Advanced Graphics and Image Processing

Colour perception and colour spaces

Part 1/5 – physics of light

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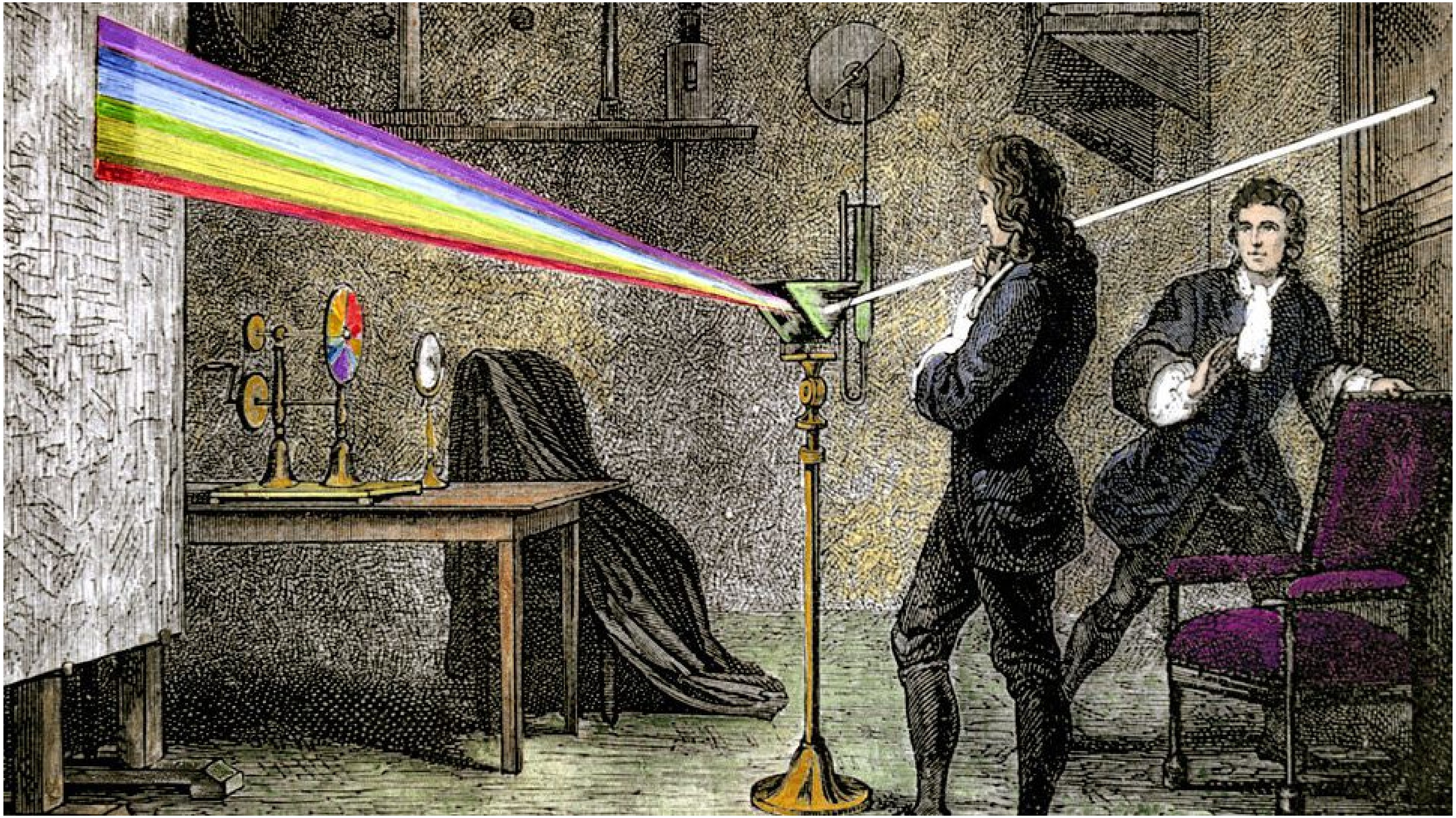
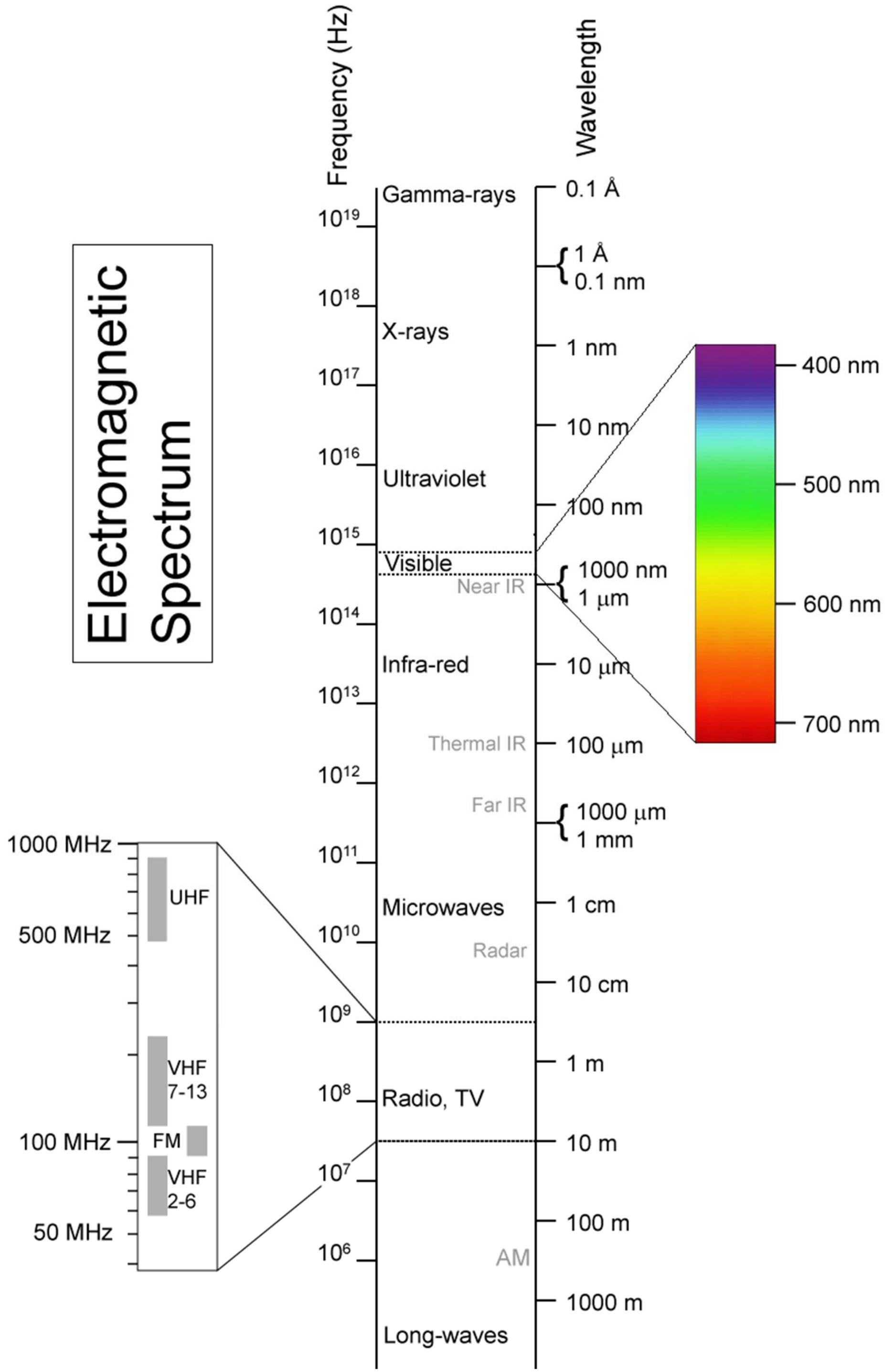


Electromagnetic spectrum

- 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

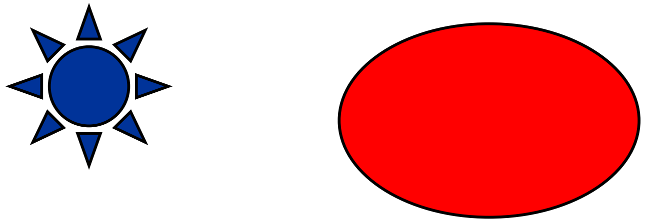


Colour

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

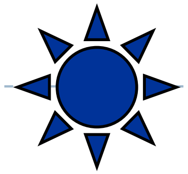
- For reflective displays / objects

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



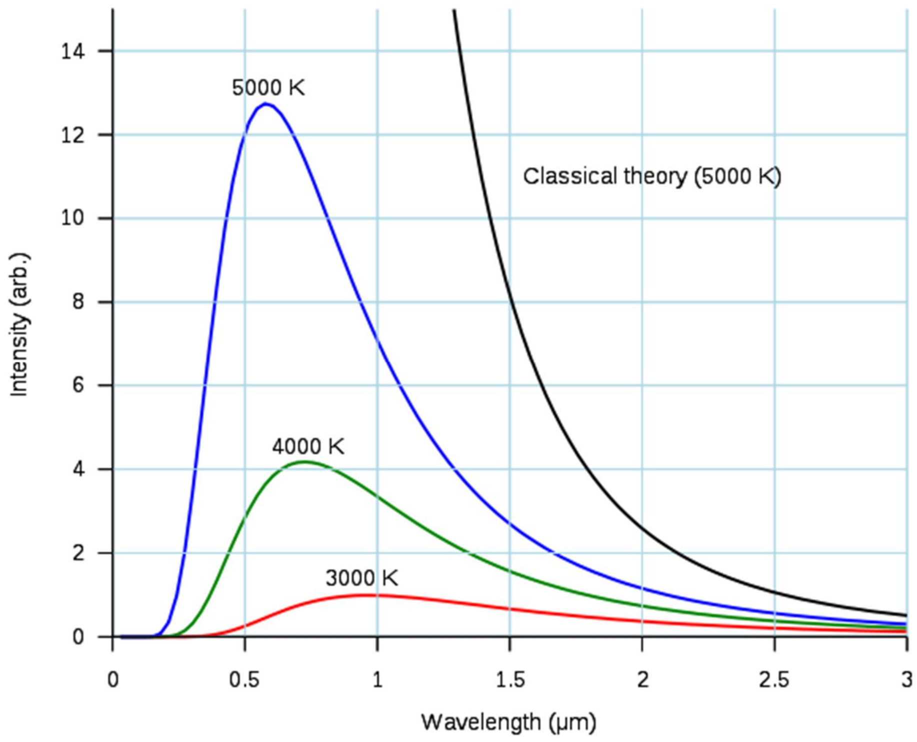
- For emissive objects or displays

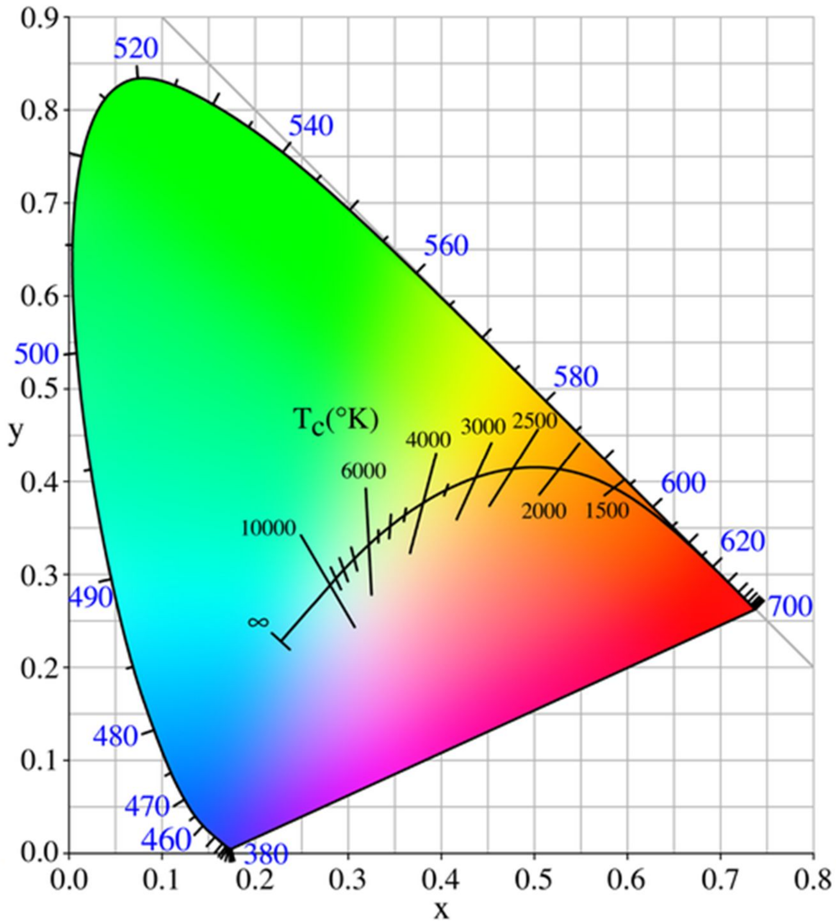
$$\text{colour} = \text{perception}(\ \text{emission}\ )$$



Black body radiation

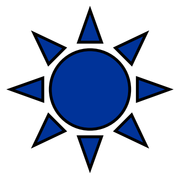
- Electromagnetic radiation emitted by a perfect absorber at a given temperature
  - Graphite is a good approximation of a black body





