

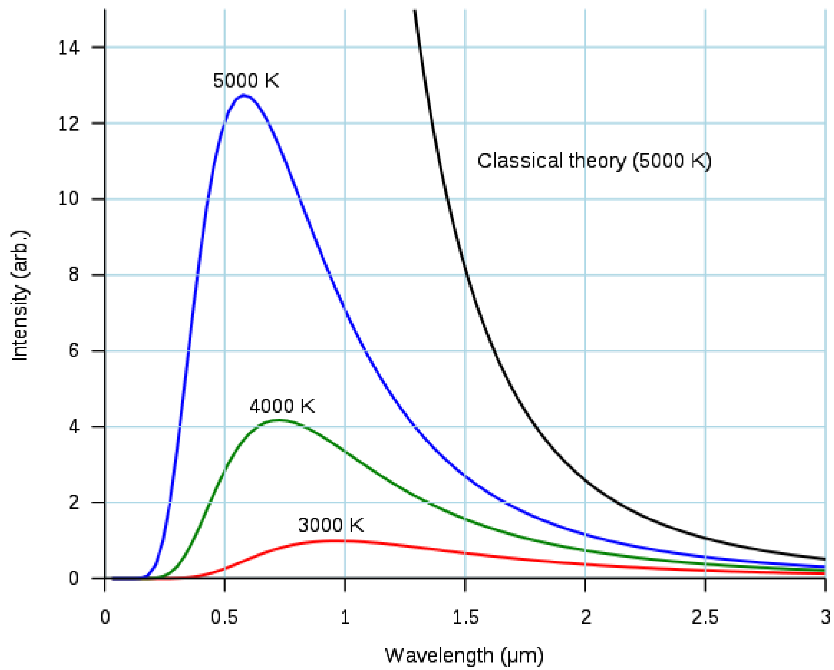
- There is no physical definition of colour – colour is the result of our perception

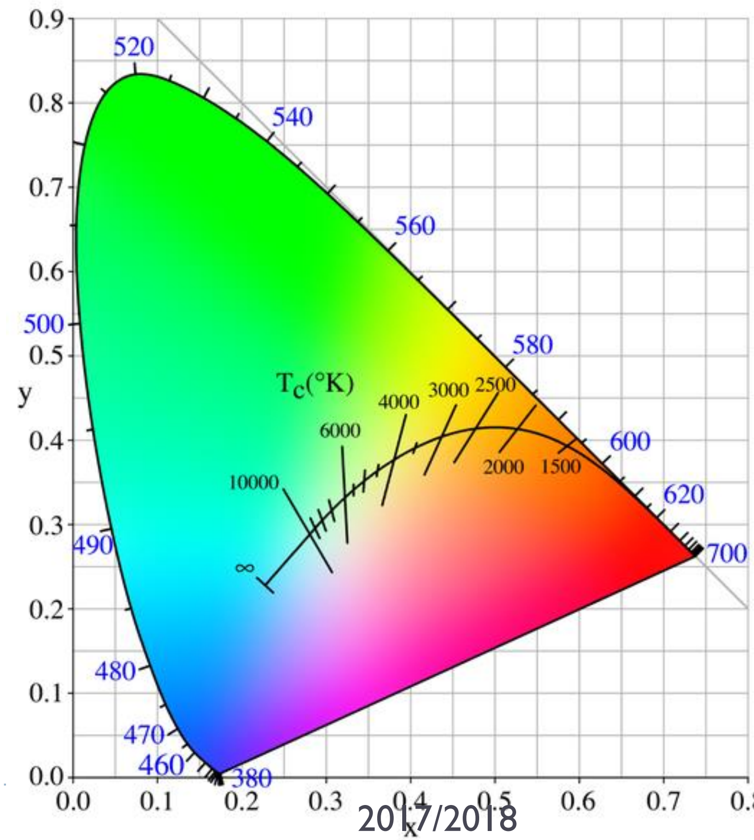
colour = perception(illumination * reflectance)



Black body radiation

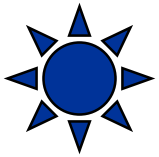
- Electromagnetic radiation emitted by a perfect absorber at a given temperature
  - Graphite is a good approximation of a black body





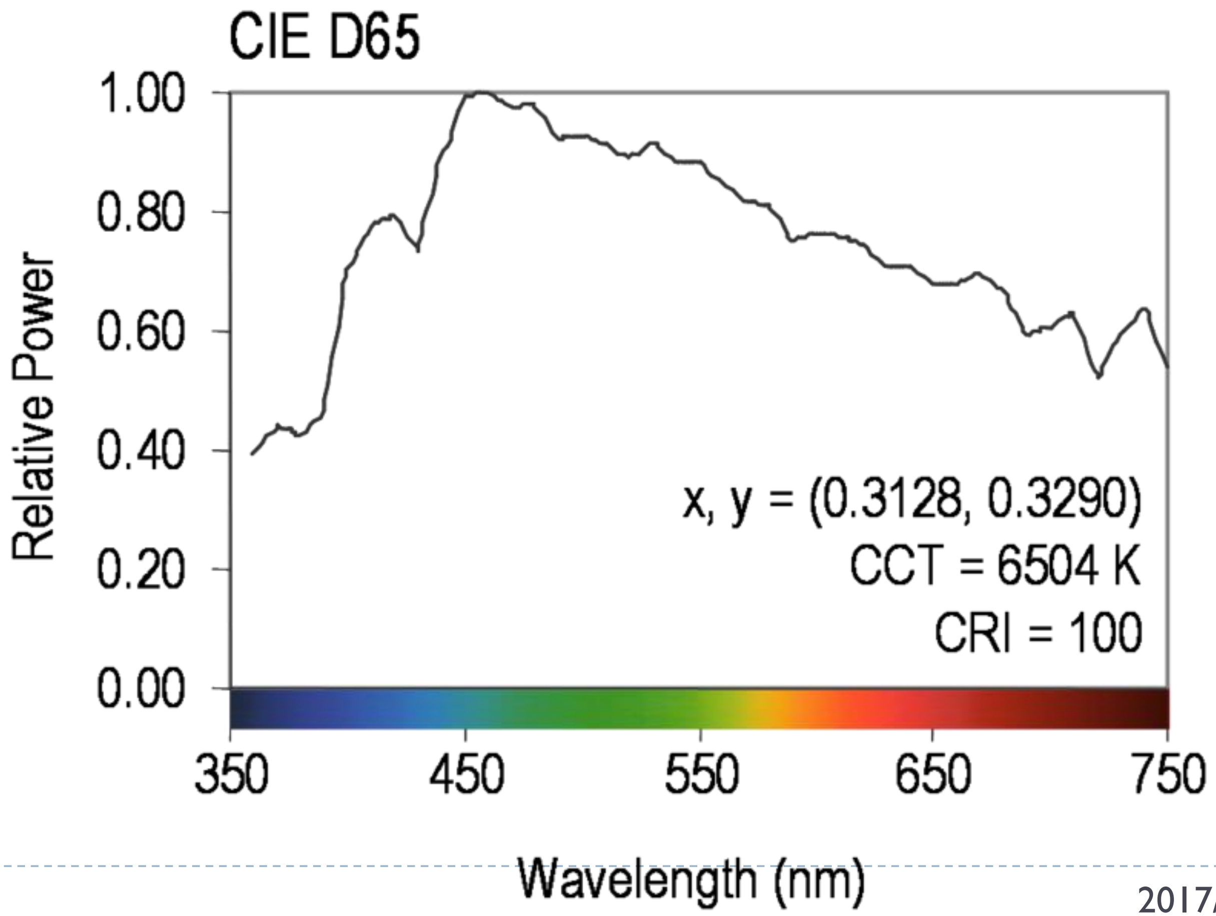
Correlated colour temperature

- The temperature of a black body radiator that produces light most closely matching the particular source
- Examples:
  - Typical north-sky light: 7500 K
  - Typical average daylight: 6500 K
  - Domestic tungsten lamp (100 to 200 W): 2800 K
  - Domestic tungsten lamp (40 to 60 W): 2700 K
  - Sunlight at sunset: 2000 K
- Useful to describe colour of the **illumination** (source of light)



Standard illuminant D65

- Mid-day sun in Western Europe / Northern Europe
- Colour temperature approx. 6500 K



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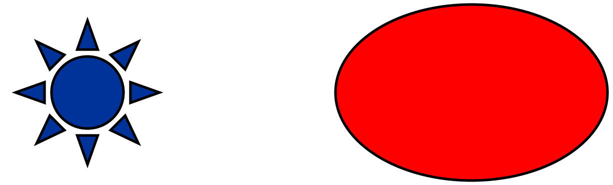
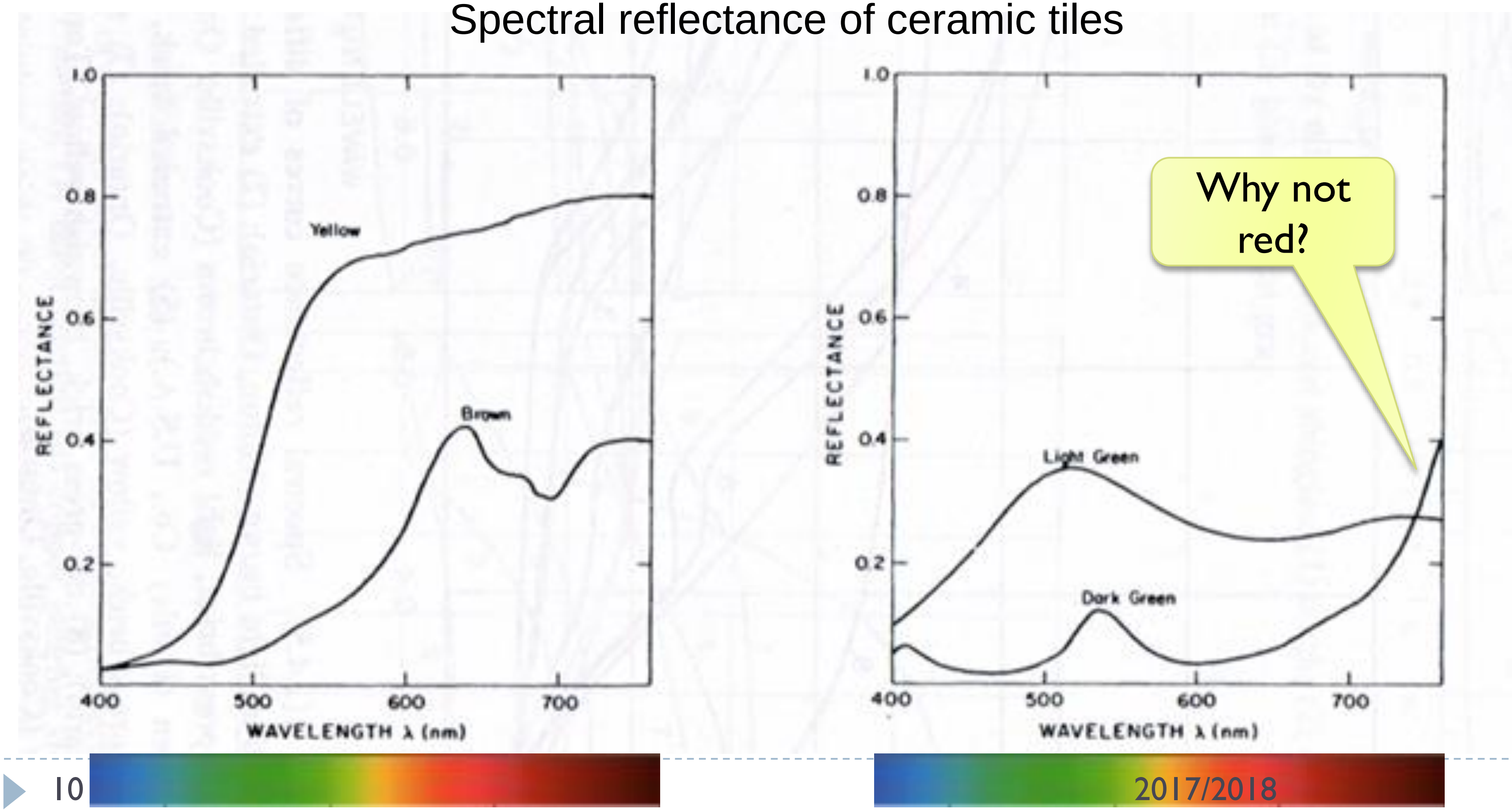


