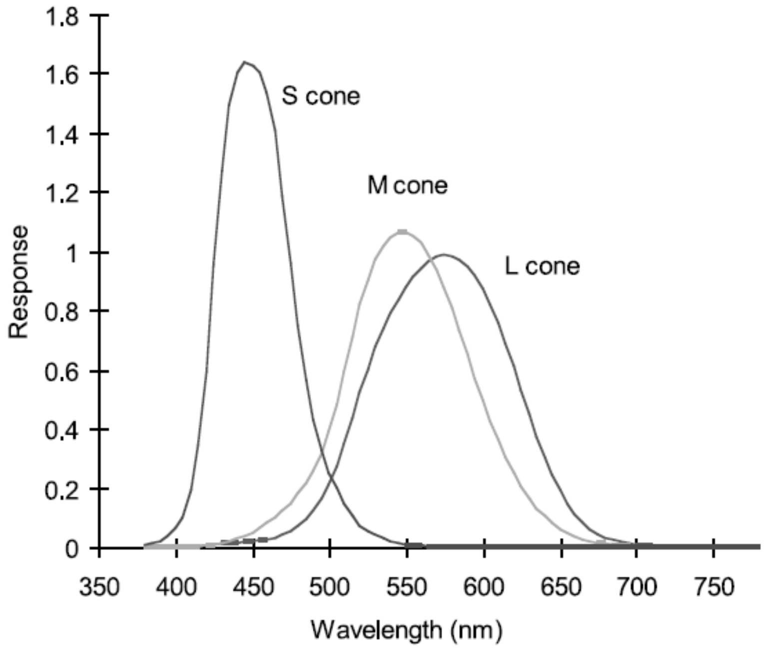
Il colore

Multimedia

THE HUMAN VISUAL SYSTEM

- The human eye has three types of light receptors: L (long), M (middle), and S (short) cones. Humans recognize color after processing the light information from the cones through nerves to the brain.
- The stimuli from the cones are converted into luminance, red–green, and yellow–blue signals. These signals are transmitted to the brain for recognition as another set of color attributes, such as lightness, chroma, and hue.
- In addition to the cones, an eye has another type of receptor, which is called rod. Because it is deactivated in a bright environment, it does not contribute to the recognition of color.
- It is only active in a dark environment during which the three cones are deactivated. A single receptor does not give spectral information, so color is not sensed in such a dark environment.

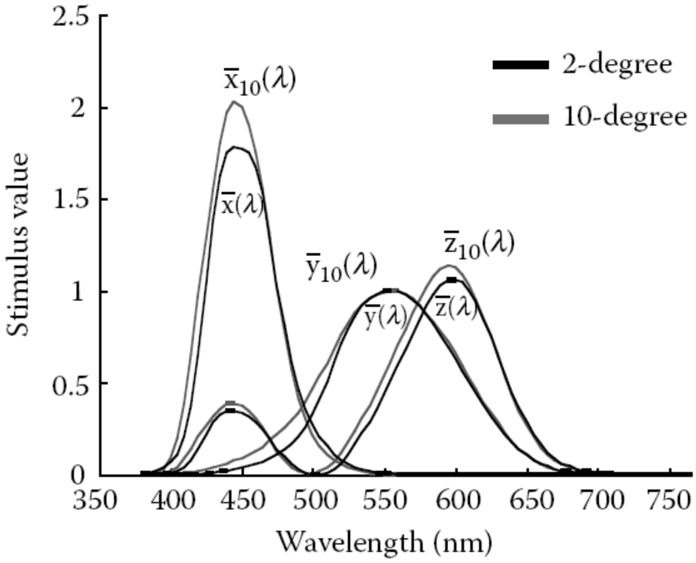
THE HUMAN VISUAL SYSTEM (2)



COLOR-MATCHING FUNCTIONS AND TRISTIMULUS VALUES (1)

- In industrial use, it is desired that color information be quantified and exchangeable. CIE (International Commission on Illumination) specifies the methodology, which is called colorimetry.
- It essentially traces the process in the human visual system with some modifications, approximations, and simplification for easy use in industry.
- Instead of the cone sensitivities, a set of equivalent sensitivity curves is defined as a linear transformation of the set of cone sensitivities. The sensitivity curves, are called the CIE color-matching functions.

