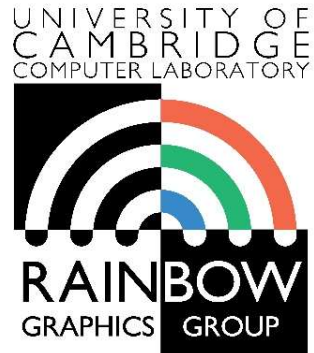




Advanced Graphics and Image Processing

Colour perception and colour spaces

Part 1/5 – physics of light

Rafał Mantiuk

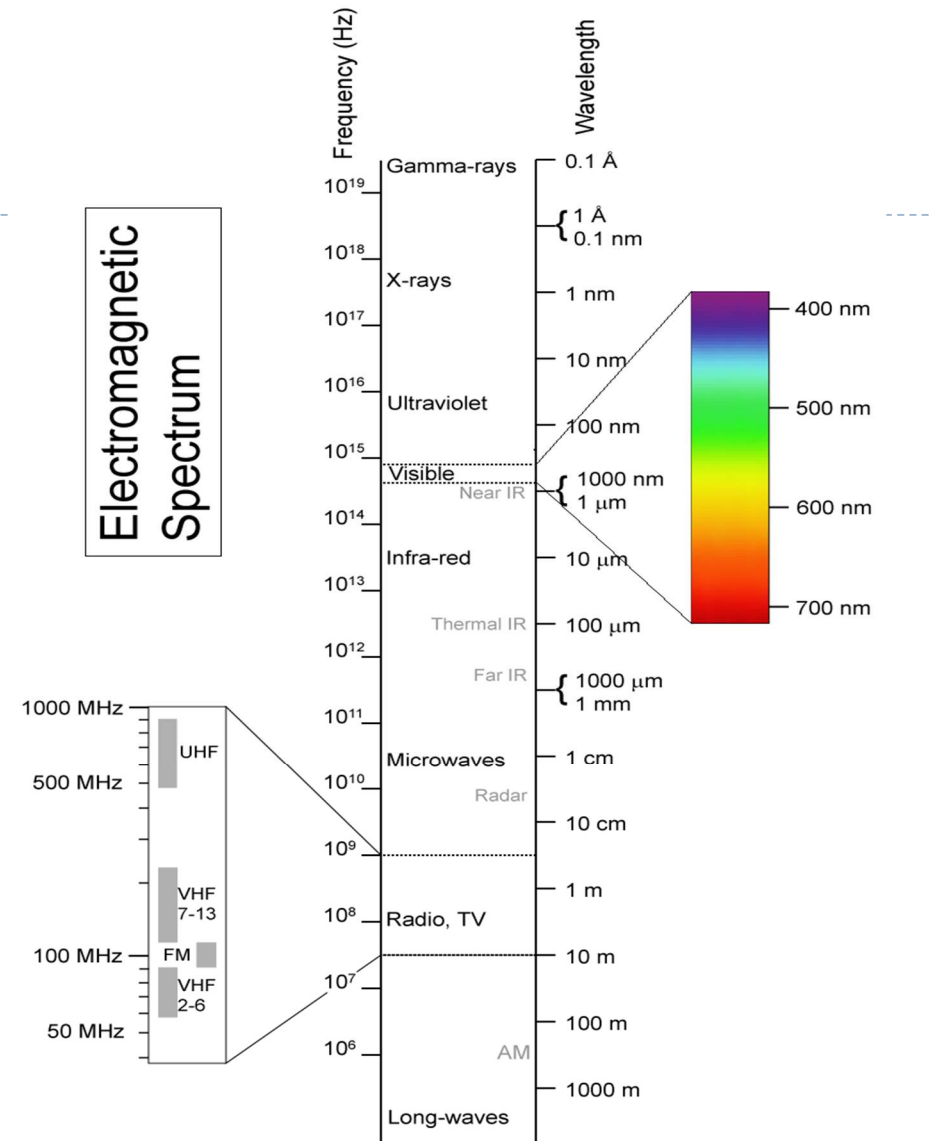
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Electromagnetic spectrum

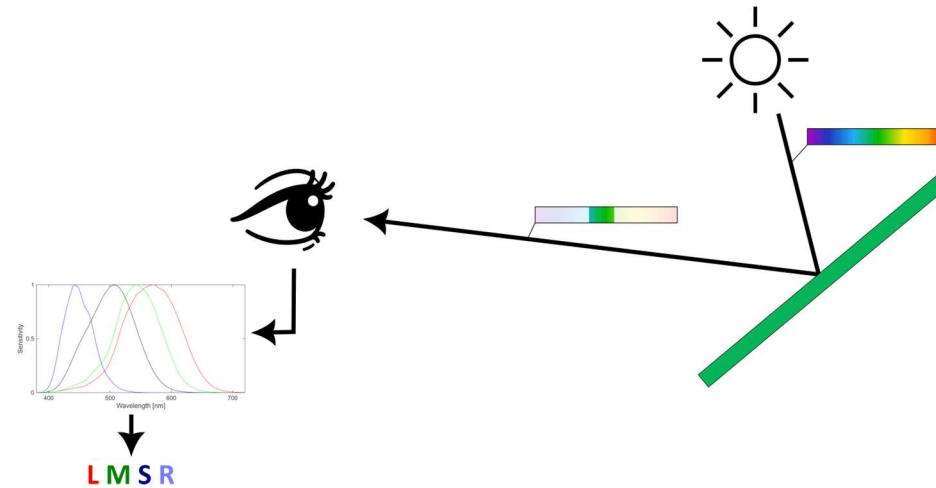
▶ Visible light

- ▶ 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

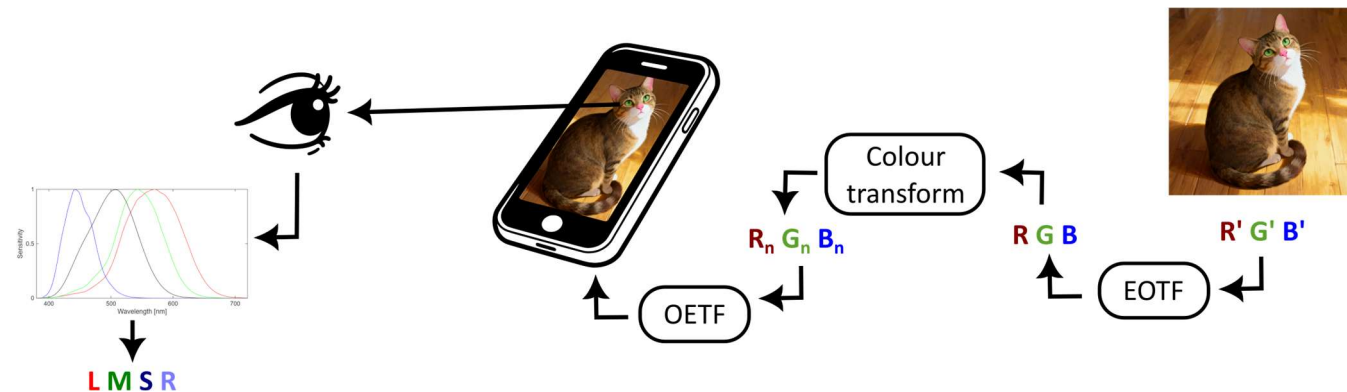


Colour perception and digital colour processing

Colour perception in physical world

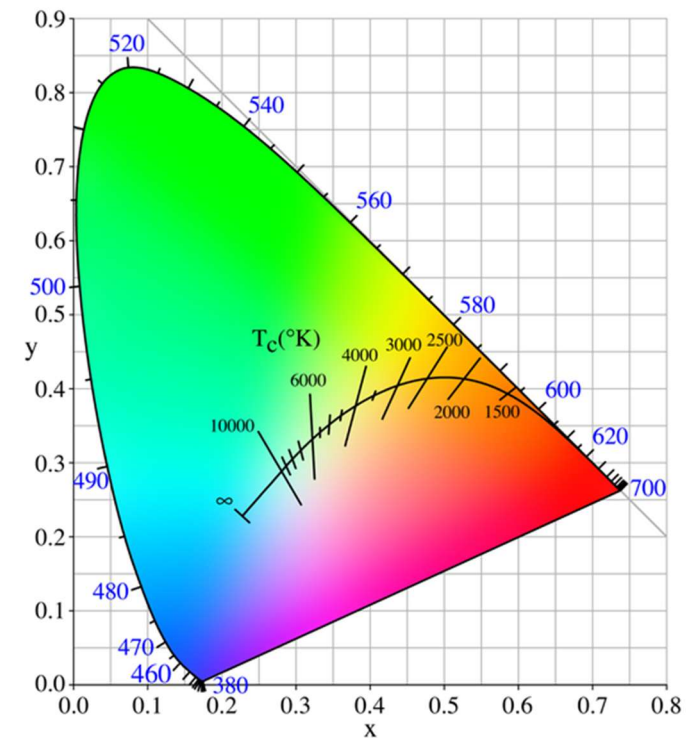
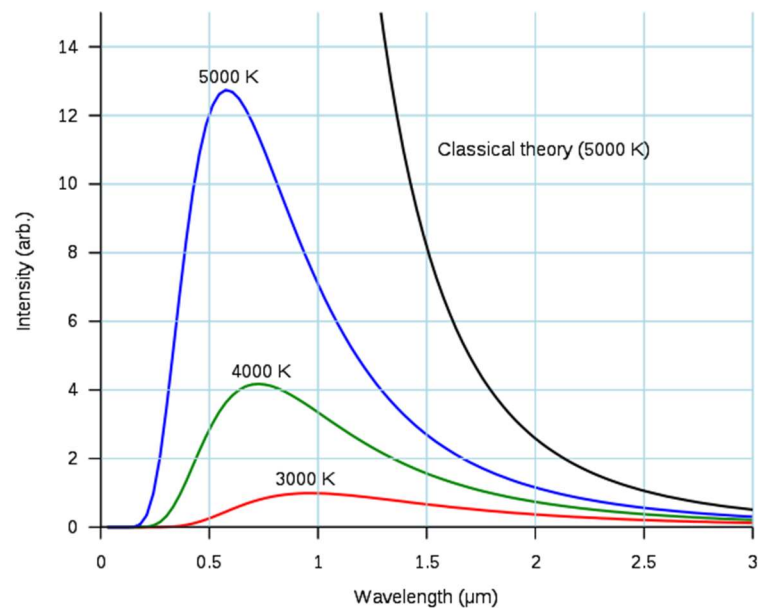


Digital colour processing



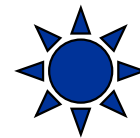
Black body radiation

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

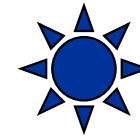


Correlated colour temperature

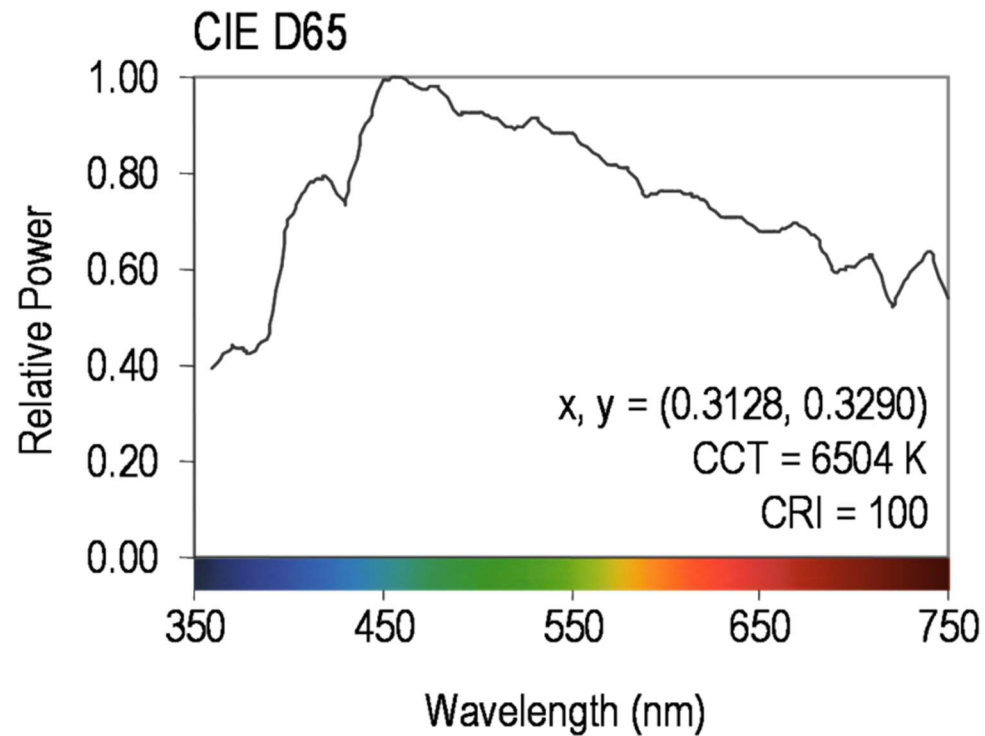
- ▶ The temperature of a black body radiator that produces light most closely matching the particular source
- ▶ Examples:
 - ▶ Typical north-sky light: 7500 K
 - ▶ Typical average daylight: 6500 K
 - ▶ Domestic tungsten lamp (100 to 200 W): 2800 K
 - ▶ Domestic tungsten lamp (40 to 60 W): 2700 K
 -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



