

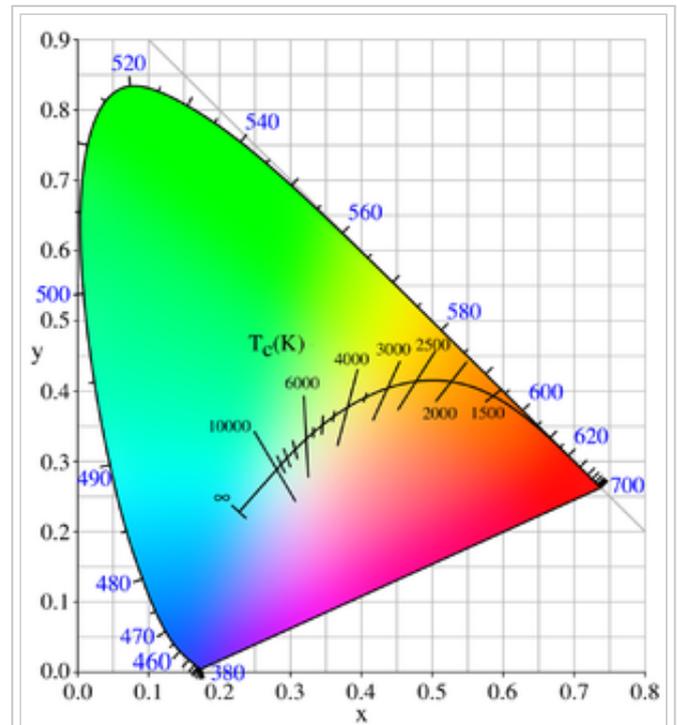
# Color temperature

From Wikipedia, the free encyclopedia

The color temperature of a light source is the temperature of an ideal black-body radiator that radiates light of comparable hue to that of the light source. Color temperature is a characteristic of visible light that has important applications in lighting, photography, videography, publishing, manufacturing, astrophysics, horticulture, and other fields. In practice, color temperature is only meaningful for light sources that do in fact correspond somewhat closely to the radiation of some black body, i.e., those on a line from reddish/orange via yellow and more or less white to blueish white; it does not make sense to speak of the color temperature of, e.g., a green or a purple light. Color temperature is conventionally stated in the unit of absolute temperature, the Kelvin, having the unit symbol K.

Color temperatures over 5,000 K are called cool colors (bluish white), while lower color temperatures (2,700 – 3,000 K) are

called warm colors (yellowish white through red).<sup>[1]</sup> This relation, however, is a psychological one in contrast to the physical relation implied by Wien's displacement law, according to which the spectral peak is shifted towards shorter wavelengths (resulting in a more blueish white) for higher temperatures.



The CIE 1931 x,y chromaticity space, also showing the chromaticities of black-body light sources of various temperatures (Planckian locus), and lines of constant correlated color temperature.

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## Categorizing different lighting

The color temperature of the

Temperature	Source
1,700 K	Match flame, low pressure sodium lamps (LPS/SOX)
1,850 K	Candle flame, sunset/sunrise
2,700 – 3,300 K	Incandescent lamps
3,000 K	Soft (or Warm) White compact fluorescent lamps
3,200 K	Studio lamps, photofloods, etc.
3,350 K	Studio "CP" light
4,100 – 4,150 K	Moonlight <sup>[2]</sup>
5,000 K	Horizon daylight
5,000 K	Tubular fluorescent lamps or cool white/daylight compact fluorescent lamps (CFL)
5,500 – 6,000 K	Vertical daylight, electronic flash
6,200 K	Xenon short-arc lamp <sup>[3]</sup>
6,500 K	Daylight, overcast
6,500 – 10,500 K	LCD or CRT screen
15,000 – 27,000 K	Clear blue poleward sky
These temperatures are merely characteristic; considerable variation may be present.	

electromagnetic radiation emitted from an ideal black body is defined as its surface temperature in Kelvin, or alternatively in mireds (micro-reciprocal Kelvin).<sup>[4]</sup> This permits the definition of a standard by which light sources are compared.

To the extent that a hot surface emits thermal radiation but is not an ideal black-body radiator, the color temperature of the light is not the actual temperature of the surface. An incandescent lamp's light is thermal radiation, and the bulb approximates an ideal black-body radiator, so its color temperature is essentially the temperature of the filament.

