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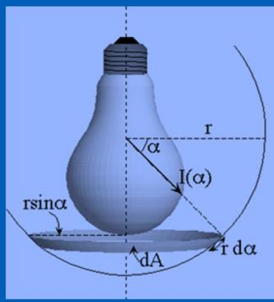
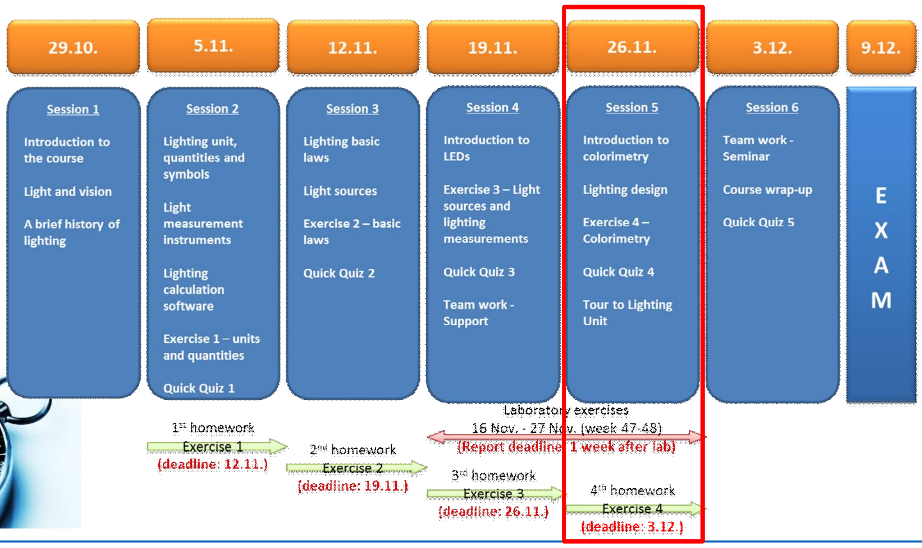


ELEC-E8700 Principles and fundamentals of lighting

Session 5

26.11.2015

Course timeline and deadlines



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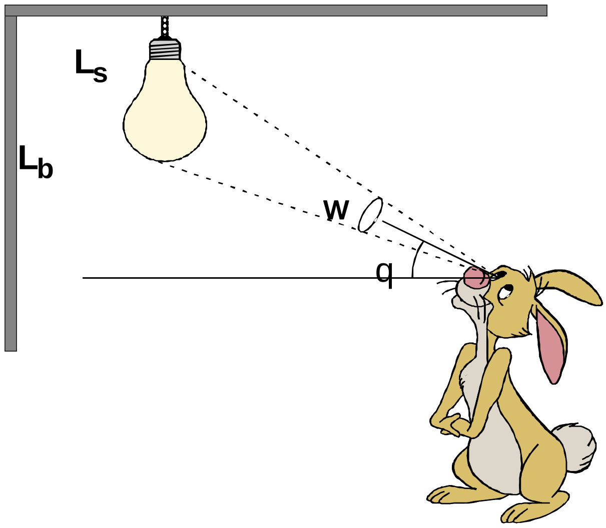
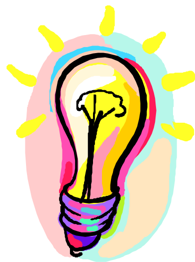
Contact session 5
Outline

- **Introduction to colorimetry**
- **Lighting design aspects**
- **Lighting calculation software**
- **Exercise 4 – colorimetry**
- **Quick quiz 4**
- **Short tour to Lighting Unit**



Contact session 5
Learning outcomes



At the end of this session, you should be able to:

- Relate light, vision and colour perception
- Define colorimetry
- Define colour rendering index
- Define colour and correlated colour temperature
- Apply the fundamental rules of colorimetry
- Analyse and differentiate the basic technical aspects lighting design of interior spaces

Introduction to colorimetry

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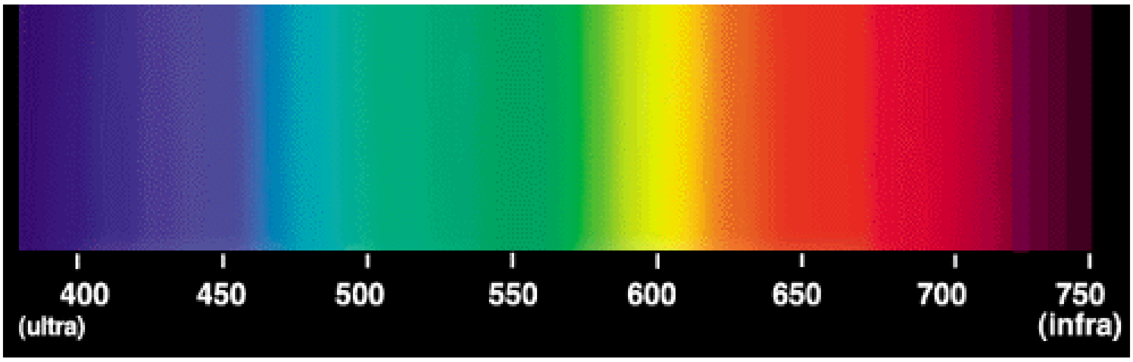
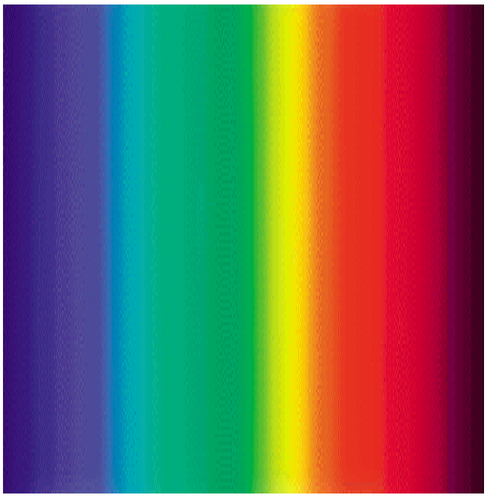
Light as part of the EM spectrum
On colours

The human eye perceive visible light of each wavelength as a specific colours.

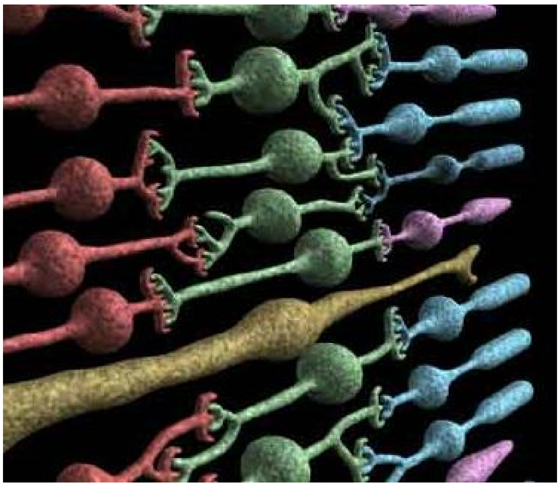


Light as part of the EM spectrum
On colours

380 nm	**- violet -**	**420 nm**
420 nm	**- indigo -**	**450 nm**
450 nm	**- blue -**	**495 nm**
495 nm	**- green -**	**566 nm**
566 nm	**- yellow -**	**589 nm**
589 nm	**- orange -**	**627 nm**
627 nm	**- red -**	**780 nm**



Light, colour and human eye
Cone receptors



Only the cones distinguish colours.

- There are 4 500 000 cones in average on the retina.
- They are less sensitive to light than rods.
- They are arranged mostly in fovea and macula.
- They contribute to vision in well lit environment – photopic vision.

