Color Measurement

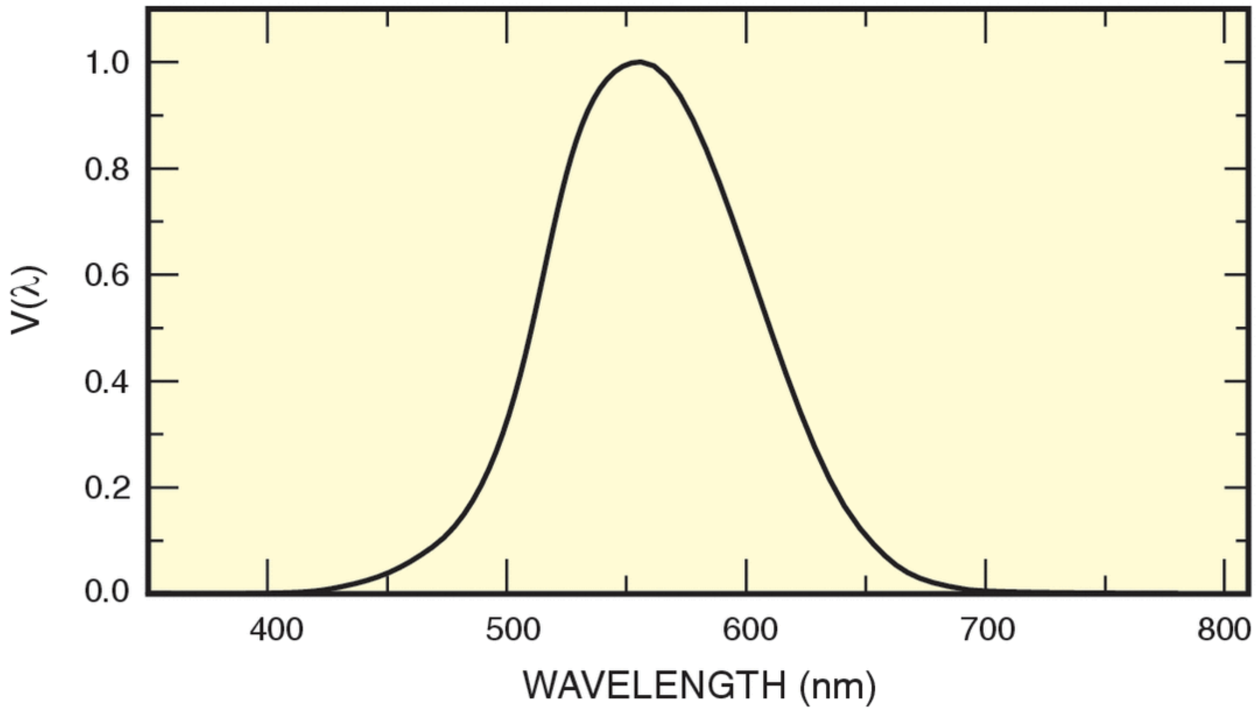
- Quantification of eye response
- Chromaticity diagram
- Spectrometers for color measurement

Terminology

Radiometric	**Spectral**	**Photometric**
Power (Watts)	Spectral Density (Watts-nm^{-1})	Luminous Flux (Lumens)
Irradiance (W-m^{-2})	Spectral Irradiance (W-m^{-2}-nm^{-1})	Illuminance (Lux=Lumens-m^{-2})
Radiant Intensity (W-sr^{-1})	Spectral Intensity (W-sr^{-1}-nm^{-1})	Luminous Intensity (Candela=Lumens-sr^{-1})
Radiance (W-m^{-2}-sr^{-1})	Spectral Radiance (W-m^{-2}-sr^{-1}-nm^{-1})	Luminance (nit=Lumens-m^{-2} –sr^{-1})

Normalized Eye Response

1924 CIE Spectral Luminous Efficiency Function



$$Luminance = (683 Lumens / Watt) \int Radiance(\lambda) \bullet V(\lambda) d\lambda$$

1931 and 1978 CIE Eye Sensitivity Functions

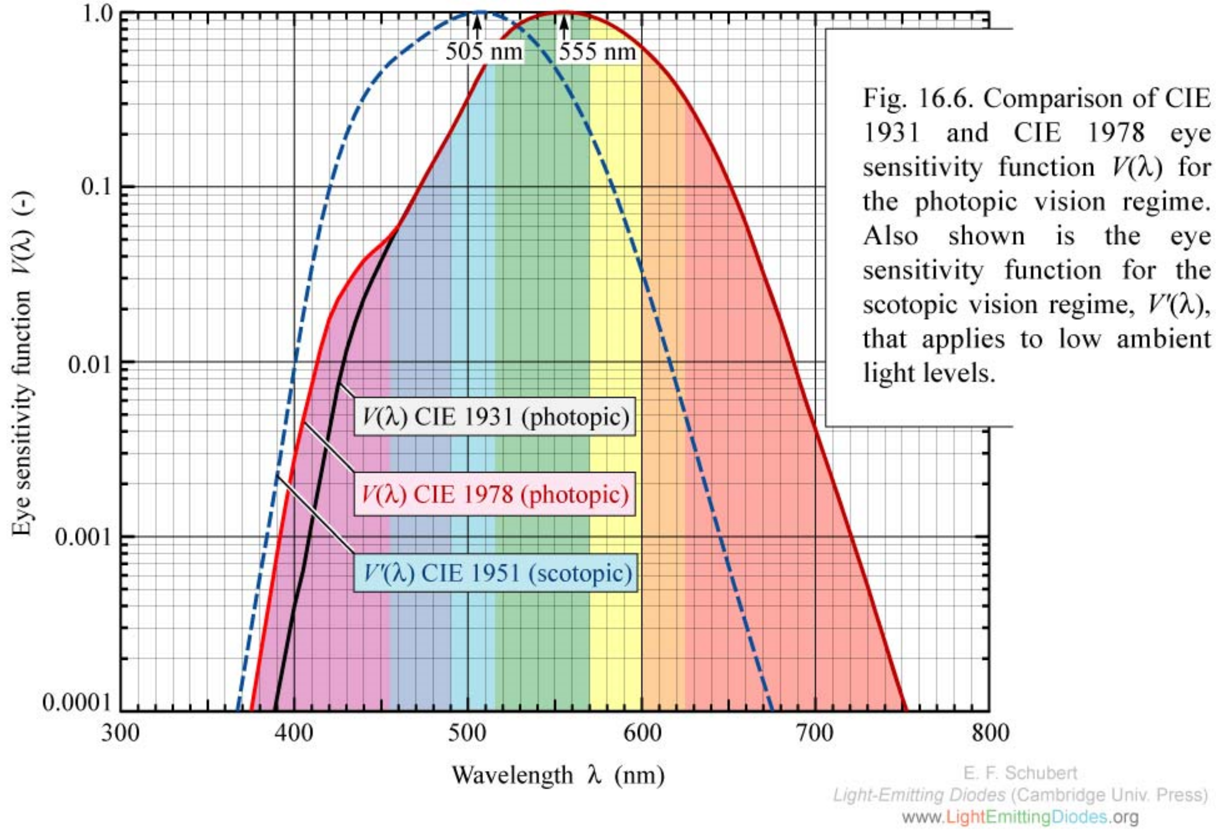


Fig. 16.6. Comparison of CIE 1931 and CIE 1978 eye sensitivity function $V(\lambda)$ for the photopic vision regime. Also shown is the eye sensitivity function for the scotopic vision regime, $V'(\lambda)$, that applies to low ambient light levels.

