2. Lighting Terms

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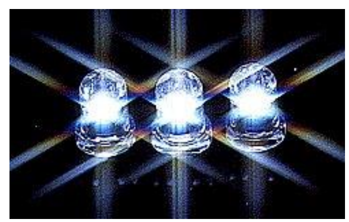
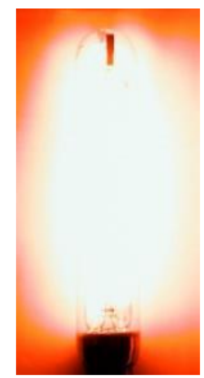


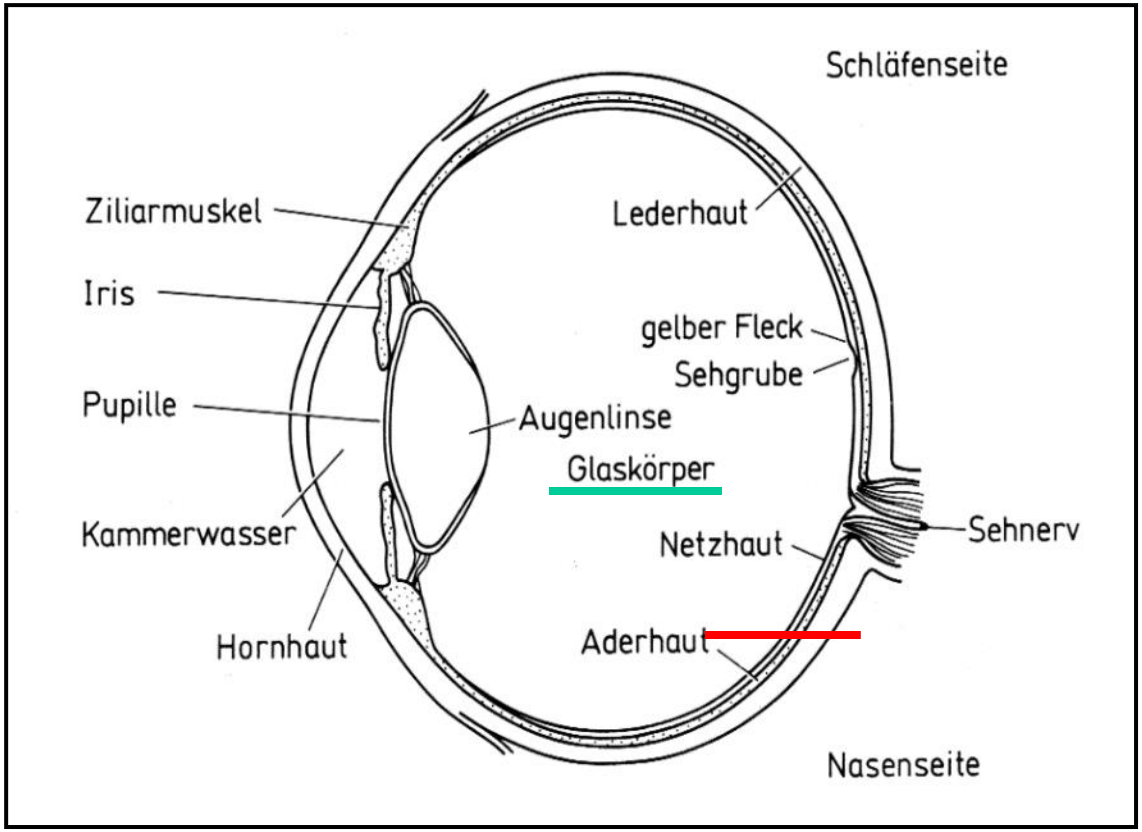


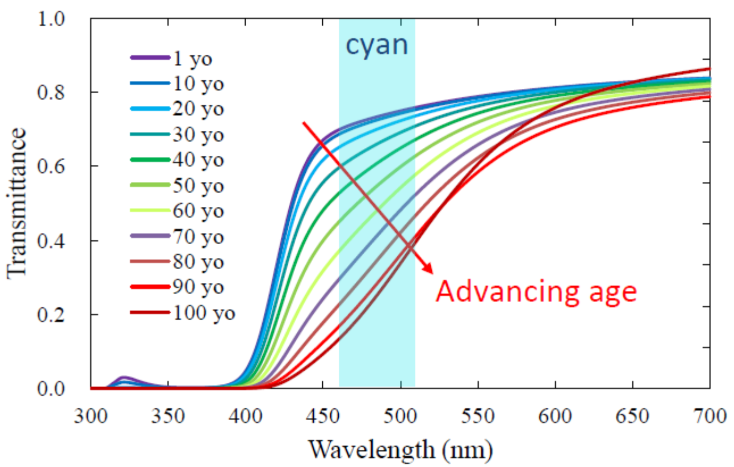
Luminous flux ↑

2.1 Vision

Schematic build-up of the human eye

Why is the visible range for humans 380 - 780 nm?

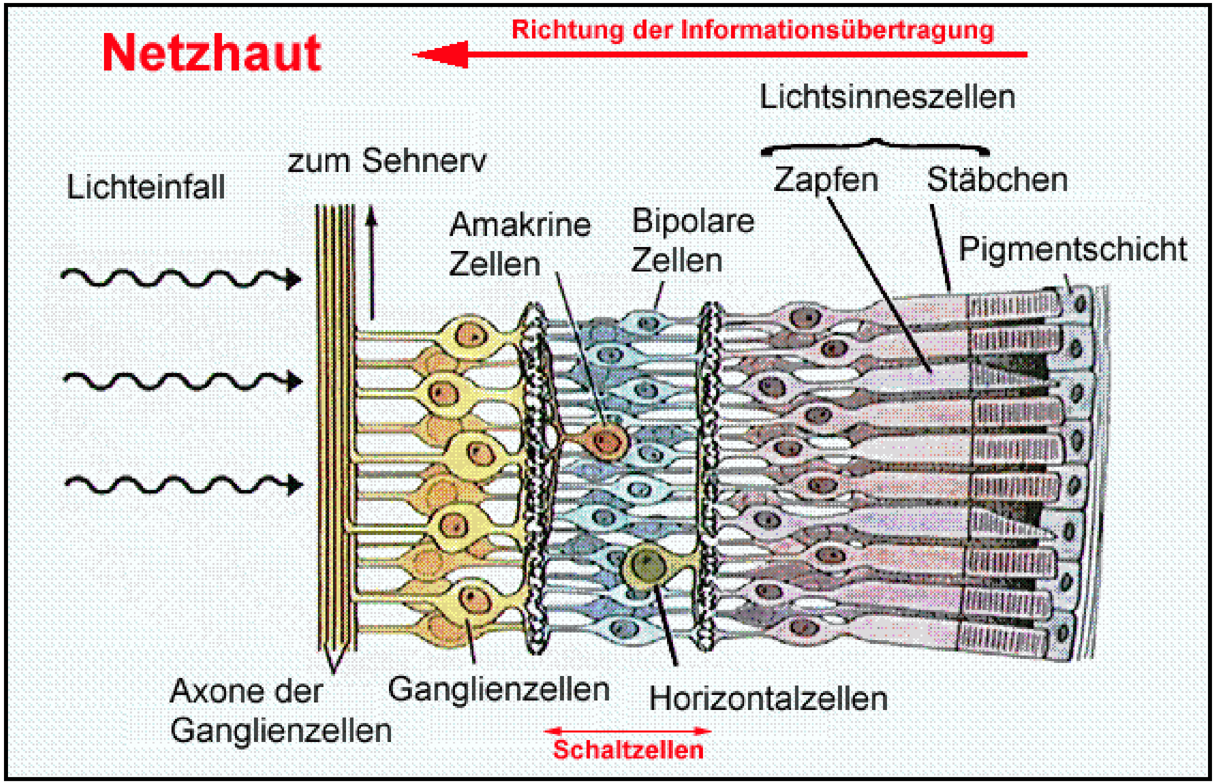


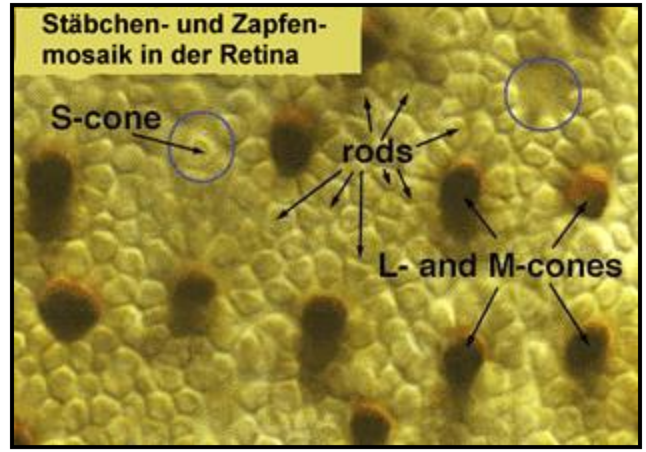


Source: Nichia, PGS2019

2.1 Vision

Structure of the retina (rods and cones)





Rods

→ **Black-white vision, i.e. shape and brightness of objects (contrast)**

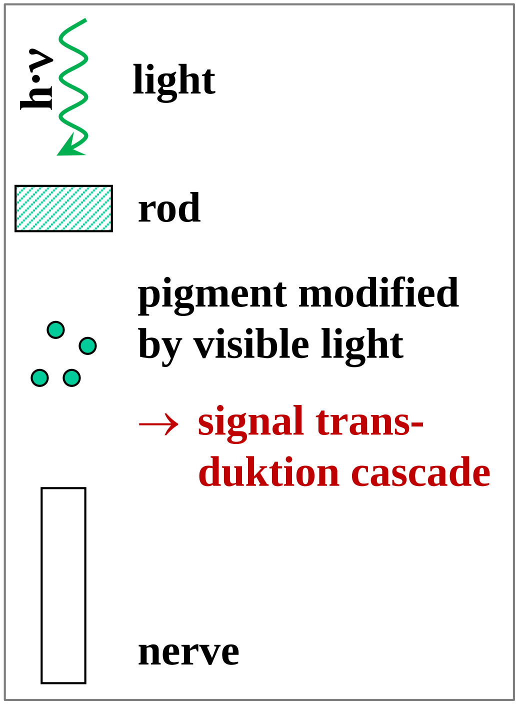
Cones (L, M, and S)		Fraction
S	420 nm	1
M	534 nm	10
L	564 nm	20

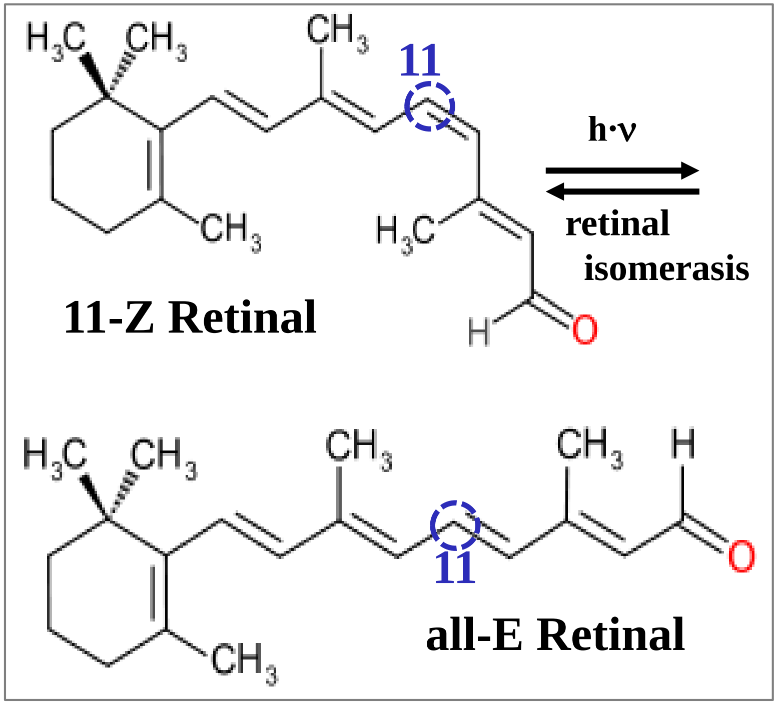
→ **Colour perception**

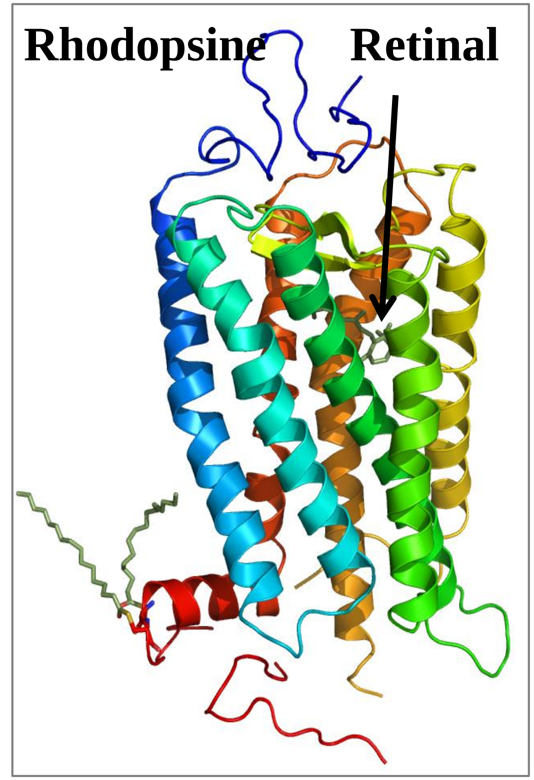
Retina of human eyes ~ **120 million rods**
~ **6 million cones**

2.1 Vision

The process of vision (e.g. rods → B/W vision)







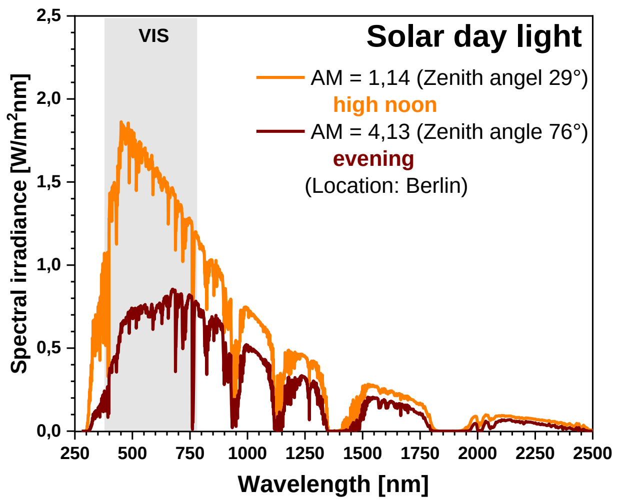
- **Rhodopsine pigment can be decomposed by solely 2 to 3 photons, which yields a protein (opsine) and all-trans (E) retinal**
- **All-trans retinal is then isomerized to 11-cis (Z) retinal, which reacts again with opsine to yield rhodopsine**
- **The aldyhde retinal is the oxidation product of retinol (vitamine A)**

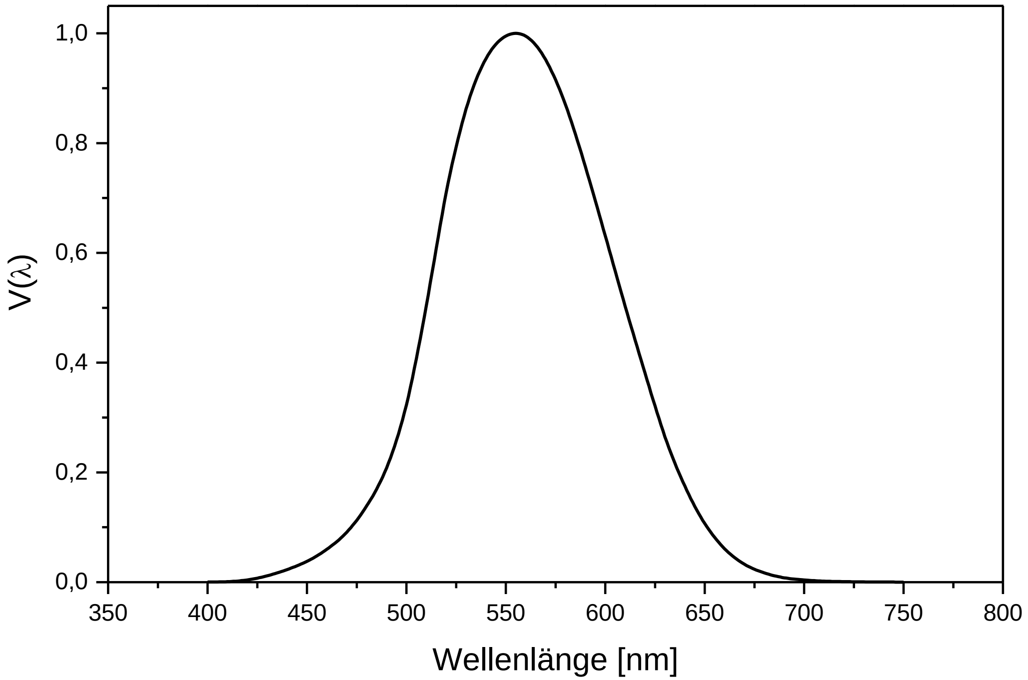
2.2 Spectral Sensitivity of the Eye

Photopic vision (high brightness situation)