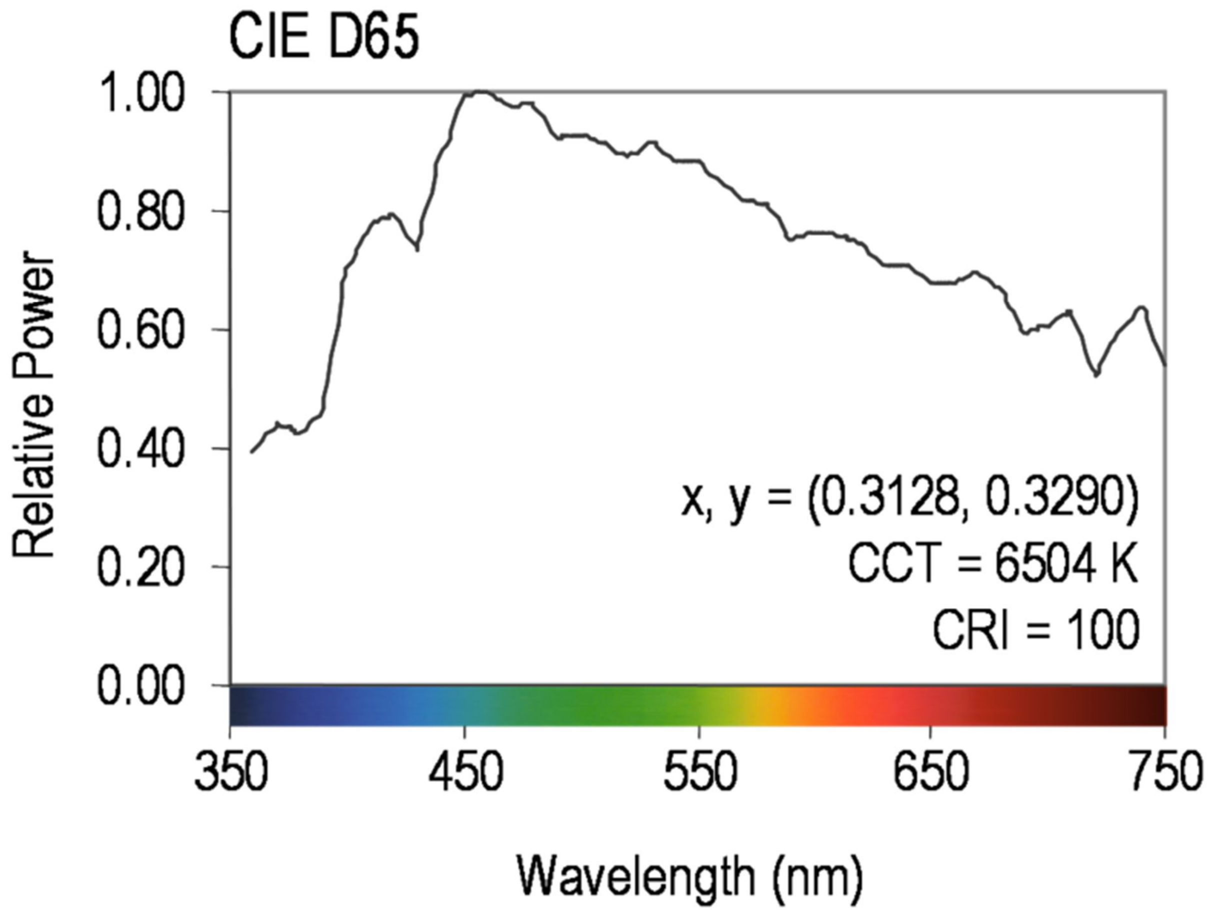
Correlated colour temperature

- 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

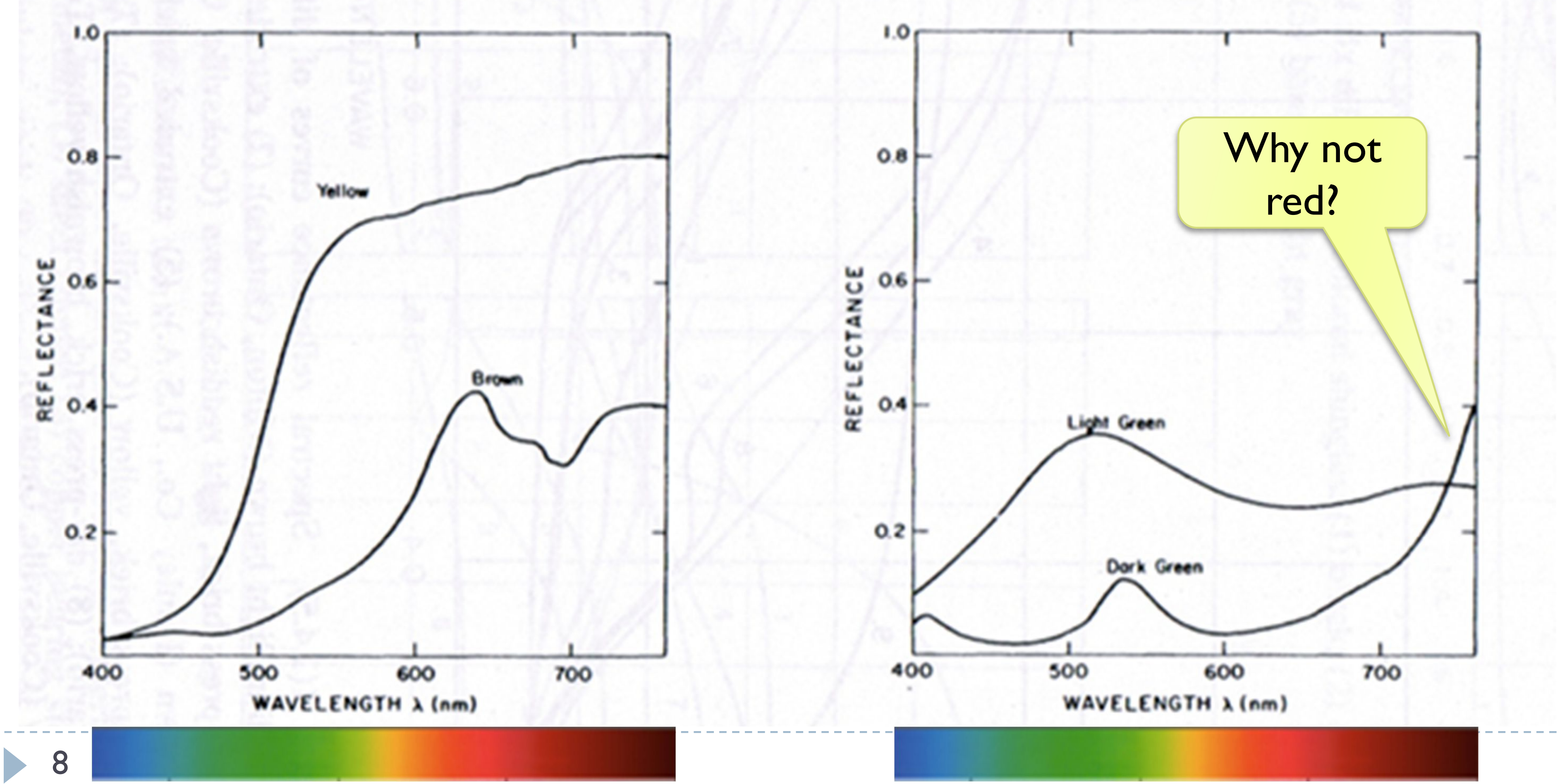
- Mid-day sun in Western Europe / Northern Europe
- Colour temperature approx. 6500 K



Reflectance

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

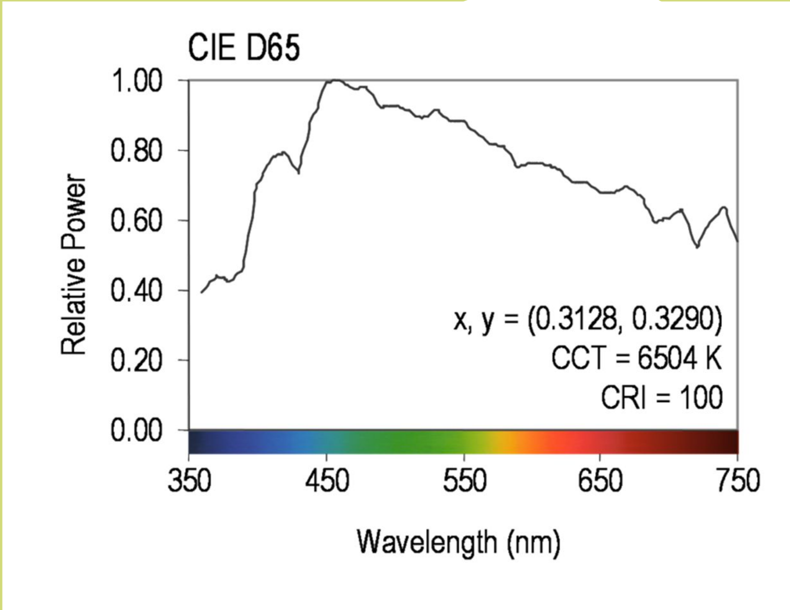
Spectral reflectance of ceramic tiles

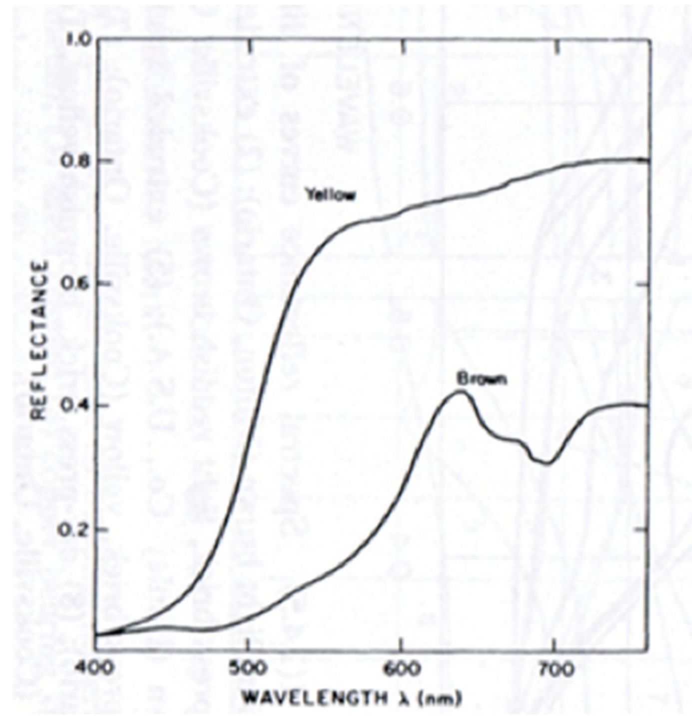


Reflected light

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

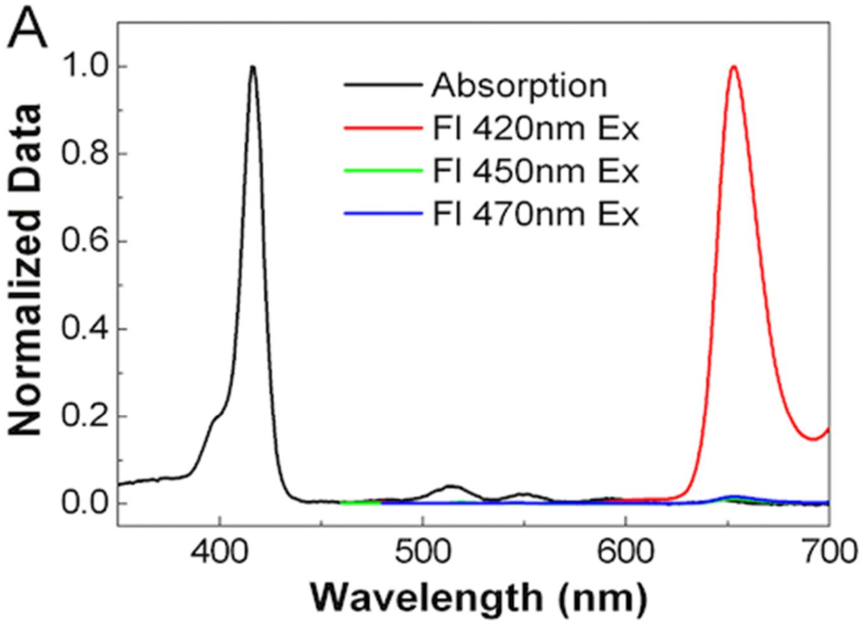
- Reflected light = illumination × reflectance

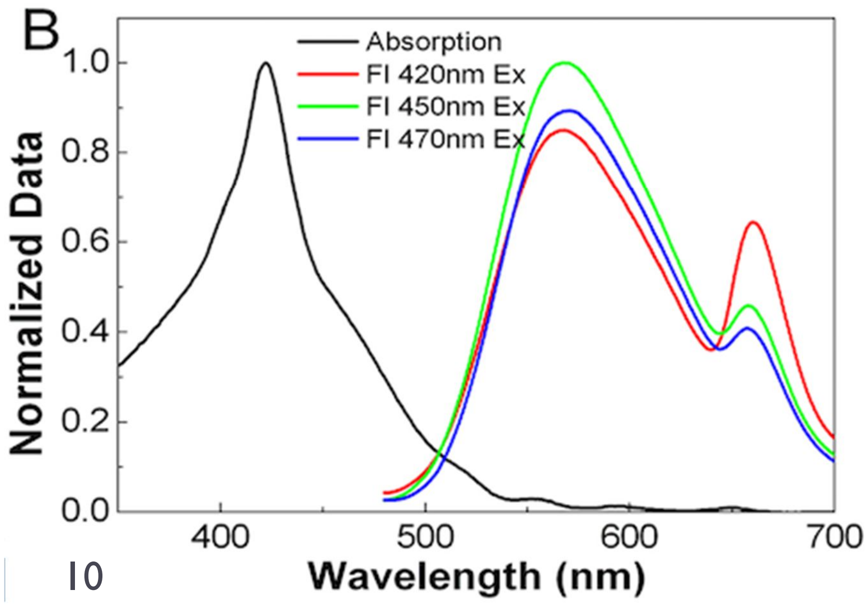


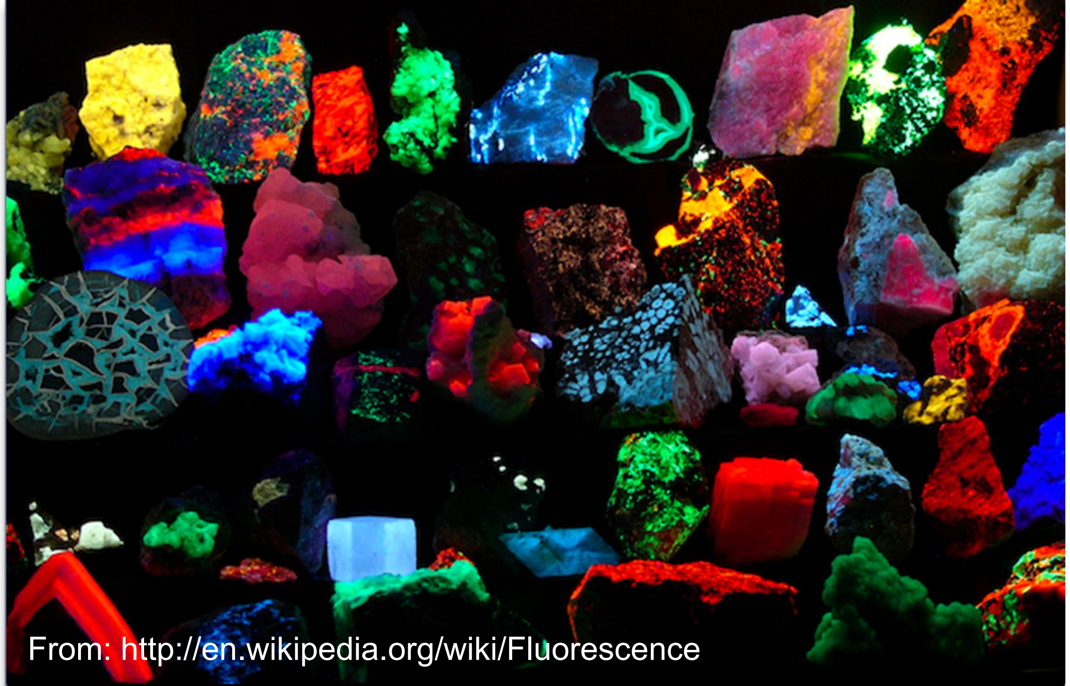


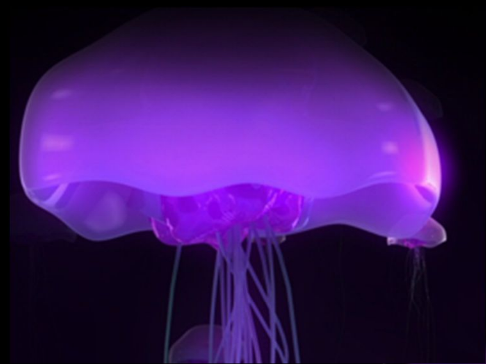
The same object may appear to have different color under different illumination.

