



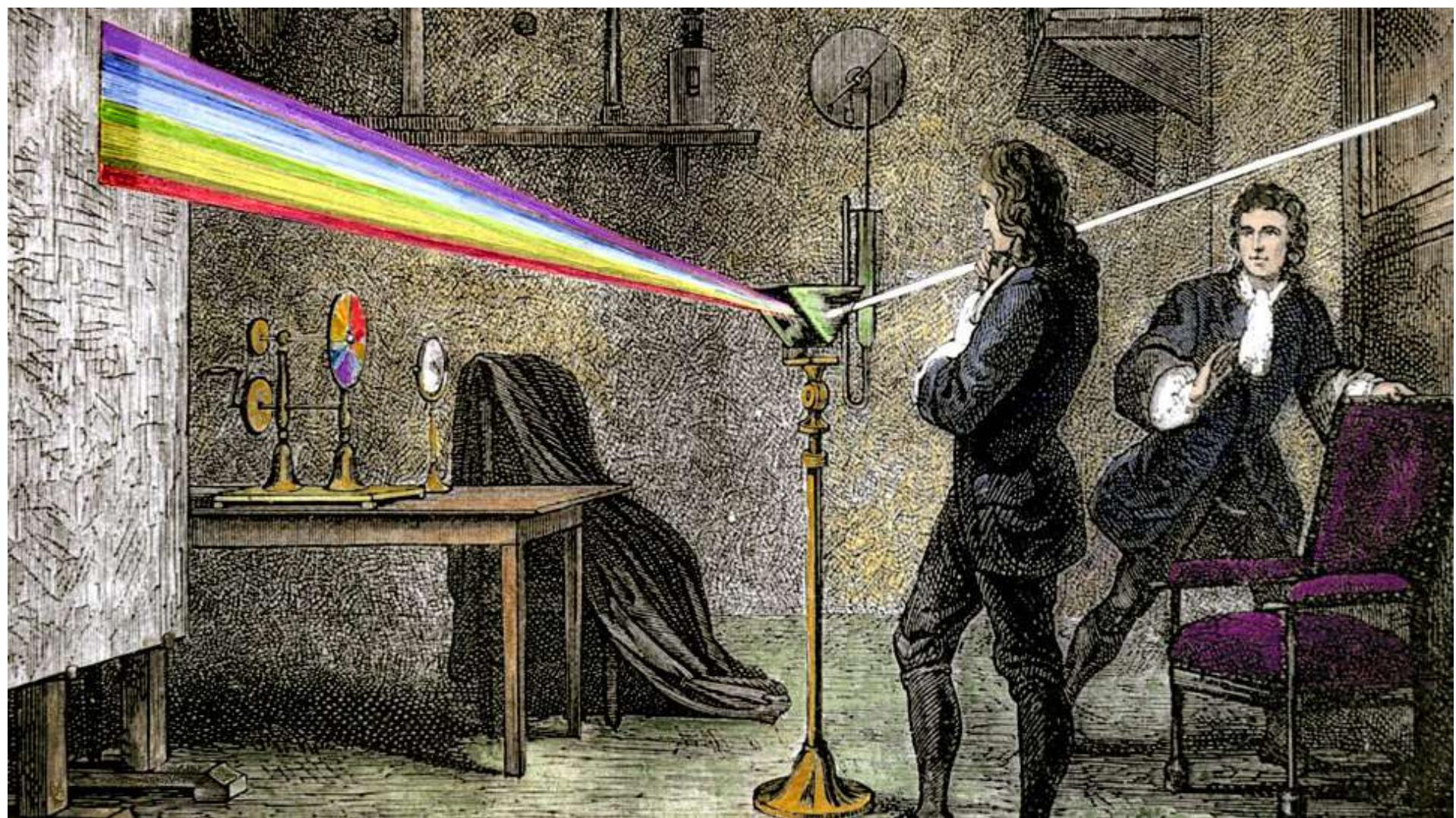
## Advanced Graphics and Image Processing

### Colour perception and colour spaces

#### Part 1/5 – physics of light

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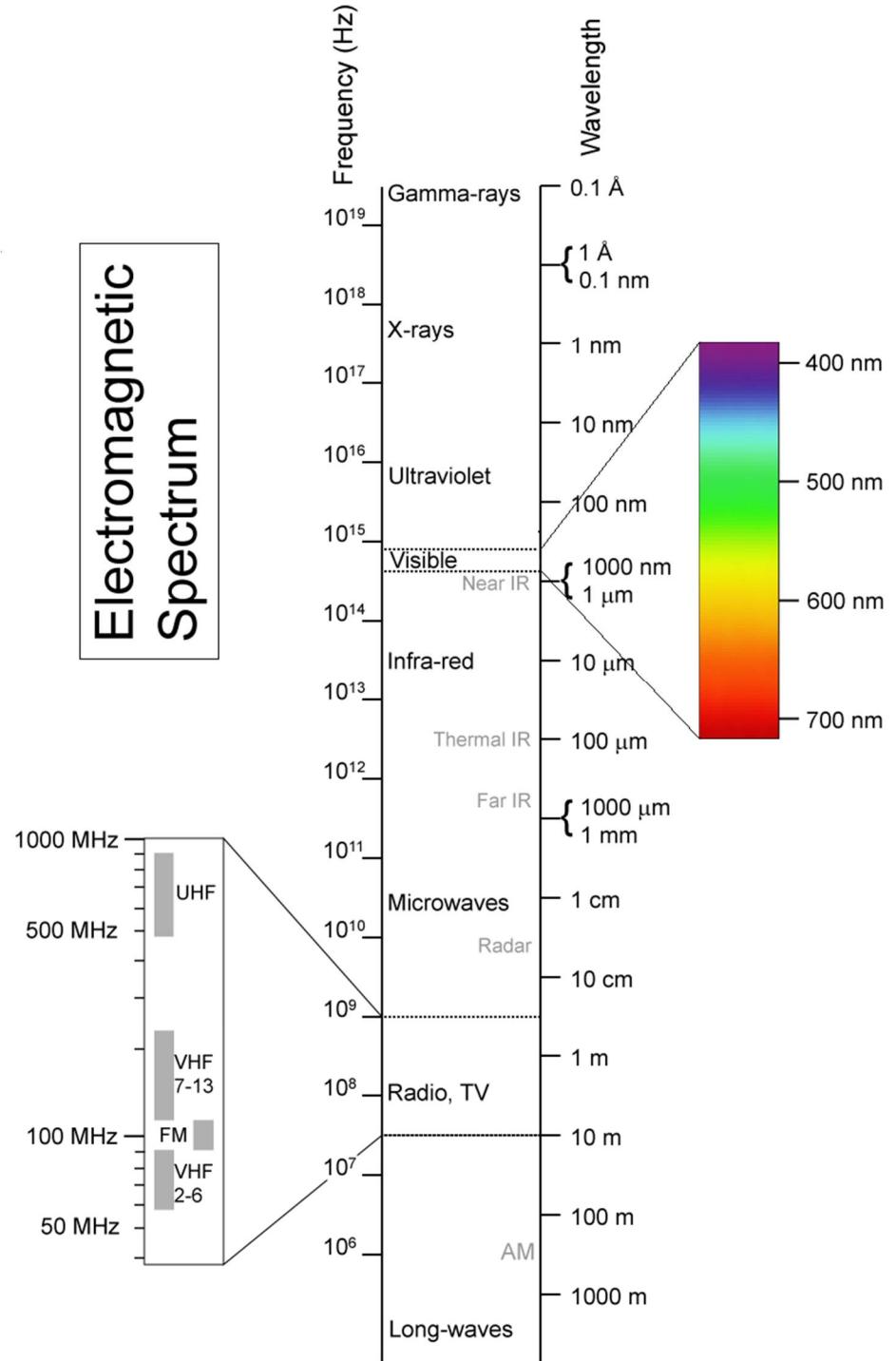


# Electromagnetic spectrum

## ▶ 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

Electromagnetic Spectrum

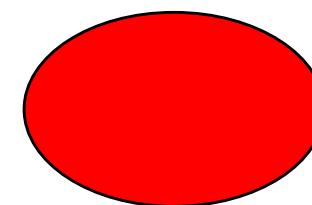
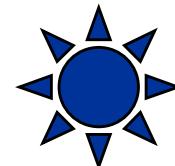


# Colour

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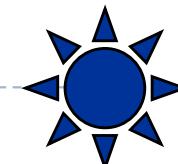
- ▶ There is no physical definition of colour – colour is the result of our perception
- ▶ For reflective displays / objects

$$\text{colour} = \text{perception}(\text{ illumination} \times \text{reflectance})$$



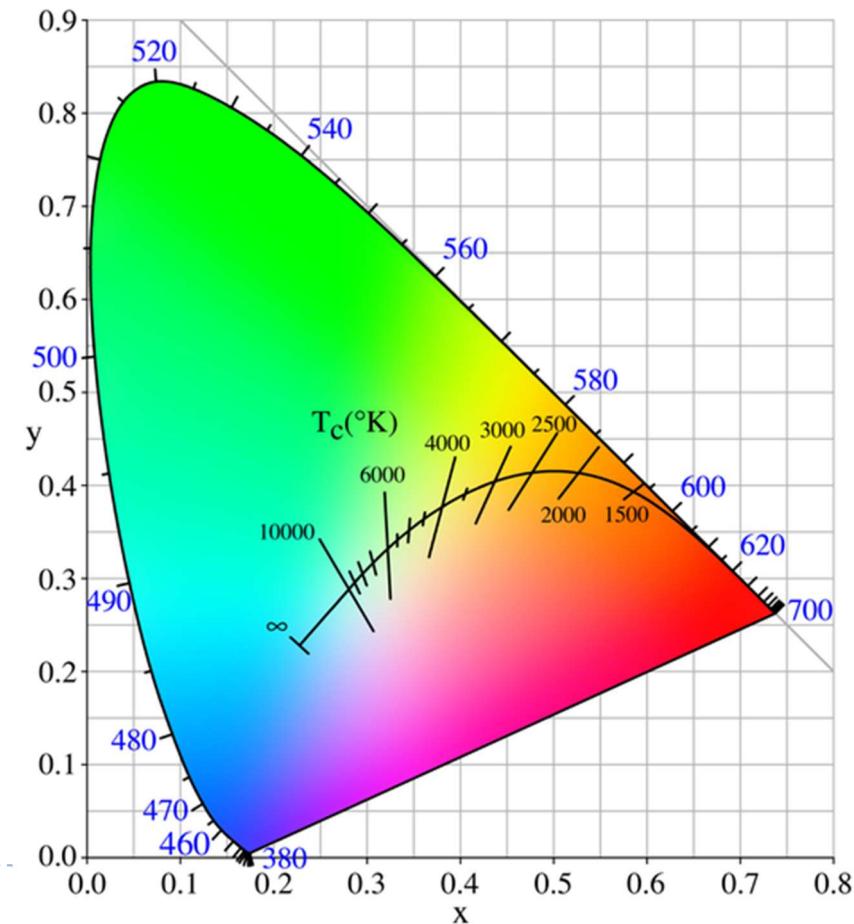
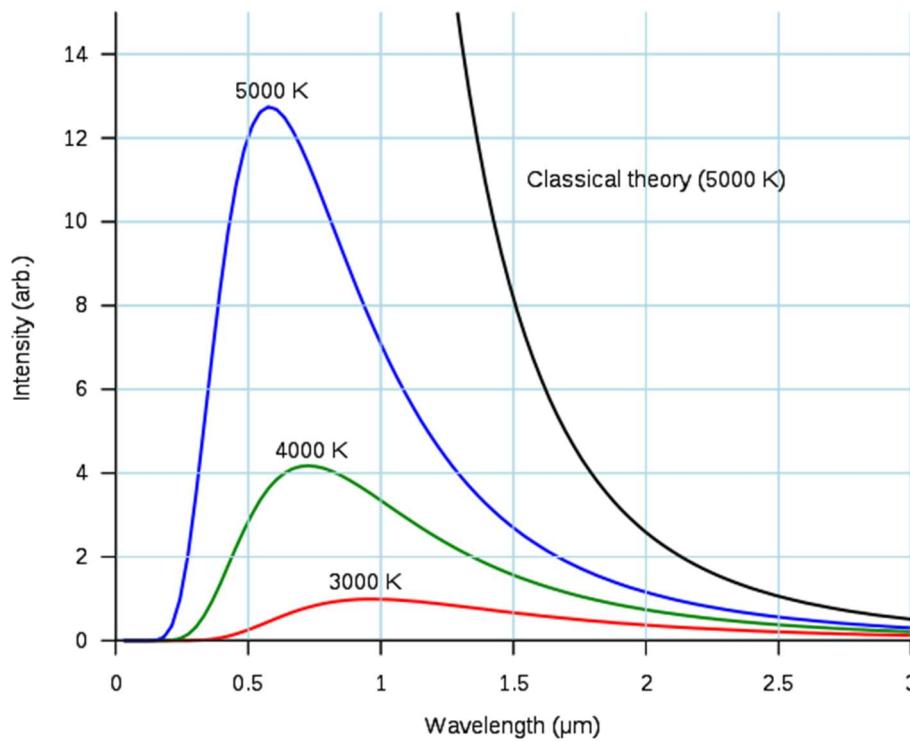
- ▶ For emissive objects or displays

$$\text{colour} = \text{perception}(\text{ emission })$$



# Black body radiation

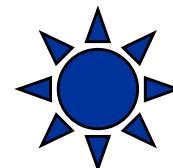
- ▶ Electromagnetic radiation emitted by a perfect absorber at a given temperature
  - ▶ Graphite is a good approximation of a black body



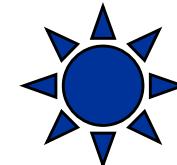
# Correlated colour temperature

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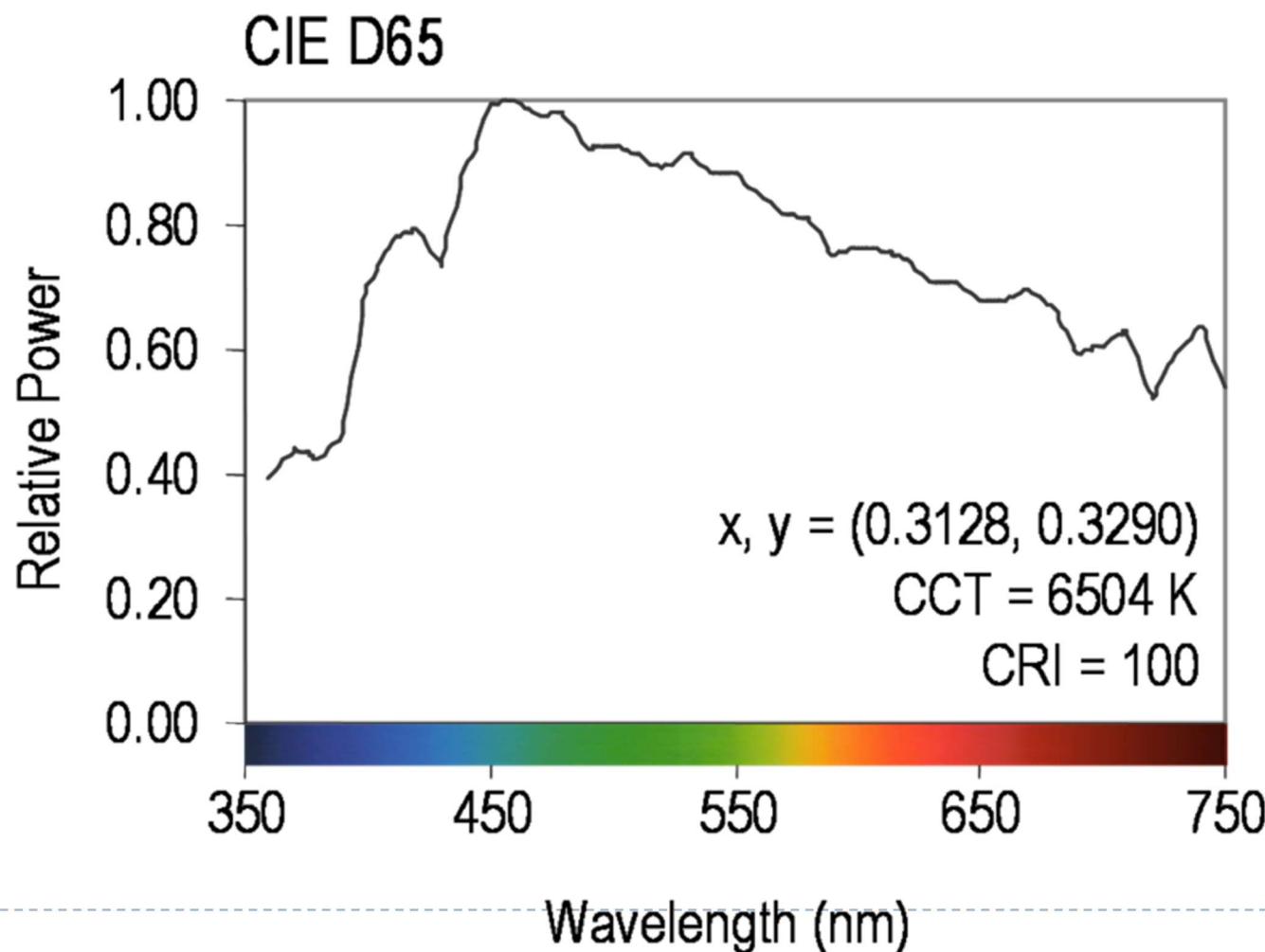
- ▶ The temperature of a black body radiator that produces light most closely matching the particular source
- ▶ Examples:
  - ▶ Typical north-sky light: 7500 K
  - ▶ Typical average daylight: 6500 K
  - ▶ Domestic tungsten lamp (100 to 200 W): 2800 K
  - ▶ Domestic tungsten lamp (40 to 60 W): 2700 K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