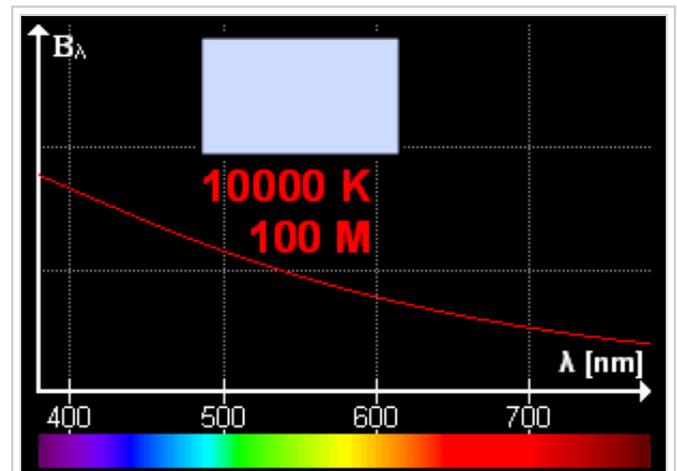
Many other light sources, such as fluorescent lamps, or LEDs (light emitting diodes) emit light primarily by processes other than thermal radiation. This means that the emitted radiation does not follow the form of a black-body spectrum. These sources are assigned what is known as a correlated color temperature (CCT). CCT is the color temperature of a black-body radiator which to human color perception most closely matches the light from the lamp. Because such an approximation is not required for incandescent light, the CCT for an incandescent light is simply its unadjusted temperature, derived from the comparison to a black-body radiator.

## The Sun

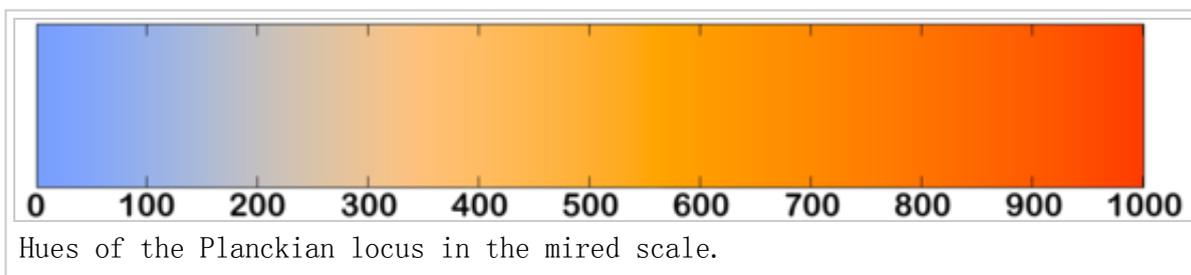
The Sun closely approximates a black-body radiator. The effective temperature, defined by the total radiative power per square unit, is about 5,780 K.<sup>[5]</sup> The color temperature of sunlight above the atmosphere is about 5,900 K.<sup>[6]</sup>

As the Sun crosses the sky, it may appear to be red, orange, yellow or white depending on its position. The changing color of the Sun over the course of the day is mainly a result of scattering of light and is not due to changes in black-body radiation. The blue color of the sky is caused by Rayleigh scattering of the sunlight from the atmosphere, which tends to scatter blue light more than red light.

Daylight has a spectrum similar to that of a black body with a correlated color temperature of 6,500 K (D65 viewing standard) or 5,500 K (daylight-balanced photographic film standard).



The black-body radiance ( $B_\lambda$ ) vs. wavelength ( $\lambda$ ) curves for the visible spectrum. Vertical axes of Planck's law plots building this animation were proportionally transformed to keep equal areas between functions and horizontal axis for wavelengths 380 - 780 nm.



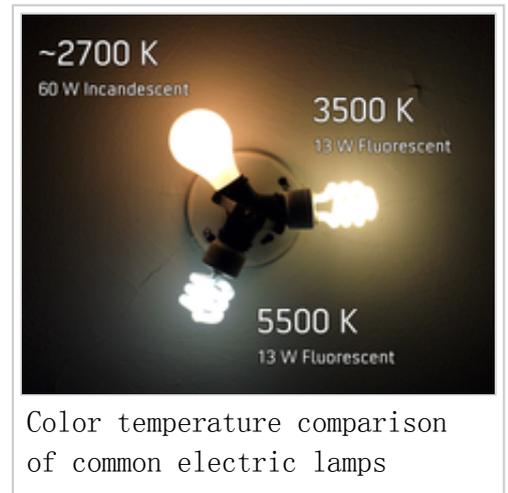
For colors based on black-body theory, blue occurs at higher temperatures, while red occurs at lower, cooler, temperatures. This is the opposite of the cultural associations attributed to colors, in which "red" is "hot", and "blue" is "cold".<sup>[7]</sup>

## Color temperature applications

### Lighting

For lighting building interiors, it is often important to take into account the color temperature of illumination. For example, a warmer (i. e., lower color temperature) light is often used in public areas to promote relaxation, while a cooler (higher color temperature) light is used to enhance concentration in offices. <sup>[8]</sup>

CCT dimming for LED technology is regarded as a difficult task, since binning, age and temperature drift effects of LEDs change the actual color value output. Here feedback loop systems are used for example with color sensors, to actively monitor and control the color output of multiple color mixing LEDs. <sup>[9]</sup>



## Aquaculture

In fishkeeping, color temperature has different functions and foci, for different branches.

