Computer vision

Introduction

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Colour

Colour measurement

important for many applications

textile industry

paper industry

leather industry

graphics arts industry

...

standardized

Color Atlas

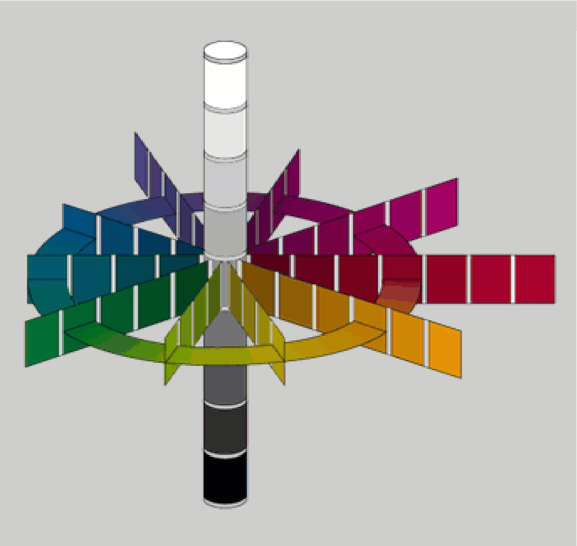
Munsell Color Atlas

Munsell notation

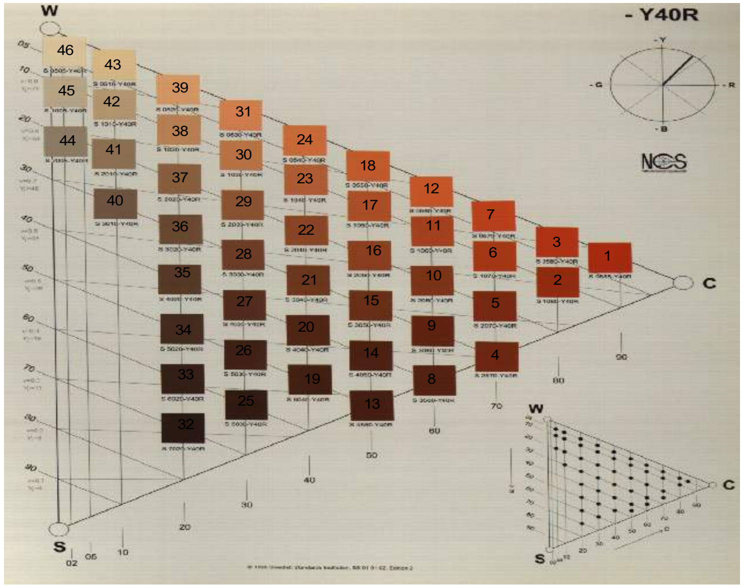
for a chromatic color is written

symbolically: H V/C. For example, 5.3R 6.1/14.4.