Eye adapted to high brightness level, i.e. $L_v = 10 - 10^8$ cd/m²

Spectral sensitivity curve of the human eye V(λ): Daylight vision





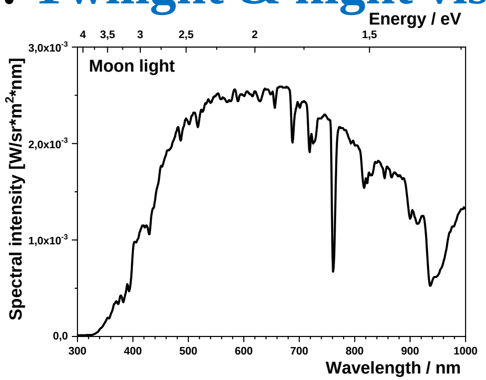
At daylight condition the human eye is around 20 times more sensitive for yellow-green (555 nm) then for red (670 nm) or blue light (450 nm)
This property is described quantitatively by spectral sensitivity curve V(λ)

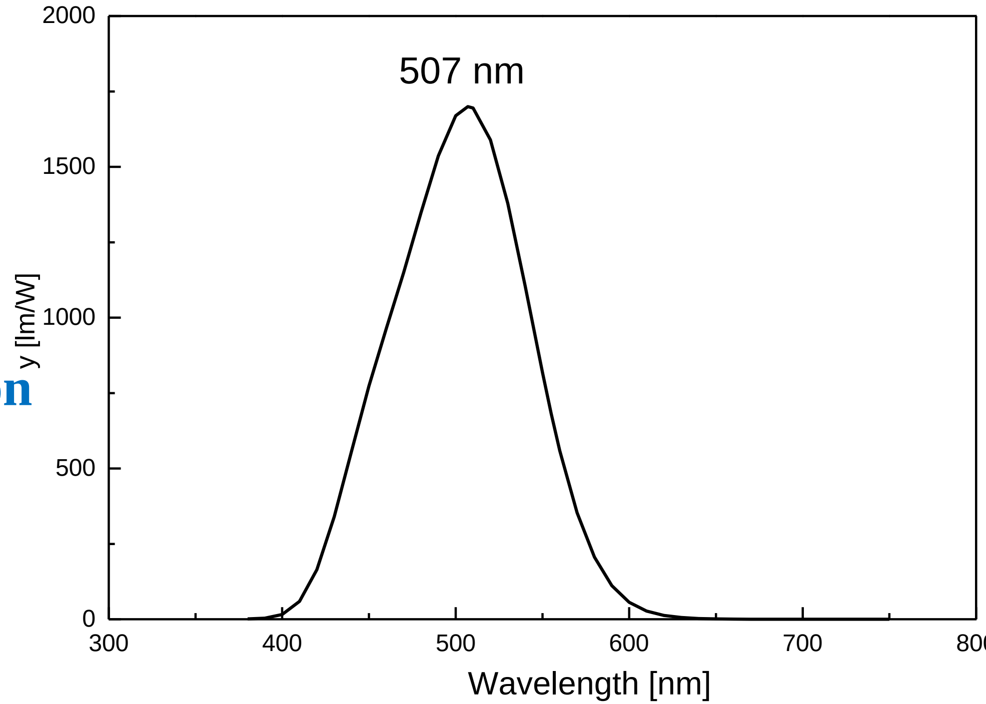
2.2 Spectral Sensitivity of the Eye

Scotopic vision (low brightness situation)

Eye adapted to low brightness level,
i.e. $L_v = 10^{-3} - 10^{-6}$ cd/m^2

Spectral sensitivity curve of the human eye V´(λ): Twilight & night vision





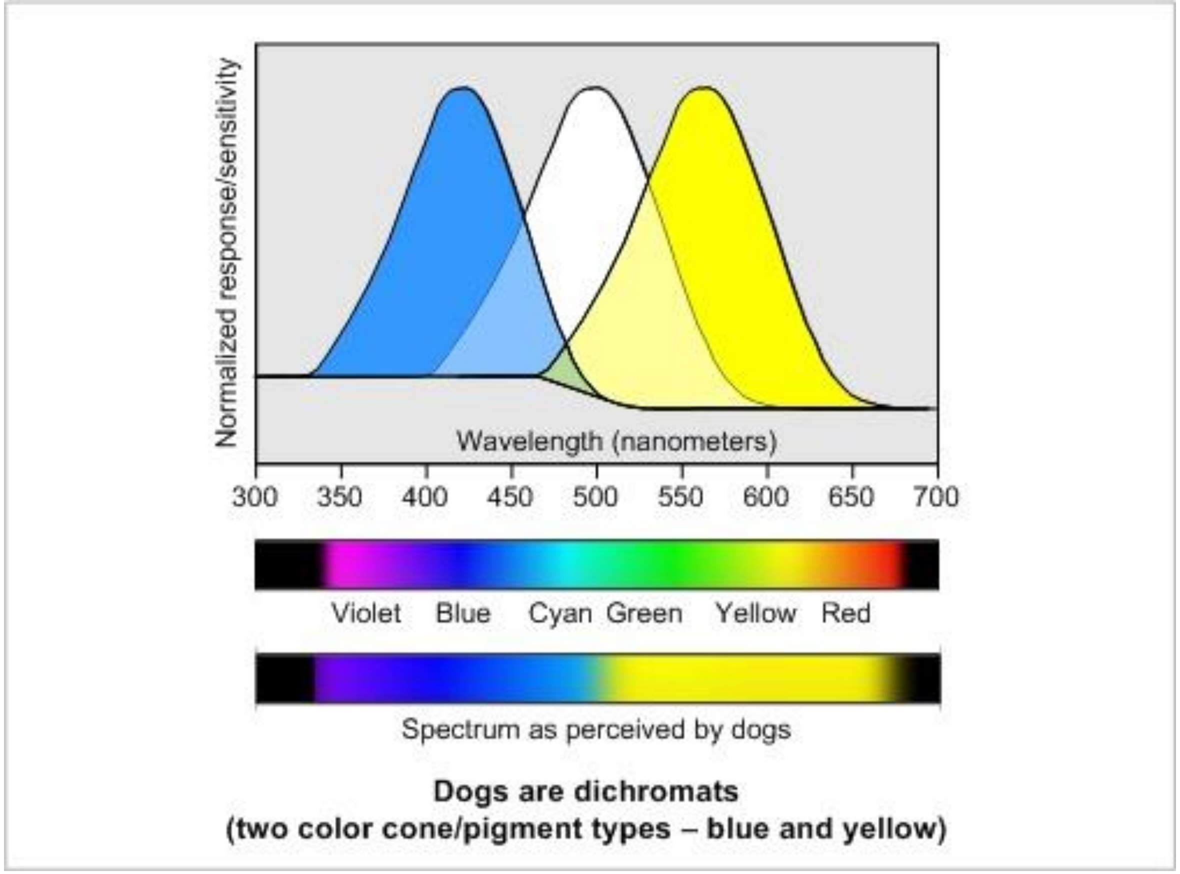
At intermediate brightness level, i.e. $L_V = 10 - 10^{-3}$ cd/m^2 is called mesopic vision

Maximum of the eye sensitivity is in the blue-green spectral range
Light sources with high blue-green fraction are favourably in the night
(e.g. Xe/Hg-lamps for automotive headlights or white LEDs with high CCT)

2.2 Spectral Sensitivity of the Eye

Dogs (carnivores) with lens eyes

- **Maximal sensitivity at about 420 and 560 nm**
- **Dogs are thus dichromates and can solely perceive blue and yellow colours**



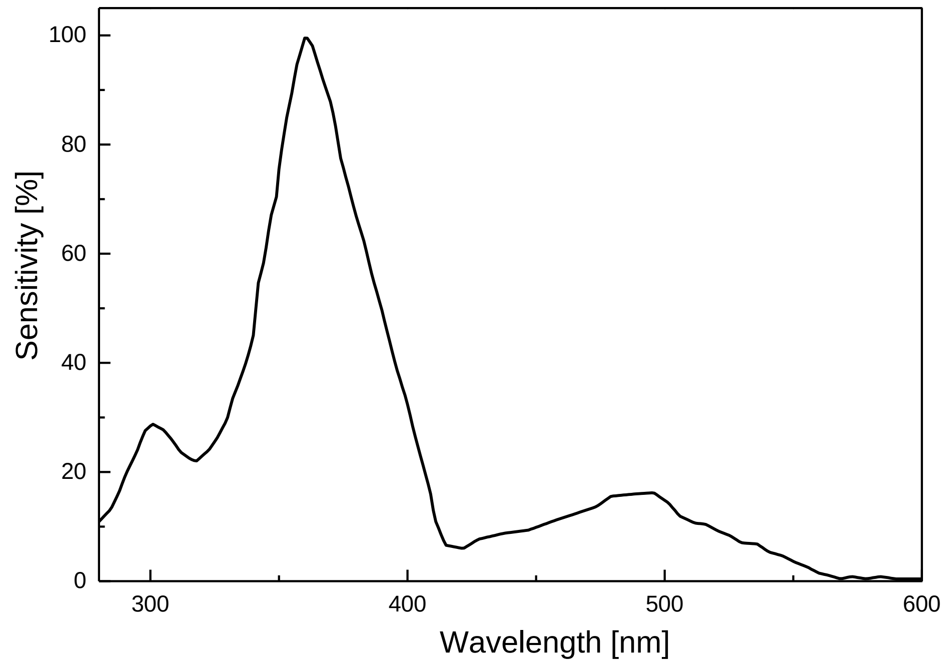
Dogs cannot distinguish between green and red colours!

2.2 Spectral Sensitivity of the Eye

Insects (arthropoda) with facet eyes

- **Maximal sensitivity at 350 nm, i.e. in the UV-A range**

- **Insects are also trichromatic, however, they can not see in the yellow-red range, but in contrast to that in the UV-A and UV-B range**



Light sources with high UV or blue fraction attract insects, in contrast to yellow and red light sources

Lit.: Moths are strongly attracted to UV and blue radiation (G. Brehm, J. Niemann, D. Enseling, T. Jüstel, L. Jaimes, J.C. Axmacher, E. Warrant, K. Fiedler, Insect Conservation and Diversity 14(2) 2021)

2.2 Spectral Sensitivity of the Eye

Biological evolution of visual pigments (opsines)

Ancestors of vertebrates and articulates
UV + B + G + R

Arthropoda (Articulates)
UV + B + G + R

Insecta (e.g. bees + bumble bees)
UV + B + G
350 450 530 nm

Vertebrata (Vertebrates)
UV + B + G + R

Reptilia + Dinosauria
UV + B + G + R

early Aves (Birds)
UV + B + G + R

present-day Aves
UV + B + G + R S/W
370 445 508 565 nm

early Mammalia (mammals, nocturnal)
B + R

Whales + seals

early primates
B + G + R

Homo Sapiens
B + G + R
437 533 564 nm
2% red-green blind

Lit.: Spektrum der Wissenschaft 1/07 (2007) 96

2.3 Radiometric Quantities

Measured quantities (parameters) for the characterization of the output (proportional to number of emitted photons per unit time) = energy quantities

<u>Measured quantities on detector (photomultiplier, photodiode, human eye and so on)</u>

Intensity I_e = number of photons/area*time [$N_{h\upsilon}/m^2s$]
(German: Intensität)

↓ $E = N \cdot [h\upsilon]$

Irradiance E_e = number of photons/area*time [$J/m^2s = W/m^2$]
(German: Bestrahlungsstärke)

⇒ **These quantities are proportional to counting rate on detector [Counts/s]**

Radiant exposure H_e = number of photons/area [J/m^2]
(German: Bestrahlung)

with $H_e = E_e{*}t$ **(Radiant energy per area)**

2.3 Radiometric Quantities

Quantity	Symbol	Definition	Unit
Radiant power (Radiant flux)	Φ_e	$= dW/dt$	[W] or [J/s]
Spectral radiant power (Spectral radiant flux)	Φ_λ	$= d\Phi_e/d\lambda$	[W/nm]
Irradiance (Radiant emittance)	E_e	$= d\Phi_e/dA$	[W/m^2]
Spectral irradiance (Spectral radiant emittance)	E_λ	$= dD_e/d\lambda$	[W/m^{2}nm]

Irradiance of the earth: $E_e = 1.368 * 10^3$ $J/m^2s = 1368$ W/m^2 *(solar constant)*

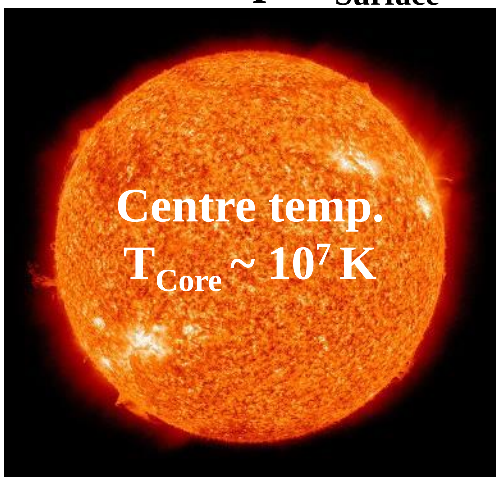
Calculation of photon number: $E = h\nu = hc/\lambda$ and $h\nu_{550} = 4.0 * 10^{-19}$ J

$\Rightarrow$ 1 W = 1 J/s = $2.5 * 10^{18}$ photons per second of wavelength 550 nm

2.3 Radiometric Quantities

System Sun – Earth: Average distance ~ (149.6 ± 2.5)·10⁶ km

Surface temp. $T_{Surface}$ ~ 5780 K



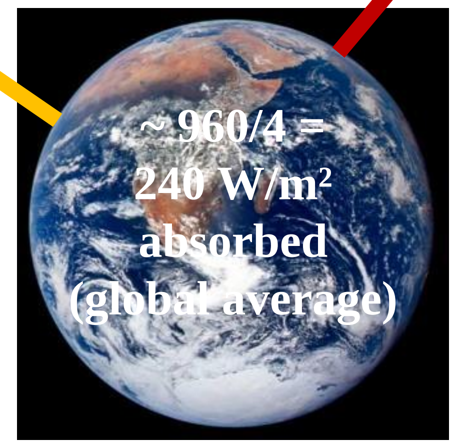
Source: NASA

$6.3 \cdot 10^7$ W/m²

Irradiance ~ 1368 W/m²

Albedo ~ 30%

σT_E^4, T_E = 255 K



Source: Apollo 17

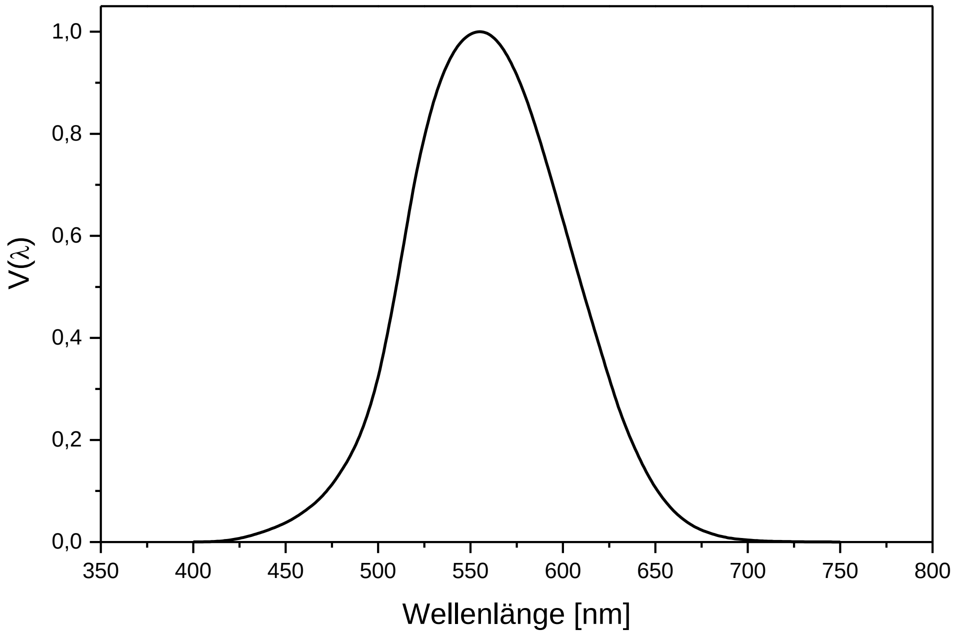
	Sun	Earth
Radiant power	$3.846 \cdot 10^{26}$ J/s (W)	$1.730 \cdot 10^{17}$ J/s (W)
Radiant flux per year	$1.214 \cdot 10^{34}$ J/a	$5.459 \cdot 10^{24}$ J/a

Compare: Global primary energy consumption ~ $5.2 \cdot 10^{20}$ J/a ~ 0.01%

2.4 Photometric Quantities

Quantities which consider the sensitivity of the observer

Luminous flux $\Phi_v = \Phi_e / M_0$ [lm]



M_0 = energetic lumen equivalent

= 0.001464 W/lm (≡ 1/683 W/lm)

K_{max} = 683 lm/W (at 555 nm)

$K(\lambda) = K_{max} V(\lambda)$

$$\Phi_v = K_{max} \int_{380}^{780} V(\lambda)\Phi_e(\lambda)d\lambda$$

Luminous intensity $I_v = d\Phi_v / d\Omega$ [cd]

Ω = Solid angle [sr]

(Spherical surface = $4\pi r^2$)

Light source with 1 cd, which is isotropic in all spatial directions, emits thus 1 cd per sr (~12.566 lm in total)

2.4 Photometric Quantities

Definition of the SI-Unit candela [cd]

One candela is the luminous intensity of a radiation source, which emits monochromatic radiation ($4.1 \cdot 10^{15}$ Photonen) with a frequency $540 \cdot 10^{12}$ Hz ($E_{hv} = 3.578 \cdot 10^{-19}$ J) (equal to wavelength of 555 nm), with a radiant power of 1/683 W (J/s) per steradiant (luminous intensity of ~1/60 1 cm^2 of black body at a temperature 2045.5 K, which is the melting point of Platinum Pt).