Luminous Efficacy

Max at 555nm

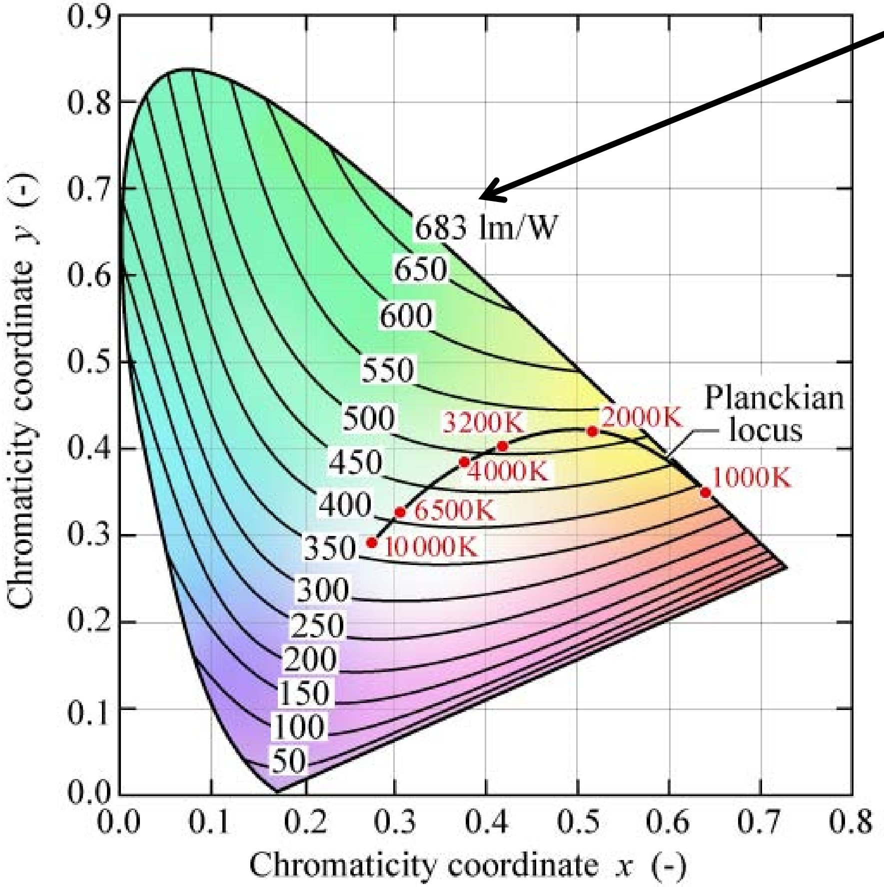


Fig. 16.8. Relation of maximum possible luminous efficacy (lumens per optical Watt) and chromaticity in the CIE 1931 *x*, *y* chromaticity diagram (adopted from MacAdam, 1950).

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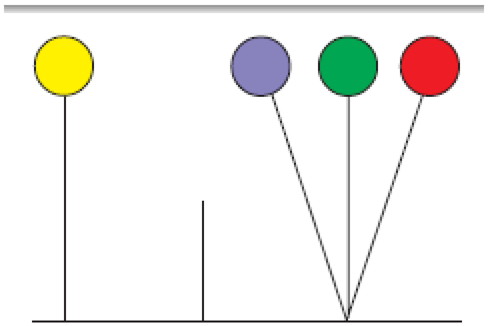
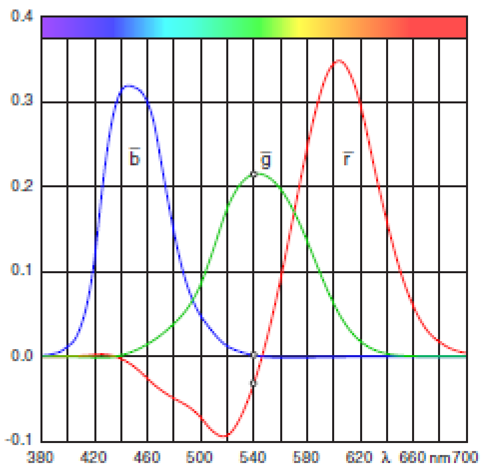
RGB Color Matching





RGB Color-matching functions

- View an arbitrary monochromatic color, D
- Mix monochromatic RGB colors to match
- RGB wavelengths: 435.8, 546.1, 700.0 nm
- Negative R values: R must be added to color D to match with G,B. Then D+R = G+B, or D = G+B-R

CIE Tristimulus Values

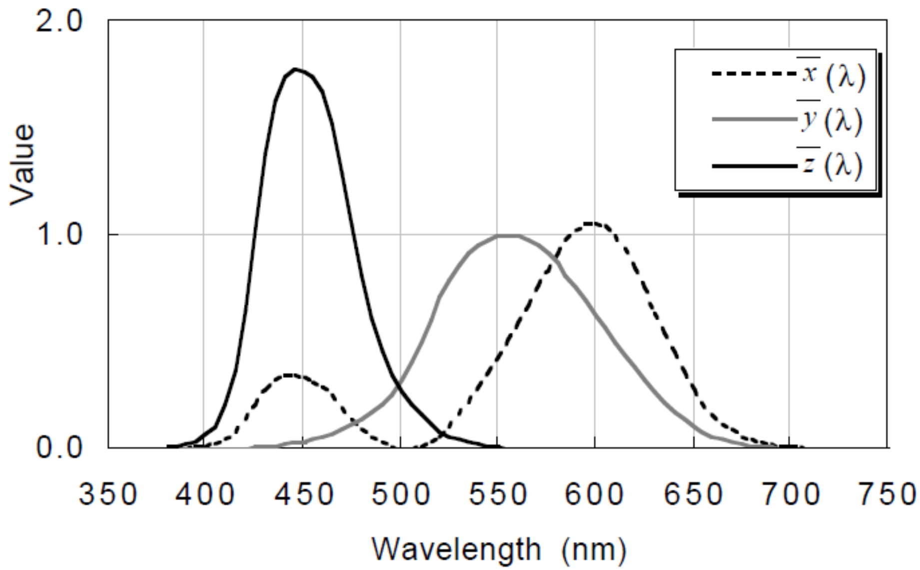


Figure 2 – CIE 1931 XYZ color matching functions.