# Standard illuminant D65



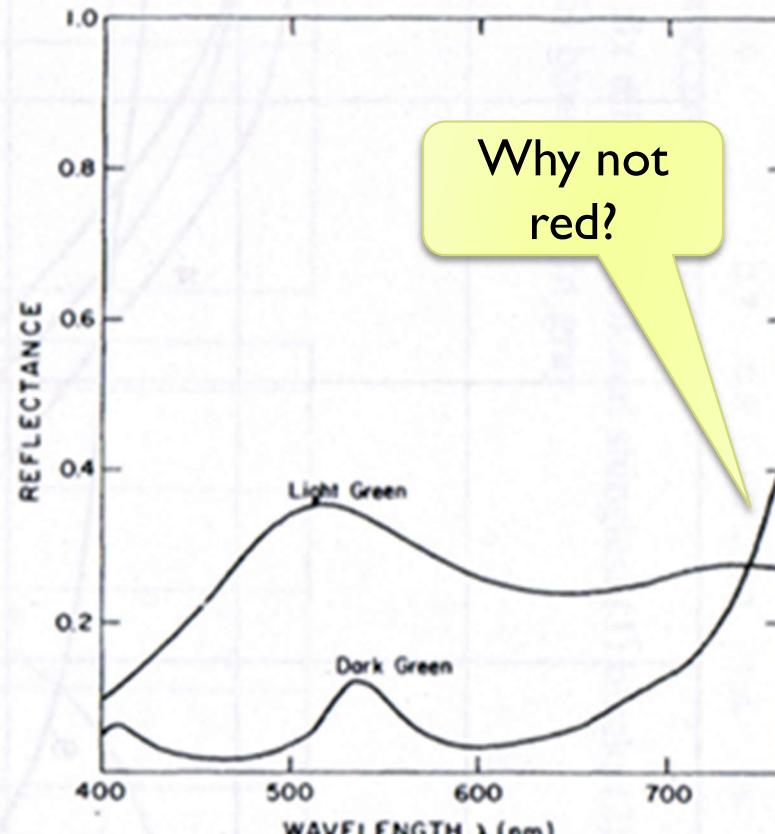
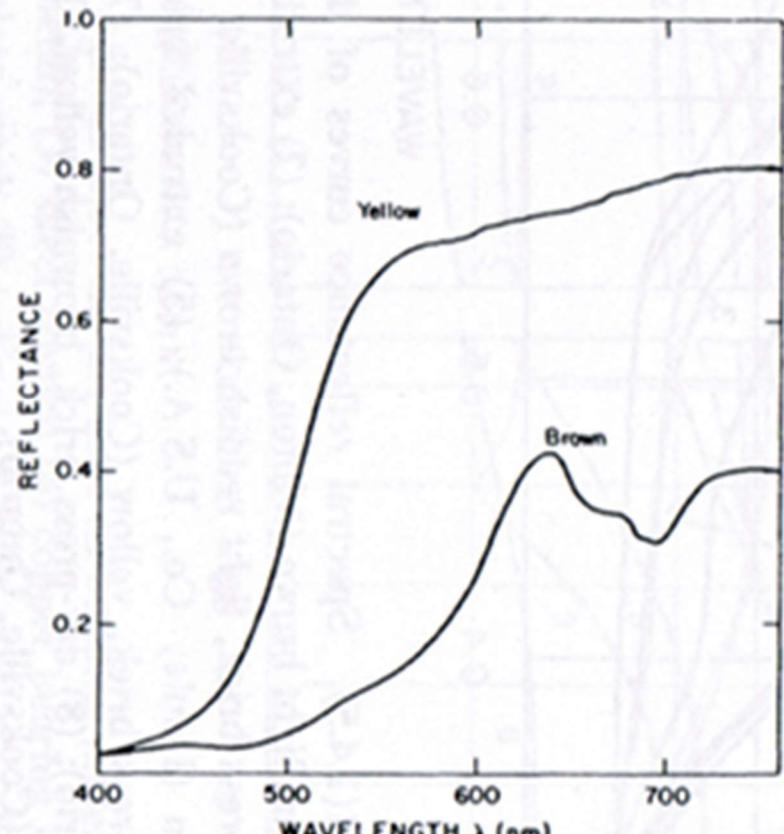
- ▶ Mid-day sun in Western Europe / Northern Europe
- ▶ Colour temperature approx. 6500 K



# Reflectance

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

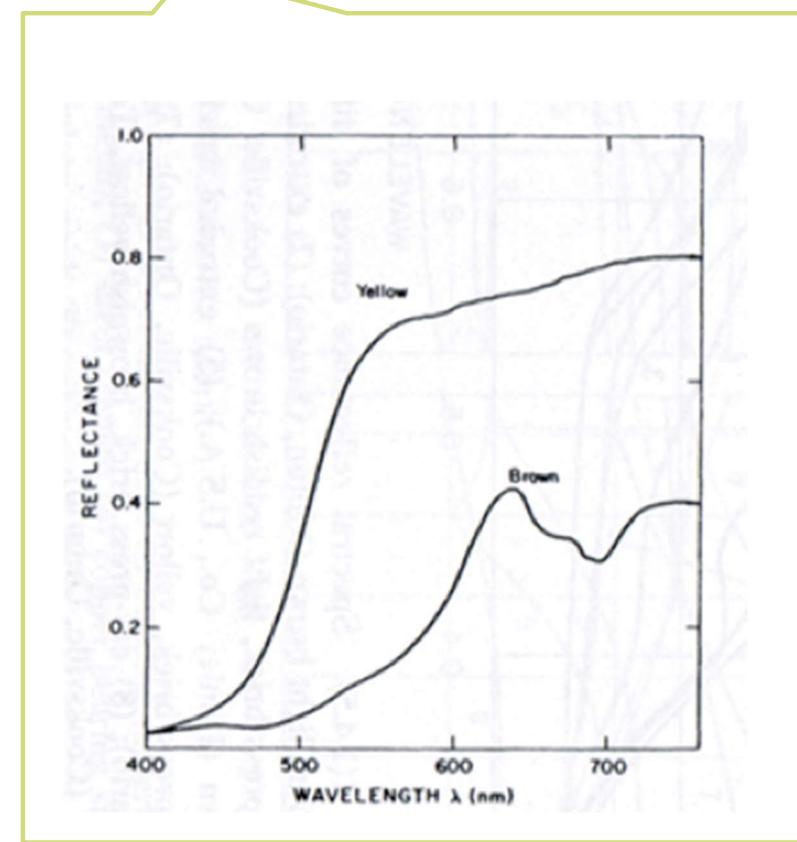
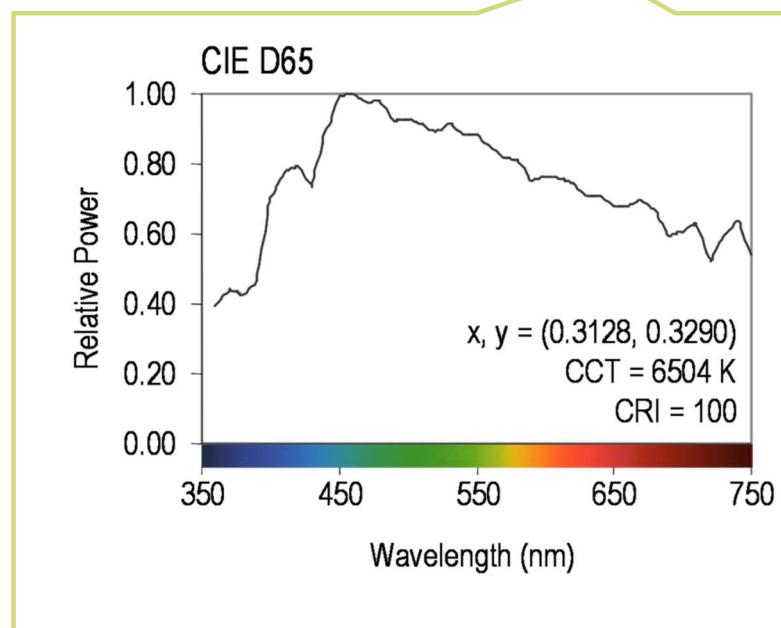
Spectral reflectance of ceramic tiles



# Reflected light

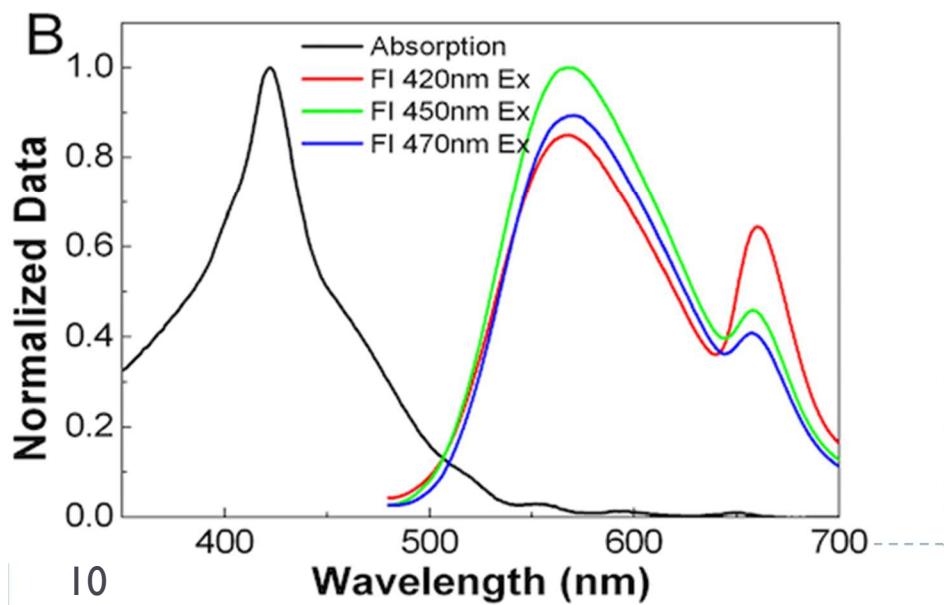
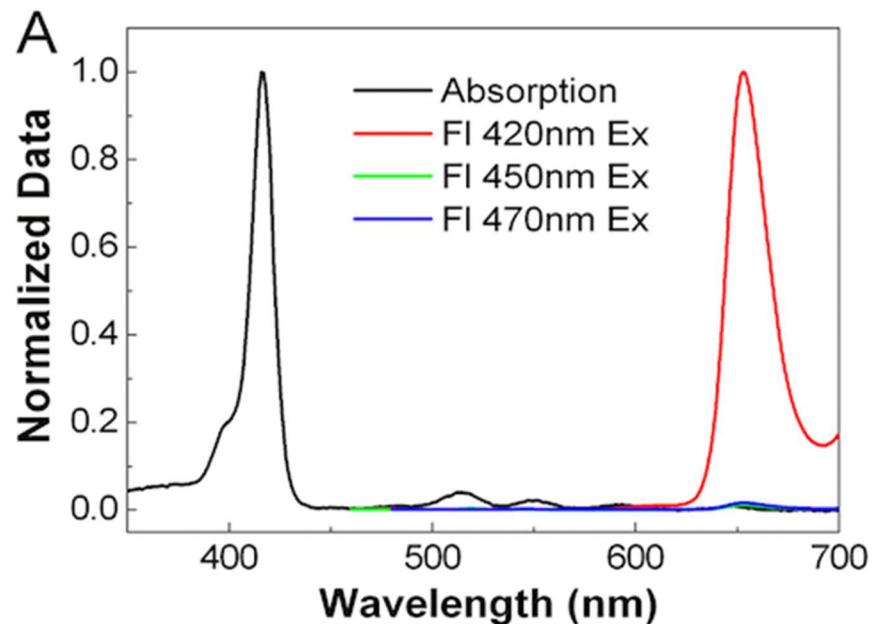
$$L(\lambda) = I(\lambda)R(\lambda)$$

- ▶ Reflected light = illumination × reflectance



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

# Fluorescence





## Advanced Graphics and Image Processing

### **Colour perception and colour spaces**

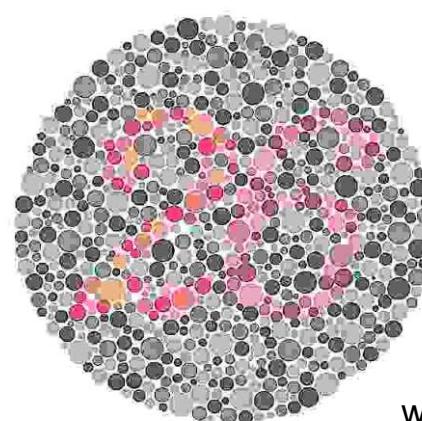
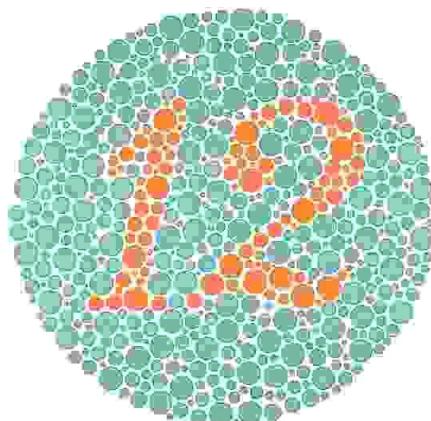
### **Part 2/5 – perception, cone fundamentals**

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# Colour perception

- ▶ Di-chromaticity (dogs, cats)
  - ▶ Yellow & blue-violet
  - ▶ Green, orange, red indistinguishable
- ▶ Tri-chromaticity (humans, monkeys)
  - ▶ Red-ish, green-ish, blue-ish
  - ▶ Colour-deficiency
    - ▶ Most often men, green-red colour-deficiency

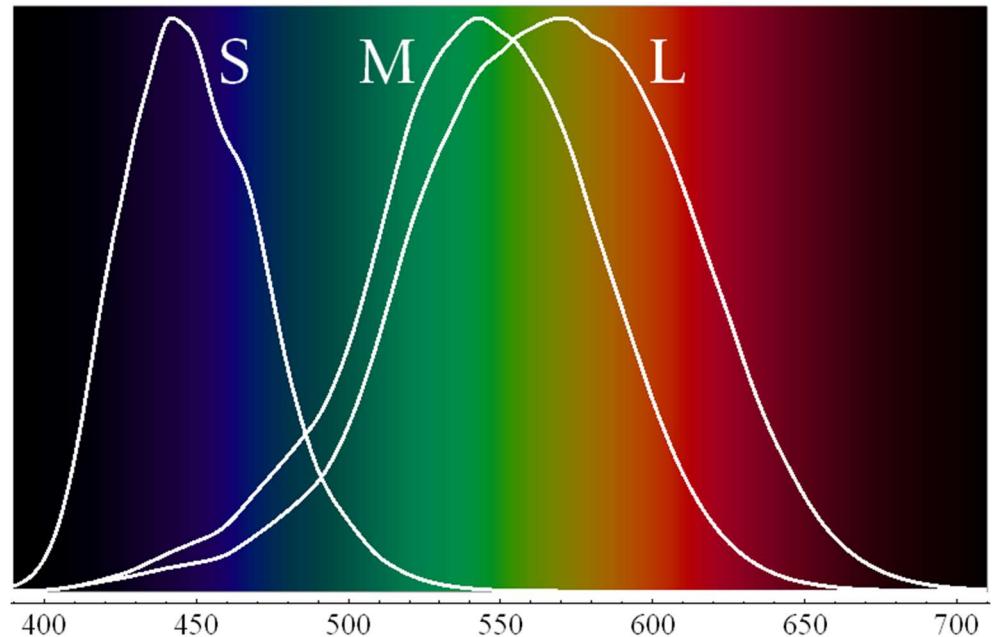


[www.colordcube.com/illusions/clrblnd.html](http://www.colordcube.com/illusions/clrblnd.html)