- In freshwater aquaria, color temperature is generally of concern only for producing a more attractive display. Lights tend to be designed to produce an attractive spectrum, sometimes with secondary attention to keeping plants alive.
- In a saltwater/reef aquarium, color temperature is an essential part of tank health. Within about 400 to 3000 nanometers, light of shorter wavelength can penetrate deeper into water than longer wavelengths (see Electromagnetic absorption by water), <sup>[10][11][12]</sup> providing essential energy sources to the algae hosted in (and sustaining) coral. This is equivalent to an increase of color temperature with water depth in this spectral range. Because coral, typically living in shallow water, receives intense, direct tropical sunlight, the focus was once on simulating this with 6,500 K lights. Higher temperature light sources have become more popular, first with 10,000 K and more recently 16,000 K and 20,000 K. Meanwhile, actinic lighting is used to make the somewhat fluorescent colors of many corals and fish "pop", creating brighter "display" tanks.

## Digital photography

In digital photography, color temperature is sometimes used interchangeably with white balance, which allow a remapping of color values to simulate variations in ambient color temperature. Most digital cameras and RAW image software provide presets simulating specific ambient values (e. g., sunny, cloudy, tungsten, etc.) while others allow explicit entry of white balance values in Kelvin. These settings vary color values along the blue - yellow axis, while some software includes additional controls (sometimes labeled tint) adding the magenta - green axis, and are to some extent arbitrary and subject to artistic interpretation. <sup>[13]</sup>

## Photographic film

Photographic emulsion film sometimes appears to exaggerate the color of the light, as it does not adapt to lighting color as human visual perception does. An object that appears to the eye to be white may turn out to look very blue or orange in a photograph. The color balance may need to be corrected while shooting or while printing to achieve a neutral color print.

Photographic film is made for specific light sources (most commonly daylight film and tungsten film), and used properly, will create a neutral color print. Matching the sensitivity of the film to the color temperature of the light source is one way to balance color. If tungsten film is used indoors with incandescent lamps, the yellowish-orange light of the tungsten incandescent lamps will appear as white (3,200 K) in the photograph.

Filters on a camera lens, or color gels over the light source(s) may also be used to correct color balance. When shooting with a bluish light (high color temperature) source such as on an overcast day, in the shade, in window light or if using tungsten film with white or blue light, a yellowish-orange filter will correct this. For shooting with daylight film (calibrated to 5,600 K) under warmer (low color temperature) light sources such as sunsets, candlelight or tungsten lighting, a bluish (e.g., #80A) filter may be used.

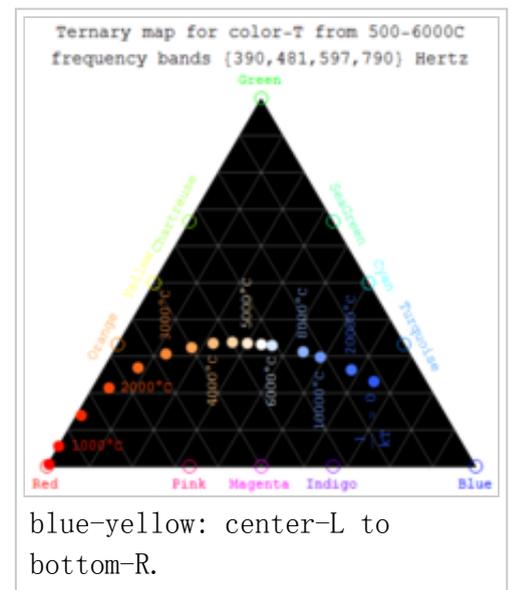
If there is more than one light source with varied color temperatures, one way to balance the color is to use daylight film and place color-correcting gel filters over each light source.

Photographers sometimes use color temperature meters. Color temperature meters are usually designed to read only two regions along the visible spectrum (red and blue); more expensive ones read three regions (red, green, and blue). However, they are ineffective with sources such as fluorescent or discharge lamps, whose light varies in color and may be harder to correct for. Because it is often greenish, a magenta filter may correct it. More sophisticated colorimetry tools can be used where such meters are lacking.

## Desktop publishing

In the desktop publishing industry, it is important to know a monitor's color temperature. Color matching software, such as Apple's ColorSync for Mac OS, will measure a monitor's color temperature and then adjust its settings accordingly. This enables on-screen color to more closely match printed color. Common monitor color temperatures, along with matching standard illuminants in parentheses, are as follows:

- 5,000 K (D50)
- 5,500 K (D55)
- 6,500 K (D65)
- 7,500 K (D75)
- 9,300 K.



D50 is scientific shorthand for a standard illuminant: the daylight spectrum at a correlated color temperature of 5,000 K. Similar definitions exist for D55, D65 and D75. Designations such as D50 are used to help classify color temperatures of light tables and viewing booths. When viewing a color slide at a light table, it is important that the light be balanced properly so that the colors are not shifted towards the red or blue.

Digital cameras, web graphics, DVDs, etc., are normally designed for a 6,500 K color temperature. The sRGB standard commonly used for images on the Internet stipulates (among other things) a 6,500 K display whitepoint.