Munsell color space



NCS Natural Color System – SIS Standardiseringen i Sverige



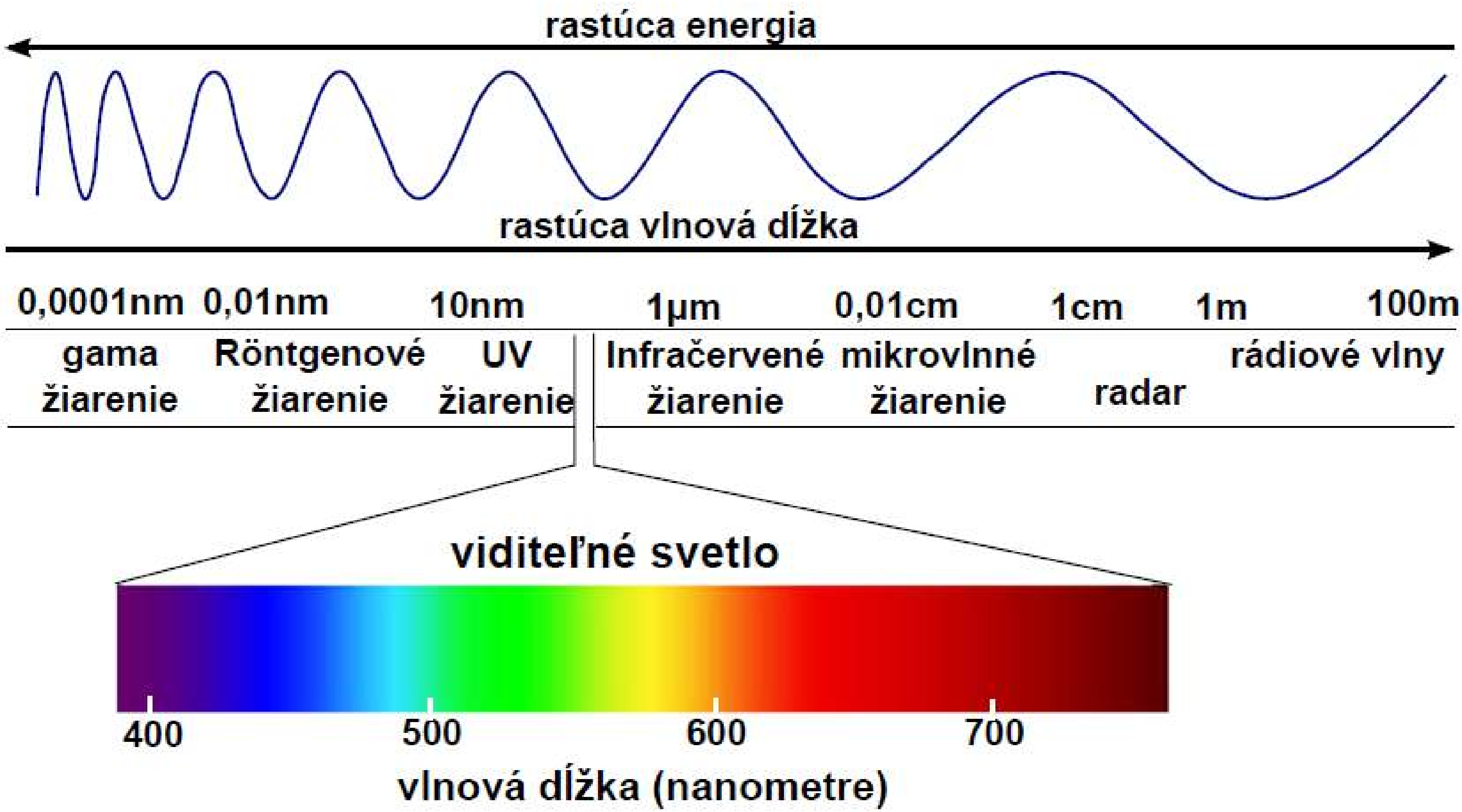
Radiometry vs. Photometry

Radiometry is the science and technology of the measurement of electromagnetic radiation over the whole spectrum of electromagnetic waves.

Photometry is the science of the measurement of light, in terms of its perceived brightness to the human eye.

Spectrum of light

Electromagnetic spectrum



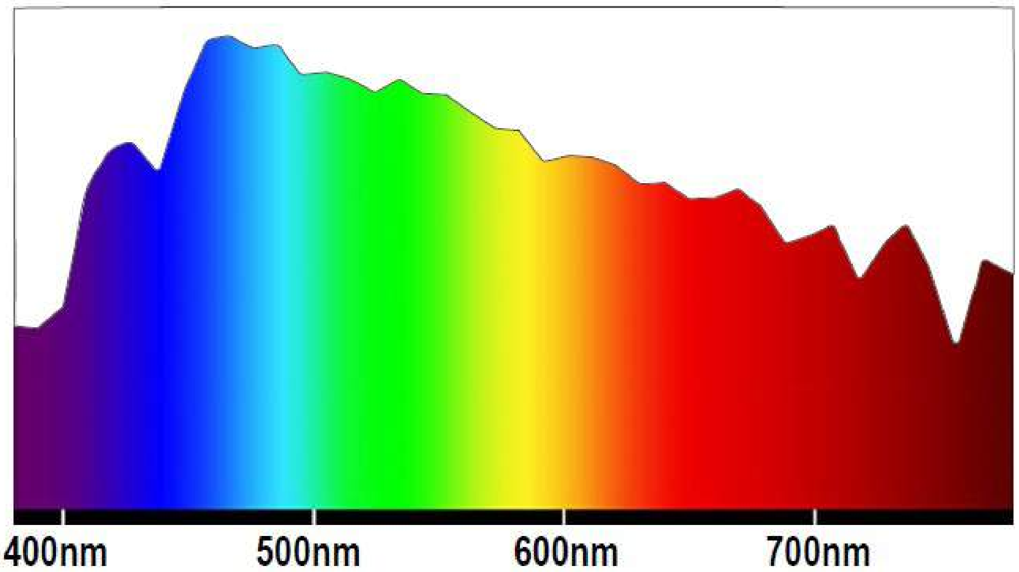
Visible range of the electromagnetic spectrum

Spectral power distribution (SPD)

Representation of the radiant power emitted by a light source at each wavelength or band of wavelengths in the visible region of the electromagnetic spectrum (360 to 770 nm).