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

# Colour vision

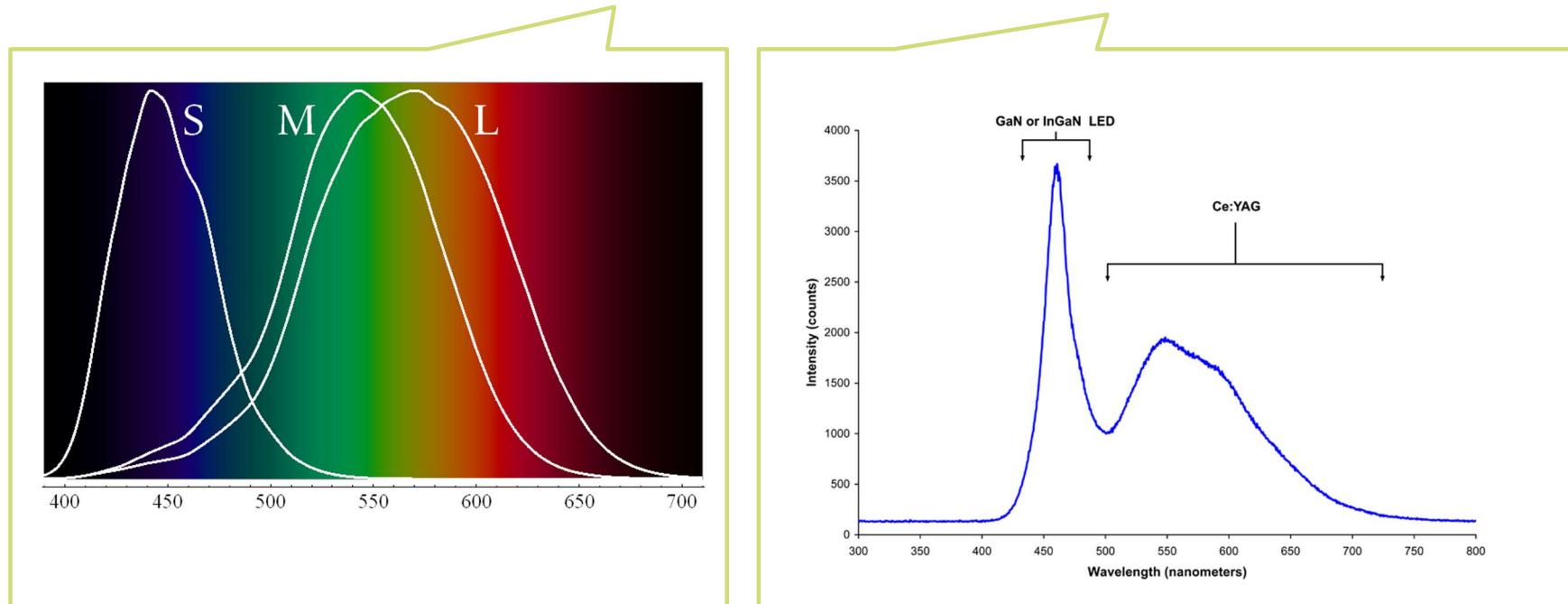
- ▶ Cones are the photoreceptors responsible for colour vision
  - ▶ Only daylight, we see no colours when there is not enough light
- ▶ Three types of cones
  - ▶ S – sensitive to short wavelengths
  - ▶ M – sensitive to medium wavelengths
  - ▶ L – sensitive to long wavelengths



Sensitivity curves – probability that a photon of that wavelengths will be absorbed by a photoreceptor. S,M and L curves are normalized in this plot.

# 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

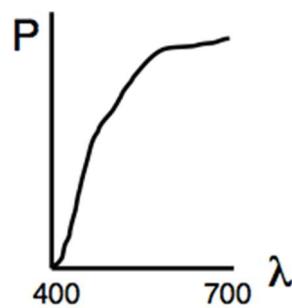
Formally

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

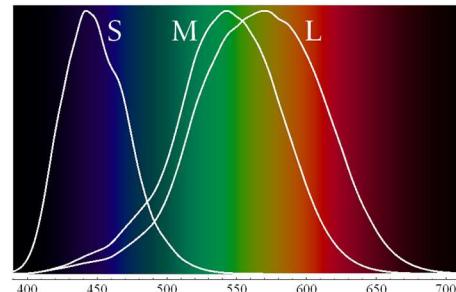
Index S for S-cones

# Metamers

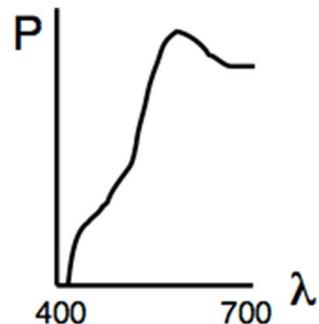
- ▶ Even if two light spectra are different, they may appear to have the same colour
- ▶ The light spectra that appear to have the same colour are called **metamers**
- ▶ Example:



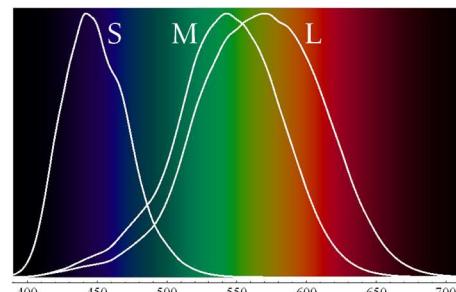
\*



$$= [L_1, M_1, S_1]$$



\*



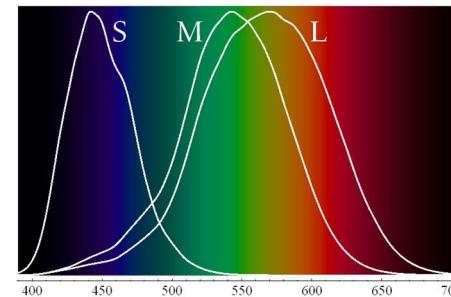
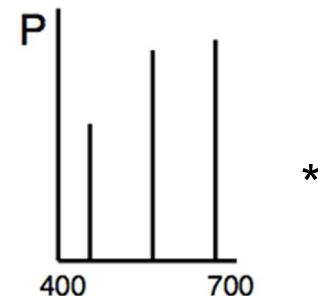
||

$$= [L_2, M_2, S_2]$$

# Practical application of metamerism

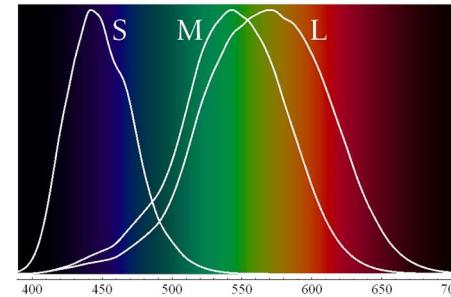
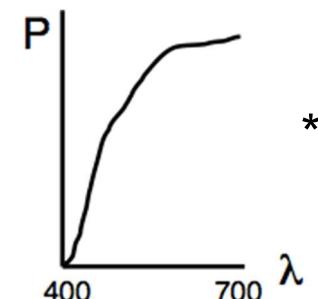
- ▶ Displays do not emit the same light spectra as real-world objects
- ▶ Yet, the colours on a display look almost identical

On the display



$$= [L_1, M_1, S_1]$$

II



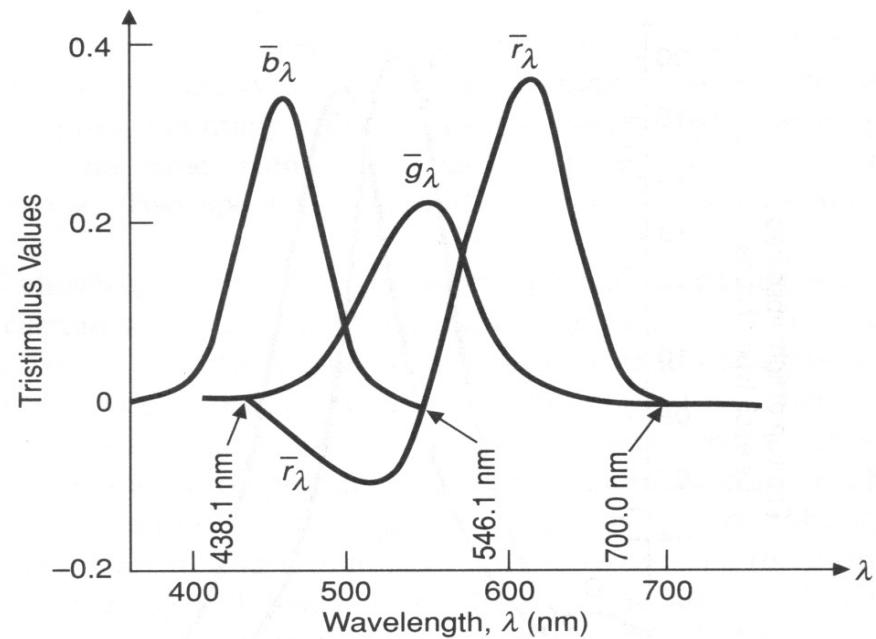
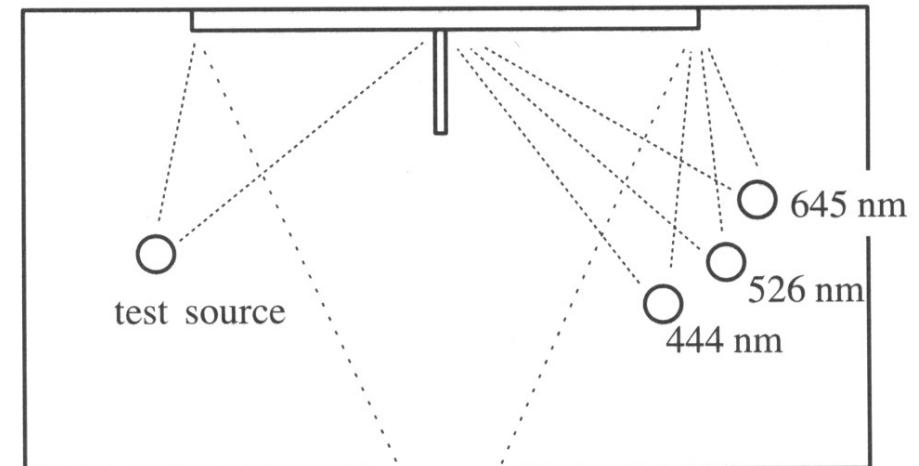
$$= [L_2, M_2, S_2]$$

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 monochromatic spectral colours of equal intensity
  - ▶ With respect to a certain set of primary colours



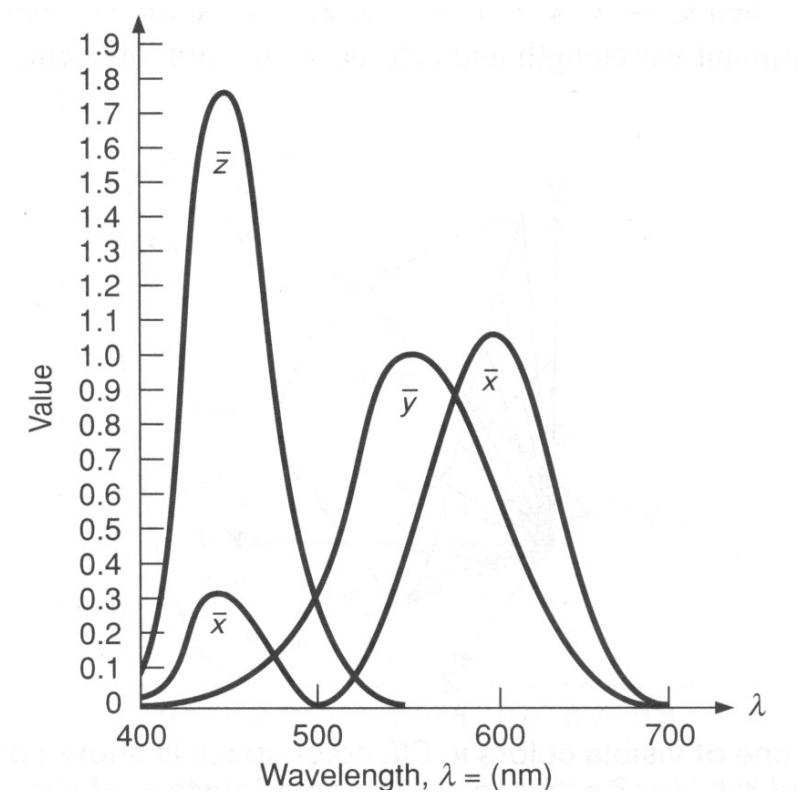
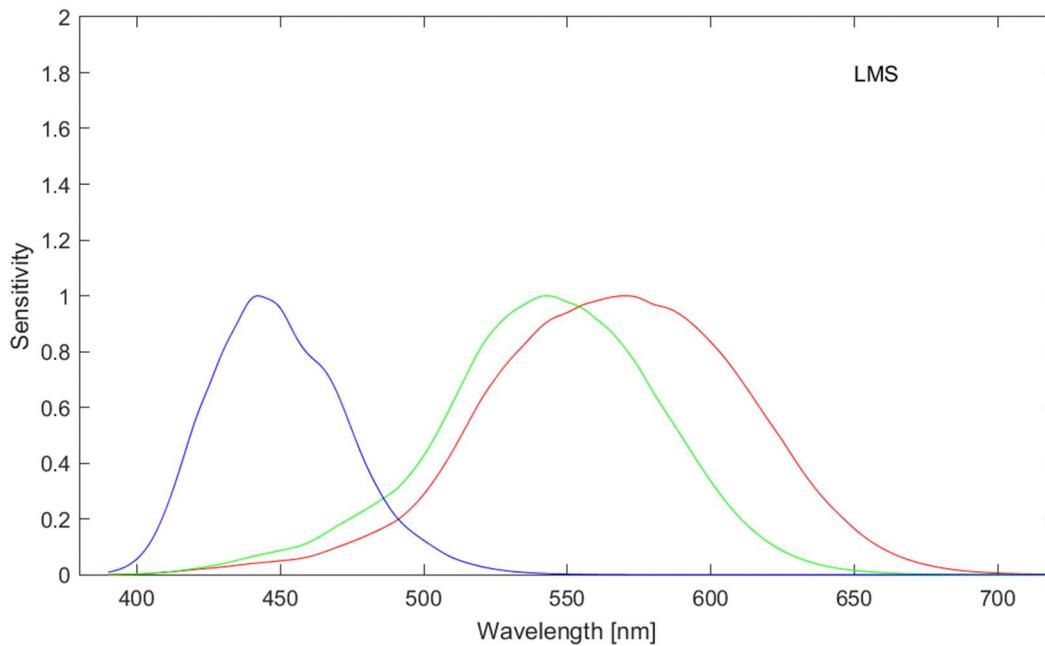
# Standard Colour Space CIE-XYZ

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- ▶ 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 colour 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 an experiment
    - ▶ All matching functions are positive
    - ▶ Primary „Y“ is roughly proportionally to achromatic response (luminance)

# Standard Colour Space CIE-XYZ

- ▶ Standardized imaginary primaries CIE XYZ (1931)
  - ▶ Could match all physically realizable colour stimuli
  - ▶ Cone sensitivity curves can be obtained by a linear transformation of CIE XYZ