Reflectance

- Most of the light we see is reflected from objects
- These objects absorb a certain part of the light spectrum

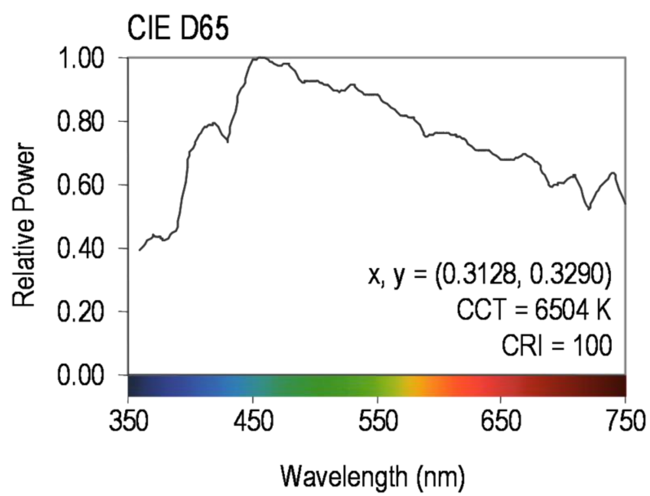
Spectral reflectance of ceramic tiles

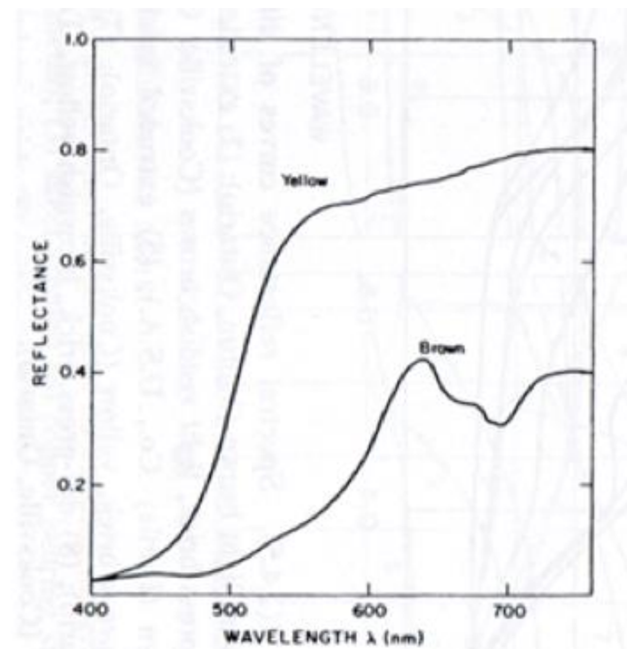


Reflected light

$$L(\lambda) = I(\lambda) \times R(\lambda)$$

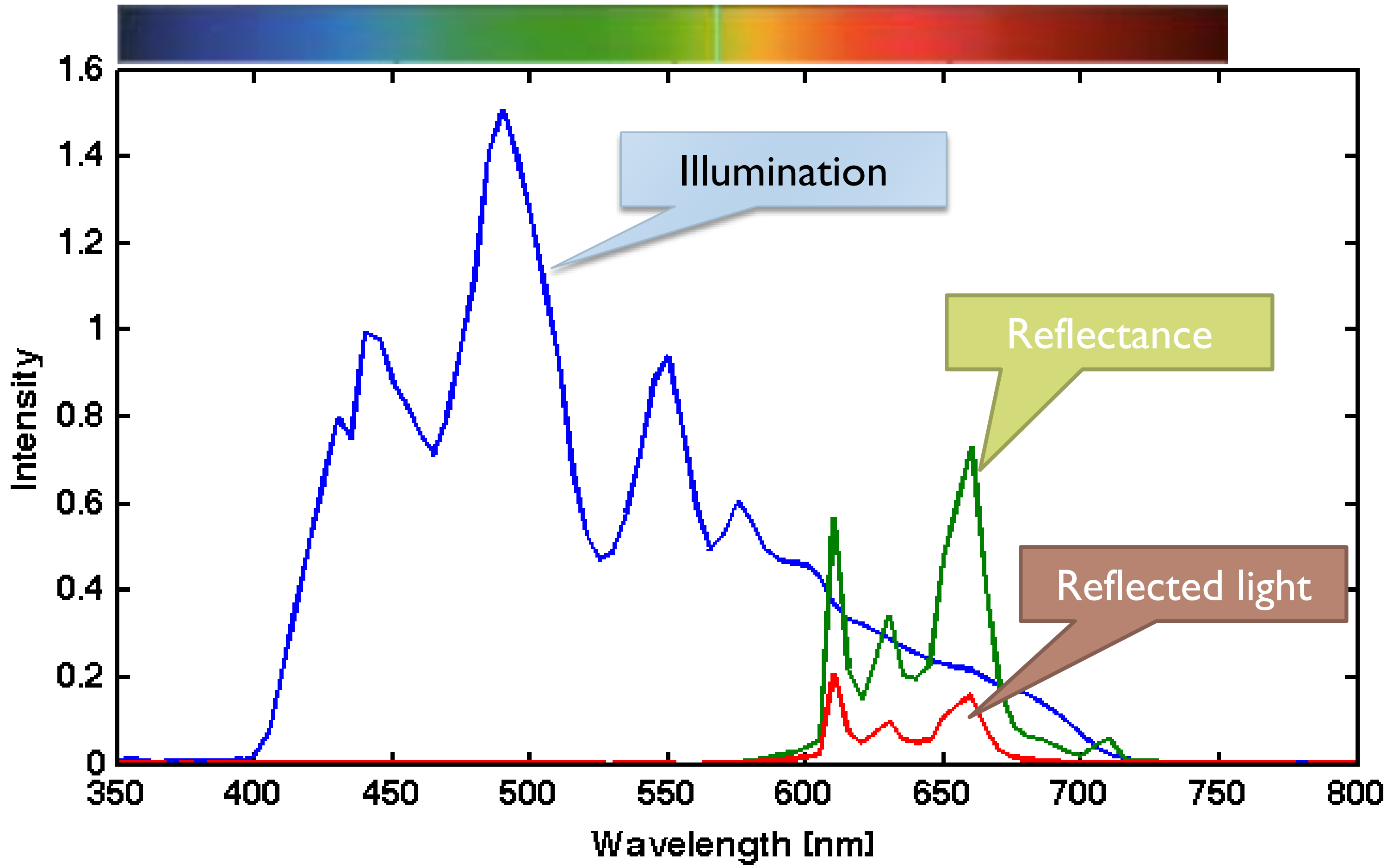
- Reflected light = illumination * reflectance





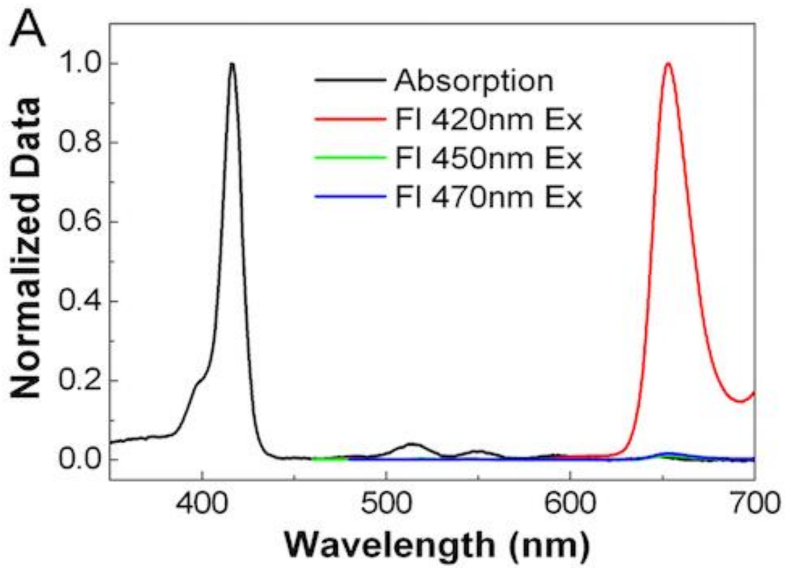
The same object may appear to have different color under different illumination.