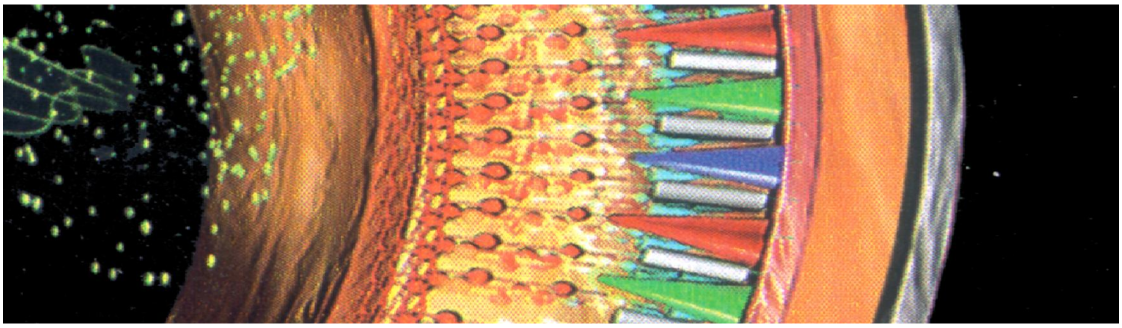
Light, colour and human eye
Cone receptor cells

Humans normally have three kinds of cones.

L-cones - respond most to long wavelengths, peaking in the yellow region.

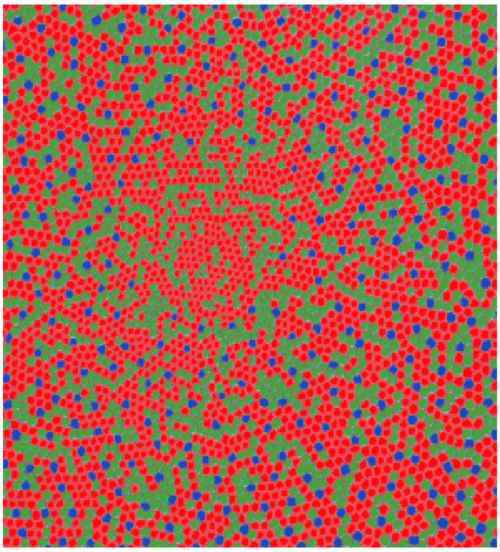
M-cones - respond most to medium-wavelength, peaking at green.

S-cones - respond most to short-wavelength light of a violet colour.



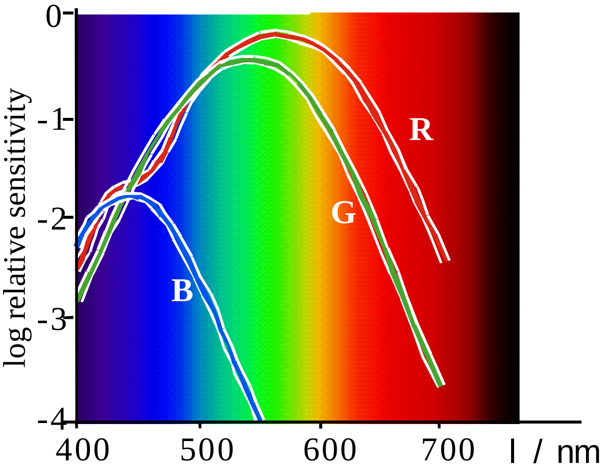
Light, colour and human eye
Cone receptor cells

- The number of individual types of cones in the retina is different.
- There is only 7 % of "blue" cones in the central part of the retina (i.e. fovea) and "green" and "red" are in the ratio 1:1,5.
- There is no "blue" cones right in the middle and there is only 1 % of them on the whole retina.



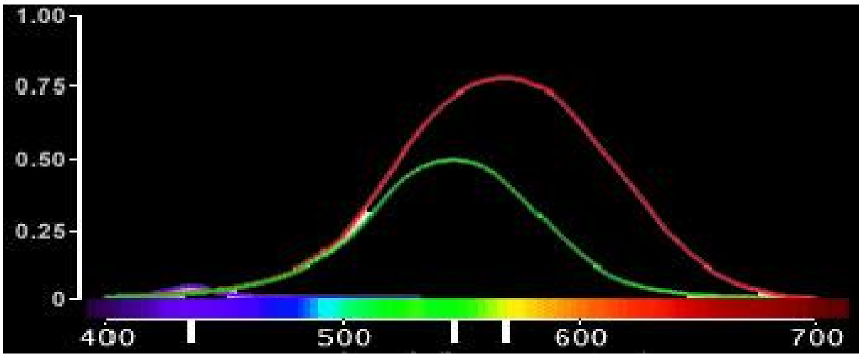
Light, colour and human eye
Cone receptor cells

- The sensitivity curves of different cones (have not yet been standardised!).
- Three kinds of cone receptors
  - *S (B – "blue"): sensitive to short wavelengths*
  - *M (G – "green"): sensitive to medium wavelengths*
  - *L (R – "red"): sensitive to long wavelengths*

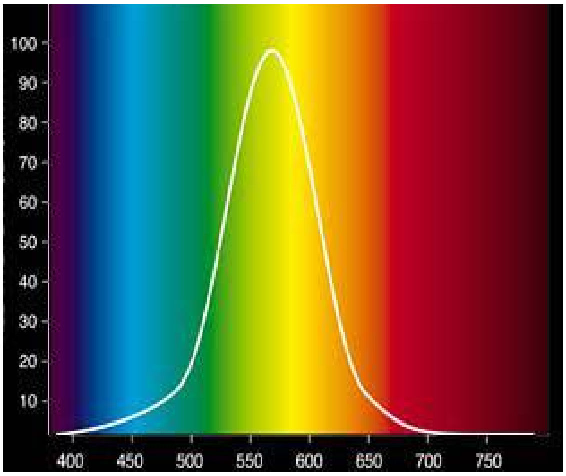


Light, colour and human eye
Cone receptor cells

Response of different kinds of cones are different having peeks at around 420 nm, 534 nm and 564 nm.



Light, colour and human eye
Cone receptor cells



All three together give us a spectral sensitivity of the eye V(λ) with peek at 555 nm.

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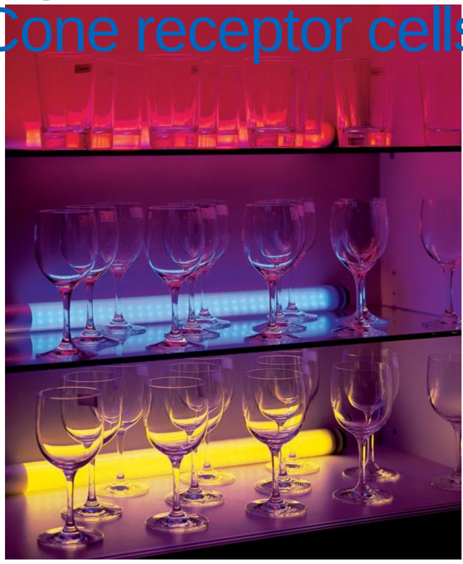
Light, colour and human eye
Cone receptor cells



That is why we see better when light is yellow than when it is red or blue and why we cannot see if light is in the IR or UV range.

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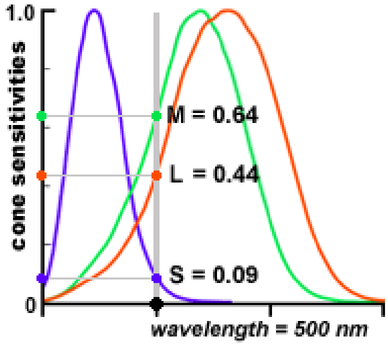
Light, colour and human eye
Cone receptor cells

The perceived colour depends on response of the different type of cones.



On light with 500 nm

- "blue" cones response with 0,09
- "green" cones response with 0,64
- "red" cones response with 0,44

The light would be perceived as green.

