Colour

MSc Architecture, Energy & Sustainability
Module ADP033
Daylighting & Energy Efficient Artificial Lighting

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Structure

I Introduction

II Colour Vision

III Colour Systems

IV Colour Temperature

V Colour Rendering

I *Introduction*

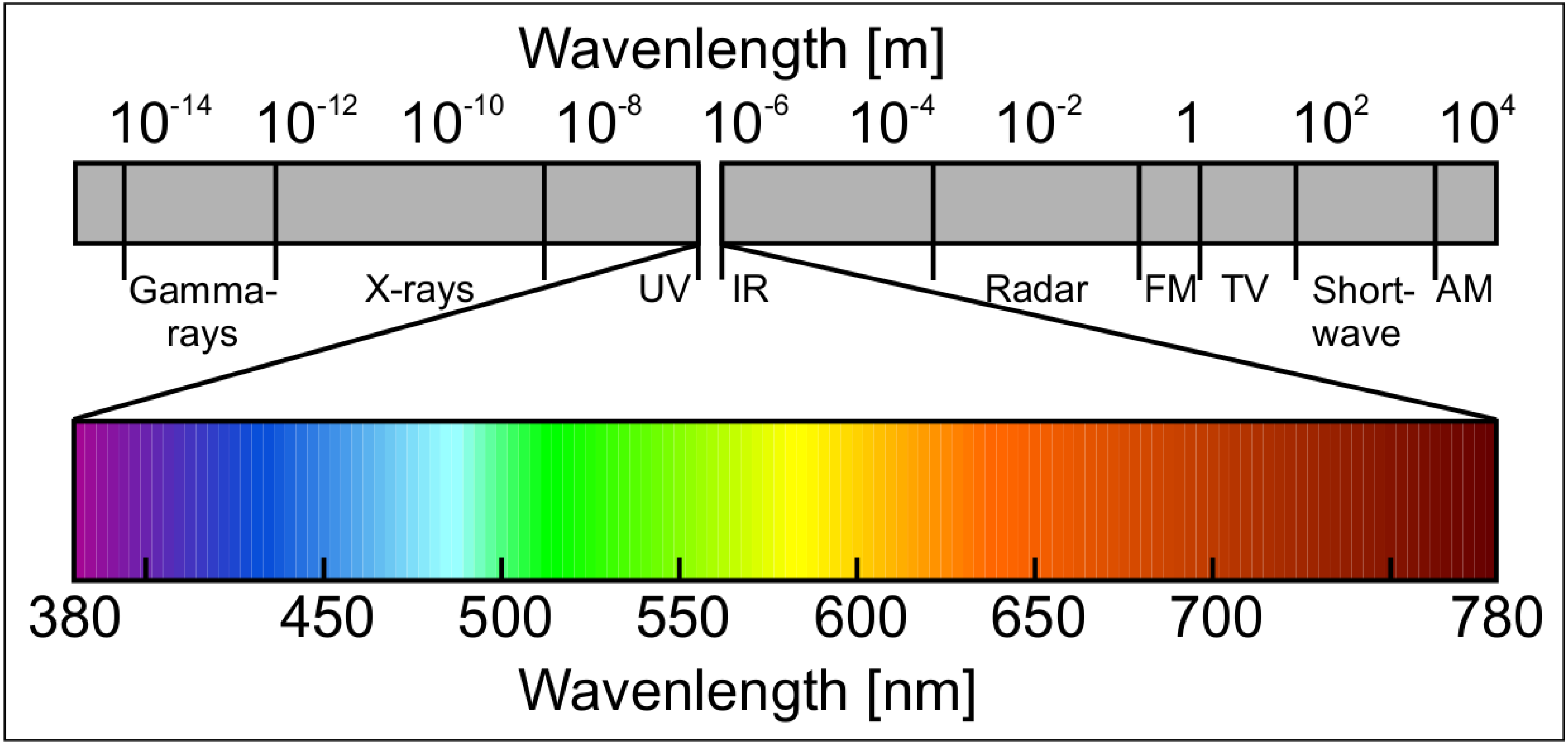
What is Colour?

“Colour is the visual perceptual property corresponding in humans to the categories called red, green, blue and others. Colour derives from the spectrum of light (distribution of light energy versus wavelength) interacting in the eye with the spectral sensitivities of the light receptors.

“The science of colour is sometimes called chromatics. It includes the perception of color by the human eye and brain, the origin of colour in materials, colour theory in art, and the physics of electromagnetic radiation in the visible range (that is, what we commonly refer to as simply as light).