COLOR-MATCHING FUNCTIONS AND TRISTIMULUS VALUES (2)



These functions are noted as x(λ), y(λ), z(λ), where y(λ) is adjusted to represent luminance to fulfill industrial demands.

COLOR-MATCHING FUNCTIONS AND TRISTIMULUS VALUES (3)

When an arbitrary object with spectral reflectance, *R*(λ), is illuminated by a light source with spectral radiance, *L*(λ), tristimulus values, which are also a linear transformation of the cone sensitivities, can be obtained as follows:

$$X = \int L(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int L(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int L(\lambda)R(\lambda)\bar{z}(\lambda)d\lambda$$

This is called the CIE 1931 (1964) standard colorimetric system. Here, the *Y* value provides luminance and the *X* and *Z* values physically have no meaning.

CHROMATICITY AND UNIFORM COLOR SPACE (1)

- Two forms of representing color have become prevalent: chromaticity coordinates and uniform color spaces.
- The former is a simplified way of ignoring the luminance axis and may be easily understood by a two-dimensional representation.
- The latter attempts to imitate human color recognition in three dimensions.

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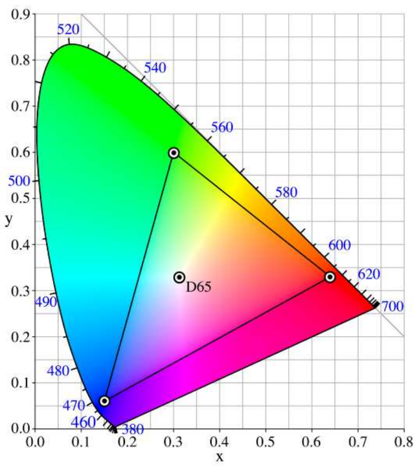
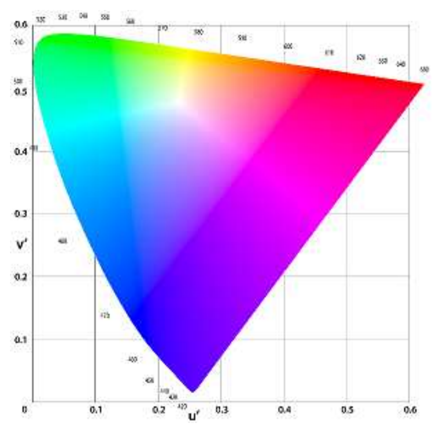
CHROMATICITY AND UNIFORM COLOR SPACE (2)





$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}$$

$$u' = \frac{4X}{X+15Y+3Z}, \quad v' = \frac{9Y}{X+15Y+3Z}$$

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CHROMATICITY AND UNIFORM COLOR SPACE (3)

- For uniform color spaces, the CIE 1976 *L*a*b** color space and the CIE 1976 *L*u*v** color space recommended by CIE in 1976 are widely used. These are designed to simulate color recognition.
- These equations require the tristimulus values of the white point for normalization.
- It should be noted that the color spaces were developed for a specific observing condition (a color patch with a neutral gray background (*L**= 50)). If the background does not match the condition, the uniformity of the color spaces is not guaranteed.

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CHROMATICITY AND UNIFORM COLOR SPACE (4)

$$X_n = \begin{cases} \left(\frac{X}{X_0}\right)^{\frac{1}{3}} & \frac{X}{X_0} > 0.008856 \\ 7.787\left(\frac{X}{X_0}\right) + \frac{16}{116} & \frac{X}{X_0} \le 0.008856 \end{cases}$$

$$Y_n = \begin{cases} \left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} & \frac{Y}{Y_0} > 0.008856 \\ 7.787\left(\frac{Y}{Y_0}\right) + \frac{16}{116} & \frac{Y}{Y_0} \le 0.008856 \end{cases}$$

$$Z_n = \begin{cases} \left(\frac{Z}{Z_0}\right)^{\frac{1}{3}} & \frac{Z}{Z_0} > 0.008856 \\ 7.787\left(\frac{Z}{Z_0}\right) + \frac{16}{116} & \frac{Z}{Z_0} \le 0.008856 \end{cases}$$

$$L^* = \begin{cases} 116\left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} - 16 & \frac{Y}{Y_0} > 0.008856 \\ 903.29\left(\frac{Y}{Y_0}\right) & \frac{Y}{Y_0} \le 0.008856 \end{cases}$$