$$X = k\int_{\lambda} \Phi(\lambda)\bar{x}(\lambda)\mathrm{d}\lambda$$

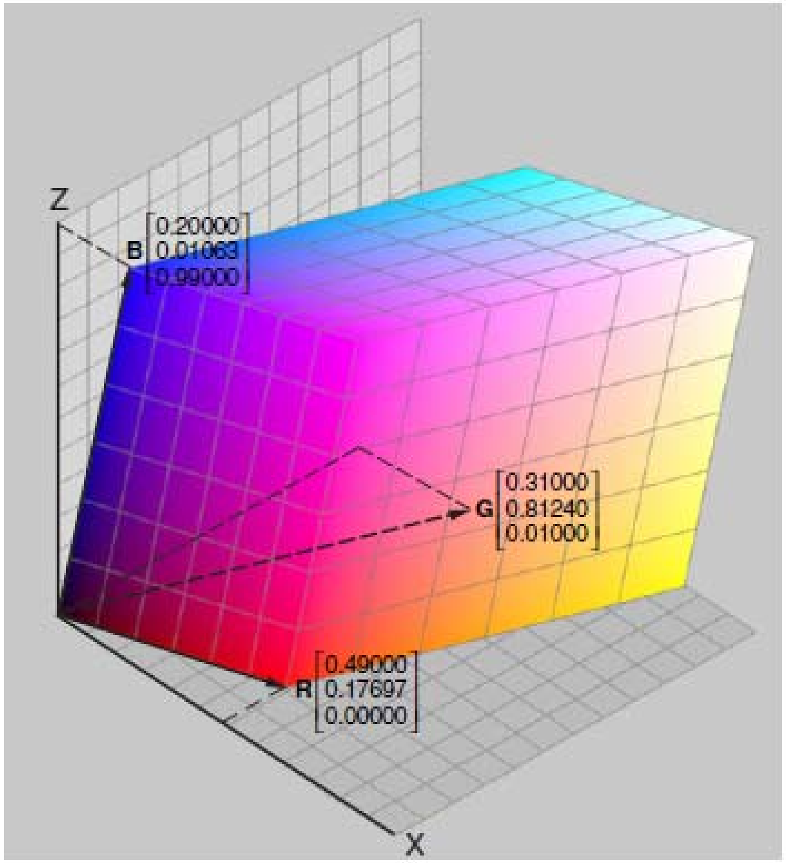
$$Y = k\int_{\lambda} \Phi(\lambda)\bar{y}(\lambda)\mathrm{d}\lambda$$

$$Z = k\int_{\lambda} \Phi(\lambda)\bar{z}(\lambda)\mathrm{d}\lambda\,,$$

Revised to eliminate negative values; RGB → XYZ

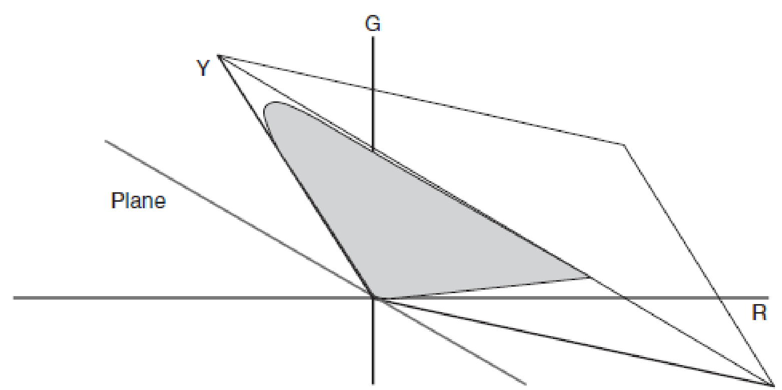
$\phi(\lambda)$ = spectrum to be matched ; k=normalization eg. 683 lm/W

Color Coordinate Transformation



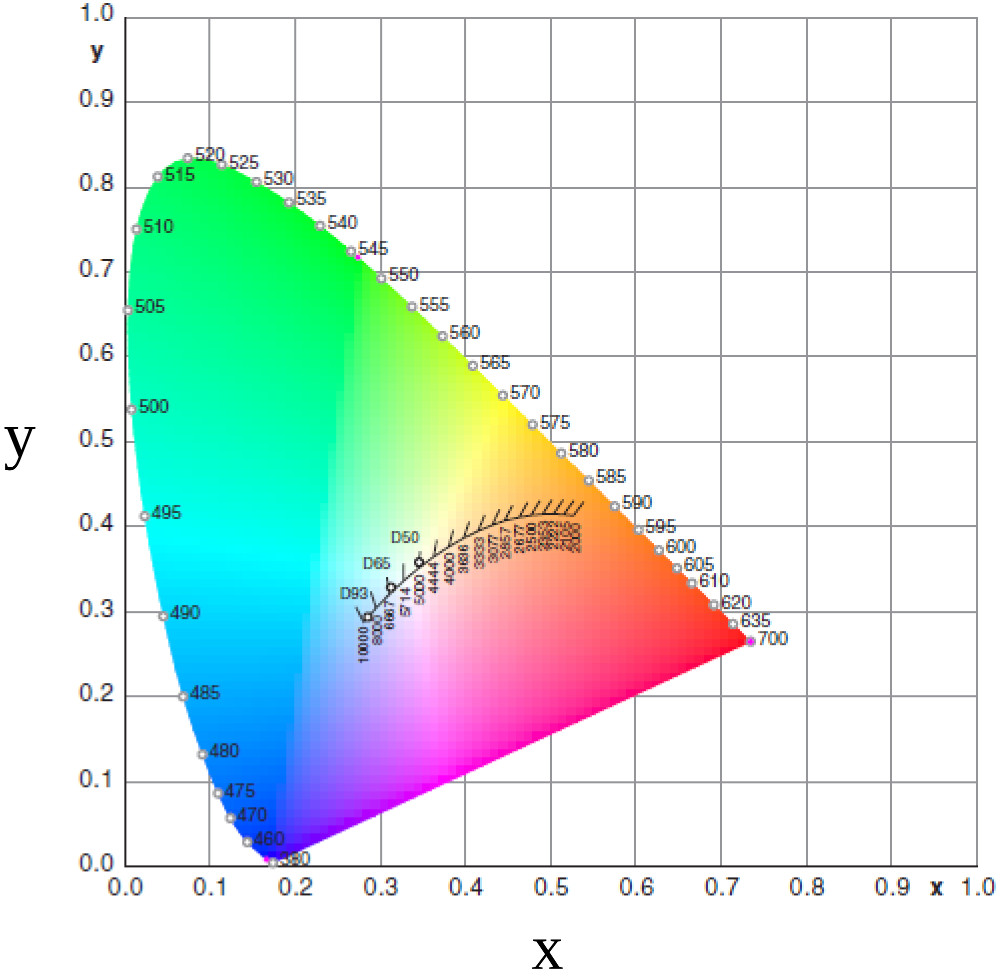
RGB base vectors and color cube in XYZ

- XYZ = linear comb. of RGB
- Colors exist in 3D space
- Project onto 2D plane by demanding coordinates $x + y + z = 1$