Standard illuminant D65



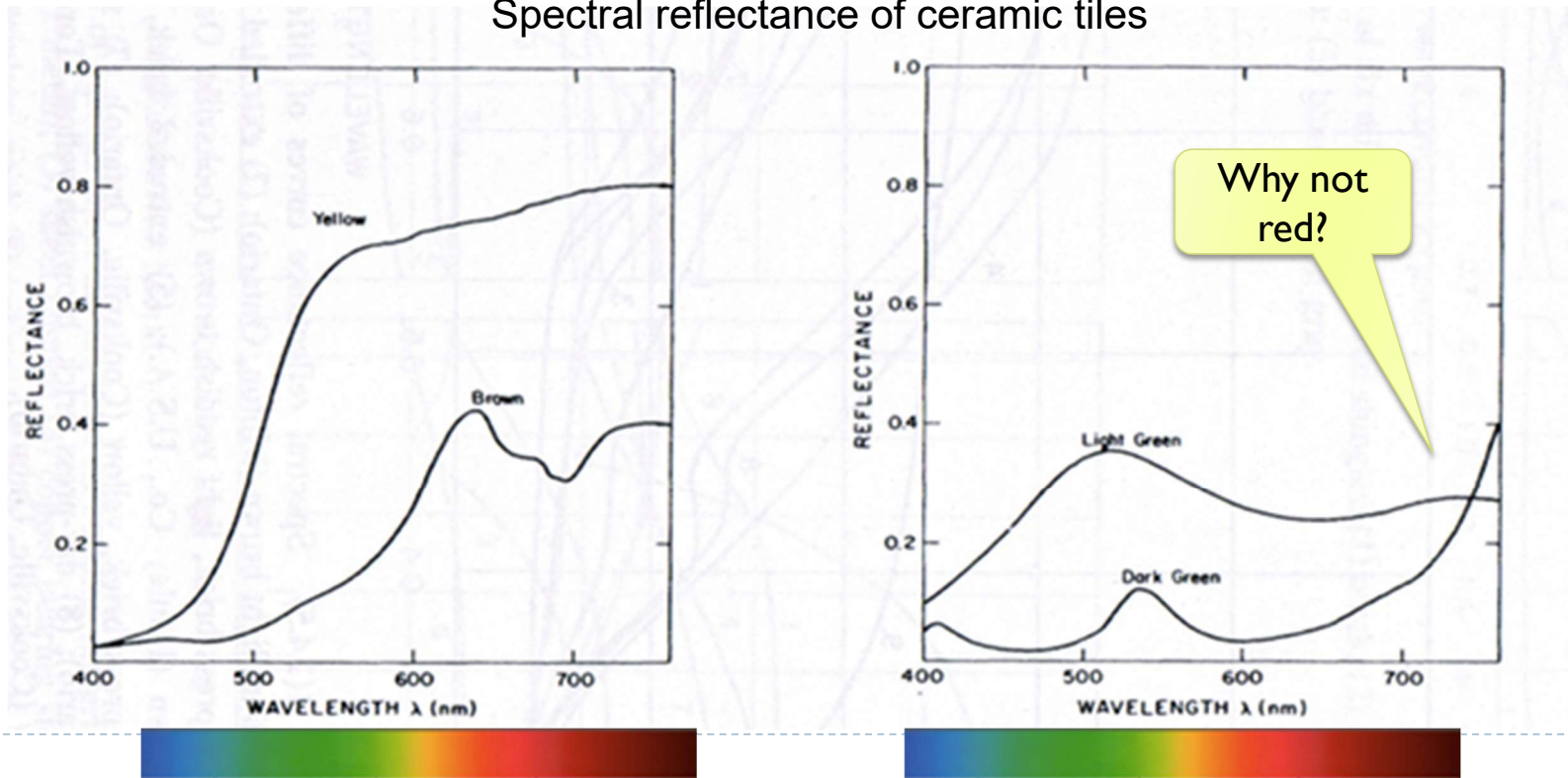
- ▶ Mid-day sun in Western Europe / Northern Europe
- ▶ Colour temperature approx. 6500 K



Reflectance

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

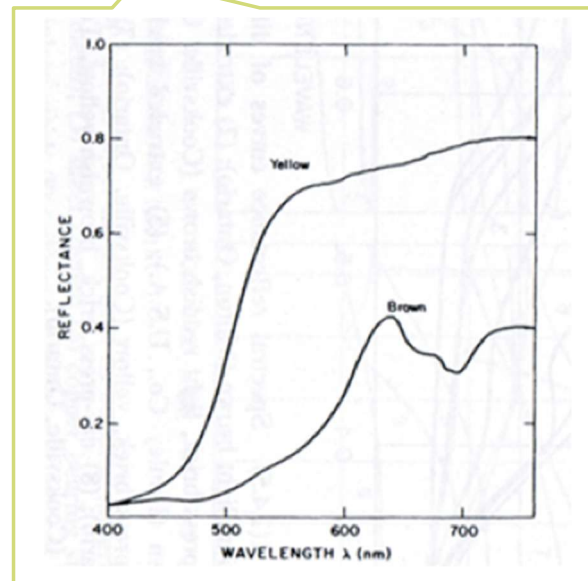
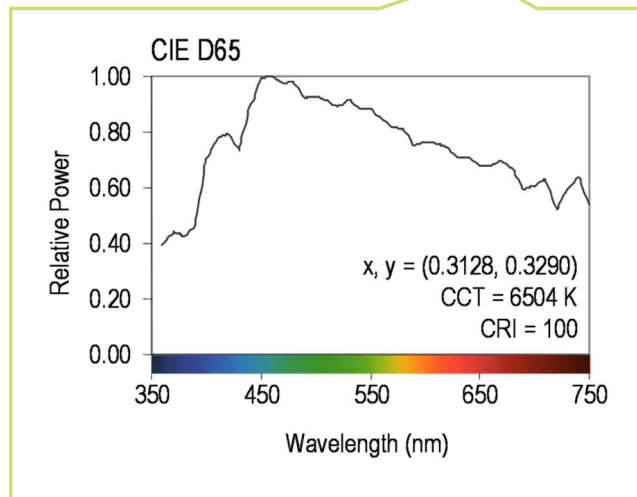
Spectral reflectance of ceramic tiles



Reflected light

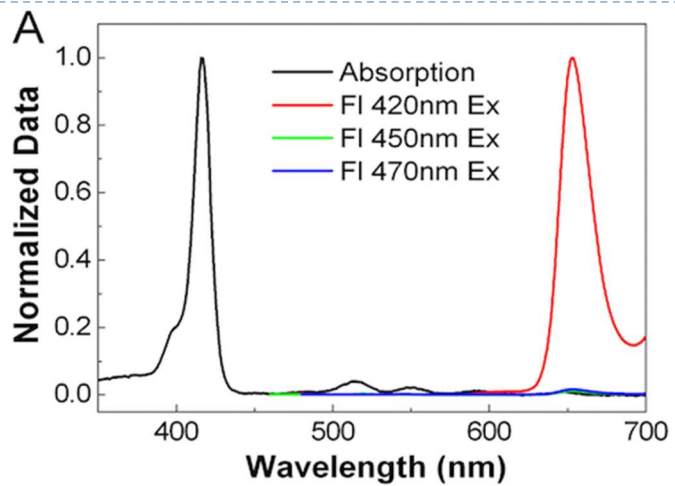
$$L(\lambda) = I(\lambda)R(\lambda)$$

- ▶ Reflected light = illumination $\times$ reflectance

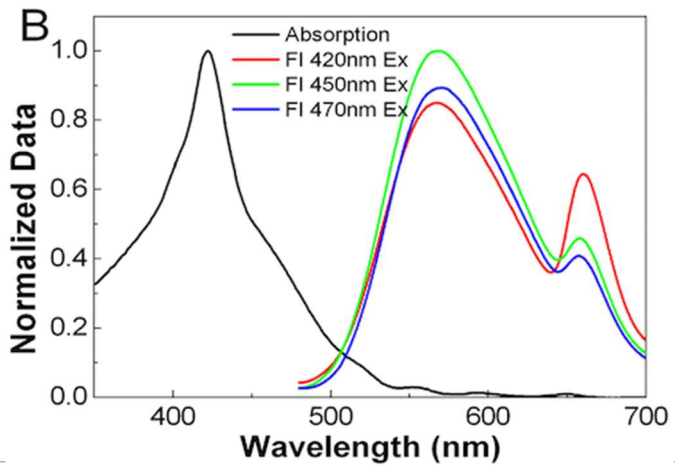


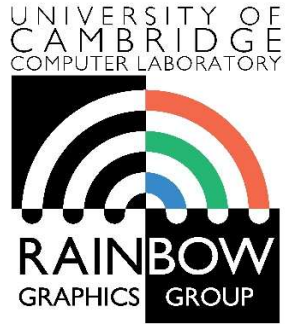
The same object may appear to have a different color under different illumination.

Fluorescence



en.wikipedia.org/wiki/Fluorescence





Advanced Graphics and Image Processing

Colour perception and colour spaces

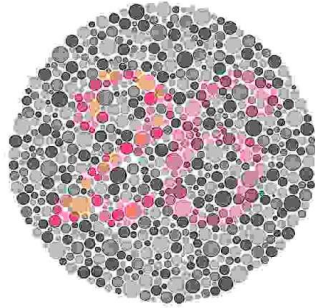
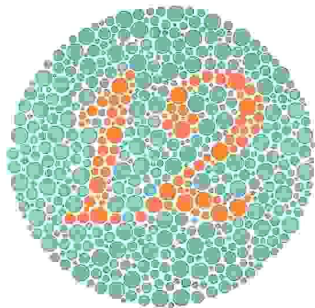
Part 2/5 – perception, cone fundamentals

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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