As for all photometric quantities, is this unit dependent on the eye sensitivity curve $V(\lambda)$.
For the reference wavelength it applies:
V(555 nm) = 1.0, i.e. 1 W radiation at 555 nm corresponds to 683 lm.

1. Example: Household candle (40 W, 0.0184 W optical power! ~ almost 40 W heat)
Luminous flux: about 12.566 lm ⇒ Luminous intensity $I_v = 12.566\ lm/4\pi \cdot sr = 1$ cd

2. Example: 100 W Incandescent lamp
Luminous flux: about 1500 lm ⇒ Luminous intensity $I_v = 1500\ lm/4\pi \cdot sr \sim 120$ cd

2.4 Photometric Quantities

Origin of the quantity of the energetic light equivalent M_0 = 0.001464 W/lm

Reference light source is the candle *Emission spectrum of a diner light (~16 g)*

P ~ 40 W = 40 J/s (paraffine ~ 42 MJ/kg, burning time ~ 4.6-4.7 h)

$P_{optical}$ = 0.0184 W (integrating sphere)

η = 0.046%

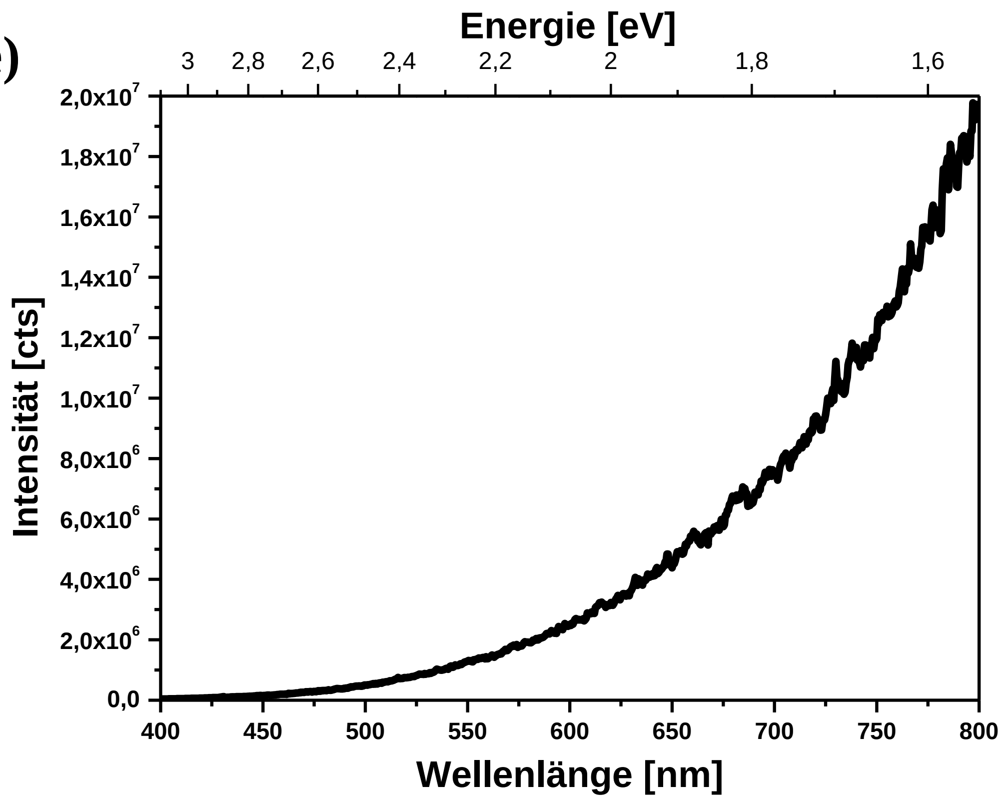
I_v = 1 cd ~ 12.566 lm

$\Rightarrow$ 0.31415 lm/W or 3.1832 W/lm

Efficiency η = 0.00046

$\Rightarrow$ 0.001464 W/lm

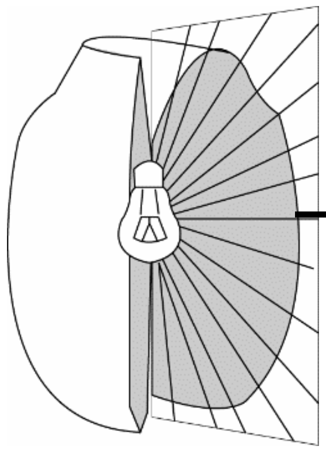
$\Rightarrow$ 683 lm/W (q.e.d.)



2.4 Photometric Quantities

Luminous flux Φ_v (German: Lichtstrom)

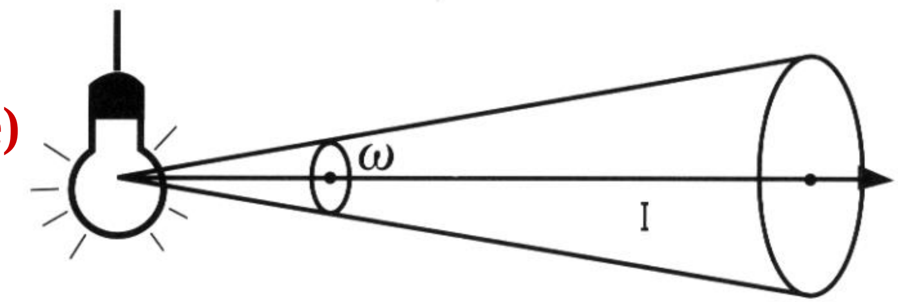
Entire radiant power, emitted by a light source in all spatial directions, which is weighed by the sensitivity of the human eye.



$$\text{Lichtstrom}\ \Phi_v = 683 \int_{380}^{780} V_{rel}(\lambda)\Phi_e(\lambda)d\lambda$$

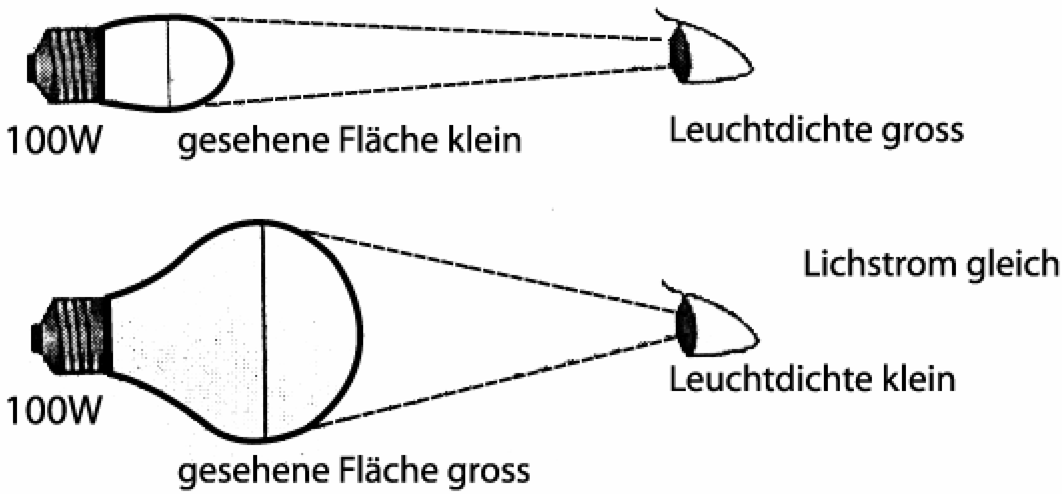
Luminous intensity I_v (German: Lichtstärke)

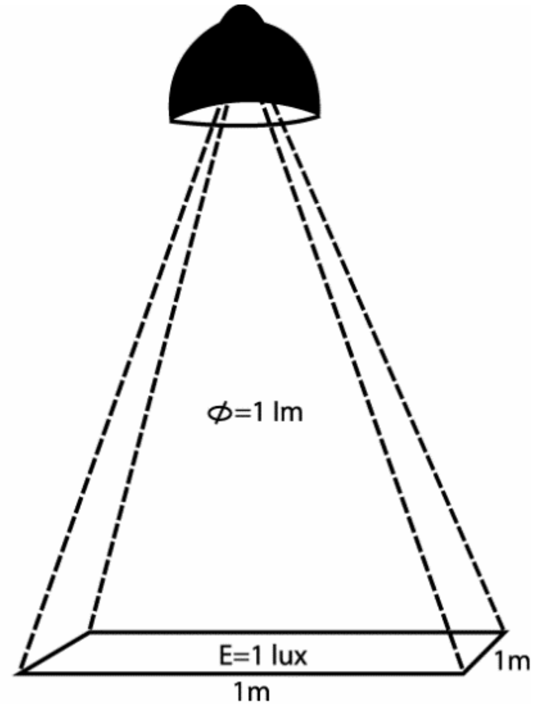
Intensity of light emitted in a particular direction



2.4 Photometric Quantities

Illuminance and Luminance





Illuminance (German: Beleuchtungsstärke) — Ratio of the incident luminous flux to the irradiated area. Luminous flux/area [lm/m^2 = lux]

Luminance (German:Leuchtdichte) — Perceived brightness of a light source. Luminous intensity/area [cd/m^2]

2.4 Photometric Quantities

Integral quantities

Luminous flux $\Phi_v = \Phi_e/M_0$ [lm]

Illuminance $E_v = d\Phi_v/dA$ [lux = lm/m^2]

Angle related quantities (per 1 sr)

Luminous intensity $I_v = d\Phi_v/d\Omega$ [cd]

Luminance $L_v = dI/dA\cos\gamma$ [cd/m^2] = [nit]

Light source	Luminance [cd/cm^2]
Sun	150000
Discharge arc lamp	20000 - 100000
Incandescent lamp (clear)	200 – 2000
Incandescent lamp (opaque)	5 – 50
fluorescent lamp	0.4 – 1.4
candles	0.75
blue sky	0.3 – 0.5
full moon	0.25
TV screen	0.05

2.4 Photometric Quantities

Typical Lux Values

The illuminance in closed rooms is much lower than for being in open air

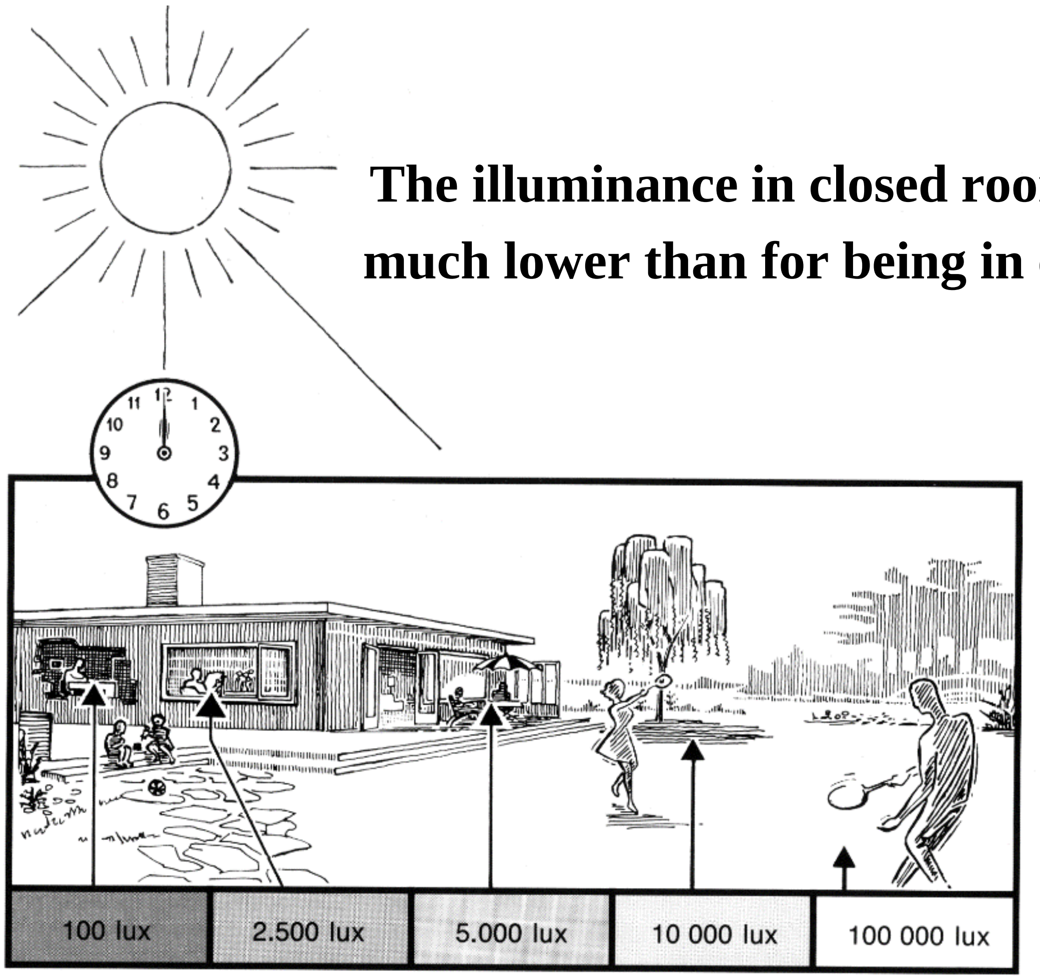


Fig. 2 Variations in lighting level under a clear sky.

CCT [K]	VISUAL DATA		MELANOPIC ACTION FACTOR
	Luminous flux [lm]		alpha (smel)
	K-SOLIS	K-SOLIS Pure	
1,800	1,480	1,650	0.226
2,000	1,745	1,945	0.252
2,500	2,170	2,495	0.324
2,700	2,090	2,400	0.357
3,000	2,000	2,300	0.407
3,500	1,910	2,195	0.484
4,000	1,850	2,130	0.554
4,500	1,815	2,085	0.618
5,000	1,790	2,055	0.676
5,500	1,775	2,040	0.728
6,000	1,765	2,025	0.774
6,500	1,755	2,015	0.816
7,000	1,750	2,010	0.852
8,000	1,745	2,000	0.915
9,000	1,740	1,995	0.965
10,000	1,735	1,990	1.033
12,000	1,730	1,970	1.168
14,000	1,720	1,950	1.304
16,000	1,710	1,935	1.439

From a physiological point of view, daily live takes place in darkness

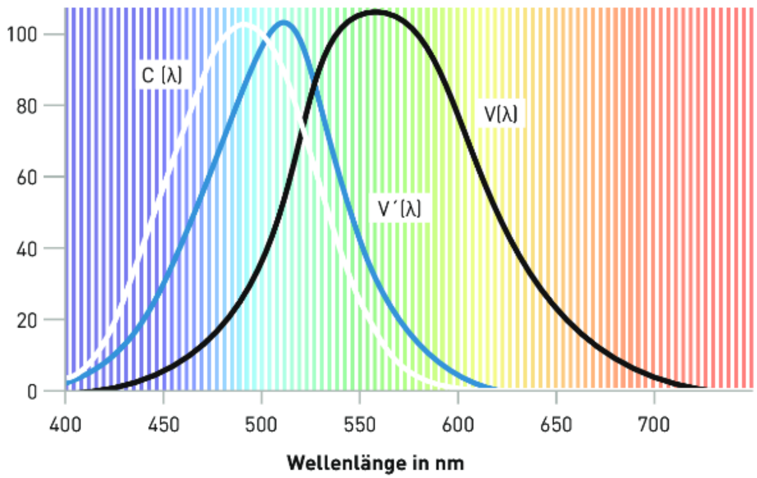
Lack of melatonin suppression, i.e. low melanopic action factor or circadian efficacy.