Fluorescence









Advanced Graphics and Image Processing

Colour perception and colour spaces

Part 2/5 – perception, cone fundamentals

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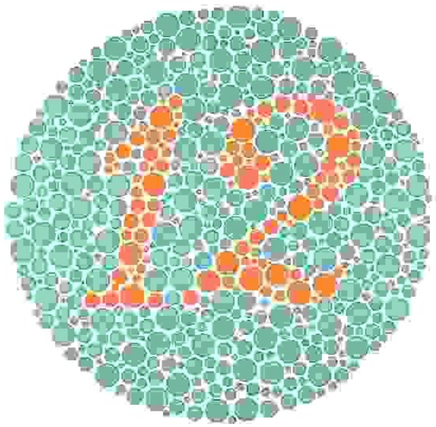
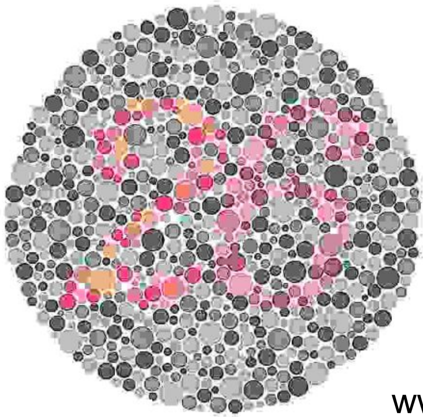
Colour perception

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

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

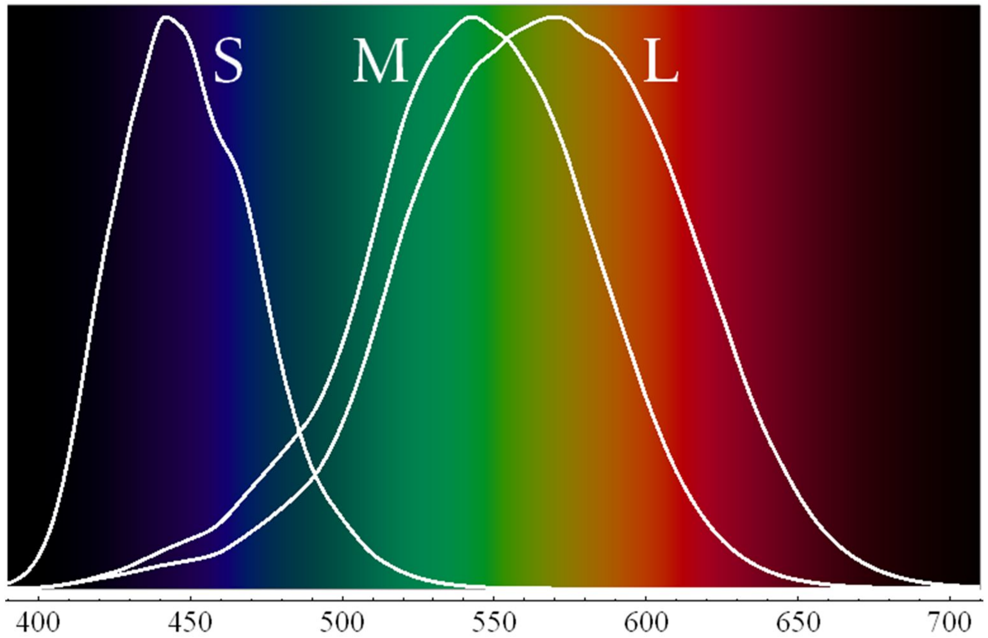




www.colorcube.com/illusions/clrblnd.html

Colour vision

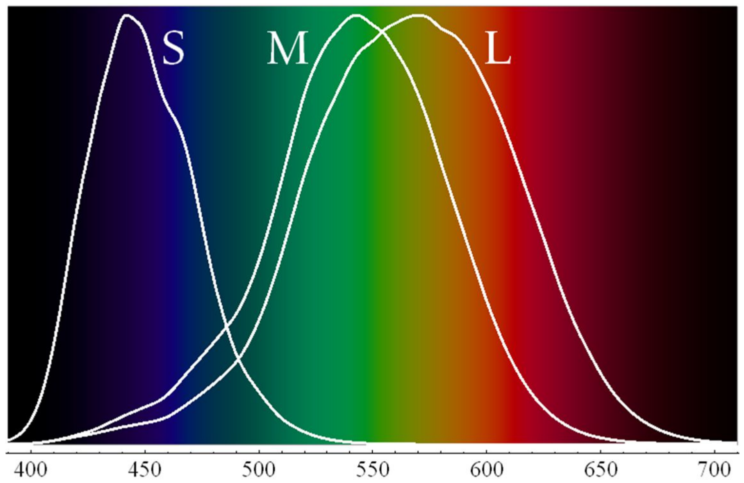
- Cones are the photreceptors responsible for colour vision
  - Only daylight, we see no colours when there is not enough light
- Three types of cones
  - S – sensitive to short wavelengths
  - M – sensitive to medium wavelengths
  - L – sensitive to long wavelengths

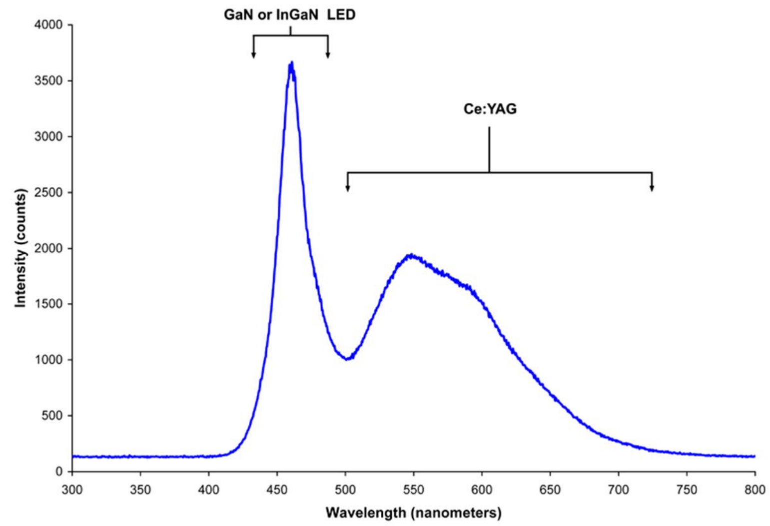


Sensitivity curves – probability that a photon of that wavelengths will be absorbed by a photoreceptor. S,M and L curves are normalized in this plot.

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

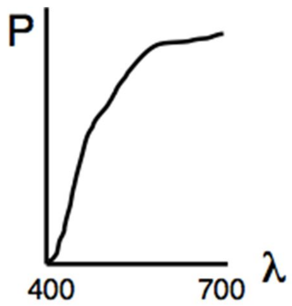
Formally

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

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:



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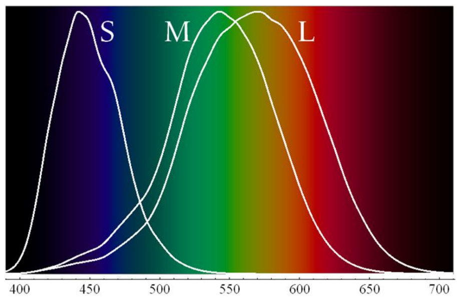
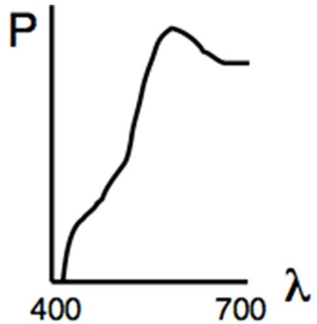


$= [L_1, M_1, S_1]$

||



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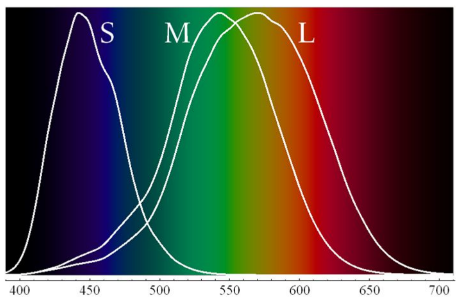
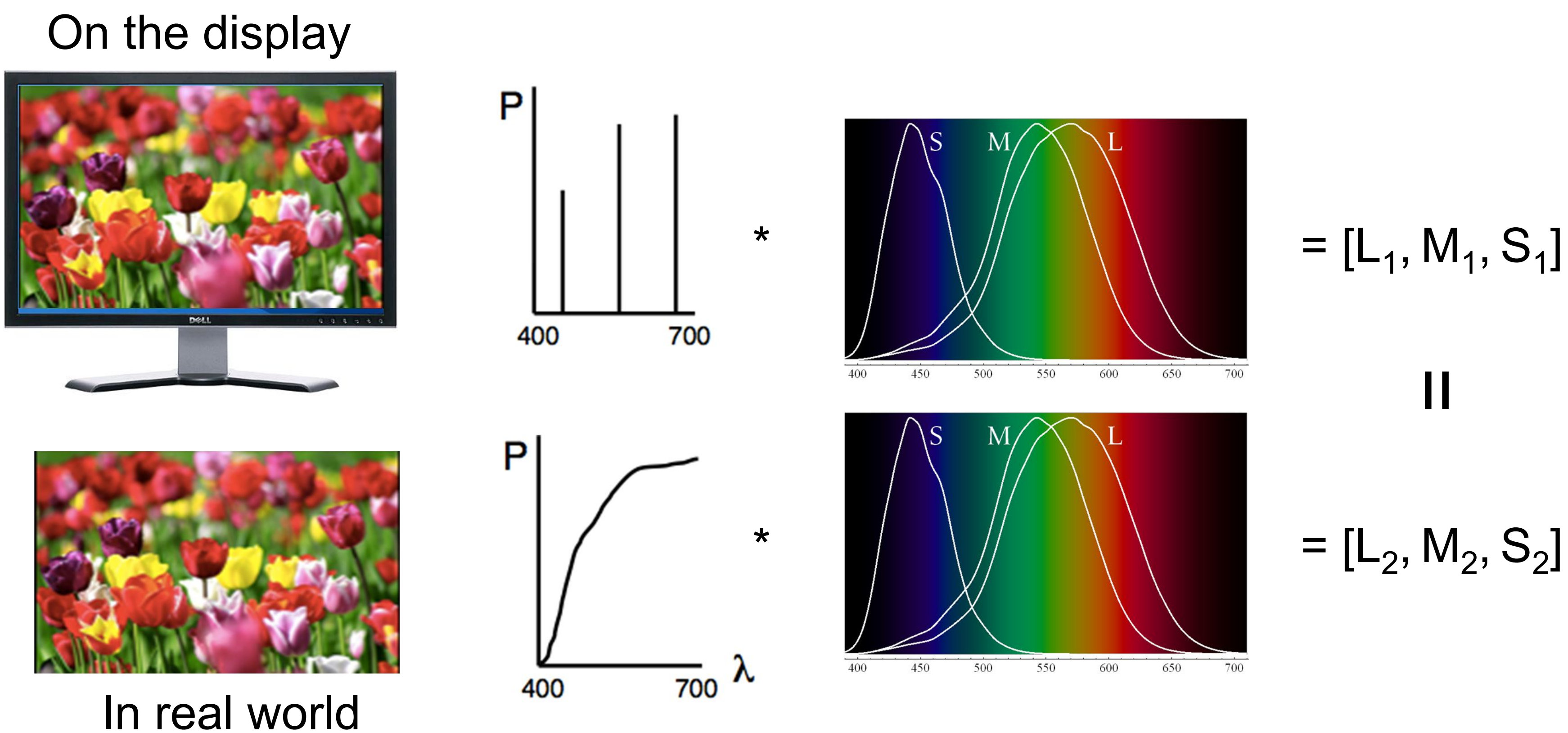


$= [L_2, M_2, S_2]$

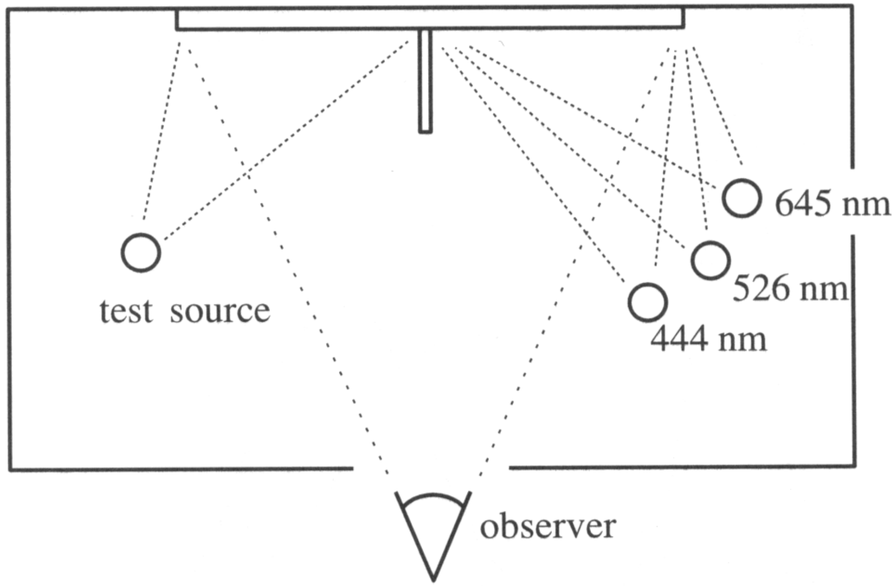
Practical application of metamerism

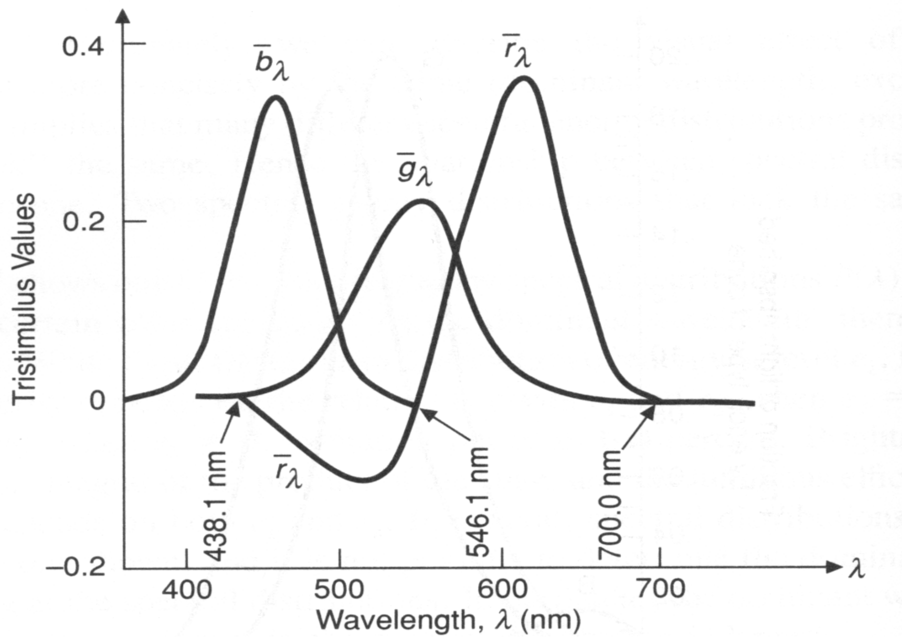
- Displays do not emit the same light spectra as real-world objects
- Yet, the colours on a display look almost identical



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



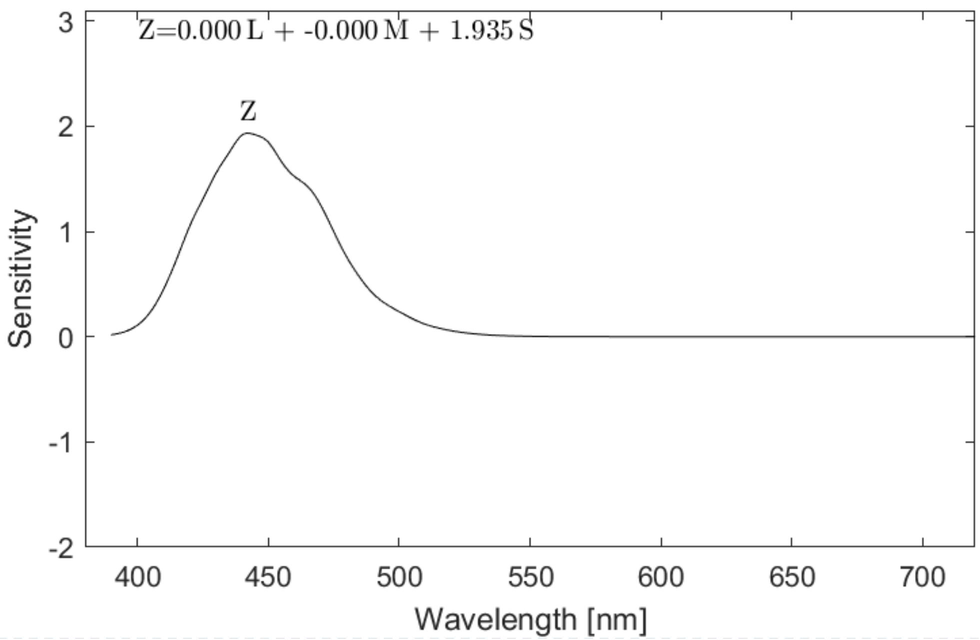


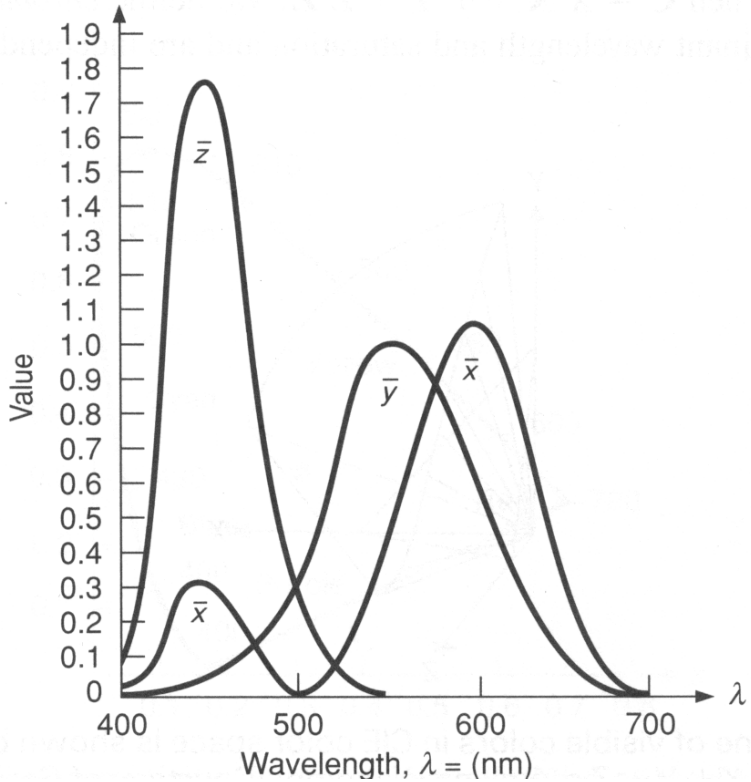
Standard Colour Space CIE-XYZ

- 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 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