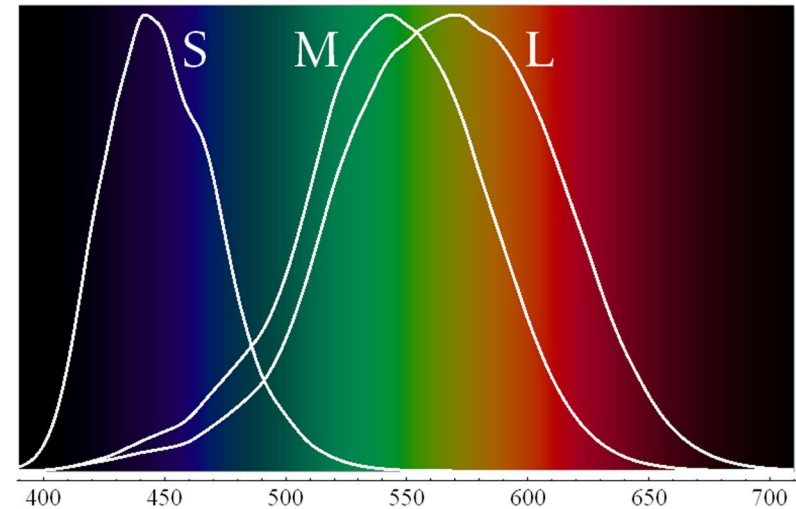


www.lam.mus.ca.us/cats/color/

www.colorcube.com/illusions/clrbld.html

Colour vision

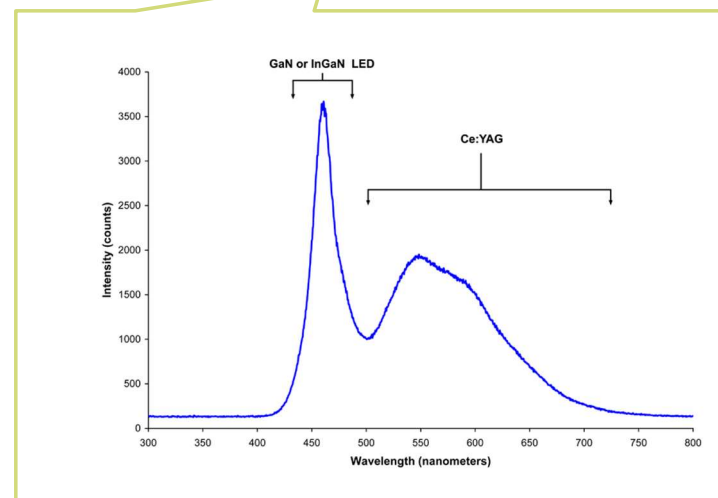
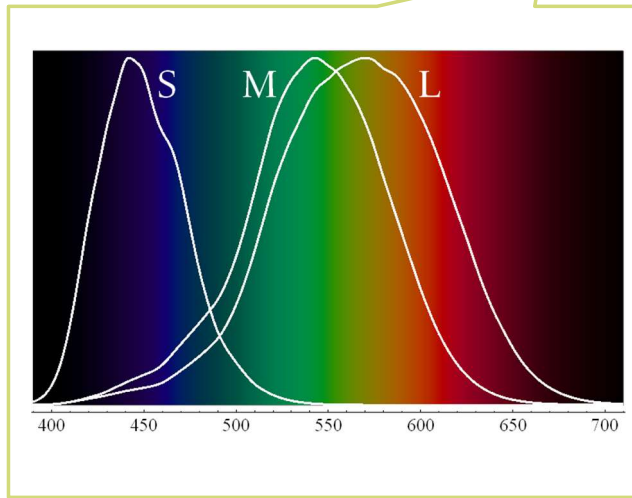
- ▶ Cones are the photoreceptors responsible for colour vision
 - ▶ Only daylight, we see no colours when there is not enough light
- ▶ Three types of cones
 - ▶ S – sensitive to short wavelengths
 - ▶ M – sensitive to medium wavelengths
 - ▶ L – sensitive to long wavelengths



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

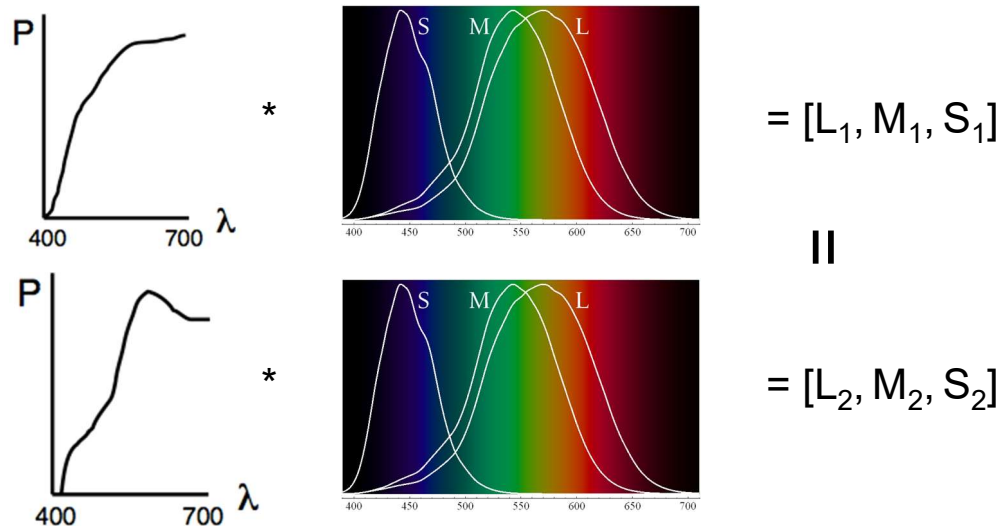
Formally

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

Index S for S-cones

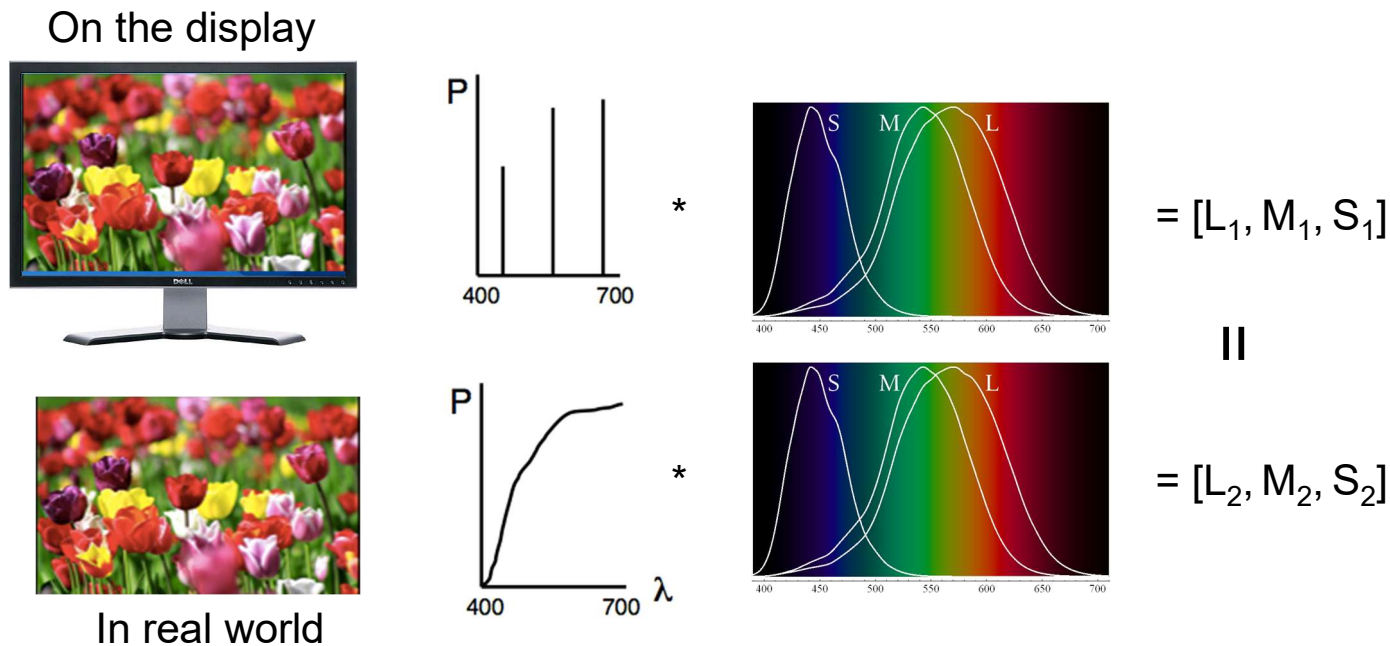
Metamers

- ▶ 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:



Practical application of metamerism

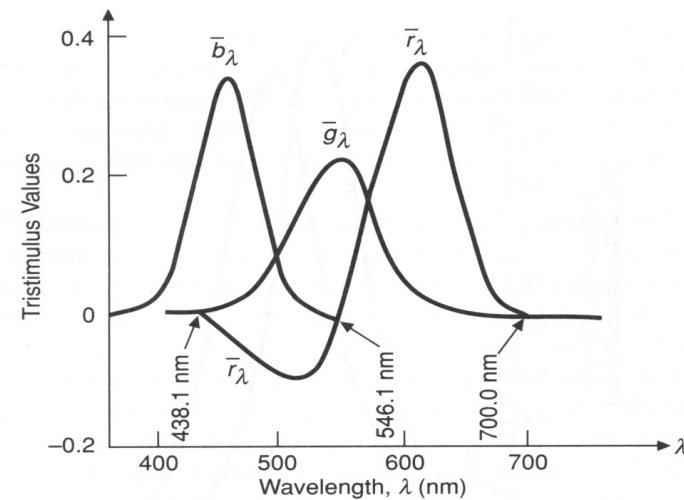
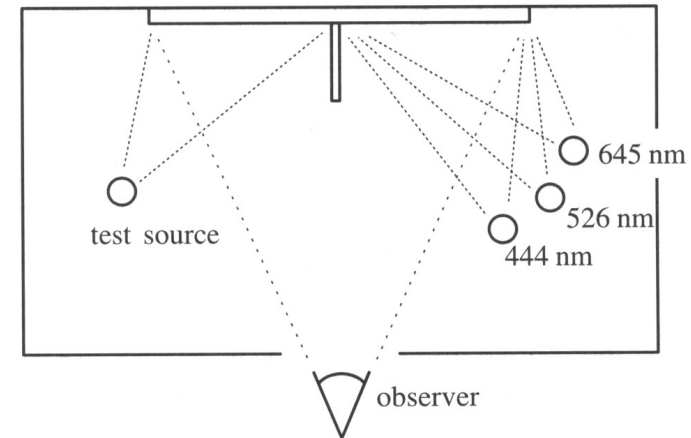
- ▶ Displays do not emit the same light spectra as real-world objects
- ▶ Yet, the colours on a display look almost identical



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

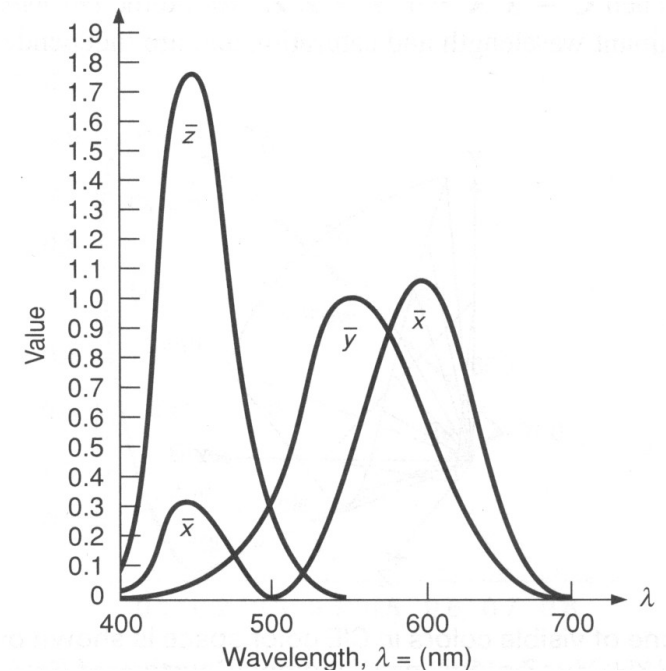
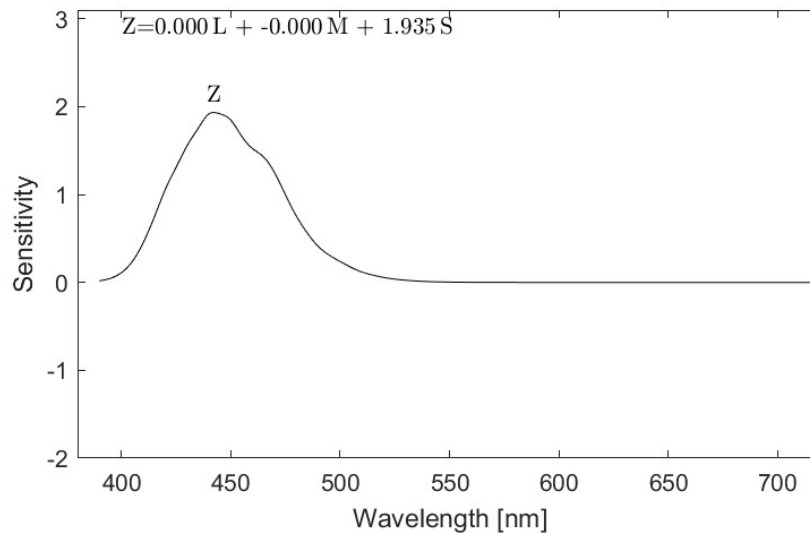