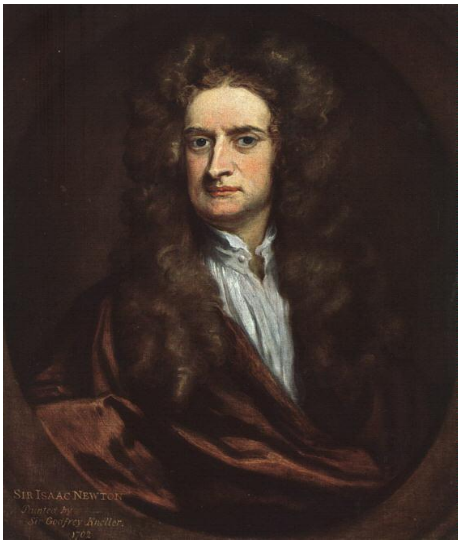
Light, colour and human eye
Cone receptor cells

But perceived colour depends also on each individual and his/hers nervous system.

Modern Science of Colorimetry

Sir Isaac Newton (1642-1727)

- Light consists of particles.
- White light results from mixing the seven primary colours.
- The human eye cannot perceive the components of mixed light.
- Two colours with different spec-tral composition may appear to be identical.
- Seven primaries: red, orange, yellow, green, blue, indigo and violet



Modern Science of Colorimetry
The trichromatic theory

Prof. Christian Ernst Wünsch (1744-1828)

- Newton’s seven primary colours are combinations of the three others. (1722)

Thomas Young (1773-1829)

- Wave theory of light
- Three type of receptors on the retina (1801)
- Primaries: red, green and violet

Portrait of Thomas Young

Modern Science of Colorimetry
The trichromatic theory

James Clerk Maxwell (1831–1879)

- Foundation for practical colour photography
- Demonstrated in 1861 during an Royal Institution lecture on colour theory
- Principle of three-colour analysis and synthesis
- von Helmholtz developed equations for colour mixing with James Clerk Maxwell

Engraving of James Clerk Maxwell by G. J. Stodart from a photograph by Fergus of Greenock

Modern Science of Colorimetry
The trichromatic theory

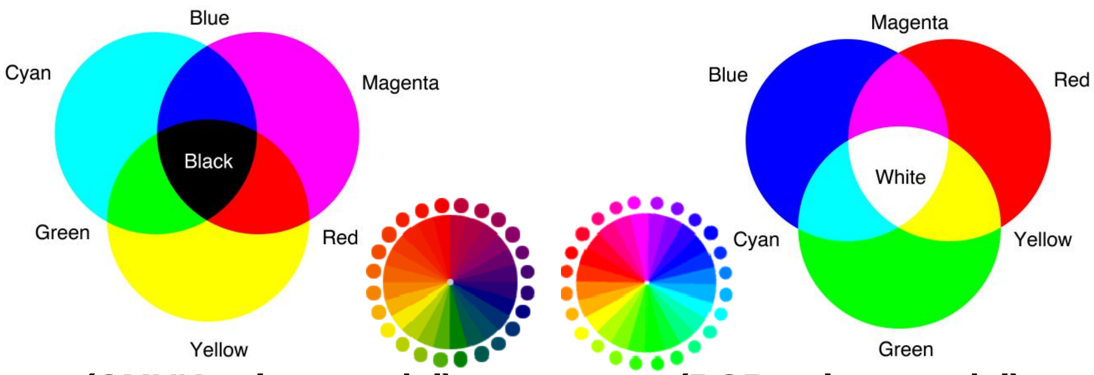
Fundamental rules Formulated by Professor H. Grassman in 1854

- Colour is independent of luminance in a wide region.
- Colour components cannot be perceived by the human eye.
- Colour matches obey the law of addition.
- Colour matches obey the law of subtraction.
- Colour matches obey the law of transition.
- Any colour can be produced by mixing three lights provided that none of the three is a combination of the other two.
- A colour match can be stated in equation form as $C = R(R) + G(G) + B(B)$

Colour mixing

One of the fundamental aspects of colorimetry is colour mixing and matching.

Subtractive colour mixing | **Additive colour mixing**



(CMYK colour model) | **(RGB colour model)**

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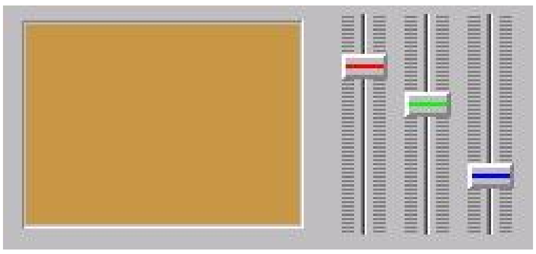
How to describe colour?

Colour can be described using combination of three primary colours.



Primary colours should be selected so that the third can not be obtained by mixing two of them.

Typically, the selected three colours are red, green and blue to which the cones in human eye are sensitive.

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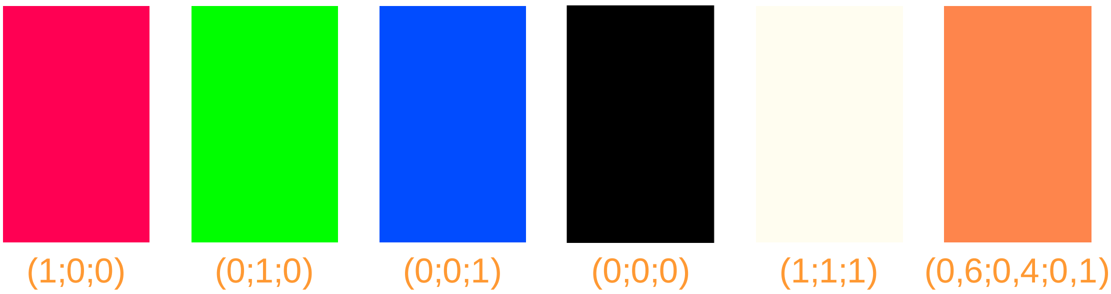
How to describe colour?

Colours can so be represented by a combination of three numbers (R;G;B)



How to describe colour?

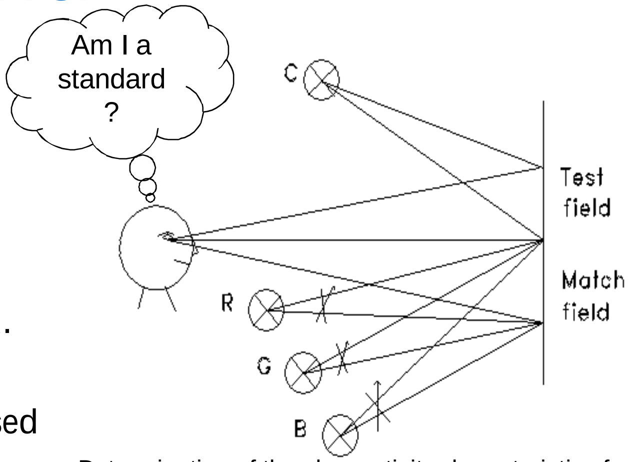
This principle is used in CIE XYZ colour system where physical tristimulus values (shares) of the primary colours are denoted with *R* for red (R), *G* for green (G) and *B* for blue (B) (i.e. three imaginary primary colours).

$$C = R(\mathrm{R}) + G(\mathrm{G}) + B(\mathrm{B})$$

The coefficients *R*, *G*, and *B* are called tristimulus values.