2D visualization for RG and XY

Chromaticity Diagram



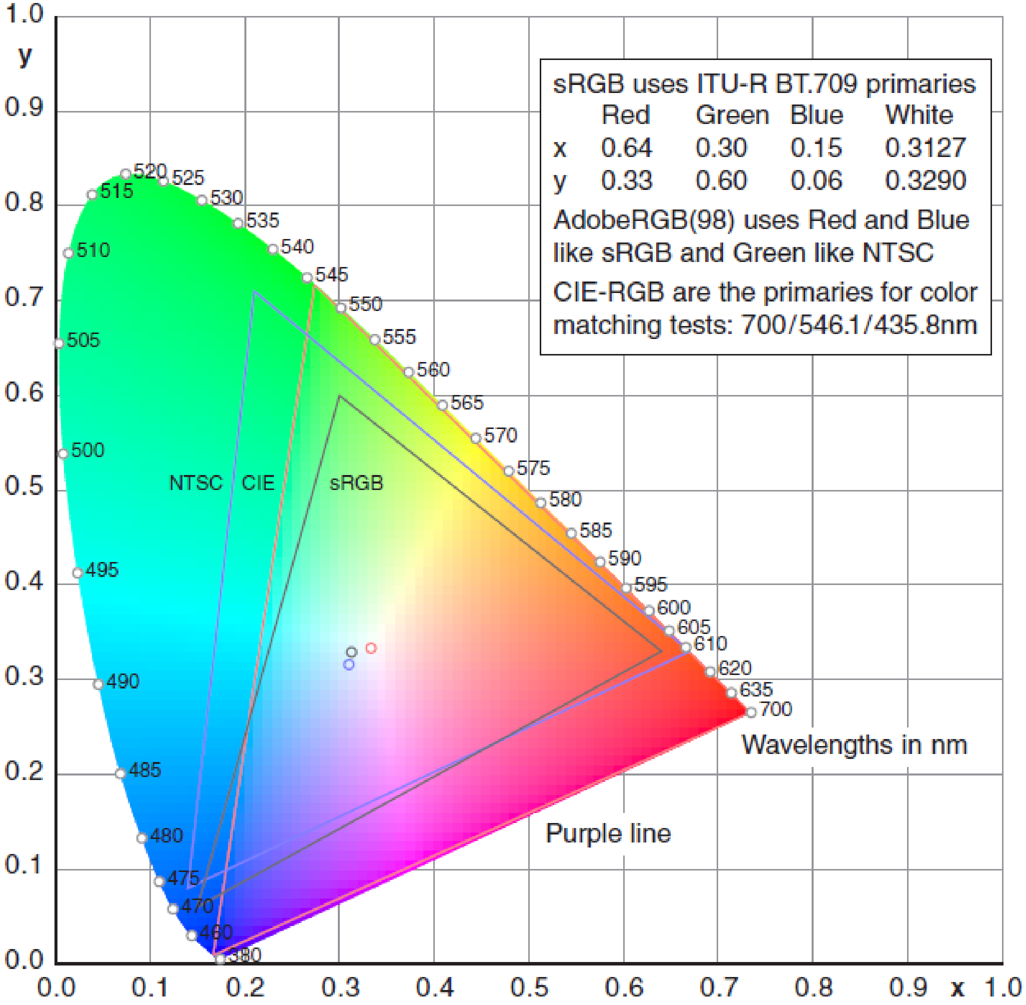
$$x = \frac{X}{X+Y+Z}$$

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

- X=tristimulus value

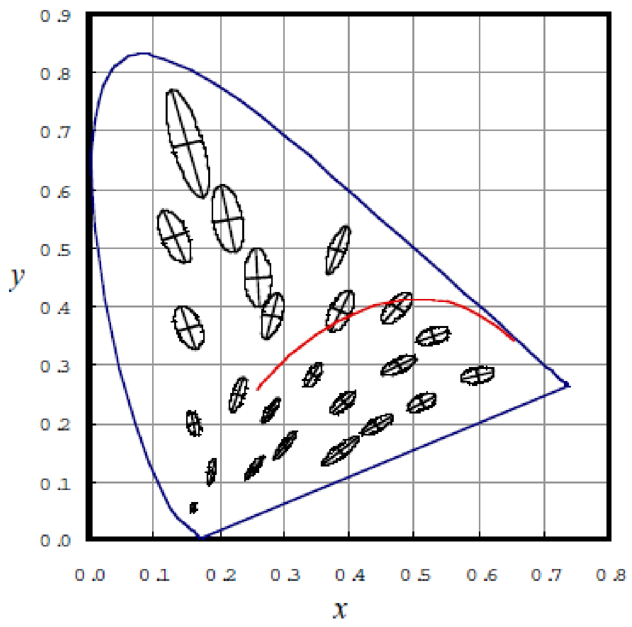
  x = color coordinate

Color Gamut

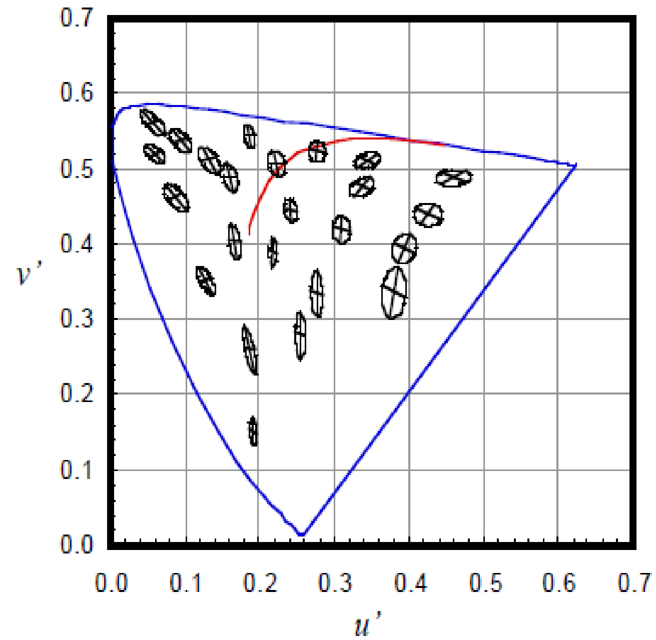


- Gamut = range of colors
- This display does not show full CIE 1931 gamut
- Various standards shown
- Various others proposed