Standard Colour Space CIE-XYZ

- ▶ **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

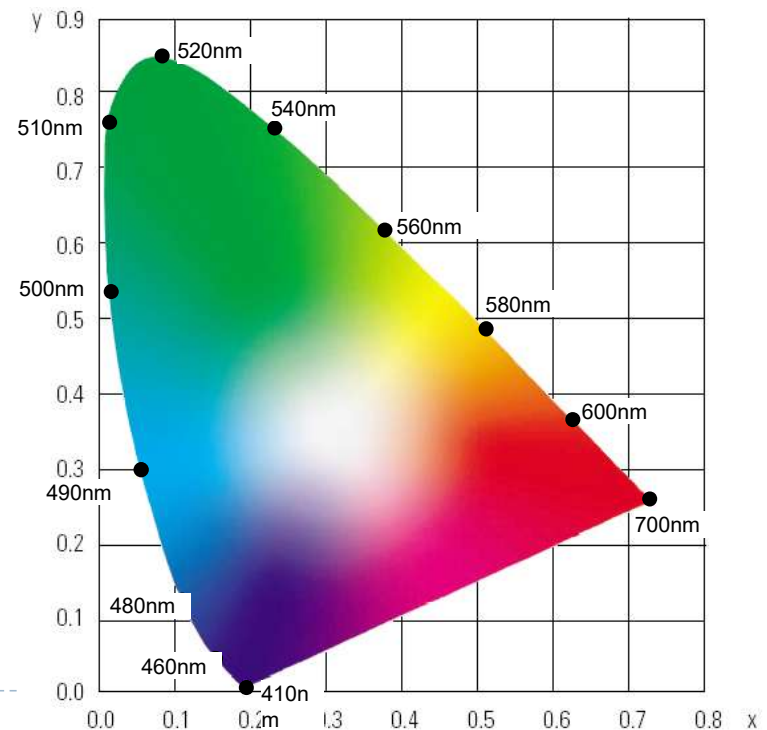


CIE chromaticity diagram

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

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

- ▶ 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

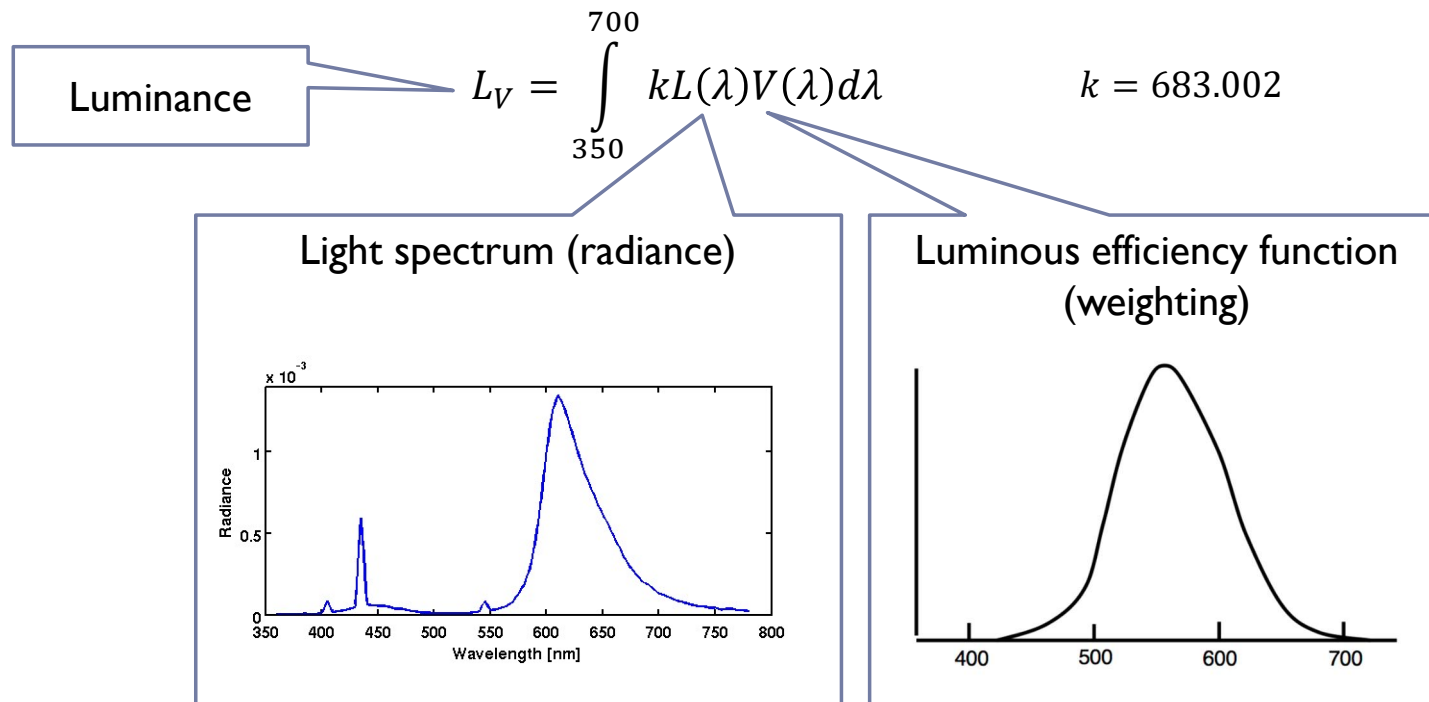
Colour perception and colour spaces
Part 3/5 – colour opponent processing

Rafał Mantiuk

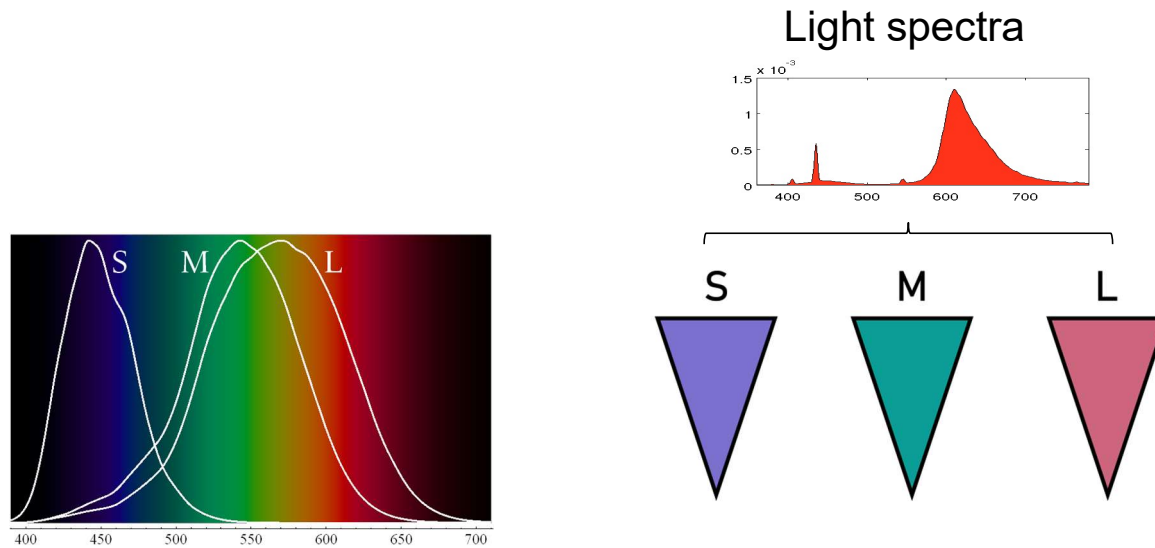
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Luminance

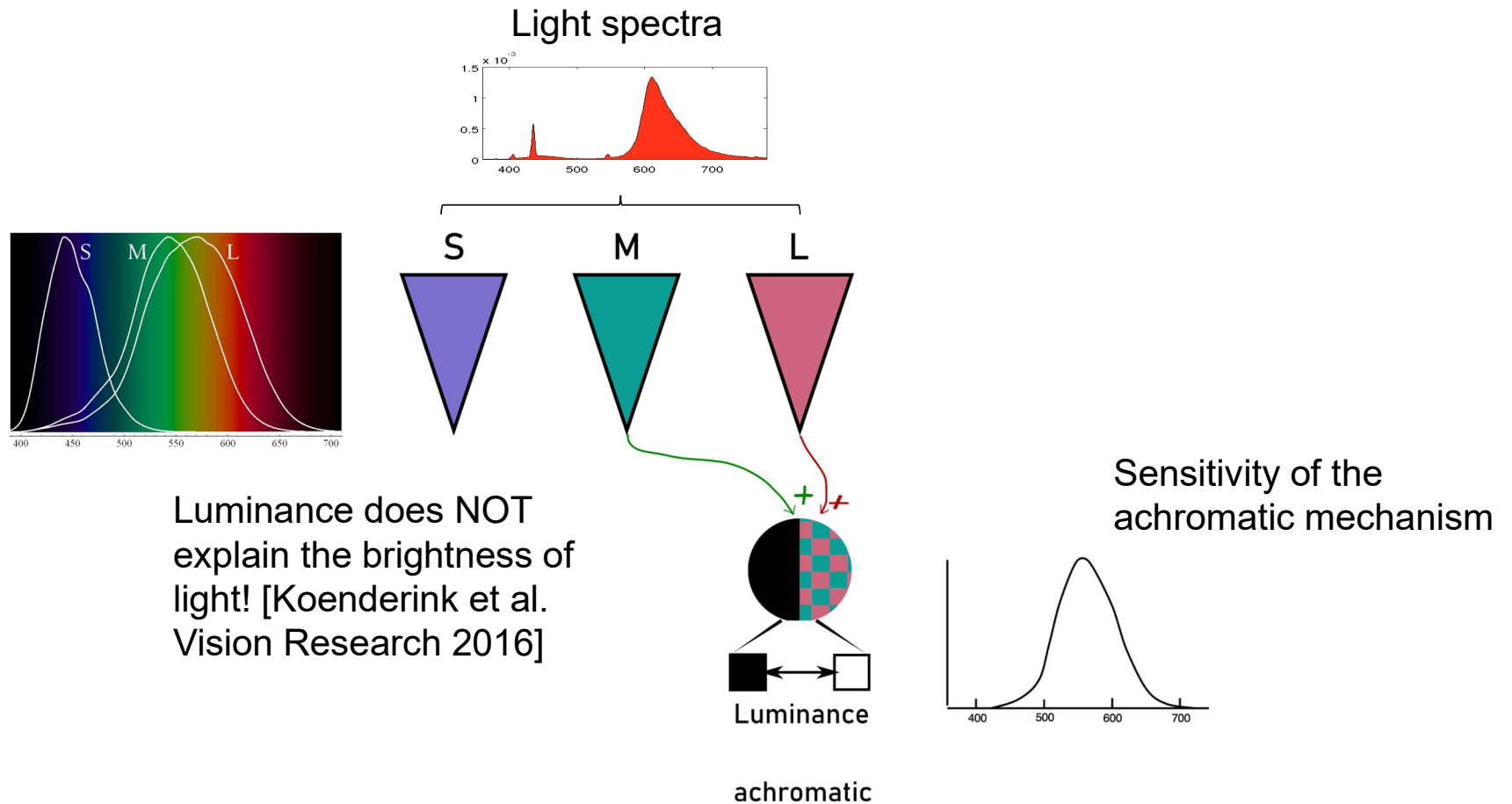
- Luminance – measure of light weighted by the response of the achromatic mechanism. Units: cd/m^2 (ISO) or nit