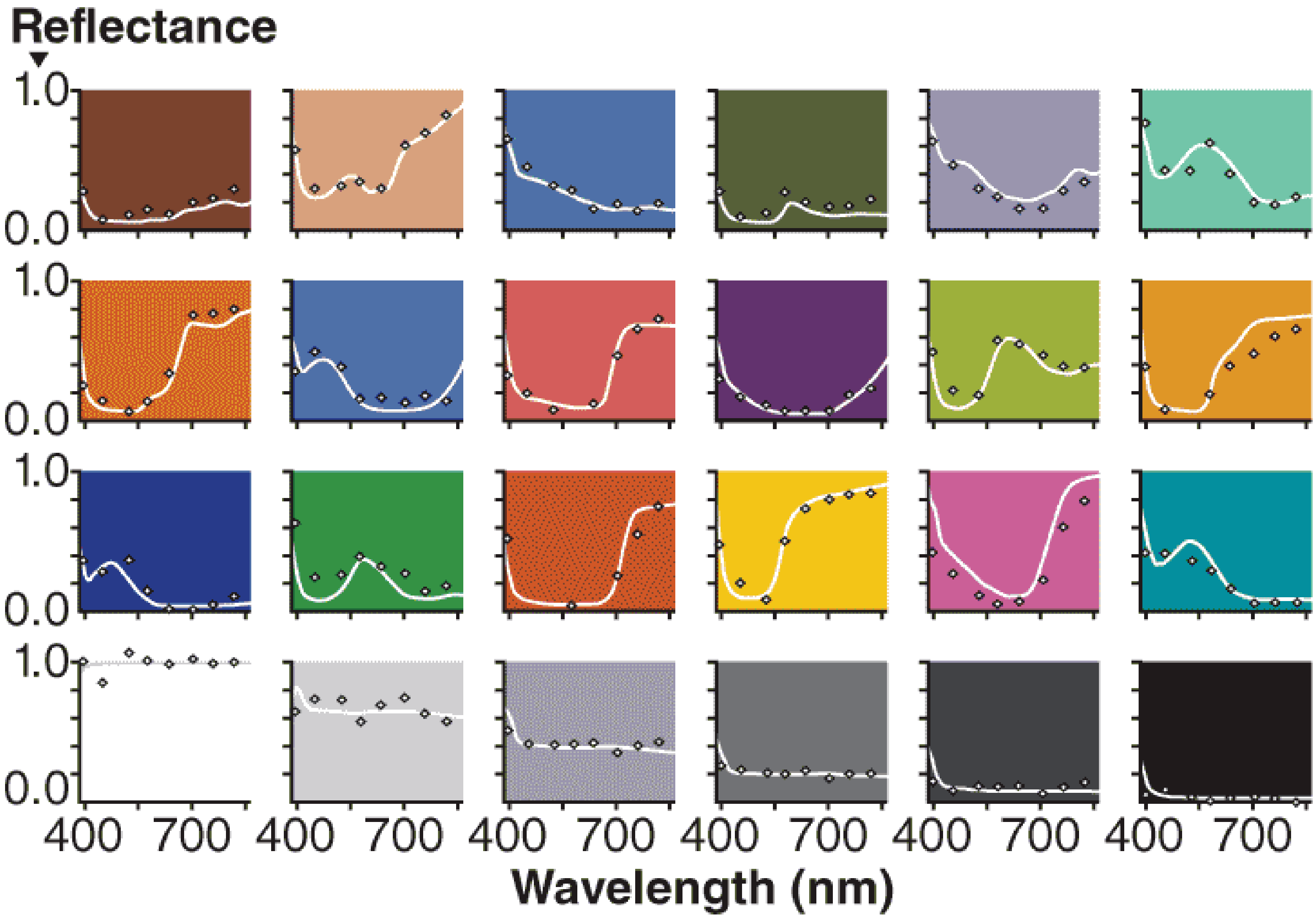
Wikipedia

Electromagnetic Radiation

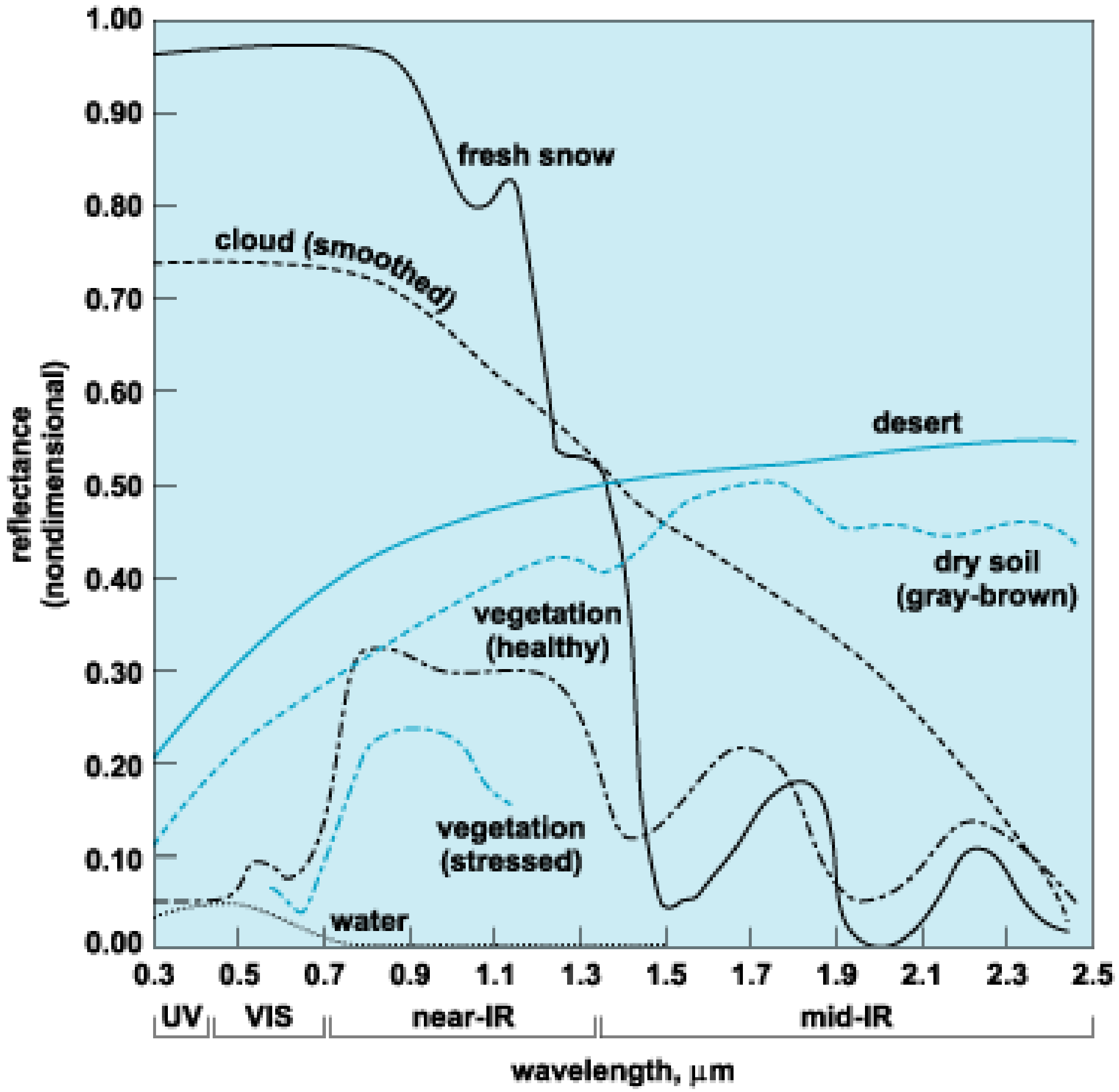


Macbeth Test Colours

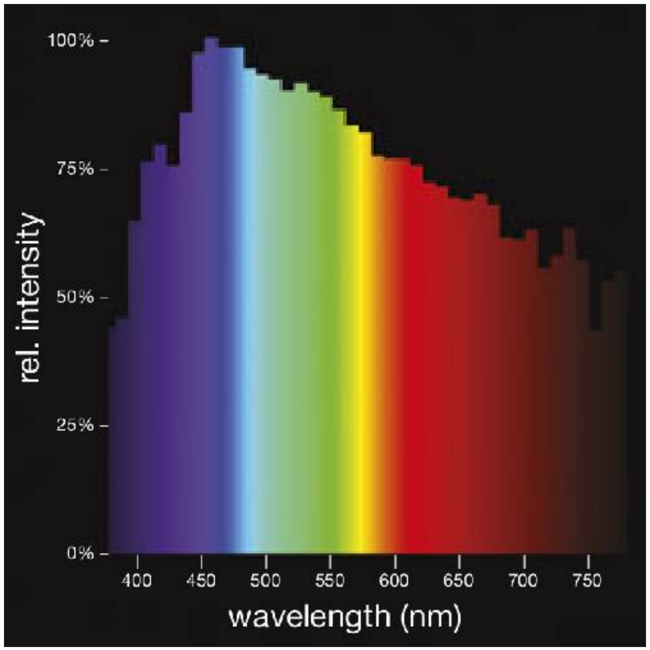
Visual Spectral Reflectance



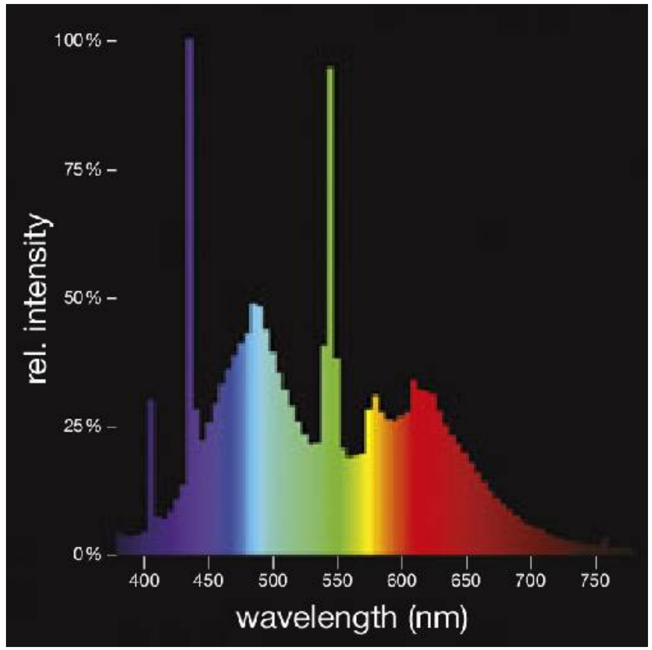
Spectral Reflectance



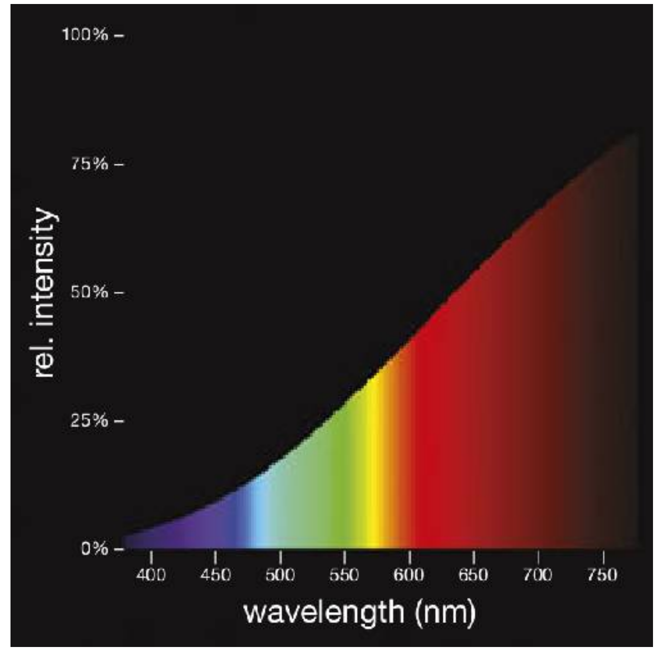
Spectral Power



Daylight



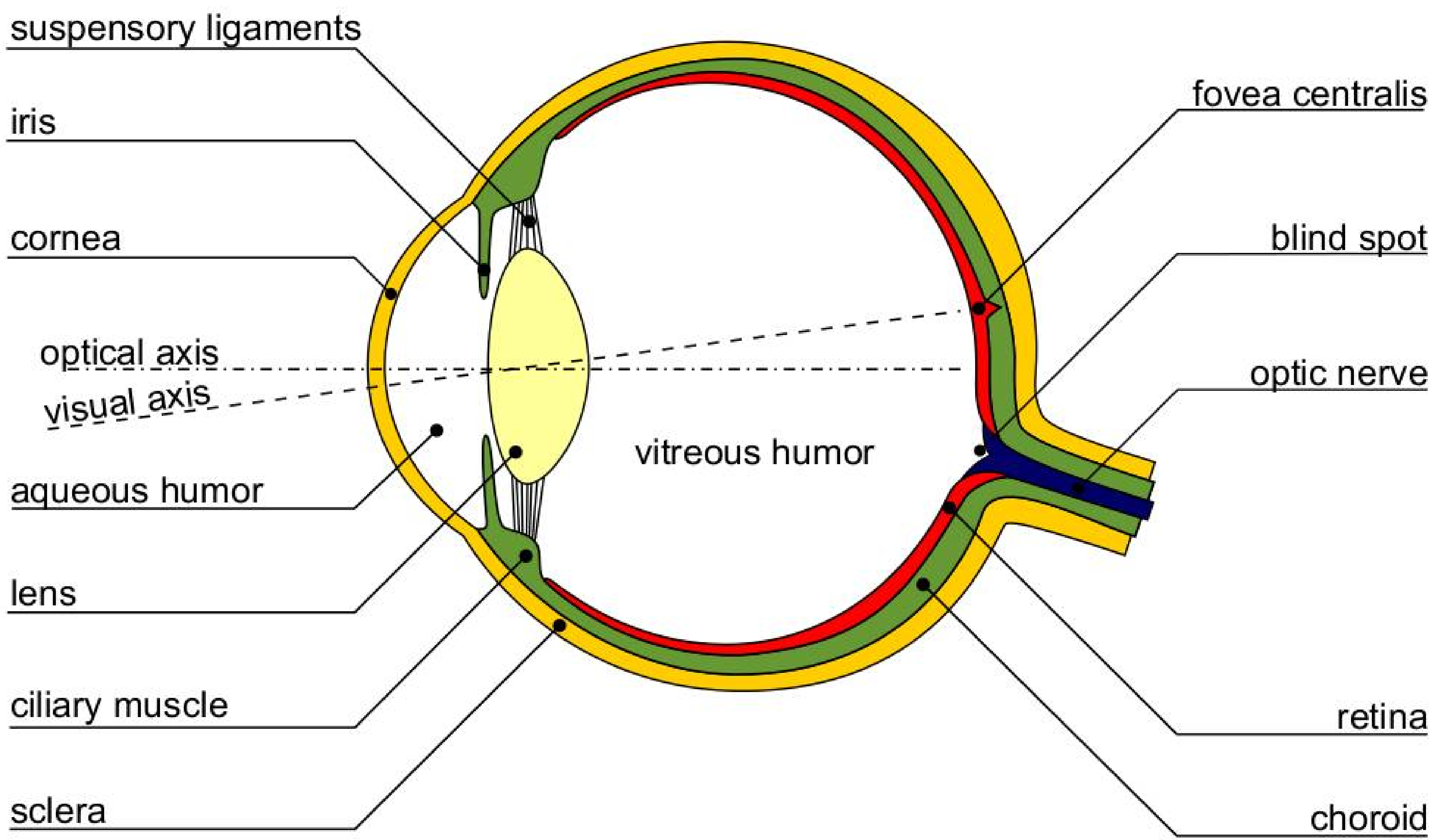
Fluorescent



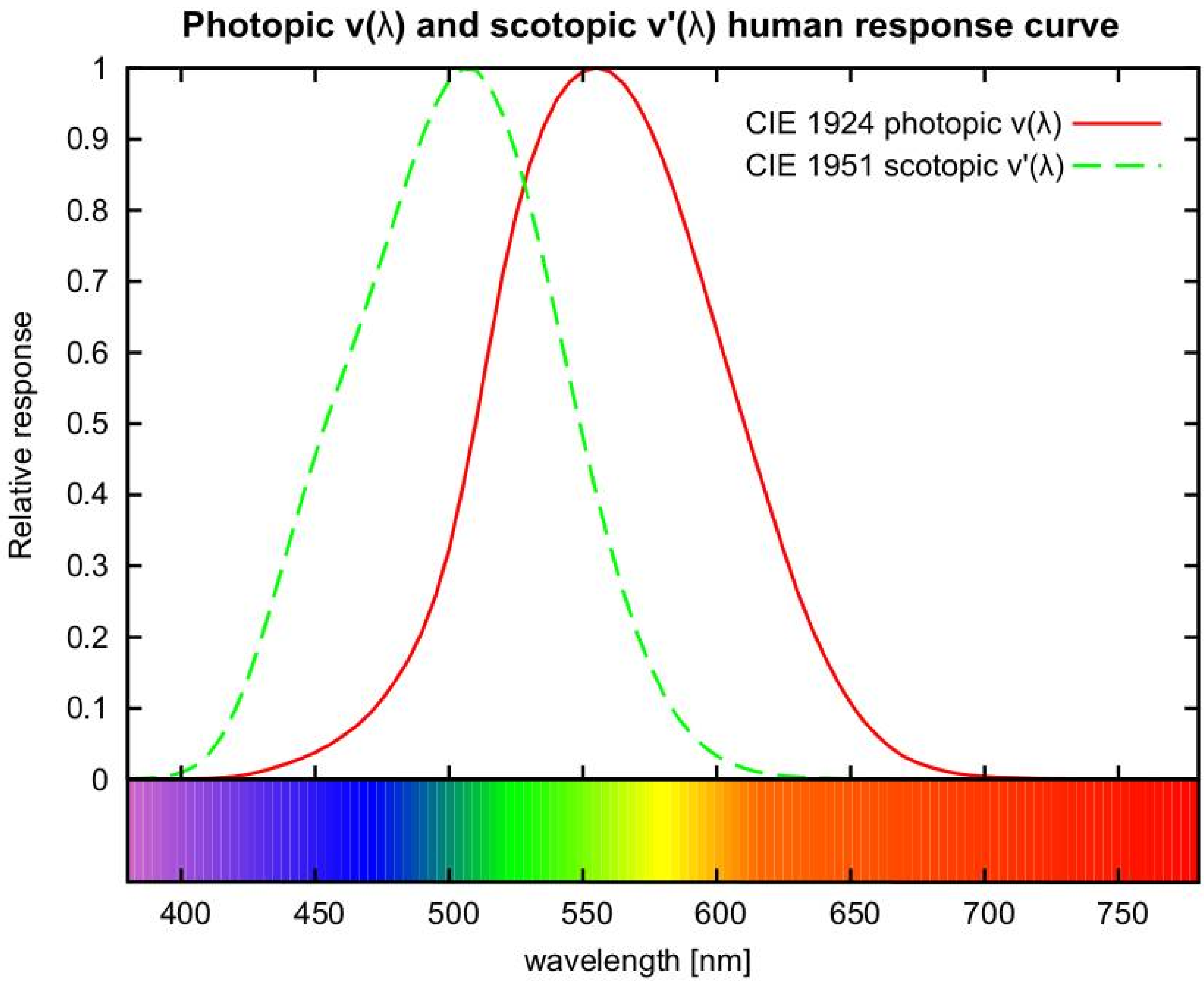
Tungsten

II *Colour Vision*

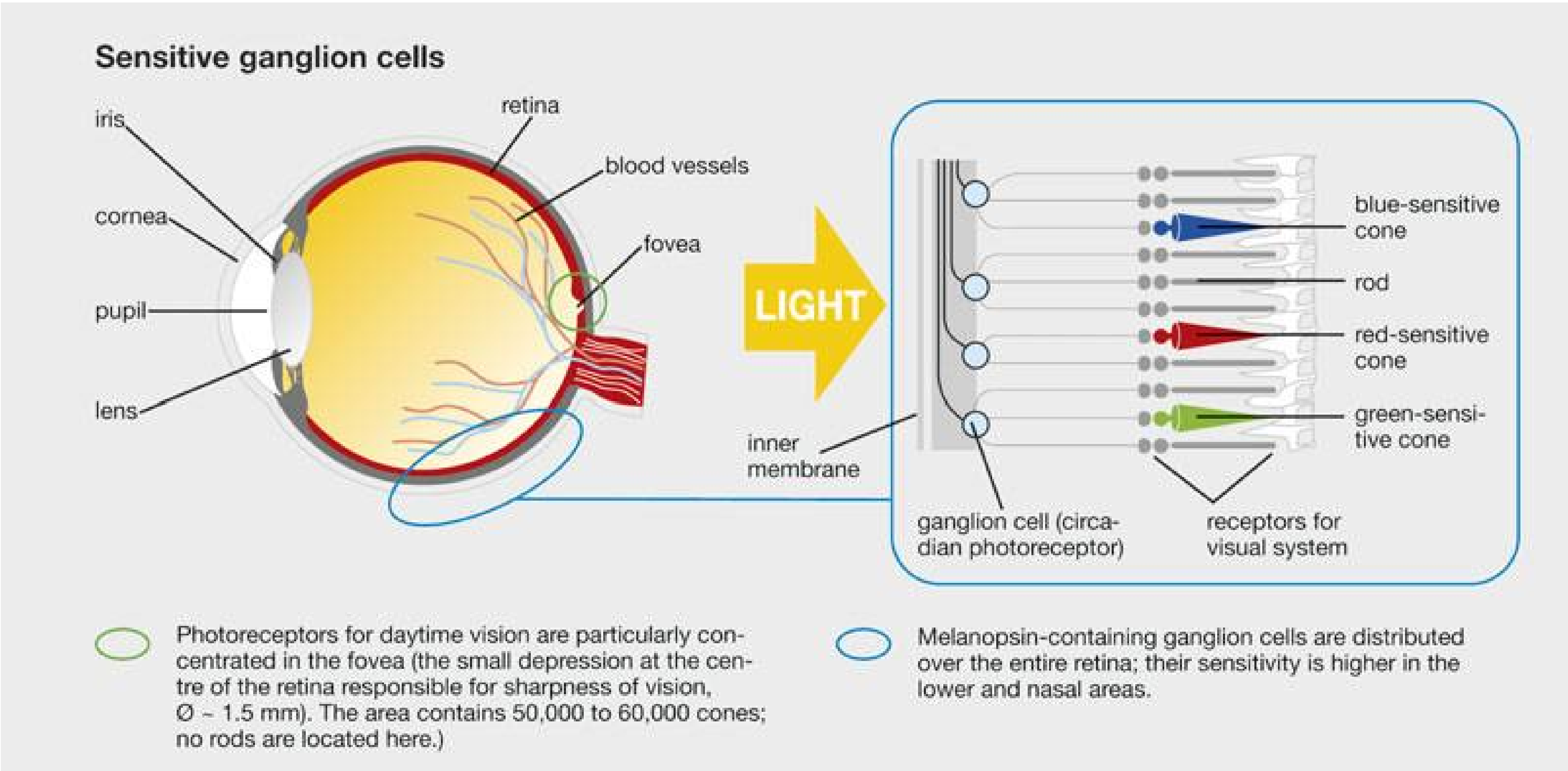
Eye


suspensory ligaments
iris
cornea
optical axis
visual axis
aqueous humor
lens
ciliary muscle
sclera
vitreous humor
fovea centralis
blind spot
optic nerve
retina
choroid