$$a^* = 500(X_n - Y_n)$$

$$b^* = 200(Y_n - Z_n)$$

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COLOR DIFFERENCE

The geometrical difference of two colors in a uniform color space should be proportional to the apparent, or perceived, color difference. The color difference is denoted by ΔE^* (delta E). In the $L^*a^*b^*$ color space, ΔE is written as ΔE^*_{ab} and is computed as follows:

$$\Delta E^*_{ab} = \left[\left(L^*_1 - L^*_2 \right)^2 + \left(a^*_1 - a^*_2 \right)^2 + \left(b^*_1 - b^*_2 \right)^2 \right]^{\frac{1}{2}}$$

CHARACTERIZATION OF A CAMERA (1)

A typical methodology to characterize a camera with a linear matrix colorimetrically is to use test patches whose spectral responses are similar to those of real objects. Suppose that the target tristimulus values for color targets are given by:

$$T = \begin{bmatrix} X_1 & \cdots & X_i & \cdots & X_n \\ Y_1 & \cdots & Y_i & \cdots & Y_n \\ Z_1 & \cdots & Z_i & \cdots & Z_n \end{bmatrix}$$

and the estimated tristimulus values are given by:

$$\hat{T} = \begin{bmatrix} \hat{X}_1 & \cdots & \hat{X}_i & \cdots & \hat{X}_n \\ \hat{Y}_1 & \cdots & \hat{Y}_i & \cdots & \hat{Y}_n \\ \hat{Z}_1 & \cdots & \hat{Z}_i & \cdots & \hat{Z}_n \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \cdot \begin{bmatrix} r_1 & \cdots & r_i & \cdots & r_n \\ g_1 & \cdots & g_i & \cdots & g_n \\ b_1 & \cdots & b_i & \cdots & b_n \end{bmatrix} = A \cdot S$$

where matrix *S* is measurement data through the camera. To obtain 3 X 3 matrix A, simple linear optimization or recursive nonlinear optimization can be applied.

CHARACTERIZATION OF A CAMERA (2)

The coefficients are to be retrieved for each device.

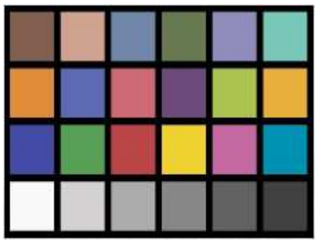
Usually a statistical retrieving phase is used with the Macbeth chart:

– Several image acquisitions of the chart (without dominant colours);

– Mean (to reduce the noise effects);

– Linear regression obtaining the a_{ij} *values.*

$$A = T \cdot S^T \cdot (S \cdot S^T)^{-1}$$



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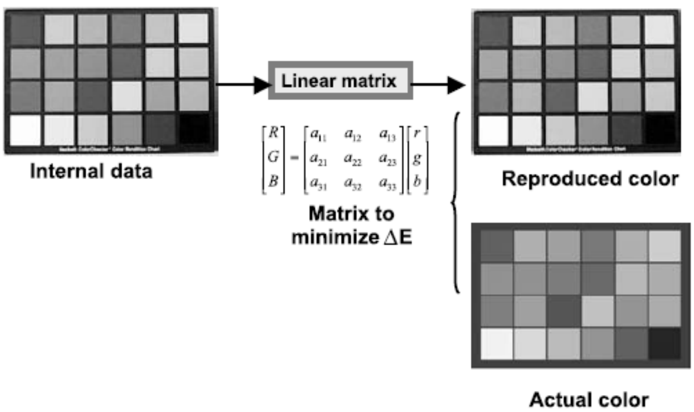
CHARACTERIZATION OF A CAMERA (3)

An alternate method minimizes the total visual color difference, *J,* using a recursive conversion technique. ΔE may be calculated in a CIE uniform color space:

$$J = \sum_{i=1}^{n} w_i \Delta E(X_i, Y_i, Z_i, \hat{X}_i, \hat{Y}_i, \hat{Z}_i)$$

where w_i is a weight coefficient.