1931 and 1976 Chromaticity Diagrams



(a) CIE 1931 (*x*, *y*) chromaticity diagram

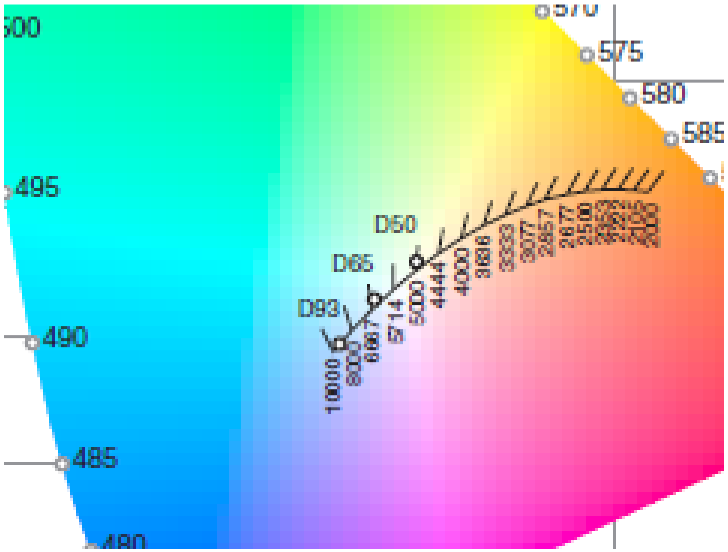


(b) CIE 1976 (*u'*,*v'*) chromaticity diagram

- 1931: “MacAdams ellipses of uniform color are nonuniform
- 1976: u’, v’ derived from x,y to improve uniformity

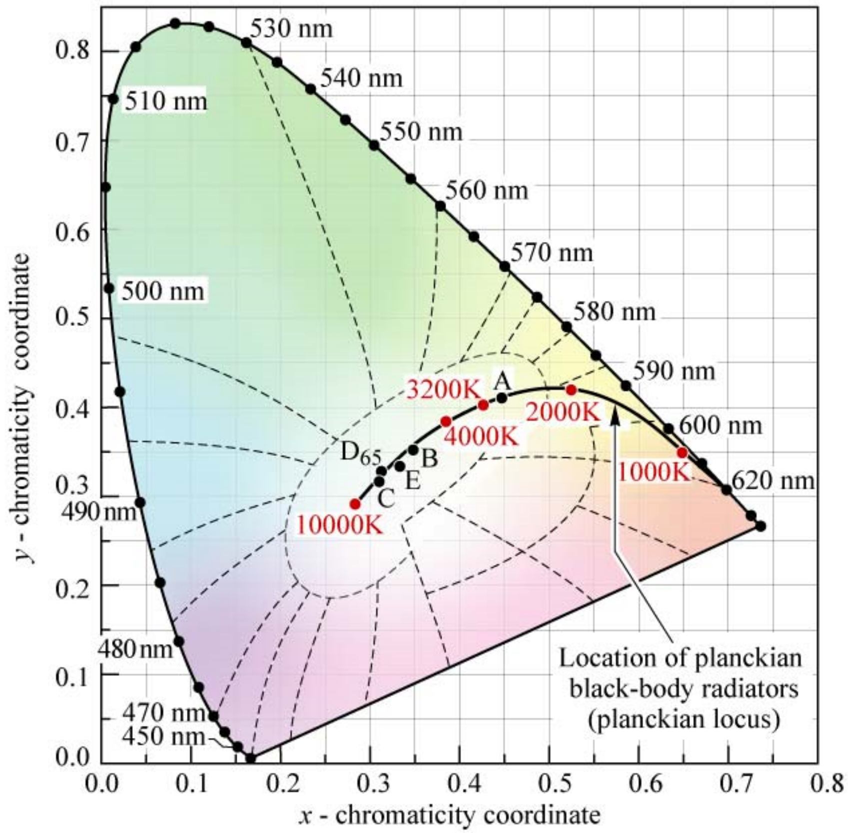
1931 version seems to be preferred

Correlated Color Temperature



- CCT compares color to that of a black body radiator
- CCT = value of closest point on black body (Plankian) curve
- Standard illuminants, eg.
- Illuminant A (CCT 2856) ~ light bulb
- D65 ~ daylight, CCT 6504K

Standard Illuminants



Illuminant A
$(x, y) = (0.4476, 0.4074)$
(Incandescent source, $T = 2856$ K)

Illuminant B
$(x, y) = (0.3484, 0.3516)$
(Direct sunlight, $T = 4870$ K)

Illuminant C
$(x, y) = (0.3101, 0.3162)$
(Overcast source, $T = 6770$ K)

Illuminant D_{65}
$(x, y) = (0.3128, 0.3292)$
(Daylight, $T = 6500$ K)

Illuminant E (equal-energy point)
$(x, y) = (0.3333, 0.3333)$

Fig. 18.3. Chromaticity diagram showing planckian locus, the standardized white Illuminants A, B, C, D_{65}, and E, and their color temperature (after CIE, 1978).

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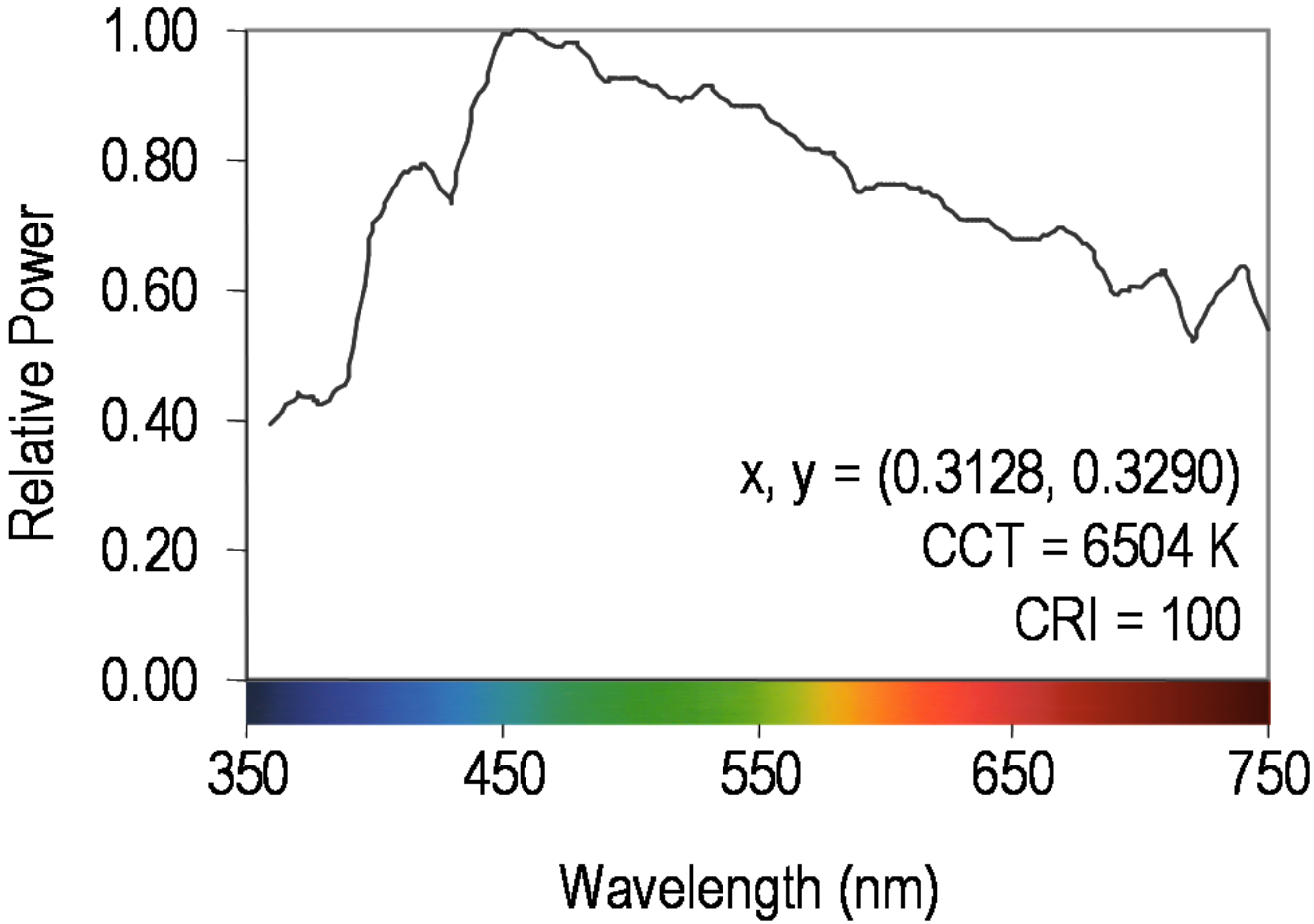
CIE D65 Spectrum