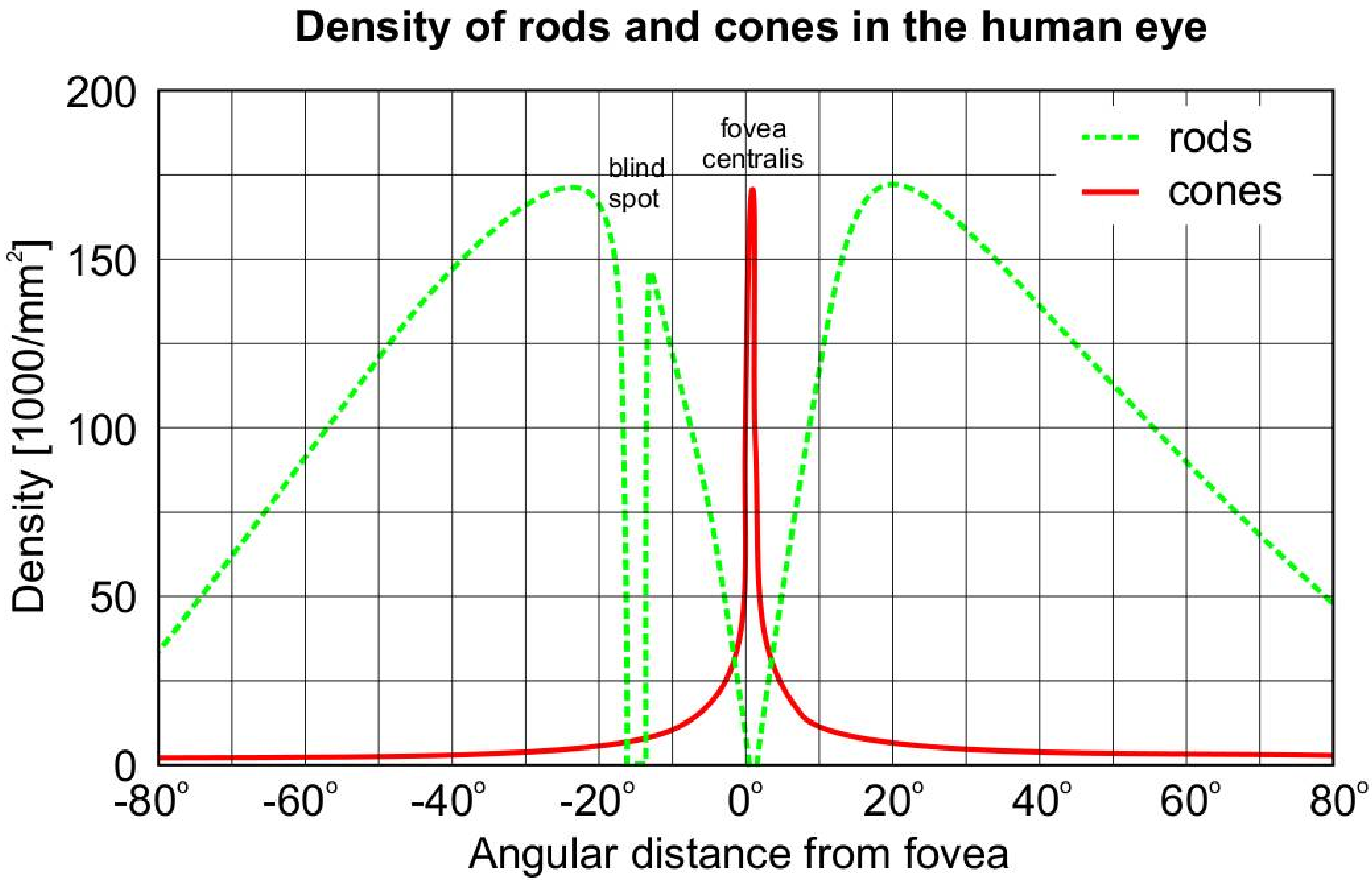
Brightness Response



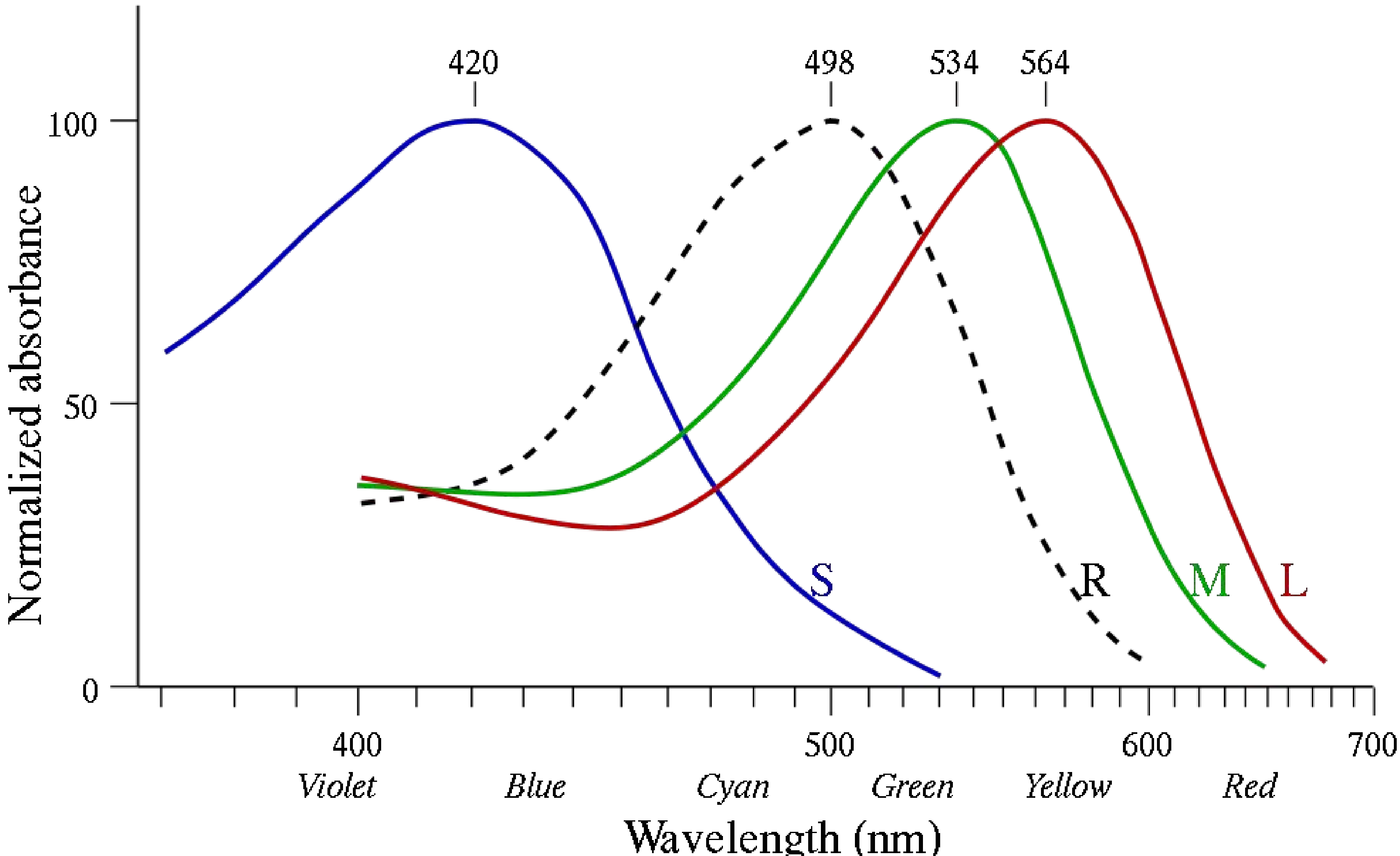
Photoreceptors



Distribution of Photoreceptors



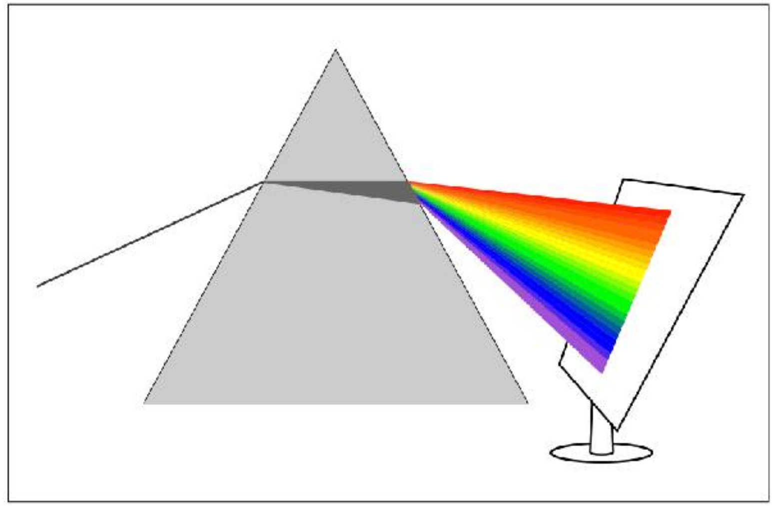
Spectral Response



Wikipedia

Isaac Newton

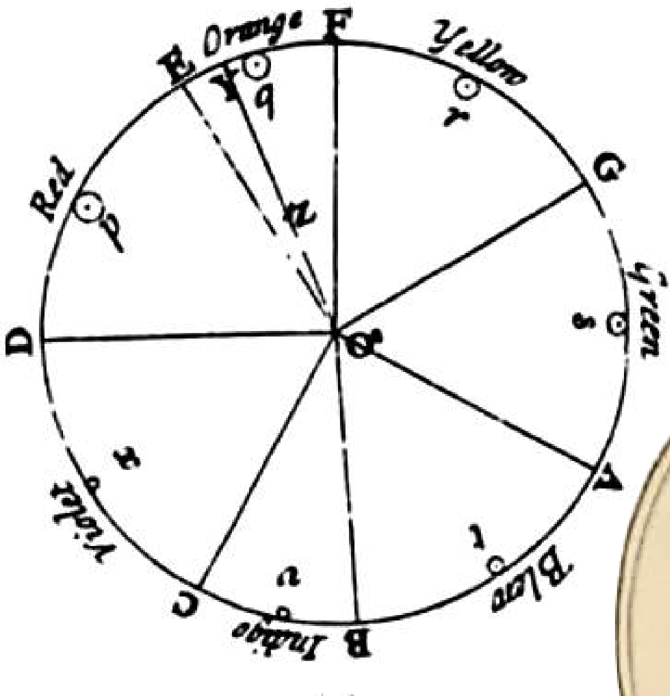
- *Opticks*, 1704: ”For the rays to speak properly are not coloured. In them there is nothing else than a certain power and disposition to stir up a sensation of this or that colour.”
- The sensation of colour vision was produced from sympathetic vibrations set in motion “on the bottom of the eye” by the arriving light.



Pink Floyd's The Dark Side of the Moon

How Many Colours?

- Newton: 7



Richard of York

- Modern Science: 6

Wavelength	Colour	Colour name
380-450 nm		violet
450-490 nm		blue
490-560 nm		green
560-590 nm		yellow
590-630 nm		orange
630-780 nm		red

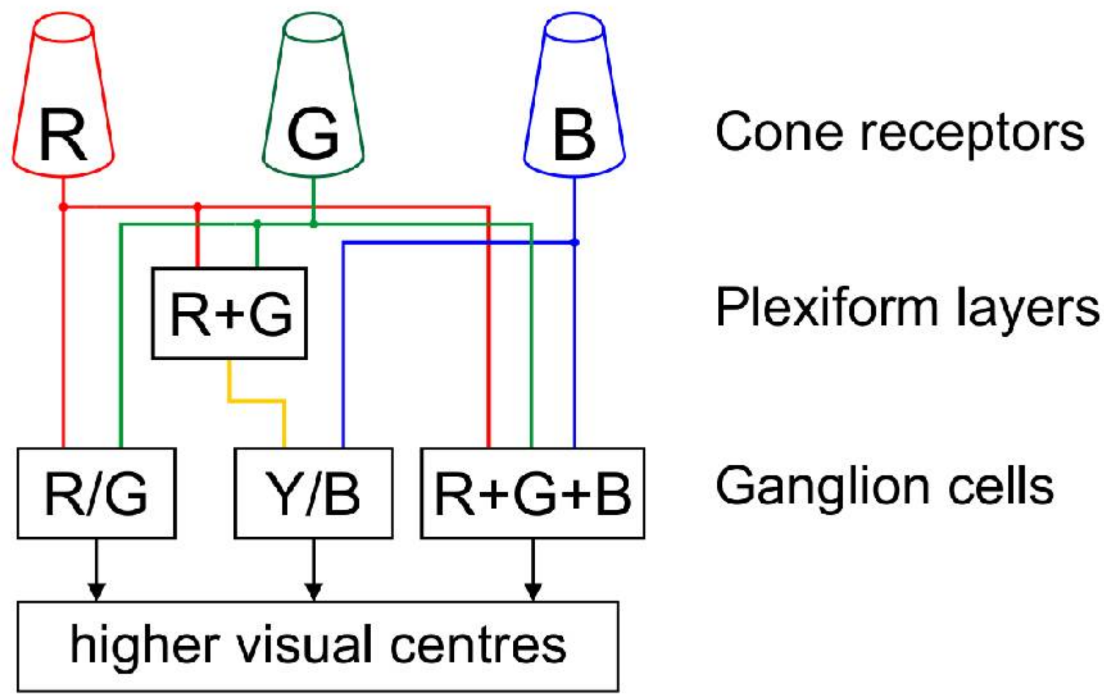
Colour Theories

- Thomas Young & Herman von Helmholtz, 19^{th} Cent.
  - Trichromatic theory
  - Red, green, blue as primaries
- Edward Hering, 1790
  - Opponent Colour Theory
  - Red-green, blue-yellow, light-dark
- Both theories can be proven and disproven experimentally.

Zone Theory

Franciscus Cornelis Donders, 1881:

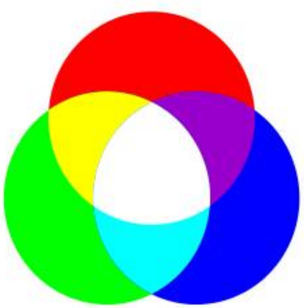
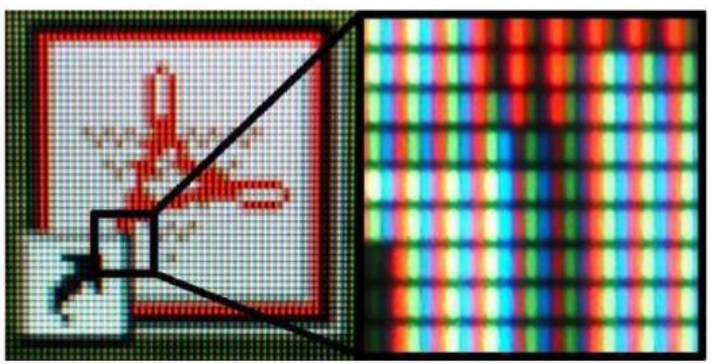
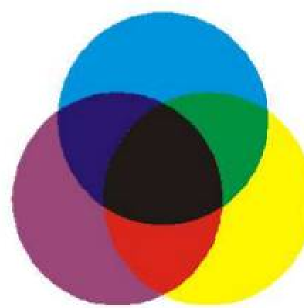
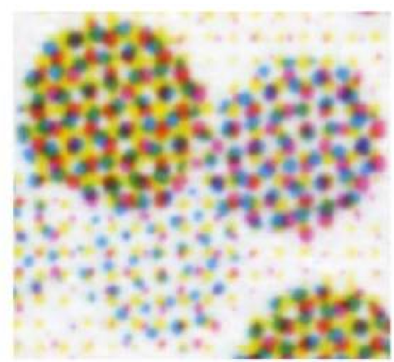
Colour vision is processed sequentially along the visual pathway. Trichromacy occurs at one level, opponency at another.



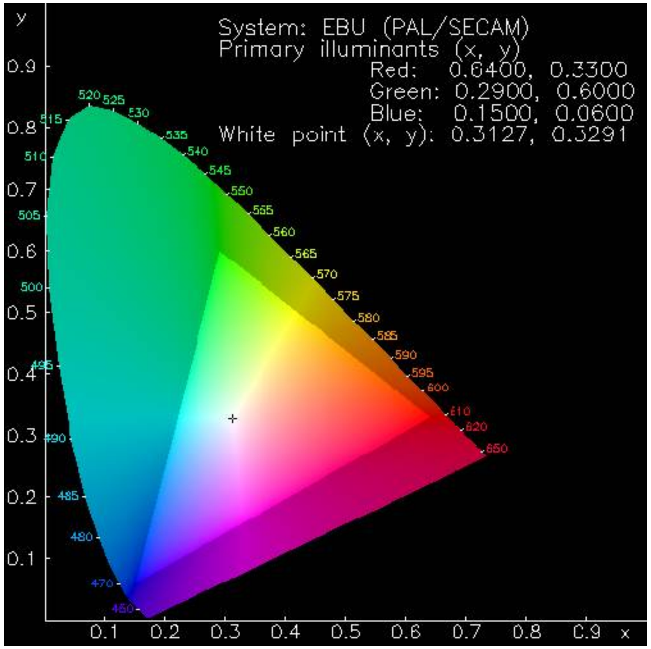
III *Colour Systems*

RGB

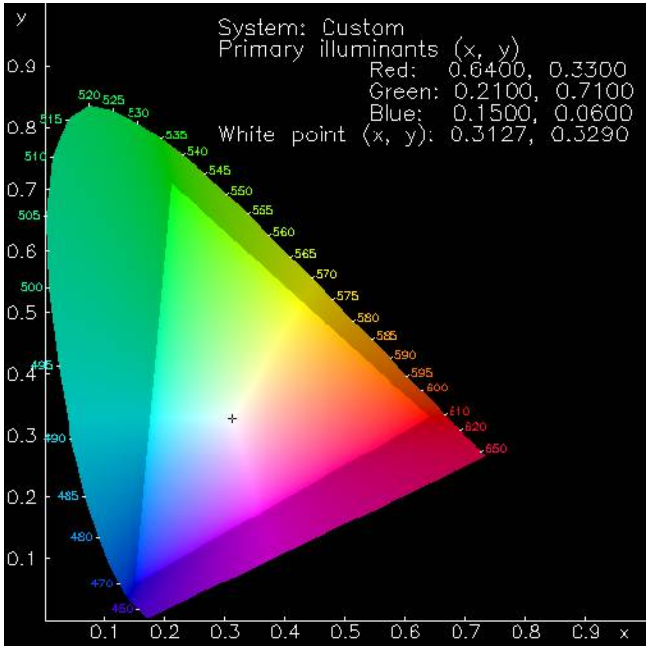
- Most well-known colour system: Computer graphics, TV
- Actually many different RGB systems, depending on monochromatic primaries and white point
- CMY(K) as special case of RGB system: Printing