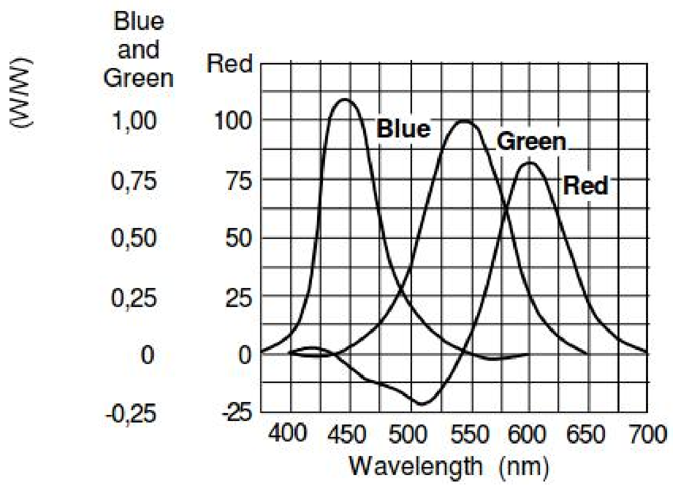
Early Mathematical Formulations
The standard observer

- W.D. Wright, J. Guild and D. Judd made a series of colour matching tests in the early 1920's.
- Based on their results, a standard observer was defined.
- The CIE 1931 model was based on these results.



Determination of the chromaticity characteristic of the standard observer

Early Mathematical Formulations
CIE primaries



The CIE 1931 XYZ System

CIE introduced in 1931 a new system with non-physical reference stimuli X, Y and Z. The following criteria were used:

- The tristimulus values of each real colour are positive.
- Only one value (Y) is used to describe luminance.
- If one unit of each reference stimulus is mixed, one unit of equi-energy white results.

The CIE 1931 XYZ system

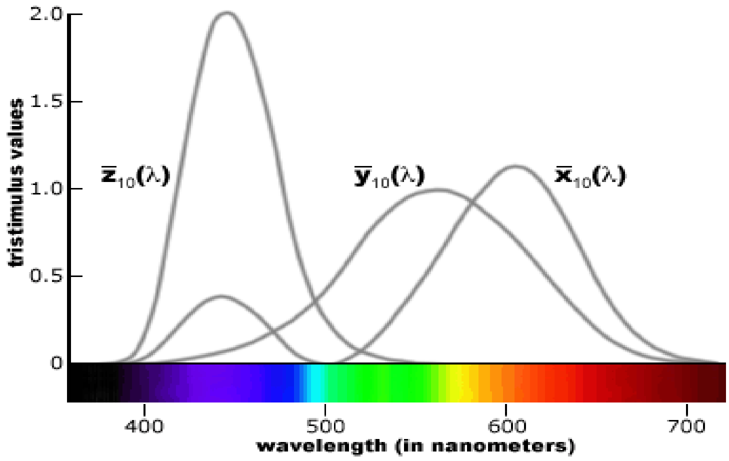
X, Y and Z can be calculated from the R, G and B values by linear transformation:

$$X = 2{,}7690\, R + 1{,}7518\, G + 1{,}1300\, B$$

$$Y = 1{,}0000\, R + 4{,}5907\, G + 0{,}0601\, B$$

$$Z = 0{,}0000\, R + 0{,}0565\, G + 5{,}5943\, B$$

The CIE 1931 XYZ system
The colour matching functions



The CIE 1931 XYZ system
The tri-stimulus values

$$X = \int \Phi_e(\lambda) \cdot \bar{x}(\lambda)\, d\lambda$$
$$Y = \int \Phi_e(\lambda) \times \bar{y}(\lambda)\, d\lambda$$
$$Z = \int \Phi_e(\lambda) \times \bar{z}(\lambda)\, d\lambda$$

where,

$\Phi_e(\lambda)$ = spectral density of radiant flux

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ = colour matching functions

The CIE 1931 XYZ system
The chromaticity co-ordinates

Chromaticity co-ordinates are calculated from the tri-stimulus values:

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

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

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

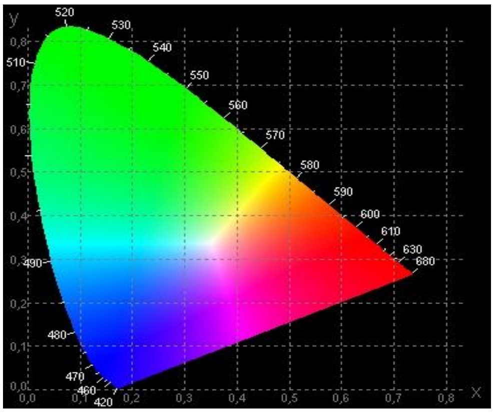
$$x + y + z = 1$$

The CIE 1931 XYZ system

Wavelength	Colour matching coefficients			Chromaticity co-ordinates	
nm	$\bar{x}$	$\bar{y}$	$\bar{z}$	x	y
570	0,7621	0,9520	0,0021	0,4441	0,5547
580	0,9163	0,8700	0,0017	0,5125	0,4866
590	1,0263	0,7570	0,0011	0,5752	0,4242
600	1,0622	0,6310	0,0008	0,6270	0,3725
610	1,0026	0,5030	0,0003	0,6658	0,3340
620	0,8544	0,3810	0,0002	0,6915	0,3083
630	0,6424	0,2650	0,0000	0,7079	0,2920
640	0,4479	0,1750	0,0000	0,7190	0,2809
650	0,2835	0,1070	0,0000	0,7260	0,2740
660	0,1649	0,0610	0,0000	0,7300	0,2700
670	0,0874	0,0320	0,0000	0,7320	0,2680
680	0,0468	0,0170	0,0000	0,7334	0,2666
690	0,0227	0,0082	0,0000	0,7344	0,2656
700	0,0114	0,0041	0,0000	0,7347	0,2653
710	0,0058	0,0021	0,0000	0,7347	0,2653
720	0,0029	0,0010	0,0000	0,7347	0,2653
730	0,0014	0,0005	0,0000	0,7347	0,2653
740	0,0007	0,0003	0,0000	0,7347	0,2653
750	0,0003	0,0001	0,0000	0,7347	0,2653

The CIE 1931 XYZ system
Chromaticity diagram

ideal green



ideal blue

ideal red

The CIE colour space chromaticity diagram uses coordinates x and y.

It is part of the CIE xyY colour space where Y parameter is (also) a measure of the brightness or luminance of the colour.

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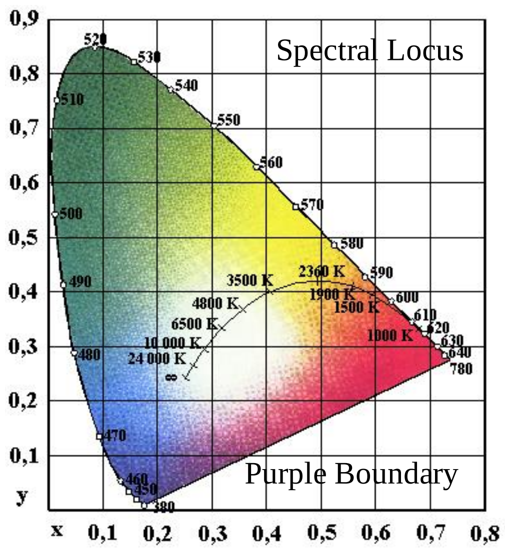
The CIE 1931 XYZ system
Chromaticity diagram

- Every real colour is within the area defined by spectral locus and the purple boundary.
- Spectral colours are on the locus(edge).
- R, G and B are on the spectral locus.
- Pure spectral colour cannot be achieved by mixing primary colours
- X, Y and Z are not within the spectral locus.