Plankian Locus in (u',v') Diagram

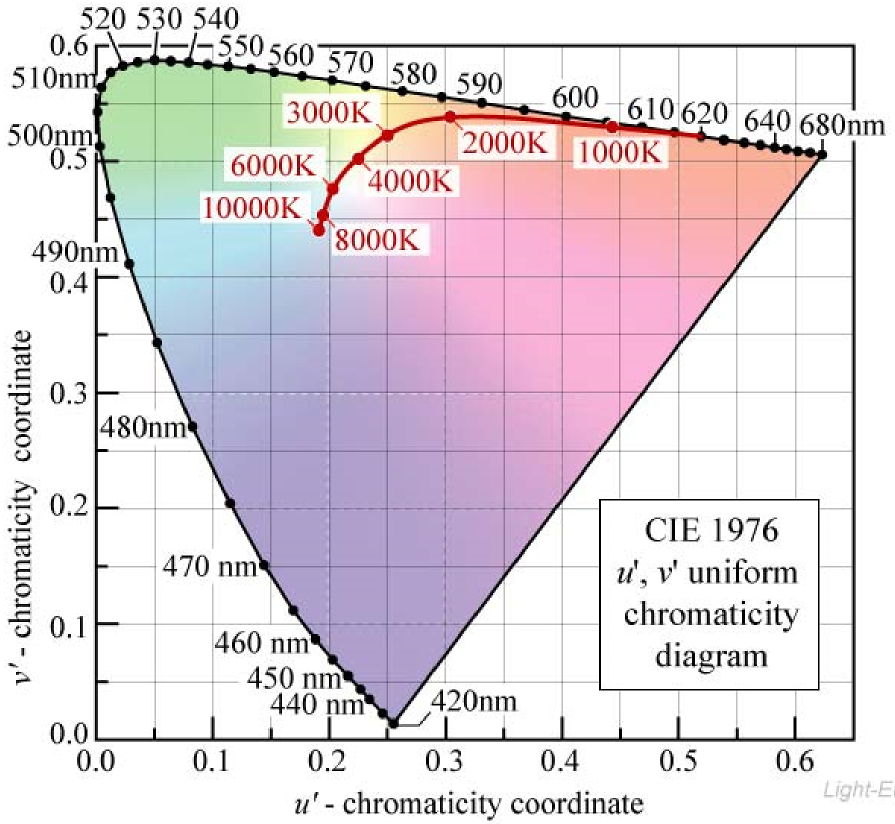


Fig. 18.4. CIE 1976 (*u*', *v*') uniform chromaticity diagram calculated using the CIE 1931 2° standard observer and planckian locus.

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CCT in (u',v') coordinates

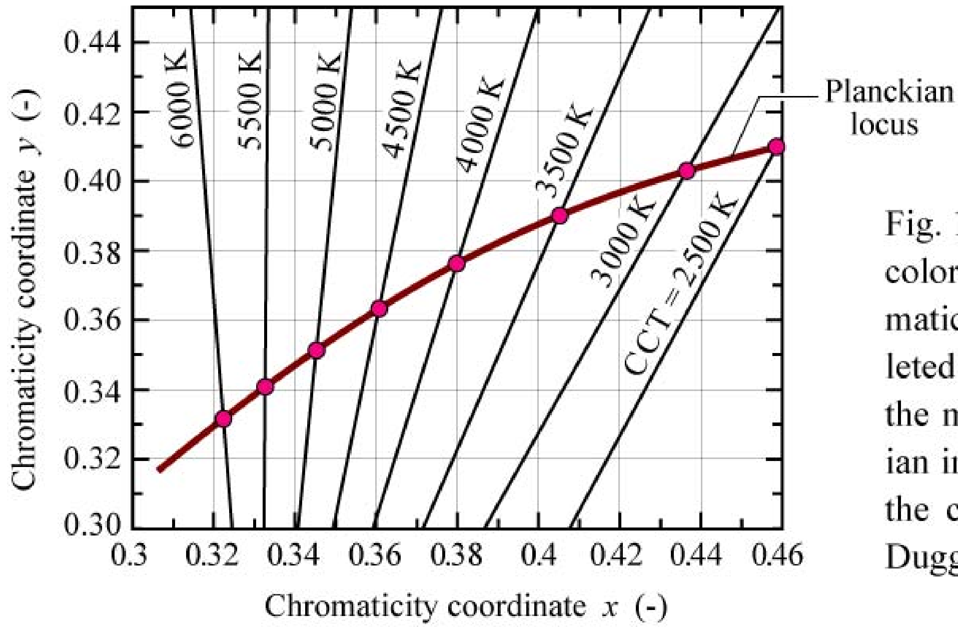

Fig. 18.5. Lines of constant correlated color temperature in the (x, y) chromaticity diagram. Whereas the correleted color temperature follows from the minimum distance to the planckian in the (u', v') diagram, this is not the case in the (x, y) diagram (after Duggal, 2004).