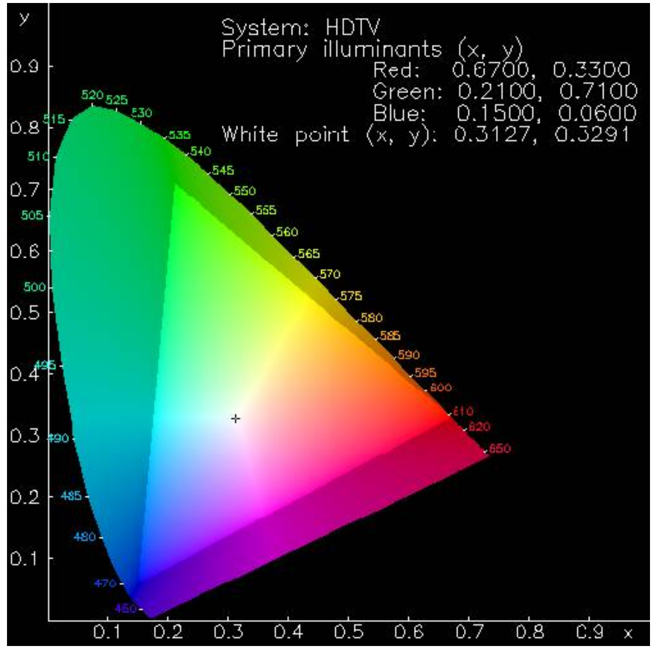
Some RGB Colour Spaces



Television



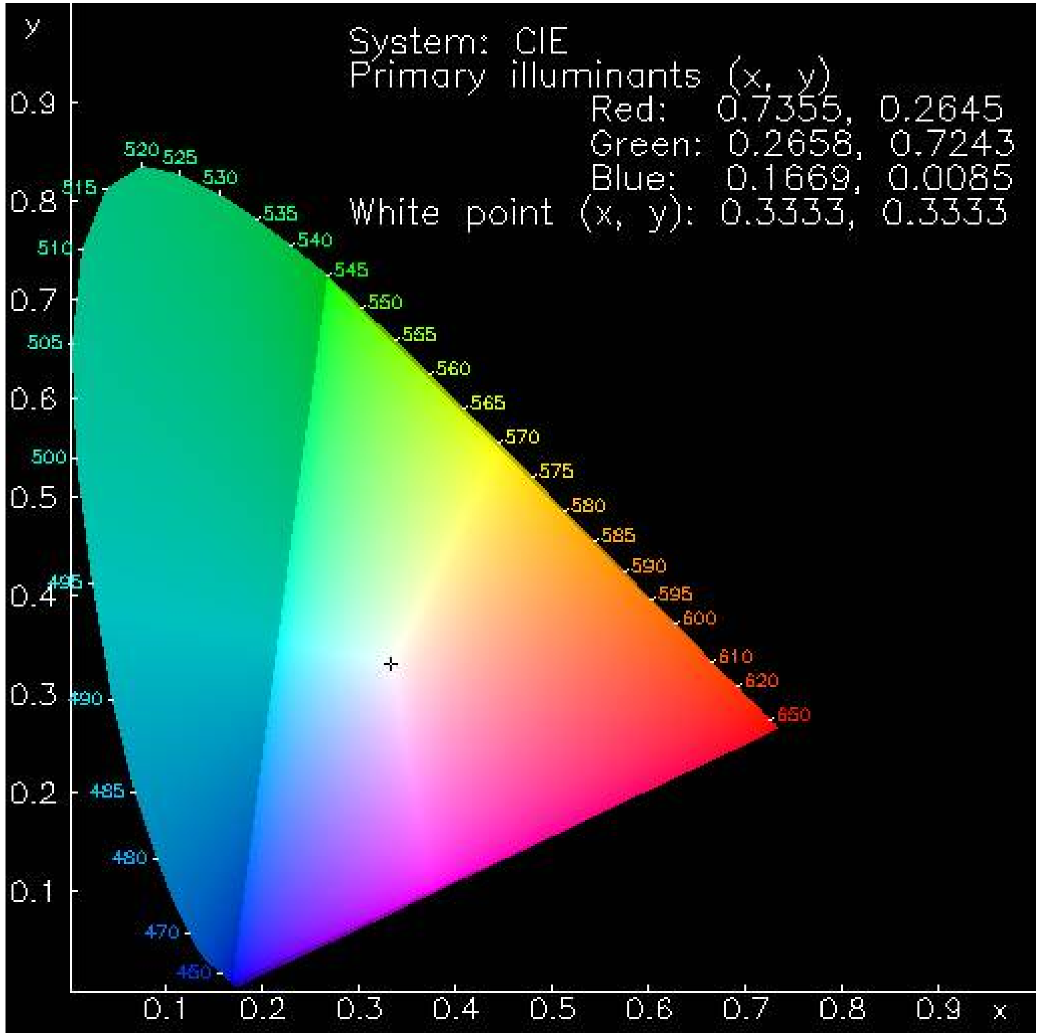
Adobe



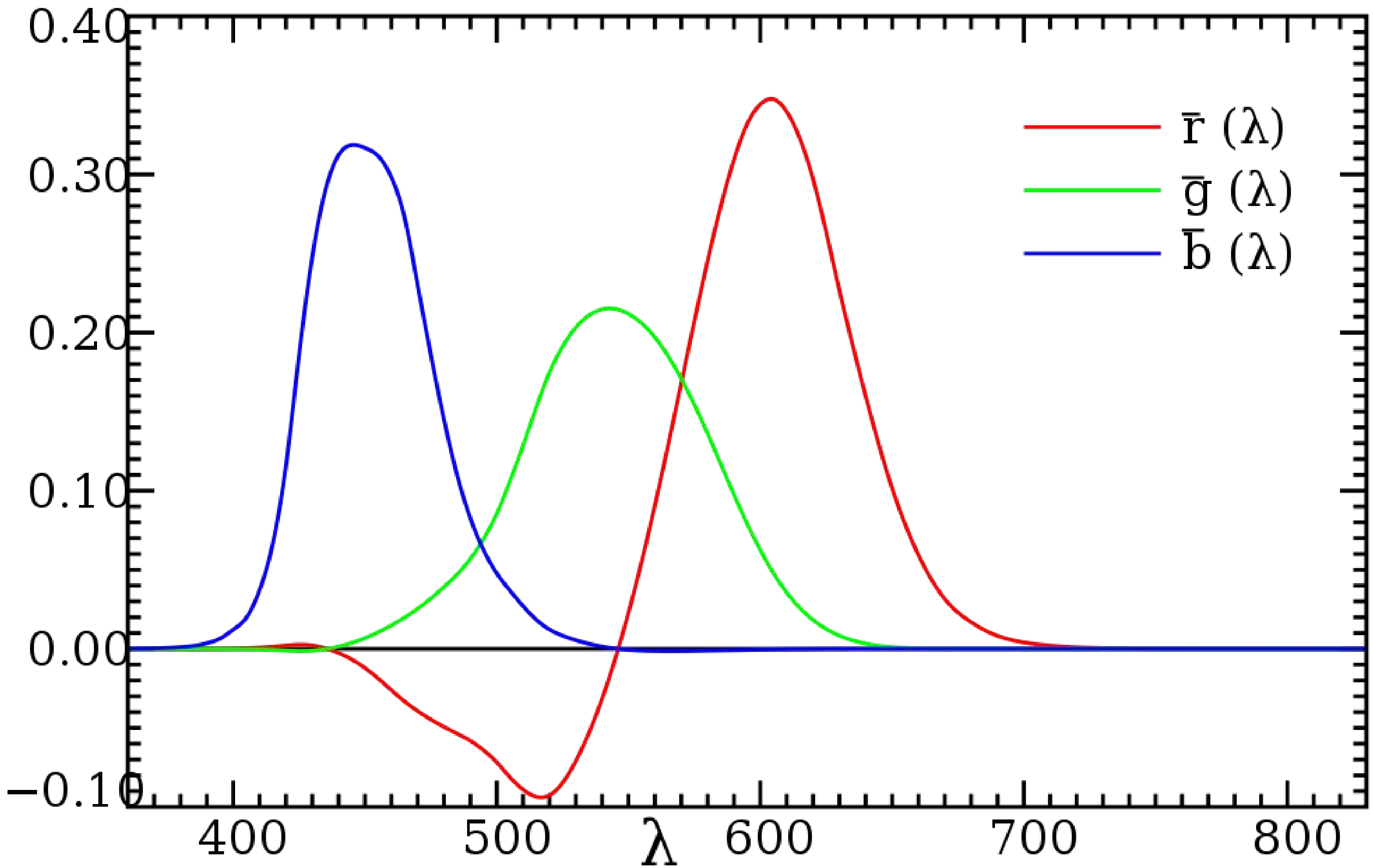
HDTV

CIE RGB

- Experiments by Wright and Guild in 1920s
- Primaries:
  - 700 nm (red)
  - 546.1 nm (green)
  - 435.8 nm (blue)
- Some colours required negative amounts of a primary colour



CIE 1931 “Standard Observer”



Wikipedia

CIE 1931 XYZ

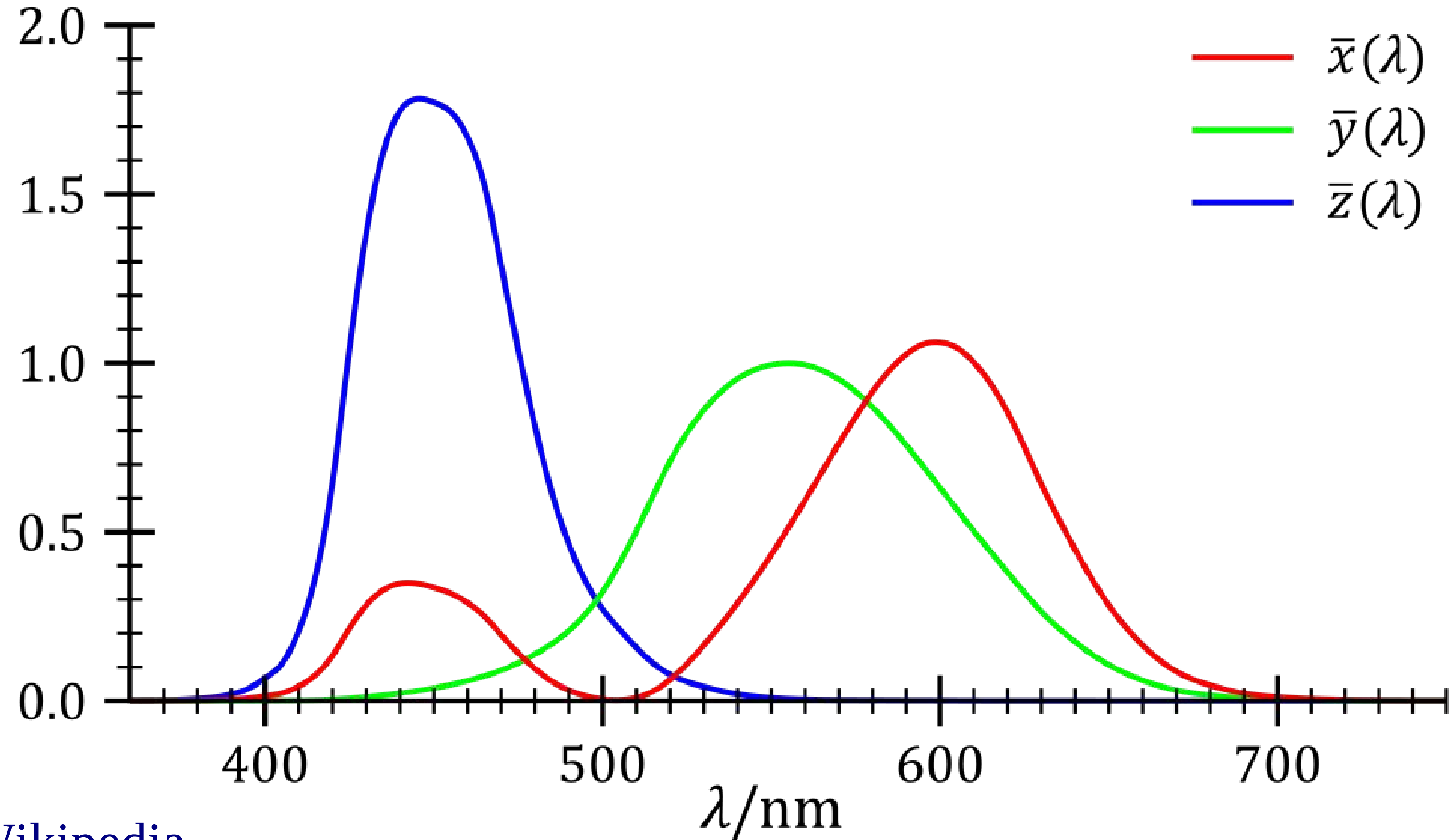
- Remedy problem with RGB space: no negative primaries
- Y is the Luminance Factor: response curve of the human eye
- For plotting in two dimensions: normalise so that x + y + z = 1

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

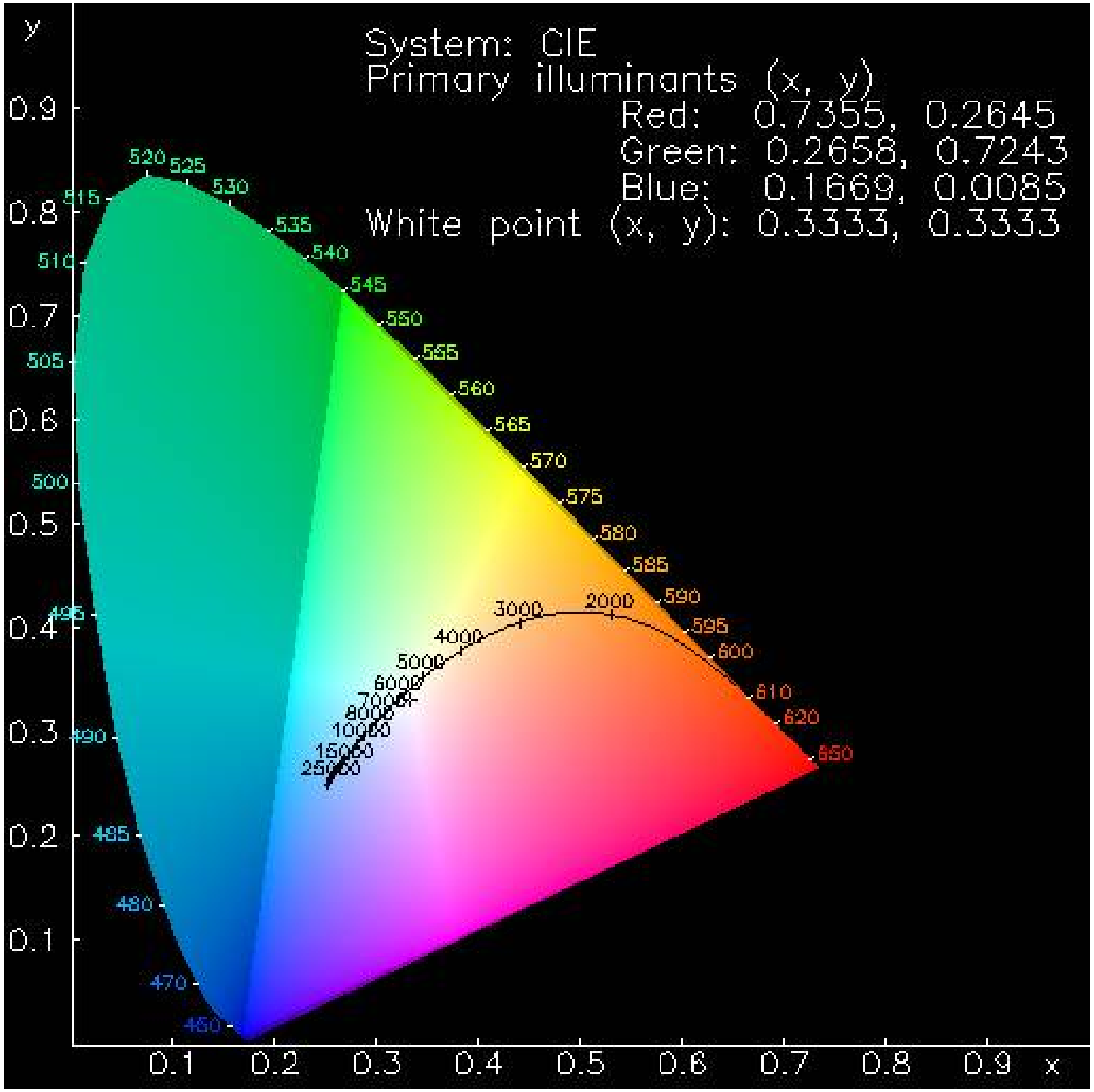
$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