$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} r \\ g \\ b \end{bmatrix}$$

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White Balance (1)

- One of the most challenging processes in a digital camera is to find an appropriate white point and to adjust color.
- Real scenes contain many light sources. In such a situation, the human visual system adapts to the circumstances and recognizes the objects as if they were observed in typical lighting conditions, while a camera's sensor still outputs raw signals.
- For instance, they recognize white paper as white in the shadow of a clear sky even though its tristimulus values give a bluish color because the paper is illuminated by sky blue.
- It is known that the major adjustment is performed in the retina by adjusting each cone's sensitivity. This process is called chromatic adaptation.

White Balance (2)

Incorrect white balance

Correct white balance

http://www.cambridgeincolour.com/tutorials/white-balance.htm

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White Balance (3)

- Color correction is based on the (Von Kries) diagonal hypothesis
- It states that a color balancing can be obtained by a different gain application on each color channel.
- On a RGB image representation a diagonal transform is performed as follows:

$$\begin{bmatrix} R_b \\ G_b \\ B_b \end{bmatrix} = \begin{bmatrix} k_r & 0 & 0 \\ 0 & k_g & 0 \\ 0 & 0 & k_b \end{bmatrix} \begin{bmatrix} R_i \\ G_i \\ B_i \end{bmatrix}$$

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Typical approaches

- They are based on strong assumption in the scene content.

- Two classical methods are used:
  - Gray world approach (GW)
  - White patch approach (WP)

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Gray World approach

- It assumes that the average of all surface reflactance in a scene is gray. Each deviation is due to the illuminant.
- The algorithm works as follow:
  - Retrieve the mean value for each color channel;
  - Retrieve the k_i coefficients in order to set these value in the mid point.

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White Patch approach

- It assumes that a white object is always in the scene (i.e. the maximum values for each channel is to be the maximum allowed).
- The algorithm works as follow:
  - Retrieve the max value for each channel (Rmax, Gmax, Bmax)
  - Retrieve the k_i coefficients in order to set these value in the maximum allowed by the representation.

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Gw and WP limits

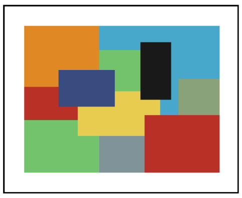
gray-world hypothesis problem scenary:

- ✓ very simple scenes with few colors.
- ✓ images with a limited range of dominant hues, i.e. underwater images,
- ✓ synthetic graphic…

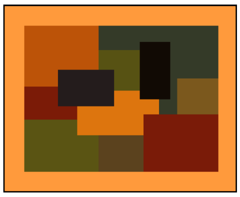
White-patch hypothesis problem scenary:

- ✓ High contrast scenes: white pixels could be saturated.
- ✓ Noise sensitivity
- ✓ metallic and specular surfaces
- ✓ a real white object could be present on the scene

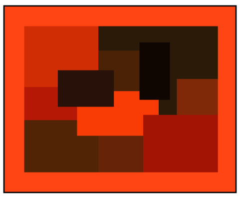
GW and WP critical examples



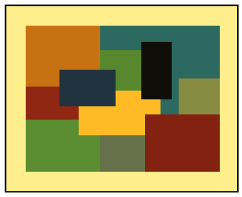
Original image



Neon illuminant

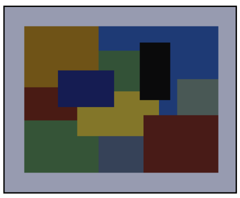


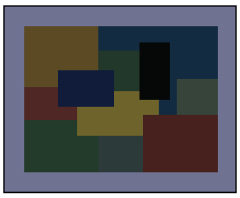
Red

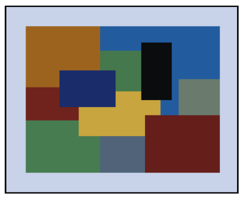


Nitraphot

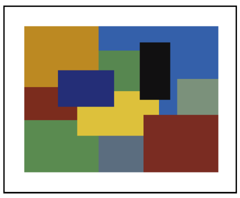
Recovered images under gray world assumption

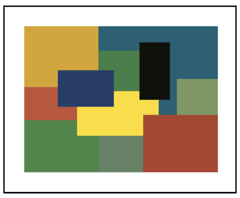


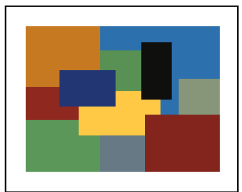




Recovered images under white patch assumption







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Critical examples

Underwater image

AWB Processed image

With constrained approaches, chromatic distortion is introduced when a real dominant hue is present.