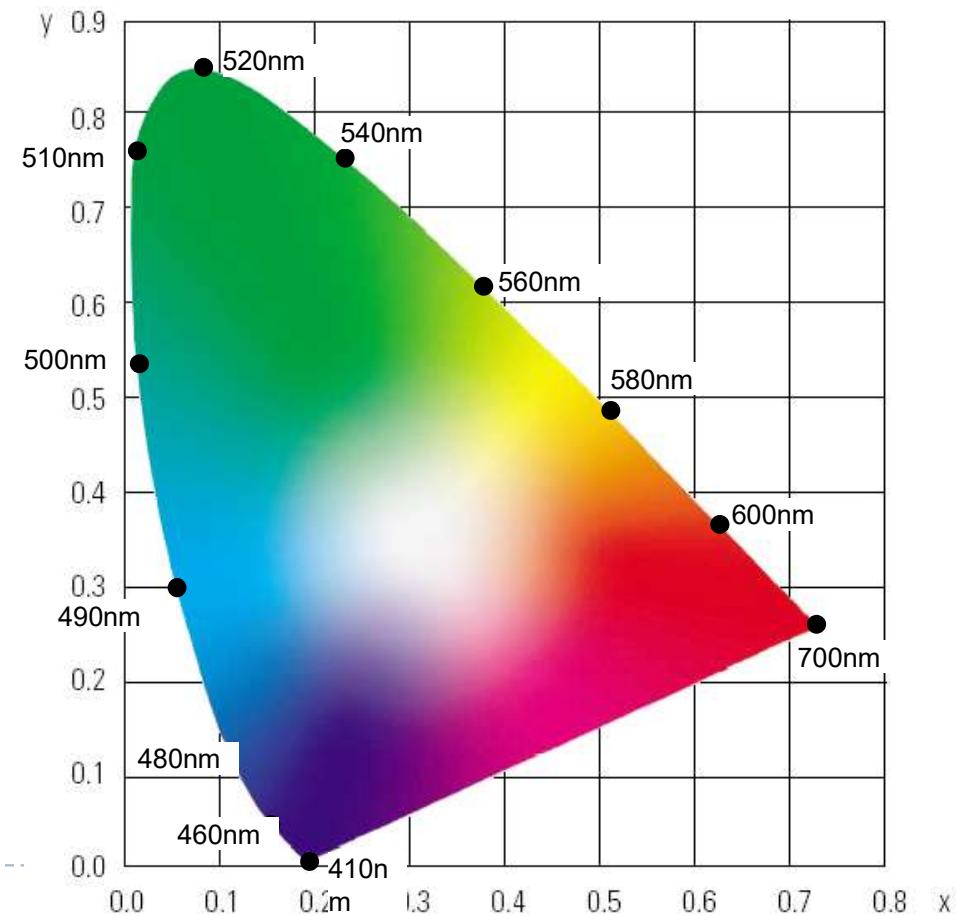


# CIE chromaticity diagram

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

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

- ▶ 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





## Advanced Graphics and Image Processing

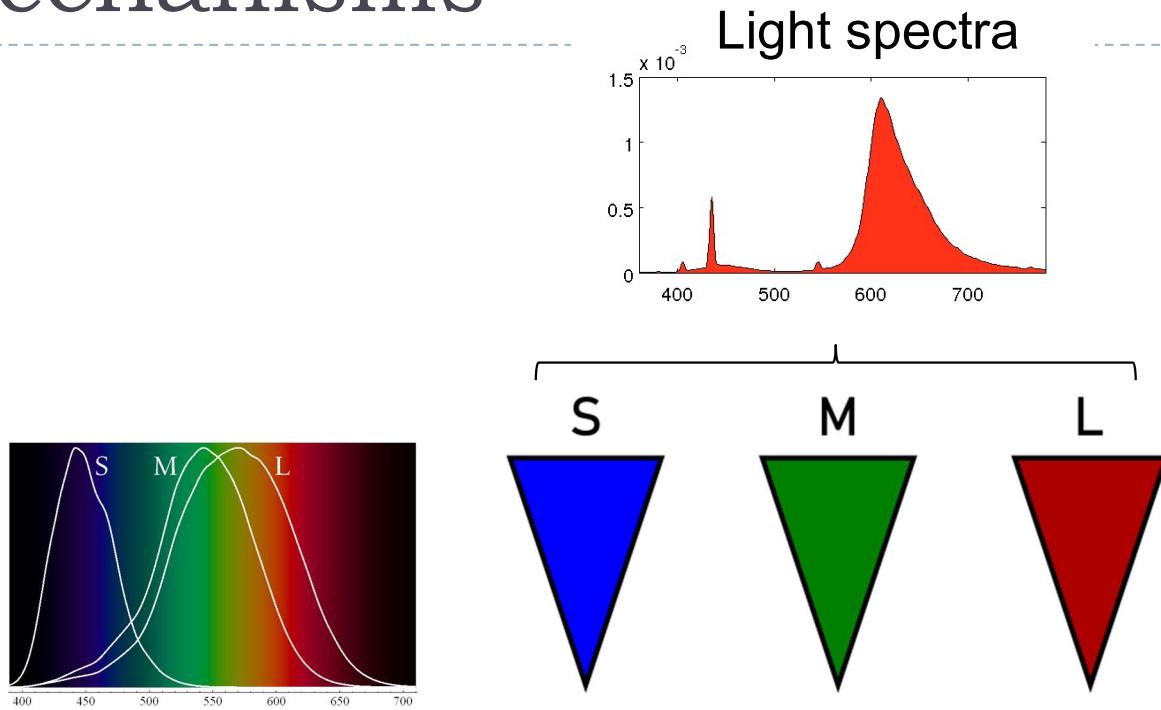
### **Colour perception and colour spaces**

### **Part 3/5 – colour opponent processing**

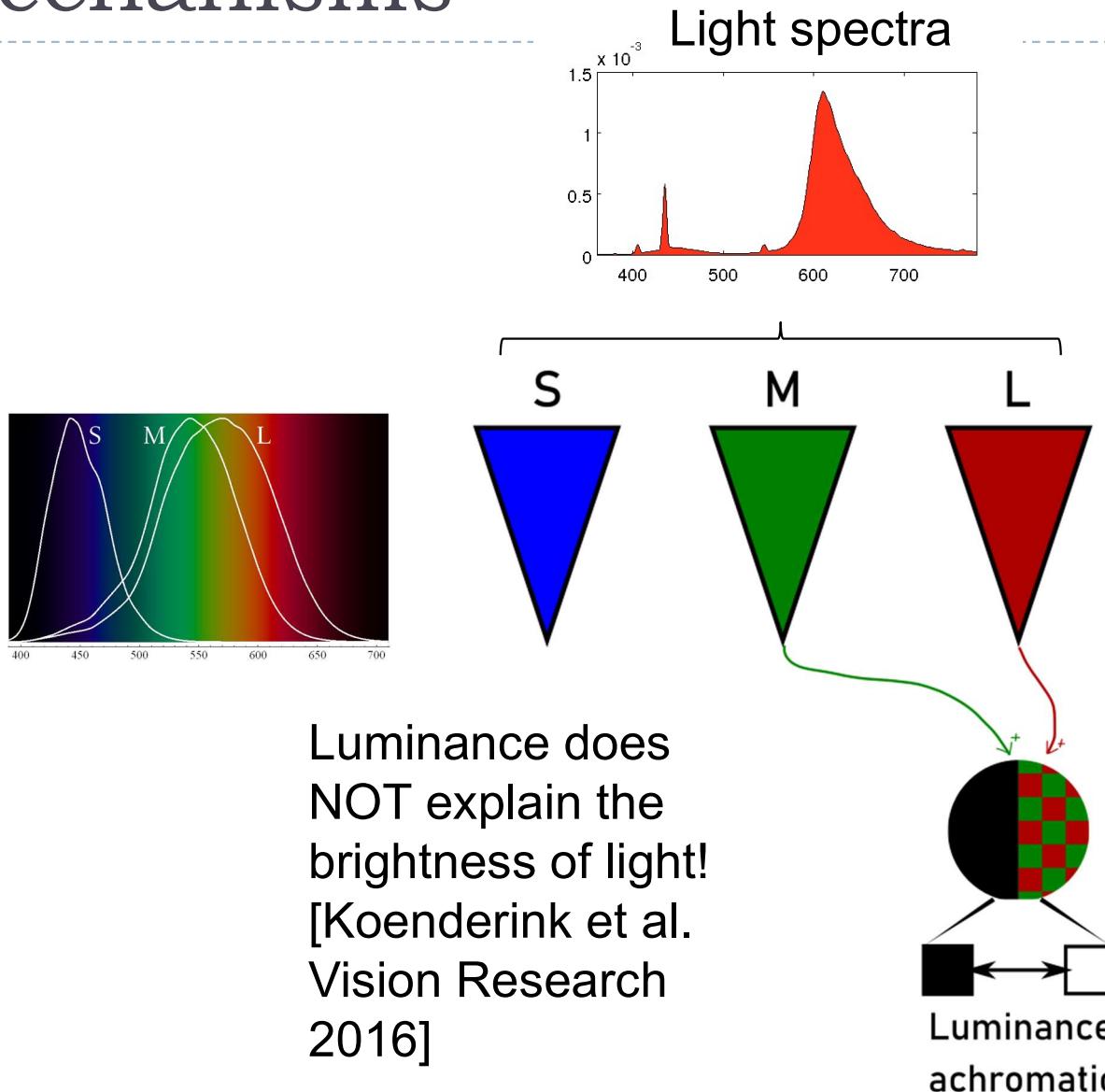
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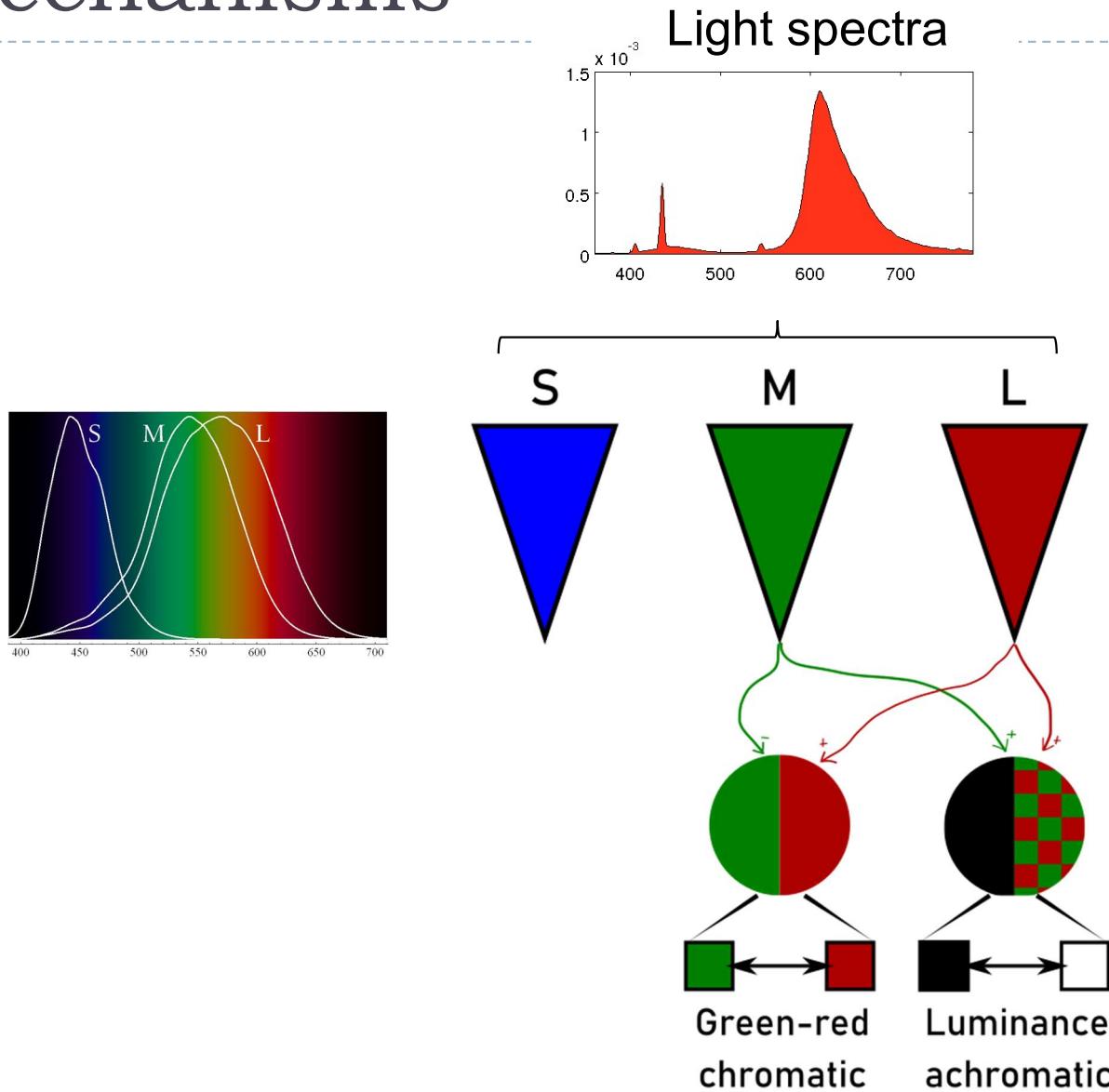
# Achromatic/chromatic vision mechanisms



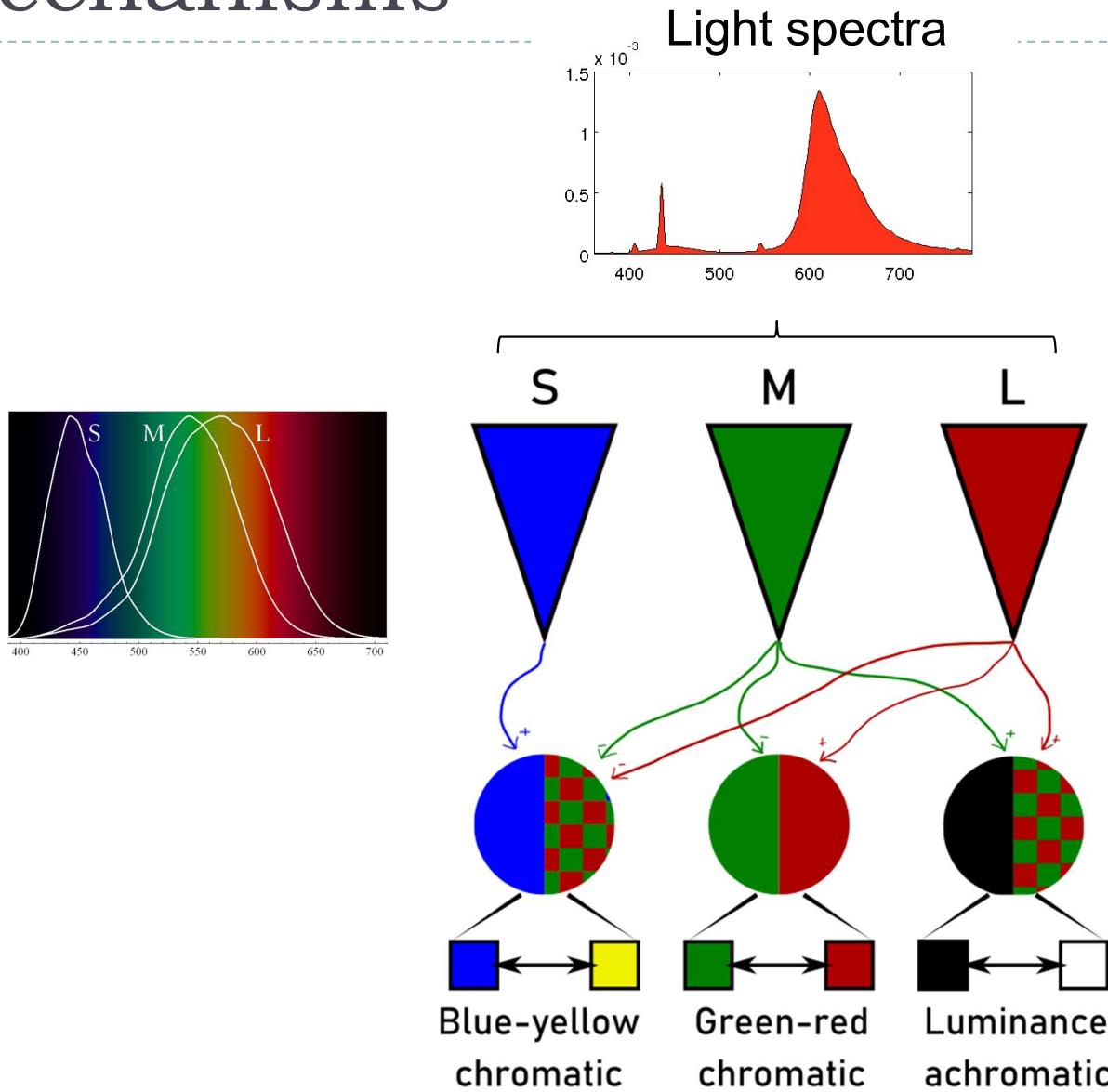
# Achromatic/chromatic vision mechanisms