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Color Difference in 3D (u',v',L) space

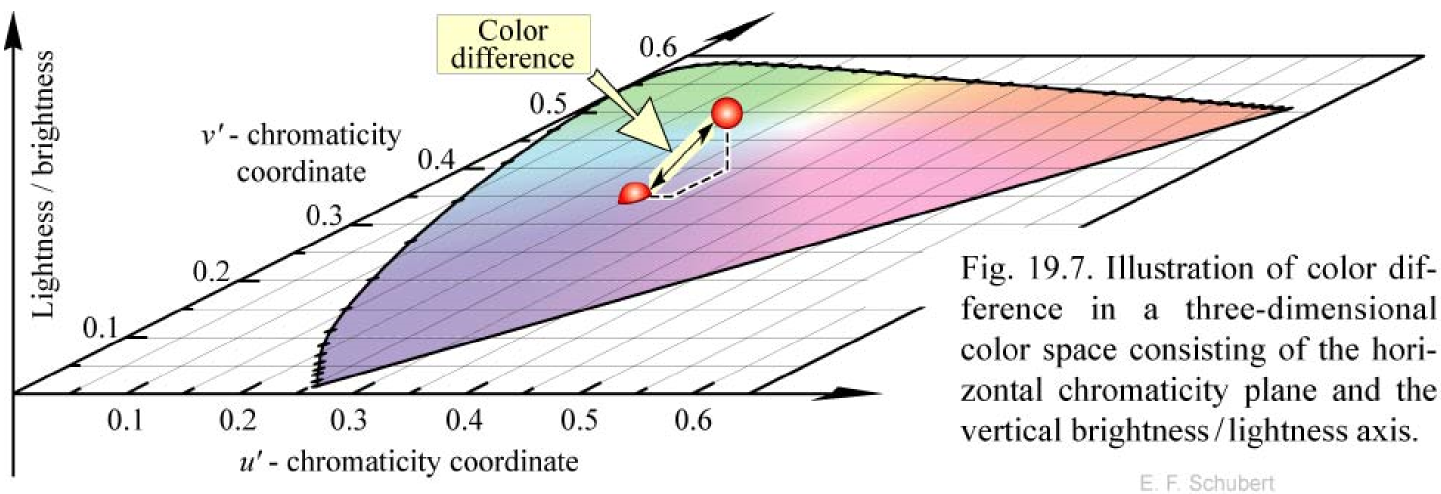

Fig. 19.7. Illustration of color difference in a three-dimensional color space consisting of the horizontal chromaticity plane and the vertical brightness / lightness axis.

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Color Rendering Index

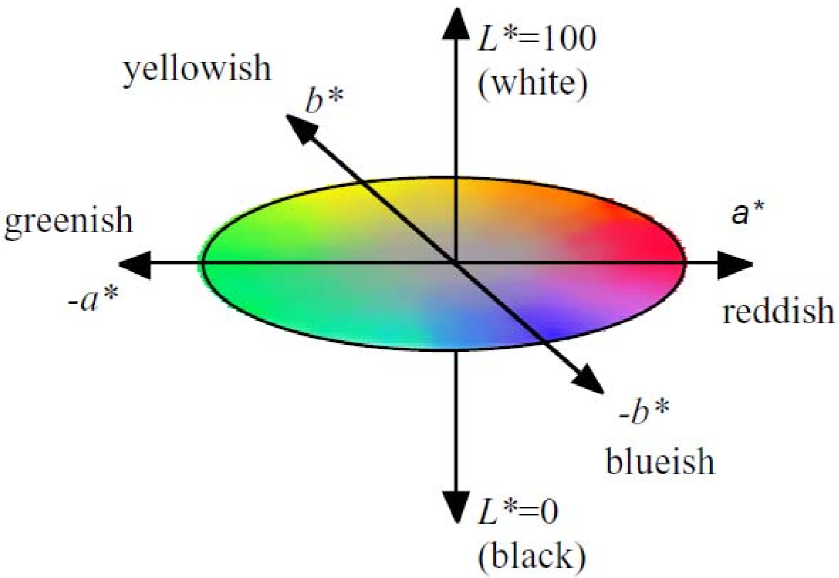

Figure 4 – CIELAB color space.

- Yet another color space related to RGB, defined by axes L*, a*, b*
- Difference ΔE_{ab} between colors:

$$\Delta E^*_{ab} = \sqrt{\left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2}$$

$$CRI_i = 100 - 4.6\Delta E^*_i$$

where *i* refers to some standard, eg. D65

Color Difference in (u',v') coordinates

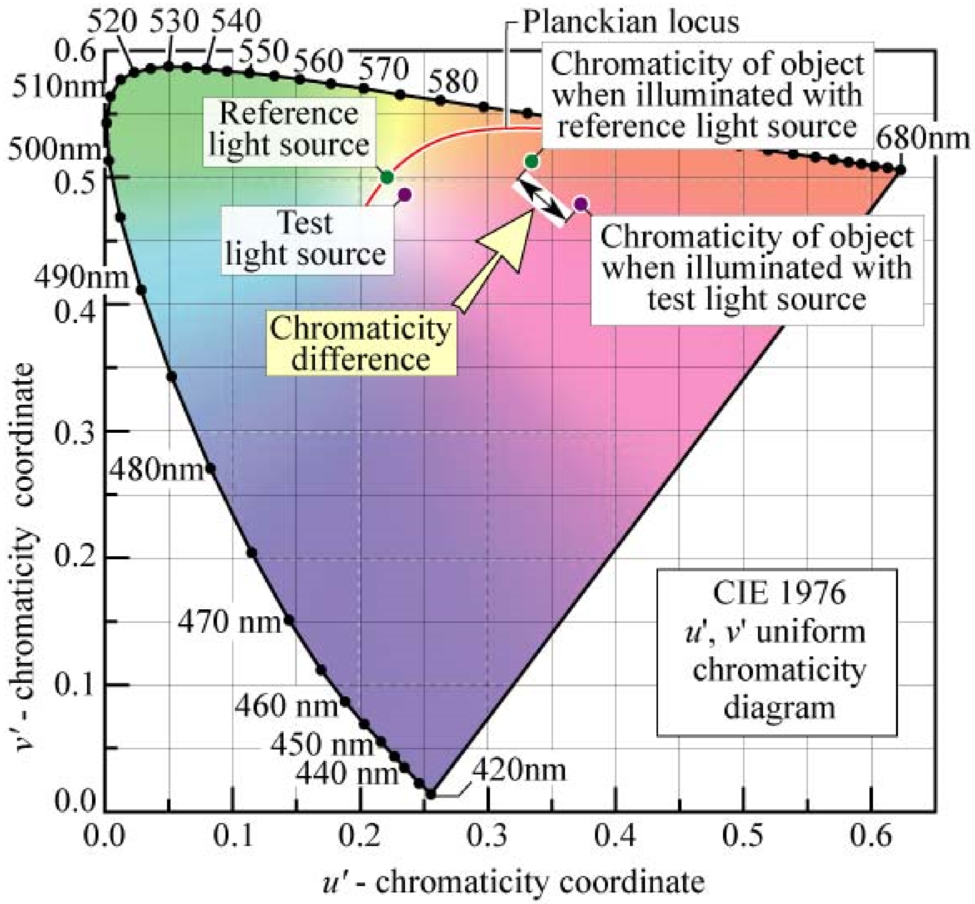

Fig. 19.6. Chromaticity difference resulting from the illumination of an object with a reference and a test light source. In the CIE 1976 u', v' uniform chromaticity diagram, the color difference is directly proportional to the geometric distance. The reference light source is located on the planckian locus at the correlated color temperature of the test light source.