## TV, video, and digital still cameras

The NTSC and PAL TV norms call for a compliant TV screen to display an electrically black and white signal (minimal color saturation) at a color temperature of 6,500 K. On many consumer-grade televisions, there is a very noticeable deviation from this requirement. However, higher-end consumer-grade televisions can have their color temperatures adjusted to 6,500 K by using a preprogrammed setting or a custom calibration. Current versions of ATSC explicitly call for the color temperature data to be included in the data stream, but old versions of ATSC allowed this data to be omitted. In this case, current versions of ATSC cite default colorimetry standards depending on the format. Both of the cited standards specify a 6,500 K color temperature.

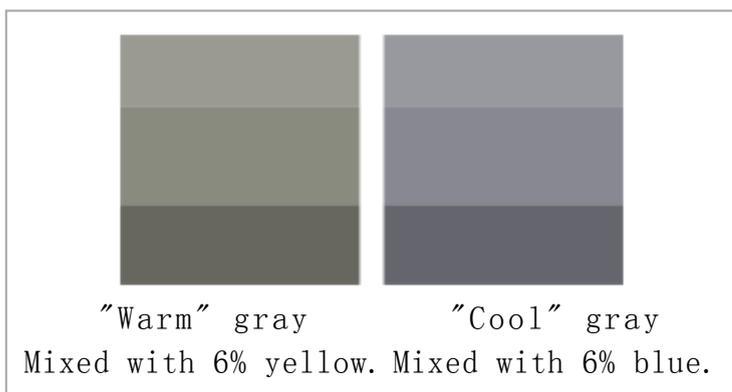
Most video and digital still cameras can adjust for color temperature by zooming into a white or neutral colored object and setting the manual "white balance" (telling the camera that "this object is white"); the camera then shows true white as white and adjusts all the other colors accordingly. White-balancing is necessary especially when indoors under fluorescent lighting and when moving the camera from one lighting situation to another. Most cameras also have an automatic white balance function that attempts to determine the color of the light and correct accordingly. While these settings were once unreliable, they are much improved in today's digital cameras, and will produce an accurate white balance in a wide variety of lighting situations.

## Artistic application via control of color temperature

Video camera operators can white-balance objects which aren't white, downplaying the color of the object used for white-balancing. For instance, they can bring more warmth into a picture by white-balancing off something light blue, such as faded blue denim; in this way white-balancing can serve in place of a filter or lighting gel when those are not available.

Cinematographers do not "white balance" in the same way as video camera operators; they can use techniques such as filters, choice of film stock, pre-flashing, and after shooting, color grading (both by exposure at the labs and also digitally). Cinematographers also work closely with set designers and lighting crews to achieve the desired effects.

For artists, most pigments and papers have a cool or warm cast, as the human eye can detect even a minute amount of saturation. Gray mixed with yellow, orange or red is a "warm gray". Green, blue, or purple, create "cool grays". Note that this sense of temperature is the reverse of that of real temperature; bluer is described as "cooler" even though it corresponds to a higher-temperature black body.



Lighting designers sometimes select filters by color temperature, commonly to match light that is

theoretically white. Since fixtures

using discharge type lamps produce a light of considerably higher color temperature than tungsten lamps, using the two in conjunction could potentially produce a stark contrast, so sometimes fixtures with HID lamps, commonly producing light of 6,000 - 7,000 K, are fitted with 3,200 K filters to emulate tungsten light. Fixtures with color mixing features or with multiple colors, (if including 3,200 K) are also capable of producing tungsten-like light. Color temperature may also be a factor when selecting lamps, since each is likely to have a different color temperature.<sup>[14]</sup>

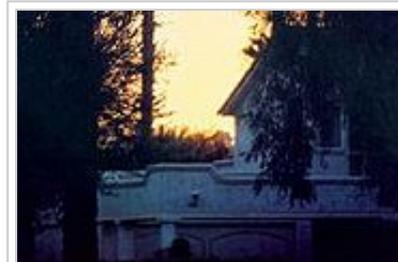
## Correlated color temperature

The correlated color temperature ( $T_{cp}$ ) is the temperature of the Planckian radiator whose perceived color most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions

— CIE/IEC 17.4:1987 (<http://www.cie.co.at/publ/abst/17-4-89.html>), International Lighting Vocabulary (ISBN 3900734070)<sup>[15]</sup>

### Motivation

Black-body radiators are the reference by which the whiteness of light sources is judged. A black body can be described by its color temperature, whose hues are depicted above. By analogy, nearly Planckian light sources such as certain fluorescent or high-intensity discharge lamps can be judged by their correlated color temperature (CCT); the color temperature of the Planckian radiator that best approximates them. The question is: what is the relationship between the light source's relative spectral power distribution and its correlated color temperature?



The house above appears a light cream during the midday, but seems a bluish white here in the dim light before full sunrise. Note the different color temperature of the sunrise in the background.