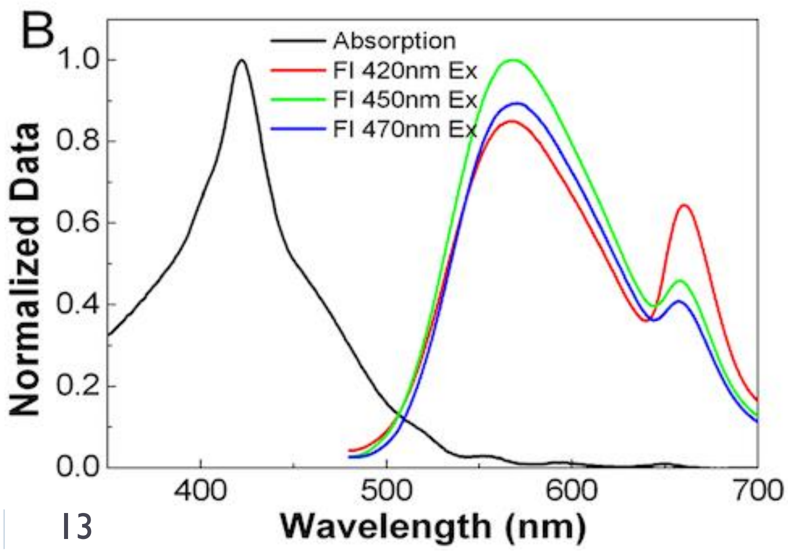
Example

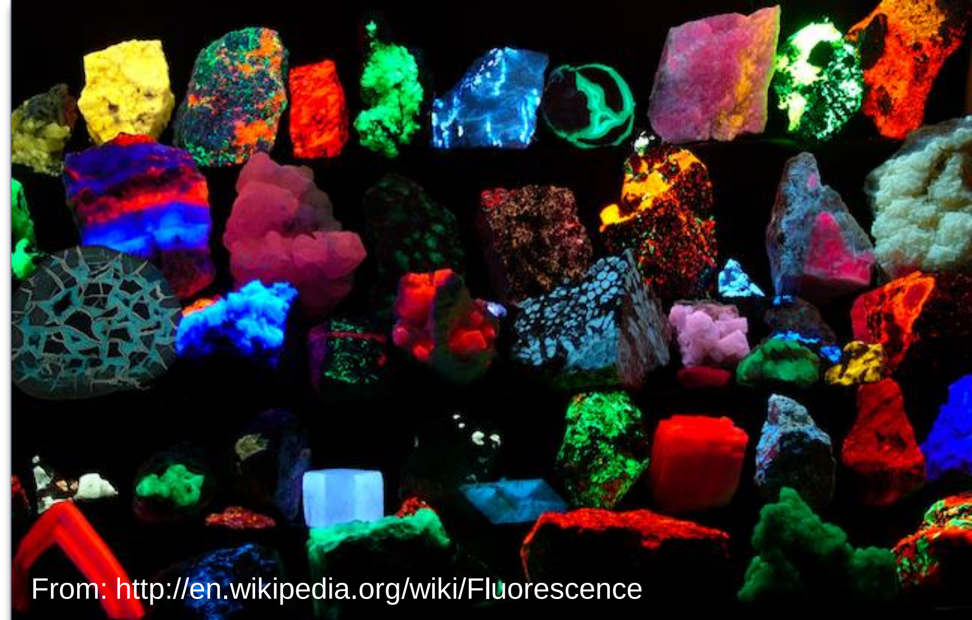


Can any paint be brighter than white?

Fluorescence







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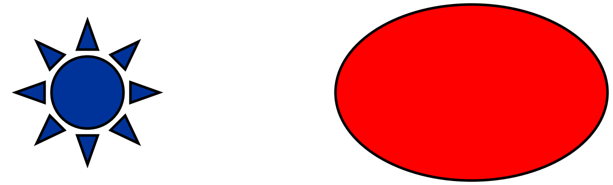
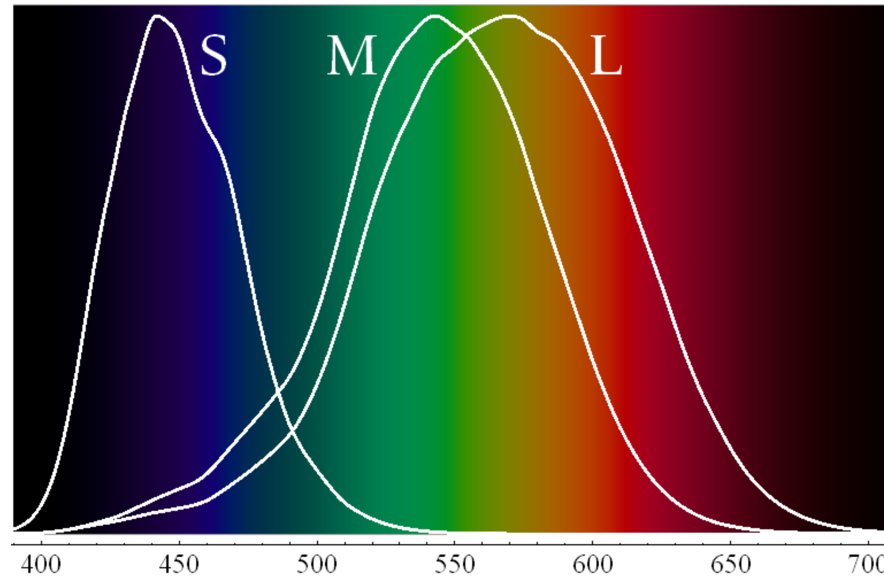


Colour vision

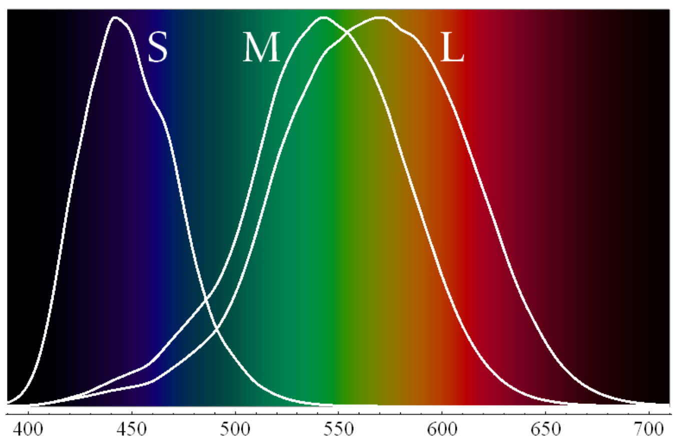
- Cones are the photreceptors responsible for color vision
  - Only daylight, we see no colors when there is not enough light
- Three types of cones
  - S – sensitive to short wavelengths
  - M – sensitive to medium wavelengths
  - L – sensitive to long wavelengths

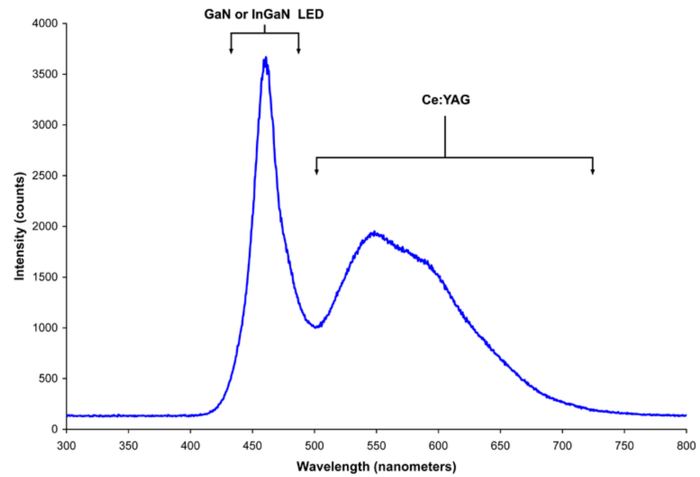


Sensitivity curves – probability that a photon of that wavelengths will be absorbed by a photoreceptor

Perceived light

- cone response = sum(sensitivity * reflected light)





Although there is an infinite number of wavelengths, we have only three photoreceptor types to sense differences between light spectra

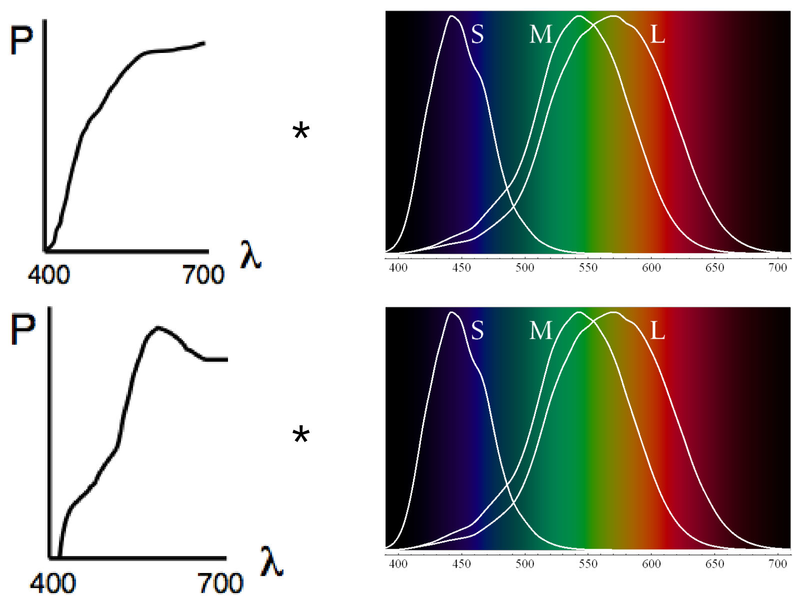
Formally

$$R_S = \int_{380}^{730} S_S(\lambda) \cdot L(\lambda) d\lambda$$

Index S for S-cones

Metamers

- Even if two light spectra are different, they may appear to have the same colour
- The light spectra that appear to have the same colour are called **metamers**
- Example:



$= [L_1, M_1, S_1]$

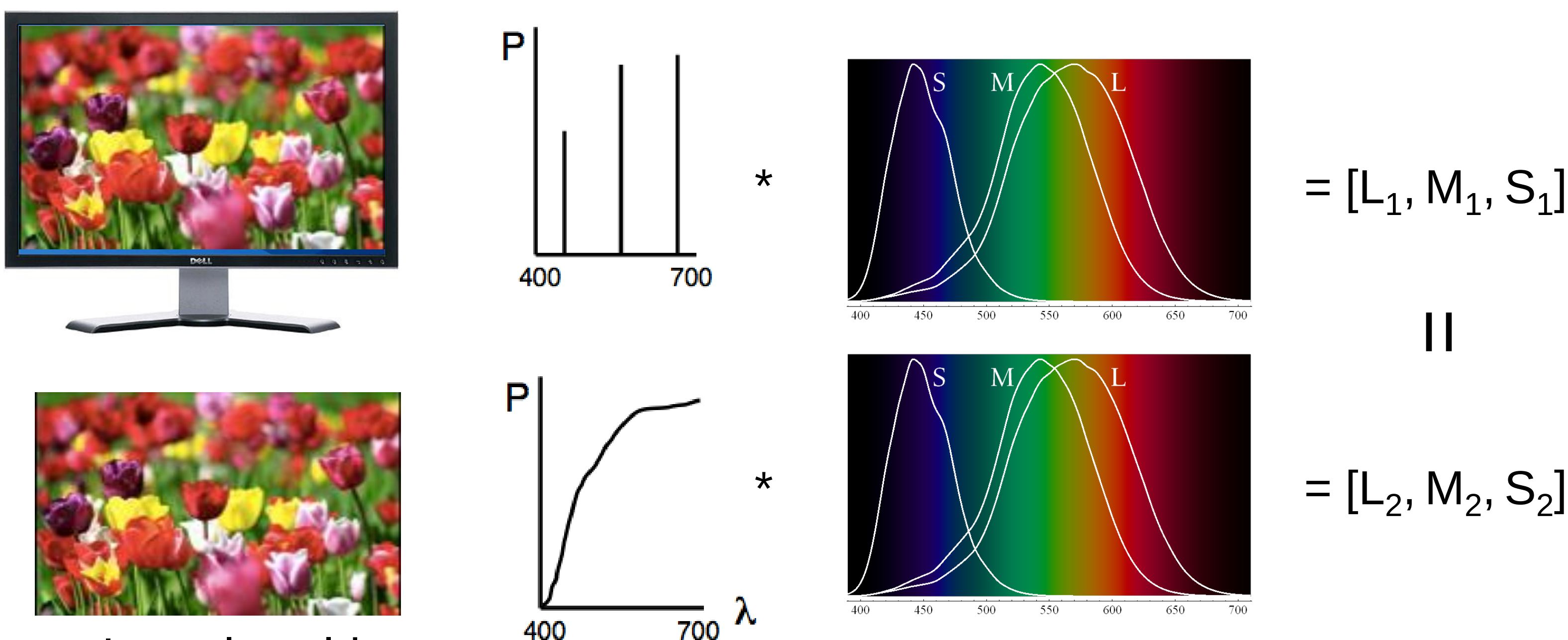
$||$

$= [L_2, M_2, S_2]$

Practical application of metamerism

- Displays do not emit the same light spectra as real-world objects
- Yet, the colours on a display look almost identical

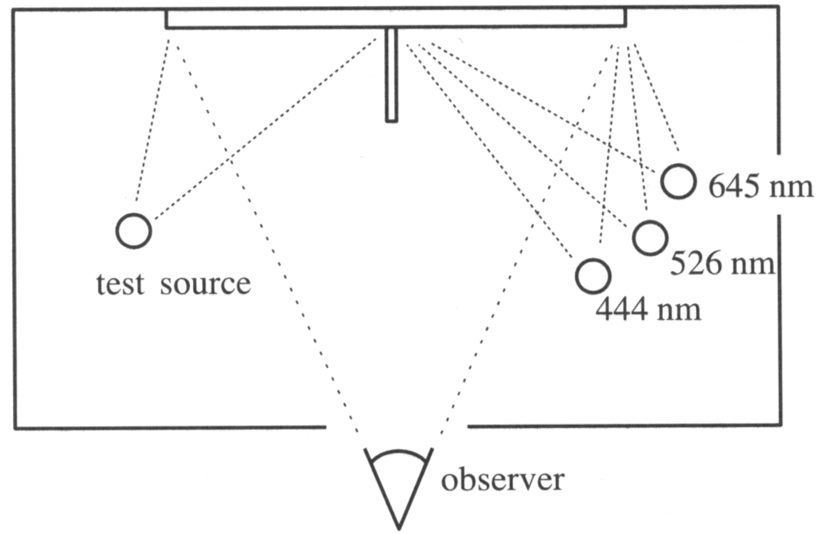
On display

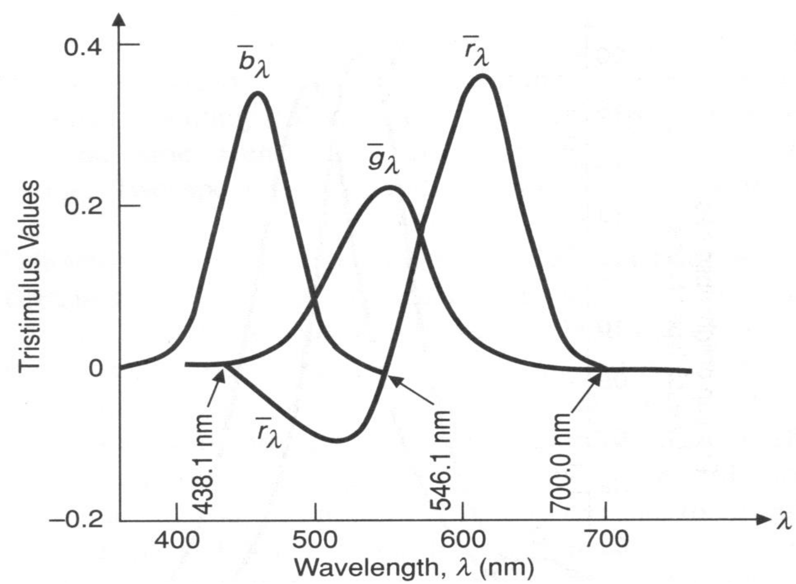


In real world

Tristimulus Colour Representation

- Observation
  - Any colour can be matched using three linear independent reference colours
  - May require "negative" contribution to test colour
  - Matching curves describe the value for matching mono-chromatic spectral colours of equal intensity
    - With respect to a certain set of primary colours



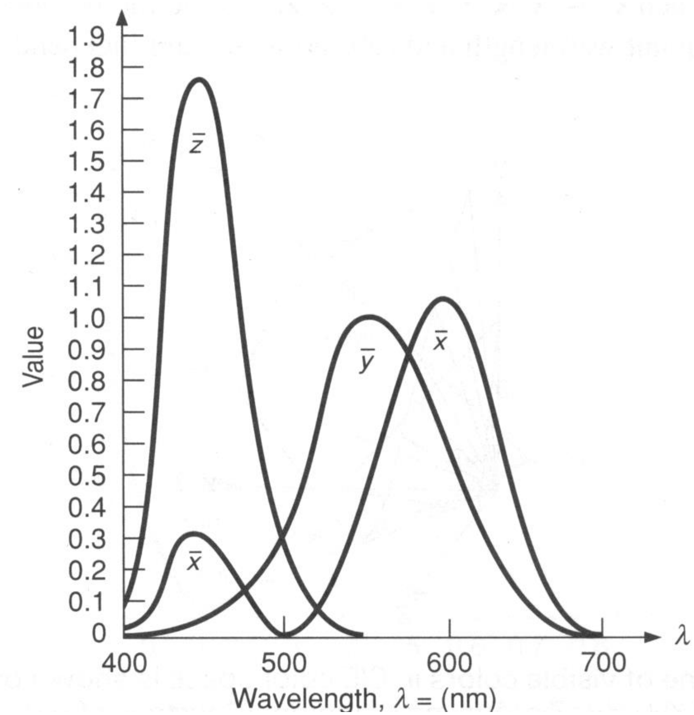


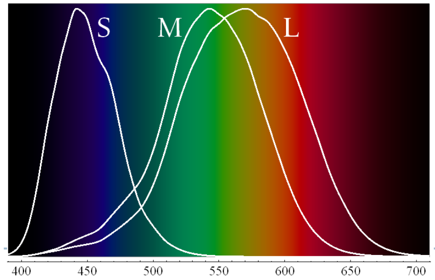
Standard Colour Space CIE-XYZ

- CIE Experiments [Guild and Wright, 1931]
  - Colour matching experiments
  - Group ~12 people with „normal“ colour vision
  - 2 degree visual field (fovea only)
- CIE 2006 XYZ
  - Derived from LMS color matching functions by Stockman & Sharpe
  - S-cone response differs the most from CIE 1931
- CIE-XYZ Colour Space
  - Goals
    - Abstract from concrete primaries used in experiment
    - All matching functions are positive
    - One primary is roughly proportionally to light intensity

Standard Colour Space CIE-XYZ

- Standardized imaginary primaries CIE XYZ (1931)
  - Could match all physically realizable colour stimuli
  - Y is roughly equivalent to luminance
    - Shape similar to luminous efficiency curve
  - Monochromatic spectral colours form a curve in 3D XYZ-space





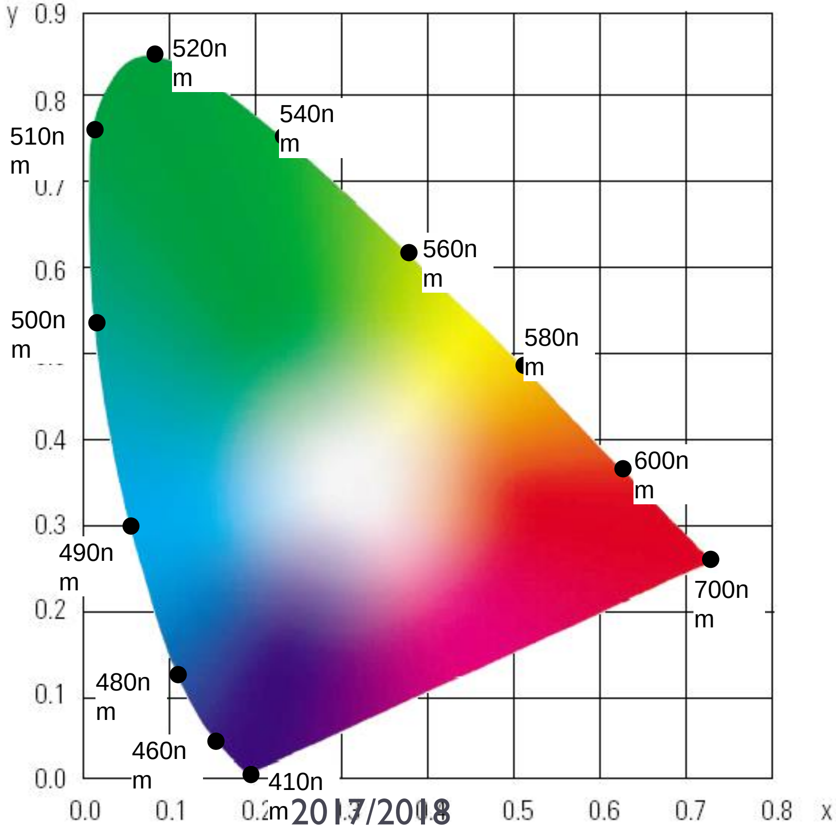
Cone sensitivity curves can be obtained by a linear transformation of CIE XYZ