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Gamma correction

- HVS has a non-linear response to colour intensity.
- A Gamma correction is to be applied in order to enhance the image quality.
- The Gamma controls the overall brightness of an image.

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How to

- The Gamma is usually an exponential value.
- All the colour channel is powered with the Gamma value:

$$new\_val = \left(\frac{old\_val}{\max\_val} \right)^{\gamma} \cdot \max\_val$$

- Where *max_val* is the maximum allowed value (e.g. 255 for 8 bit-depth representation).

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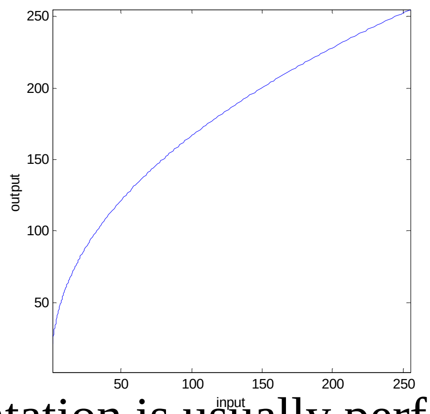
Implementation

- For Gamma=2.2 the transform is:



- The implementation is usually performed with a Look Up Table (LUT); the output is retrieved with the code: *output=LUT[input]*

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Example

Original

Gamma=2.2

Post processing techniques

- Other techniques can better enhance the colour rendition;
- Usually they are a post-processing algorithms;
- Different approaches exists in literature.

An example

- The technique individuates the scene components and adapts the colour taking into account such regions.
- The algorithm works as follows:
  - Image segmentation;
  - Object classification (e.g. sky, vegetation, skin);
  - Object colour enhancement;
  - Image Merging
  - The technique provides better visual quality results, but has a high computational cost

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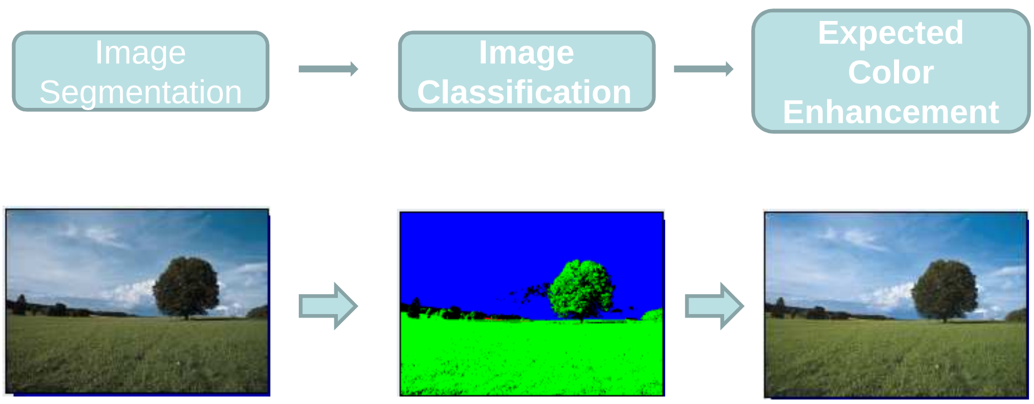
Color Enhancement

A Post-Processing Solution based on expected colors:



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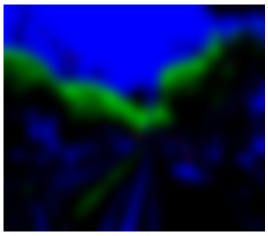
Example (1)



Input

Enhanced version

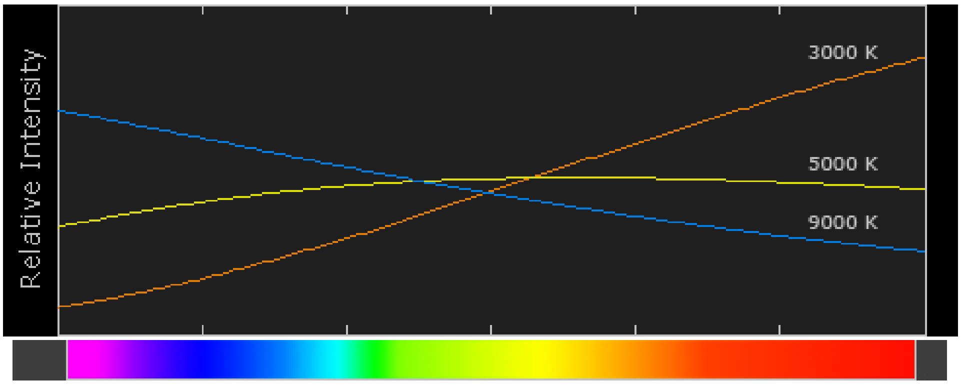
Example (2)