## Background

The notion of using Planckian radiators as a yardstick against which to judge other light sources is not a new one.<sup>[16]</sup> In 1923, writing about "grading of illuminants with reference to quality of color...the temperature of the source as an index of the quality of color", Priest essentially described CCT as we understand it today, going so far as to use the term apparent color temperature, and astutely recognized three cases:<sup>[17]</sup>

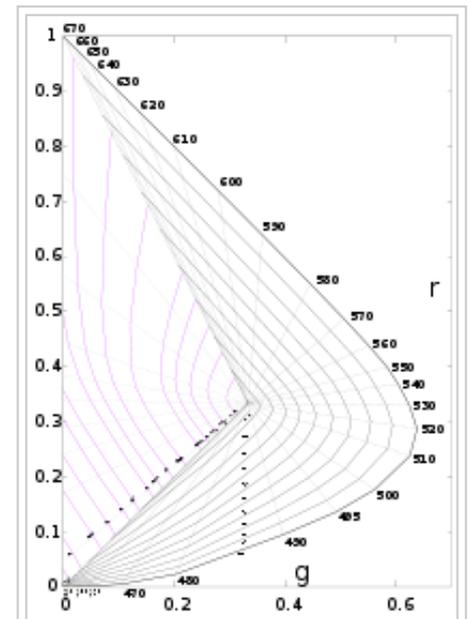
- "Those for which the spectral distribution of energy is identical with that given by the Planckian formula."
- "Those for which the spectral distribution of energy is not identical with that given by the Planckian formula, but still is of such a form that the quality of the color evoked is the same as would be evoked by the energy from a Planckian radiator at the given color temperature."
- "Those for which the spectral distribution of energy is such that the color can be matched only approximately by a stimulus of the Planckian form of spectral distribution."

Several important developments occurred in 1931. In chronological order:

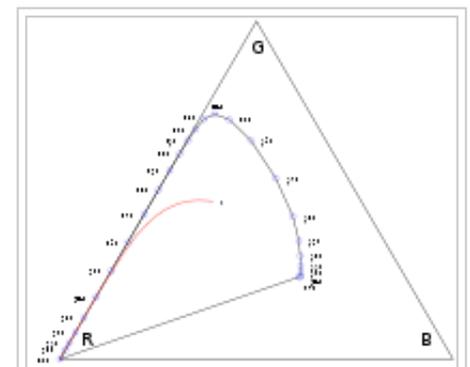
1. Raymond Davis published a paper on correlated color temperature (his term). Referring to the Planckian locus on the r-g diagram, he defined the CCT as the average of the primary component temperatures (RGB CCTs), using trilinear coordinates.<sup>[18]</sup>
2. The CIE announced the XYZ color space.
3. Deane B. Judd published a paper on the nature of "least perceptible differences" with respect to chromatic stimuli. By empirical means he determined that the difference in sensation, which he termed  $\Delta E$  for a "discriminatory step between colors...Empfindung" (German for sensation) was proportional to the distance of the colors on the chromaticity diagram. Referring to the (r,g) chromaticity diagram depicted aside, he hypothesized that<sup>[19]</sup>

$$K \Delta E = |c_1 - c_2| = \max(|r_1 - r_2|, |g_1 - g_2|).$$

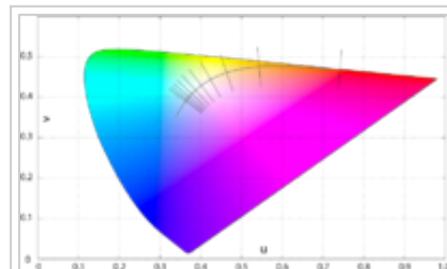
These developments paved the way for the development of new chromaticity spaces that are more suited to the estimation of correlated color temperatures and chromaticity differences. Bridging the concepts of color difference and color temperature, Priest made the observation that the eye is sensitive to constant differences in reciprocal temperature:<sup>[20]</sup>



Judd's (r,g) diagram. The concentric curves indicate the loci of constant purity.



Judd's Maxwell triangle. Planckian locus in red. Translating from trilinear co-ordinates into Cartesian co-ordinates leads to the next diagram.



Judd's uniform chromaticity space (UCS), with the Planckian locus and the isotherms from 1,000 K to 10,000 K, perpendicular to the locus. Judd calculated the isotherms in this space before translating them back into the (x,y) chromaticity space, as depicted in the diagram at the top of the article.

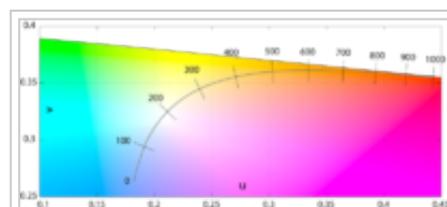
A difference of one micro-reciprocal-degree ( $\mu$ rd) is fairly representative of the doubtfully perceptible difference under the most favorable conditions of observation.