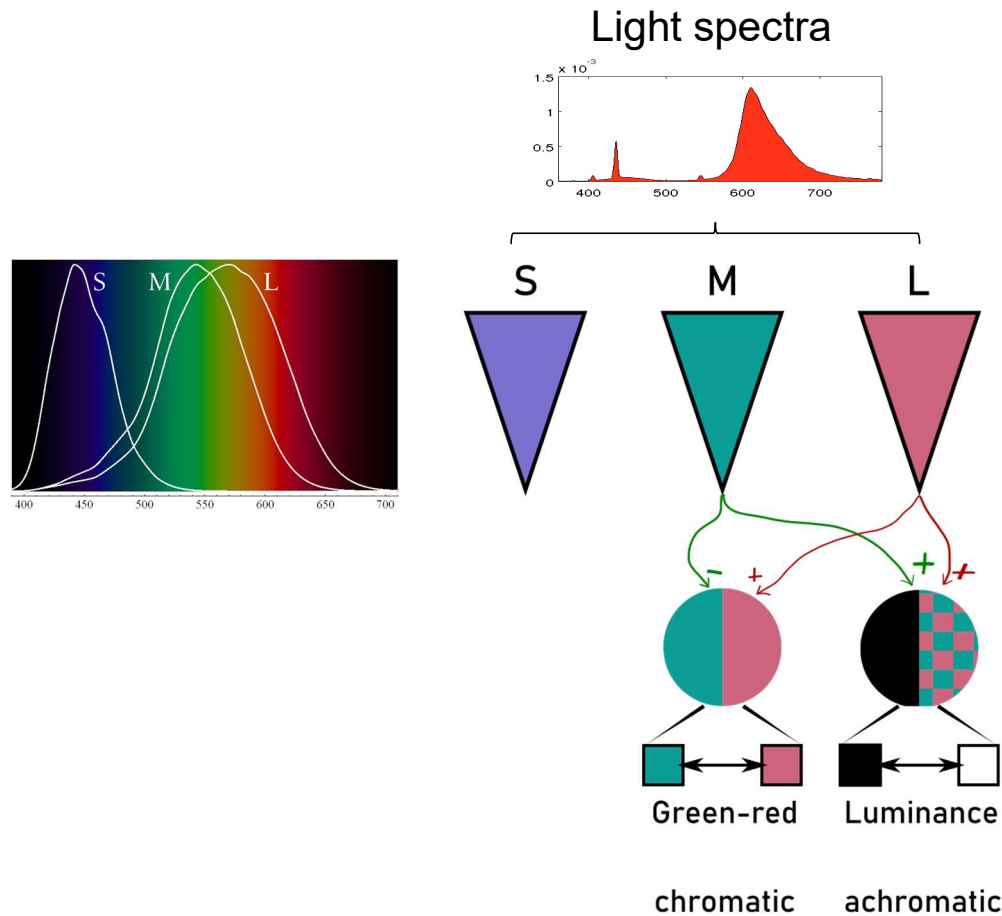
Achromatic/chromatic vision mechanisms



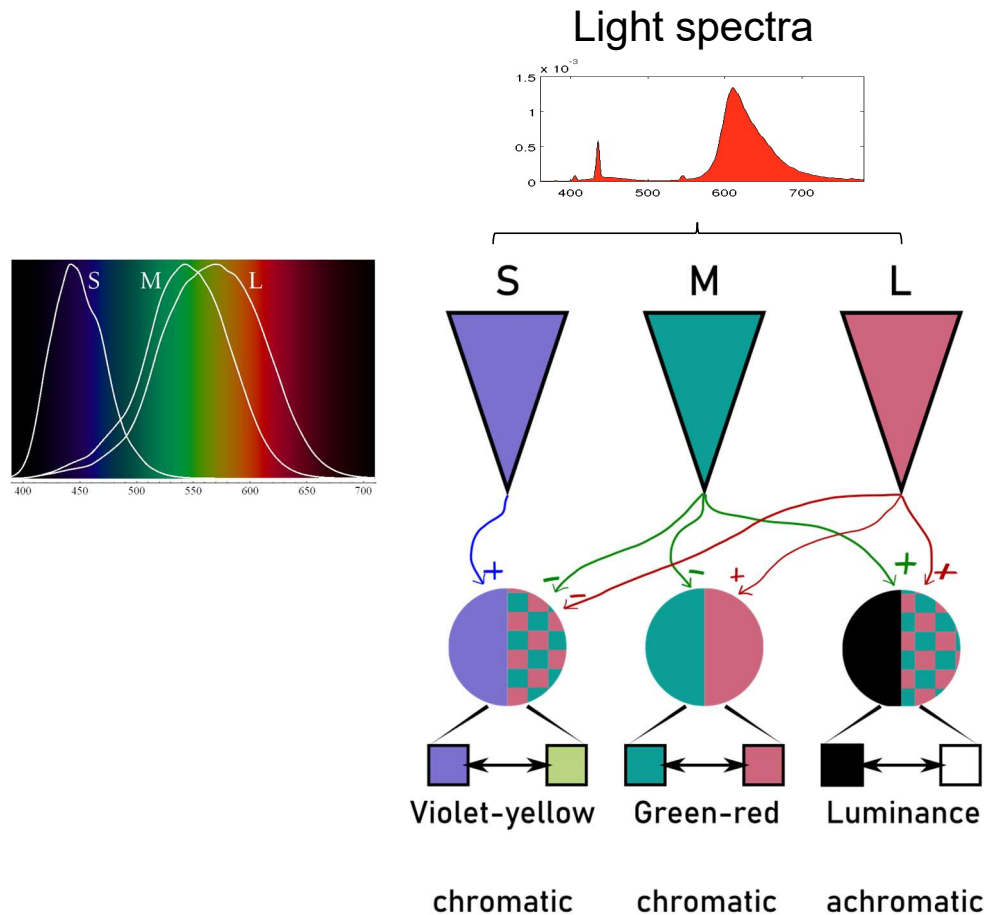
Achromatic/chromatic vision mechanisms



Achromatic/chromatic vision mechanisms

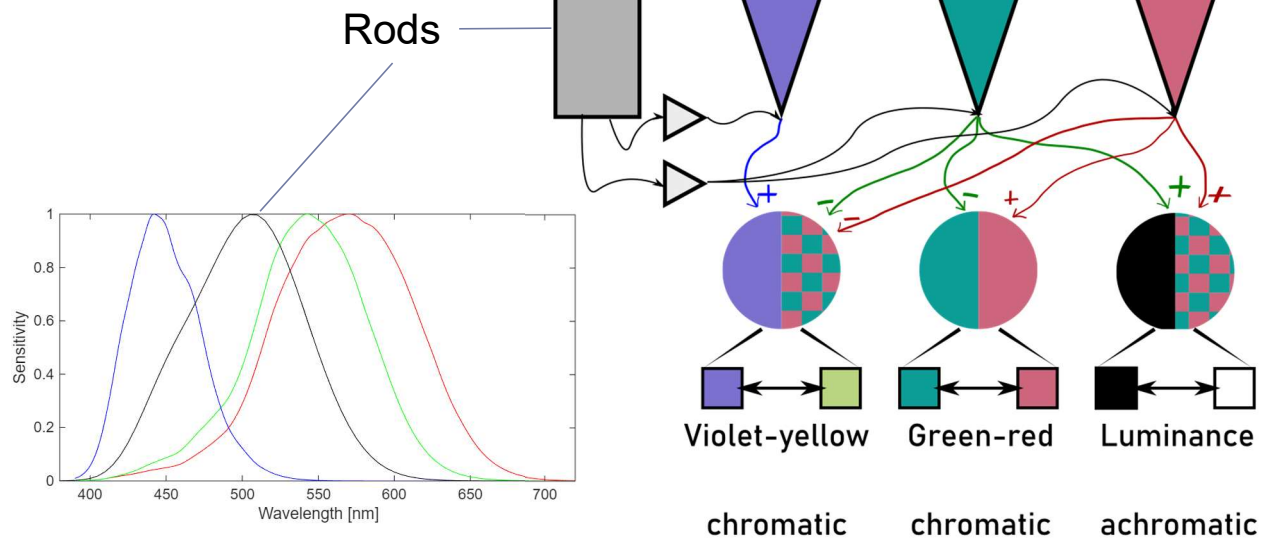
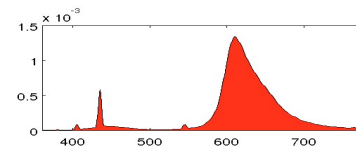


Achromatic/chromatic vision mechanisms



Achromatic/chromatic vision mechanisms

Light spectra





Advanced Graphics and Image Processing

Colour perception and colour spaces

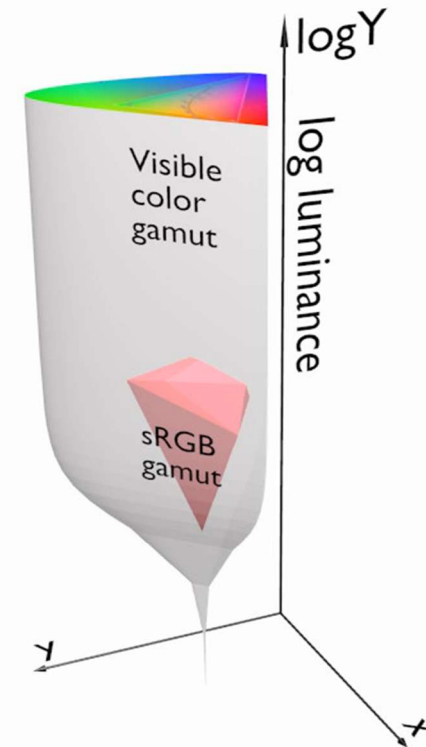
Part 4/5 – gamuts, linear and gamma-encoded colour

Rafał Mantiuk

Computer Laboratory, University of Cambridge

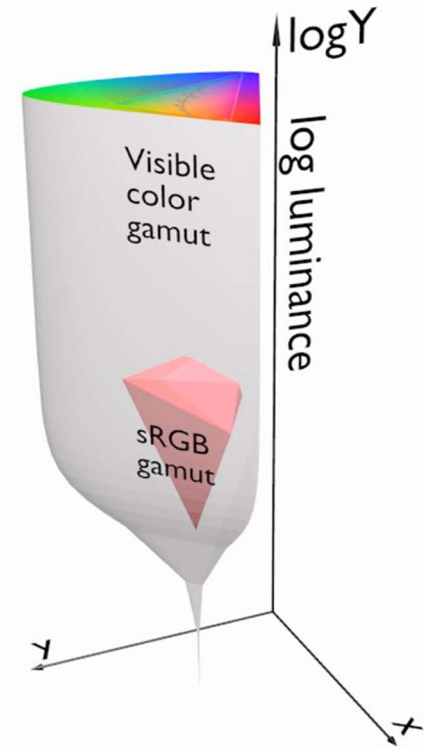
Visible vs. displayable colours

- ▶ 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

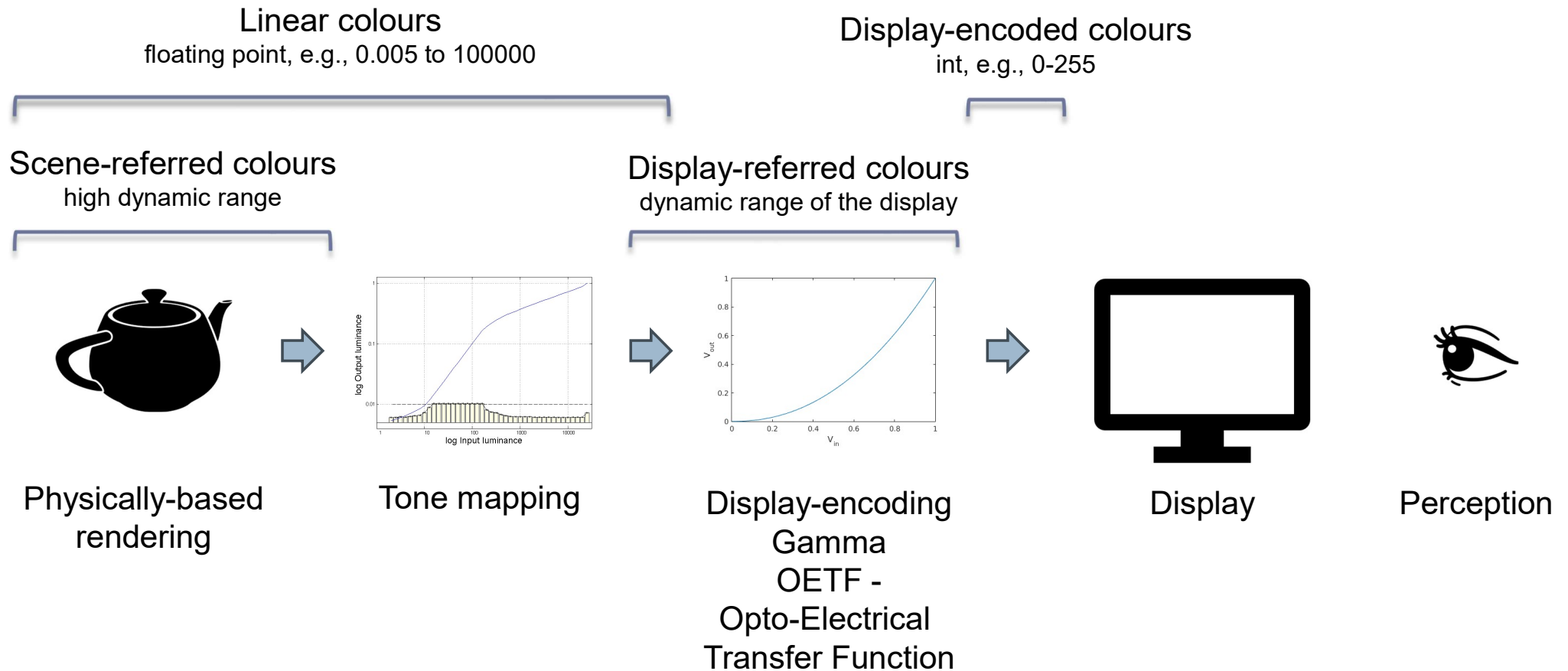


Standard vs. High Dynamic Range

- ▶ **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



Display encoding (EOTF) for SDR: gamma

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

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

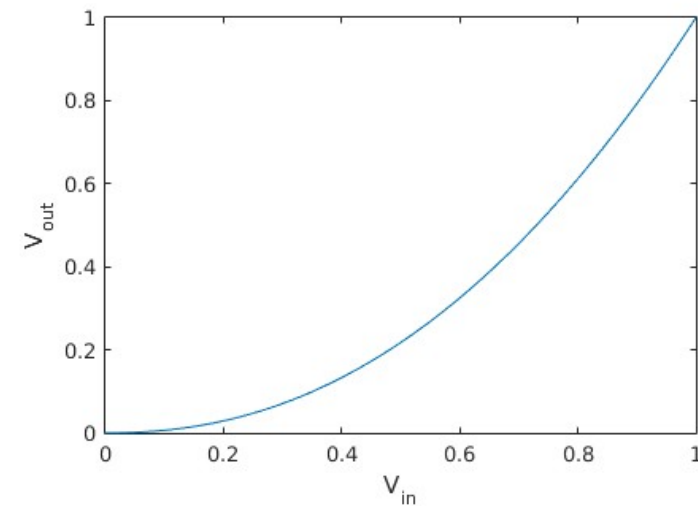
Gain

Gamma (usually =2.2)