CIE chromaticity diagram

- *chromaticity* values are defined in terms of x, y, z

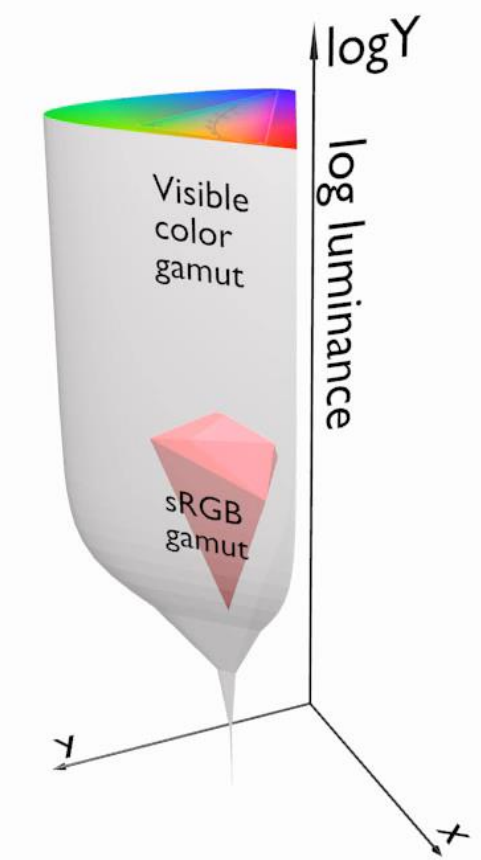
$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z} \quad \therefore \quad x + y + z = 1$$

  - ignores luminance
  - can be plotted as a 2D function
- pure colours (single wavelength) lie along the outer curve
- all other colours are a mix of pure colours and hence lie inside the curve
- points outside the curve do not exist as colours



Visible vs. displayable colours

- All physically possible and visible colours form a solid in XYZ space
- Each display device can reproduce a subspace of that space
- A chromacity diagram is a slice taken from a 3D solid in XYZ space
- Colour Gamut – the solid in a colour space
  - Usually defined in XYZ to be device-independent



Luminance – photometric quantity

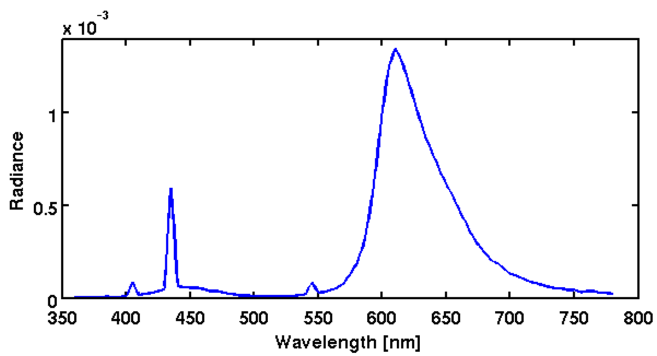
- Luminance – perceived brightness of light, adjusted for the sensitivity of the visual system to wavelengths

Luminance

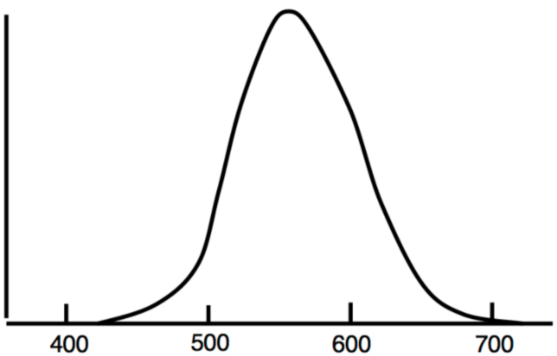
$$L_v = \int_{350}^{700} L(\lambda)V(\lambda)d\lambda$$

ISO Unit: cd/m²

Light spectrum (radiance)

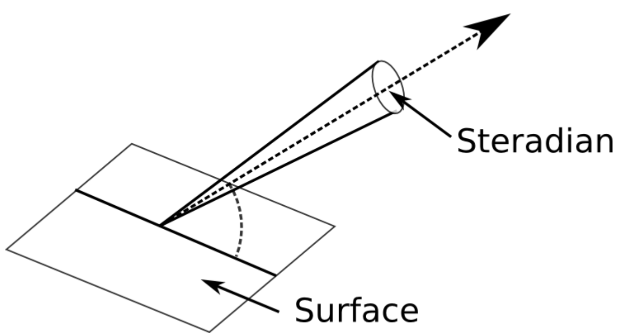


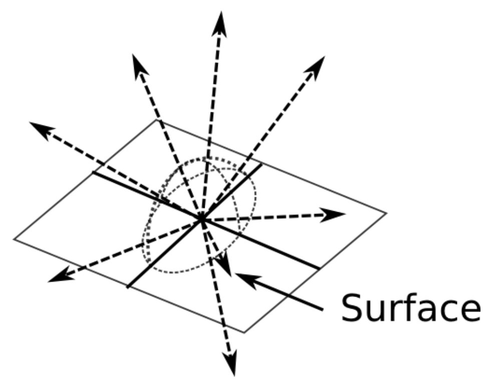
Luminous efficiency function (weighting)

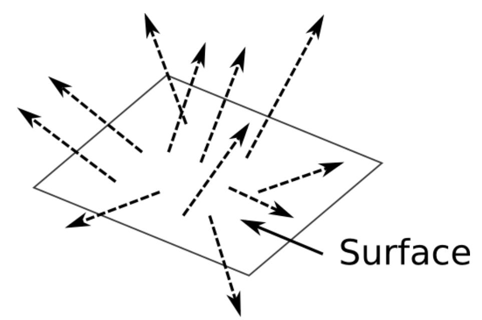


Photometric units

Quantity	Units	Symbol
Luminance	candela per sq. meter [cd/m^2=lm/(sr*m^2)]	L_V
Illuminance	lux [lx = lm/m^2 = cd*sr/m^2]	E_V
Luminous flux	lumen [lm = cd*sr]	F







Luminance – light emitted from a point on a surface in a particular direction

Illuminance – light emitted from a point on a surface in all directions

Luminous flux – light emitted from the entire surface in all directions

All these units can measure either incoming or emitted light

Luminous flux - lumens

- Total light emitted
- Useful to measure and compare light sources
  - For example fluorescent and incandescent light bulbs
- But also used for digital projectors

Integrating sphere – to measure all light emitted

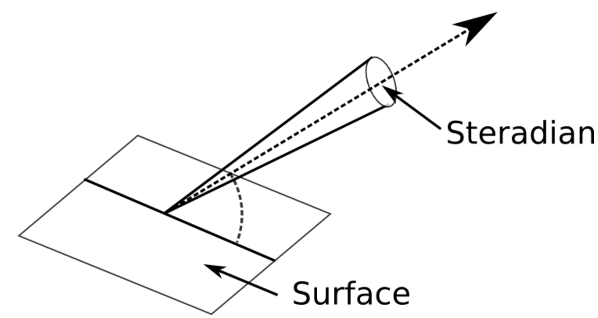
Illuminance - lux

- Measures light coming (or emitted) from all directions
- Useful to measure lighting conditions
  - Whether street lighting is bright enough, etc.

Illuminance meter

Luminance – candela per square meter

- Light emitted (or incomming) from a point in a particular direction
- Luminance is the same regardless of the distance to the emitter
- The light sensed by our eyes is relative to luminance