# Achromatic/chromatic vision mechanisms

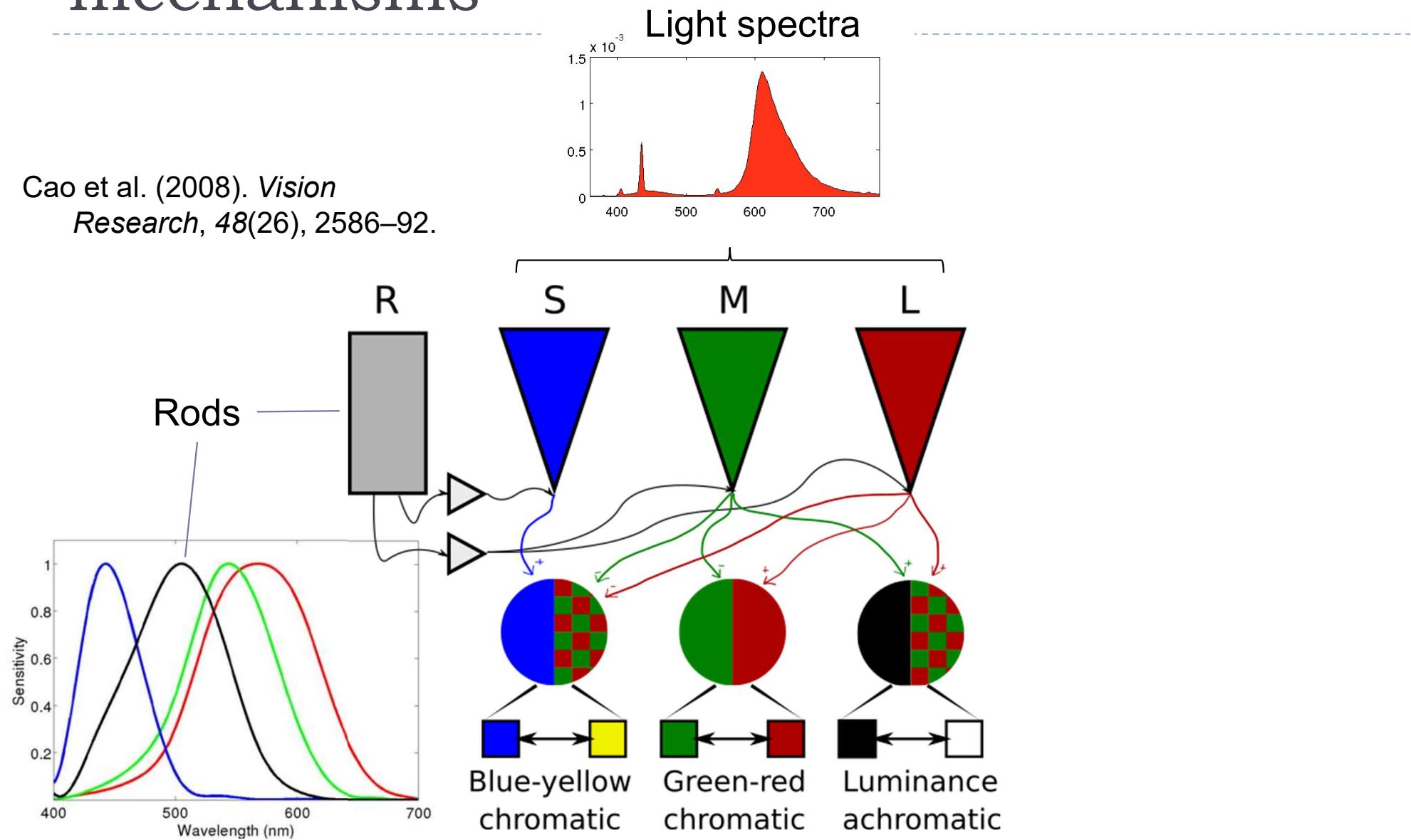


# Achromatic/chromatic vision mechanisms



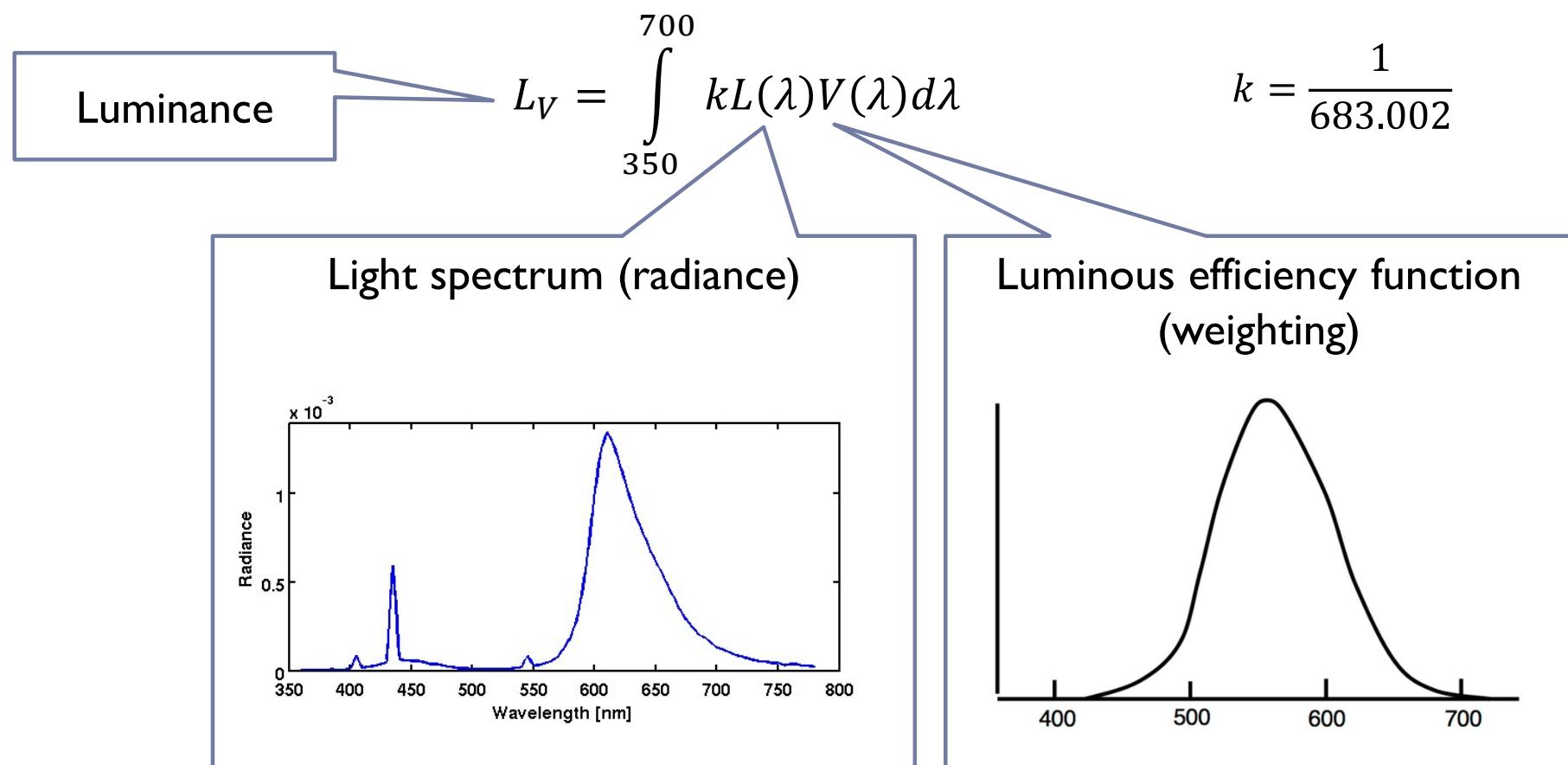
# Achromatic/chromatic vision mechanisms

Cao et al. (2008). *Vision Research*, 48(26), 2586–92.



# Luminance

- ▶ Luminance – measure of light weighted by the response of the achromatic mechanism. Units:  $\text{cd/m}^2$





## Advanced Graphics and Image Processing

### **Colour perception and colour spaces**

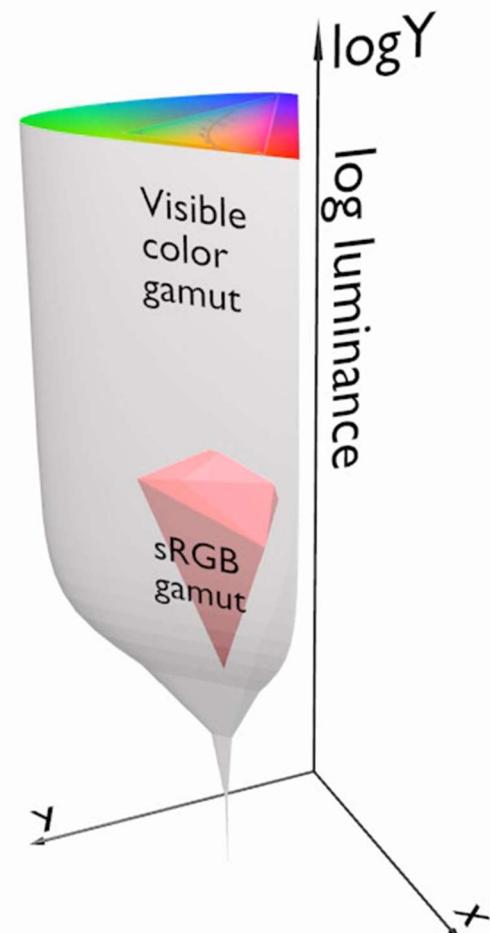
**Part 4/5 – gamuts, linear and  
gamma-encoded colour**

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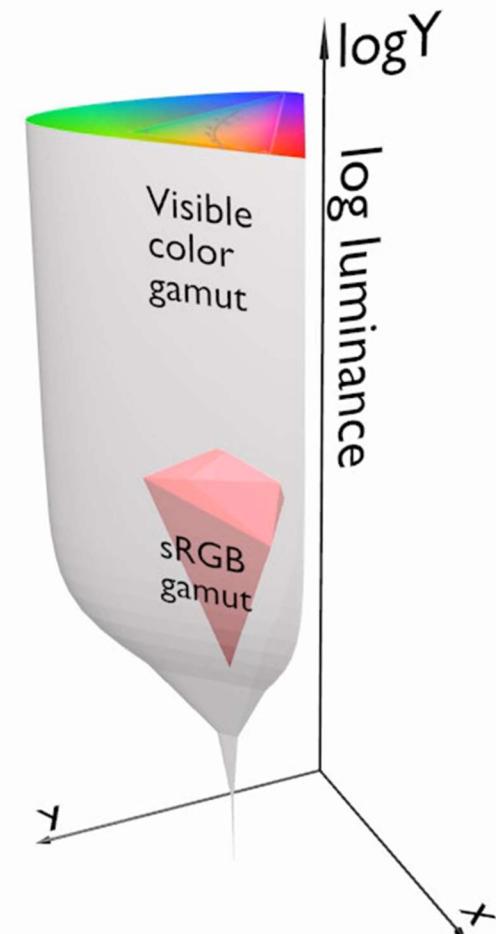
# Visible vs. displayable colours

- ▶ All physically possible and visible colours form a solid in the XYZ space
- ▶ Each display device can reproduce a subspace of that space
- ▶ A chromacity diagram is a projection of 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

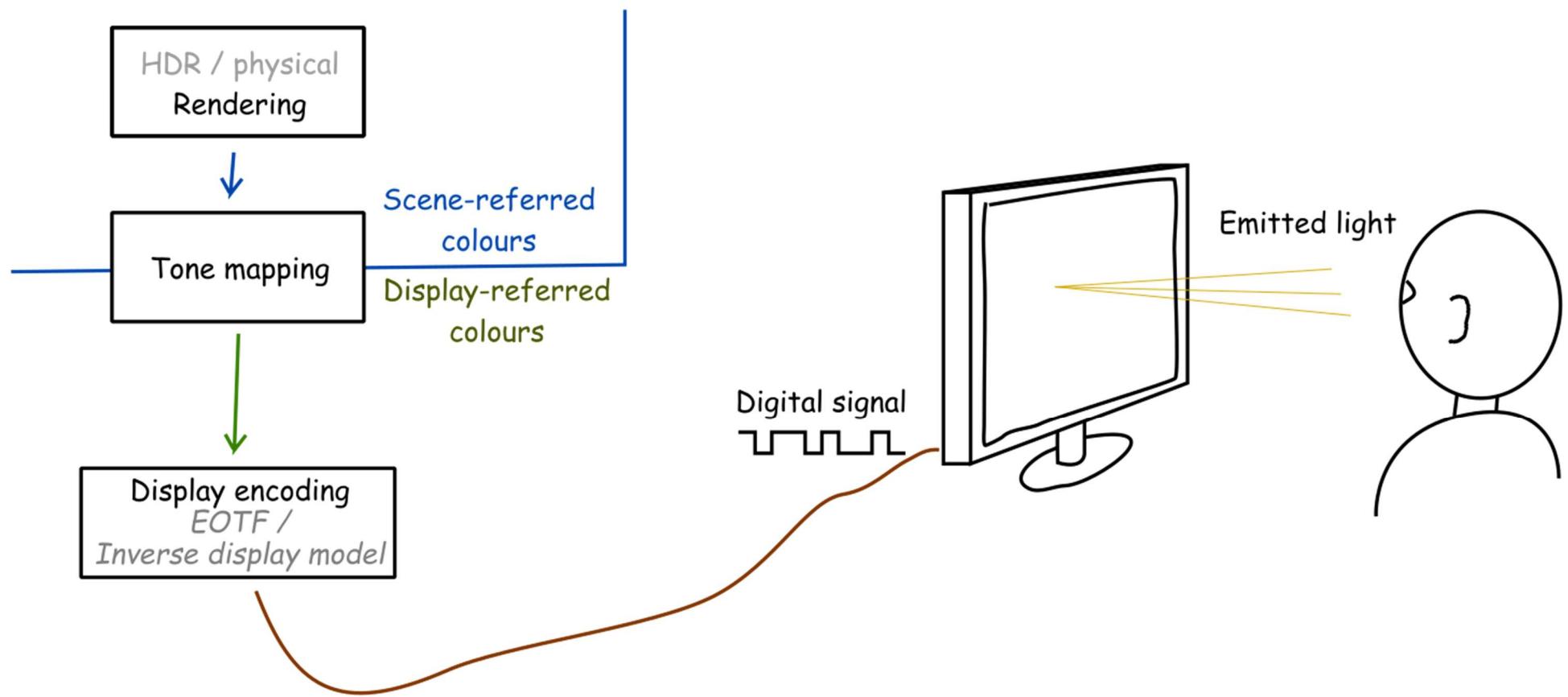


# Standard vs. High Dynamic Range

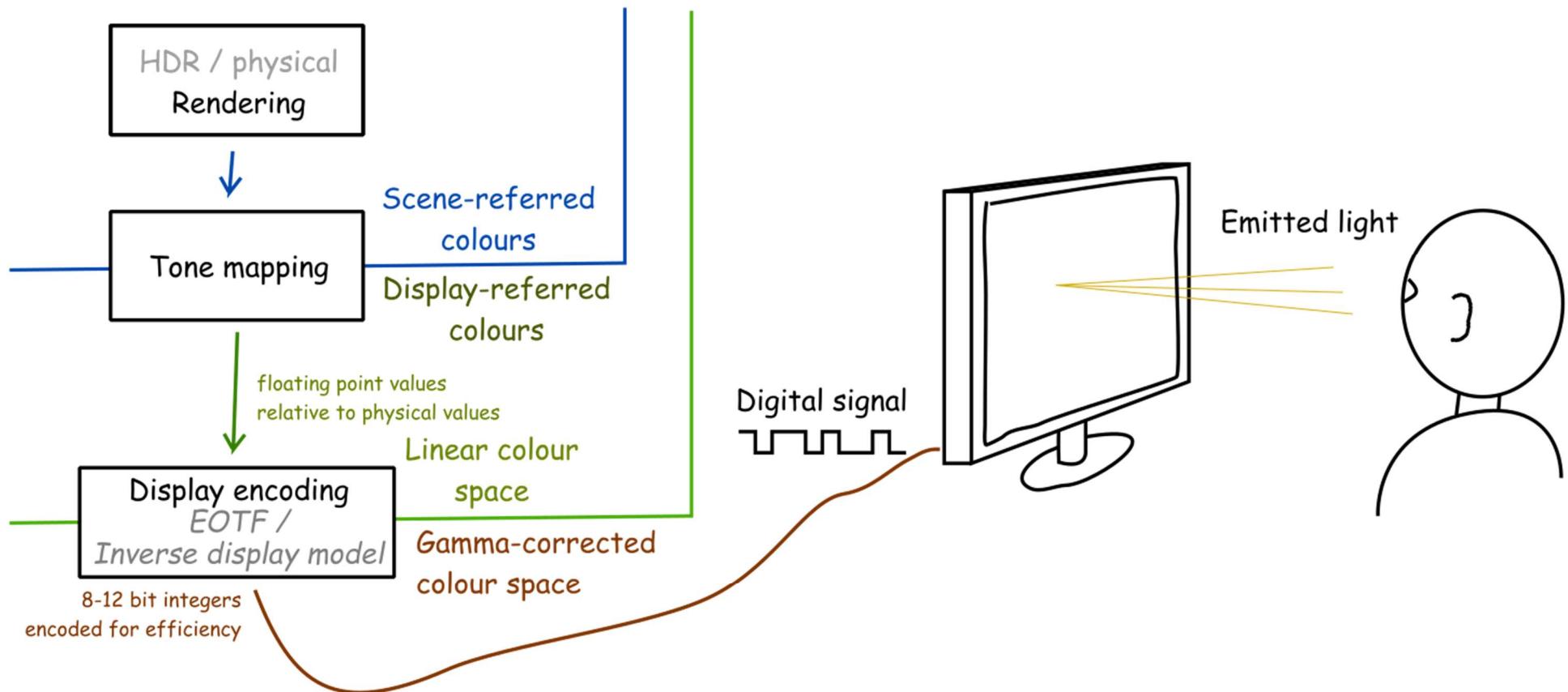
- ▶ **HDR** cameras/formats/displays attempt capture/represent/reproduce (almost) all visible colours
  - ▶ They represent scene colours and therefore we often call this representation *scene-referred*
- ▶ **SDR** cameras/formats/devices attempt to capture/represent/reproduce only colours of a standard sRGB colour gamut, mimicking the capabilities of CRTs monitors
  - ▶ They represent display colours and therefore we often call this representation *display-referred*