Input

Enhanced

Color Temperature

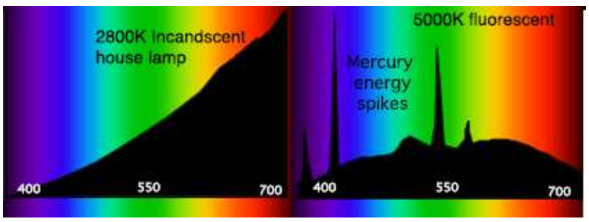
Color temperature describes the spectrum of light which is radiated from a "blackbody" with that surface temperature. A blackbody is an object which absorbs all incident light neither reflecting it nor allowing it to pass through.



Counterintuitively, higher color temperatures (5000 K or more) are "cool" (green–blue) colors, and lower color temperatures (2700–3000 K) "warm" (yellow–red) colors (shorter wavelengths contain light of higher energy).

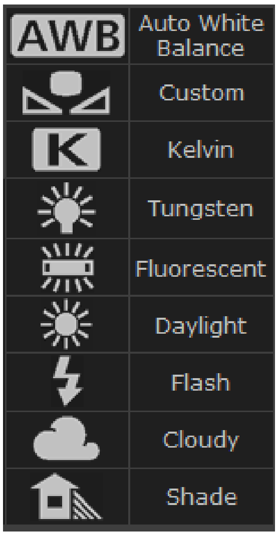
Color Temperature (2)

Color Temperature	Light Source
1000-2000 K	Candlelight
2500-3500 K	Tungsten Bulb (household variety)
3000-4000 K	Sunrise/Sunset (clear sky)
4000-5000 K	Fluorescent Lamps
5000-5500 K	Electronic Flash
5000-6500 K	Daylight with Clear Sky (sun overhead)
6500-8000 K	Moderately Overcast Sky
9000-10000 K	Shade or Heavily Overcast Sky



Light sources such as daylight and tungsten bulbs closely mimic the distribution of light created by blackbodies, although others (e. g. fluorescent) depart from blackbodies significantly.

White balance



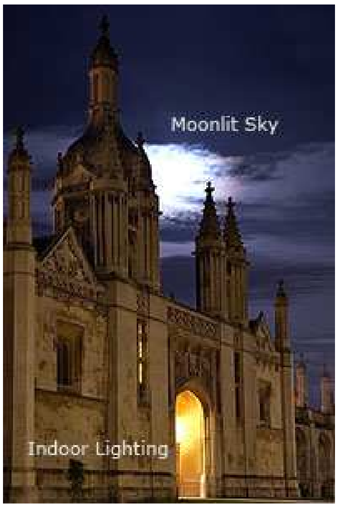
Most digital cameras contain a variety of preset white balances.
Auto white balance is available in all digital cameras and uses a best guess algorithm within a limited range usually between 3000/4000 K and 7000 K.
Custom white balance allows you to take a picture of a known gray reference under the same lighting, and then set that as the white balance for future photos.
With "Kelvin" you can set the color temperature over a broad range.

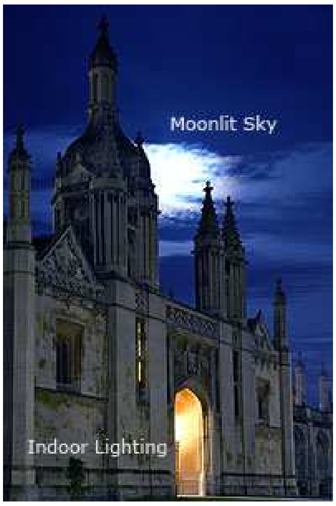
Custom white balance

Automatic white balance

Custom white balance

Mixed lighting





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References

- Image Sensors and Signal Processing for Digital Still Cameras -J. Nakamura –CRC Press, 2006;
- http://www.cambridgeincolour.com/tutorials.htm

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