2.4 Photometric Quantities

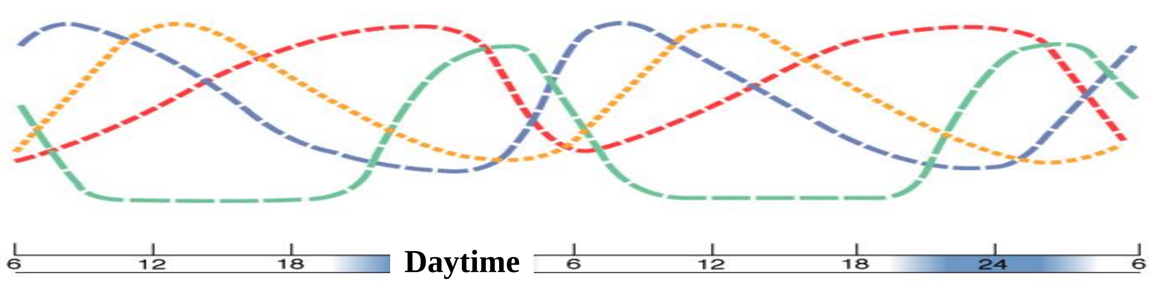
Circadian Efficacy c(λ)

505 nm

480 nm 555 nm



Light source	Luminous efficacy photopic	Luminous efficacy circadian / photopic
Daylight 6500 K	100 lm/W	2.78
FL 3000 K	90 lm/W	1.00
FL 4100 K	90 lm/W	1.85
LED 5500 K	200 lm/W	2.91 (~ LCDs)



Body temperature

Melatonin (sleep hormone)

Cortisol (stress hormone)

Attentiveness

2.5 Energy and Light Efficiency

Definitions

Radiant efficiency $\eta_e = W_{h\nu(visible)}/W_{electrical}*100$ [%] „energy efficiency“ „wall plug efficiency“

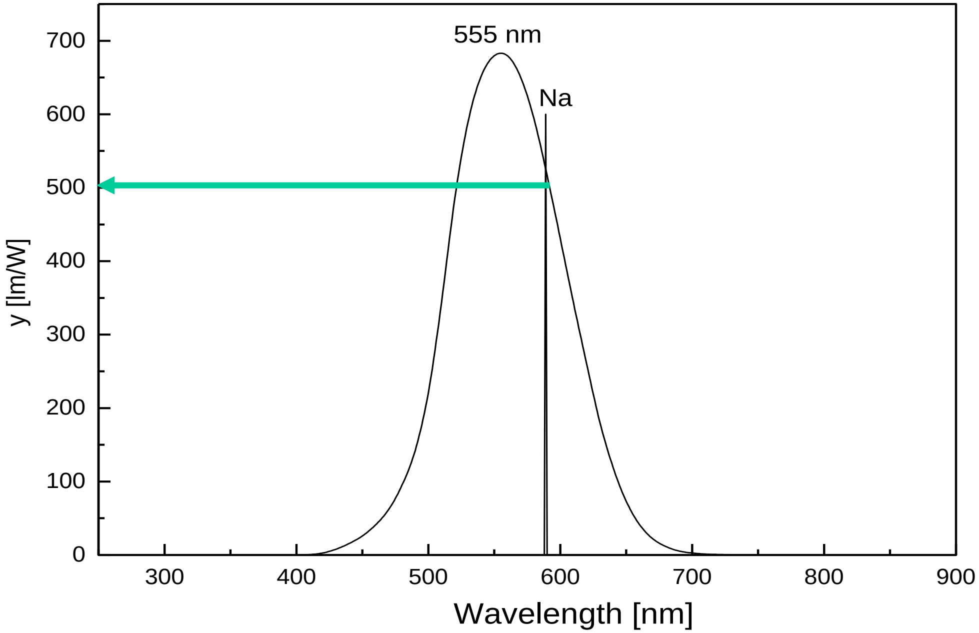
Luminous efficacy $\eta_v = \Phi_v / W_{electrical}$ [lm/W] $*\eta_e \Rightarrow$ „light efficiency“

Light source	Energy efficiency [%]	Light efficiency [lm/W]
• Colour TV	1	2 - 3
• Incandescent lamp	5	10
• Halogen lamp	8 - 10	15 - 20
• Energy-saving lamp	15 - 20	70
• High pressure mercury lamp	15 - 20	65
• Fluorescent tube	29	100
• High pressure sodium lamp	31	130
• Low pressure sodium lamp	40	200
• Cold white LED	70	250

2.5 Energy and Light Efficiency

The "light efficiency" or "light yield" of a light source is therefore the result of its energy efficiency (η) and its luminous efficacy (LE), thus the luminous efficacy.

Example: Low pressure sodium lamp with single emission line at 589.3 nm (energy efficiency η = 40%)



Luminous efficacy of a light source = The amount of lumens per 1 Watt of optical photons:

$$LE = \int_{380}^{780} y(\lambda)E(\lambda)d\lambda$$

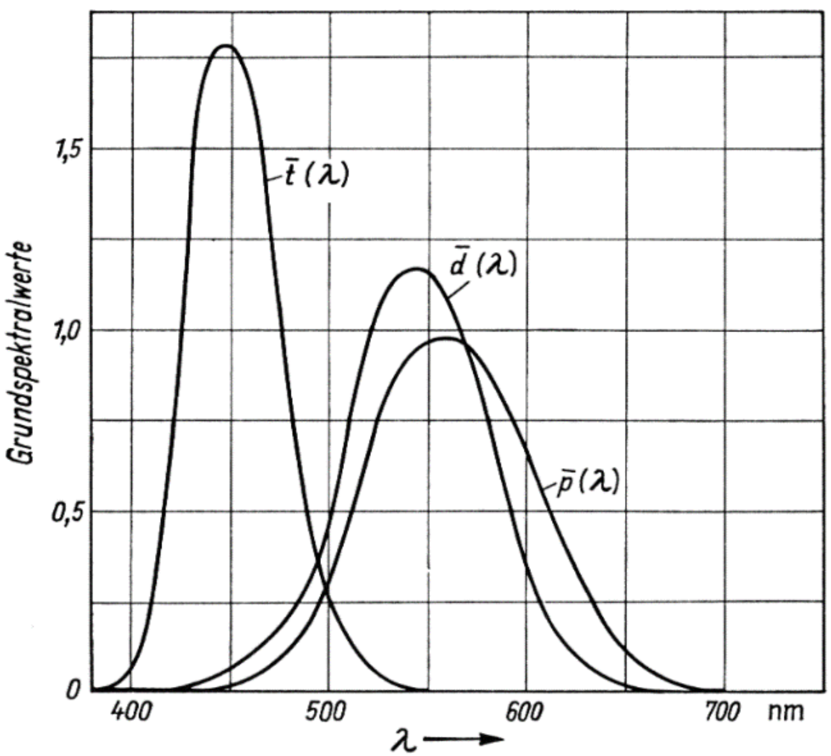
Light efficiency or yield of a light source = energy efficiency η * lumen equivalent LE

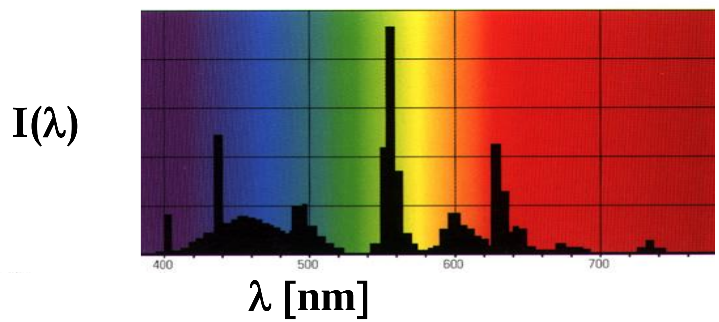
η_e	= 40%
LE	= 500 lm/W_{opt}
⇒ "Light efficiency"	= 200 $lm/W_{electrical}$

2.6 Colour Coordinates

Human eyes possess three different cones with three different organic pigments
⇒ Trichromatic vision

The absorption curves of these three cone pigments are described by the t(λ), d(λ), and p(λ) curves (also called S, M, L types)





By these three absorption curves the following parameters of an emission spectrum I(λ) can be calculated :

$$T = \int I(\lambda) \cdot t(\lambda) \cdot d\lambda$$

$$D = \int I(\lambda) \cdot d(\lambda) \cdot d\lambda$$

$$P = \int I(\lambda) \cdot p(\lambda) \cdot d\lambda$$

2.6 Colour Coordinates

Tristimulus values

A certain wavelength, e.g. 550 nm stimulates at least two pigments, e. g. D/P in the ratio of 4/3. The brain settles it as a grass-green colour impression.

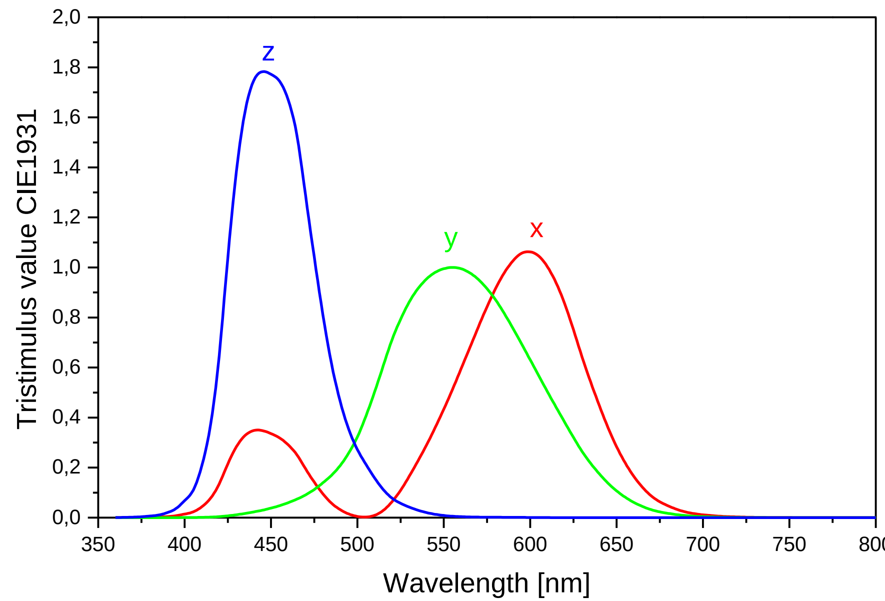
Instead of 3 absorption curves t(λ), d(λ) und p(λ) it is better to use 3 stimulant curves x(λ), y(λ) und z(λ), which result from t(λ), d(λ) und p(λ) as a linear combination.

From these curves the values X, Y, Z can be calculated:

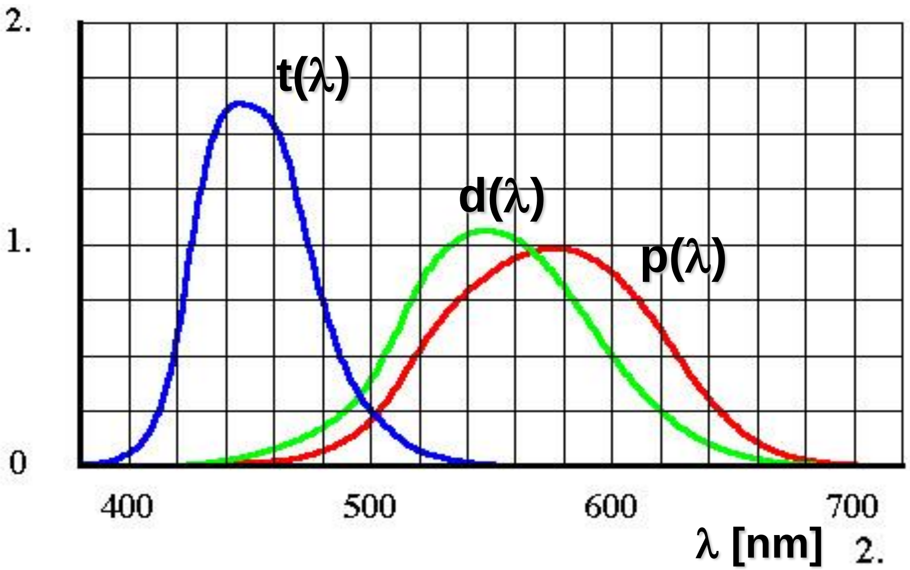
$$X = \int I(\lambda) \cdot x(\lambda) \cdot d\lambda$$ **mix of T, D, P**

$$Y = \int I(\lambda) \cdot y(\lambda) \cdot d\lambda$$ **equal to luminance**

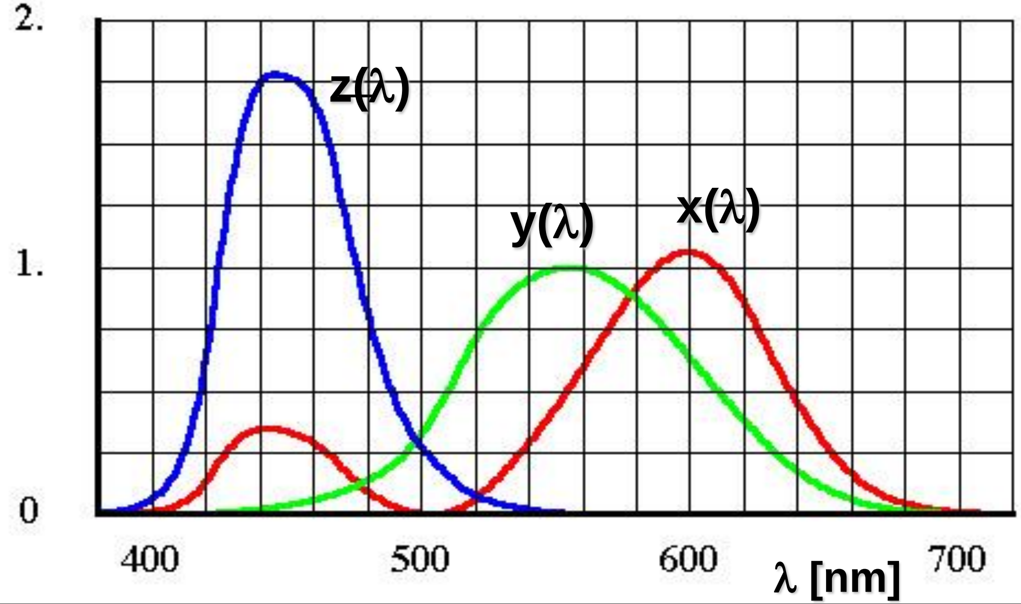
$$Z = \int I(\lambda) \cdot z(\lambda) \cdot d\lambda$$ **quasi-equal to T**



2.6 Colour Coordinates



Linear combinations



$$\begin{pmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{pmatrix} = \begin{pmatrix} 1.86 & -1.13 & 0.22 \\ 0.36 & 0.63 & 0.00 \\ 0.00 & 0.00 & 1.09 \end{pmatrix} \begin{pmatrix} t(\lambda) \\ d(\lambda) \\ p(\lambda) \end{pmatrix}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 1.86 & -1.13 & 0.22 \\ 0.36 & 0.63 & 0.00 \\ 0.00 & 0.00 & 1.09 \end{pmatrix} \begin{pmatrix} T \\ D \\ P \end{pmatrix}$$

2.6 Colour Coordinates

Derivation of the CIE1931 colour point x, y

The three values X, Y, Z can be formulated as a 3-dimentional vector.
The direction of the vector (X, Y, Z) indicates the colour and its length indicates the brightness. For the colour impression is also the direction decisive.
Thus renormalized vector (x, y, z)

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

with the same colour impression as (X, Y, Z) can be specified.