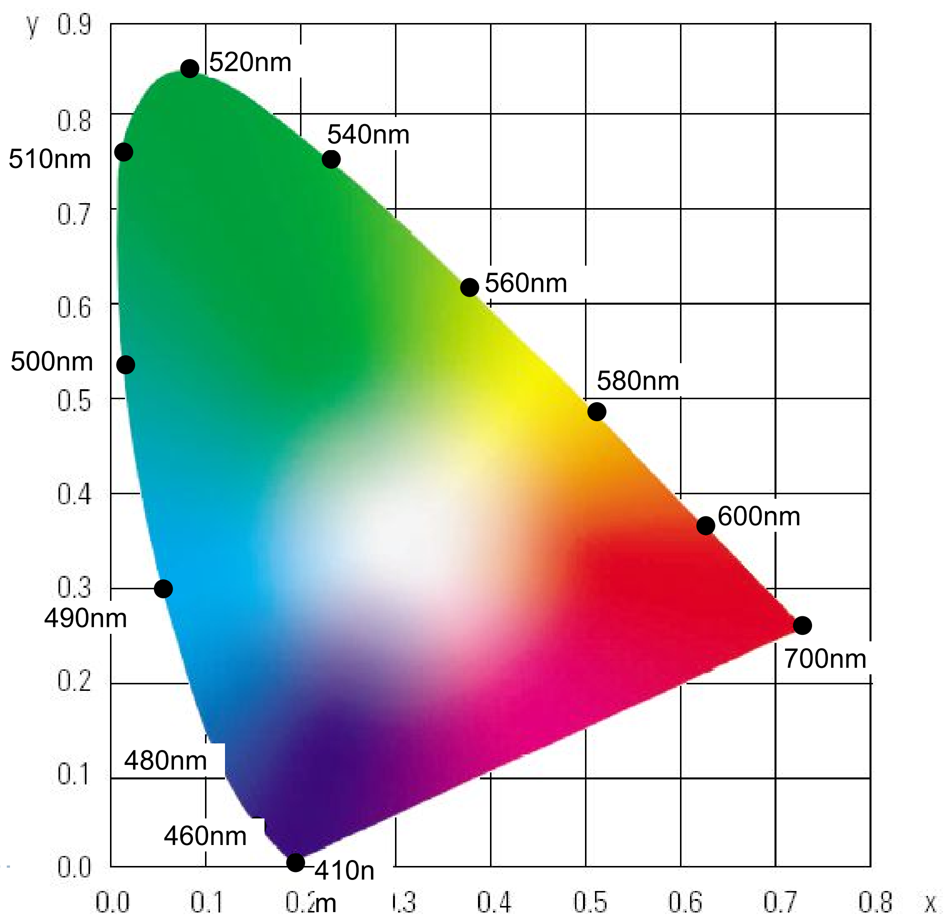


CIE chromaticity diagram

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

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

  - 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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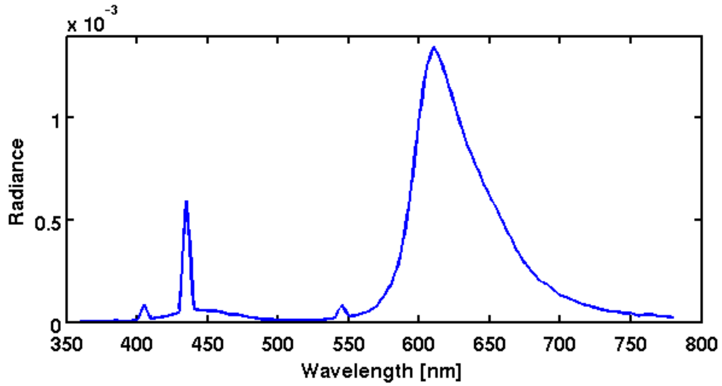
Luminance

- Luminance – measure of light weighted by the response of the achromatic mechanism. Units: cd/m² (ISO) or nit

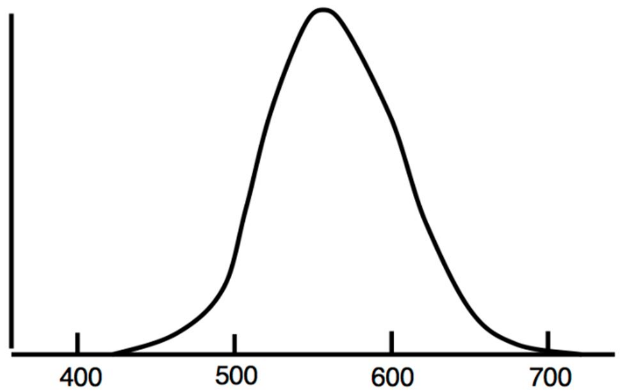
Luminance

$$L_V = \int_{350}^{700} kL(\lambda)V(\lambda)d\lambda \qquad k = 683.002$$

Light spectrum (radiance)

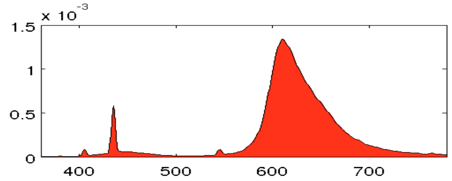


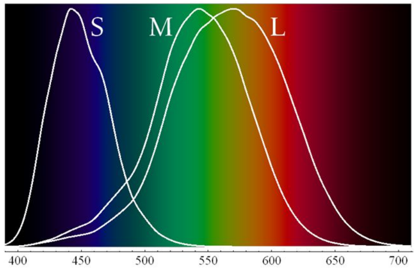
Luminous efficiency function (weighting)

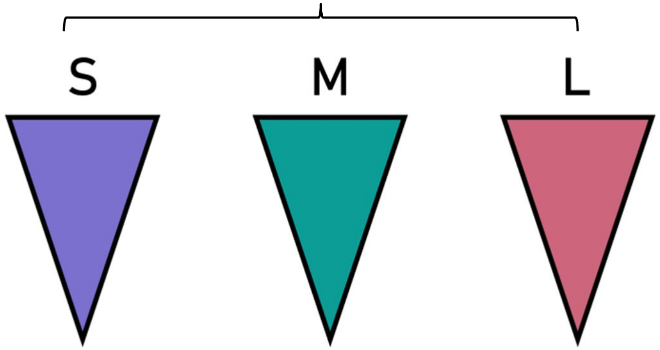


Achromatic/chromatic vision mechanisms

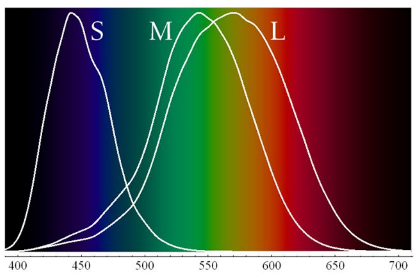
Light spectra

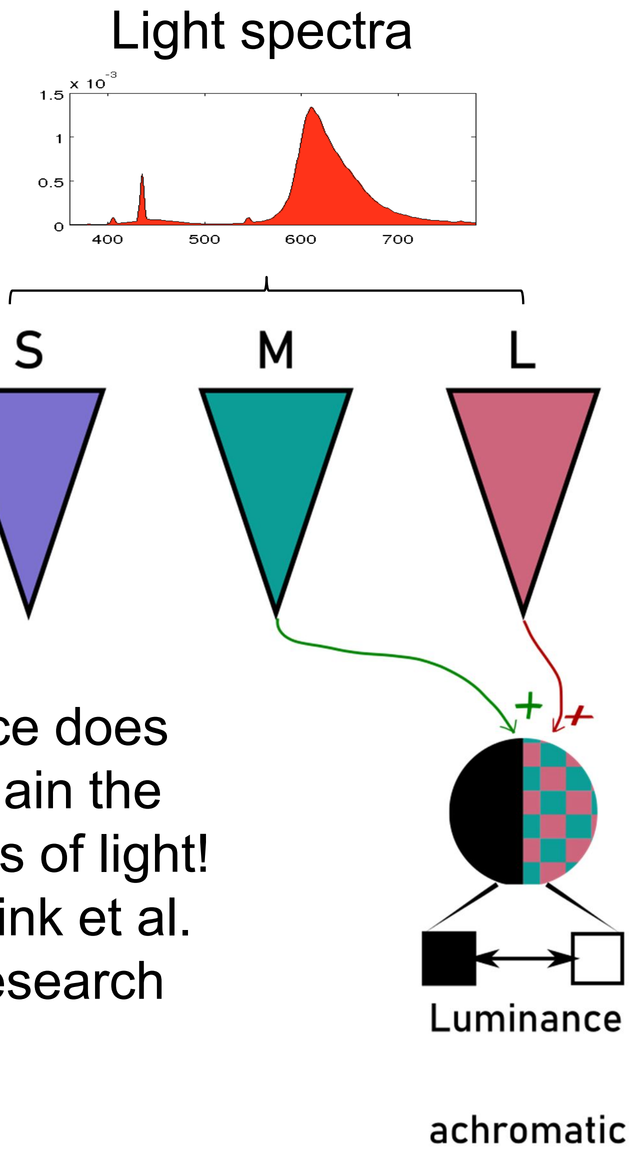






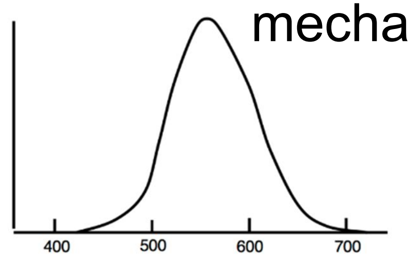
Achromatic/chromatic vision mechanisms



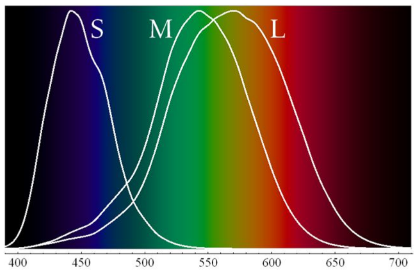


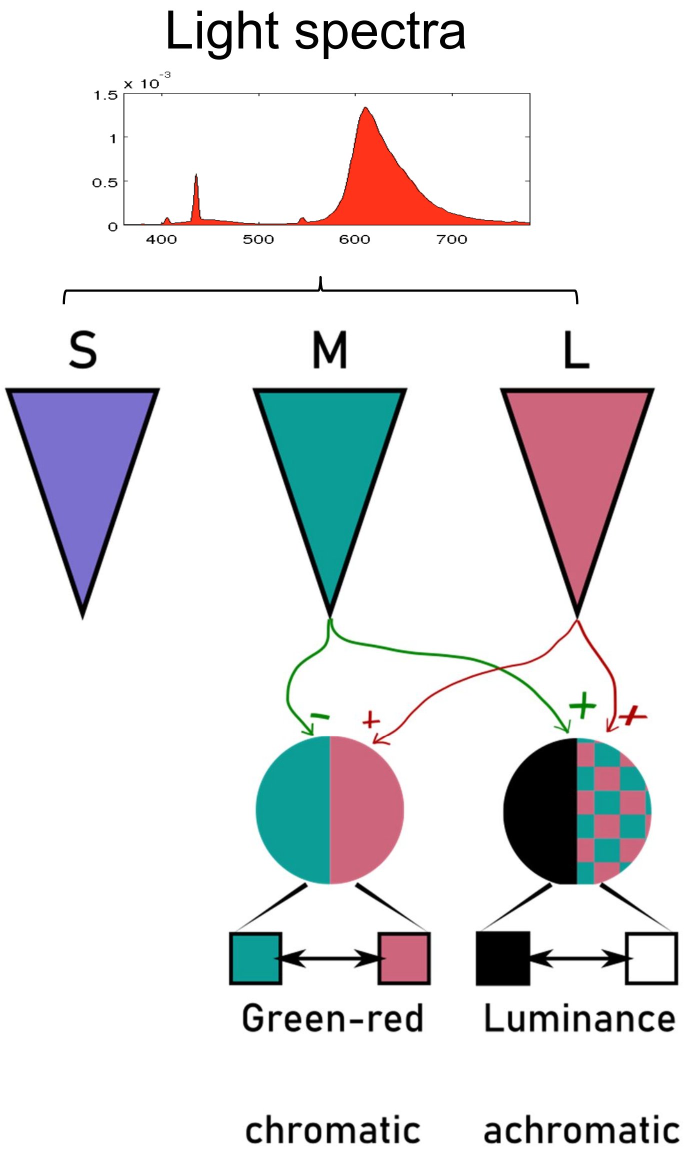
Luminance does NOT explain the brightness of light! [Koenderink et al. Vision Research 2016]