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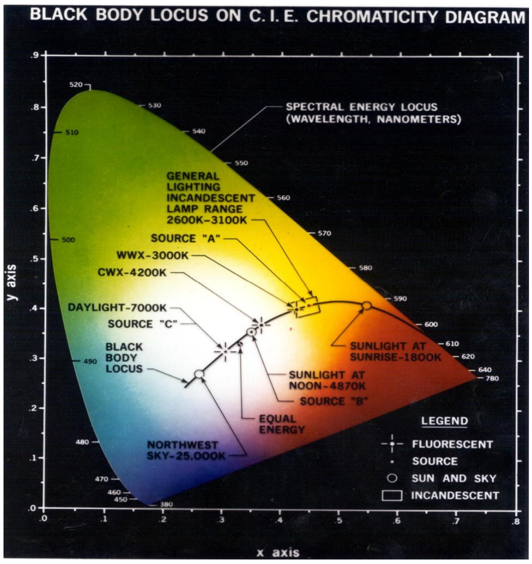
Colour Temperature

- The colour appearance of light sources is expressed by the colour of black-body radiator with the same colour coordinates described as Colour Temperature.
- For light sources that have chromaticity coordinates close to Planckian locus but not on it , their color appearance is quantified as Correlated Colour Temperature (CCT).
- Unit: Kelvin (K)



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Correlated Colour Temperature

- If the colour of a light source is not on the blackbody locus but close to it, the colour can be described by using correlated colour temperature.
- Correlated colour temperature is the temperature of a blackbody radiator that produces colour as similar to the sample as possible.
- To determine the correlated colour temperature, iso-temperature lines that cross the blackbody locus are used.

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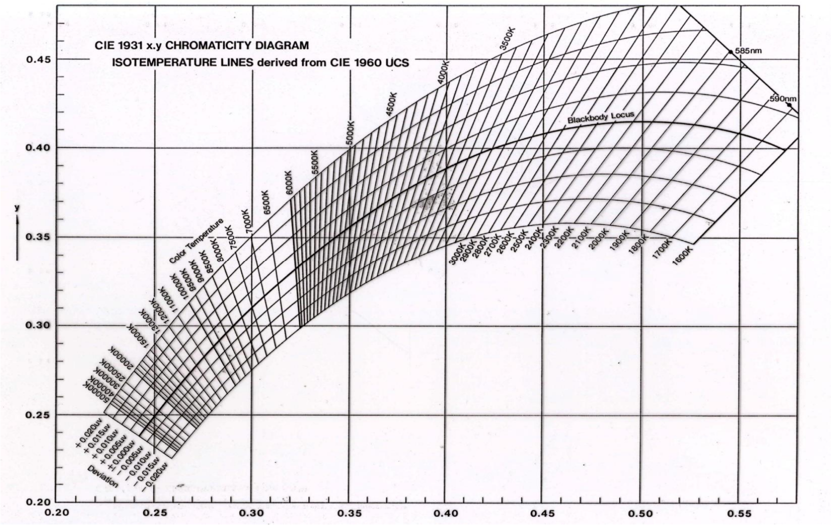
Correlated Colour Temperature



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Colour temperature

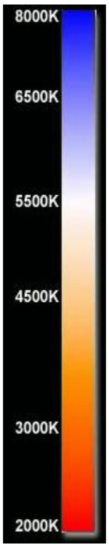
snow, water, blue sky

daylight, overcast sky

daylight at noon

average daylight (north. hemisf.)

moonlight
daylight at sunrise or sunset



“daylight” fluorescent lamp
xenon flashtube

“blue bulb” flashtube

“natural white” fluorescent lamp

studio lights
“warm white” fluorescent lamp
inscandescent bulb:
150-200W
40-60W
25 W

candle

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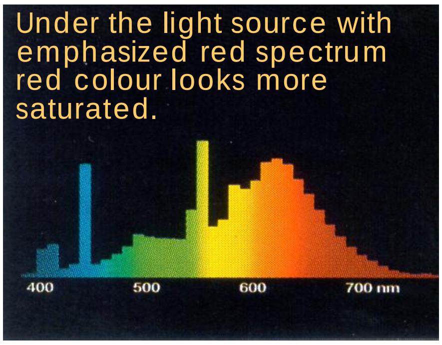
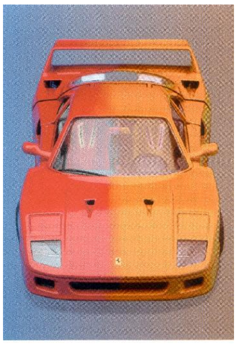
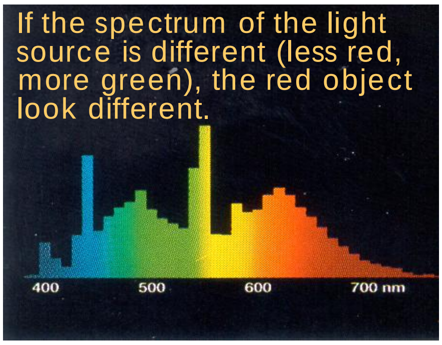
Colour Rendering Index

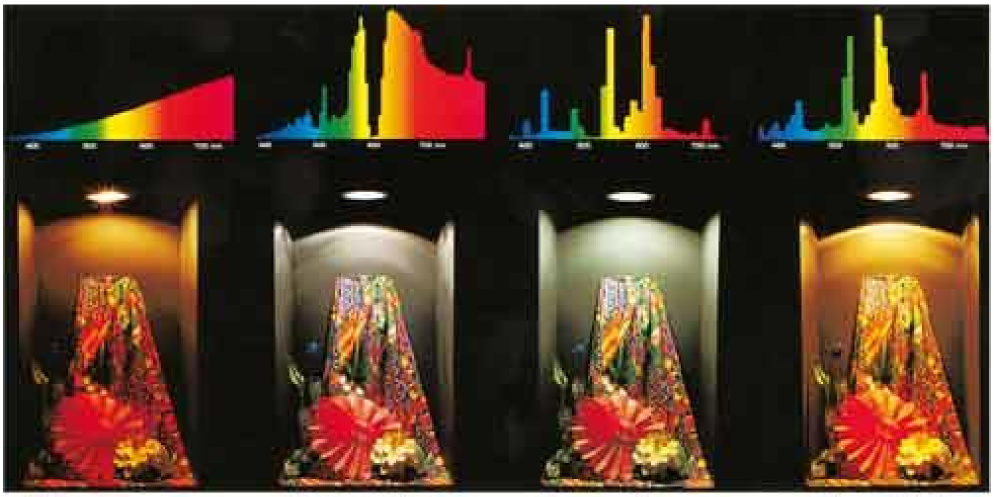
The perception of the (objects') colour depends also on the spectrum of the light source.







Colour Rendering Index

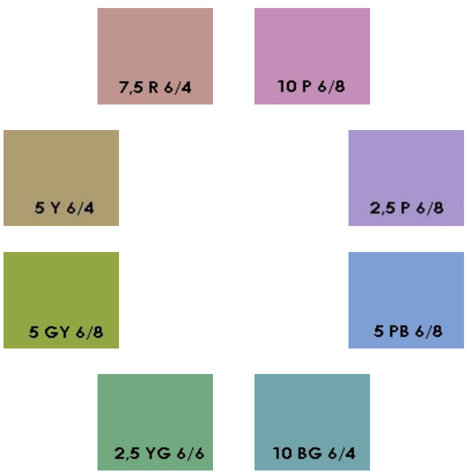


Colour Rendering Index

CIE Color Rendering Index (CRI) is a quantitative measure of the ability of a light source to render the colours of various objects in comparison with an reference source.

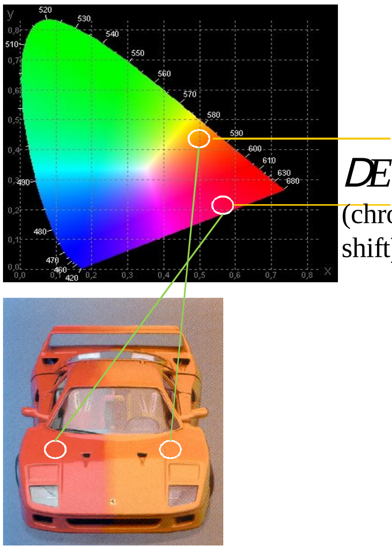
CIE CRI is defined by CIE Publication 13.3, first published in 1965.