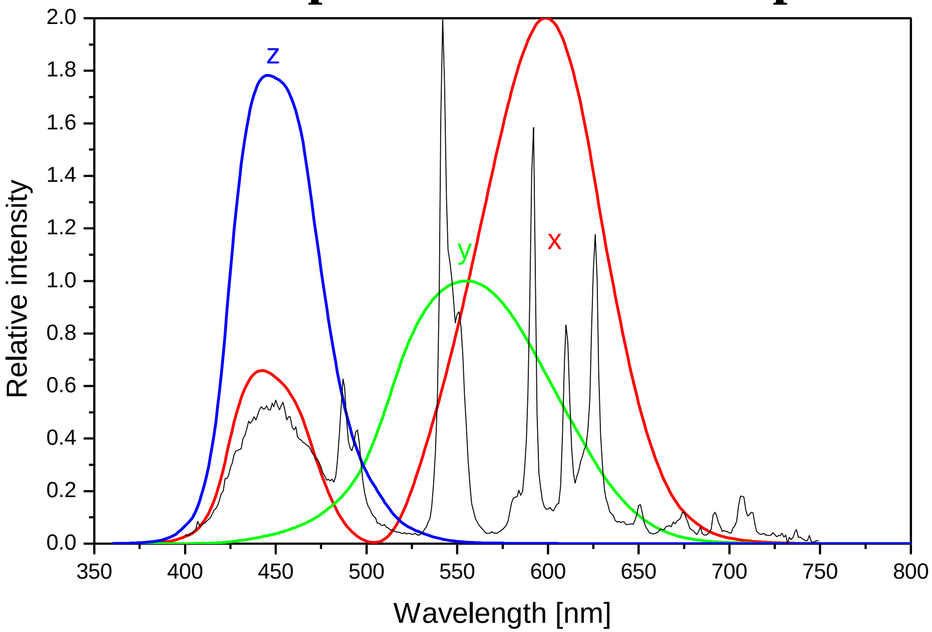
For the vector (x, y, z) it applies: x + y + z = 1

Therefore, it is sufficient to give only x and y values, to characterize the colour.
z results from z = 1 - x - y

2.6 Colour Coordinates

Determination of colour points x, y

Example: Fluorescent lamp



$$X = K\int_{380}^{780} P(\lambda)x(\lambda)d\lambda$$

$$Y = K\int_{380}^{780} P(\lambda)y(\lambda)d\lambda$$

$$Z = K\int_{380}^{780} P(\lambda)z(\lambda)d\lambda$$

with **P(λ) = Spectral power distribution**
K = Scaling factor
Result: x = 0.325, y = 0.305

2.6 Colour Coordinates

The (x, y) coordinate system C.I.E. 1931

(Commission Internationale de l'Eclairage)

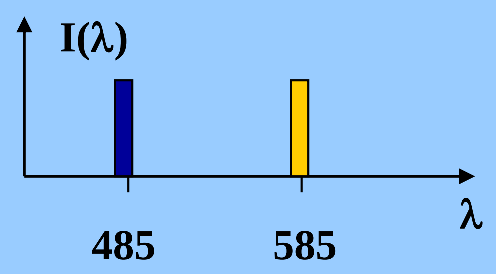
It is possible to add colours

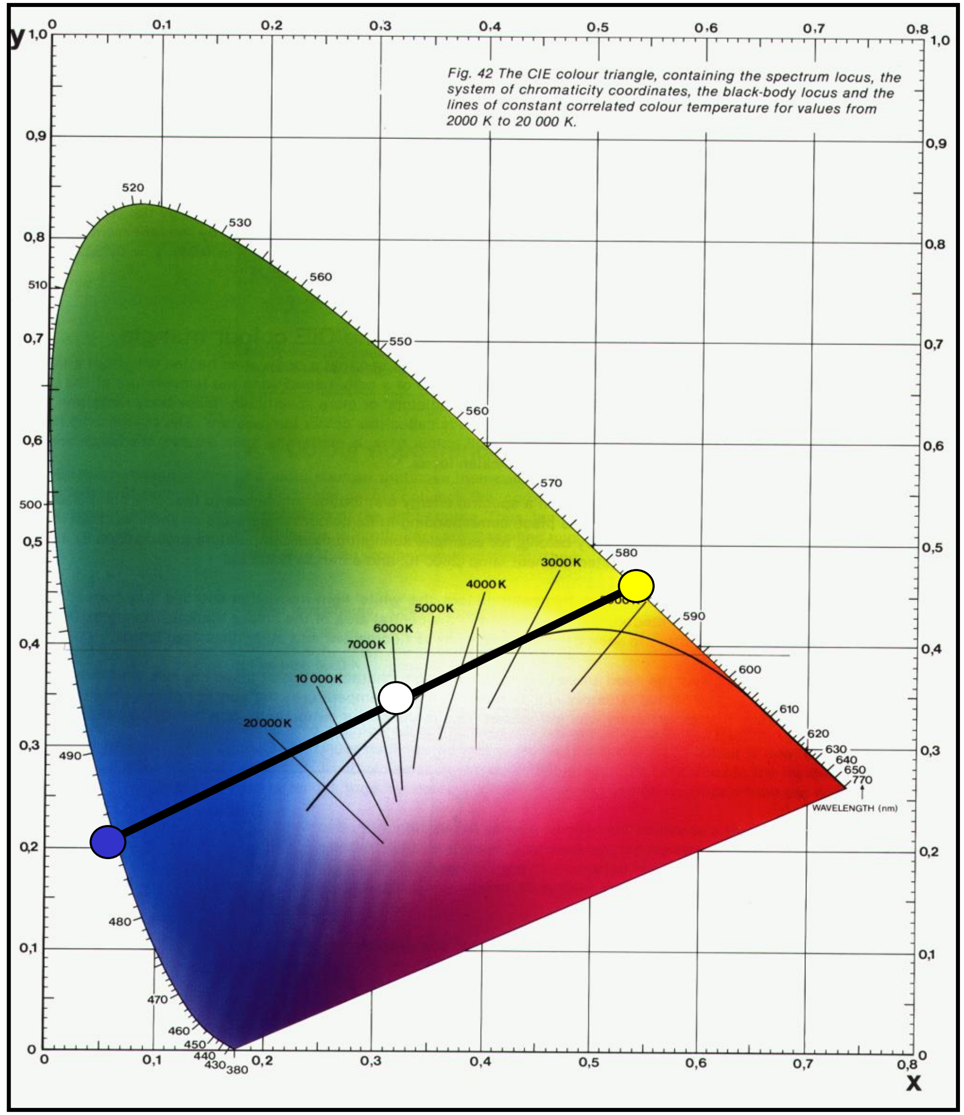
Yellow 585 nm

+ Blue 485 nm

=

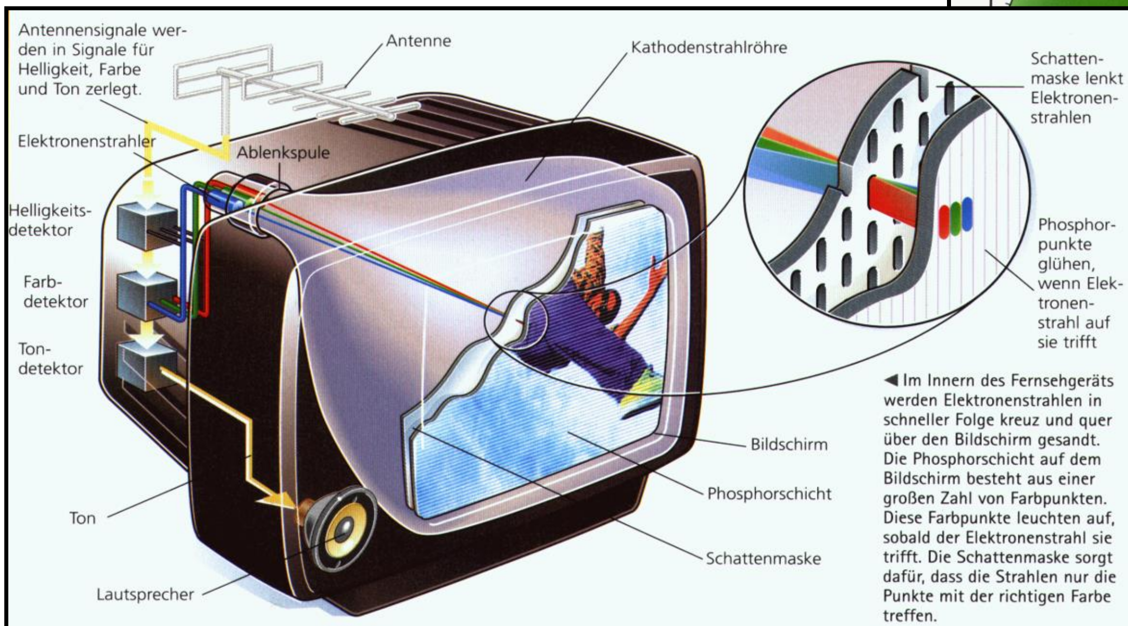
white

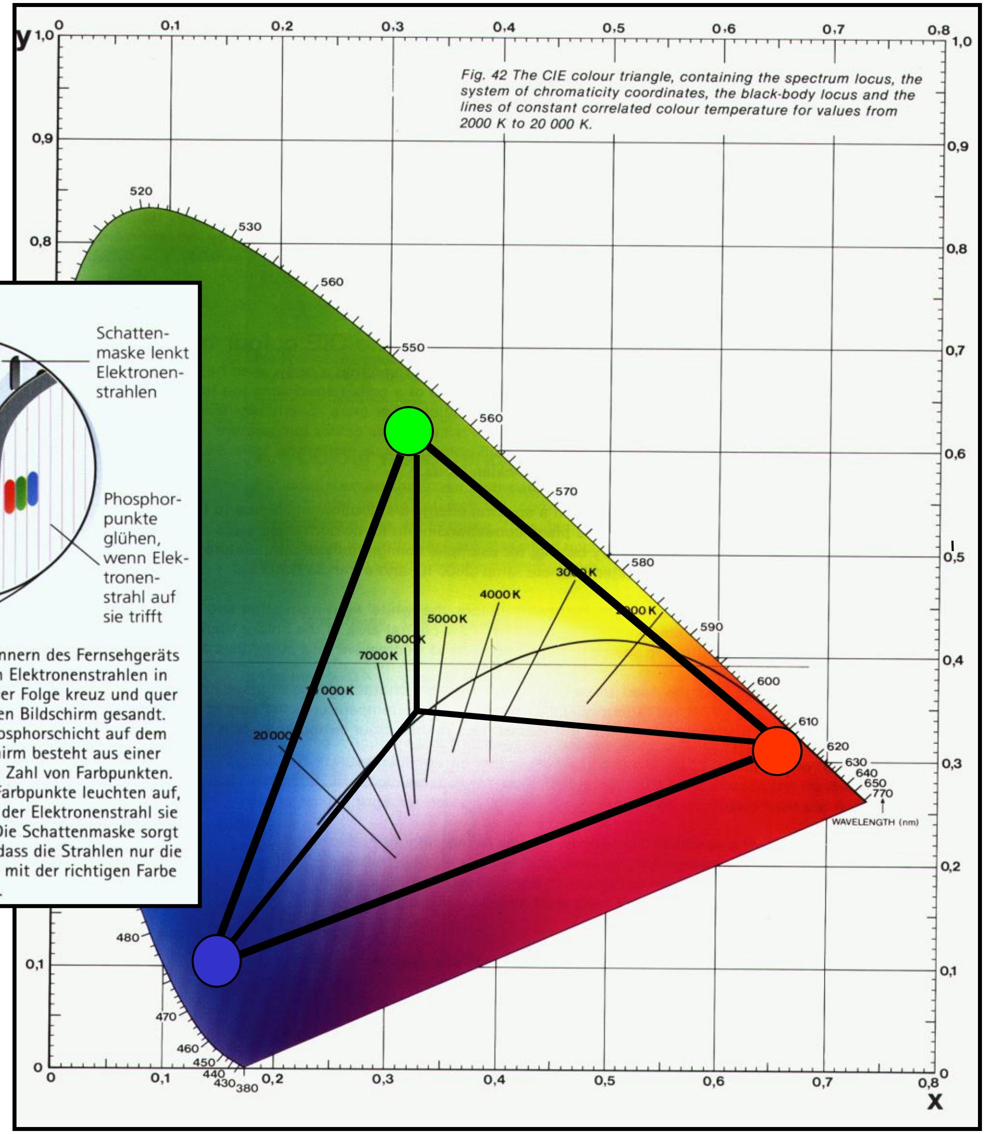




2.6 Colour Coordinates

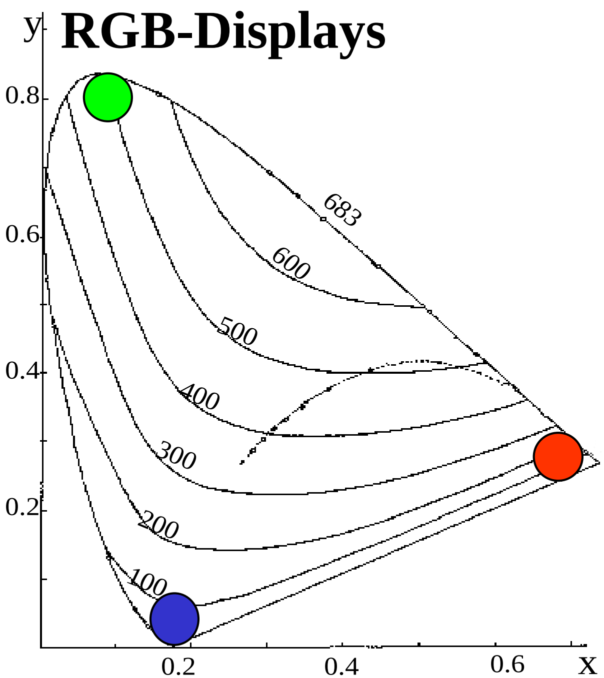
Colour mixing in the Braun‘s tube (Cathode Ray Tube)

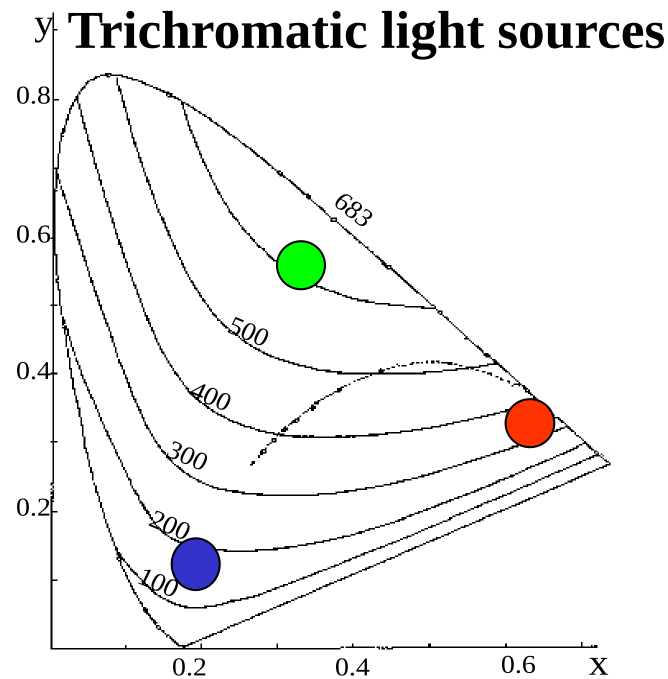




2.6 Colour Coordinates

Colour mixing: Displays vs. Light Sources





The lumen equivalent is a figure concerning the efficiency of conversion of electromagnetic radiation into luminous flux