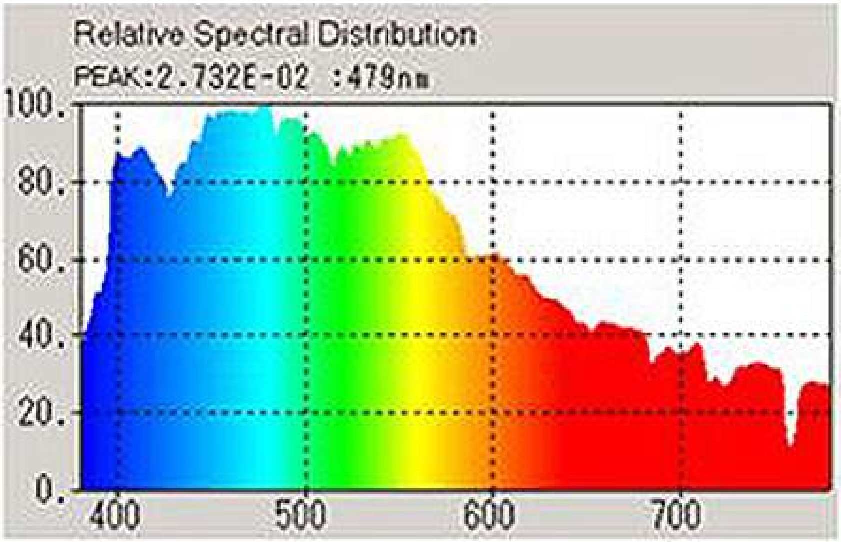
SPD describes how the power of a signal is distributed with frequency