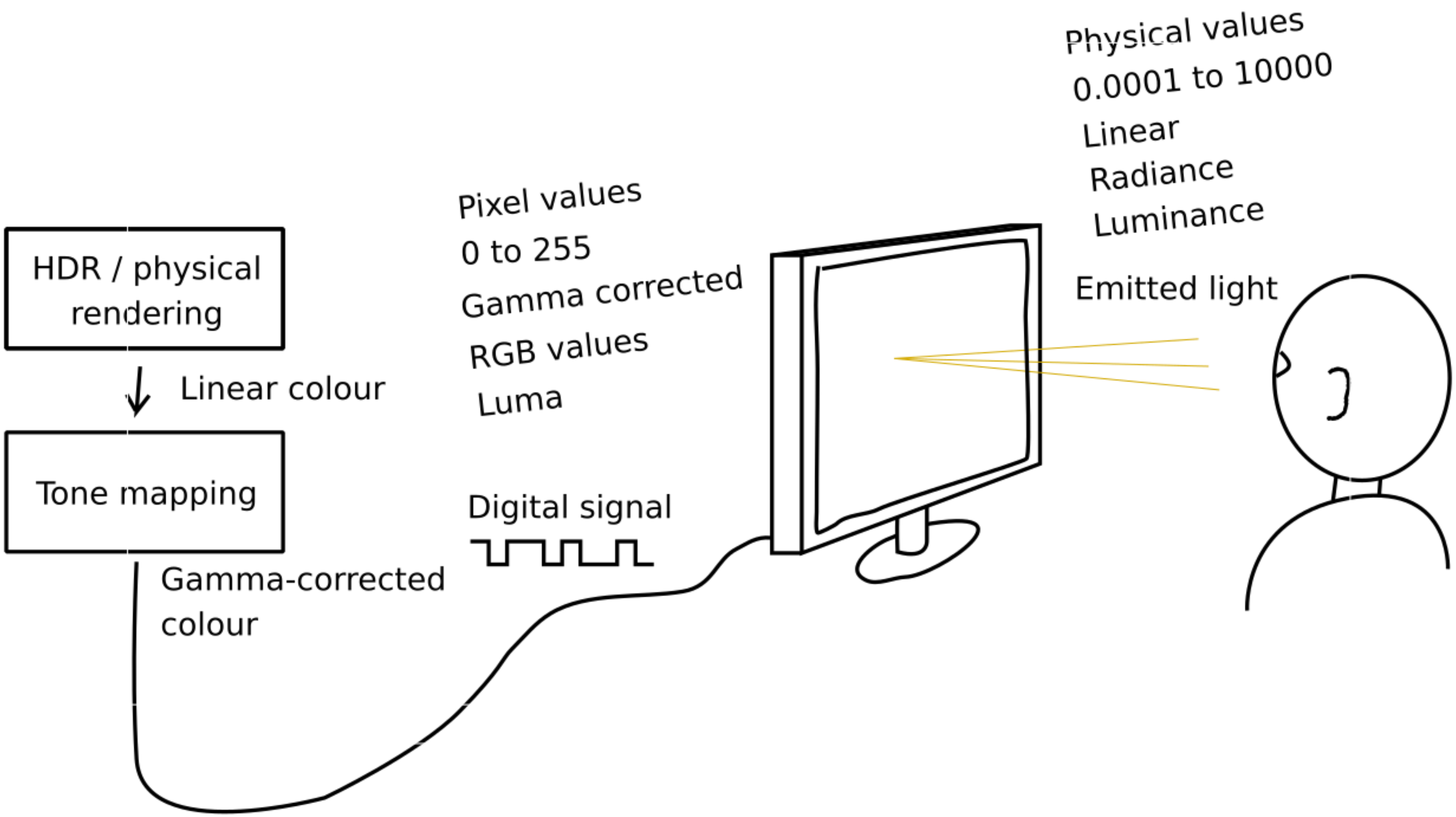


Radiometric vs. Photometric units

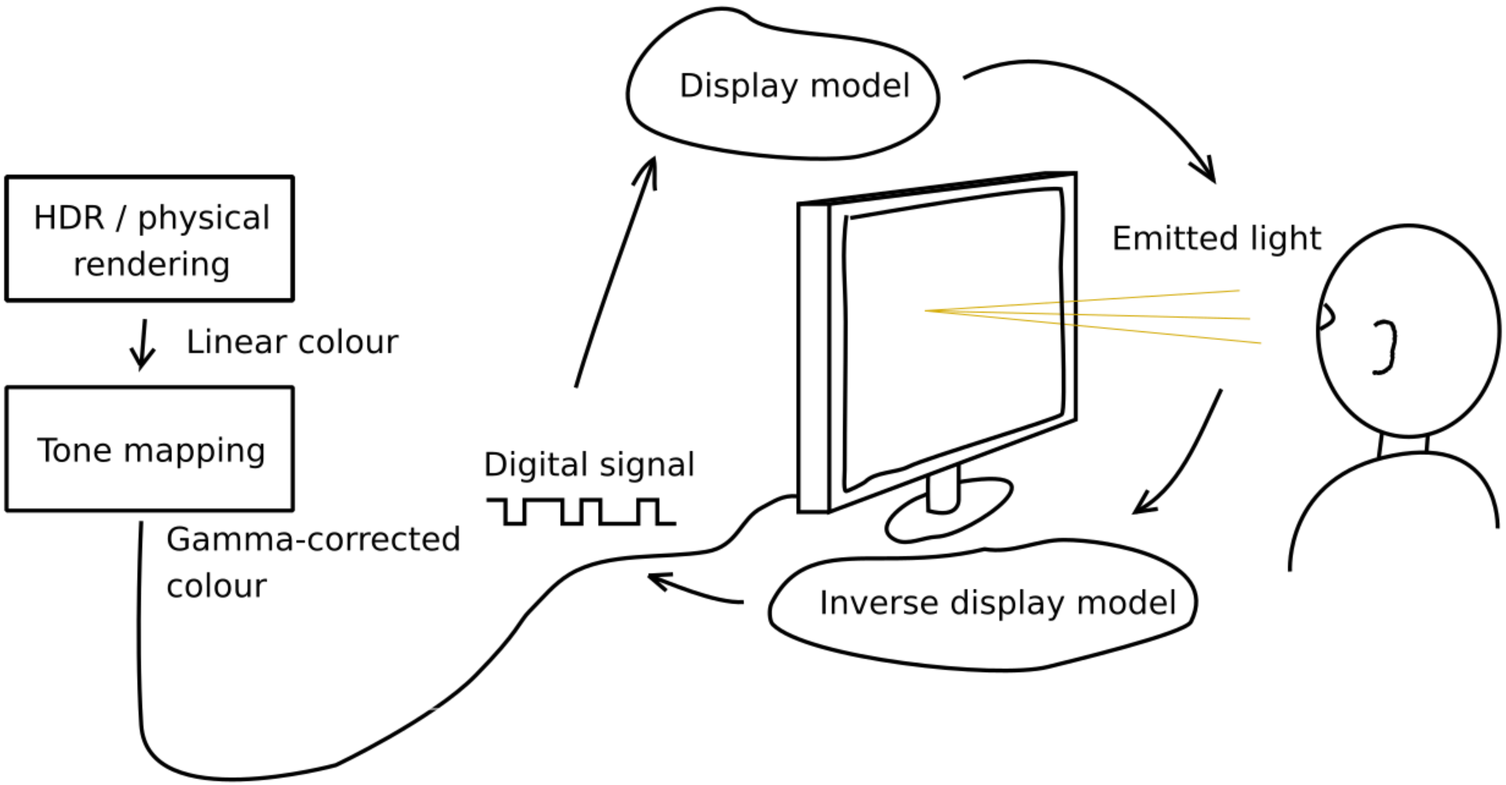
Photometry	Radiometry
Luminance [cd m^{-2}]	Radiance [W sr^{1} m^{-2}]
Illuminance [lx = lm m^{-2} = cd sr m^{-2}]	Irradiance / Exitance / Radiosity [W m^{-2}]
Luminous flux [lm = cd sr]	Radiant flux [W]

- Radiometric units integrate light over **all wavelengths** (visible and invisible)
- **Spectral radiance / irradiance / radiant flux** describe light for a single wavelength
- But, in computer graphics radiometric units are often assumed to capture a quantity integrated over a spectral basis function (e.g. red, green, blue)
- In color science, the product of radiance with a colour matching function is called **trichromatic colour value**

Linear vs. gamma-corrected values



Linear vs. gamma-corrected values



Basic display model: gamma correction

- Gamma correction is used to encode luminance or tri-stimulus color values (RGB) in imaging systems (displays, printers, cameras, etc.)

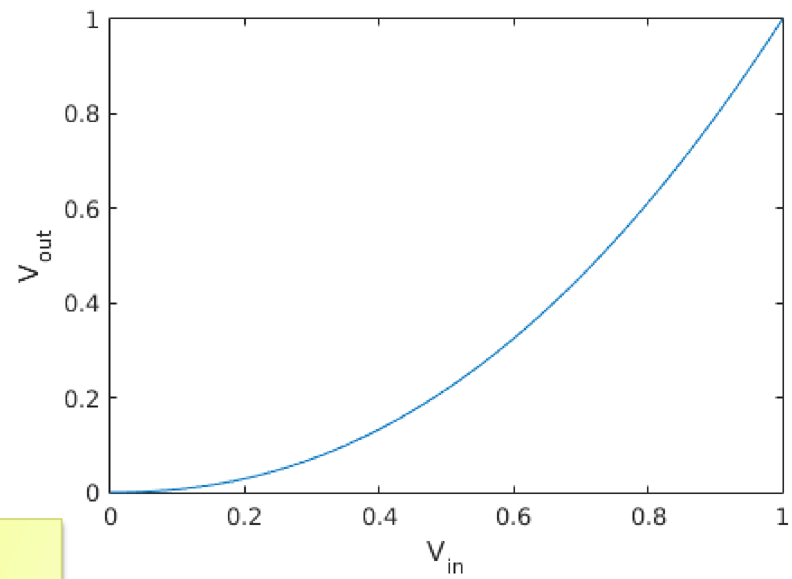
Gain

Gamma (usually =2.2)

$$V_{out} = a \cdot V_{in}^{\gamma}$$

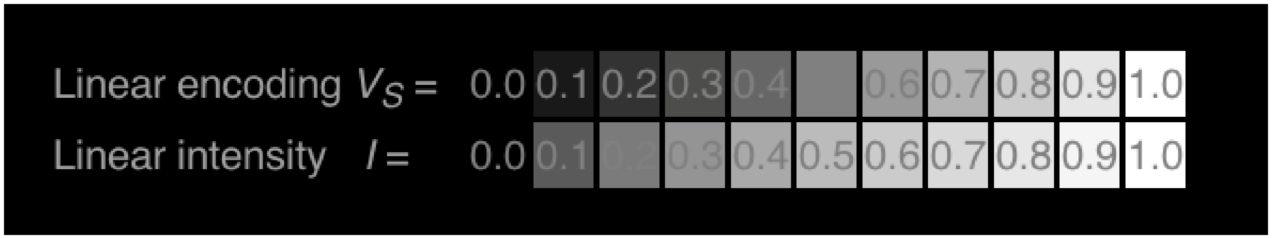
(relative) Luminance
Physical signal

Luma
Digital signal (0-1)



For color images: $R = a \cdot (R')^{\gamma}$ and the same for green and blue

Why is gamma needed?



<- Pixel value (luma)

<- Luminance

- “Gamma corrected” pixel values give a scale of brightness levels that is more perceptually uniform
- At least 12 bits (instead of 8) would be needed to encode each color channel without gamma correction
- And accidentally it was also the response of the CRT gun

Luma – gray-scale pixel value

- **Luma** - pixel brightness in *gamma corrected* units

$$L' = 0.2126R' + 0.7152G' + 0.0722B'$$

  - R', G' and B' are *gamma corrected* colour values
  - Prime symbol denotes "gamma corrected"
  - Used in image/video coding

- Note that relative **luminance** if often approximated with

$$L = 0.2126R + 0.7152G + 0.0722B$$
$$= 0.2126(R')^{\gamma} + 0.7152(G')^{\gamma} + 0.0722(B')^{\gamma}$$