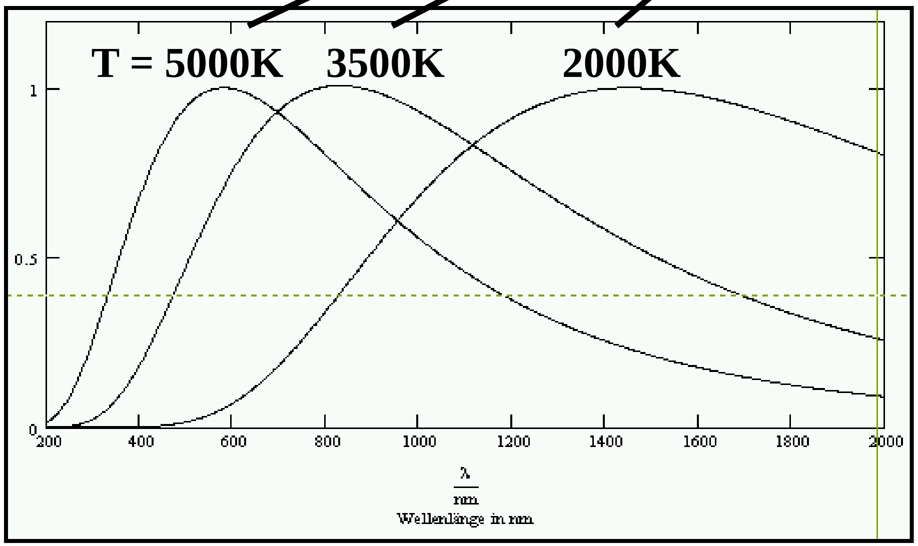
- **Optimal is green emission @ 555 nm**
- **Useful in displays:** **R ~ 630 nm, G ~ 520 nm, B ~ 440 nm**
- **Useful in light sources:** **R ~ 610 nm, G ~ 550 nm, B ~ 460 nm**

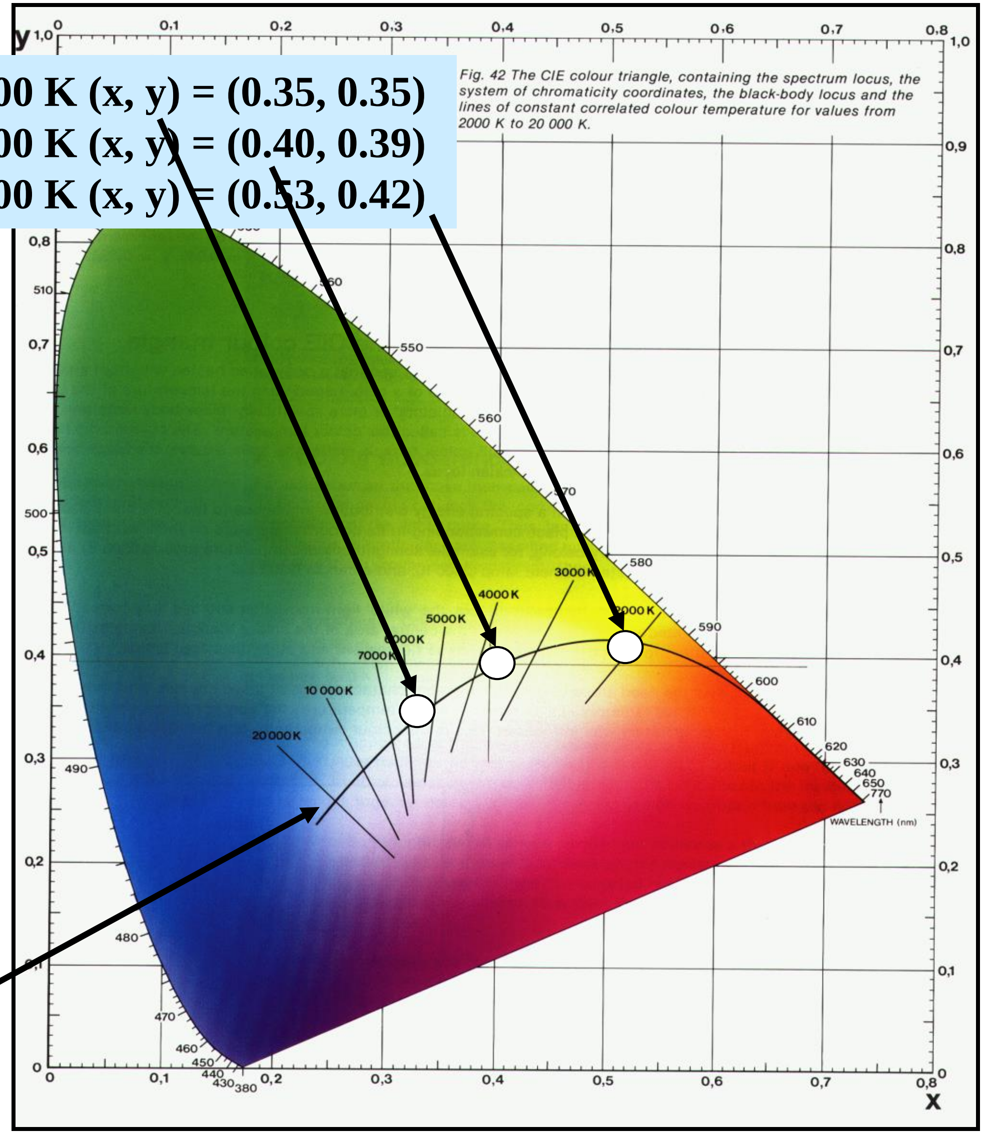
2.7 Colour Temperature

Black body radiators

Spectra of black body radiators

T = 5000 K (x, y) = (0.35, 0.35)
T = 3500 K (x, y) = (0.40, 0.39)
T = 2000 K (x, y) = (0.53, 0.42)





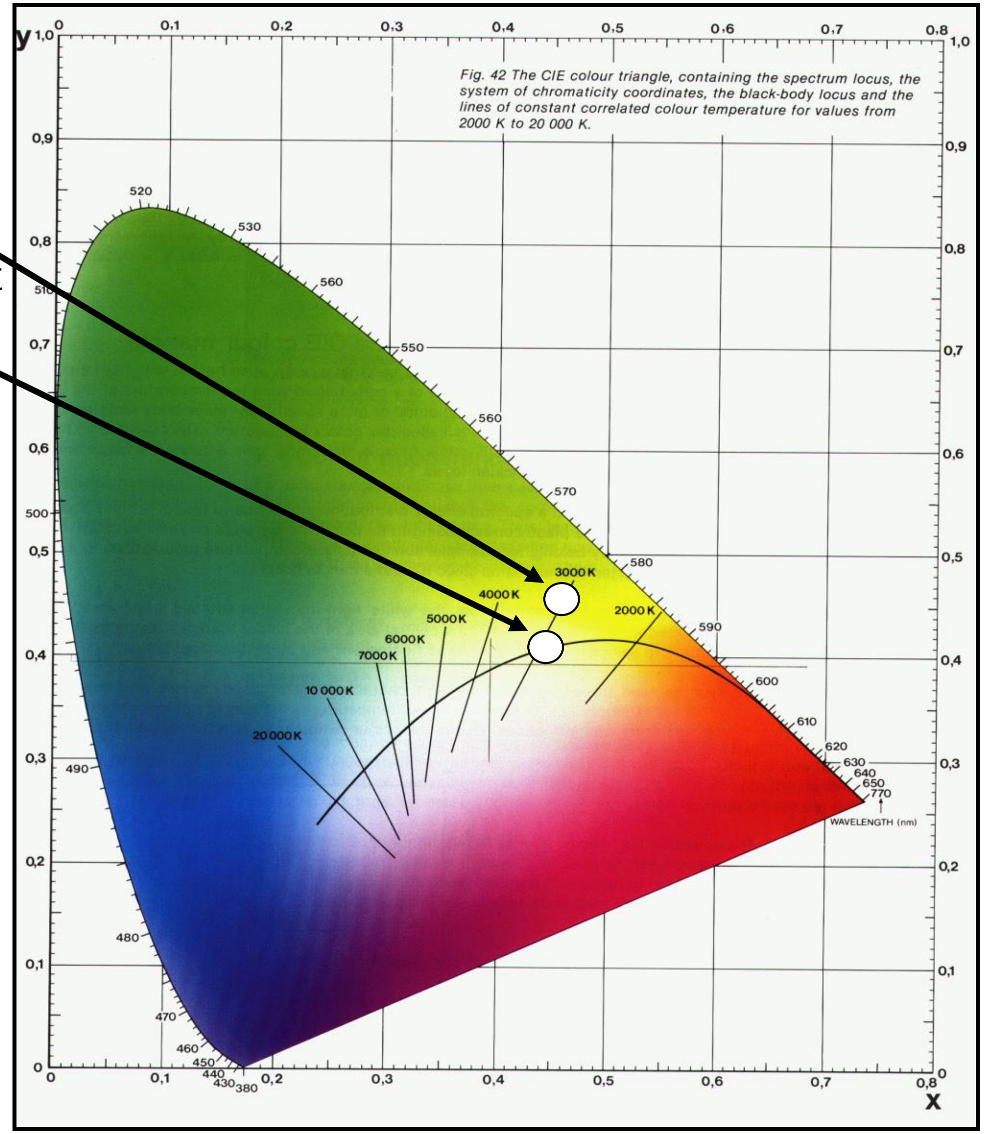
Blackbody line (BBL)
Planckian locus

2.7 Colour Temperature

Other white light sources

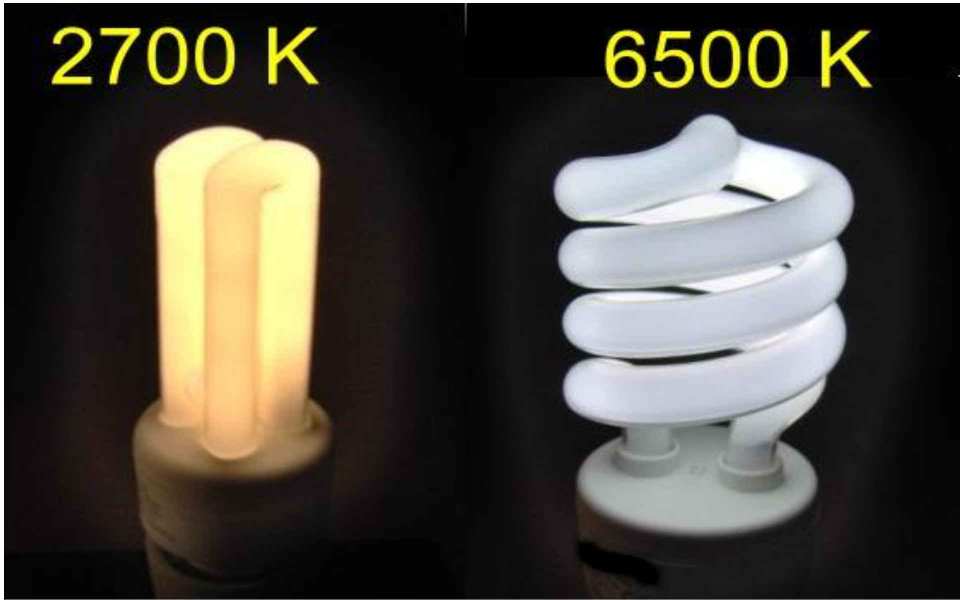
The colour temperature of an arbitrary white light source with a colour point (x, y) relates to a black body, that has a colour point (x‘, y‘) as close as possible to the colour point of the respective light source.
It is also called T_c or CCT (correlated colour temperature) described.

Examples	T_c [K]
Blue sky	15000
Cloudy sky	6500
Standard D65	6500
Fluorescent tube	4000
Halogen lamp	3300
Incandescent lamp	2700
Na-low pressure lamp	1800
Candle	1500



2.7 Colour Temperature

Terms in lighting industry



Energy saving lamps with

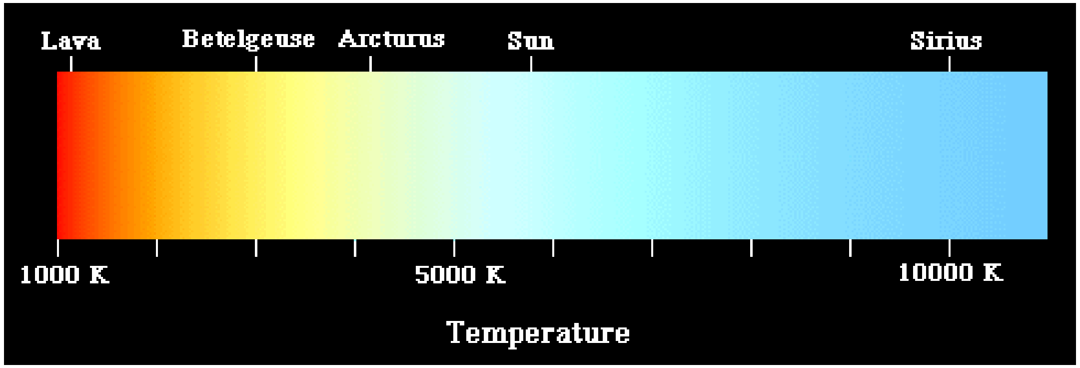
low and high colour temperature

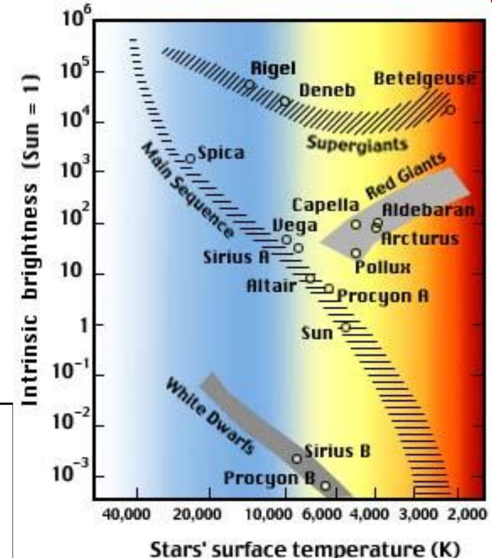
Instead of the CCT [K] lighting industry applies the following terms for their lamps

CCT in Kelvin	Term
2700	extra-warm-white
2900	warm-white
4000	neutral-white
5500	daylight
6500	cool-white

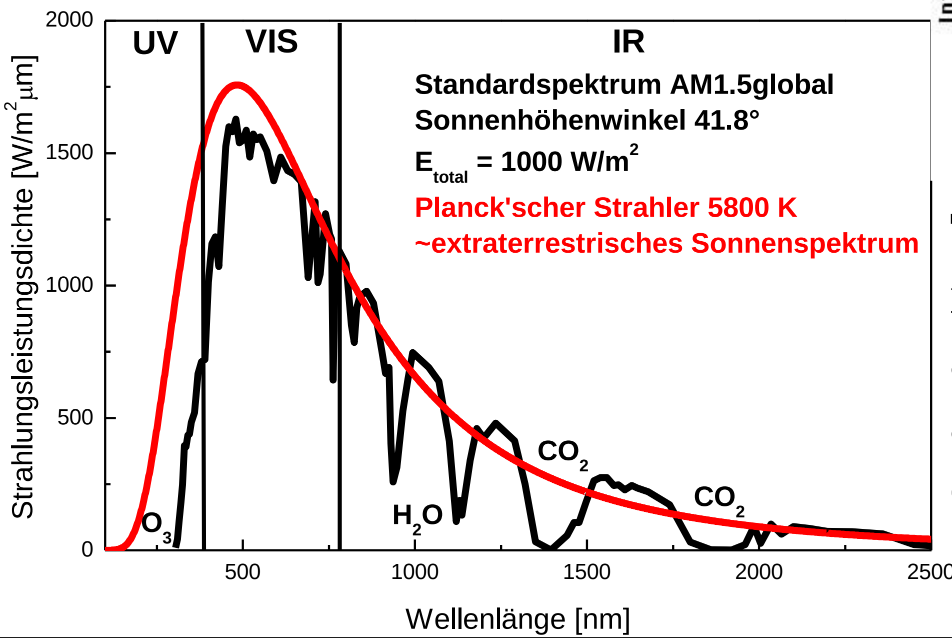
2.7 Colour Temperature

Stars: Good examples for a black body, i.e. the colour temperature corresponds approximately to their surface temperature (Fraunhofer lines are spectral narrow)





Terrestrial (AM1.5) and extraterrestrial solar spectrum



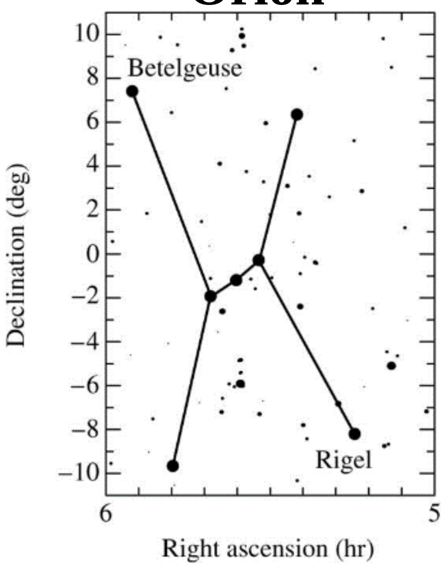
The solar spectrum is modulated due to atmospheric extinction as function of the elongation of the sun