CIE 1931 Colour Matching Function

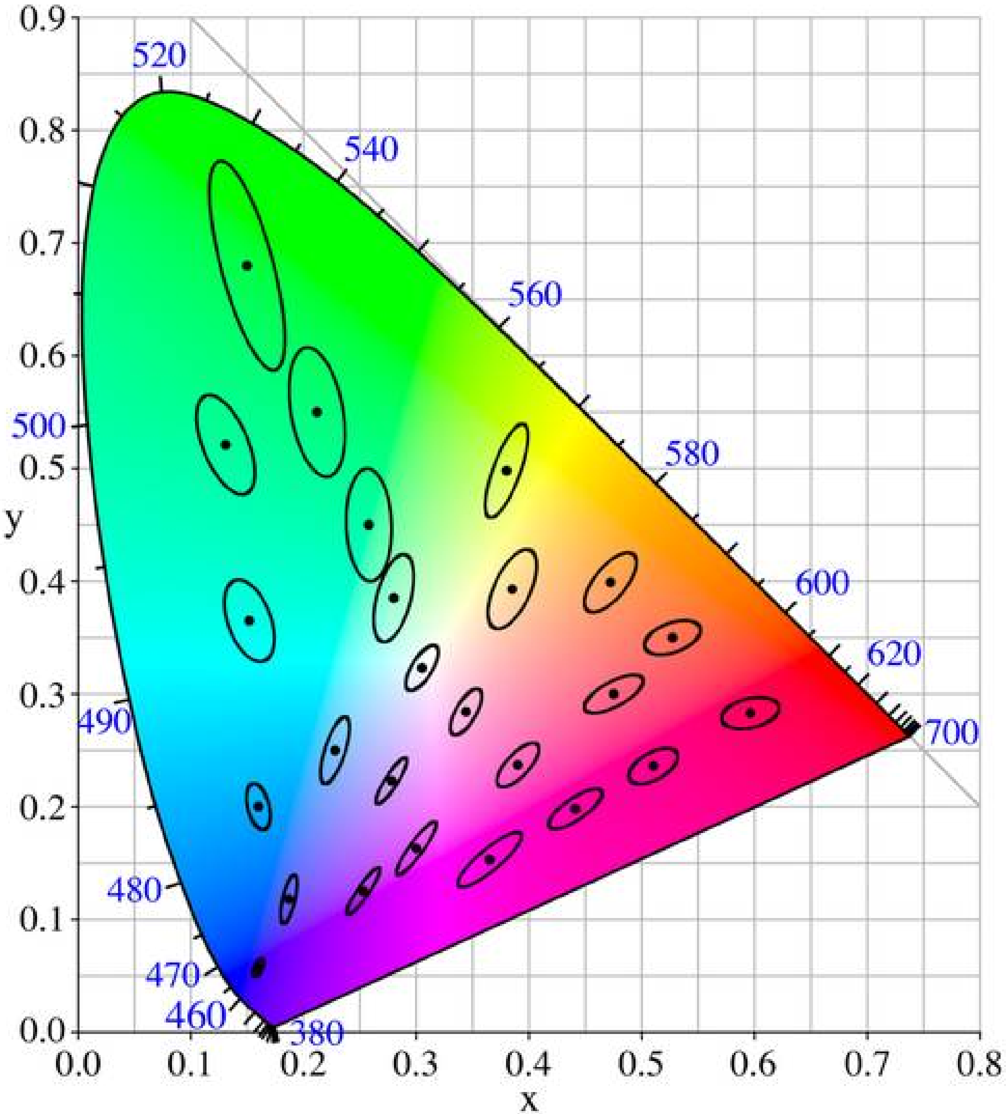


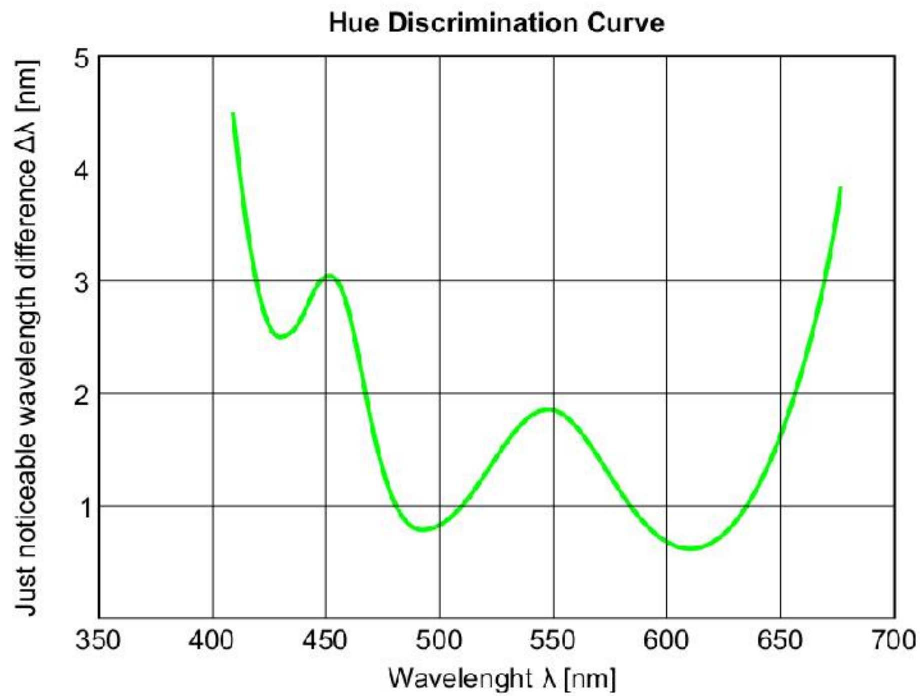
[Wikipedia]

CIE 1931 xy Diagram



Is this the same Colour?



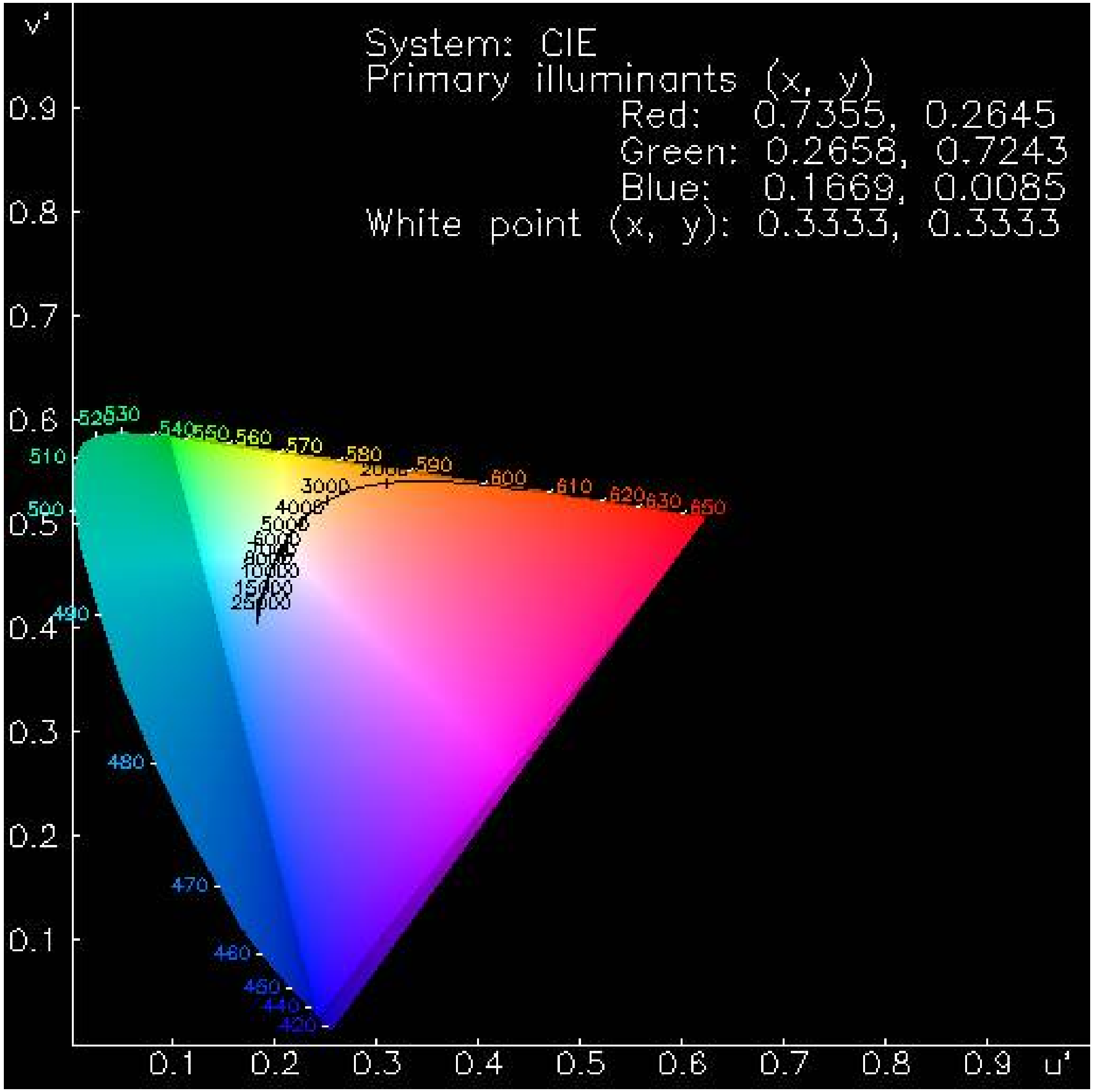


MacAdam ellipses, 1940s (10x)

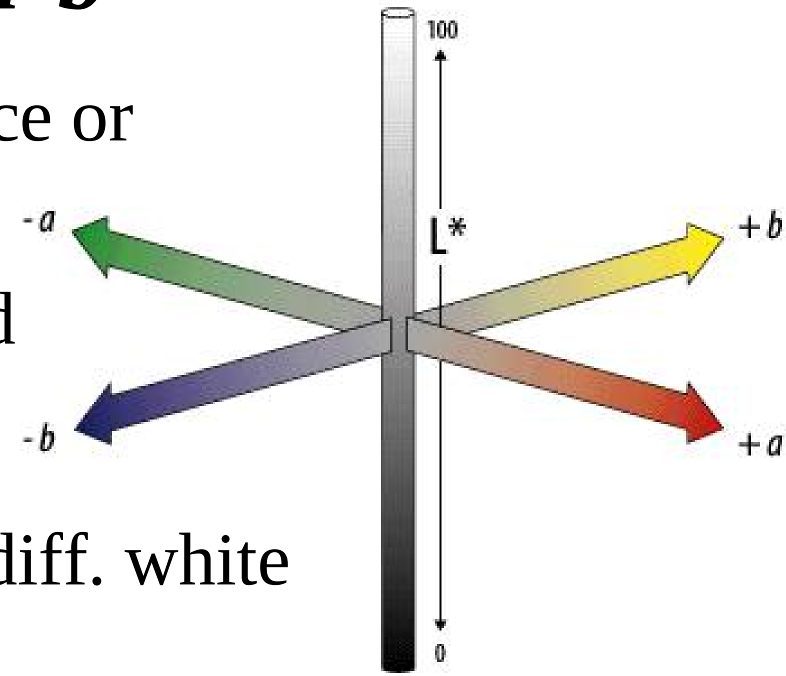
*CIE 1976 L*u'v'*

- Simple transformation of CIE 1931 XYZ
- Attempts to perceptual uniformity
- Used extensively, e.g. in computer graphics
- u'v' can be plotted in a plane

*CIE 1976 L*u'v' Diagram*



*CIE 1976 L*a*b**

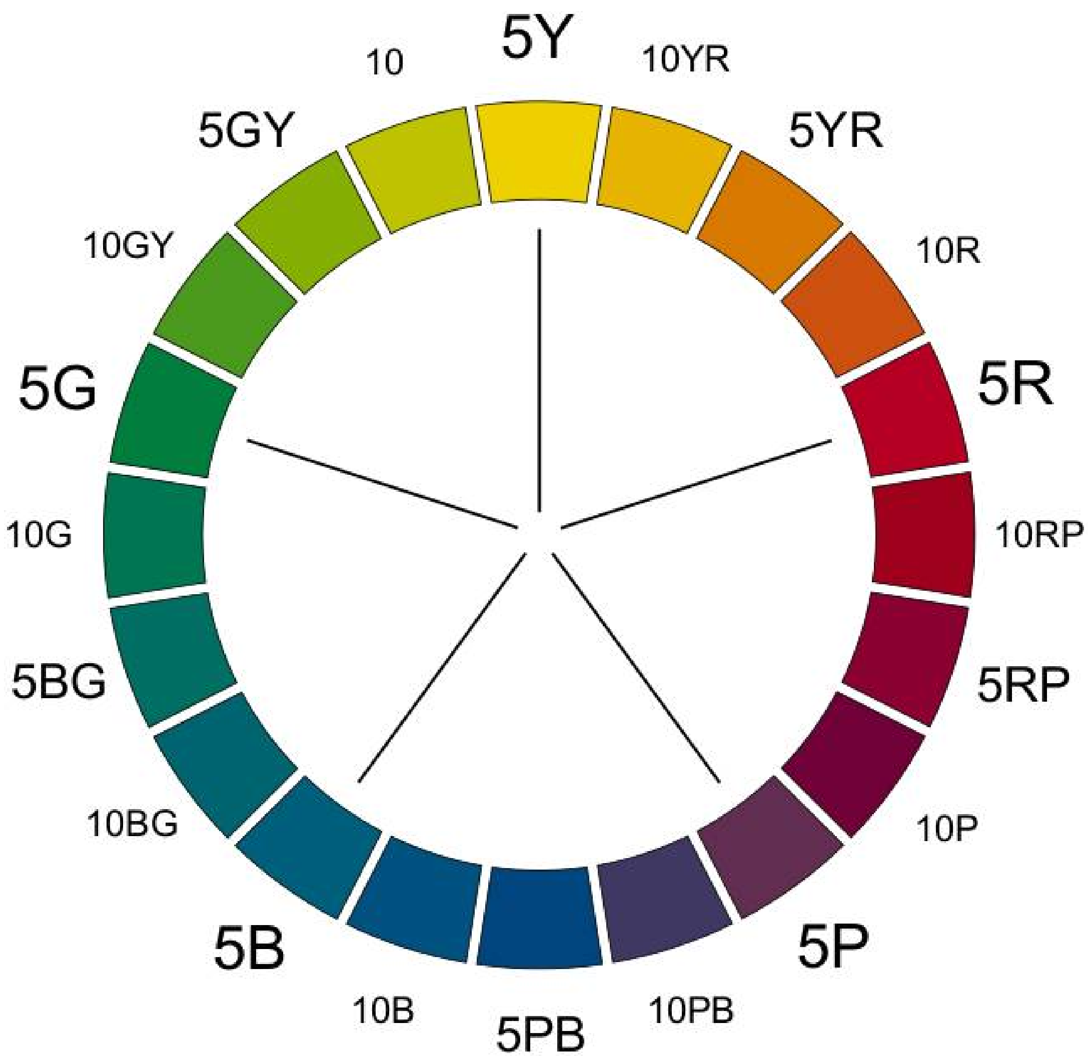


- Gamut larger than any output device or human vision (imaginary colours)
- 3d space, can't be represented in 2d
- Coordinates:
  - L* = 0 → black; L* = 100 → diff. white
  - −a* → green; +a* → red
  - −b* → blue; +b* → yellow
- Colour difference given as ΔE^*_{Lab}
- For demanding colour measurements, even CIELAB is not sufficiently uniform: CIE94, CIEDE2000