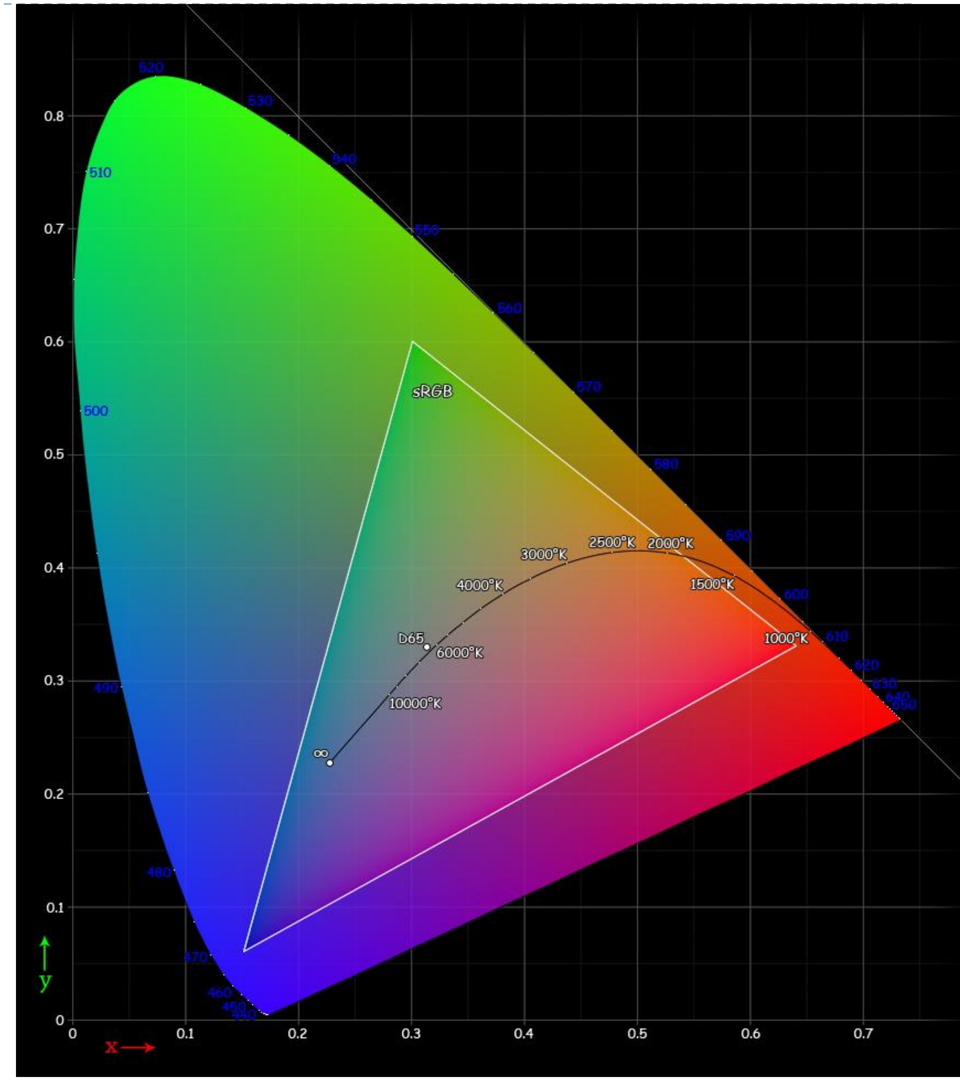
- $R, G,$ and B are *linear* colour values
- Luma and luminance are different quantities despite similar formulas

sRGB color space

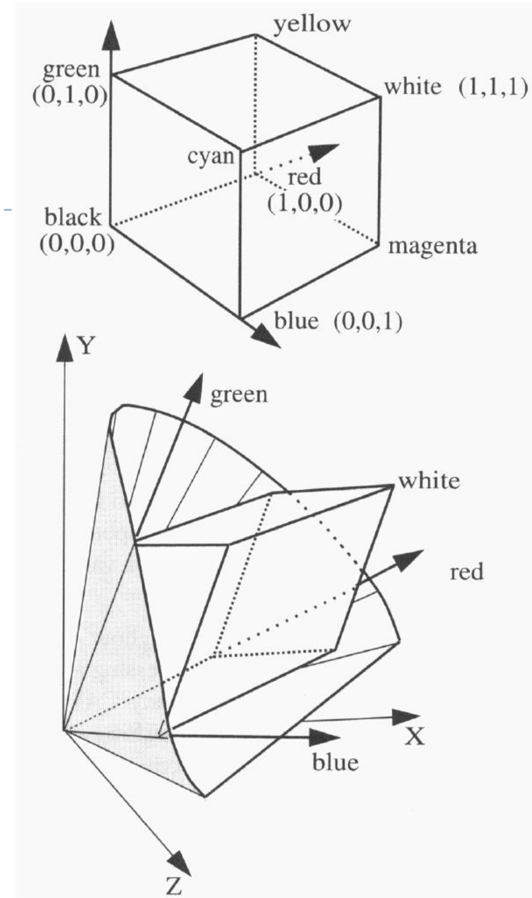
- "RGB" color space is not a standard. Colors may differ depending on the choice of the primaries
- "sRGB" is a standard color space, which most displays try to mimic (standard for HDTV)

Chromaticity	Red	Green	Blue	White point
x	0.6400	0.3000	0.1500	0.3127
y	0.3300	0.6000	0.0600	0.3290
z	0.0300	0.1000	0.7900	0.3583

- The chromacities above are also known as Rec. 709



sRGB color space



- Two step XYZ – sRGB transformation:
  - Step 1: Linear color transform

$$\begin{bmatrix} R_{\text{linear}} \\ G_{\text{linear}} \\ B_{\text{linear}} \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

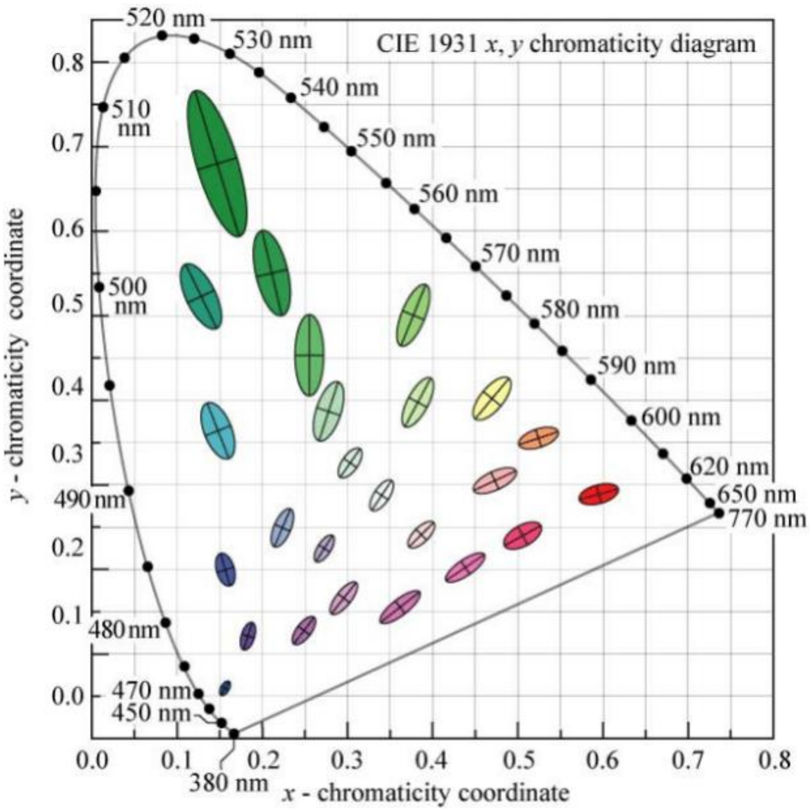
  - Step 2: Non-linearity

$$C_{\text{srgb}} = \begin{cases} 12.92 C_{\text{linear}}, & C_{\text{linear}} \le 0.0031308 \\ (1+a) C_{\text{linear}}^{1/2.4} - a, & C_{\text{linear}} > 0.0031308 \end{cases}$$

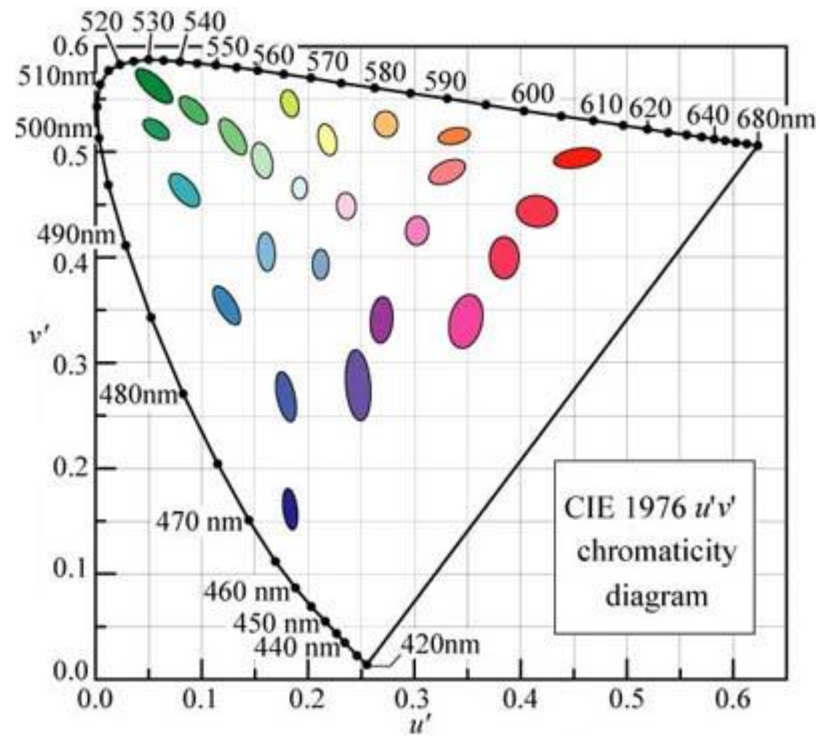
$$a = 0.055$$

Perceptually uniformity

- MacAdam ellipse - visually indistinguishable colours



In CIE xy chromatic coordinates



In CIE u'v' chromatic coordinates

CIE L*u*v* and u'v'

- Approximately perceptually uniform
- u'v' chromacity

$$u' = \frac{4X}{X+15Y+3Z} = \frac{4x}{-2x+12y+3}$$
$$v' = \frac{9Y}{X+15Y+3Z} = \frac{9y}{-2x+12y+3}$$

- CIE LUV

Lightness

$$L^* = \begin{cases} \left(\frac{29}{3}\right)^3 Y/Y_n, & Y/Y_n \le \left(\frac{6}{29}\right)^3 \\ 116(Y/Y_n)^{1/3} - 16, & Y/Y_n > \left(\frac{6}{29}\right)^3 \end{cases}$$