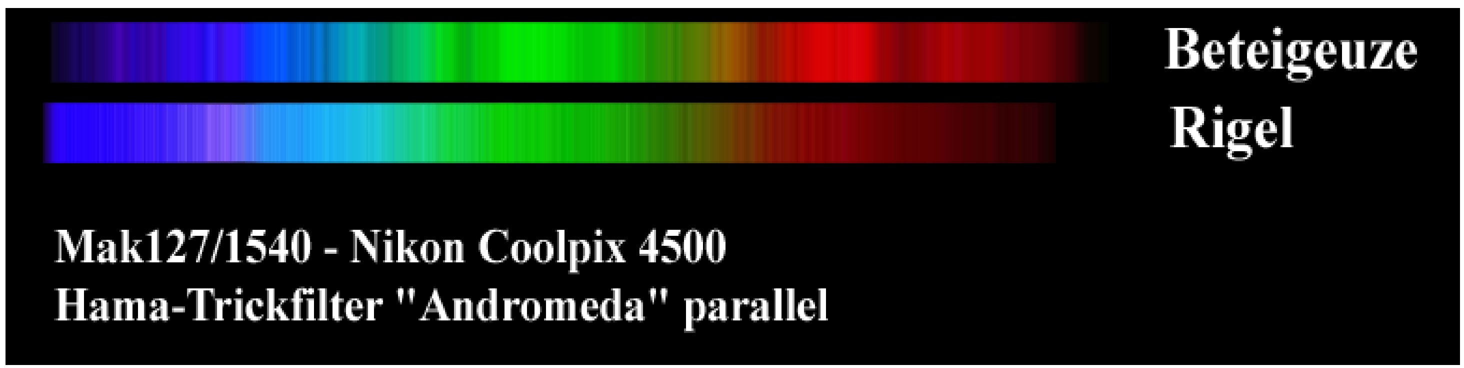
2.7 Colour Temperature

Stars: The stellar spectrum defines the daylight spectrum of the orbiting planets. In case of earth one speaks of the solar spectrum

Betelgeuse **Sun** **Rigel**

Constellation Orion





→ **Impact on astrophysics and astrobiology**

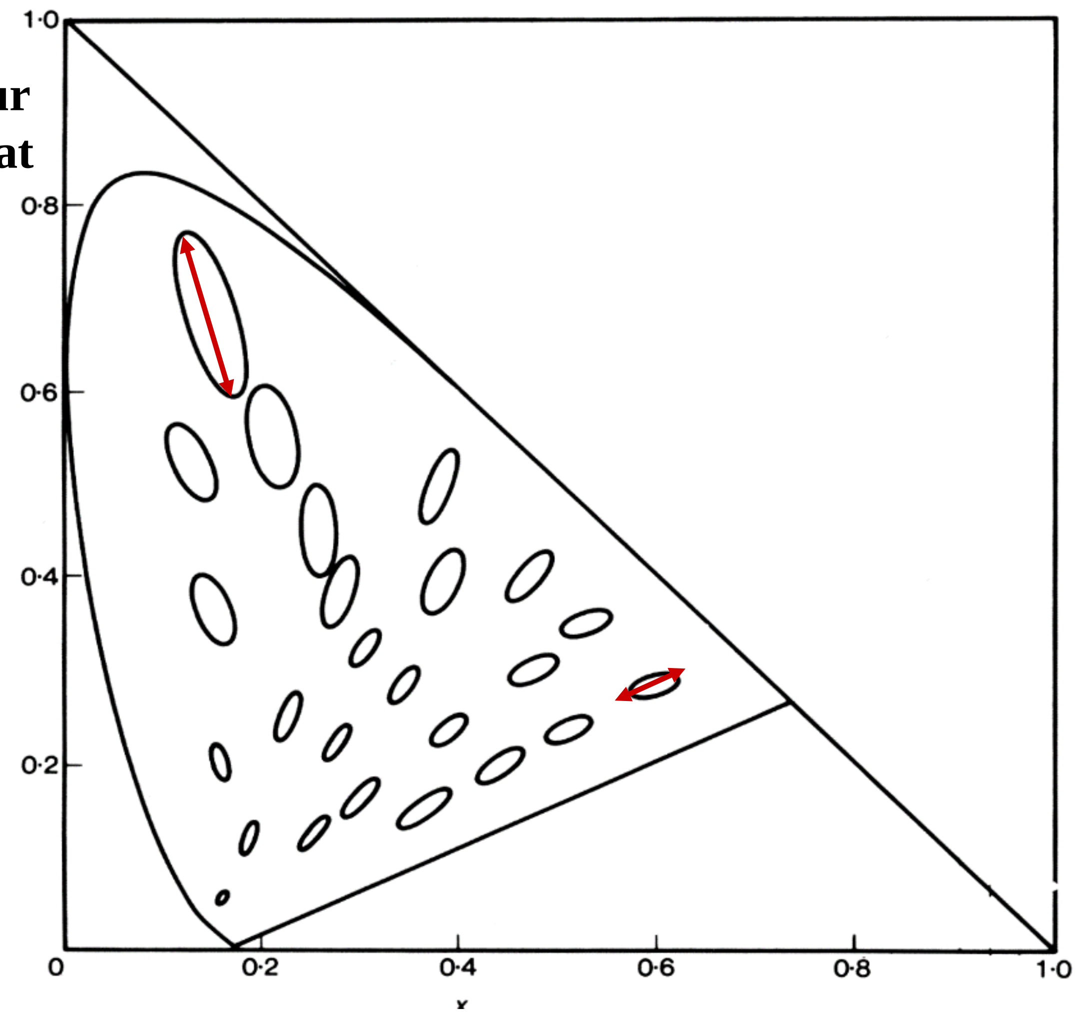
2.7 Colour Temperature

MacAdam ellipses

They indicate how should differ the colour points of two different light sources so that these light sources can be distinguished by their colours.

All colours inside of the ellipses are perceived by humen eye as identic.

The disadvantage of the x, y coordinate system is that same distances do not correspond to same colour differences.

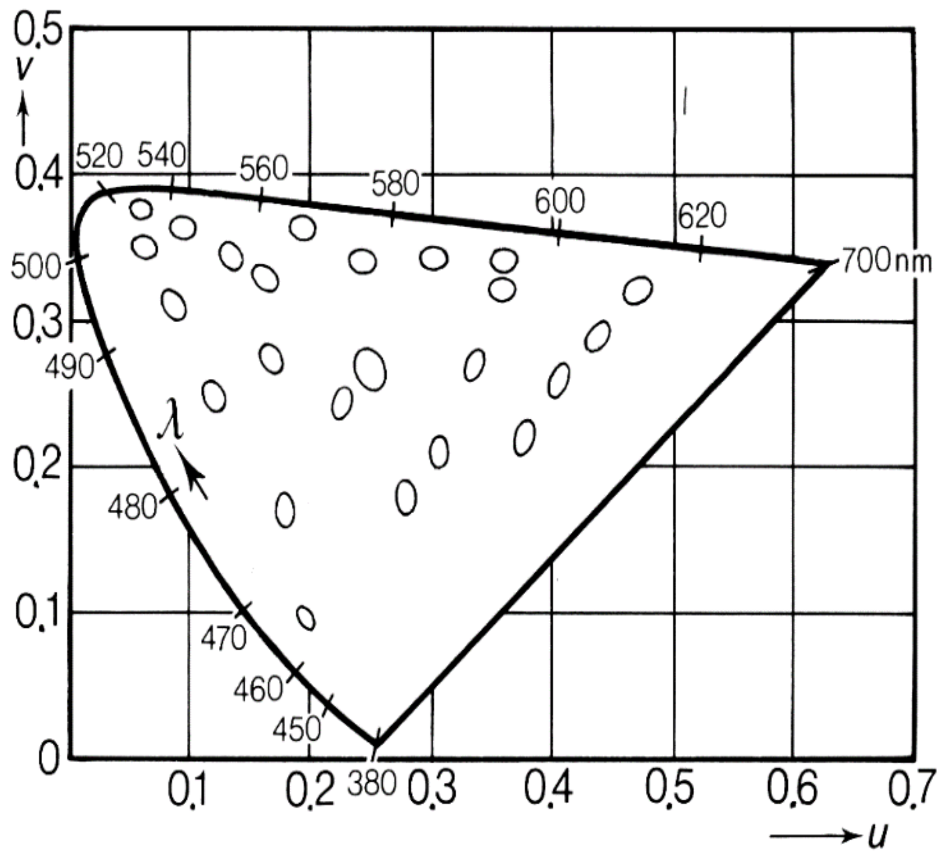


2.7 Colour Temperature

The (u‘, v‘) coordinate system C.I.E. 1976

After transformation of (x, y) coordinates into (u‘, v‘) coordinates one obtains MacAdam ellipses approximately equal circles, i.e. the same geometric distances are equal to the same colour differences.

The transformation equations are:



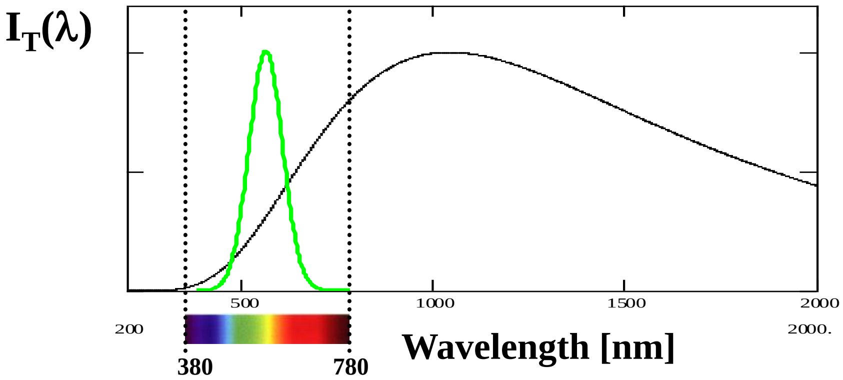
$$u' = \frac{4x}{-2x + 12y + 3}$$

$$v' = \frac{6y}{-2x + 12y + 3}$$

2.8 Colour Rendering

The light quality is described by colour rendering

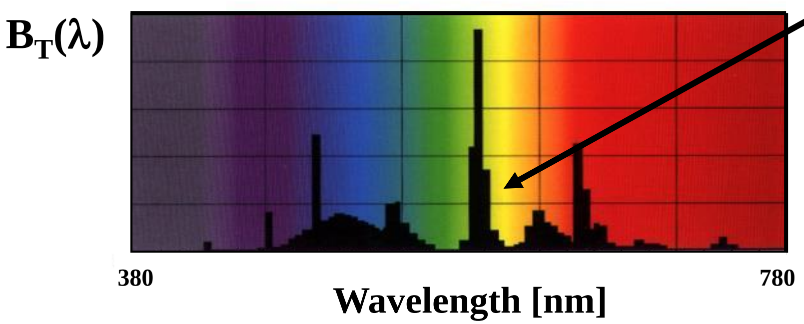
Incandescent lamp



The spectrum contains all colours
⇒ very good light quality

Colour rendering index (CRI) = 100 (by definition for incandescent lamps)

Fluorescent lamp



Certain colours are missing in the spectrum, e.g. yellow colour
⇒ with this light source yellow pigments will be not adequately perceived

Colour rendering index ≤ 100

Mathematical description:

$$I_T(\lambda) \cdot \rho_{gelb}(\lambda) = 0$$

2.8 Colour Rendering

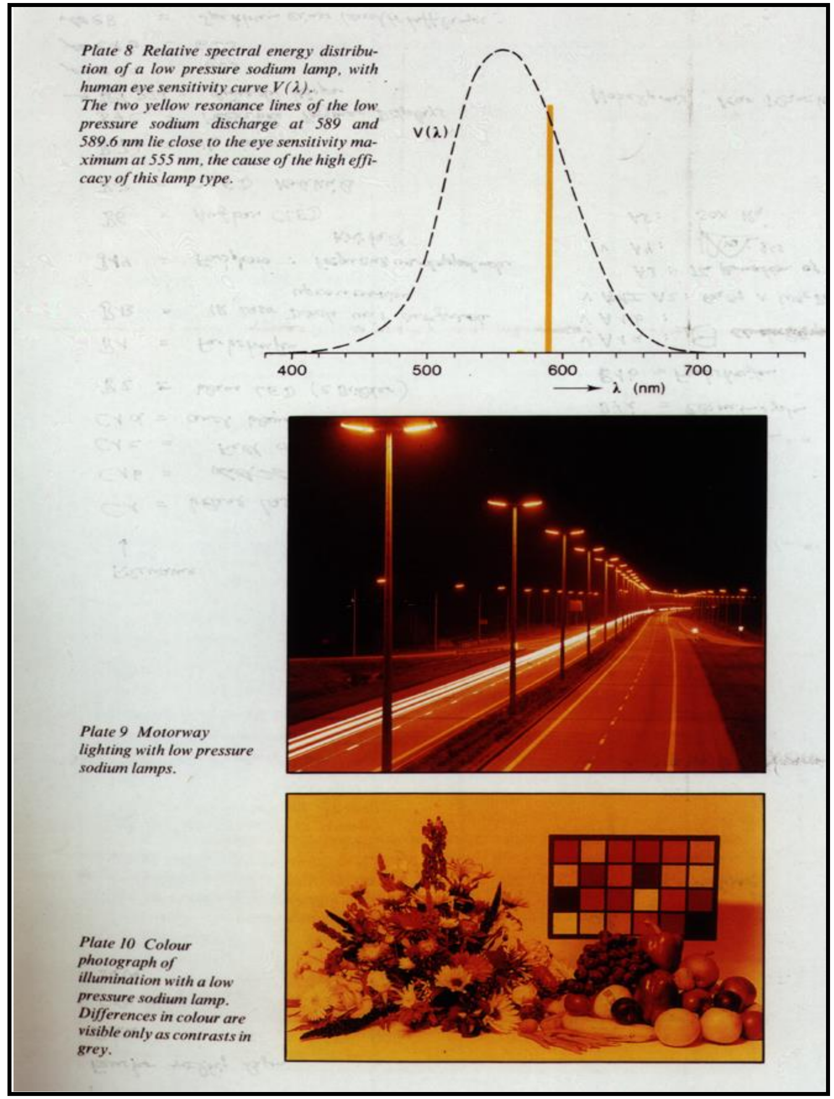
An example of bad light quality

The SOX-lamps (Na - low pressure discharge lamps) emits monochromatic light (589.0 + 589.6 nm) i.e. in the light of these light sources only yellow colour can be perceived by human eye.
Colour rendering index is therefore very low

If CCT < 5000 K a black body radiator is used as standard illuminator (reference light type)

Reference light type	$I_T(\lambda)$
Incandescent lamp	2700 K
D50	5000 K
D65	6500 K

Lit.: Philips Lighting Eindhoven



2.8 Colour Rendering

Determination of the colour rendering index

Definition of R_a (8 test colours)

1st step: Reflection spectra of 8 test colour samples are recorded upon illumination of the test source and of a reference source