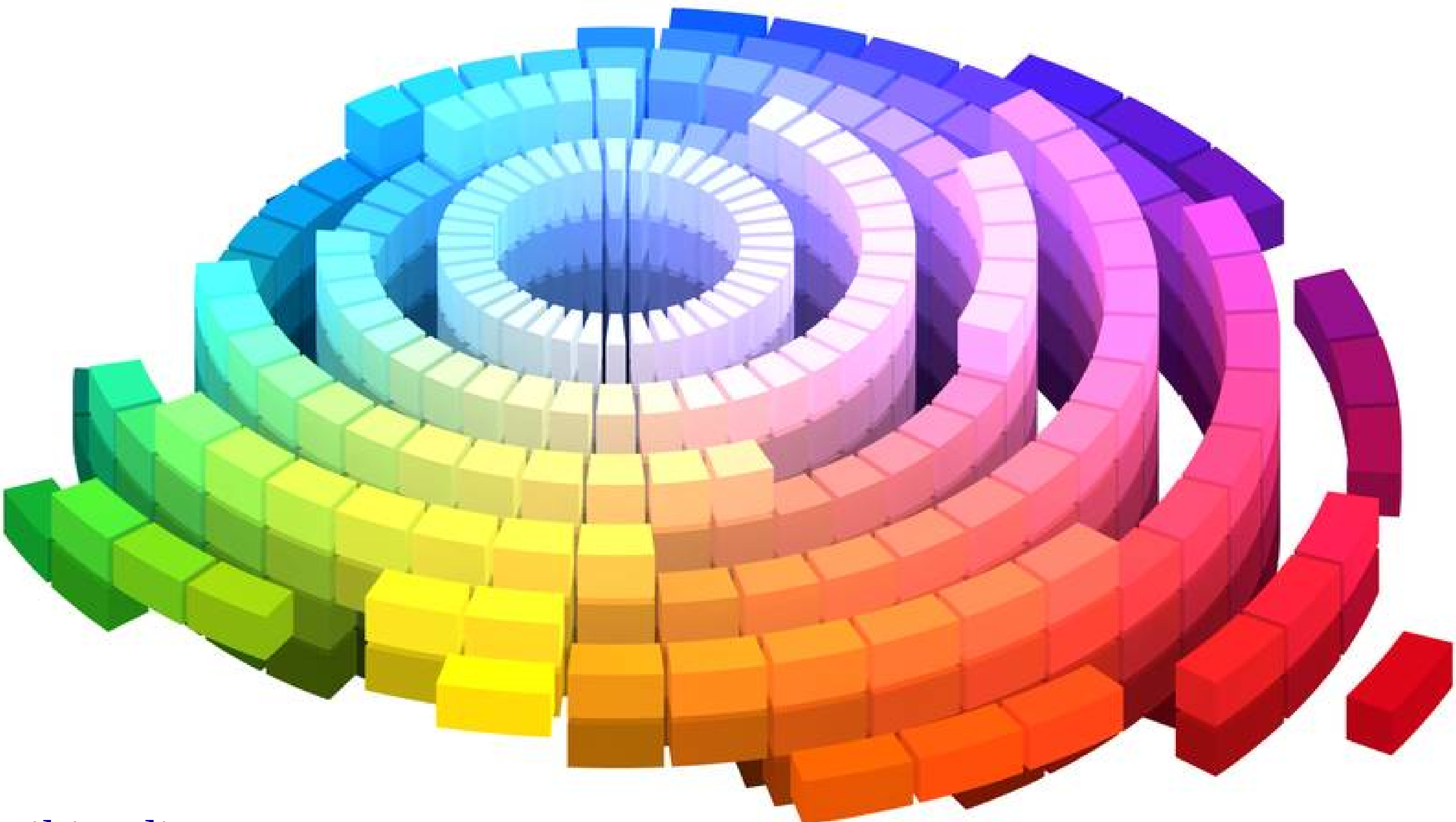
Munsell System

- Albert Henry Munsell in 1905, revised in 1943
- Considered the simplest of all colour systems, adopted by many paint manufacturers
- Three attributes:
  - Hue: five principal and five intermediate positioned hue steps, e.g. Red (5R), Yellow-Red (5YR), Yellow (5Y), Green-Yellow (5GY), ...
  - Value: lightness or darkness: black (0) to white (10)
  - Chroma: divergence from a neutral gray (0)
- Notation: H V/C, e.g. 5G 6/8

Munsell Hues



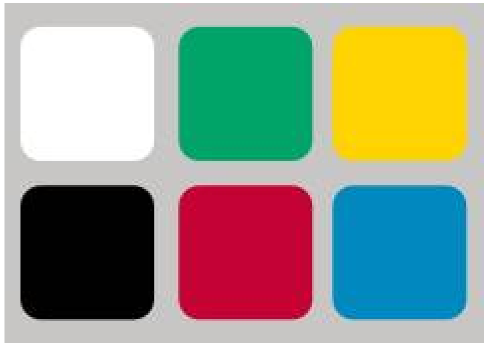
Munsell Solid



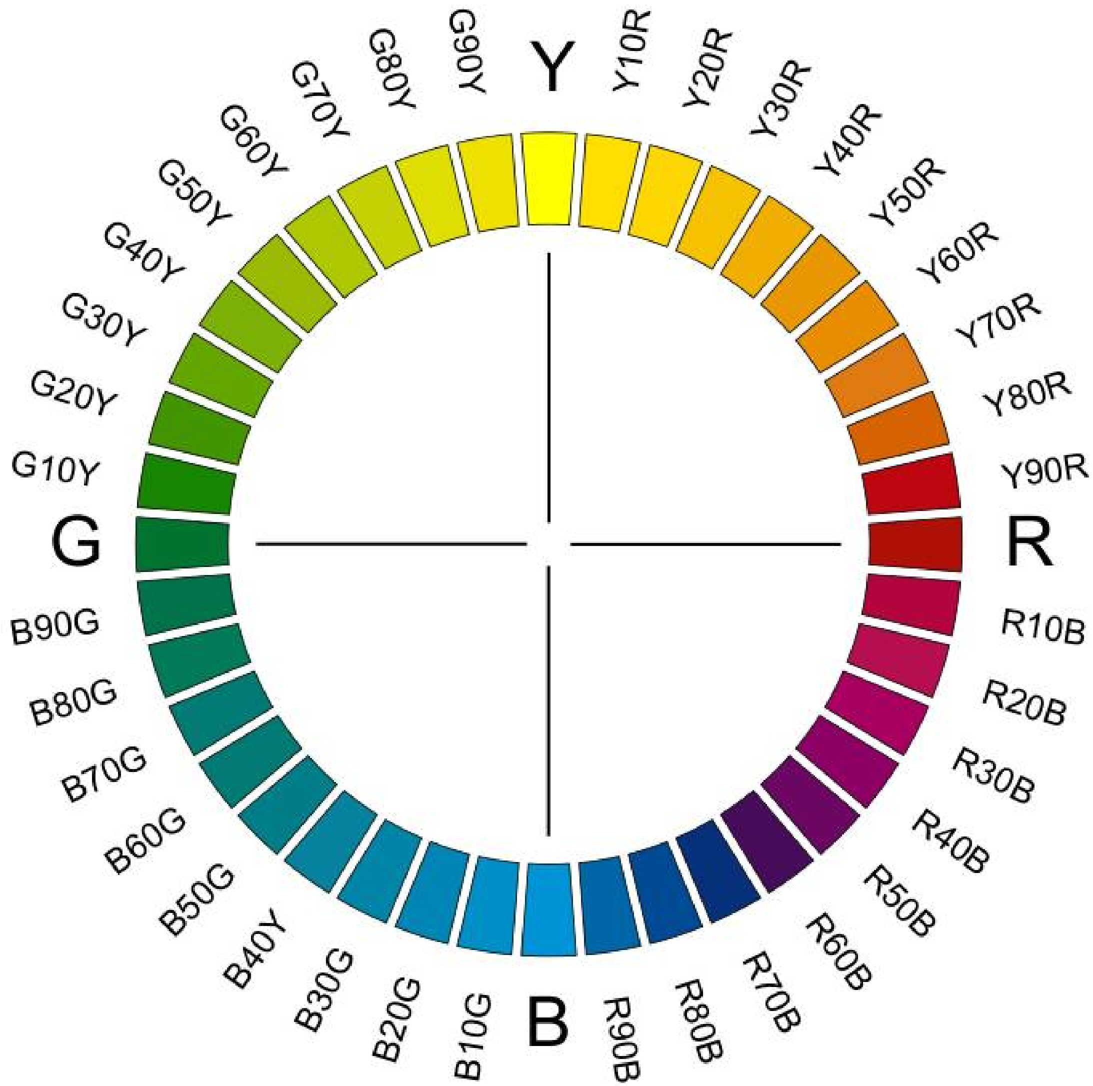
Wikipedia

Natural Colour System

- 1952: colour atlas with 600 colours
- Adoption as the Swedish standard in 1979
- Based on colour opponency: black/white, red/green, blue/yellow
- Specified by
  - Darkness
  - Saturation
  - Hue



NCS Hues


Y
Y10R
Y20R
Y30R
Y40R
Y50R
Y60R
Y70R
Y80R
Y90R
R
R10B
R20B
R30B
R40B
R50B
R60B
R70B
R80B
R90B
B
B10G
B20G
B30G
B40Y
B50G
B60G
B70G
B80G
B90G
G
G10Y
G20Y
G30Y
G40Y
G50Y
G60Y
G70Y
G80Y
G90Y

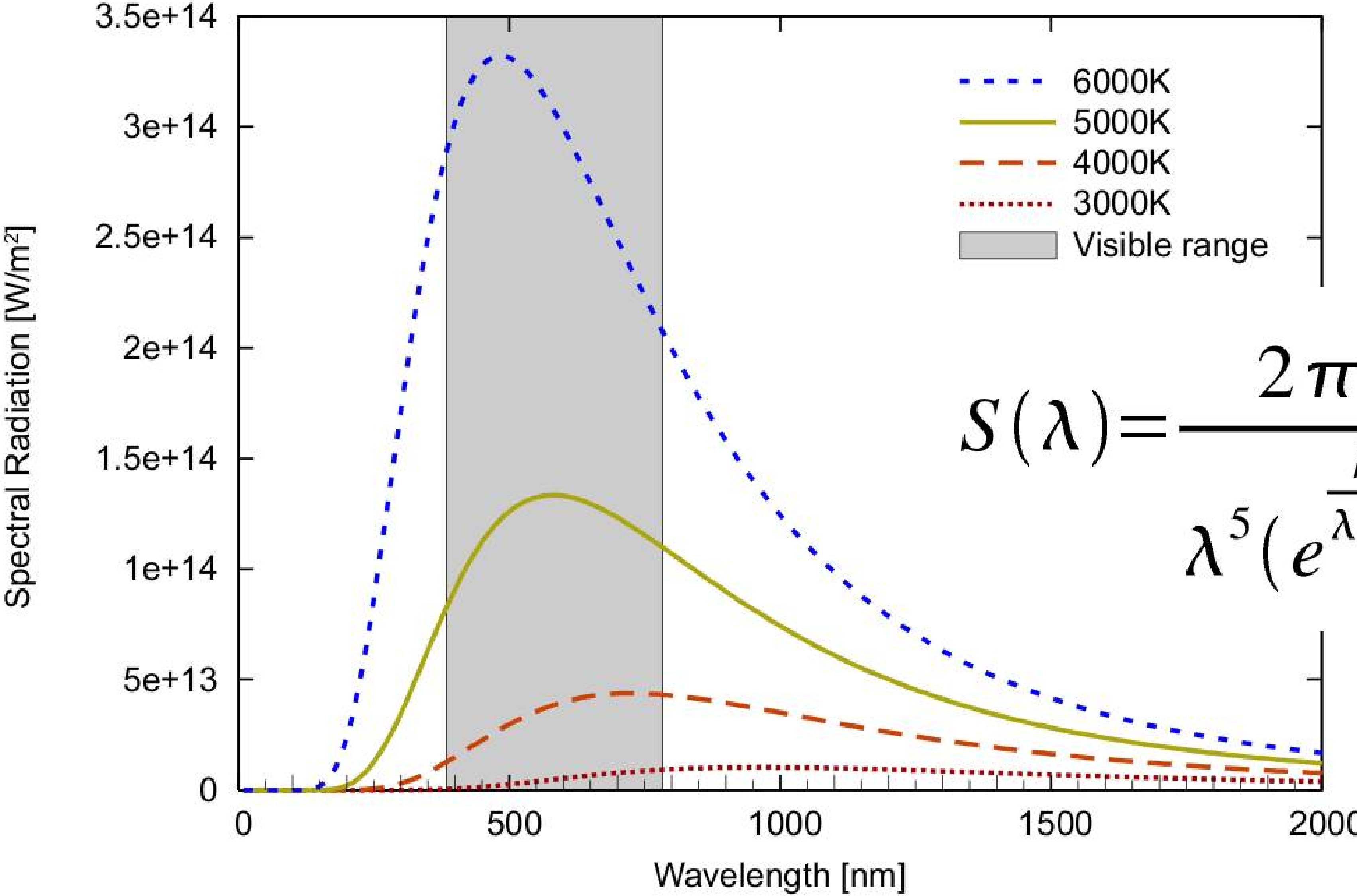
Example: Swedish Flag

- Yellow - NCS 0580-Y10R
(= 5% darkness, 80% saturation, 90% yellow + 10% red = very slightly darkish mostly saturated yellow with a slight orangish tinge)
- Blue - NCS 4055-R95B
(= 40% darkness, 55% saturation, 5% red + 95% blue = somewhat dark rather unsaturated blue with a very slight purplish tinge)