Sensitivity of the achromatic mechanism

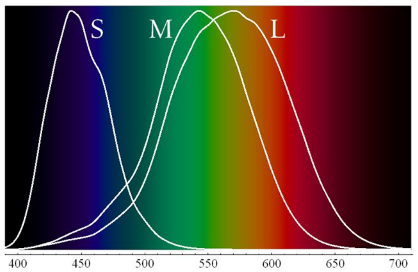


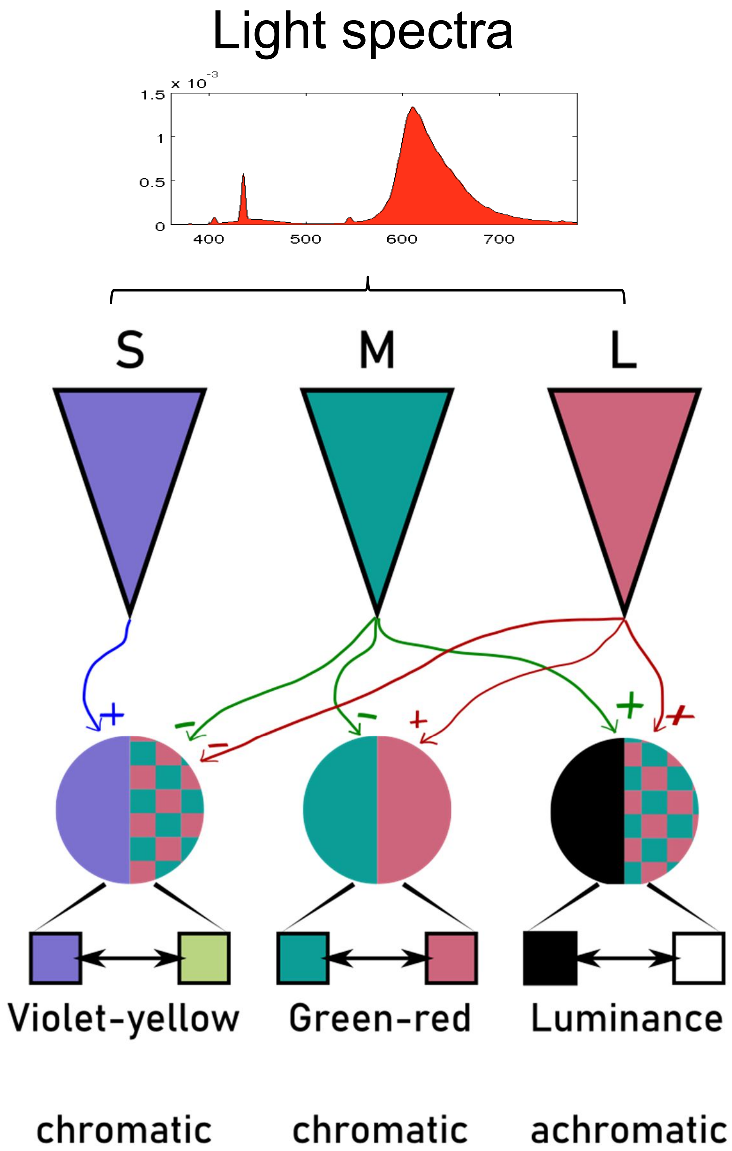
Achromatic/chromatic vision mechanisms



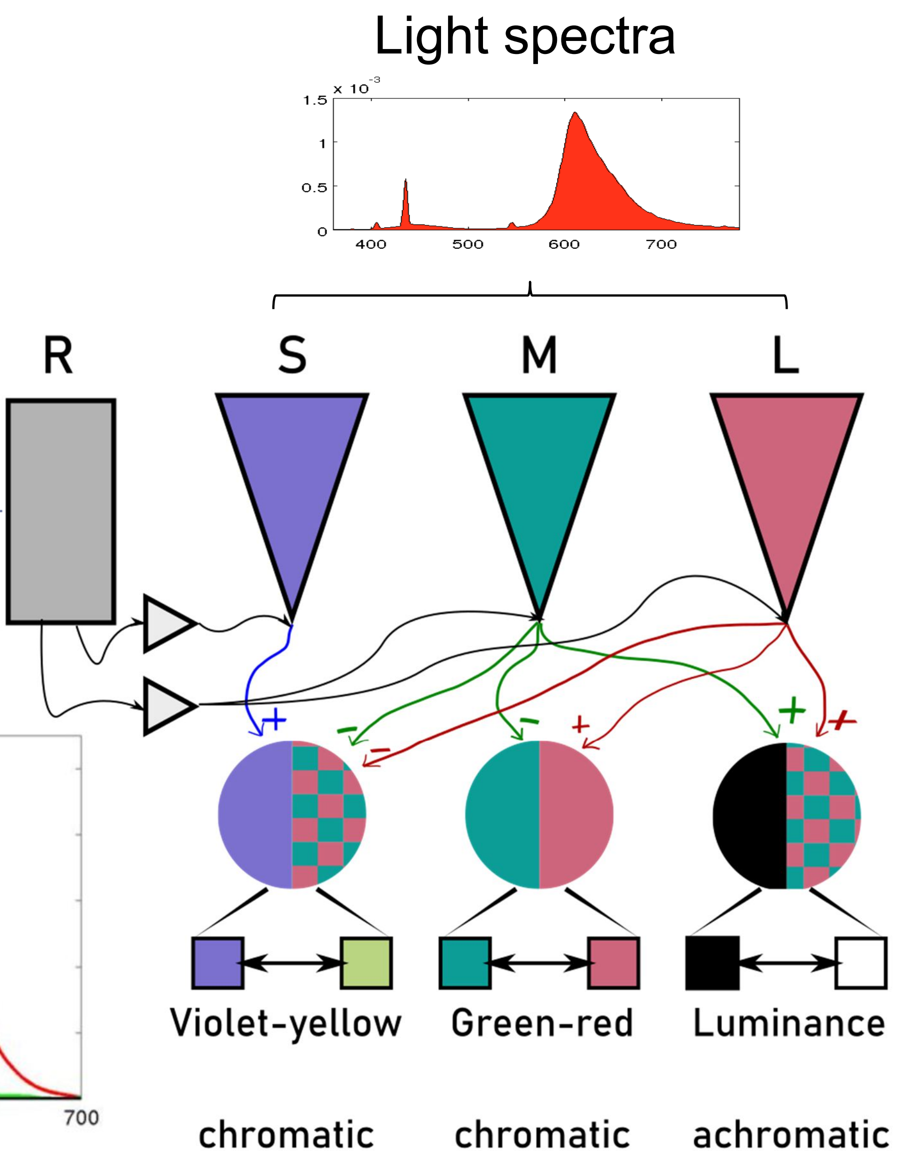


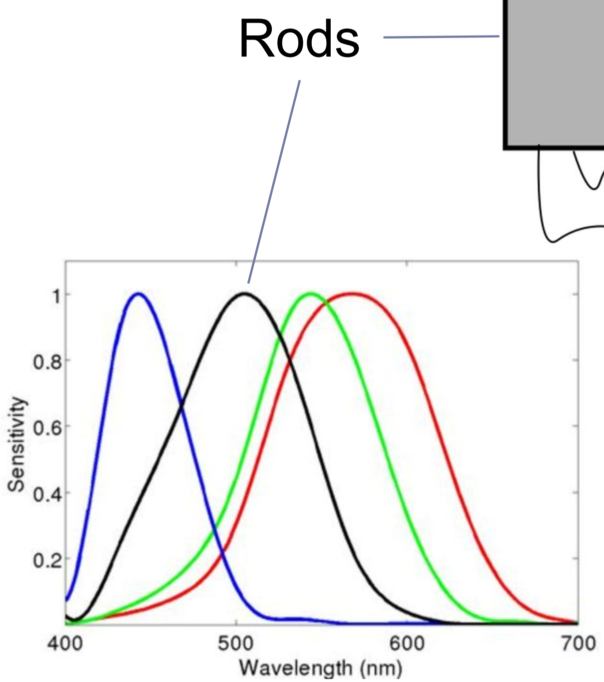
Achromatic/chromatic vision mechanisms





Achromatic/chromatic vision mechanisms





Advanced Graphics and Image Processing

Colour perception and colour spaces

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

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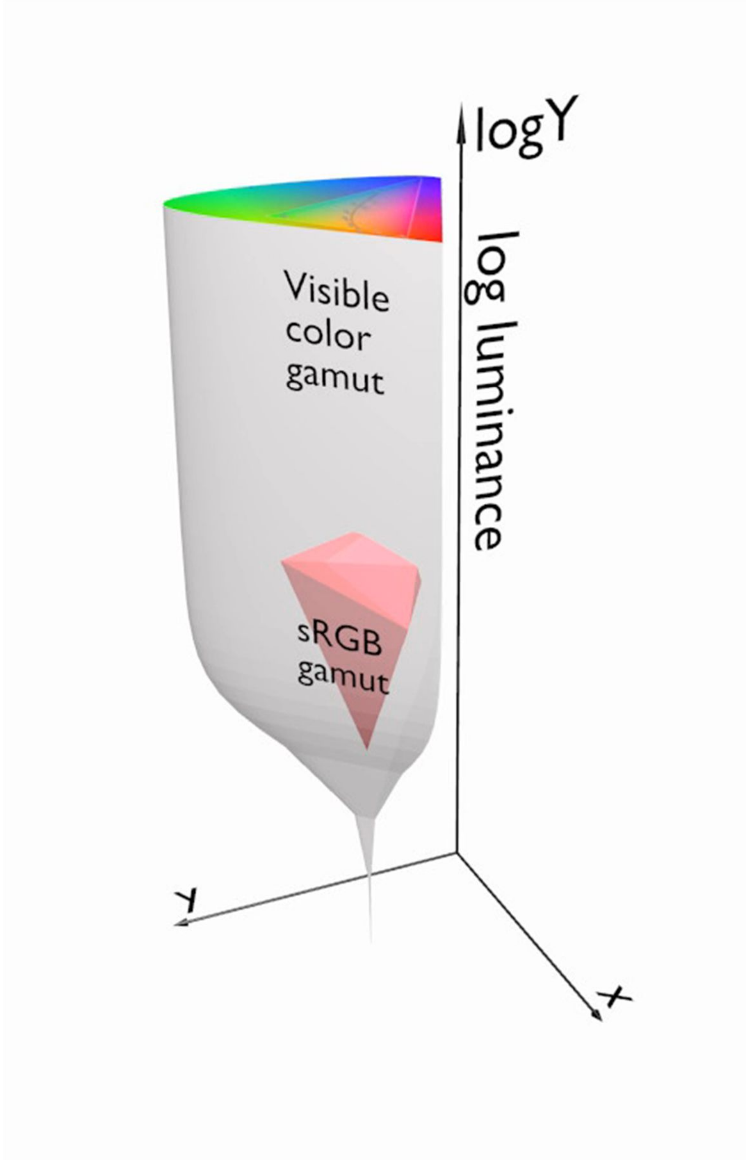
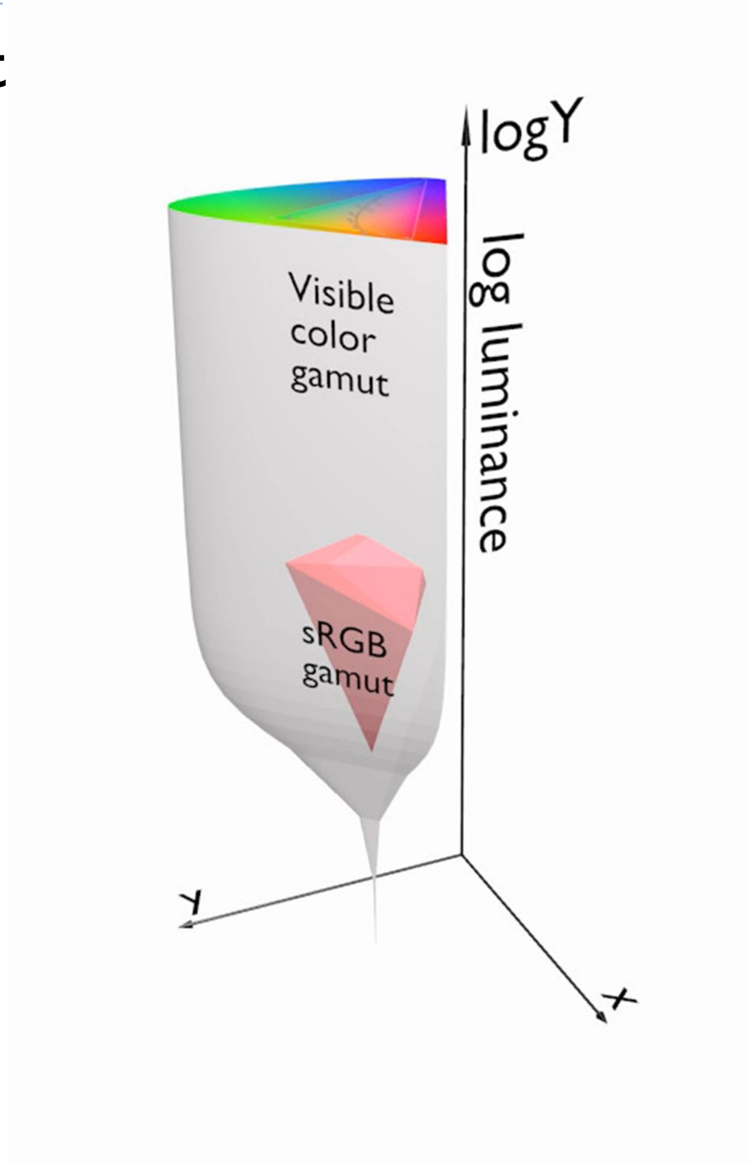
Visible vs. displayable colours

- 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

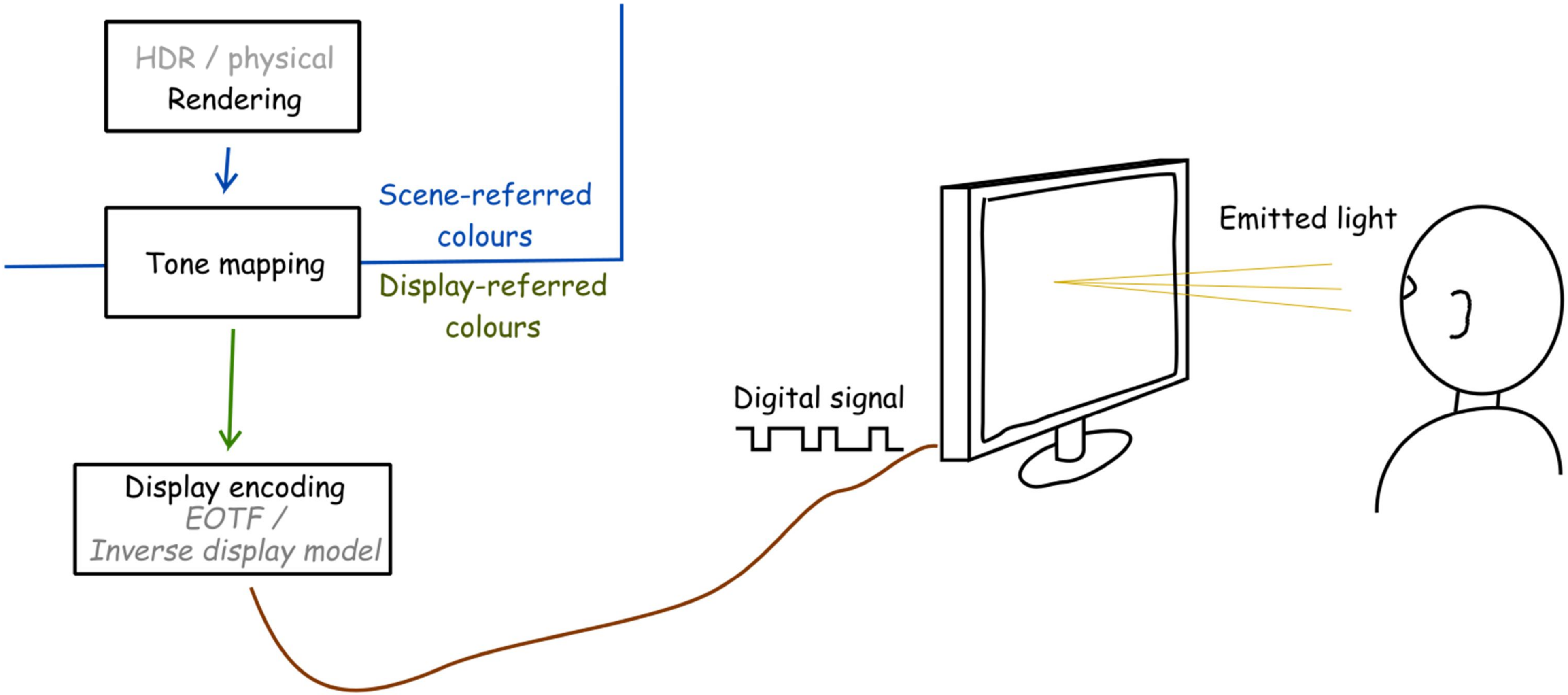


Standard vs. High Dynamic Range

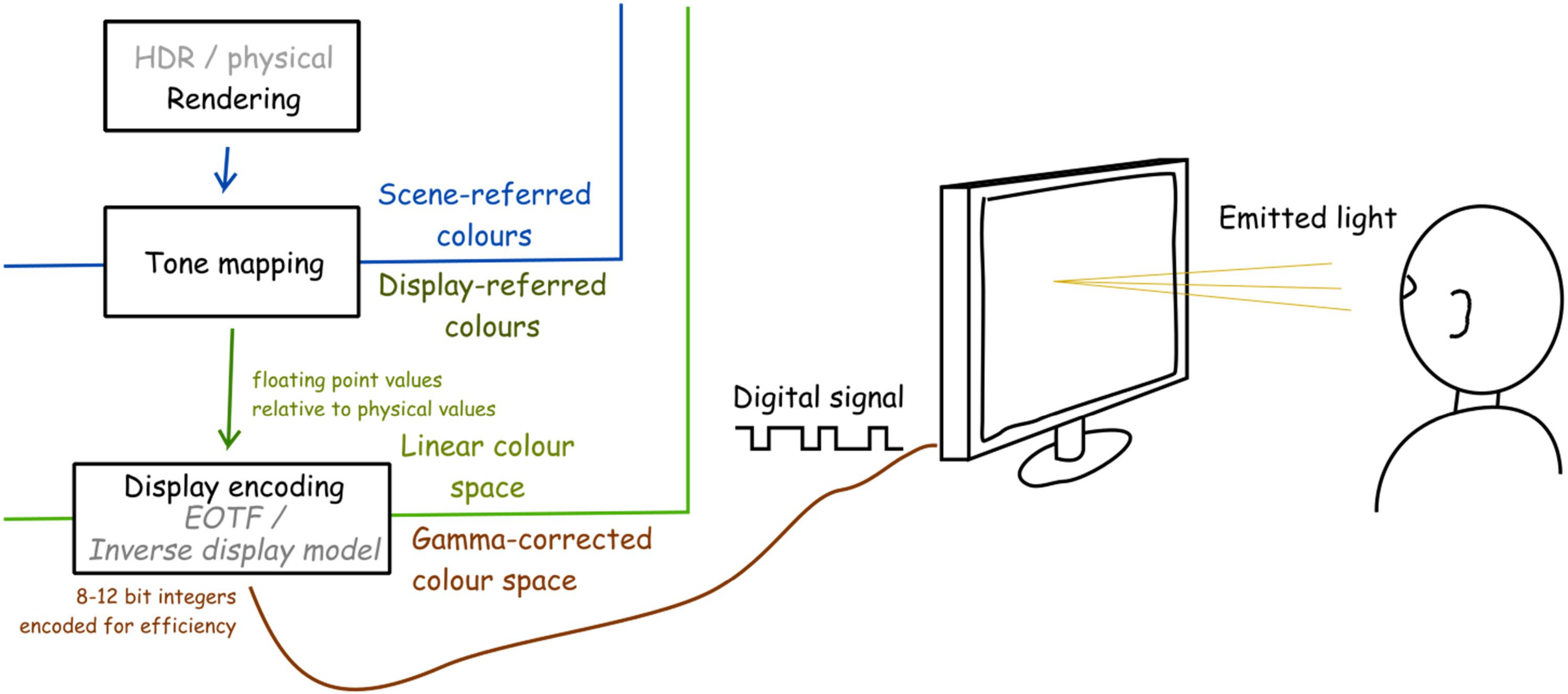
- **HDR** cameras/formats/displays attempt capture/represent/reproduce (almost) all visible colours
  - They represent scene colours and therefore we often call this representation *scene-referred*
- **SDR** cameras/formats/devices attempt to capture/represent/reproduce only colours of a standard sRGB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