Priest proposed to use "the scale of temperature as a scale for arranging the chromaticities of the several illuminants in a serial order". Over the next few years, Judd published three more significant papers:

The first verified the findings of Priest,<sup>[17]</sup> Davis,<sup>[18]</sup> and Judd,<sup>[19]</sup> with a paper on sensitivity to change in color temperature.<sup>[21]</sup>

The second proposed a new chromaticity space, guided by a principle that has become the holy grail of color spaces: perceptual uniformity (chromaticity distance should be commensurate with perceptual difference). By means of a projective transformation, Judd found a more uniform chromaticity space (UCS) in which to find the CCT. Judd determined the nearest color temperature by simply finding the nearest point on the Planckian locus to the chromaticity of the stimulus on Maxwell's color triangle, depicted aside. The transformation matrix he used to convert X,Y,Z tristimulus values to R,G,B coordinates was:<sup>[22]</sup>

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.1956 & 2.4478 & -0.1434 \\ -2.5455 & 7.0492 & 0.9963 \\ 0.0000 & 0.0000 & 1.0000 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}.$$



Close up of the Planckian locus in the CIE 1960 UCS, with the isotherms in mireds. Note the even spacing of the isotherms when using the reciprocal temperature scale, and compare with the similar figure below. The even spacing of the isotherms on the locus implies that the mired scale is a better measure of perceptual color difference than the temperature scale.

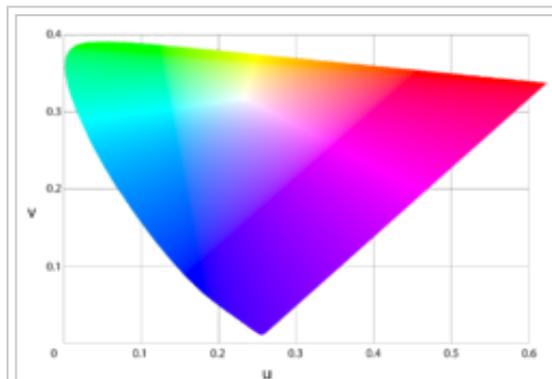
From this, one can find these chromaticities:<sup>[23]</sup>

$$u = \frac{0.4661x + 0.1593y}{y - 0.15735x + 0.2424}, \quad v = \frac{0.6581y}{y - 0.15735x + 0.2424}$$

The third depicted the locus of the isothermal chromaticities on the CIE 1931 x,y chromaticity diagram.<sup>[24]</sup> Since the isothermal points formed normals on his UCS diagram, transformation back into the xy plane revealed them still to be lines, but no longer perpendicular to the locus.

### Calculation

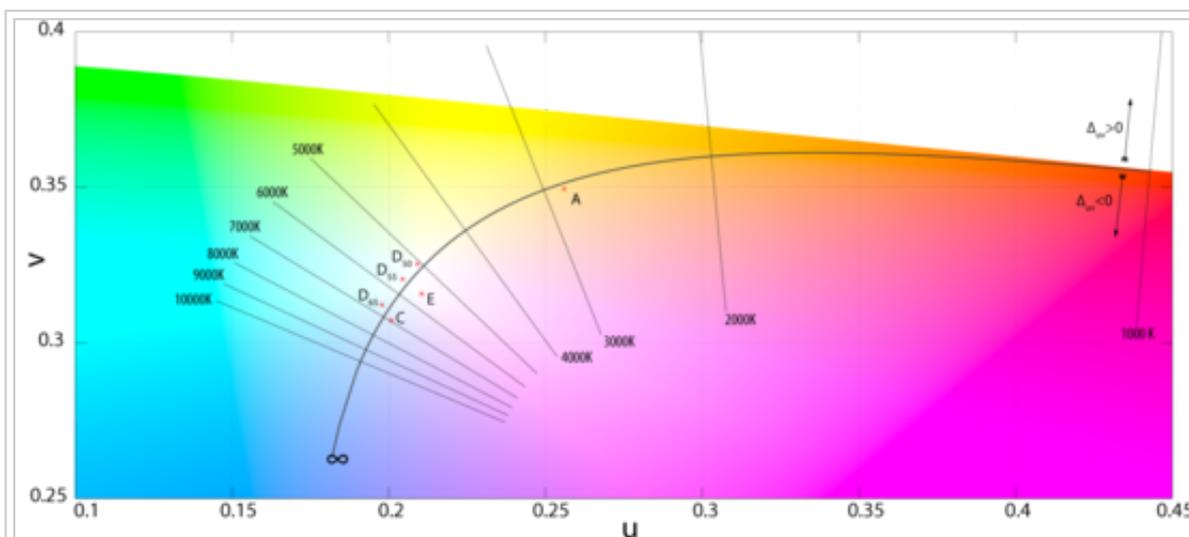
Judd's idea of determining the nearest point to the Planckian locus on a uniform chromaticity space is current. In 1937, MacAdam suggested a "modified uniform chromaticity scale diagram", based on certain simplifying geometrical considerations:<sup>[25]</sup>



MacAdam's "uniform chromaticity scale" diagram; a simplification of Judd's UCS.

$$u = \frac{4x}{-2x + 12y + 3}, \quad v = \frac{6y}{-2x + 12y + 3}$$

This (u,v) chromaticity space became the CIE 1960 color space, which is still used to calculate the CCT (even though MacAdam did not devise it with this purpose in mind).<sup>[26]</sup> Using other chromaticity spaces, such as u'v', leads to non-standard results that may nevertheless be perceptually meaningful.<sup>[27]</sup>



Close up of the CIE 1960 UCS. The isotherms are perpendicular to the Planckian locus, and are drawn to indicate the maximum distance from the locus that the CIE considers the correlated color temperature to be meaningful:

$$\Delta uv = \pm 0.05$$

The distance from the locus (i. e., degree of departure from a black body) is traditionally indicated in units of  $\Delta_{uv}$ ; positive for points above the locus. This concept of distance has evolved to become Delta E, which continues to be used today.