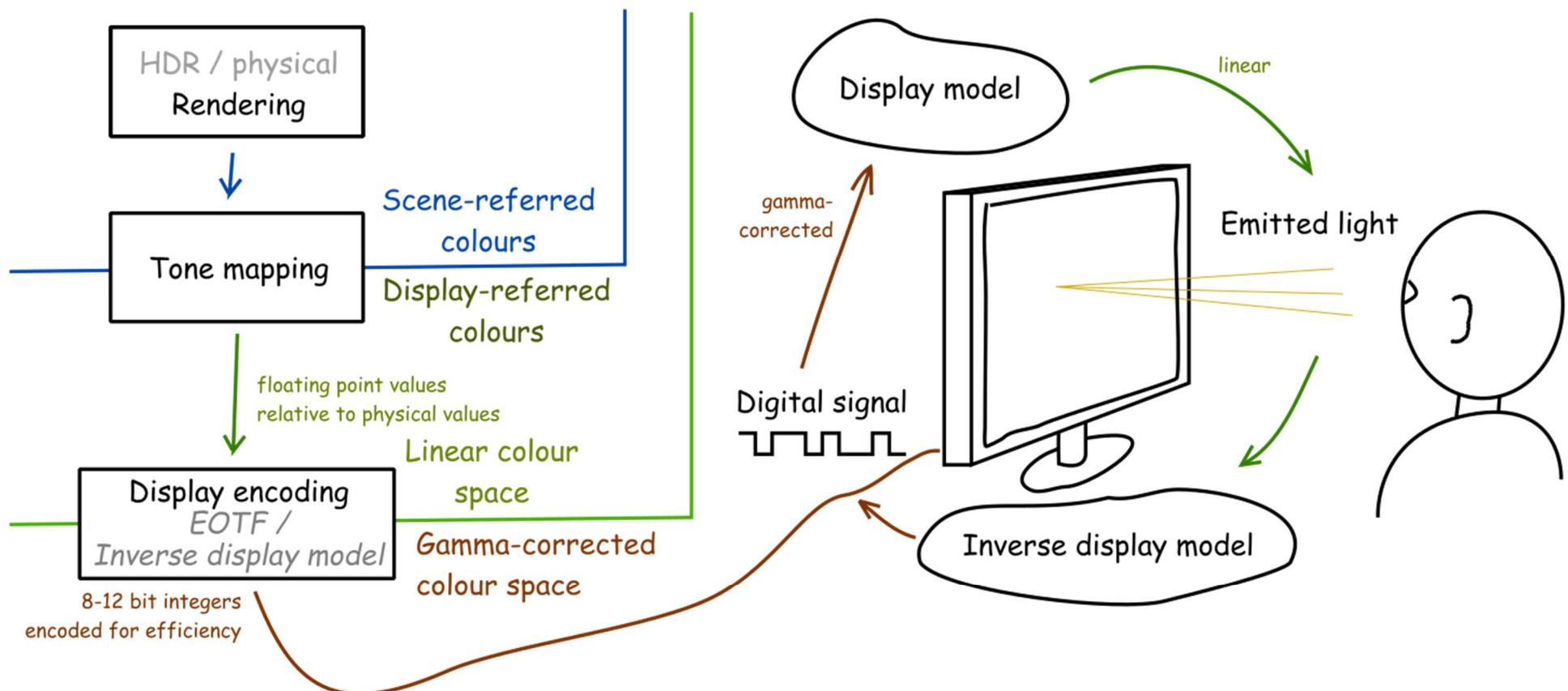
# From rendering to display



# From rendering to display



# From rendering to display



# Display encoding for SDR: gamma

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

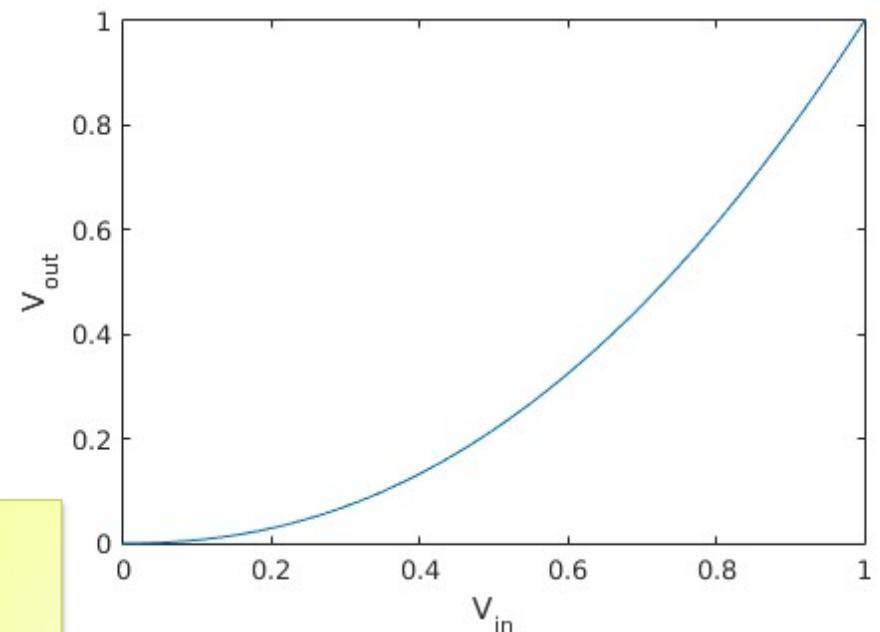
$$V_{\text{out}} = a \cdot V_{\text{in}}^{\gamma}$$

Gain

(relative) Luminance  
Physical signal

Gamma  
(usually =2.2)

Luma  
Digital signal (0-1)



$$\text{Inverse: } V_{\text{in}} = \left( \frac{1}{a} \cdot V_{\text{out}} \right)^{\frac{1}{\gamma}}$$

Colour: the same equation applied to red, green and blue colour channels.

# Why is gamma needed?

---



- ▶ *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

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- ▶ **Luma** - pixel “brightness” in *gamma corrected* units

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

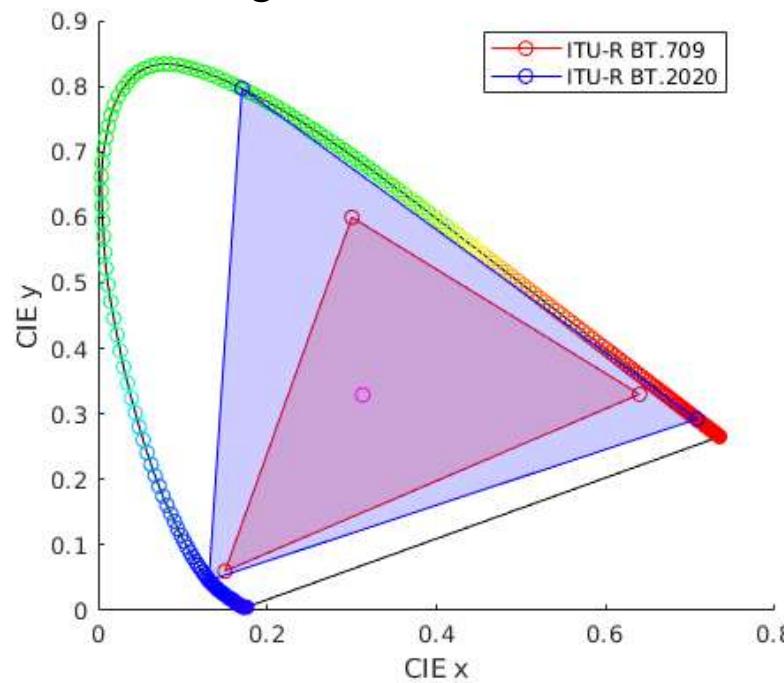
- ▶  $R'$ ,  $G'$  and  $B'$  are *gamma-corrected* colour values
  - ▶ Prime symbol denotes *gamma corrected*
  - ▶ Used in image/video coding
- 
- ▶ Note that relative **luminance** if often approximated with
  - $$L = 0.2126R + 0.7152G + 0.0722B$$
  - $$= 0.2126(R')^\gamma + 0.7152(G')^\gamma + 0.0722(B')^\gamma$$
- ▶  $R$ ,  $G$ , and  $B$  are *linear* colour values
- ▶ Luma and luminace are different quantities despite similar formulas

# Standards for display encoding

Display type	Colour space	EOTF	Bit depth
Standard Dynamic Range	ITU-R 709	2.2 gamma / sRGB	8 to 10
High Dynamic Range	ITU-R 2100 (PQ/HLG)	ITU-R 2100 (PQ/HLG)	10 to 12

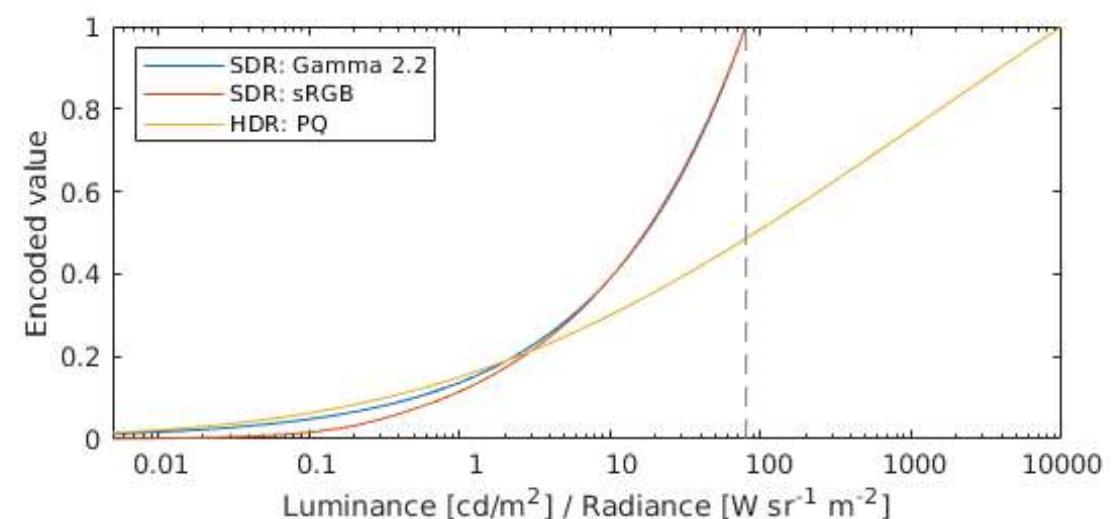
## Colour space

*What is the XYZ of “pure” red, green and blue*

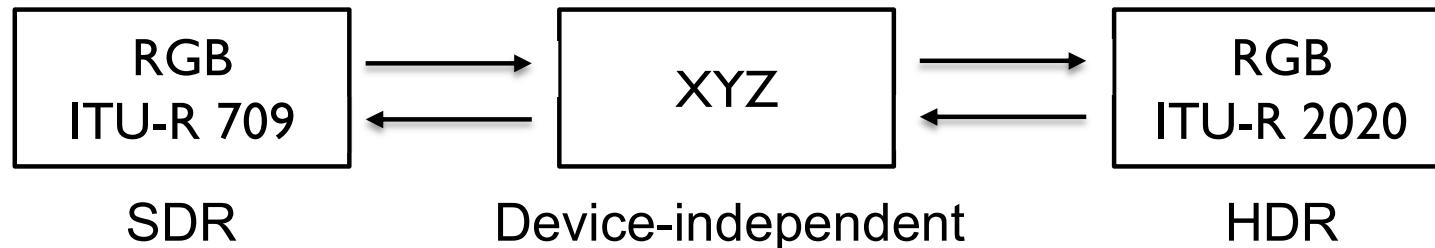


## Electro-Optical Transfer Function

*How to efficiently encode each primary colour*



# How to transform between linear RGB colour spaces?



- ▶ From ITU-R 709 RGB to XYZ:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix}_{R709 \text{ to } XYZ} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{R709}$$

Relative XYZ of the red primary

Relative XYZ of the green primary

Relative XYZ of the blue primary

Relative RGB (0-1) in the R709 space

# How to transform between RGB colour spaces?

---

- ▶ From ITU-R **709** RGB to ITU-R **2020** RGB:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{R2020} = M_{XYZtoR2020} \cdot M_{R709toXYZ} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{R709}$$

- ▶ From ITU-R **2020** RGB to ITU-R **709** RGB:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{R709} = M_{XYZtoR709} \cdot M_{R2020toXYZ} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{R2020}$$

- ▶ Where:

$$M_{R709toXYZ} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \text{ and } M_{XYZtoR709} = M_{R709toXYZ}^{-1}$$

$$M_{R2020toXYZ} = \begin{bmatrix} 0.6370 & 0.1446 & 0.1689 \\ 0.2627 & 0.6780 & 0.0593 \\ 0.0000 & 0.0281 & 1.0610 \end{bmatrix} \text{ and } M_{XYZtoR2020} = M_{R2020toXYZ}^{-1}$$



## Advanced Graphics and Image Processing

### Colour perception and colour spaces

**Part 5/5 – colour spaces**

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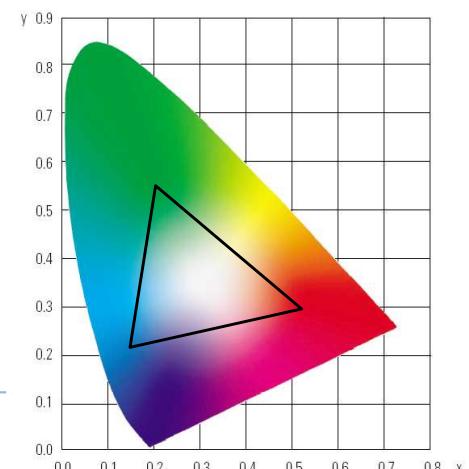
# Representing colour

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- ▶ We need a way to represent colour in the computer by some set of numbers
  - ▶ A) preferably a small set of numbers which can be quantised to a fairly **small number of bits** each
    - ▶ Gamma corrected RGB, sRGB and CMYK for printers
  - ▶ B) a set of numbers that are **easy to interpret**
    - ▶ Munsell's *artists'* scheme
    - ▶ HSV, HLS
  - ▶ C) a set of numbers in a 3D space so that the (Euclidean) distance in that space corresponds to approximately **perceptually uniform** colour differences
    - ▶ CIE Lab, CIE Luv

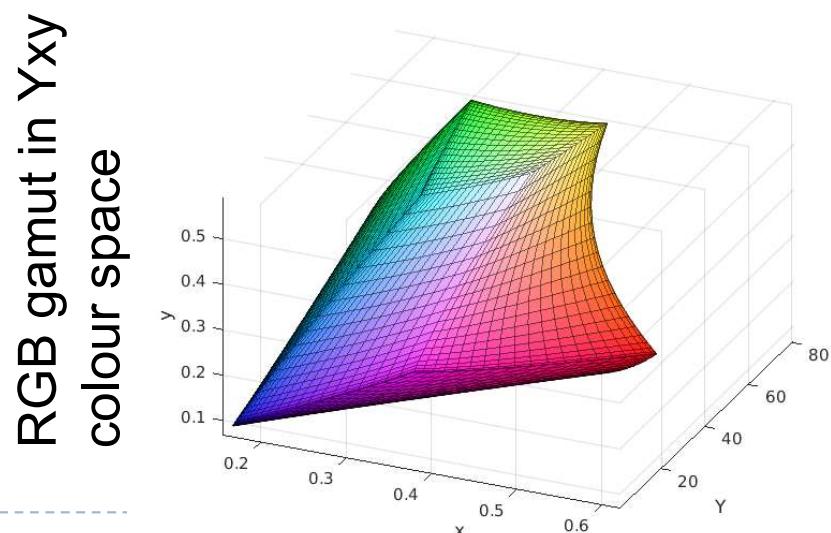
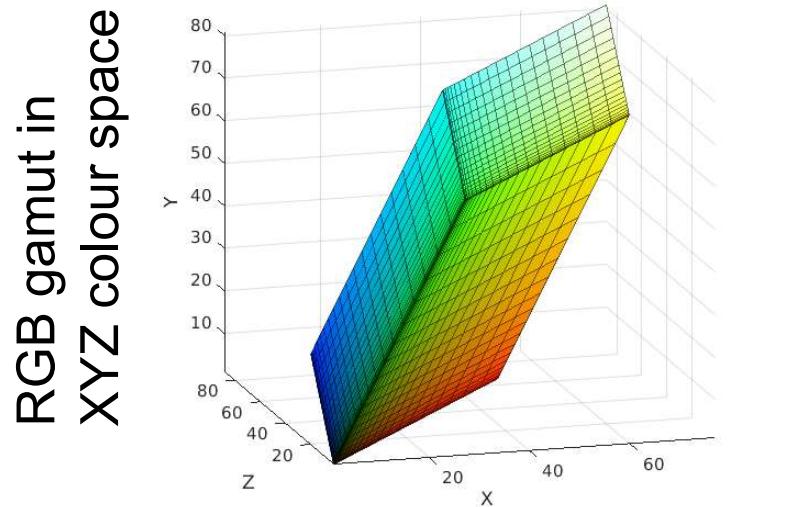
# *RGB* spaces