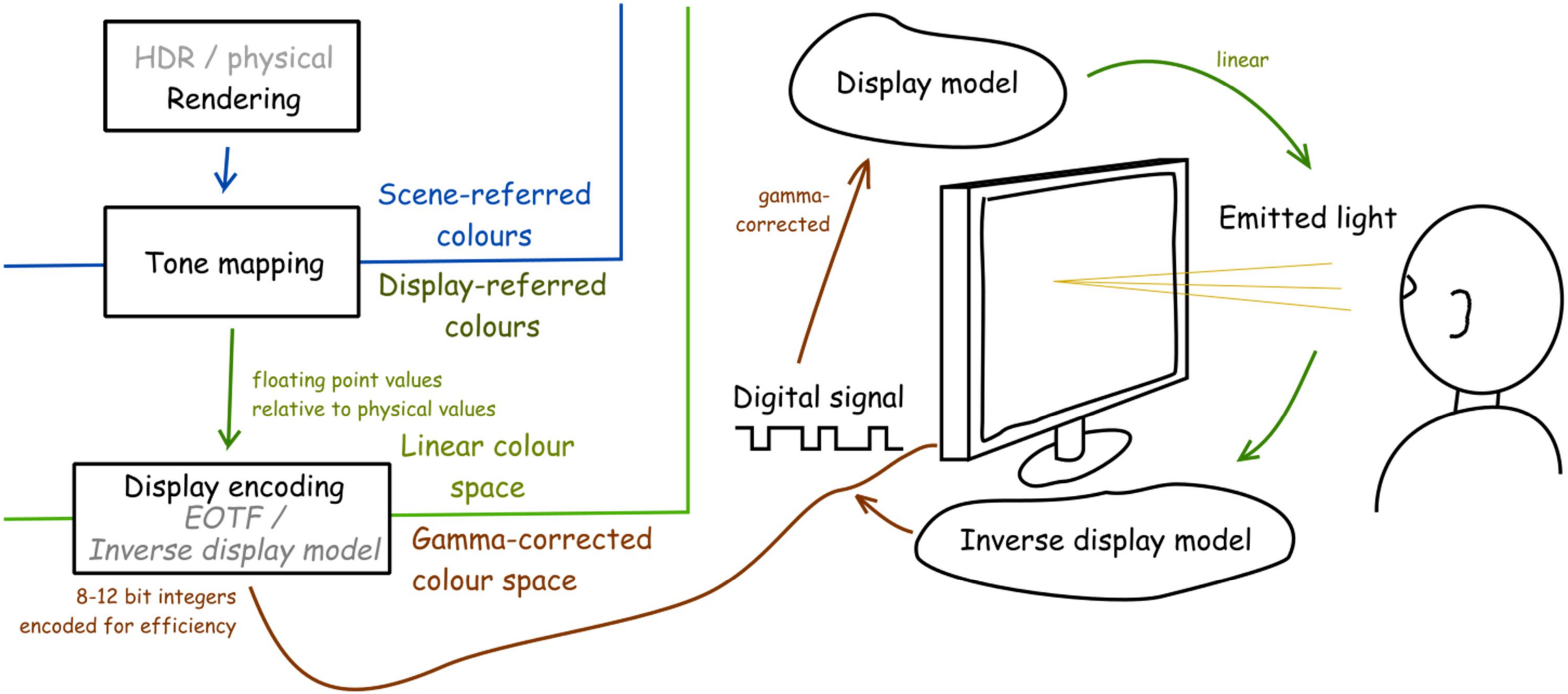
From rendering to display



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.)

Gain

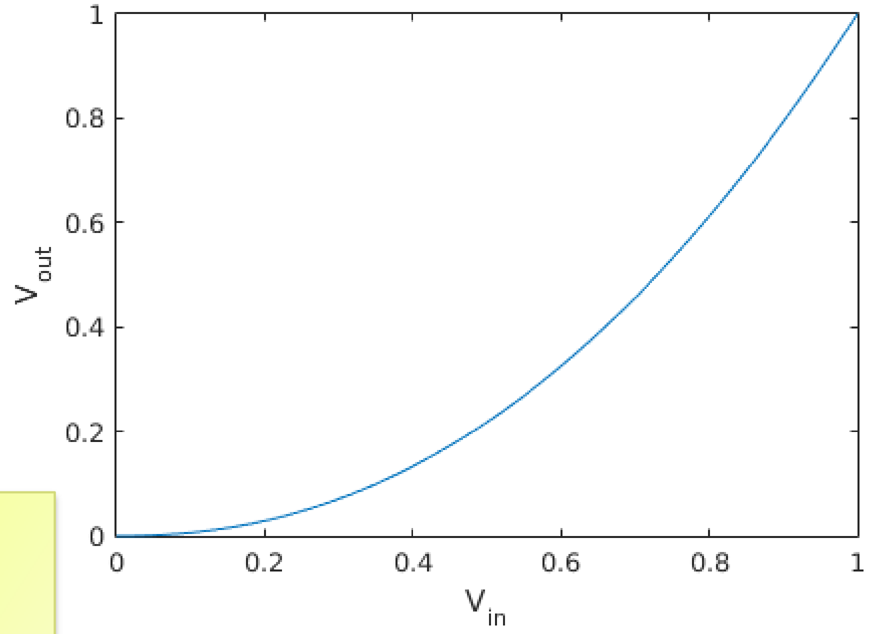
Gamma (usually =2.2)

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

(relative) Luminance
Physical signal

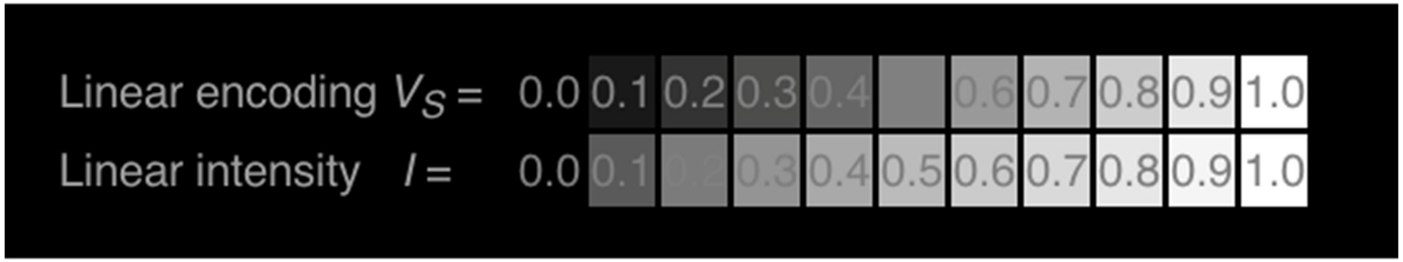
Luma
Digital signal (0-1)

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



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

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

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

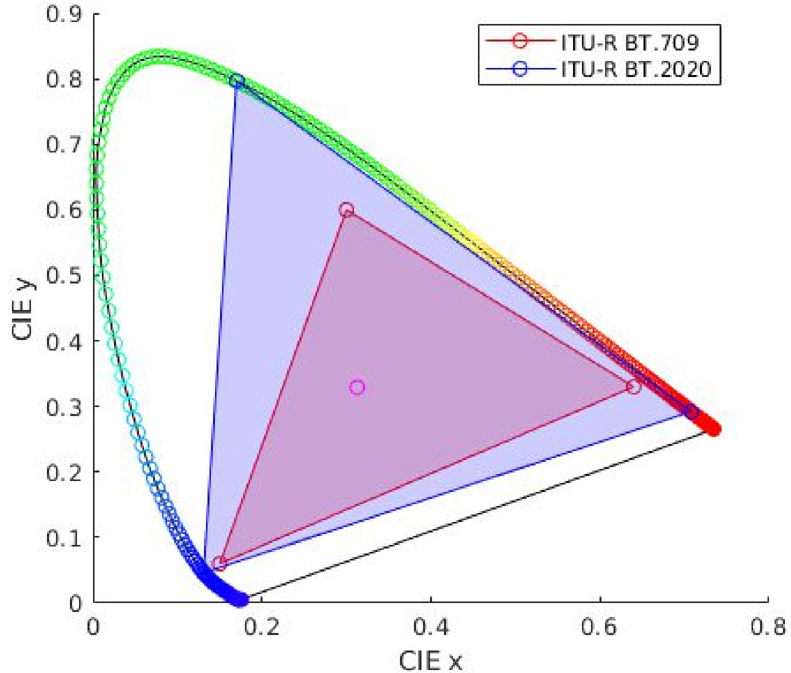
- R, G, and B are *linear* colour values
- Luma and luminace are different quantities despite similar formulas

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 2020	ITU-R 2100 (PQ/HLG)	10 to 12

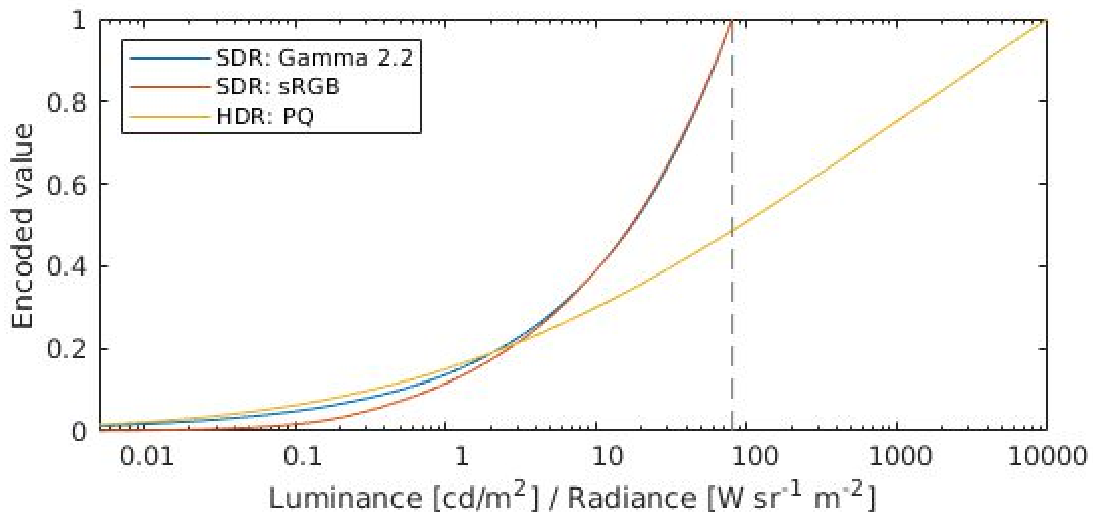
Colour space

What is the XYZ of "pure" red, green and blue

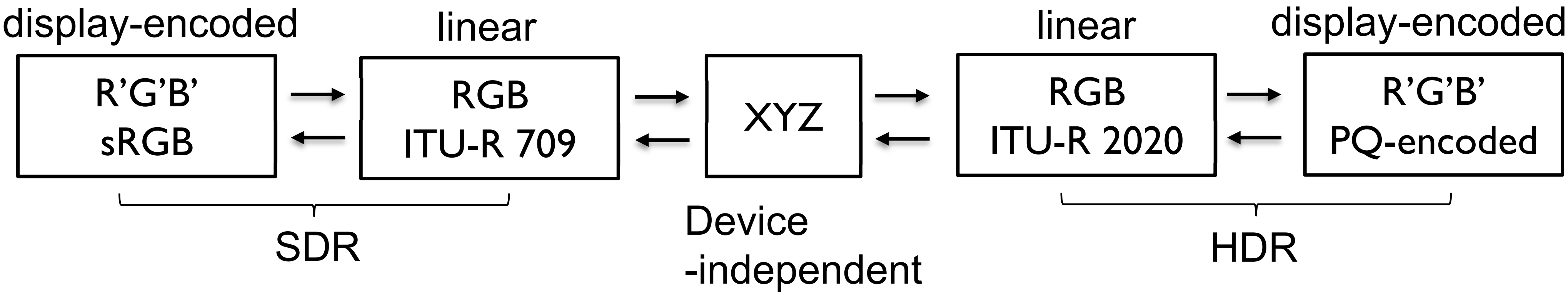


Electro-Optical Transfer Function

How to efficiently encode each primary colour



How to transform between RGB colour spaces (SDR and HDR)?



- From ITU-R 709 RGB to XYZ:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix}_{R709toXYZ} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{R709}$$

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:

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

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

Exercise 1: Map colour to a display

- We have:
  - Spectrum of the colour we want to reproduce: L (Nx1 vector)
  - XYZ sensitivities: S_{XYZ} (Nx3 matrix)
  - Spectra of the RGB primaries: P_{RGB} (Nx3 matrix)
  - Display gamma: $\gamma = 2.2$
- We need to find display-encoded R'G'B' colour values
  - Step 1: Find XYZ of the colour

$$[X \quad Y \quad Z]^T = S_{XYZ}^T \, L$$

  - Step 2: Find a linear combination of RGB primaries

$$S_{XYZ}^T \; P_{RGB} = M_{RGB \to XYZ}$$

  - Step 3: Convert and display-encode linear colour values

$$[R \quad G \quad B]^T = M_{RGB \to XYZ}^{-1} \, [X \quad Y \quad Z]^T$$
$$[R' \quad G' \quad B'] = [R^{1/\gamma} \quad G^{1/\gamma} \quad B^{1/\gamma}]$$

Exercise 2: Find a camera colour correction matrix

- We have:
  - XYZ sensitivities: S_{XYZ} (Nx3 matrix)
  - Spectral sensitivities of camera's RGB pixels: C_{RGB} (Nx3 matrix)
  - Spectrum in the real world: L (Nx1 vector)
- Find a 3x3 matrix mapping from camera's native RGB to XYZ

$$M_{C\to XYZ} C_{RGB}^T \, L \approx S_{XYZ}^T \, L$$

$$\mathrm{argmin}_{M_{C\to XYZ}} \left\| M_{C\to XYZ} C_{RGB}^T \, L - S_{XYZ}^T \, L \right\|_2$$

$$M_{C\to XYZ}^T = \left(C_{RGB}^T C_{RGB} \right)^{-1} C_{RGB}^T S_{XYZ}$$

- Show that a camera is colour-accurate if $C_{RGB}^T = N S_{XYZ}^T$

$$M N \, S_{XYZ}^T = S_{XYZ}^T \text{, where } M = N^{-1}$$

Any full rank 3x3 matrix

Advanced Graphics and Image Processing

Colour perception and colour spaces

Part 5/5 – colour spaces

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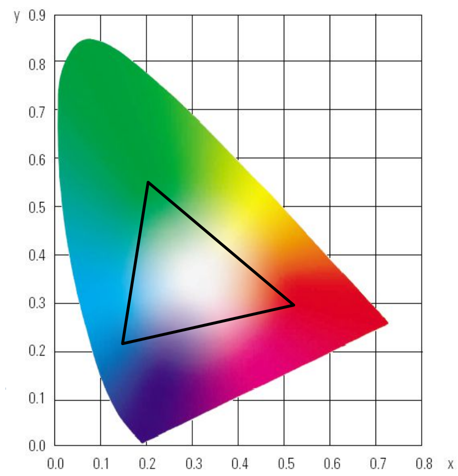
Representing colour

- 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

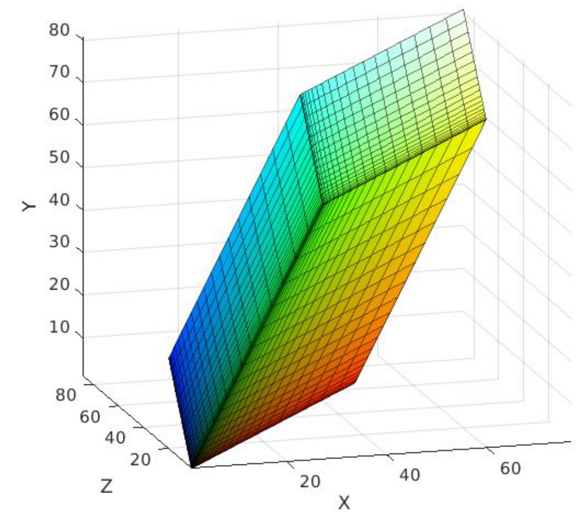
- Most display devices that output light mix red, green and blue lights to make colour
  - televisions, CRT monitors, LCD screens