### Robertson's method

Before the advent of powerful personal computers, it was common to estimate the correlated color temperature by way of interpolation from look-up tables and charts.<sup>[28]</sup> The most famous such method is Robertson's,<sup>[29]</sup> who took advantage of the relatively even spacing of the mired scale (see above) to calculate the CCT  $T_c$  using linear interpolation of the isotherm's mired values:<sup>[30]</sup>

$$\frac{1}{T_c} = \frac{1}{T_i} + \frac{\theta_1}{\theta_1 + \theta_2} \left( \frac{1}{T_{i+1}} - \frac{1}{T_i} \right),$$

where  $T_i$  and  $T_{i+1}$  are the color temperatures of the look-up isotherms and  $i$  is chosen such that  $T_i < T_c < T_{i+1}$ . (Furthermore, the test chromaticity lies between the only two adjacent lines for which  $d_i/d_{i+1} < 0$ .)

If the isotherms are tight enough, one can assume  $\theta_1/\theta_2 \approx \sin \theta_1/\sin \theta_2$ , leading to

$$\frac{1}{T_c} = \frac{1}{T_i} + \frac{d_i}{d_i - d_{i+1}} \left( \frac{1}{T_{i+1}} - \frac{1}{T_i} \right).$$

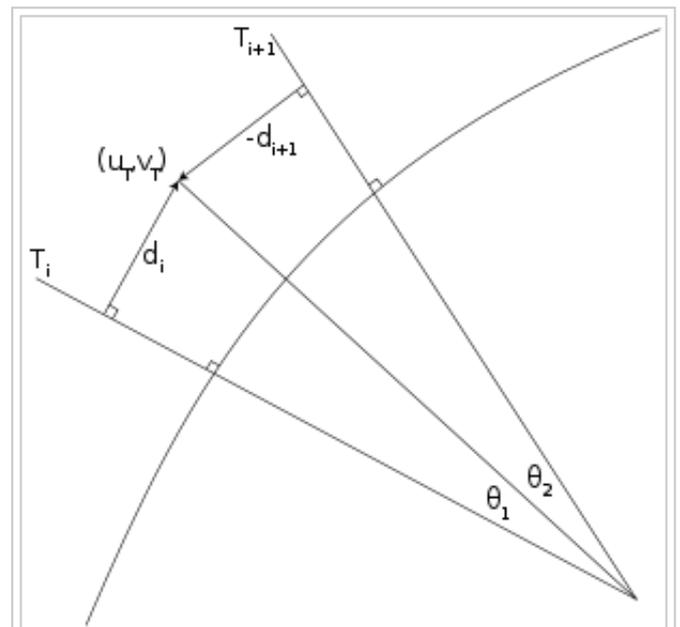
The distance of the test point to the  $i$ -th isotherm is given by

$$d_i = \frac{(v_T - v_i) - m_i(u_T - u_i)}{\sqrt{1 + m_i^2}},$$

where  $(u_i, v_i)$  is the chromaticity coordinate of the  $i$ -th isotherm on the Planckian locus and  $m_i$  is the isotherm's slope. Since it is perpendicular to the locus, it follows that  $m_i = -1/l_i$  where  $l_i$  is the slope of the locus at  $(u_i, v_i)$ .

### Precautions

Although the CCT can be calculated for any chromaticity coordinate, the result is meaningful only if the light sources are nearly white.<sup>[31]</sup> The CIE recommends that "The concept of correlated color temperature should not be used if the chromaticity of the test source differs more than  $[\Delta_{uv}=5 \times 10^{-2}]$  from the Planckian radiator."<sup>[32]</sup> Beyond a certain value of  $\Delta_{uv}$ , a chromaticity co-ordinate may be equidistant to two points on the locus, causing ambiguity in the CCT.



Computation of the CCT  $T_c$  corresponding to the chromaticity coordinate  $(u_T, v_T)$  in the CIE 1960 UCS.

## Approximation

If a narrow range of color temperatures is considered—those encapsulating daylight being the most practical case—one can approximate the Planckian locus in order to calculate the CCT in terms of chromaticity coordinates. Following Kelly's observation that the isotherms intersect in the purple region near  $(x = 0.325, y = 0.154)$ ,<sup>[28]</sup> McCamy proposed this cubic approximation:<sup>[33]</sup>

$$\text{CCT}(x, y) = -449n^3 + 3525n^2 - 6823.3n + 5520.33,$$

where  $n = (x - x_e)/(y - y_e)$  is the inverse slope line, and  $(x_e = 0.3320, y_e = 0.1858)$  is the "epicenter"; quite close to the intersection point mentioned by Kelly. The maximum absolute error for color temperatures ranging from 2856 K (illuminant A) to 6504 K (D65) is under 2 K.