(relative) Luminance
Physical signal

Luma
Digital signal (0-1)

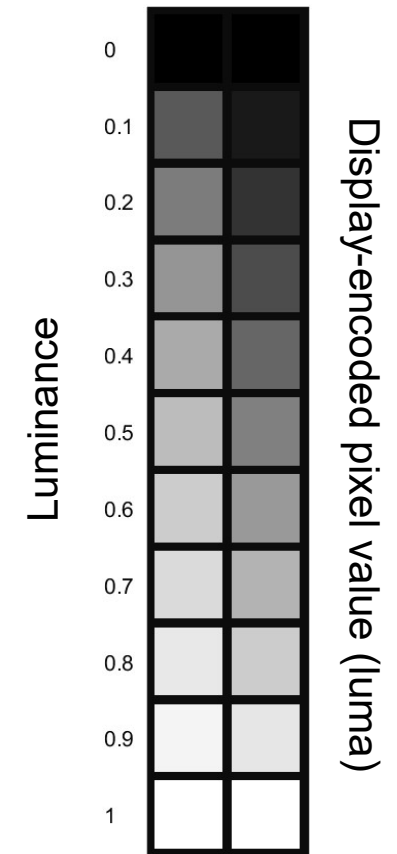
$$\text{Inverse: } V_{\text{in}} = \left(\frac{1}{a} \cdot V_{\text{out}} \right)^{\frac{1}{\gamma}}$$



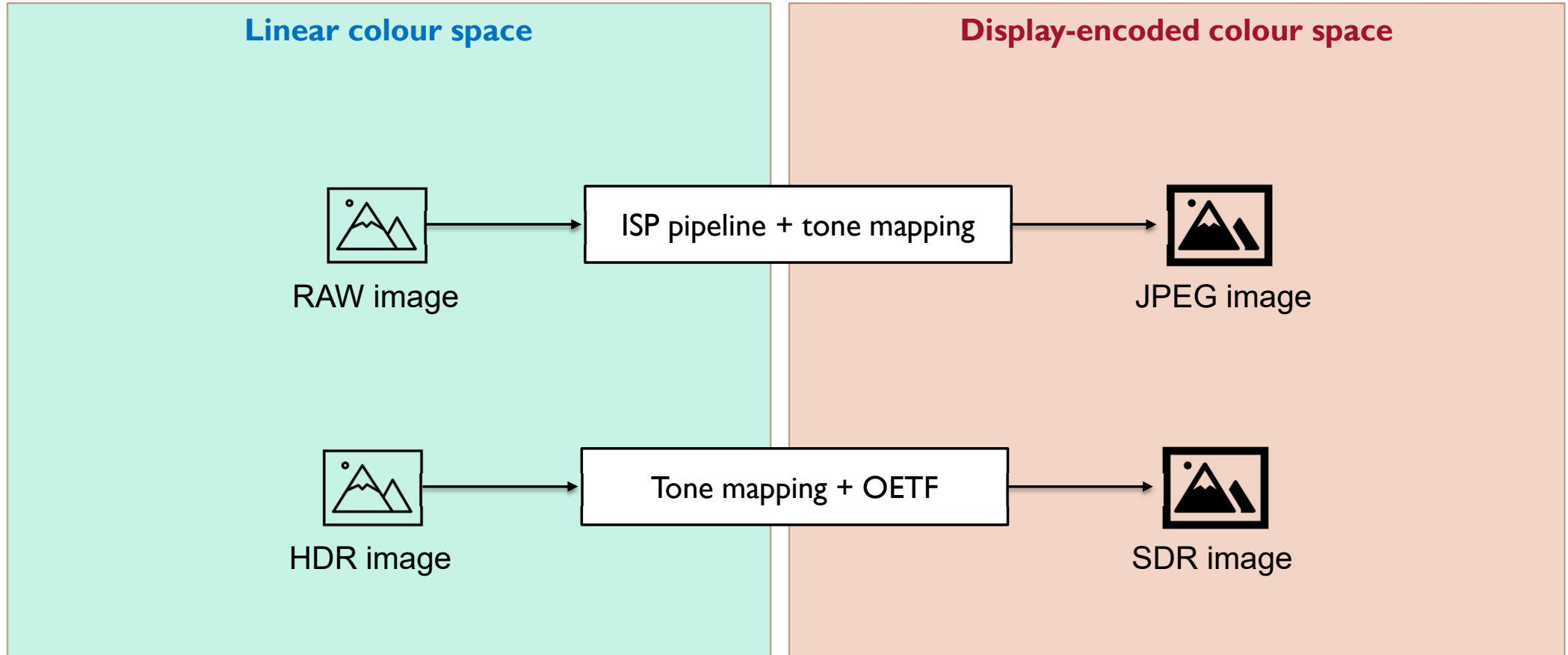
Colour: the same equation applied to red, green and blue colour channels.

Why is gamma needed?

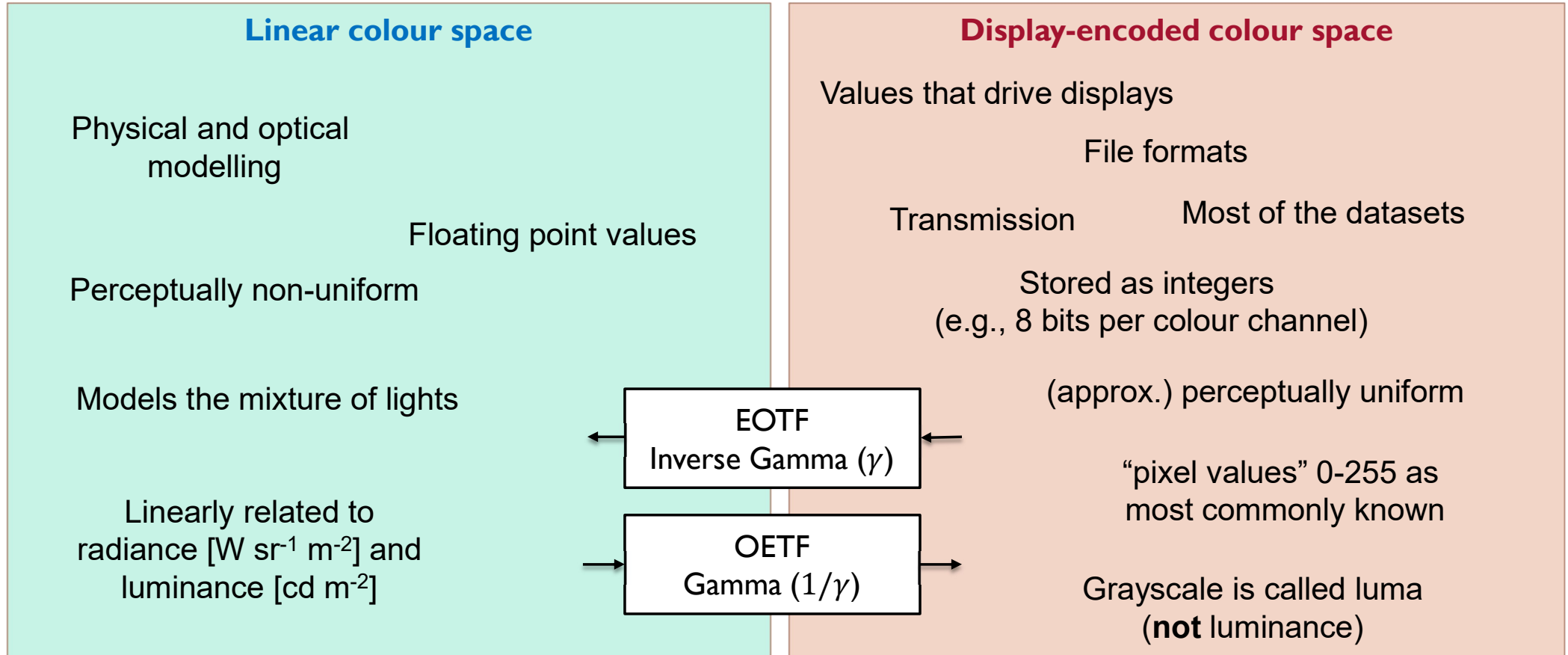
- ▶ *Gamma-corrected/display-encoded* pixel values give a scale of brightness levels that is approximately perceptually uniform
- ▶ At least 12 bits (instead of 8) would be needed to encode each color channel without gamma correction
- ▶ And accidentally it was also the response of the CRT gun



Linear and display-encoded colour spaces



Linear and display-encoded colour spaces



Luma – gray-scale pixel value

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

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

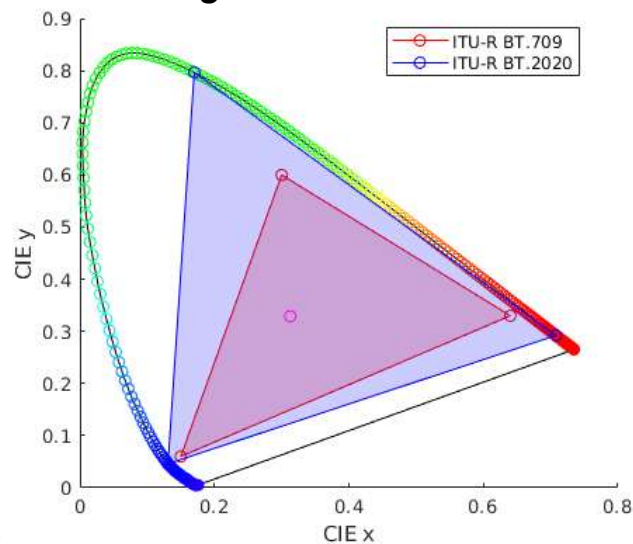
- ▶ R' , G' and B' are *gamma-corrected* colour values
 - ▶ Prime symbol denotes *gamma corrected*
 - ▶ Used in image/video coding
-
- ▶ Note that relative **luminance** is often approximated with
$$L = 0.2126R + 0.7152G + 0.0722B = 0.2126(R')^\gamma + 0.7152(G')^\gamma + 0.0722(B')^\gamma$$
 - ▶ R ,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