Wikipedia

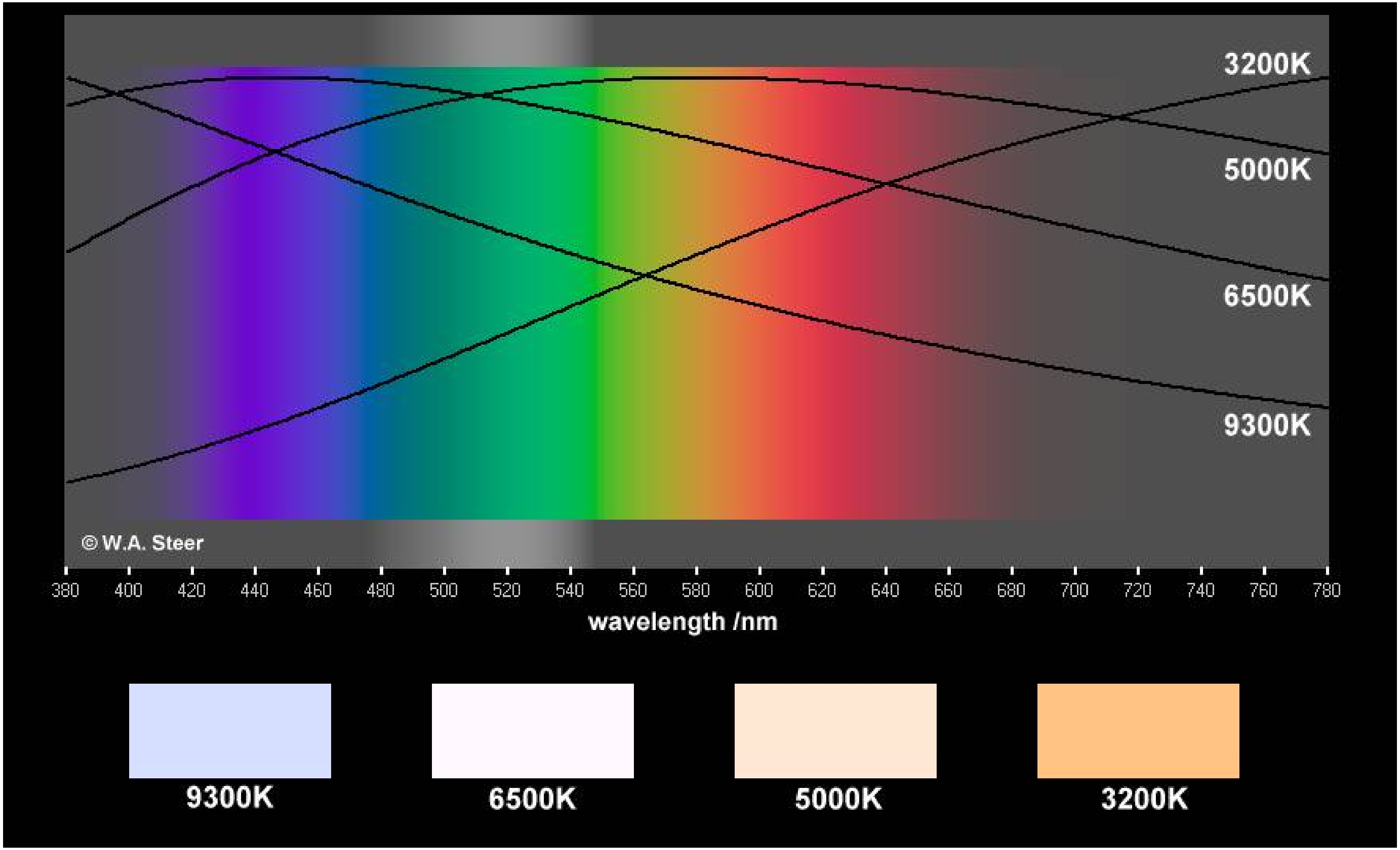
IV Colour Temperature

Blackbody Radiation

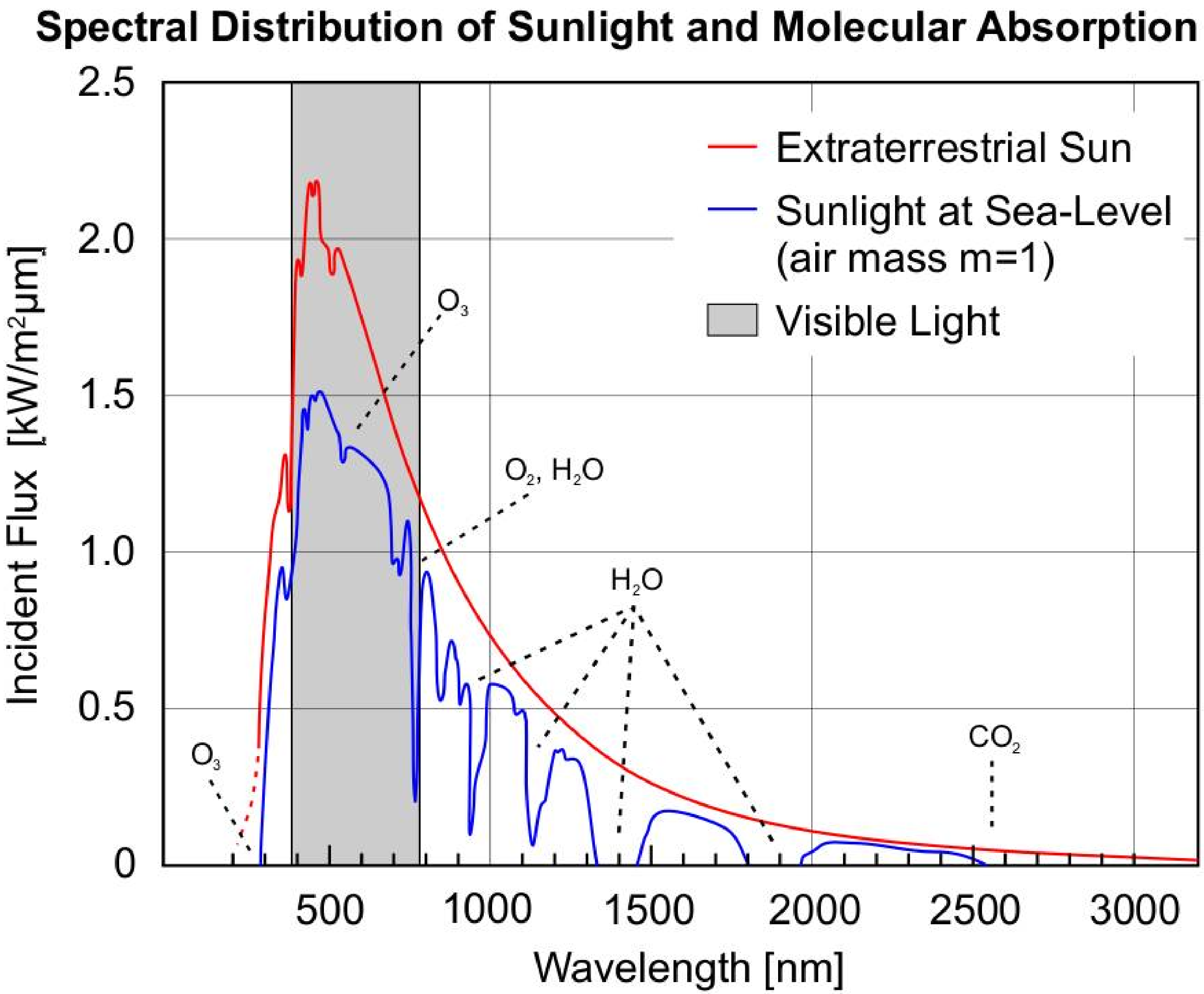


$$S(\lambda) = \frac{2\pi c^2 h}{\lambda^5 \left(e^{\frac{hc}{\lambda k T}} - 1\right)}$$

Blackbody Spectra

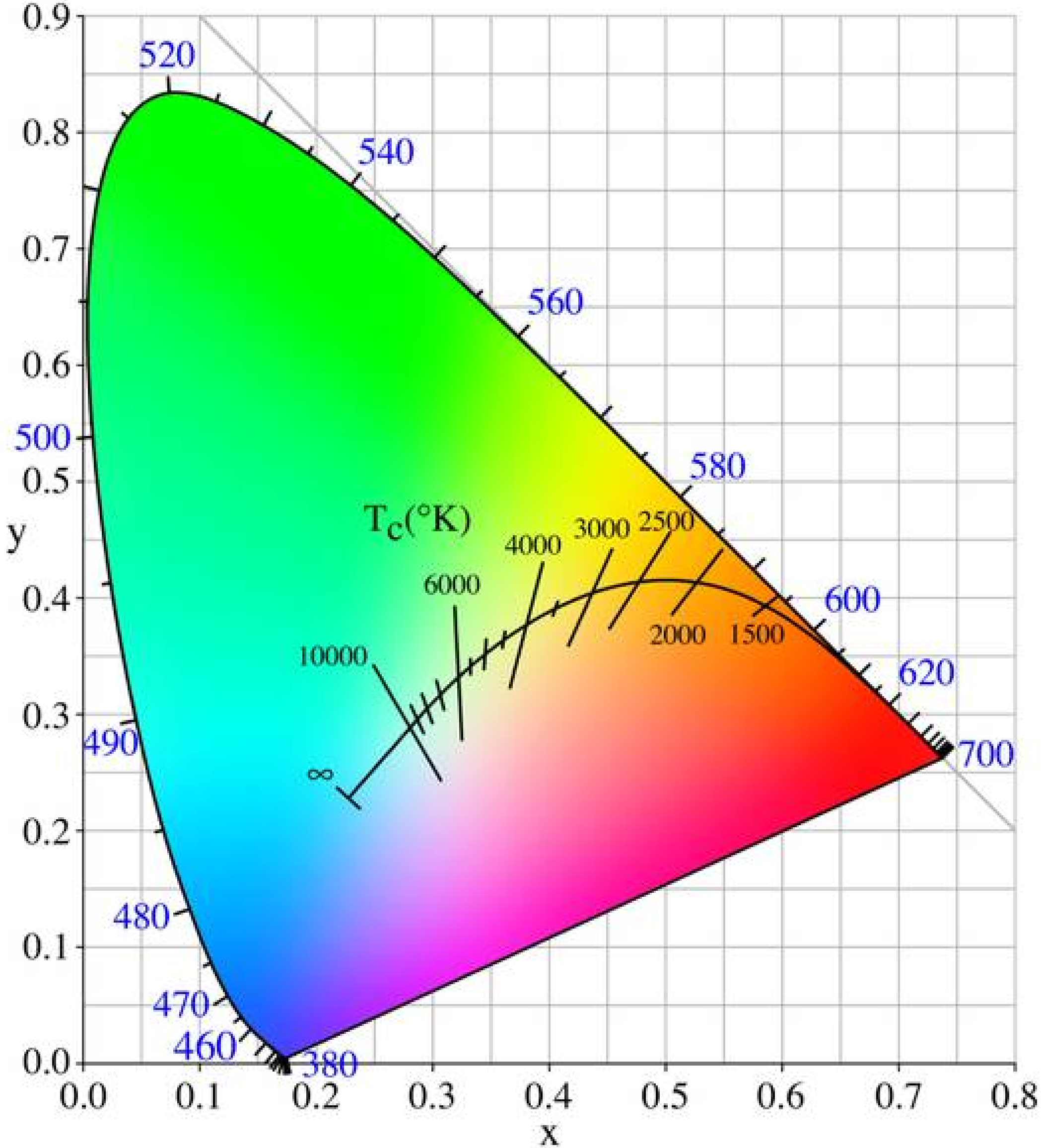


Sun – 6500K

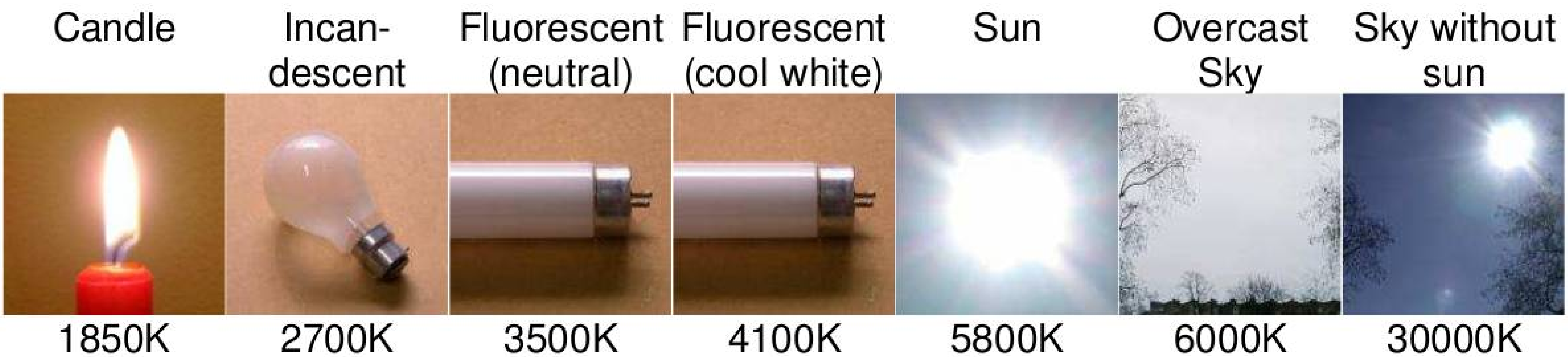


Spectral Distribution of Sunlight and Molecular Absorption
2.5
2.0
1.5
1.0
0.5
0
Incident Flux [kW/m²μm]
Extraterrestrial Sun
Sunlight at Sea-Level
(air mass m=1)
Visible Light
O3
O2, H2O
H2O
CO2
O3
500
1000
1500
2000
2500
3000
Wavelength [nm]

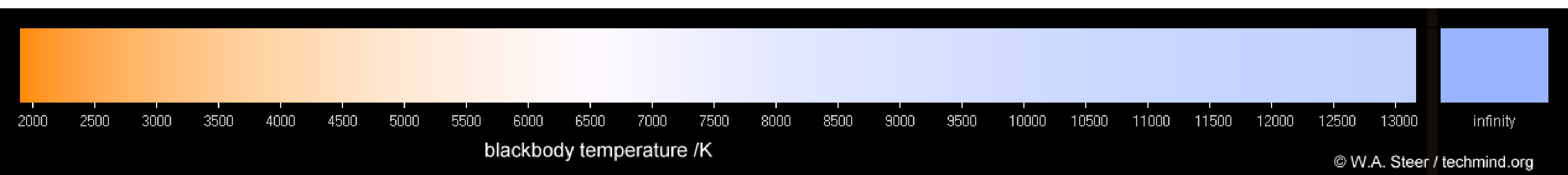
Planckian Locus



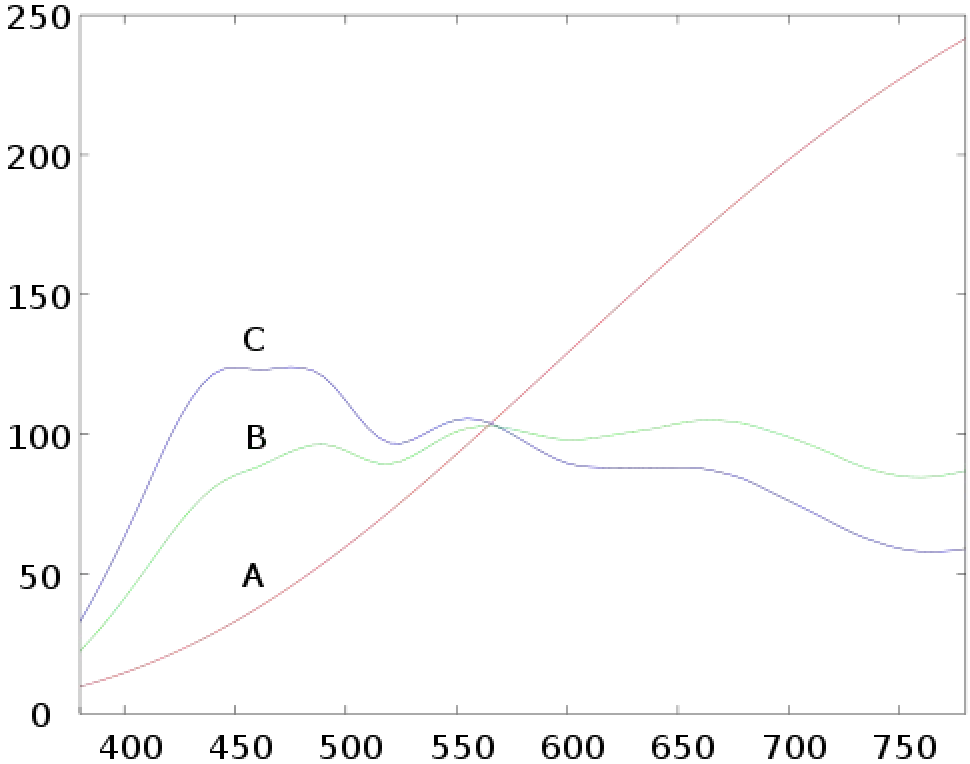
Correlated Colour Temperature



If an emitter is not on the Planckian locus, i.e. it is not a blackbody emitter, we use the Correlated Colour Temperature, CCT



Standard Illuminants



- A, B, C introduced in 1931
- B, C obsolete now
- D series for daylight
  e.g. D65
- E – equal energy
- F – various fluorescents

Source	Corresponding to	CCT	X	Y
A	tungsten-filament lamp	2854K	0.448	0.407
B	noon sunlight	4800K	0.348	0.352
C	daylight	6500K	0.310	0.316