A more recent proposal, using exponential terms, considerably extends the applicable range by adding a second epicenter for high color temperatures:<sup>[34]</sup>

$$\text{CCT}(x, y) = A_0 + A_1 \exp(-n/t_1) + A_2 \exp(-n/t_2) + A_3 \exp(-n/t_3),$$

where  $n$  is as before and the other constants are defined below:

	3 - 50 kK	50 - 800 kK
$x_e$	0.3366	0.3356
$y_e$	0.1735	0.1691
$A_0$	-949.86315	36284.48953
$A_1$	6253.80338	0.00228
$t_1$	0.92159	0.07861
$A_2$	28.70599	$5.4535 \times 10^{-36}$
$t_2$	0.20039	0.01543
$A_3$	0.00004	
$t_3$	0.07125	

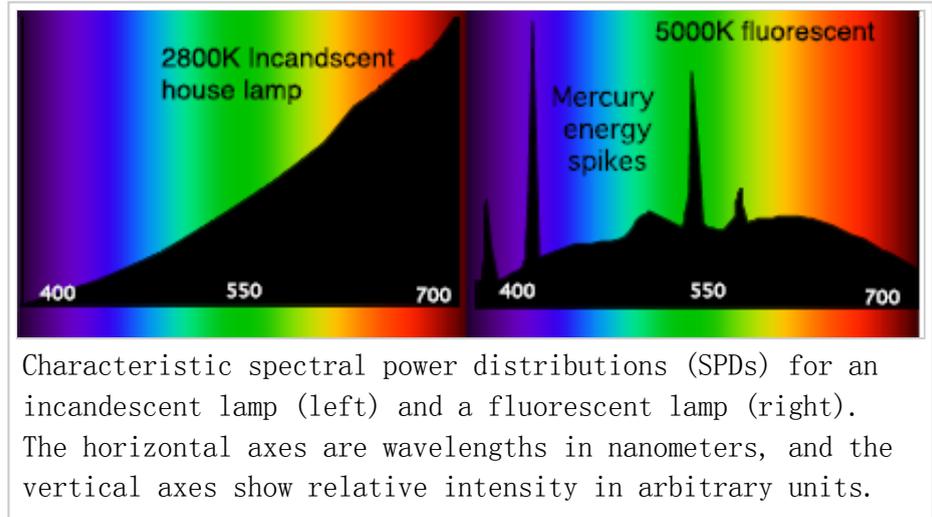
The inverse calculation, from color temperature to corresponding chromaticity coordinates, is discussed in Planckian locus.

## Color rendering index

The CIE color rendering index (CRI) is a method to determine how well a light source's illumination of eight sample patches compares to the illumination provided by a reference source. Cited together, the CRI and CCT give a numerical estimate of what reference (ideal) light source best approximates a particular artificial light, and what the difference is.

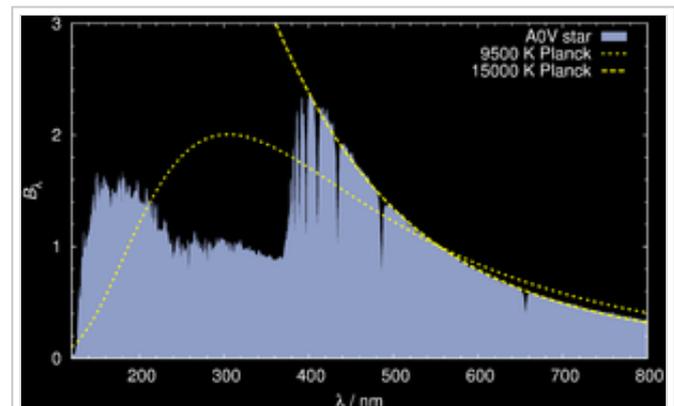
## Spectral power distribution

Light sources and illuminants may be characterized by their spectral power distribution (SPD). The relative SPD curves provided by many manufacturers may have been produced using 10 nm increments or more on their spectroradiometer.<sup>[35]</sup> The result is what would seem to be a smoother (“fuller spectrum”) power distribution than the lamp actually has. Owing to their spiky distribution, much finer increments are advisable for taking measurements of fluorescent lights, and this requires more expensive equipment.



## Color temperature in astronomy

In astronomy, the color temperature is defined by the local slope of the SPD at a given wavelength, or, in practice, a wavelength range. Given, for example, the color magnitudes *B* and *V* which are calibrated to be equal for an A0V star (e.g., Vega), the stellar color temperature  $T_C$  is given by the temperature for which the color index  $B - V$  of a blackbody radiator fits the stellar one. Besides the  $B - V$ , other color indices can be used as well. The color temperature (as well as the correlated color temperature defined above) may differ largely from the effective temperature given by the radiative flux of the stellar surface. For example, the color temperature of an A0V star is about 15,000 K compared to an effective temperature of about 9500 K.<sup>[36]</sup>



## See also

- Kruithof curve
- Luminous efficacy
- Over-illumination
- Brightness temperature
- Effective temperature
- Whiteness
- Color metamerism

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