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

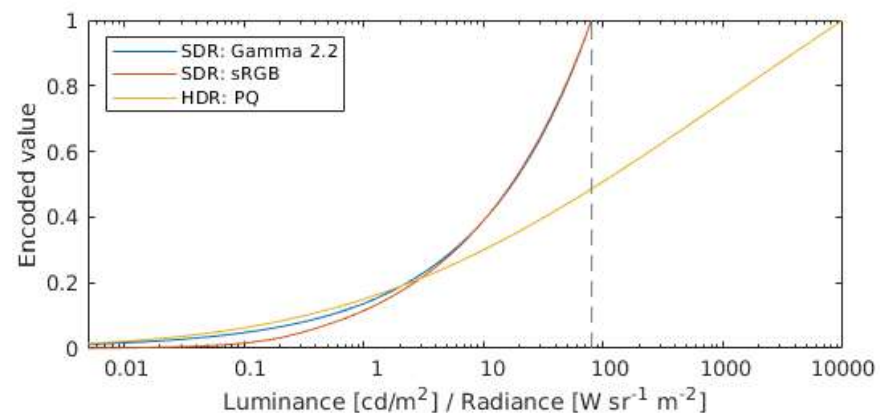
Colour space

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

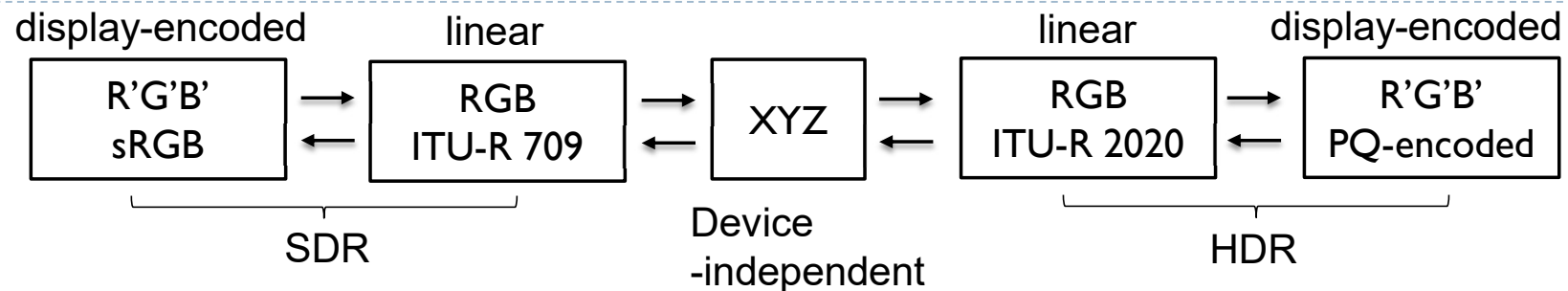


Electro-Optical Transfer Function

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:

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

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

Exercise 1: Map colour to a display

► **We have:**

- Spectrum of the colour we want to reproduce: L ($N \times 1$ vector)
- XYZ sensitivities: S_{XYZ} ($N \times 3$ matrix)
- Spectra of the RGB primaries: P_{RGB} ($N \times 3$ matrix)
- Display gamma: $\gamma = 2.2$

► **We need to find display-encoded R'G'B' colour values**

- Step 1: Find XYZ of the colour

$$\begin{bmatrix} X & Y & Z \end{bmatrix}^T = S_{XYZ}^T L$$

- Step 2: Find a linear combination of RGB primaries

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

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

$$\begin{aligned} \begin{bmatrix} R & G & B \end{bmatrix}^T &= M_{RGB \rightarrow XYZ}^{-1} \begin{bmatrix} X & Y & Z \end{bmatrix}^T \\ \begin{bmatrix} R' & G' & B' \end{bmatrix} &= \begin{bmatrix} R^{1/\gamma} & G^{1/\gamma} & B^{1/\gamma} \end{bmatrix} \end{aligned}$$

Exercise 2: Find a camera colour correction matrix

► We have:

- XYZ sensitivities: S_{XYZ} ($N \times 3$ matrix)
- Spectral sensitivities of camera's RGB pixels: C_{RGB} ($N \times 3$ matrix)
- Spectrum in the real world: L ($N \times 1$ vector)

► Find a 3×3 matrix mapping from camera's native RGB to XYZ

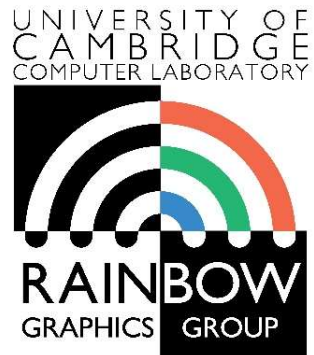
$$M_{C \rightarrow XYZ} C_{RGB}^T L \approx S_{XYZ}^T L$$
$$\operatorname{argmin}_{M_{C \rightarrow XYZ}} \|M_{C \rightarrow XYZ} C_{RGB}^T L - S_{XYZ}^T L\|_2$$

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

► 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 3×3
matrix



Advanced Graphics and Image Processing

Colour perception and colour spaces

Part 5/5 – colour spaces

Rafał Mantiuk

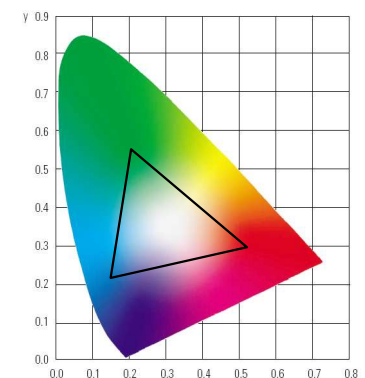
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Representing colour

- ▶ 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

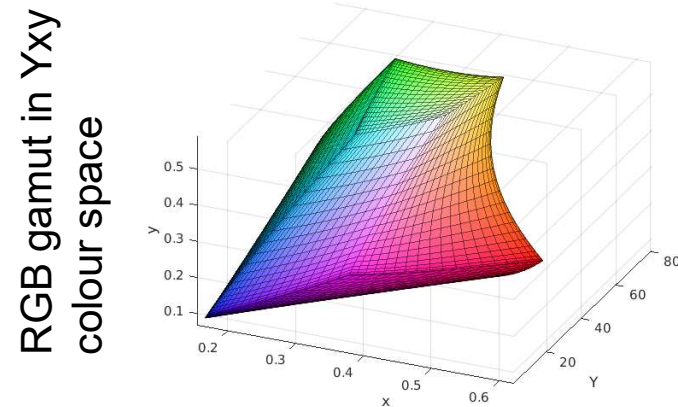
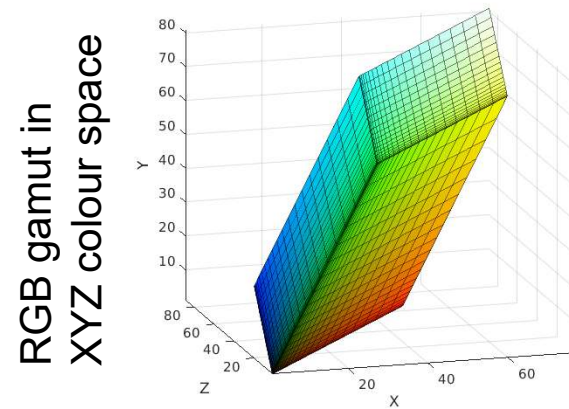
RGB spaces

- ▶ 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



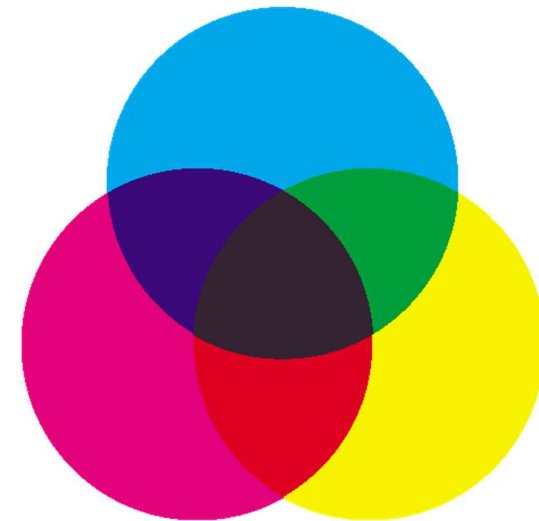
RGB in CIE *XYZ* space

- ▶ 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



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

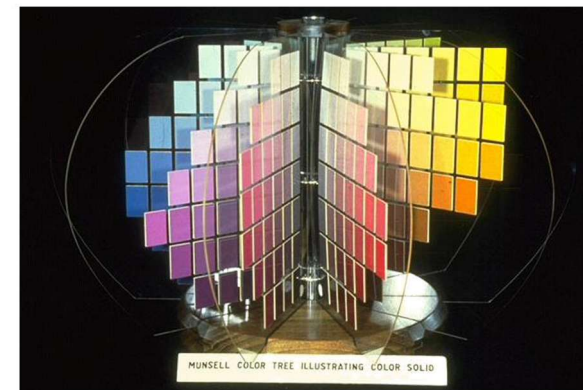
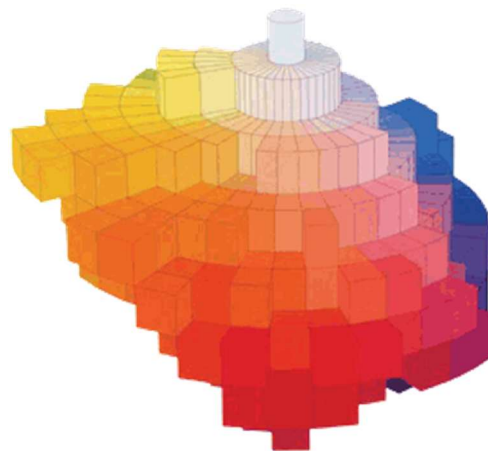
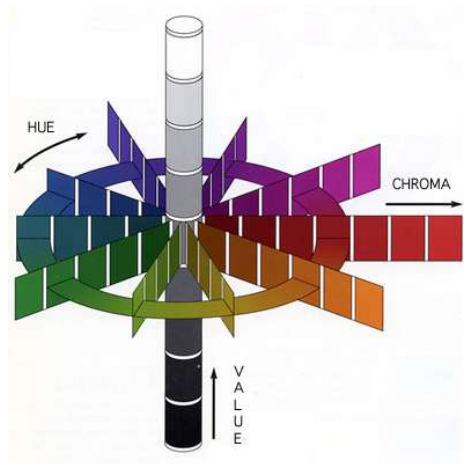
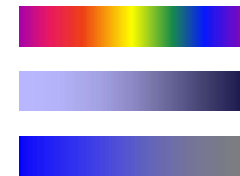


- ▶ in real printing we use black (key) as well as *CMY*
- ▶ why use black?
 - ▶ inks are not perfect absorbers
 - ▶ mixing $C + M + Y$ gives a muddy grey, not black
 - ▶ lots of text is printed in black: trying to align C, M and Y perfectly for black text would be a nightmare

Munsell's colour classification system

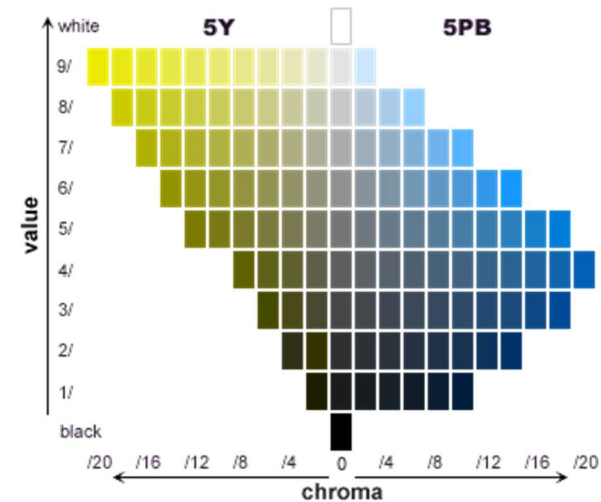
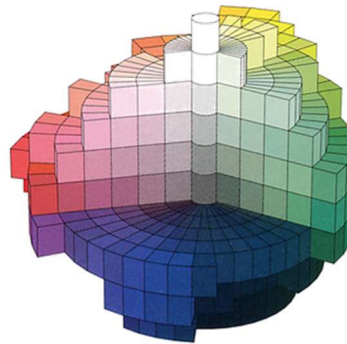
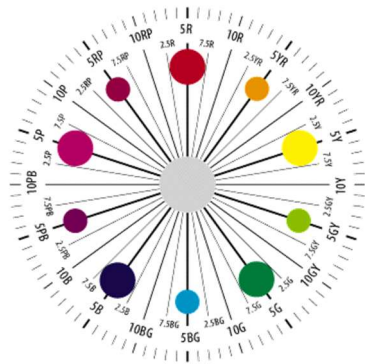
▶ three axes