- 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

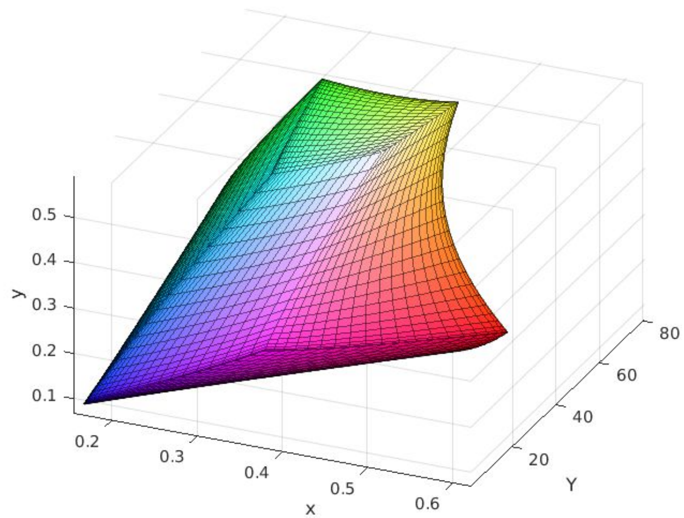


RGB in CIE *XYZ* space

- 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



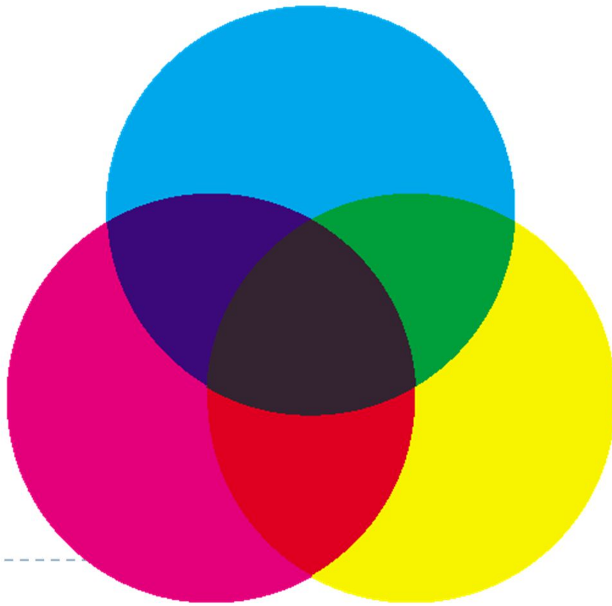
RGB gamut in XYZ colour space



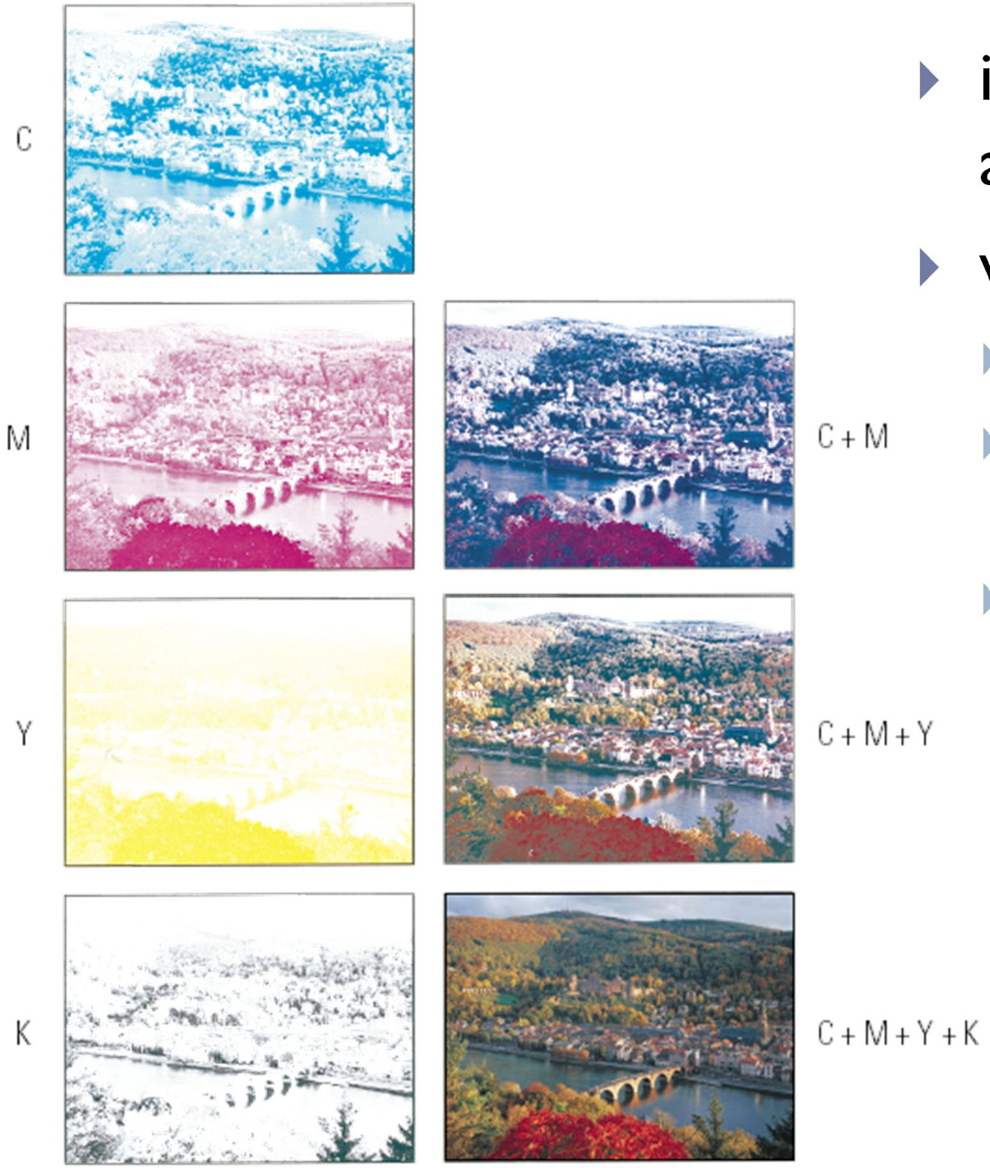
RGB gamut in Yxy colour space

CMY space

- 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



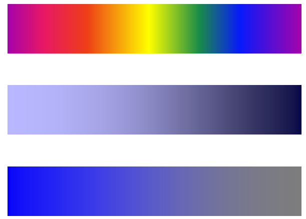
$CMYK$ space

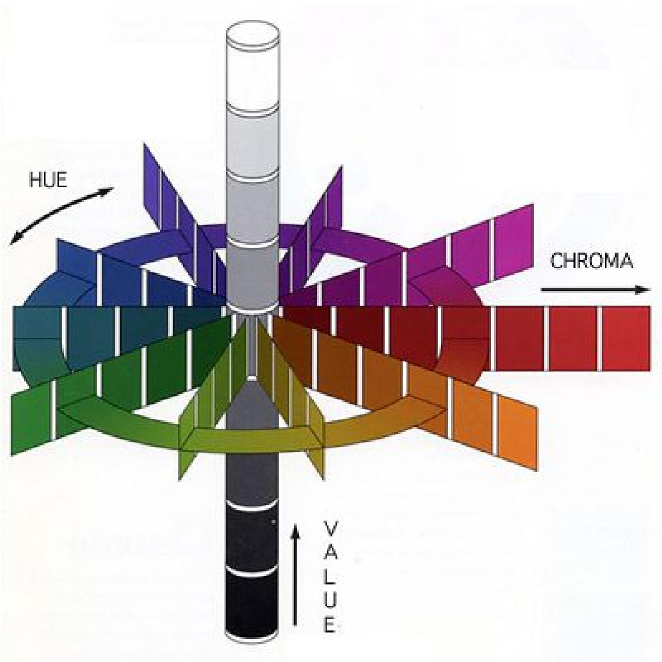


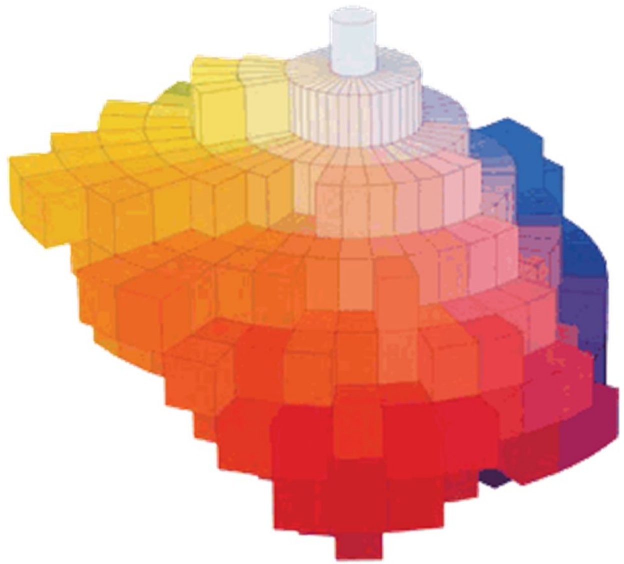
- in real printing we use black (key) as well as CMY
- why use black?
  - inks are not perfect absorbers
  - mixing $C + M + Y$ gives a muddy grey, not black
  - lots of text is printed in black: trying to align C, M and Y perfectly for black text would be a nightmare

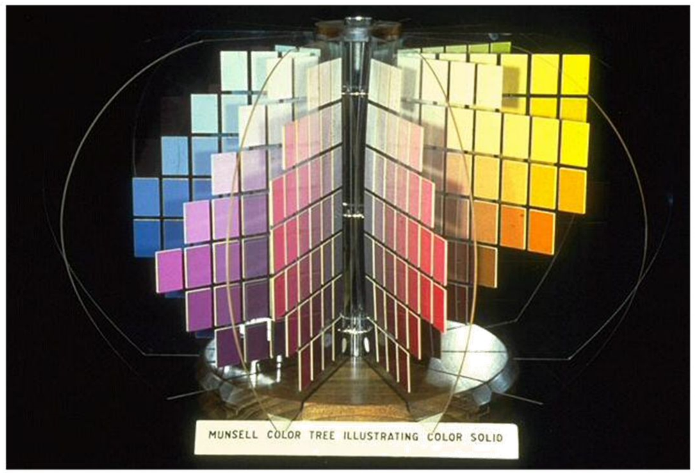
Munsell's colour classification system

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



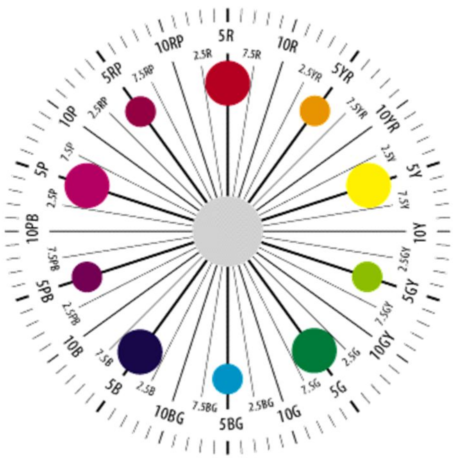


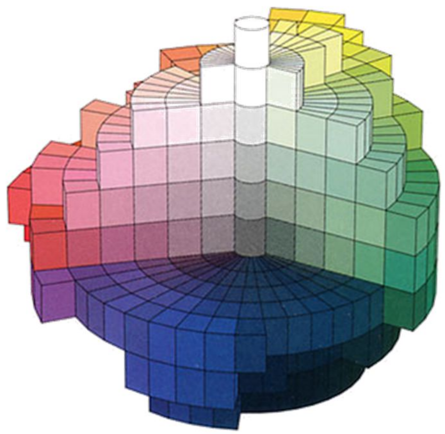


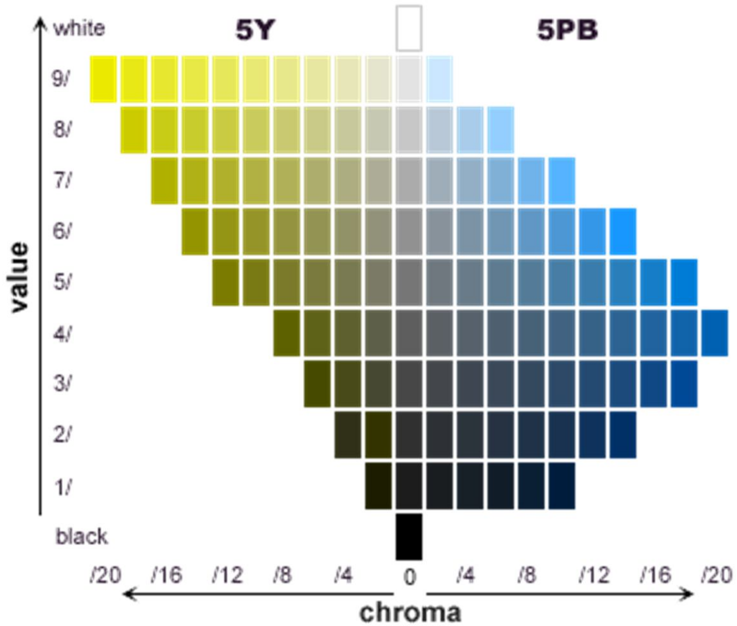


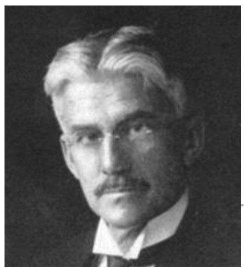
Munsell's colour classification system

- 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









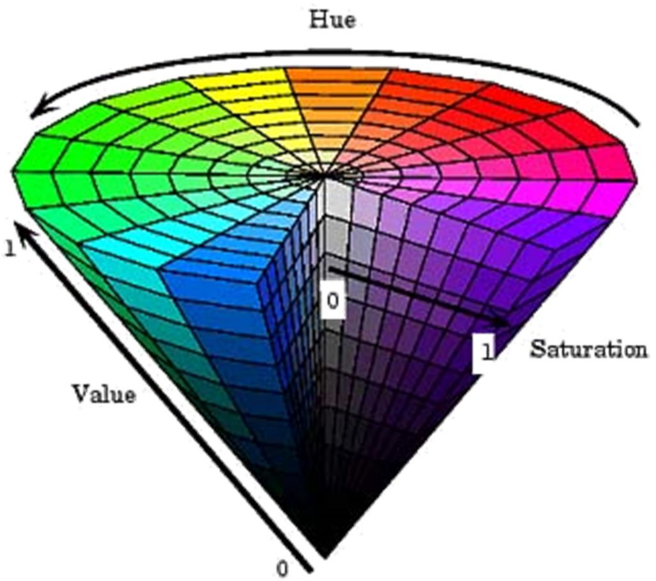
invented by Albert H. Munsell, an American artist, in 1905 in an attempt to systematically classify colours