- ▶ Most display devices that output light mix red, green and blue lights to make colour
  - ▶ televisions, CRT monitors, LCD screens
- ▶ RGB colour space
  - ▶ Can be **linear** (RGB) or **display-encoded** ( $R'G'B'$ )
  - ▶ Can be **scene-referred** (HDR) or **display-referred** (SDR)
- ▶ There are multiple RGB colour spaces
  - ▶ ITU-R 709 (sRGB), ITU-R 2020, Adobe RGB, DCI-P3
    - ▶ Each using different primary colours
    - ▶ And different OETFs (gamma, PQ, etc.)
- ▶ Nominally, *RGB* space is a cube



# *RGB* in CIE *XYZ* space

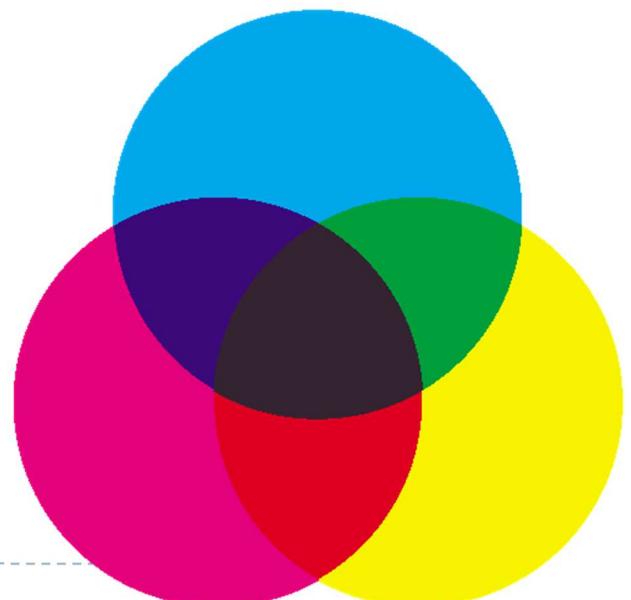
- ▶ Linear RGB colour values can be transformed into CIE XYZ
  - ▶ by matrix multiplication
  - ▶ because it is a rigid transformation the colour gamut in CIE XYZ is a rotate and skewed cube
- ▶ Transformation into Yxy
  - ▶ is non-linear (non-rigid)
  - ▶ colour gamut is more complicated



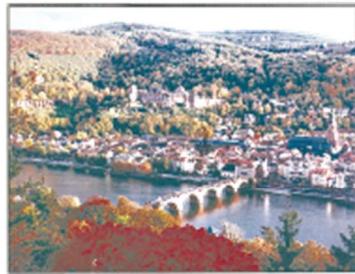
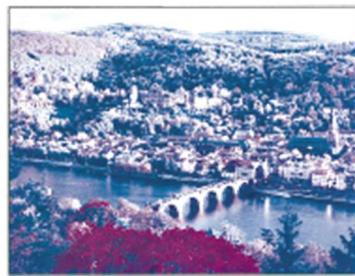
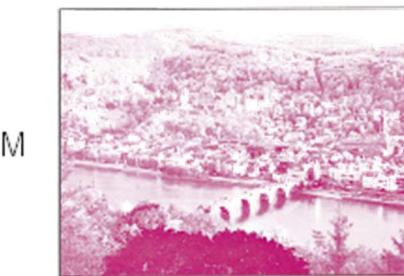
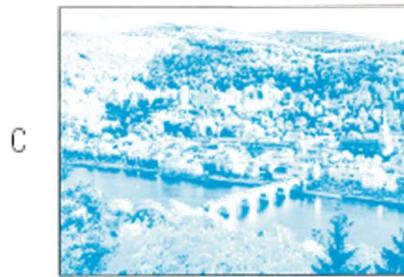
# *CMY* space

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- ▶ printers make colour by mixing coloured inks
- ▶ the important difference between inks (*CMY*) and lights (*RGB*) is that, while lights *emit* light, inks *absorb* light
  - ▶ cyan absorbs red, reflects blue and green
  - ▶ magenta absorbs green, reflects red and blue
  - ▶ yellow absorbs blue, reflects green and red
- ▶ *CMY* is, at its simplest, the inverse of *RGB*
- ▶ *CMY* space is nominally a cube



# CMYK space



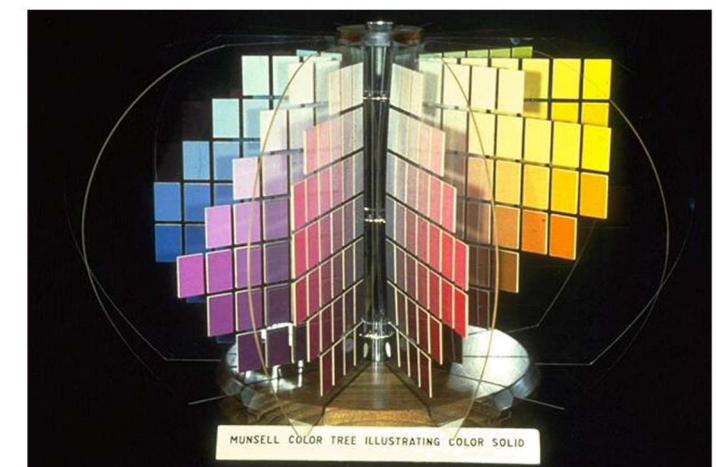
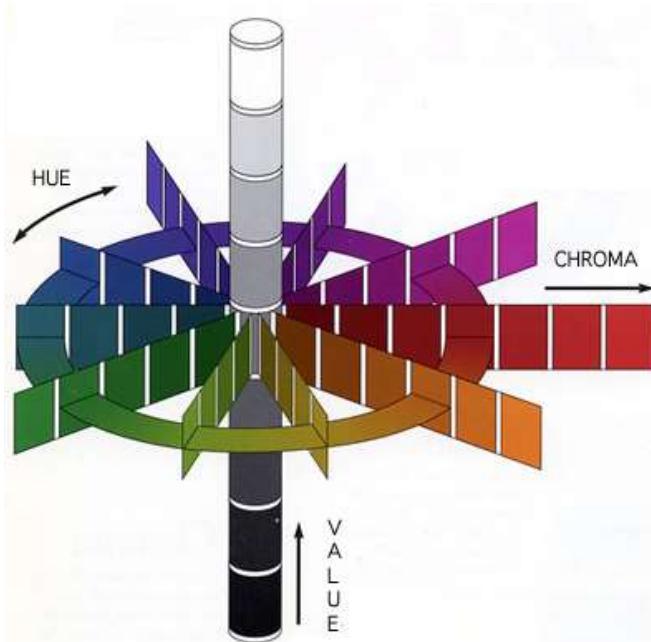
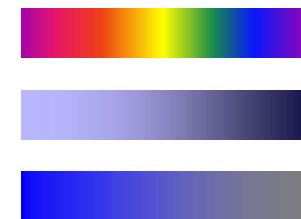
- ▶ in real printing we use black (key) as well as CMY
- ▶ why use black?
  - ▶ inks are not perfect absorbers
  - ▶ mixing  $C + M + Y$  gives a muddy grey, not black
  - ▶ lots of text is printed in black: trying to align  $C, M$  and  $Y$  perfectly for black text would be a nightmare



# Munsell's colour classification system

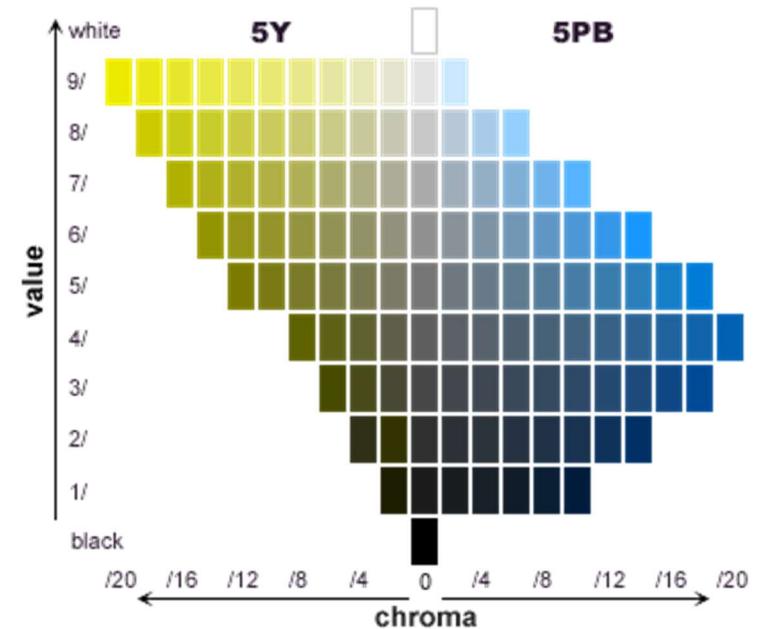
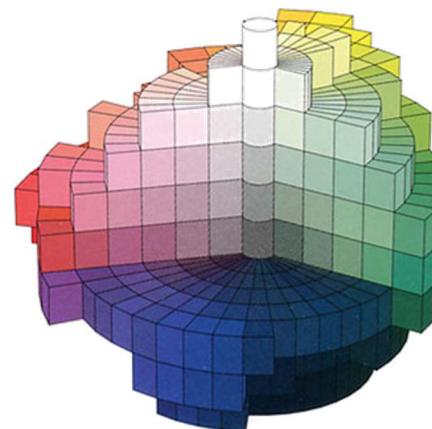
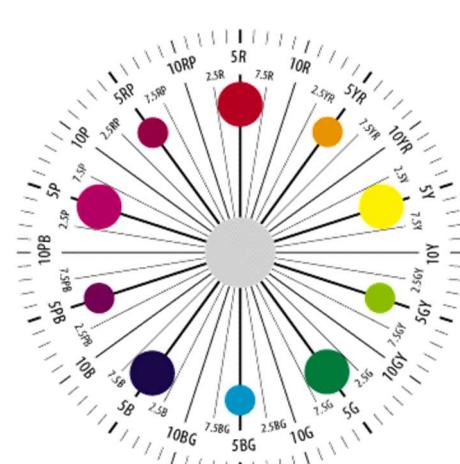
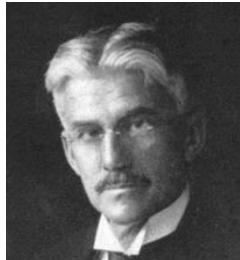
## ▶ three axes

- ▶ hue ➤ the dominant colour
- ▶ value ➤ bright colours/dark colours
- ▶ chroma ➤ vivid colours/dull colours
- ▶ can represent this as a 3D graph



# Munsell's colour classification system

- ▶ any two adjacent colours are a standard “perceptual” distance apart
  - ▶ worked out by testing it on people
  - ▶ a highly irregular space
    - ▶ e.g. vivid yellow is much brighter than vivid blue



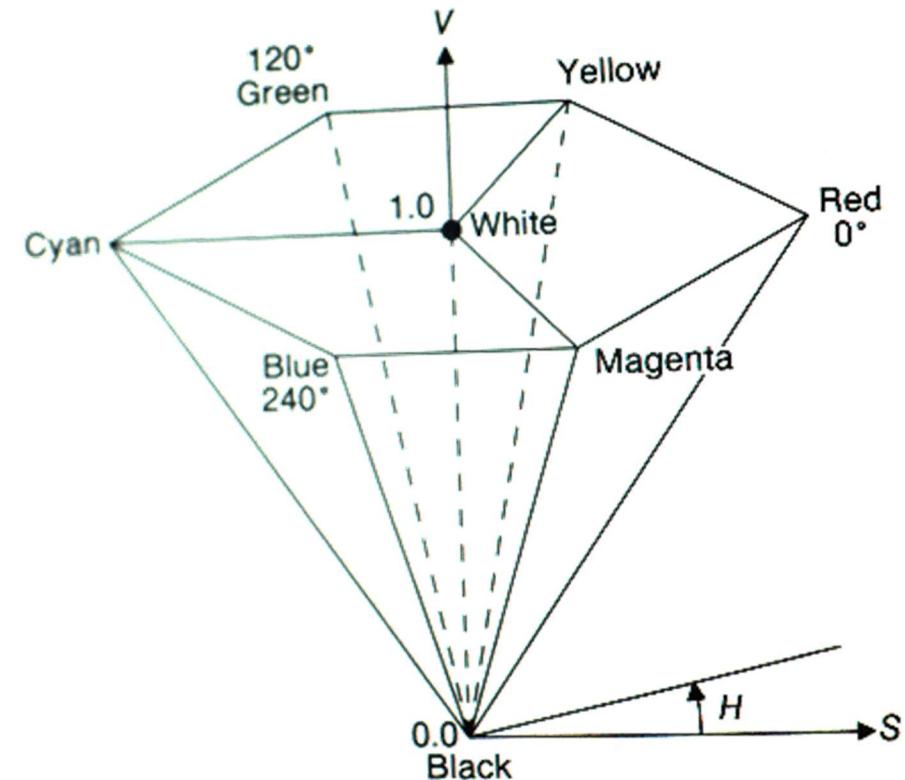
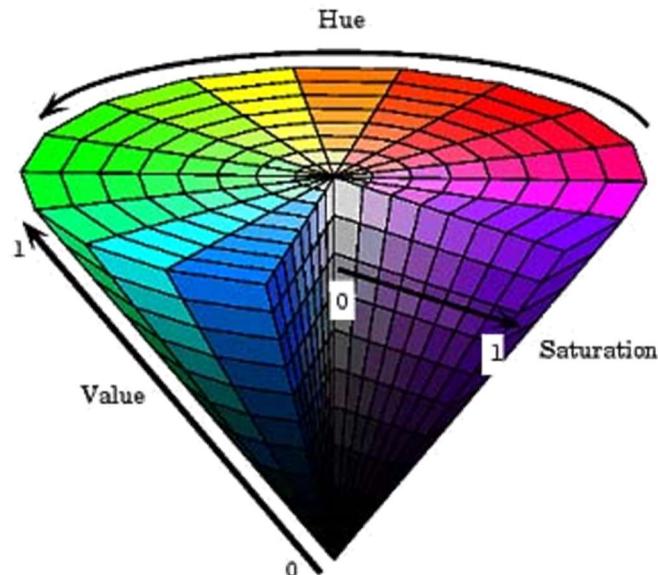
# Colour spaces for user-interfaces

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- ▶ *RGB* and *CMY* are based on the physical devices which produce the coloured output
- ▶ *RGB* and *CMY* are difficult for humans to use for selecting colours
- ▶ Munsell's colour system is much more intuitive:
  - ▶ hue — what is the principal colour?
  - ▶ value — how light or dark is it?
  - ▶ chroma — how vivid or dull is it?
- ▶ computer interface designers have developed basic transformations of *RGB* which resemble Munsell's human-friendly system

# HSV: hue saturation value

- ▶ three axes, as with Munsell
  - ▶ hue and value have same meaning
  - ▶ the term “saturation” replaces the term “chroma”
  - ▶ simple conversion from gamma-corrected RGB to HSV