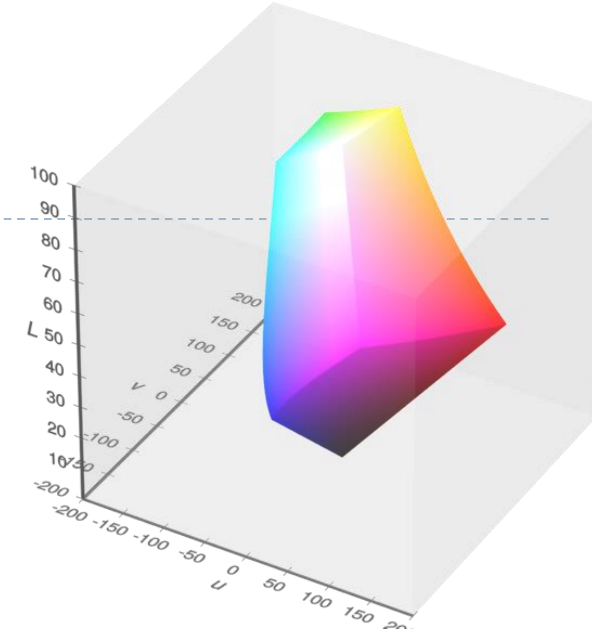
Chromacity coordinates

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

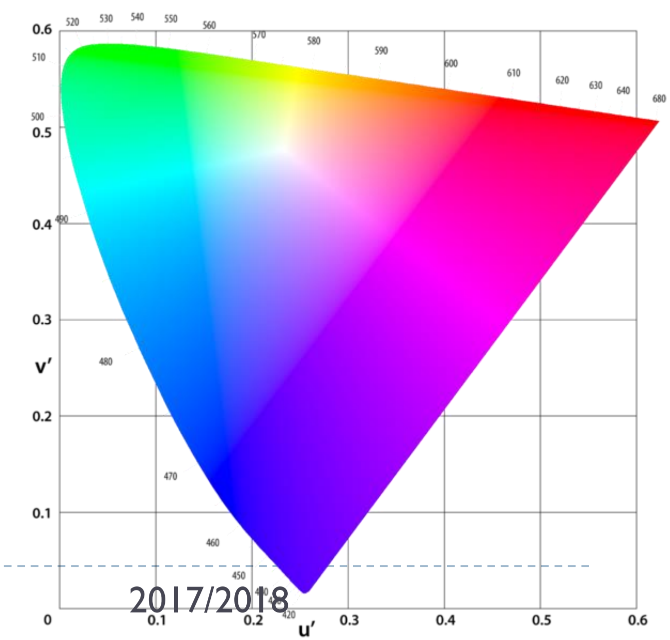
Colours less distinguishable when dark

- Hue and chroma

$$C^*_{uv} = \sqrt{(u^*)^2 + (v^*)^2}$$
$$h_{uv} = \text{atan2}(v^*, u^*),$$



sRGB in CIE L*u*v*



CIE L*a*b* colour space

- Another approximately perceptually uniform colour space

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

$$a^\star = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right)$$

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

Trichromatic values of the white point, e.g.

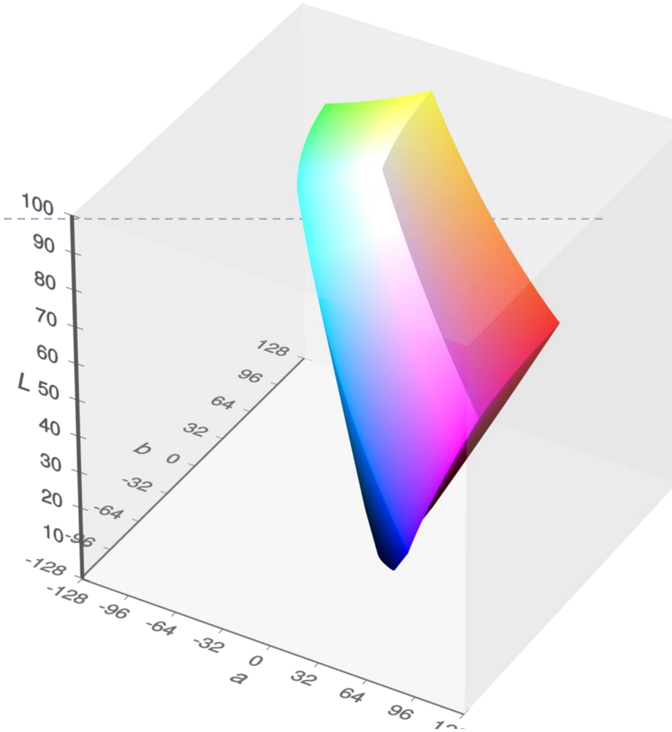
$$X_n = 95.047,\quad Y_n = 100.000,\quad Z_n = 108.883$$

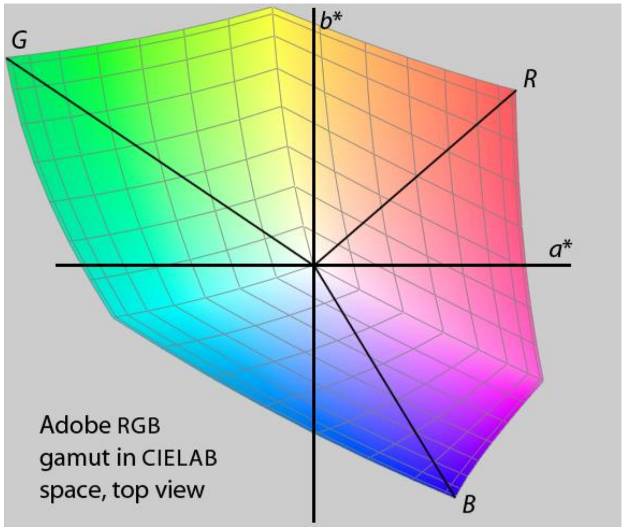
$$f(t) = \begin{cases} \sqrt[3]{t} & \text{if } t > \delta^3 \\ \frac{t}{3\delta^2} + \frac{4}{29} & \text{otherwise} \end{cases}$$

$$\delta = \frac{6}{29}$$

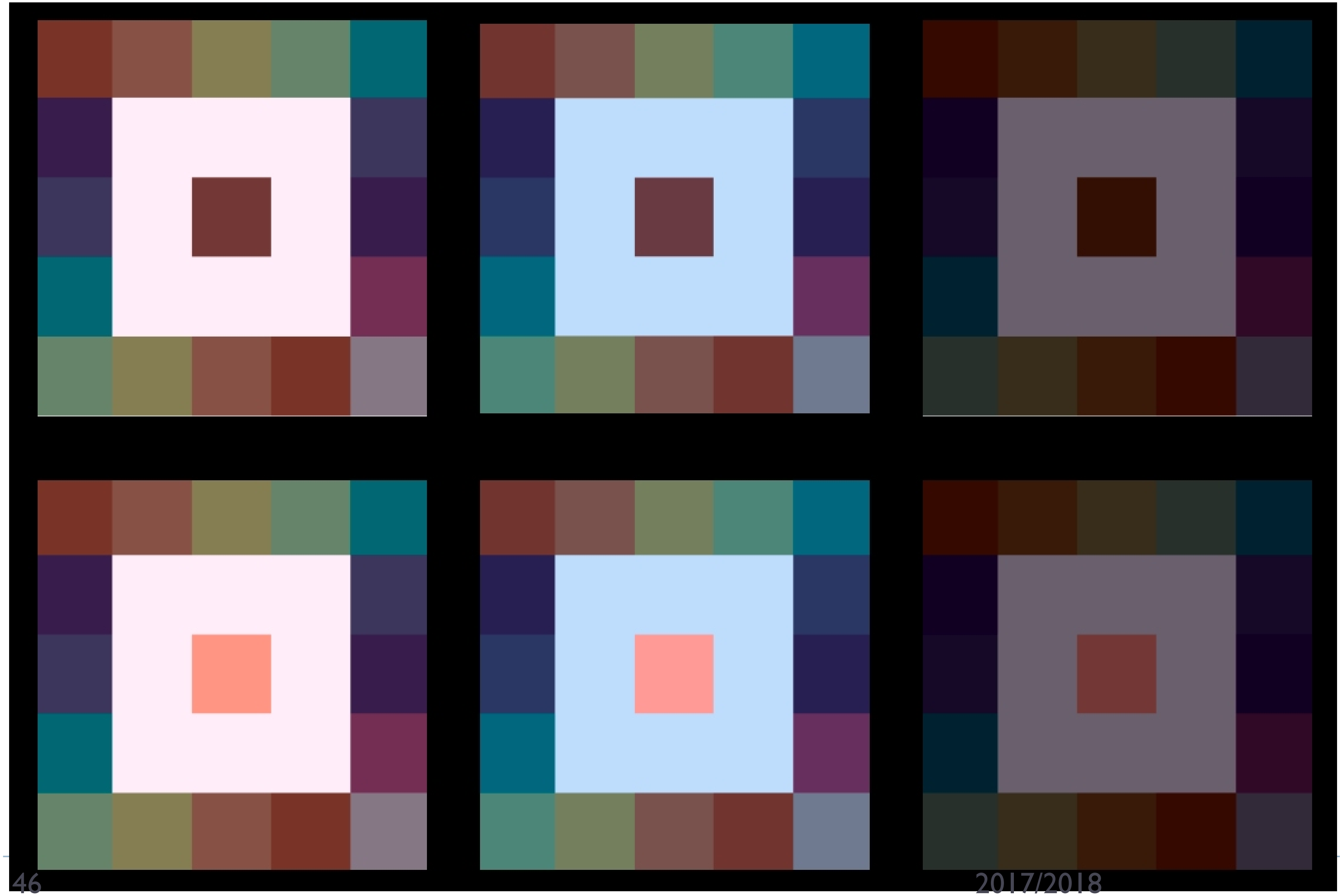
- Chroma and hue

$$C^\star = \sqrt{a^{\star 2} + b^{\star 2}}, \qquad h^\circ = \arctan\left(\frac{b^\star}{a^\star}\right)$$





Colour constancy



from: http://www.uv.es/vista/vistavalencia/color/color.html

Chromatic adaptation = colour constancy

- Visual system "estimates" the colour of the illuminant
  - and then attempts to discount it
- This works well if the scene fills the entire field of view
  - But is less effective for images
  - E.g. image on the computer monitor or developed print
- Therefore photographs require **white balance**
  - To discount the illuminant that is not discounted by the visual system

from Wikipedia

White point

- Displays are expected to have the white point D65
  - This corresponds to the color temperature of 6500K
  - But most displays do not strictly adhere to this specification
  - It is often possible to adjust the white point of a display
- Digital cameras need to discount illuminant
  - They estimate the color of white and make it D65 so that it looks white on displays
  - This is called white balance

From: http://en.wikipedia.org/wiki/File:Incand-3500-5500-color-temp-comparison.png

References

- Well written textbook
  - Fairchild, M. D. (2005). *Color Appearance Models* (second.). John Wiley & Sons.
- More detailed introduction to light and colour phenomena
  - Erik Reinhard, Erum Arif Khan, Ahmet Oguz Akyuz, G. J. (2008). *Color Imaging: Fundamentals and Applications*. CRC Press.