Colour Rendering Index



- To determine the Ra values of light sources, eight defined test colours commonly found in the environment are illuminated under the reference light source (Ra = 100) and then under the source being evaluated.
- The greater the difference in the appearance of the test colours rendered, the poorer the colour rendering properties of the light source under examination.

Colour Rendering Index



- The reference light source has the same CCT as the test source.
  - *Up to 5000 K a black-body radiant source is used.*
  - *For higher CCT a D source (daylight) is used.*
- Special colour rendering index

$$Ri = 100 - 4.6\Delta Ei$$

- General colour rendering index

$$Ra = \frac{1}{8}\sum_{i=1}^{8} Ri$$

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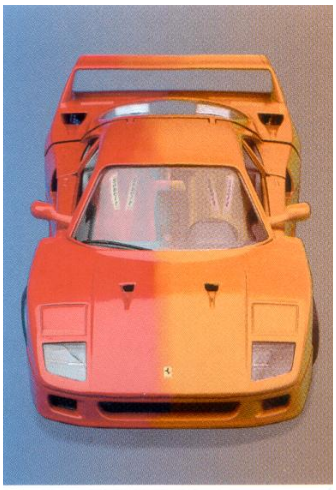
Colour Rendering Index
Metamerism

- Light source metamerism
  - *Same chromaticity*
  - *Different spectral power distribution*
  - *Different colour rendering properties*
  - *Normally such an extreme degree of metamerism is not shown by conventional light sources.*
- Other type of metamerisms:
  - *Surface colour metamerism*
  - *Observer metamerism*



The appearance of the lights is the same, but surfaces illuminated by them appear different.

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Colour rendering index
Limitations

Rapid uptake of LED lighting

- For some types of light sources, the CIE CRI does not agree well with overall perceived colour rendering.
- The disagreement tends to be significant for LED light sources that contain narrow-band spectral components.

Main technical issues

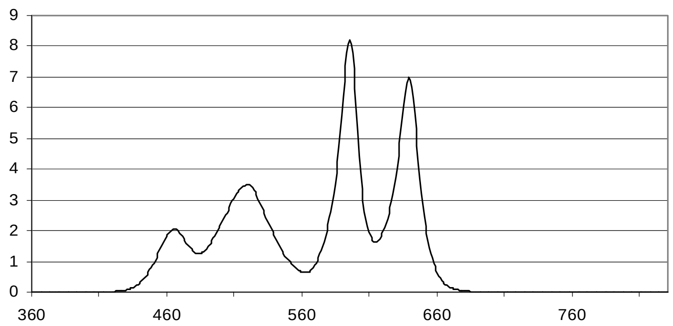
- Inaccuracy of colour appearance evaluation arising from the original 1974 CRI formulae and small number of colour test samples used in the CRI calculation.
- Limitation of the CRI due to the fact that it is simply a colour fidelity metric.

Colour rendering index - limitations
Light source metamerism

R1	93
R2	83
R3	63
R4	88
R5	83
R6	59
R7	70
R8	62
R9	38
R10	49
R11	60
R12	44
R13	84
R14	78
Ra	75

White LED light (from five different LEDs)

- (x; y): (0,4342; 0,4002)
- CCT: 3000 K



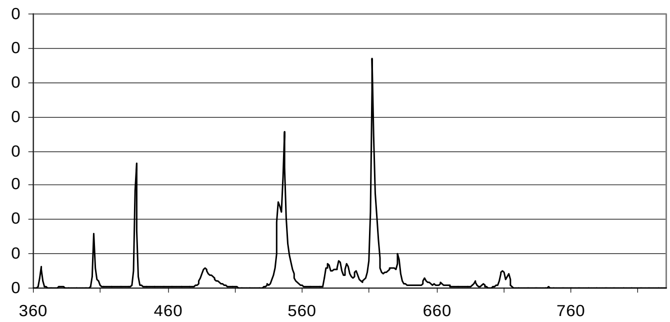
Colour rendering index – limitations

Light source metamerism

R1	98
R2	94
R3	52
R4	86
R5	86
R6	81
R7	86
R8	66
R9	-1
R10	50
R11	74
R12	46
R13	96
R14	67
Ra	**81**

Fluorescent lamp Osram Dulux L 36W/31

- (x; y): (0,4401; 0,4029)
- CCT: 2930 K



Colour rendering index

New metrics

- Colour quality characteristics other than colour fidelity are also important.
- In some experiments, subjects generally preferred illumination that slightly enhanced the colour saturation of the illuminated objects they viewed, even though the chosen light sources had lower R_a values.

Test Colour Samples

- For assessing the colour rendering properties of a light source a standardised set of surface colour samples is needed.
- CIE selected eight Munsell colours, which cover the entire colour circle. All the colours have the same value and saturation. These eight Munsell colours are used when the colour rendering index is calculated.
- In addition, four fully saturated colours and colours representing chlorophyll and human skin have been standardised.

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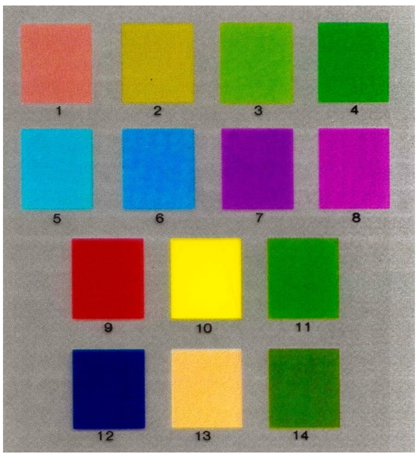
Colour Rendering Index
Test Colour Samples

Test Color Number	Munsell Notation	CIE Specification x	y	Y	ISCC-NBS Name
1.	7.5 R 6/4	0.375	0.331	29.9	Light grayish red
2.	5 Y 6/4	0.385	0.395	28.9	Dark grayish yellow
3.	5 GY 6/8	0.373	0.464	30.4	Strong yellow green
4.	2.5G 6/6	0.287	0.400	29.2	Moderate yellowish green
5.	10 BG 6/4	0.258	0.306	30.7	Light bluish green
6.	5 PB 6/8	0.241	0.243	29.7	Light blue
7.	2.5 P 6/8	0.284	0.241	29.5	Light violet
8.	10 P 6/8	0.325	0.262	31.5	Light reddish purple
9.	4.5 R 4/13	0.567	0.306	11.4	Strong red
10.	5 Y 8/10	0.438	0.462	59.1	Strong yellow
11.	4.5 G 5/8	0.254	0.410	20.0	Strong green
12.	3 PB 3/11	0.155	0.150	6.4	Strong blue
13.	5 YR 8.4	0.372	0.352	57.3	Light yellowish pink (Caucasian complexion)
14.	5 GY 4/4	0.353	0.432	11.7	Moderate olive green (leaf green)



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Colour Rendering Index

General colour rendering index CRI (Ra):

- The CRI is the arithmetic average of special indices of the CRI$_i$:s for the eight standard test colours.

$$R_a = \frac{1}{8}\sum_{i=1}^{8} R_i$$

- CRI is not absolute. For example, the general CRI of a source with CCT 6 500 K may be equal with the CRI of a source with CCT 2 800K, but the colour of their light can differ significantly.