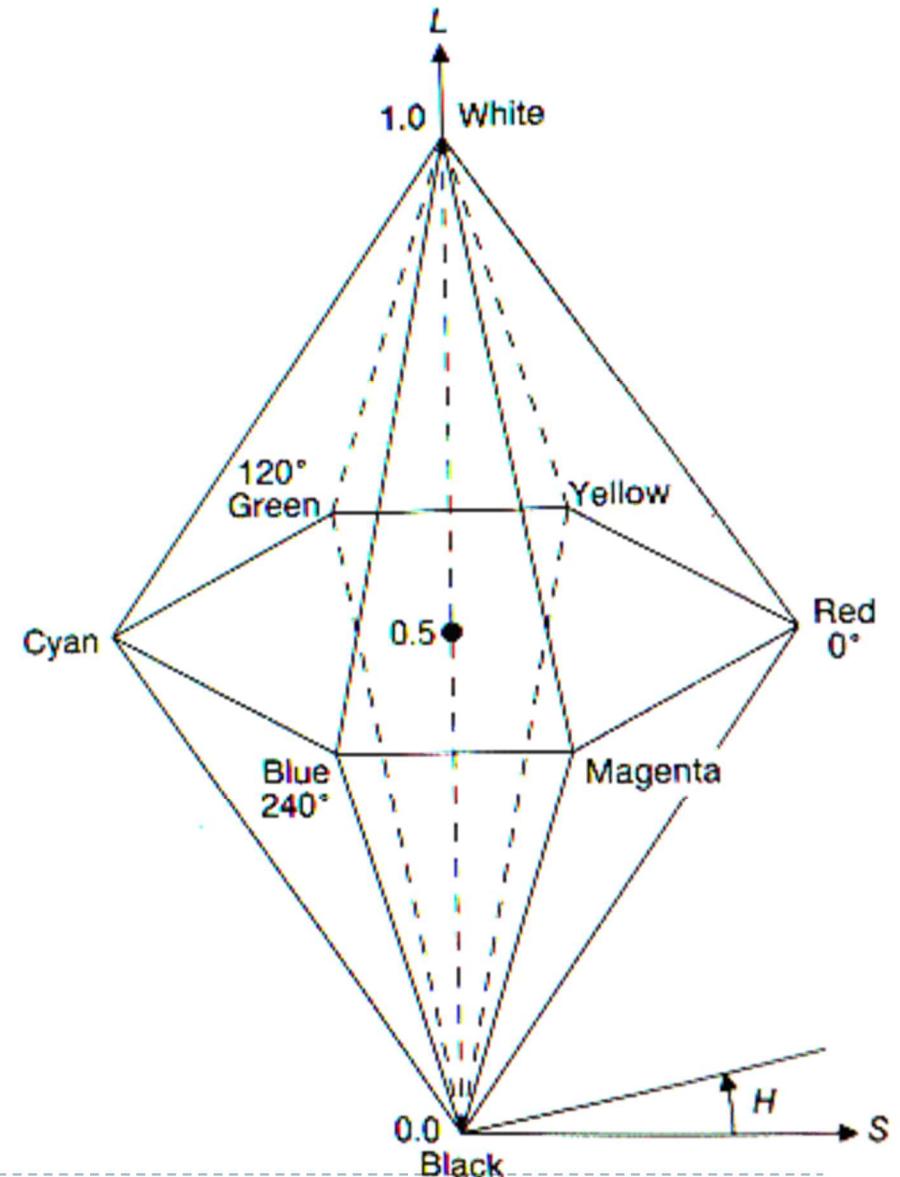


- ◆ designed by Alvy Ray Smith in 1978
- ◆ algorithm to convert *HSV* to *RGB* and back can be found in Foley et al., Figs 13.33 and 13.34



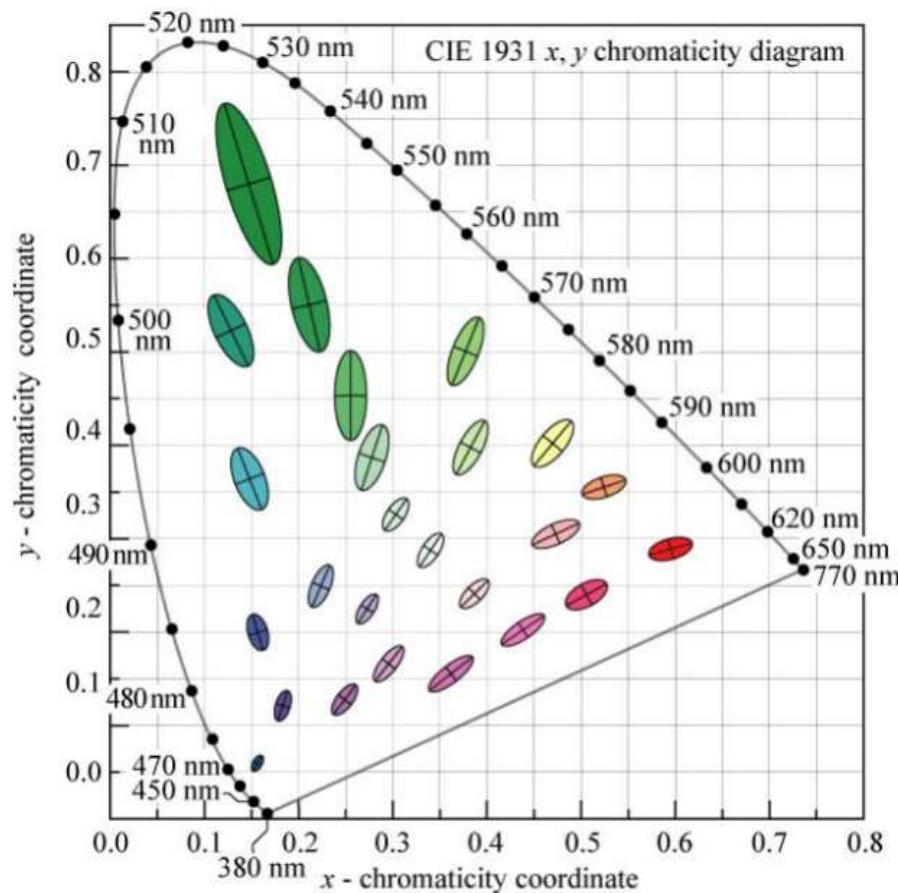
# HLS: hue lightness saturation

- ❖ a simple variation of *HSV*
  - ◆ hue and saturation have same meaning
  - ◆ the term “lightness” replaces the term “value”
- ❖ designed to address the complaint that *HSV* has all pure colours having the same lightness/value as white
  - ◆ designed by Metrick in 1979
  - ◆ algorithm to convert *HLS* to *RGB* and back can be found in Foley et al., Figs 13.36 and 13.37

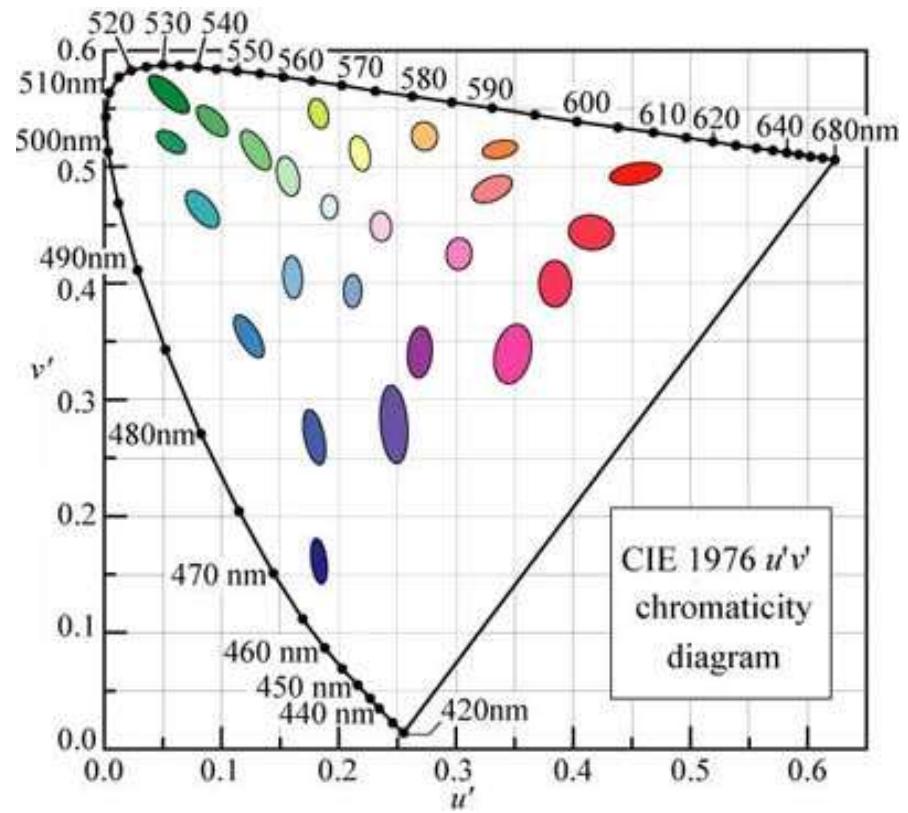


# Perceptual uniformity

- ▶ MacAdam ellipses & visually indistinguishable colours



In CIE xy chromatic coordinates



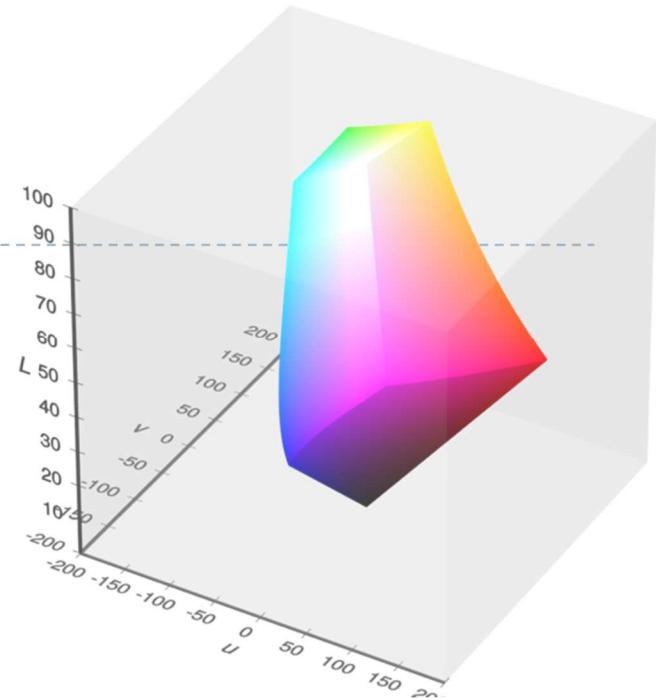
In CIE  $u'v'$  chromatic coordinates

# CIE L<sup>\*</sup>u<sup>\*</sup>v<sup>\*</sup> and u'v'

- ▶ Approximately perceptually uniform
- ▶ u'v' chromacity

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

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



sRGB in CIE L<sup>\*</sup>u<sup>\*</sup>v<sup>\*</sup>

- ▶ CIE LUV

**Lightness**

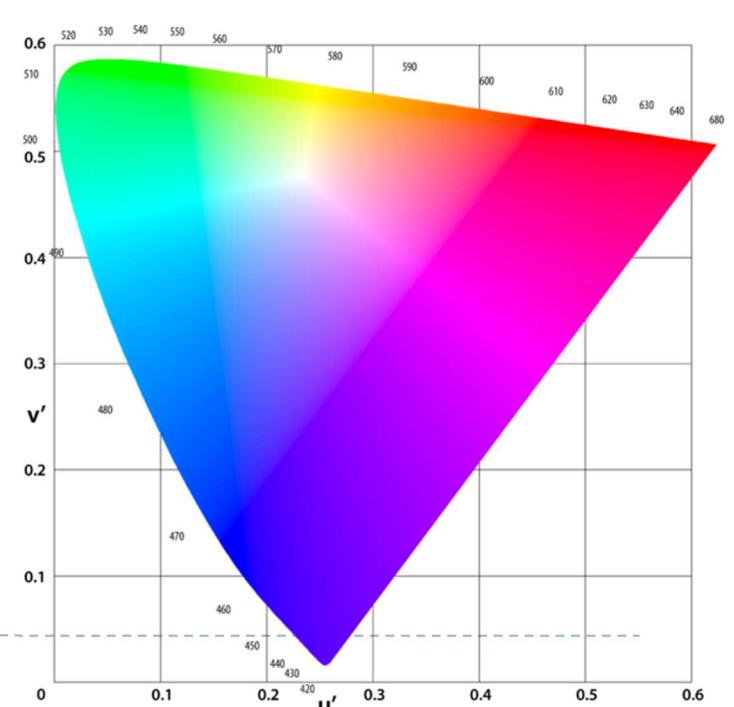
$$L^* = \begin{cases} \left(\frac{29}{3}\right)^3 Y/Y_n, & Y/Y_n \leq \left(\frac{6}{29}\right)^3 \\ 116(Y/Y_n)^{1/3} - 16, & Y/Y_n > \left(\frac{6}{29}\right)^3 \end{cases}$$

**Chromacity coordinates**

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

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

Colours less  
distinguishable  
when dark



- ▶ Hue and chroma

$$C_{uv}^* = \sqrt{(u^*)^2 + (v^*)^2}$$

$$h_{uv} = \text{atan2}(v^*, u^*),$$

# CIE L\*a\*b\* colour space

- ▶ Another approximately perceptually uniform colour space

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

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

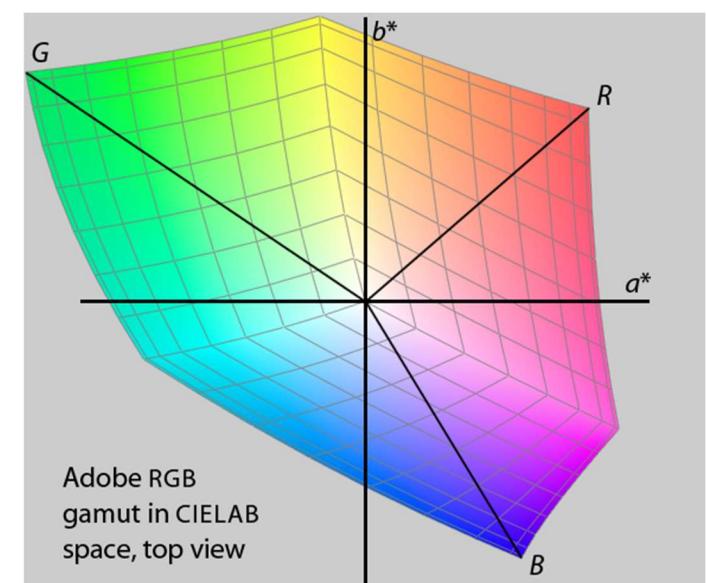
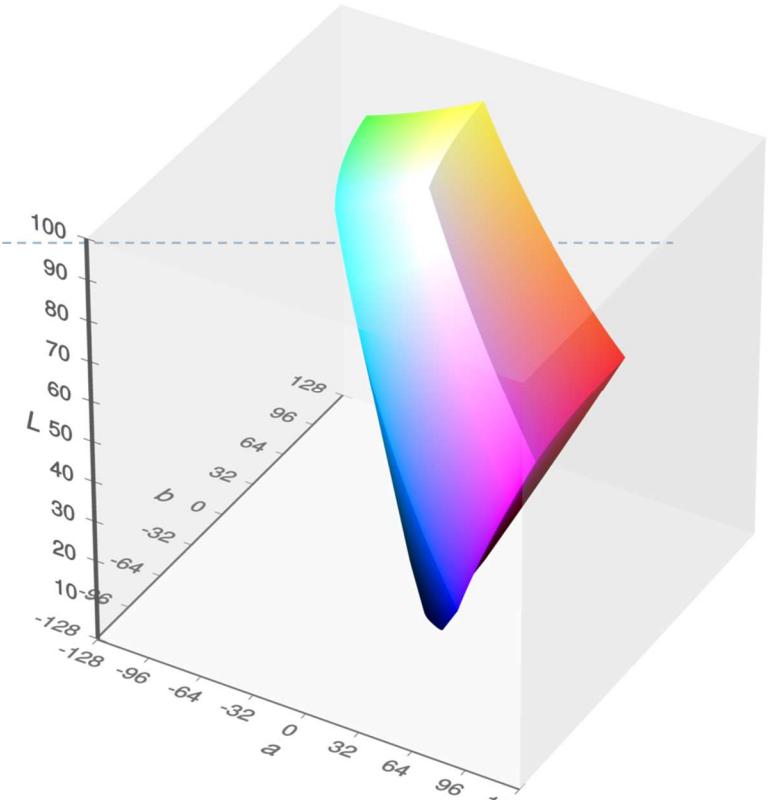
$$b^* = 200 \left( f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right) \right)$$

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

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

Trichromatic values of the white point, e.g.

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





## Lab space

- ▶ this visualization shows those colours in *Lab* space which a human can perceive
- ▶ again we see that human perception of colour is not uniform
  - ▶ perception of colour diminishes at the white and black ends of the *L* axis
  - ▶ the maximum perceivable chroma differs for different hues

# Colour - references

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- ▶ Chapters „Light” and „Colour” in
  - ▶ Shirley, P. & Marschner, S., *Fundamentals of Computer Graphics*
- ▶ Textbook on colour appearance
  - ▶ Fairchild, M. D. (2005). *Color Appearance Models* (second.). John Wiley & Sons.
- ▶ Comprehensive review of colour research
  - ▶ Wyszecki, G., & Stiles, W. S. (2000). *Color science: concepts and methods, quantitative data, and formulae* (Second ed.). John Wiley & Sons.