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CRI Test Method

Test Method

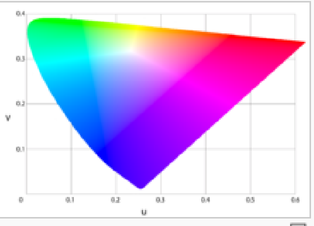
[edit]

The CRI is calculated by comparing the color rendering of the test source to that of a "perfect" source which is a black body radiator for sources with correlated color temperatures under 5000 K, and a phase of daylight otherwise (e.g. D65). Chromatic adaptation should be performed so that like quantities are compared. Specified in (Nickerson & Jerome 1965) and republished in (CIE 1995), the *Test Method* (also called *Test Sample Method* or *Test Color Method*) needs only colorimetric, rather than spectrophotometric, information.

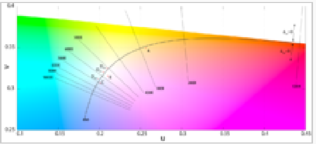
1. Using the 2° standard observer, find the chromaticity co-ordinates of the test source in the CIE 1960 color space.[4]
2. Determine the correlated color temperature (CCT) of the test source by finding the closest point to the Planckian locus on the (*u*,*v*) chromaticity diagram.
3. If the test source has a CCT<5000 K, use a black body for reference, otherwise use CIE standard illuminant D. Both sources should have the same CCT.
4. Ensure that the chromaticity distance (DC) of the test source to the Planckian locus is under 5.4×10^{-3} in the CIE 1960 UCS. This ensures the meaningfulness of the result, as the CRI is only defined for light sources that are approximately white.[5]
$$DC = \Delta_{uv} = \sqrt{(u_r - u_t)^2 + (v_r - v_t)^2}$$
5. Illuminate the first eight standard samples, from the fifteen listed below, alternately using both sources.
6. Using the 2° standard observer, find the chromaticity co-ordinates of the light reflected by each sample in the CIE 1964 color space.
7. Chromatically adapt each sample by a von Kries transform.
8. For each sample, calculate the Euclidean distance ΔE_i between the pair of co-ordinates.
9. Calculate the special (i.e., particular) CRI using the formula $R_i = 100 - 4.6\Delta E_i$[6][7]
10. Find the general CRI (R_a) by calculating the arithmetic mean of the special CRIs.

Note that the last three steps are equivalent to finding the mean color difference, $\Delta\bar{E}_{UVW}$ and using that to calculate R_a:

$$R_a = 100 - 4.6\Delta\bar{E}_{UVW}$$



CIE 1960 UCS. Planckian locus and co-ordinates of several illuminants shown in illustration below.



(u,v) chromaticity diagram with several CIE illuminants.

Chromatic adaptation

[edit]

(CIE 1995) uses this von Kries chromatic transform equation to find the corresponding color ($u_{c,i}$,$v_{c,i}$) for sample i:

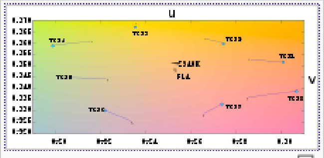
$$u_{c,i} = \frac{10.872 + 0.404(c_r/c_t)c_{t,i} - 4(d_r/d_t)d_{t,i}}{16.518 + 1.481(c_r/c_t)c_{t,i} - (d_r/d_t)d_{t,i}}$$

$$v_{c,i} = \frac{5.520}{16.518 + 1.481(c_r/c_t)c_{t,i} - (d_r/d_t)d_{t,i}}$$

$$c = (4.0 - u - 10.0v)/v$$

$$d = (1.708v - 1.481u + 0.404)/v$$

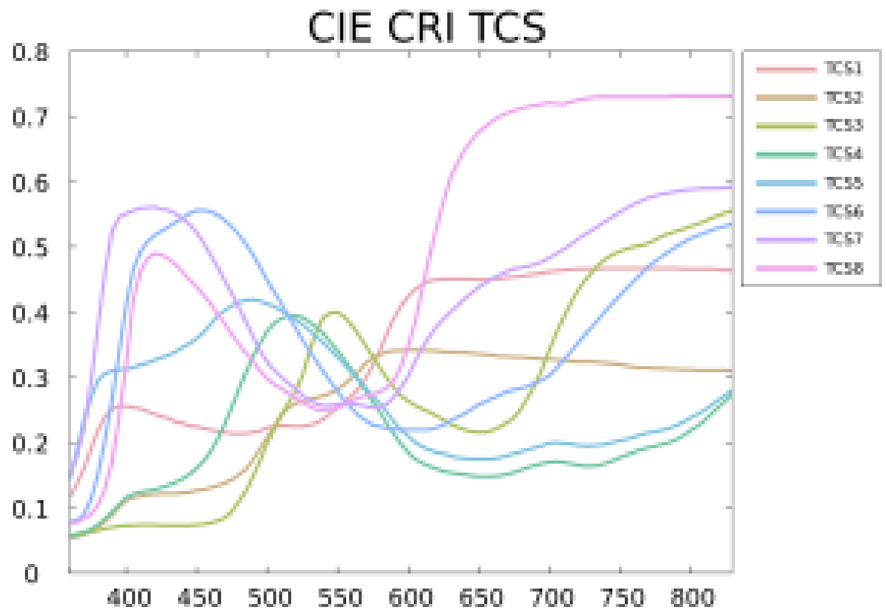
where subscripts *r* and *t* refer to reference and test light sources, respectively.



Chromatic adaptation of TCSs lit by CIE FL4 (short, black vectors, to indicate before and after) to a black body of 2940 K (cyan circles).

CIE Test Colors for CRI

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 (skin)	
TCS14	5 GY 4/4	Moderate olive green (leaf)	
TCS15	1 YR 6/4	Asian skin	



Credits

- www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org
- http://en.wikipedia.org/wiki/Colorimetry and associated links
- http://en.wikipedia.org/wiki/Color_rendering_index
- Ohno, Y., CIE Fundamentals for Color Measurement

  IS&T NIP16 Conference, Vancouver, Canada, Oct 160-20, 2000
- Hoffmann, G., CIE Color Space