Colour Rendering Index
Reference illuminants

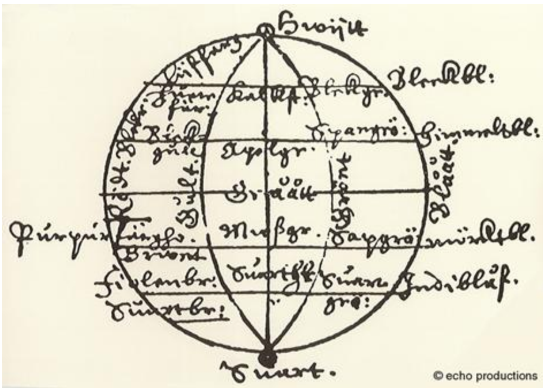
- Only the spectrum of the test illuminant is measured. The colour rendering index is then calculated
- For light sources with colour temperature less than 5000 K the Planckian radiator is used as reference
- For light sources colour temperature more than 5 000 K illuminant representing daylight is used as reference
- CIE has standardised 78 different reference illuminants of these, the closest match should be used.

Colour order systems

Early colour order systems

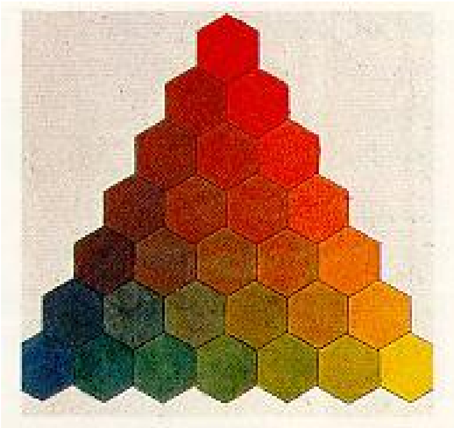
Sigfrid Aronus Forsius (1611)

- Was probably the first to device a three-dimensional model of colour space in the form of a sphere, where he systematically organized colour samples with white and black at the poles and yellow and blue, red and green at opposite points on the equator.



Early colour order systems

Tobias Mayer (1758)



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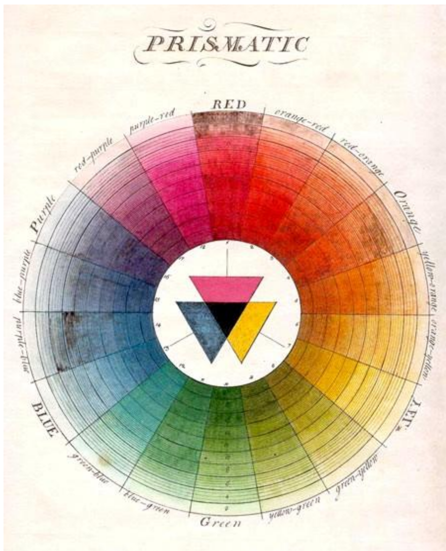
Early colour order systems

Moses Harris (1766)



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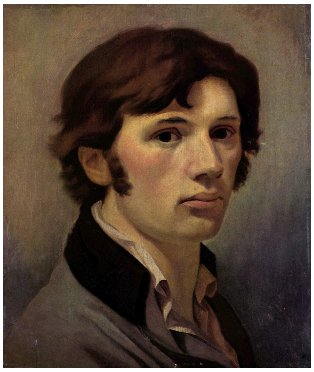
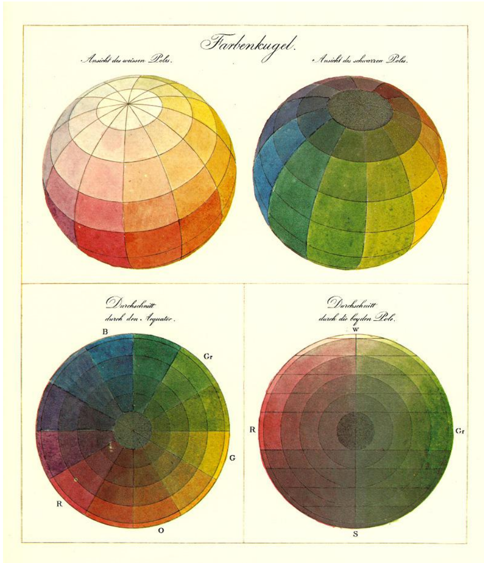
Early colour order systems

Philipp Otto Runge (1777-1810)



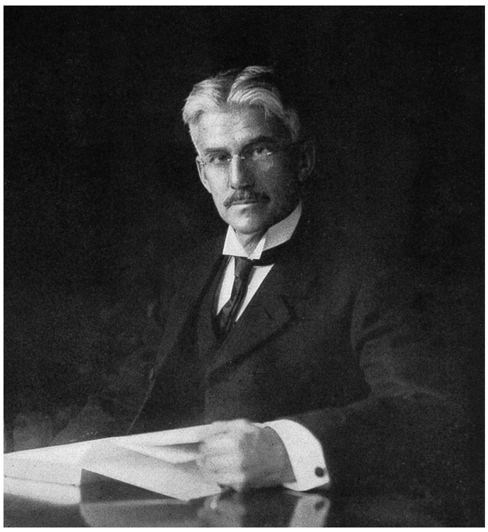
Self Portrait



Modern colour order systems
The Munsell system

Albert H. Munsell published his colour atlas in 1915

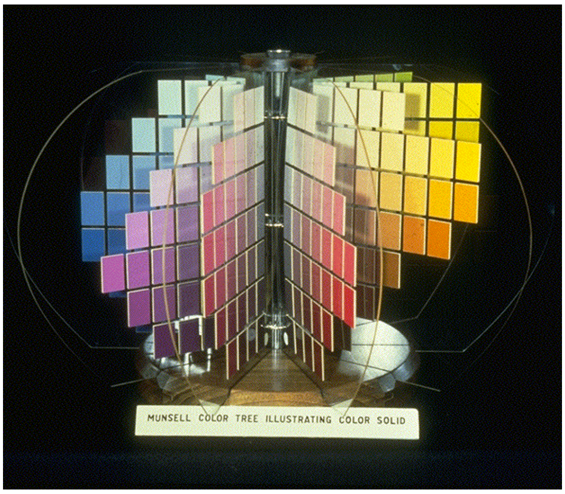
- Almost uniform color representation
- Based on rigorous measurements of human subjects' visual responses to colour.



Modern colour order systems
The Munsell System

A colour is described with three attributes (i.e. colour dimensions):

- Hue (the name of the colour)
- Value (the lightness or darkness of the colour)
- Chroma (the saturation or purity of the colour)



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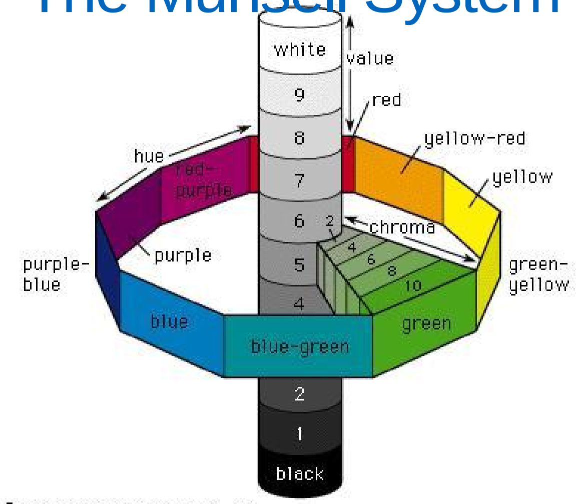
Modern colour order systems
The Munsell System



- The value is given on a scale ranging from 0 (ideal black) to 10 (ideal white).
- In practise, values 0 and 10 cannot be realised. Thus, on the colour solid there are only nine values (1-9).
- The chroma can have a value from 0 to 20, where value 0 means complete achromatism. The maximum possible value of chroma depends on the hue.