White Points

Name	CIE 1931 2°		CIE 1964 10°		CCT (K)	Hue	Note
	x_2	y_2	x_{10}	y_{10}			
A	0.44757	0.40745	0.45117	0.40594	2856		Incandescent / Tungsten
B	0.34842	0.35161	0.34980	0.35270	4874		{obsolete} Direct sunlight at noon
C	0.31006	0.31616	0.31039	0.31905	6774		{obsolete} Average / North sky Daylight
D50	0.34567	0.35850	0.34773	0.35952	5003		Horizon Light. ICC profile PCS
D55	0.33242	0.34743	0.33411	0.34877	5503		Mid-morning / Mid-afternoon Daylight
D65	0.31271	0.32902	0.31382	0.33100	6504		Noon Daylight: Television, sRGB color space
D75	0.29902	0.31485	0.29968	0.31740	7504		North sky Daylight
E	1/3	1/3	1/3	1/3	5454		Equal energy
F1	0.31310	0.33727	0.31811	0.33559	6430		Daylight Fluorescent
F2	0.37208	0.37529	0.37925	0.36733	4230		Cool White Fluorescent
F3	0.40910	0.39430	0.41761	0.38324	3450		White Fluorescent
F4	0.44018	0.40329	0.44920	0.39074	2940		Warm White Fluorescent
F5	0.31379	0.34531	0.31975	0.34246	6350		Daylight Fluorescent
F6	0.37790	0.38835	0.38660	0.37847	4150		Lite White Fluorescent
F7	0.31292	0.32933	0.31569	0.32960	6500		D65 simulator, Daylight simulator

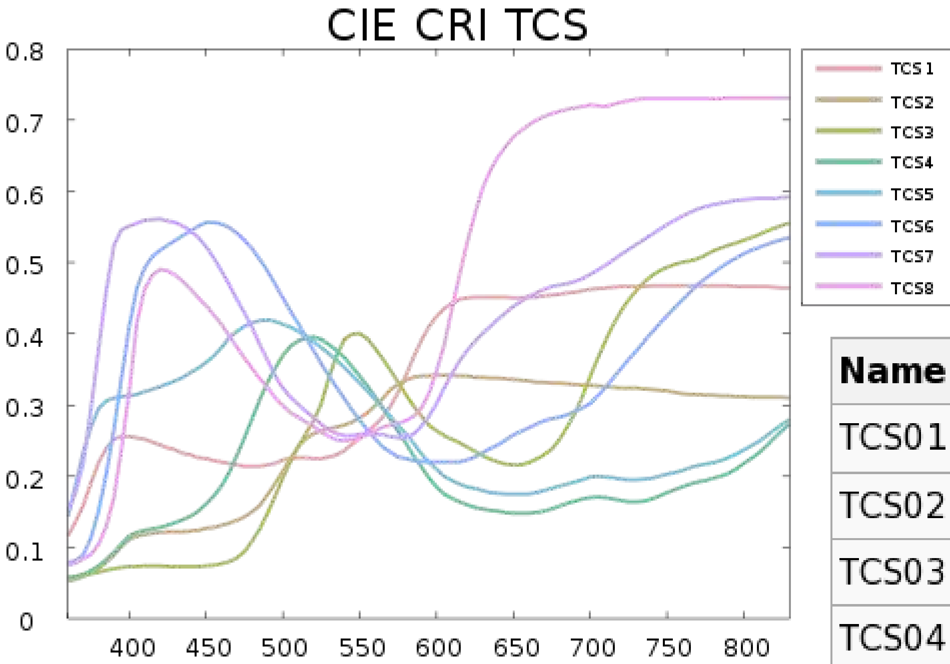
V Colour Rendering

Colour Comparator

Methodology

1. Measure chromaticity of the test source:
   CIE 1960 colour space, 2º standard observer
2. Determine the correlated color temperature CCT
3. Choose blackbody or standard illuminant C (CCT > 5000K) as reference
4. Illuminate samples alternatively with both sources
5. Measure chromaticity of reflected light:
   CIE 1964 space, 2º observer
6. Apply von Kries transform for chromatic adaptation
7. Calculate colour difference for each sample ΔE_i
8. Calculate individual CRI: $R_i = 100 - 4.6\ \Delta E_i$
9. General CRI (R_a) is the arithmetic mean of the special CRIs R_i

Test Colour Samples

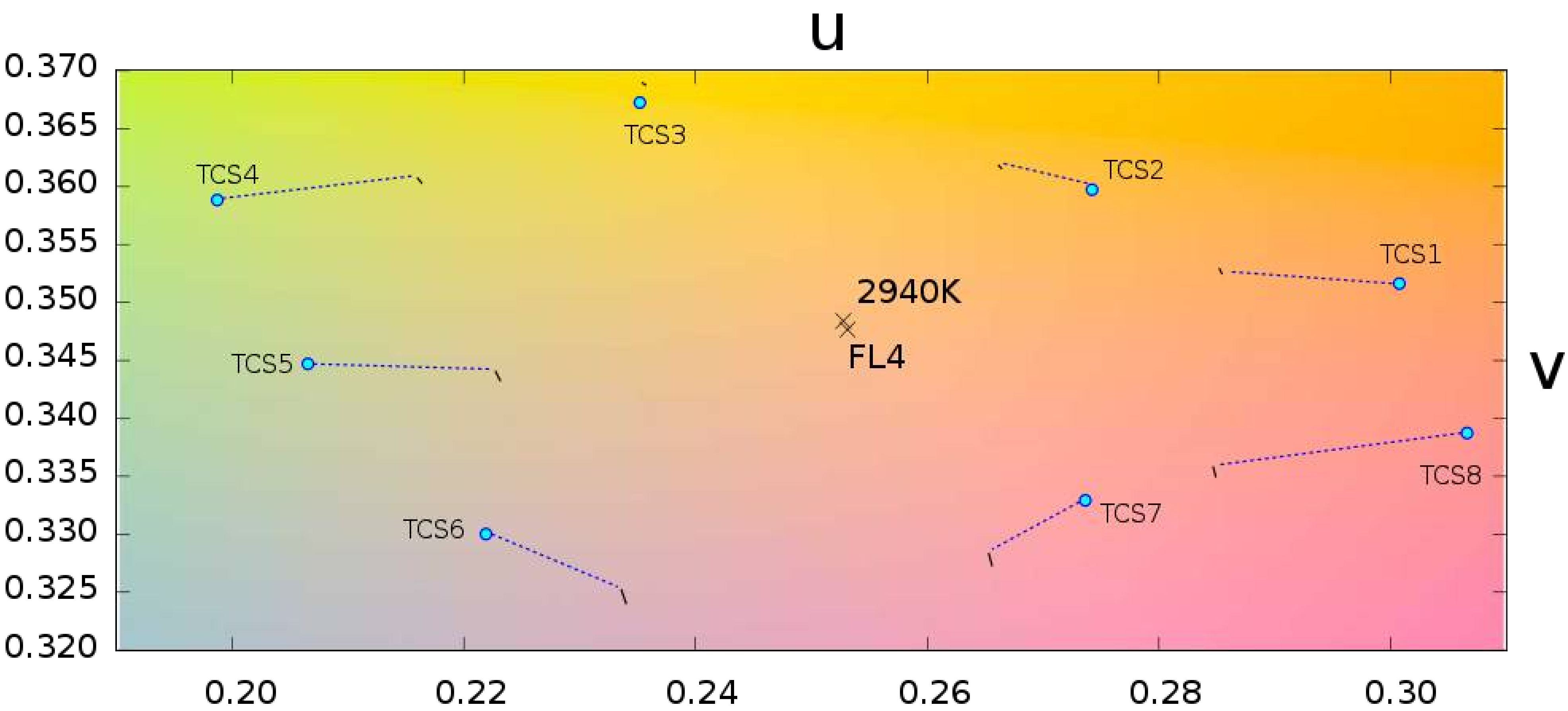


TCS01 to TCS08 for general colour rendering index Ra

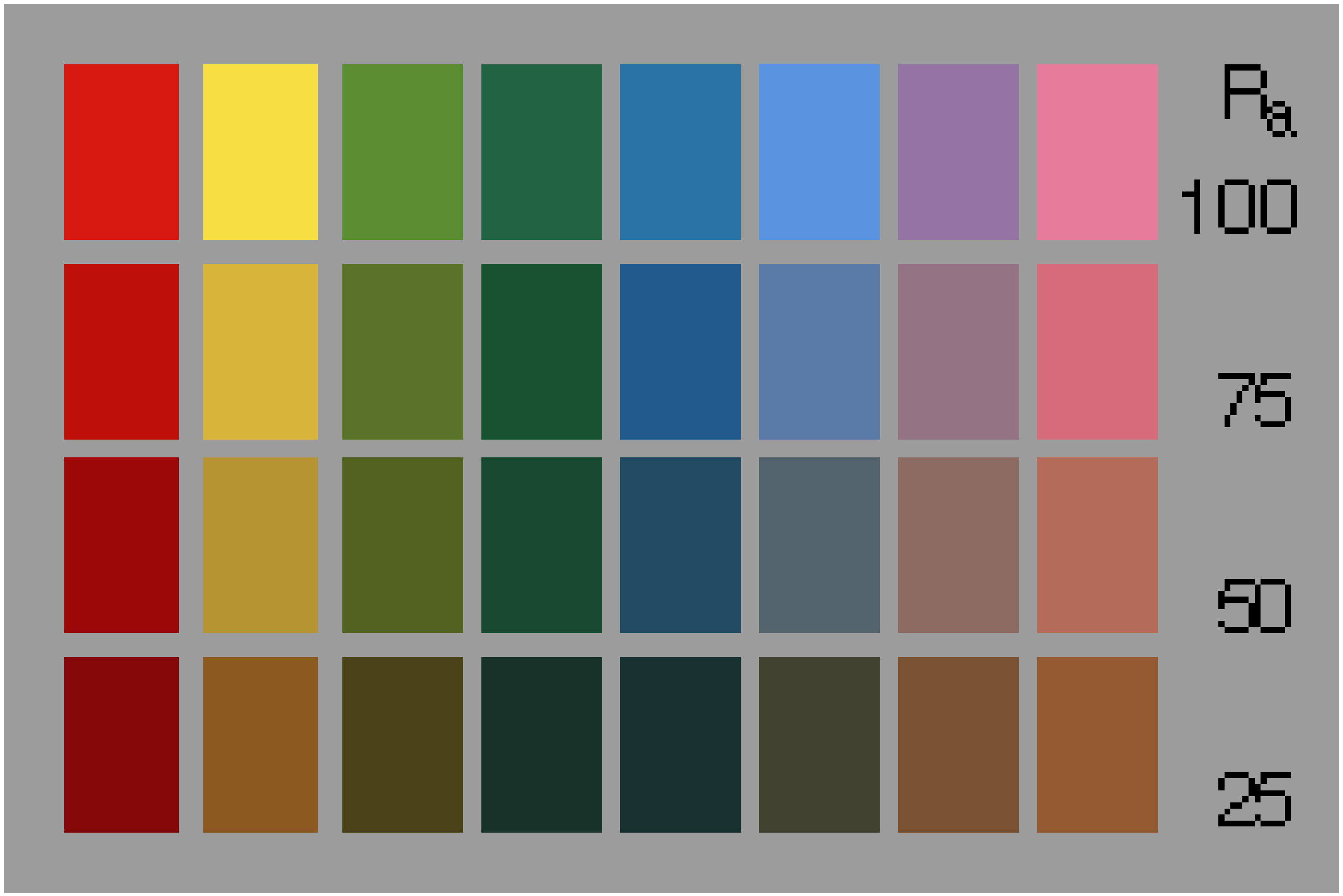
TCS09 to TCS14 for supplementary information on the colour rendering properties of the light source

Name	Appr. Munsell	Appearance under daylight	Swatch
TCS01	7,5 R 6/4	Light greyish red	
TCS02	5 Y 6/4	Dark greyish yellow	
TCS03	5 GY 6/8	Strong yellow green	
TCS04	2,5 G 6/6	Moderate yellowish green	
TCS05	10 BG 6/4	Light bluish green	
TCS06	5 PB 6/8	Light blue	
TCS07	2,5 P 6/8	Light violet	
TCS08	10 P 6/8	Light reddish purple	
TCS09	4,5 R 4/13	Strong red	
TCS10	5 Y 8/10	Strong yellow	
TCS11	4,5 G 5/8	Strong green	
TCS12	3 PB 3/11	Strong blue	
TCS13	5 YR 8/4	Light yellowish pink	
TCS14	5 GY 4/4	Moderate olive green (leaf)	

Colour Difference

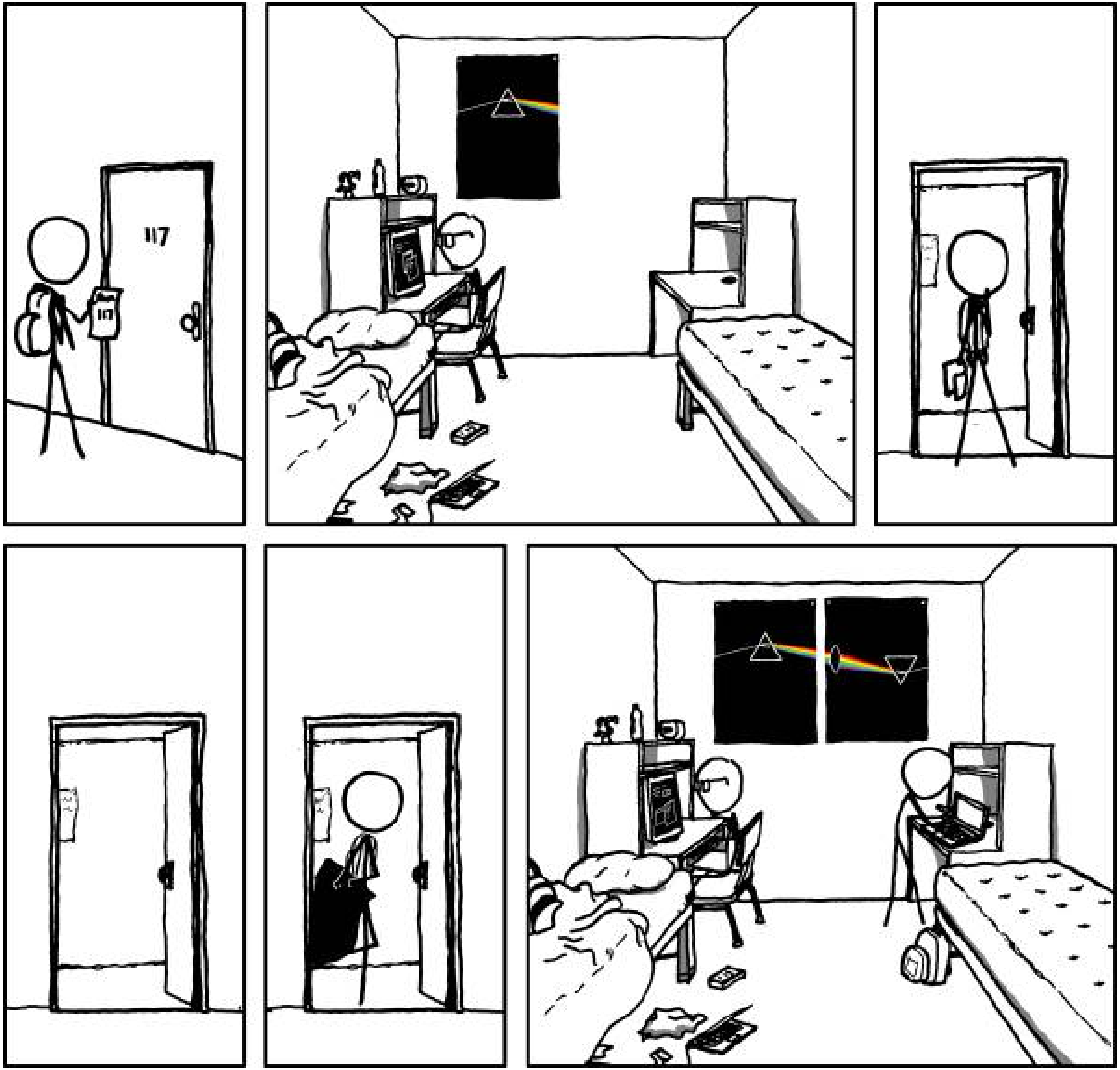


Colour Rendering Index



Resources

- Wikipedia (start with Colour)
- Minolta: Precise Color Communication
- Bruce Lindbloom
- EasyRGB
- Radiance Colour Picker on JALOXA
- R. W. G. Hunt: *Measuring Colour*, Fountain Press Ltd, 3rd edition, 2001



xkcd