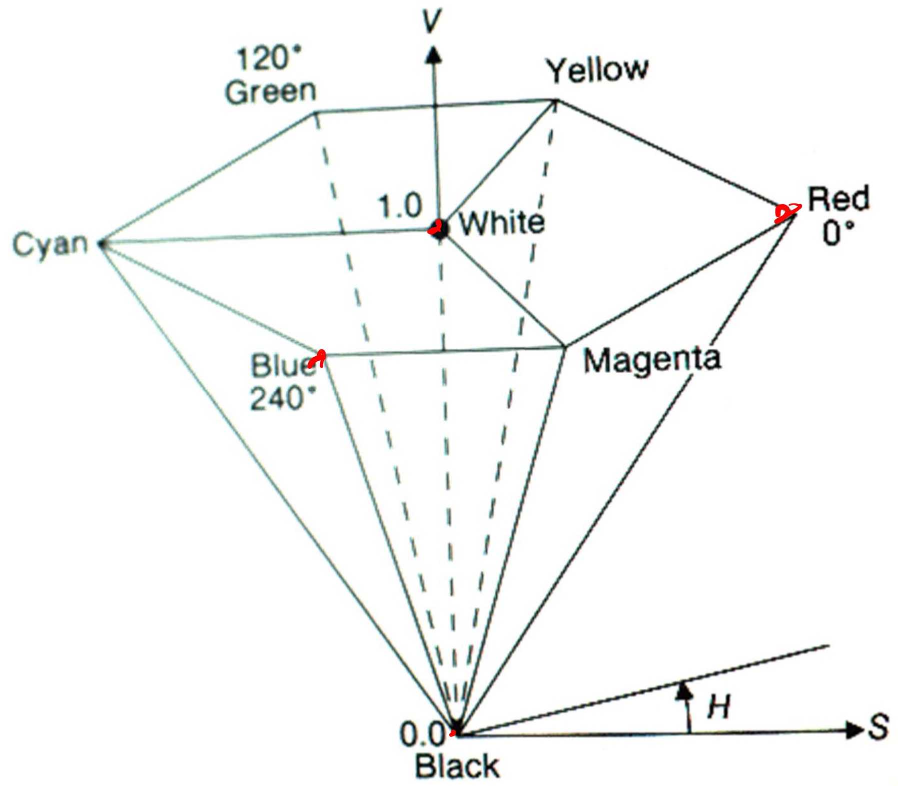
Colour spaces for user-interfaces

- *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

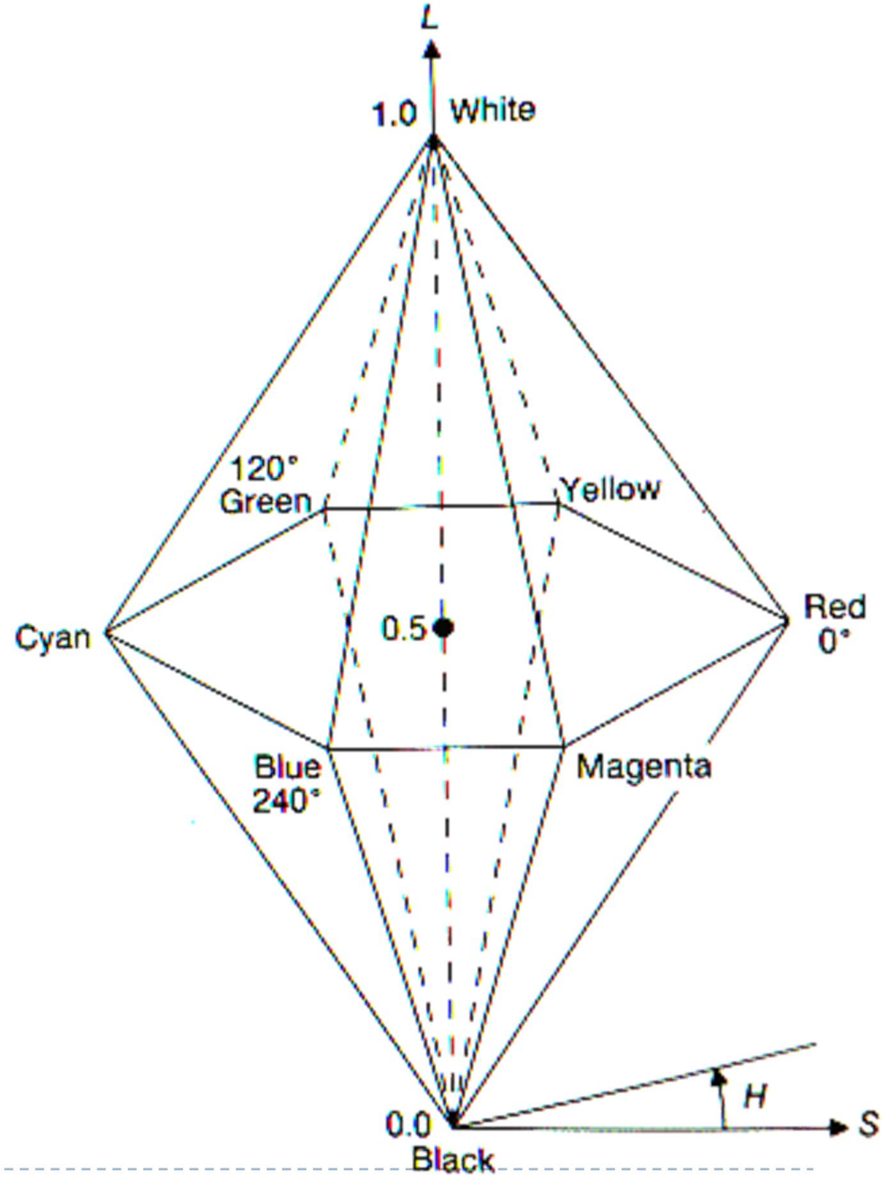




- designed by Alvy Ray Smith in 1978
- algorithm to convert *HSV* to *RGB* and back can be found in Foley et al., Figs 13.33 and 13.34

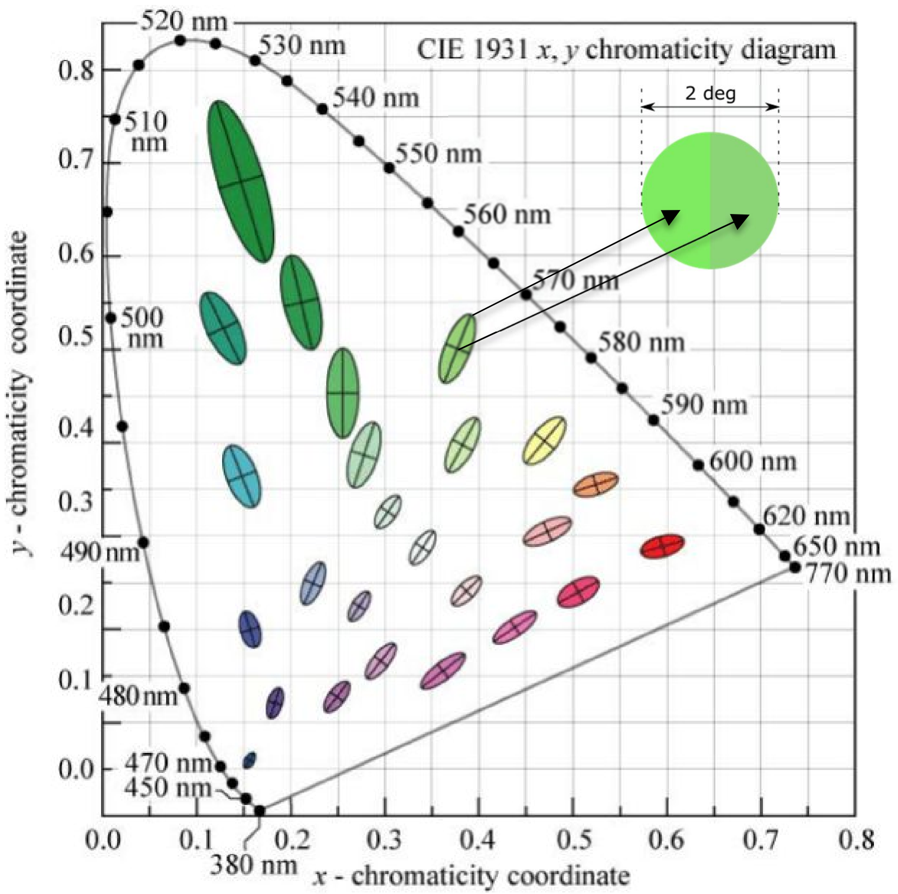
HLS: hue lightness saturation

- 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

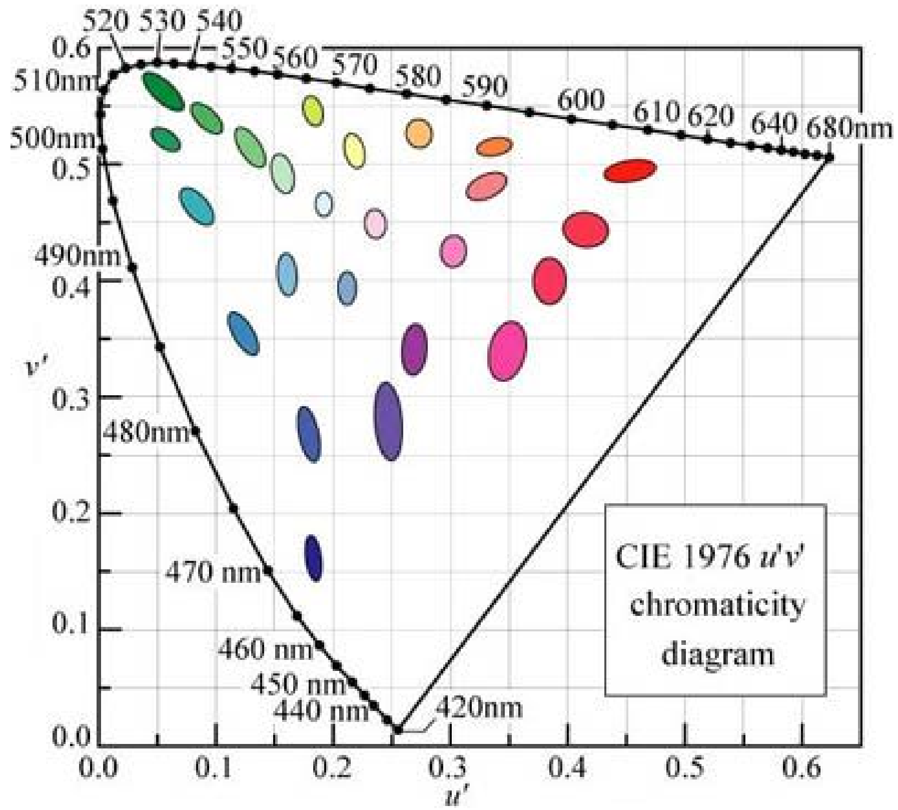


Perceptually uniformity

- MacAdam ellipses & 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

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

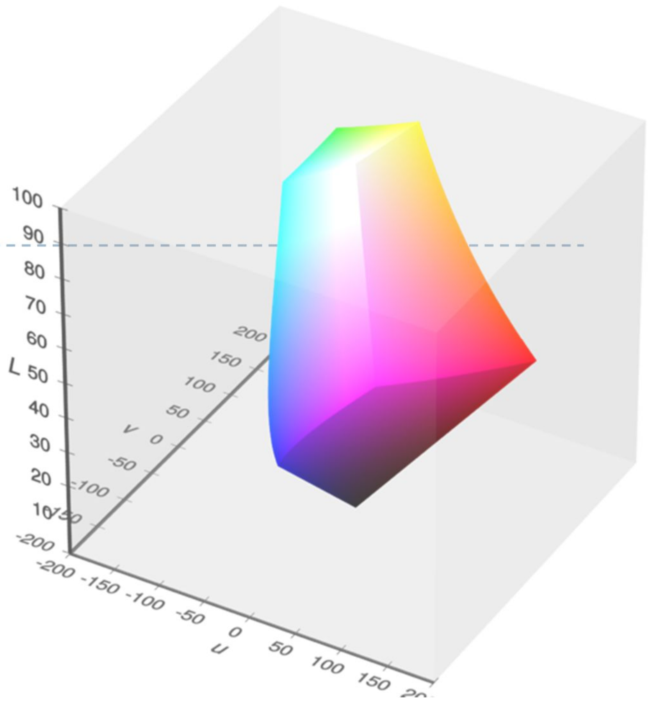
Chromacity coordinates

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

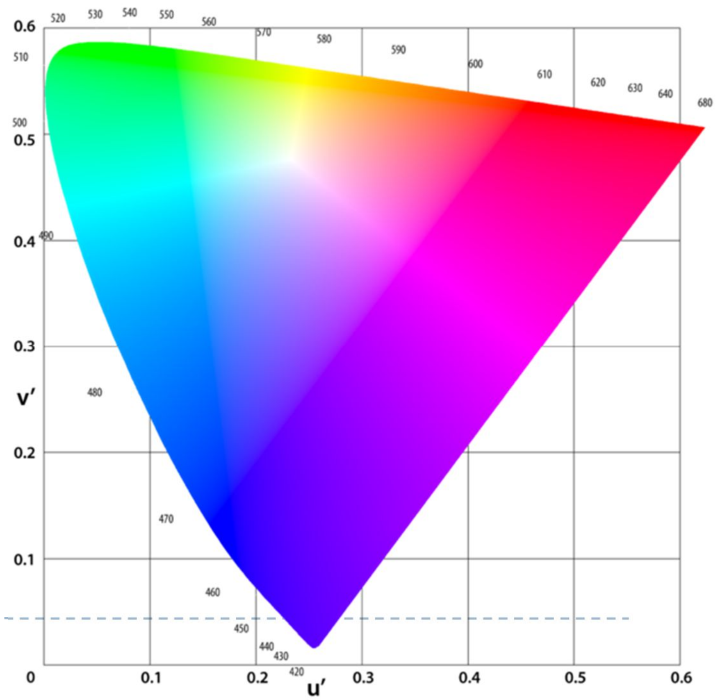
Colours less distinguishable when dark

- Hue and chroma

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



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.

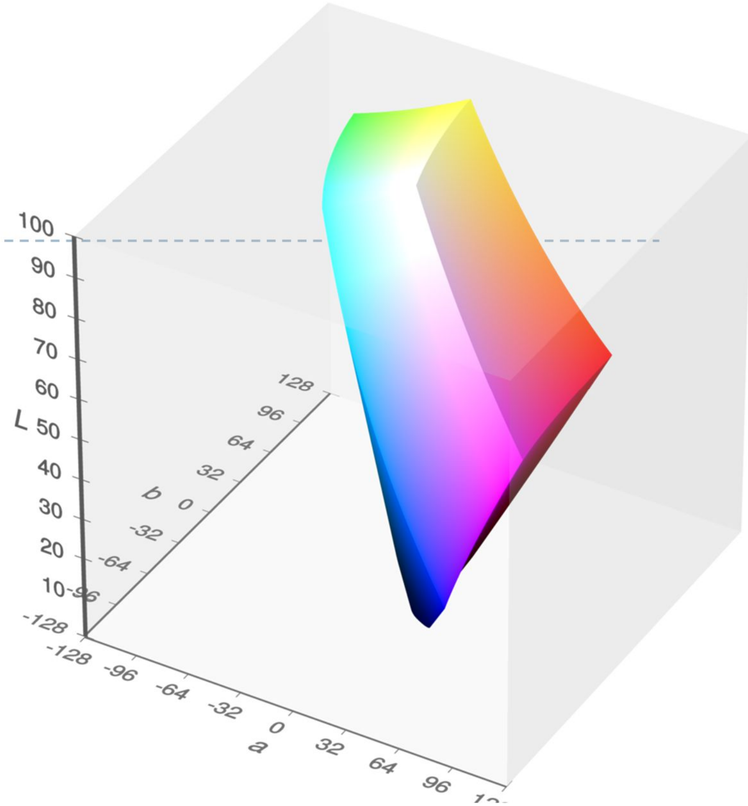
$$X_n = 95.047,\quad Y_n = 100.000,\quad Z_n = 108.883$$

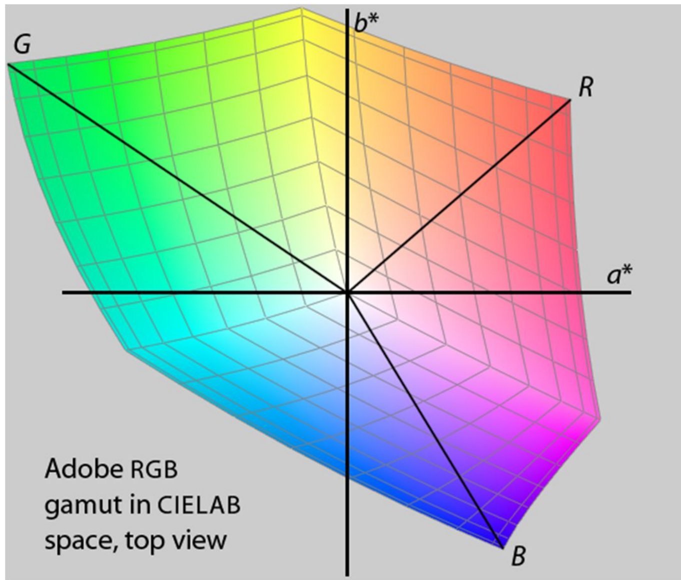
$$f(t) = \begin{cases} \sqrt[3]{t} & \text{if } t > \delta^3 \\ \frac{t}{3\delta^2} + \frac{4}{29} & \text{otherwise} \end{cases}$$

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

- Chroma and hue

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





Adobe RGB gamut in CIELAB space, top view

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

- 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.