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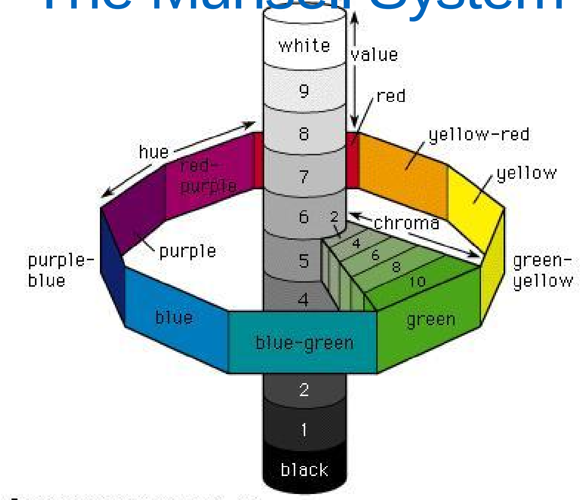
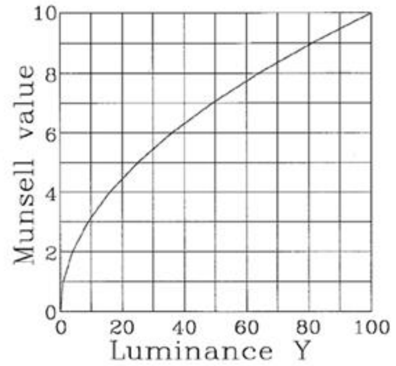
Modern colour order systems
The Munsell System

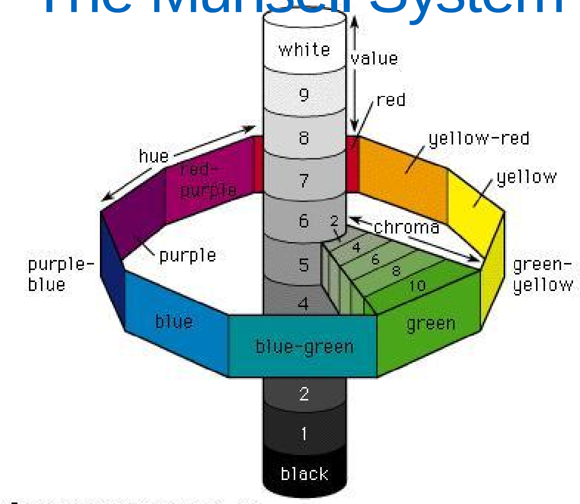


Value or lightness

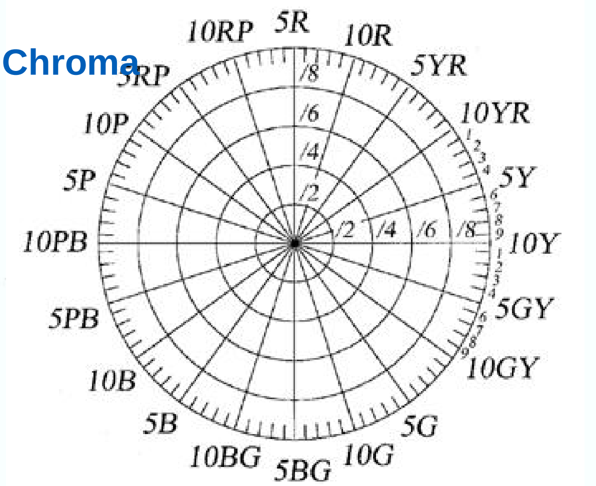


D. Malacara, *Color Vision and Colorimetry: Theory and Applications*, *Second Edition,* SPIE Press, Bellingham, WA (2011).

Modern colour order systems
The Munsell System



Chroma



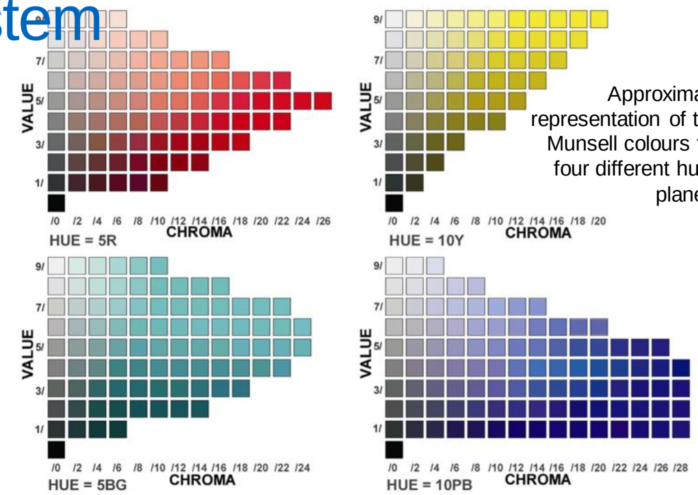
D. Malacara, *Color Vision and Colorimetry: Theory and Applications*, *Second Edition,* SPIE Press, Bellingham, WA (2011).

Modern colour order systems
The Munsell System

Colour specification:

5BG 4/12

- Hue: 5BG
- Value: 4
- Chroma: 12



Approximate representation of the Munsell colours for four different hues planes.

D. Malacara, *Color Vision and Colorimetry: Theory and Applications*, *Second Edition,* SPIE Press, Bellingham, WA (2011).

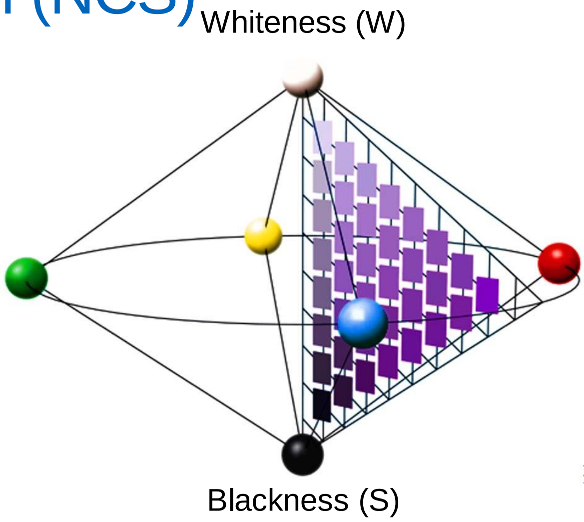
Modern colour order systems
The Munsell System

Photo by Irma Havlicek

A page from the Munsell colour chart book on soil in test trench 1 © PHM

Modern colour order systems
Natural colour system (NCS)

- First proposed by German physiologist Ewald Hering
- Published by the Scandinavian Colour Institute (Skandinaviska Färginstitutet AB) of Stockholm, Sweden
- Goal of creating a visually descriptive colour system
- Based on six elementary colours (yellow, red, blue, green, white and black)
- S+W+C = 100



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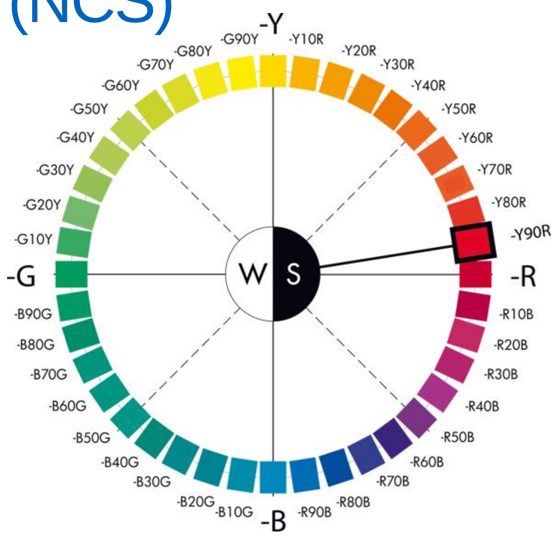

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