- ▶ 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

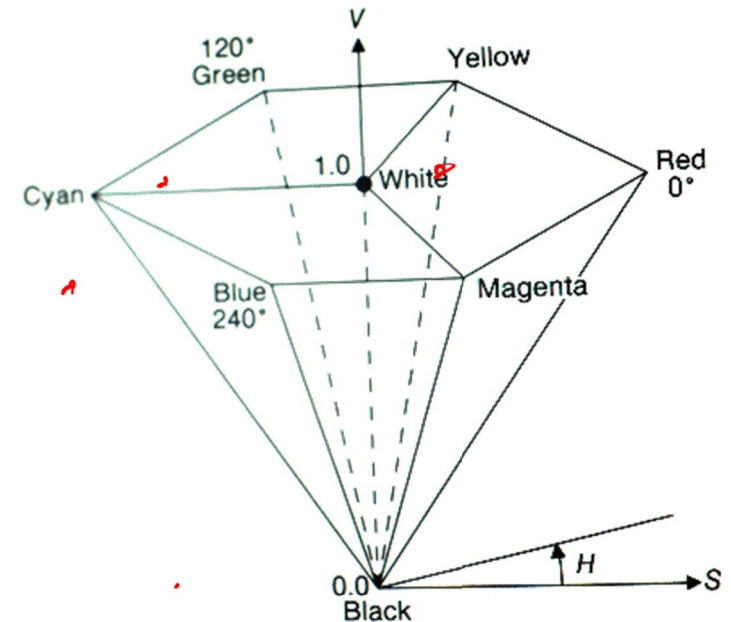
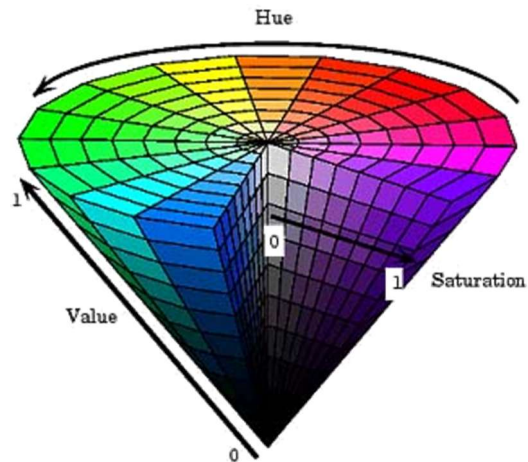


Colour spaces for user-interfaces

- ▶ *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

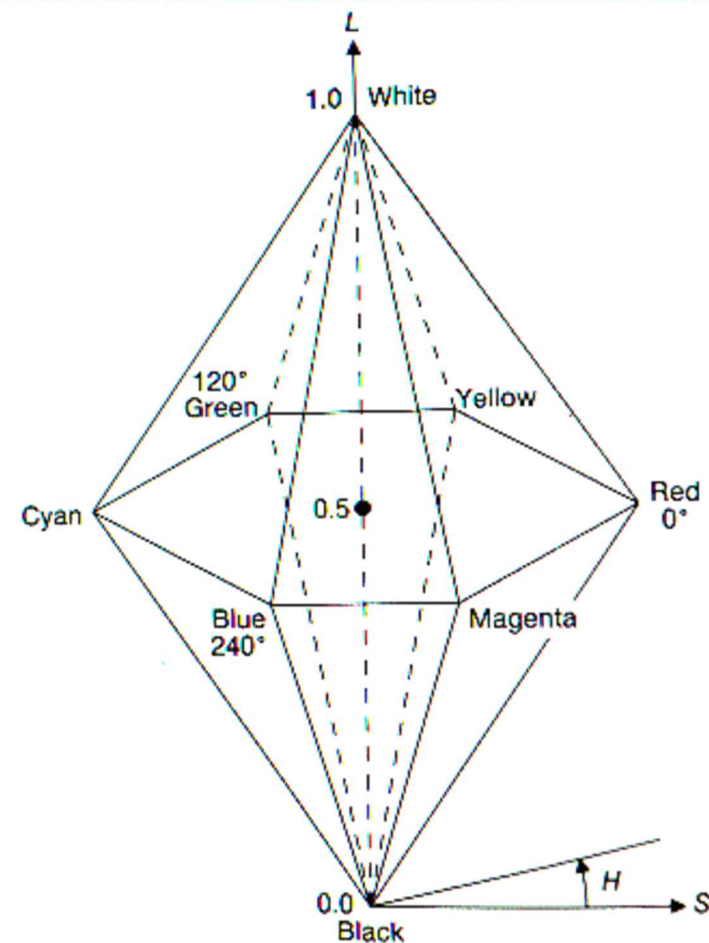
- ▶ three axes, as with Munsell
 - ▶ hue and value have same meaning
 - ▶ the term “saturation” replaces the term “chroma”
 - ▶ simple conversion from display-encoded RGB to HSV



- ◆ 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

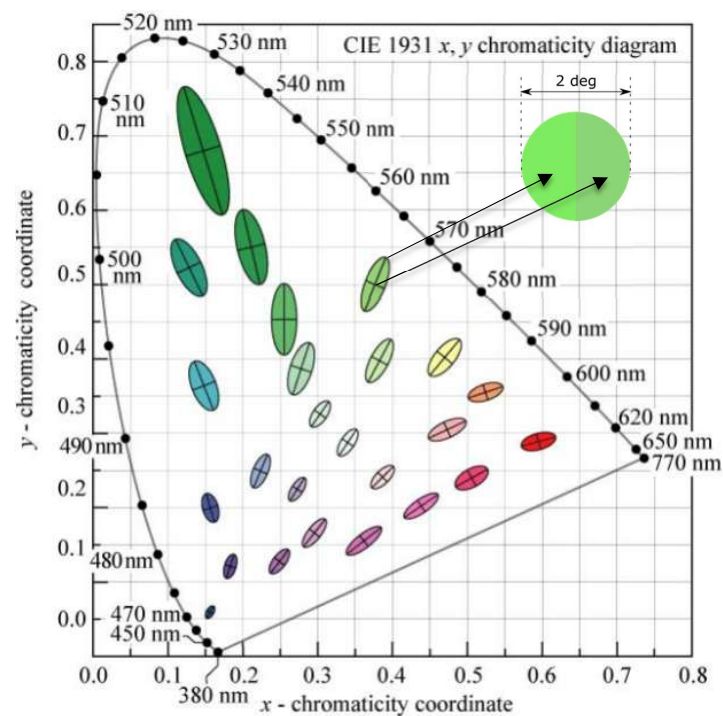
HLS: hue lightness saturation

- ★ 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

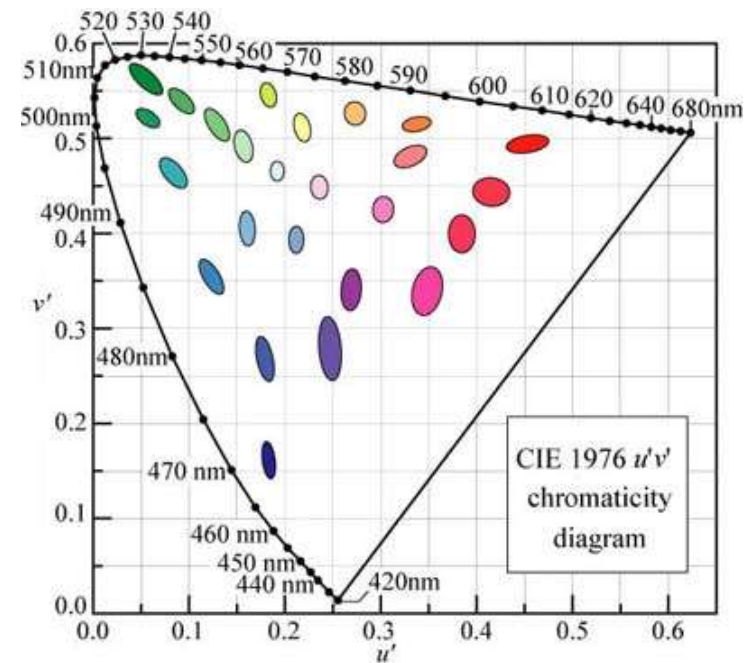


Perceptually uniformity

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

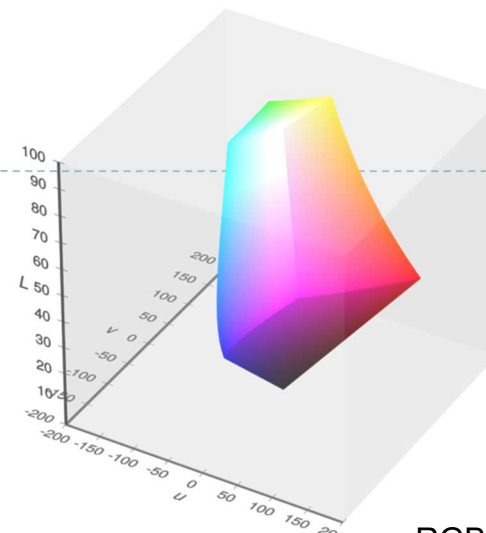
Chromaticity coordinates $\begin{cases} u^* = 13L^* \cdot (u' - u'_n) \\ v^* = 13L^* \cdot (v' - v'_n) \end{cases}$

Colours less distinguishable when dark

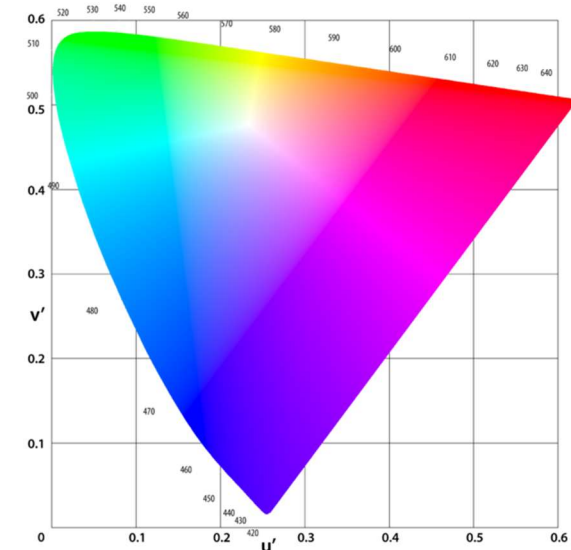
- ▶ Hue and chroma

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

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



sRGB in CIE $L^*u^*v^*$



CIE L*a*b* colour space

- ▶ Another approximately perceptually uniform colour space

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

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

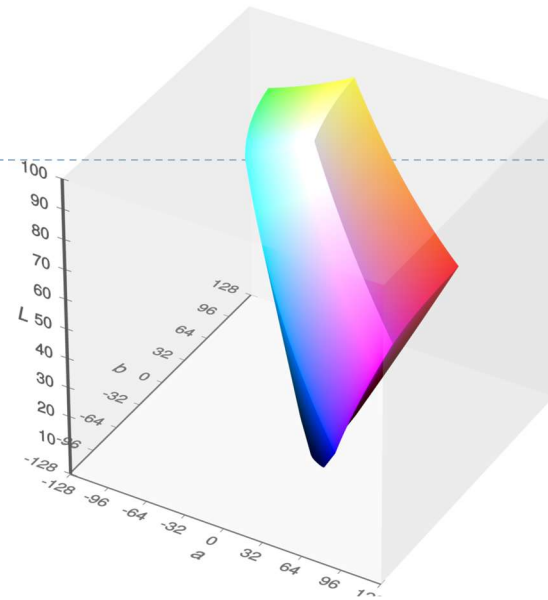
$$b^* = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right)$$

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

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

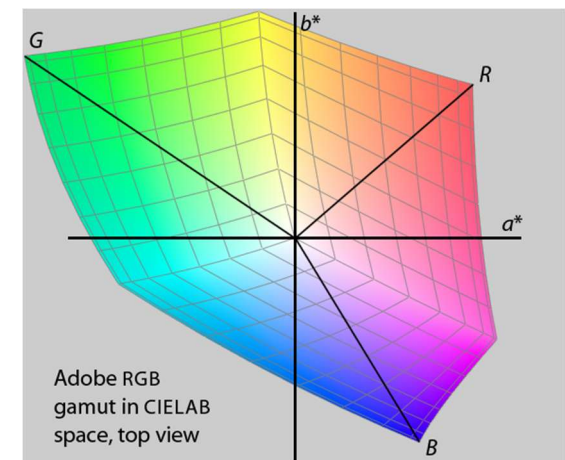
Trichromatic values of the white point, e.g.

$$\begin{aligned} X_n &= 95.047, \\ Y_n &= 100.000, \\ Z_n &= 108.883 \end{aligned}$$



- ▶ Chroma and hue

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





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.