2nd step: Following the equations

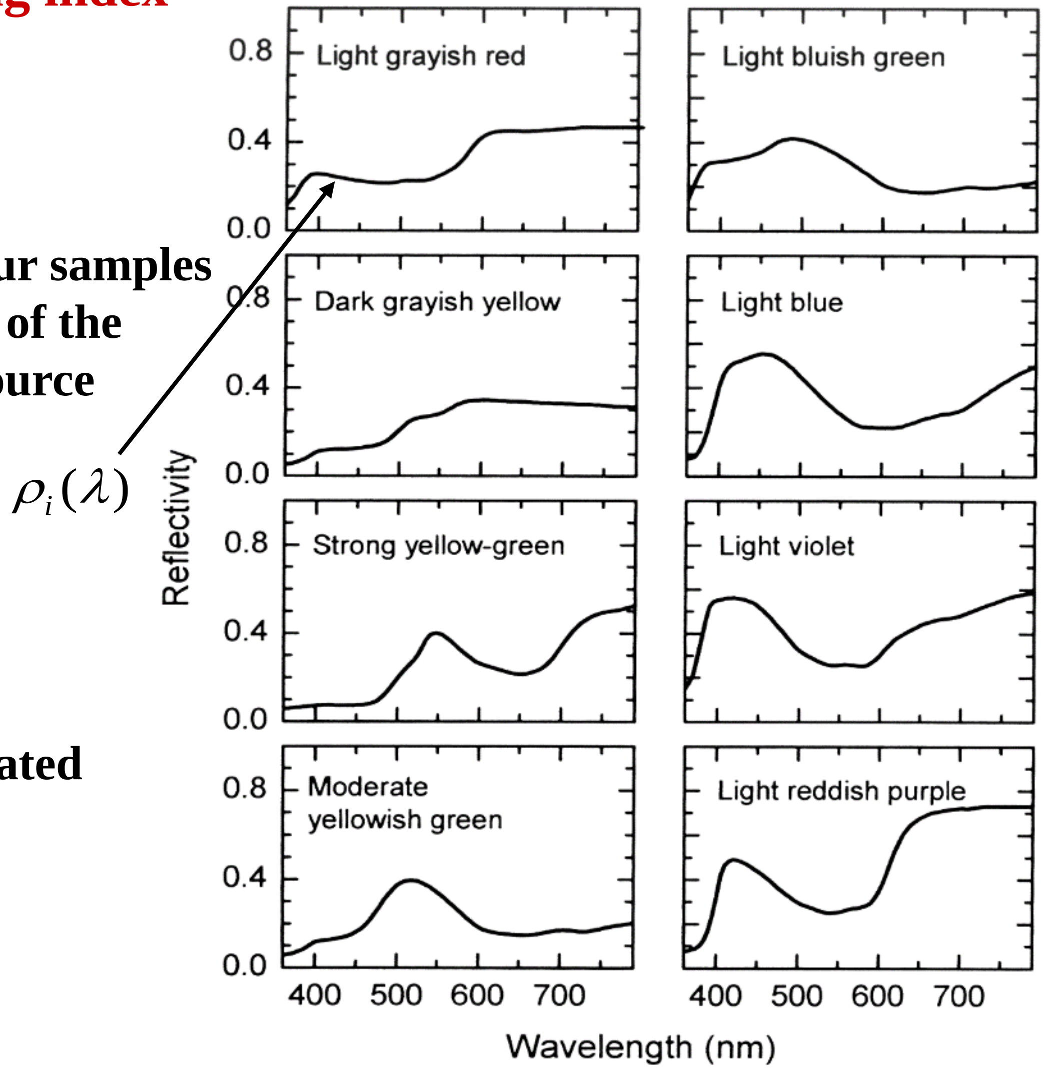
$$I_T(\lambda) \cdot \rho_i(\lambda) \rightarrow (u^*, v^*)$$

$$B_T(\lambda) \cdot \rho_i(\lambda) \rightarrow (\tilde{u}^*, \tilde{v}^*)$$

a colour point distance is calculated

3rd step: $R_i = 100 - 4.6 * \text{distance}$

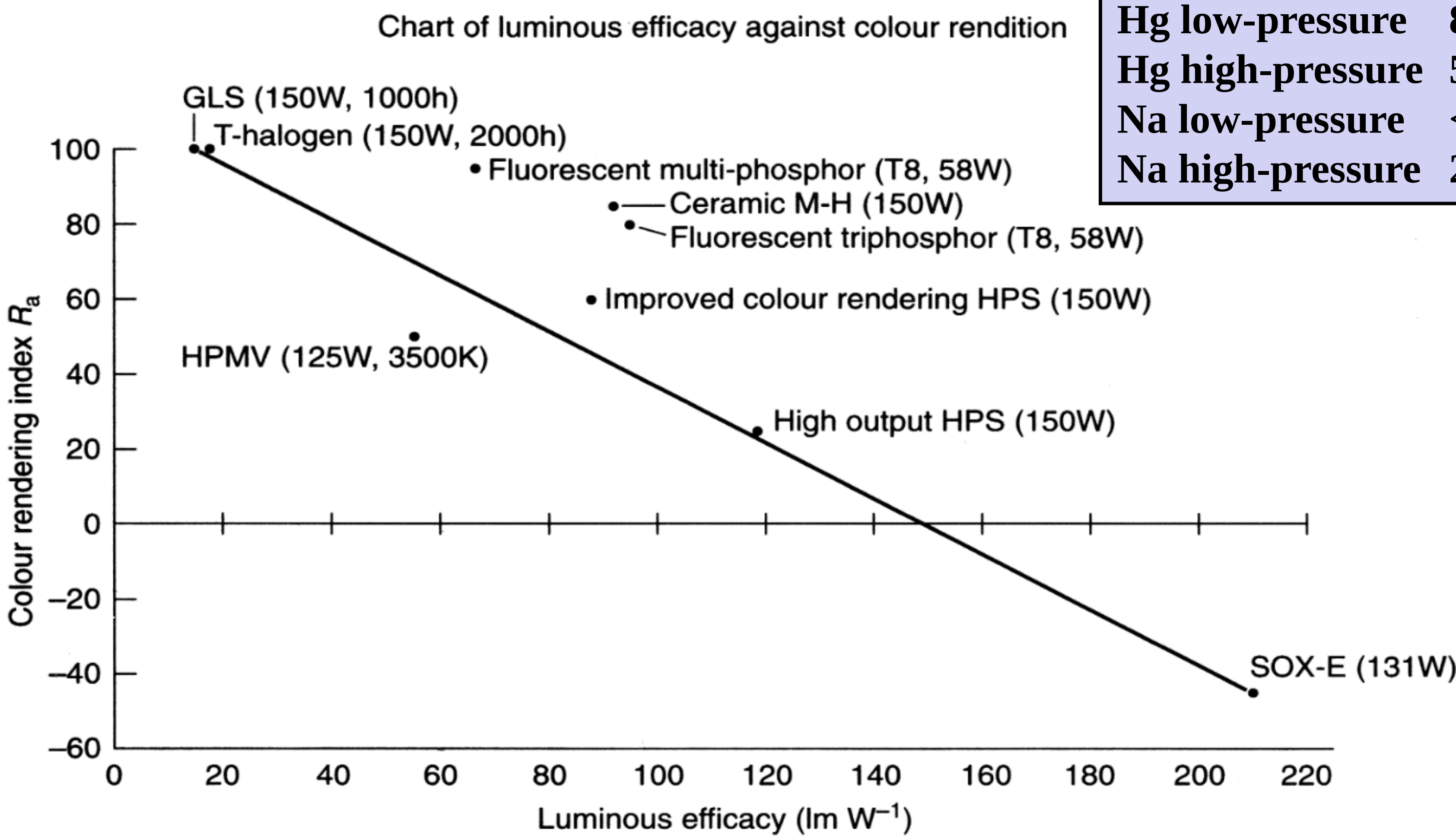
4th step: $R_a = 1/8 * (R_1 + \ldots + R_8)$



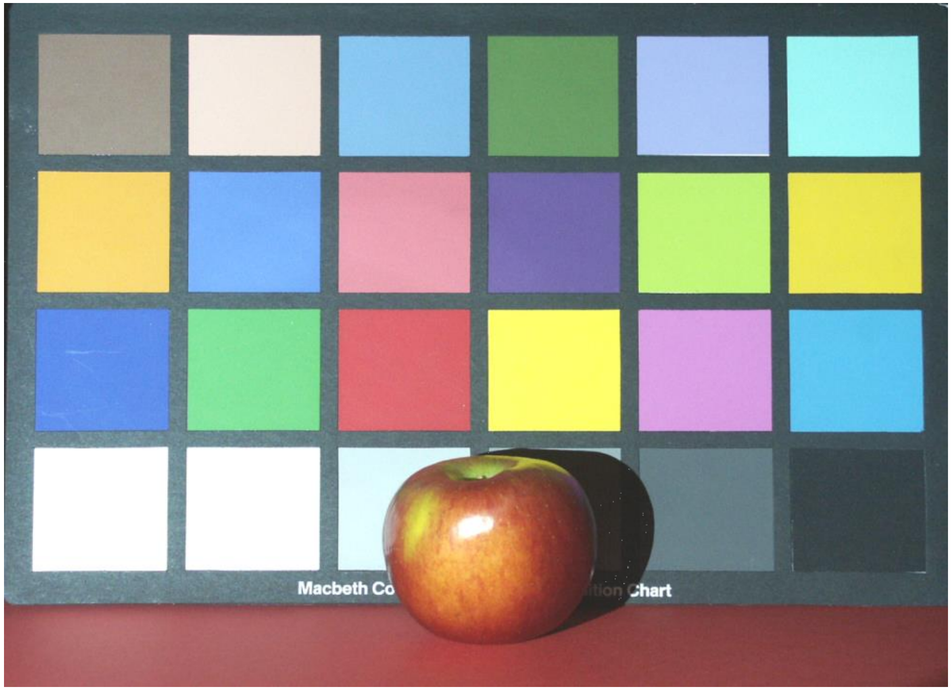
2.8 Colour Rendering

Efficiency vs. colour rendering index (CRI)

Lamp type	CRI value
Incandescent	100
Hg low-pressure	80
Hg high-pressure	50
Na low-pressure	< 0
Na high-pressure	20

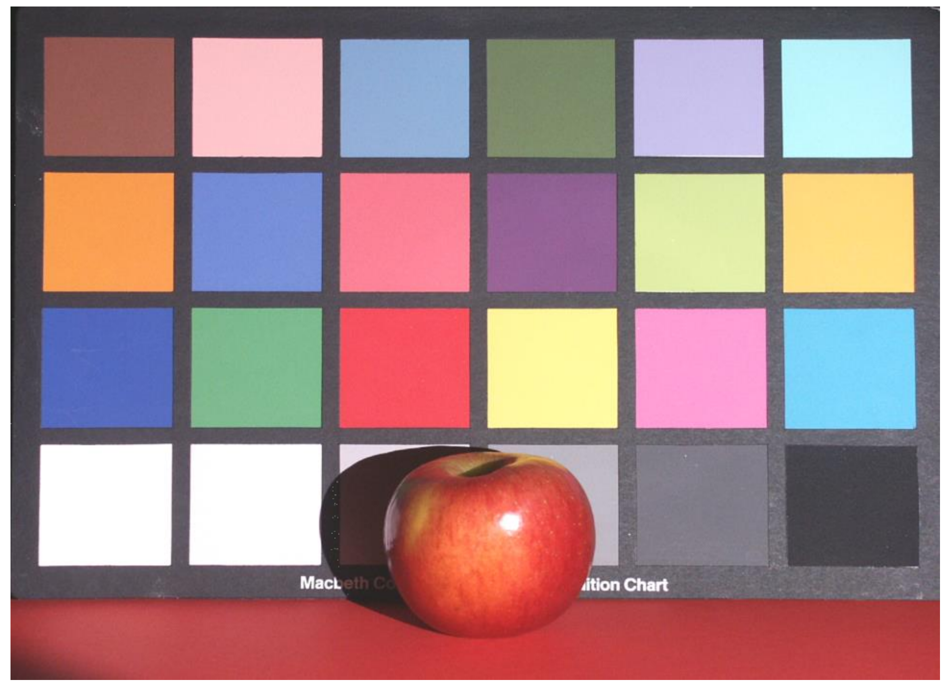


2.8 Colour Rendering

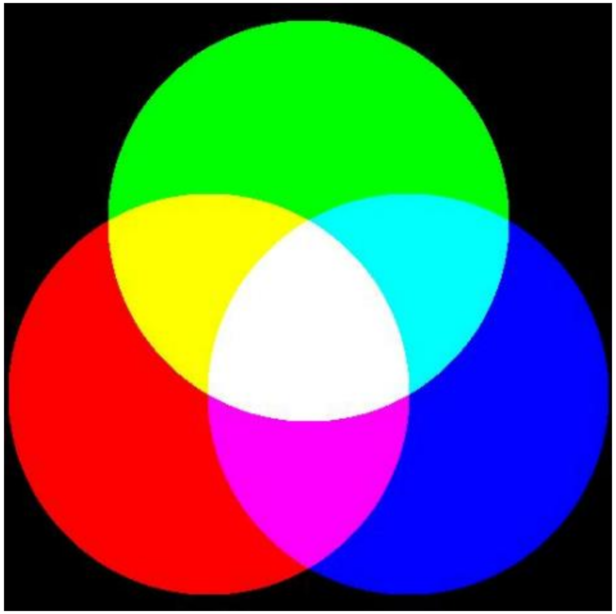


$Ra_8 \cong 65$

$Ra_8 \cong 95$

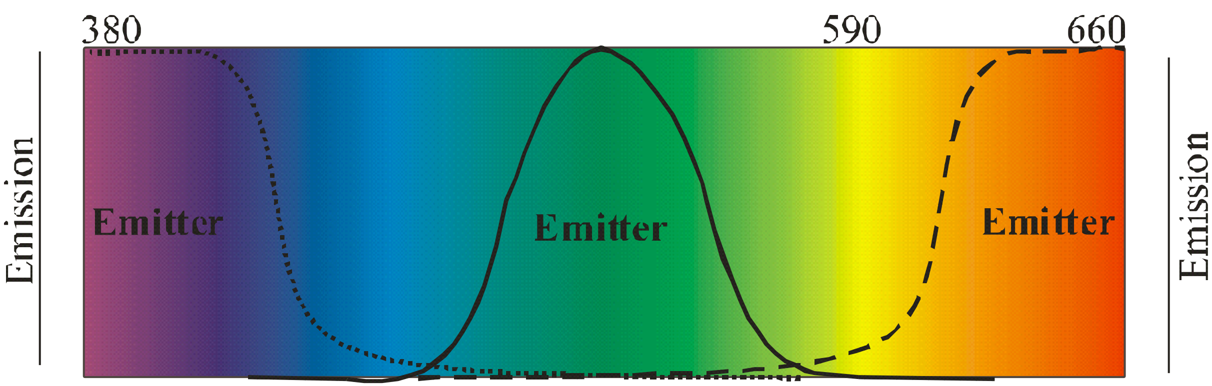


2.9 Additive Colour Mixing



Primaries: blue, green, red

- **The colour impression of a light source originates from overlapping primary colours which are part of the emitted spectrum**
- **Brightness increases upon addition**
- **Colourfulness declines**



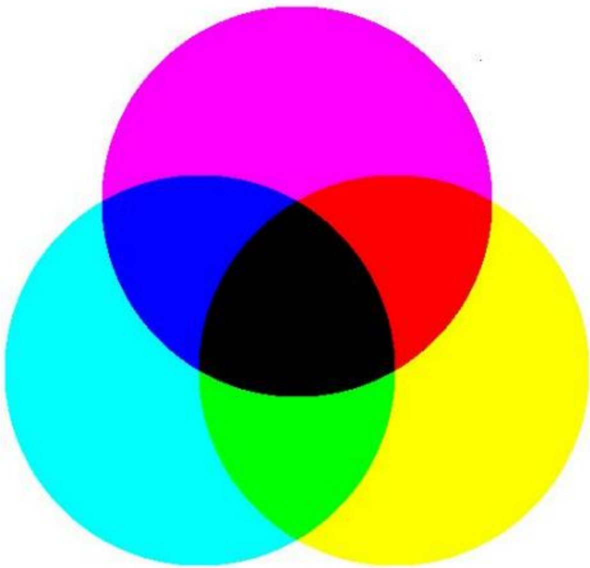
Blue + Red = Magenta

Red + Green = Yellow

Green + Blue = Cyan

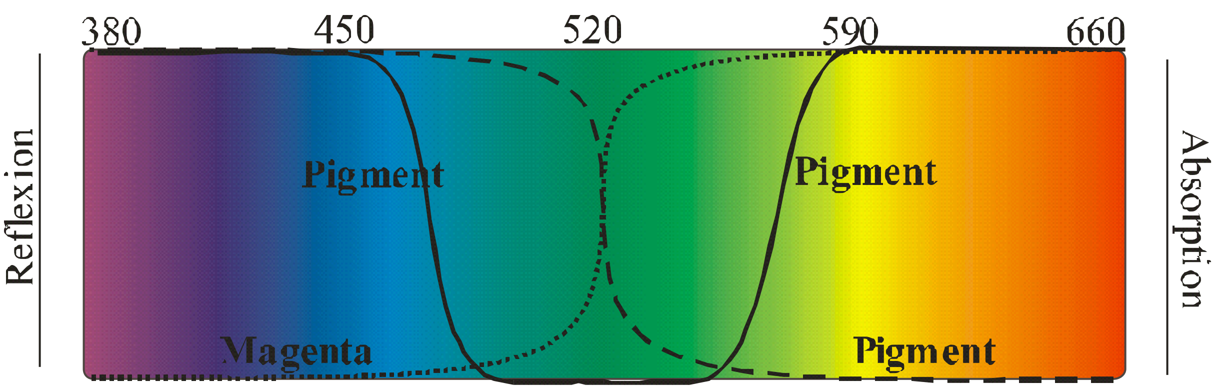
Light sources, Displays

2.10 Subtractive Colour Mixing



Primaries: cyan, magenta, yellow

- **The colour impression of a pigment originates from selective absorption of a given colour from the spectrum of a white light**
- **Brightness decreases upon addition**
- **Colourfulness increases**



Yellow + Cyan = Green

Yellow + Magenta = Red

Magenta + Cyan = Blue

Paintings, Colour printer