SPD: $S(\lambda)$

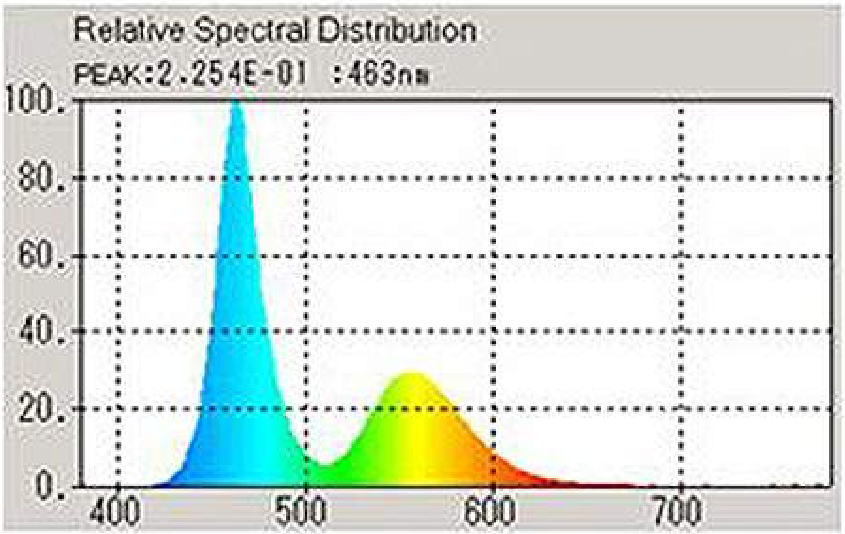


SPD curves of specific light sources

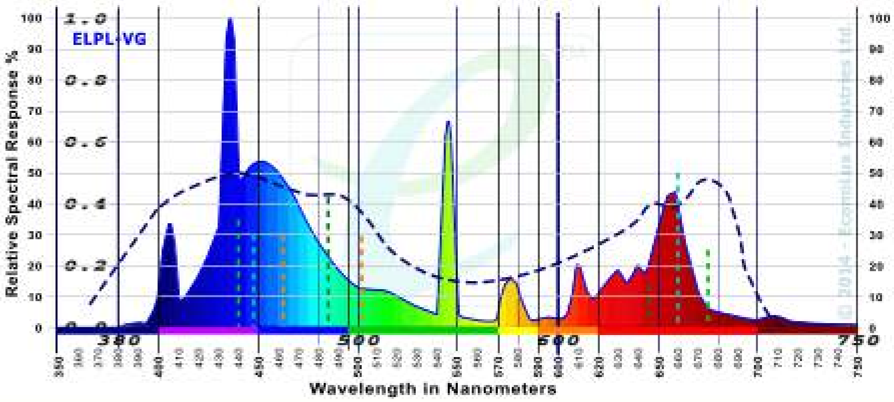
Daylight



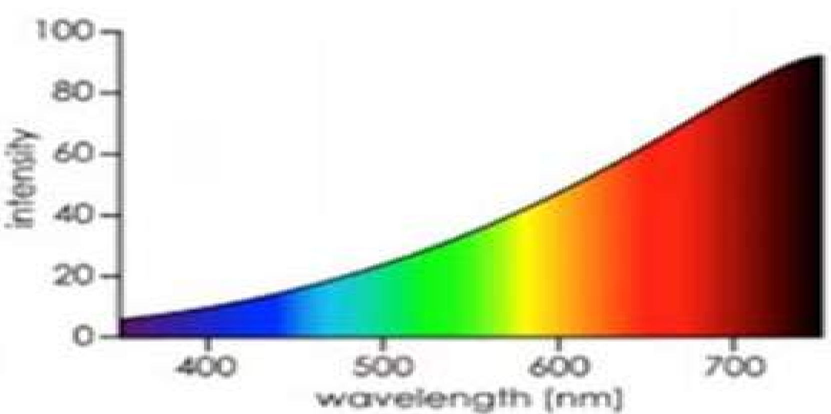
White LED



Fluorescent



Incandescent



Correlated Colour Temperature (CCT) of light sources

is defined as the value of the temperature of the black body radiator when the radiator colour matches that of the light source

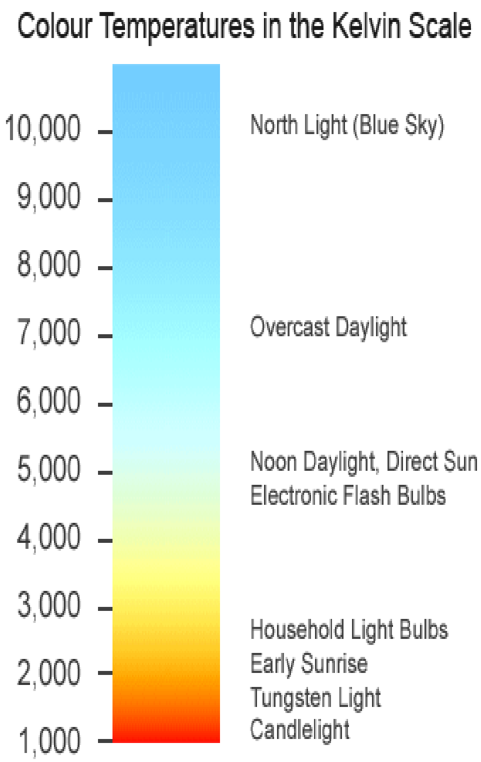


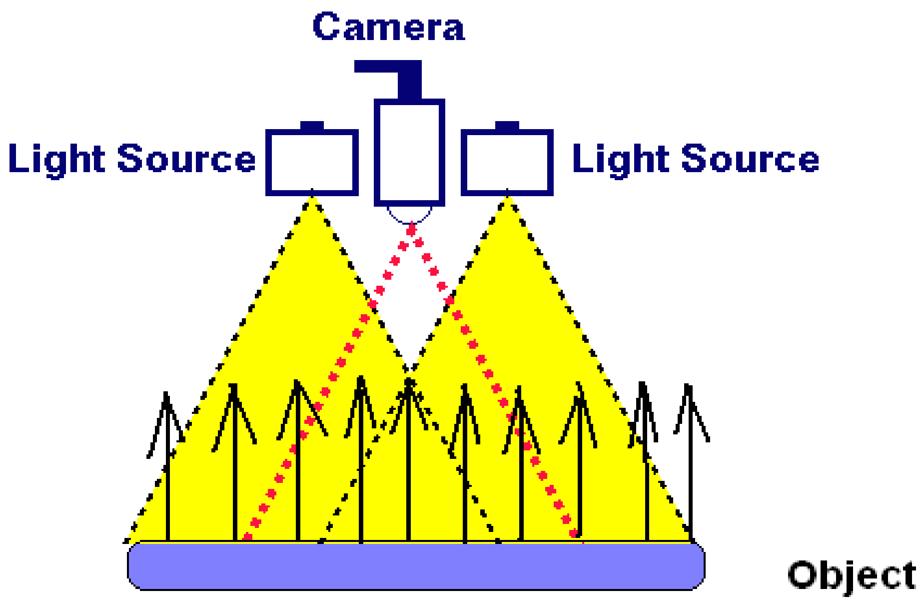
Image courtesy of www.mediacollege.com

1500 K	Candlelight
2680 K	40-watt lamp
3200 K	Sunrise/sunset
3400 K	One hour from dusk/dawn
5000-4500 K	Xenon lamp/light arc
5500 K	Sunny daylight around noon
5500-5600 K	Electronic photo flash
6500-7500 K	Overcast sky
9000-12000 K	Blue sky

Image Sensing and Acquisition

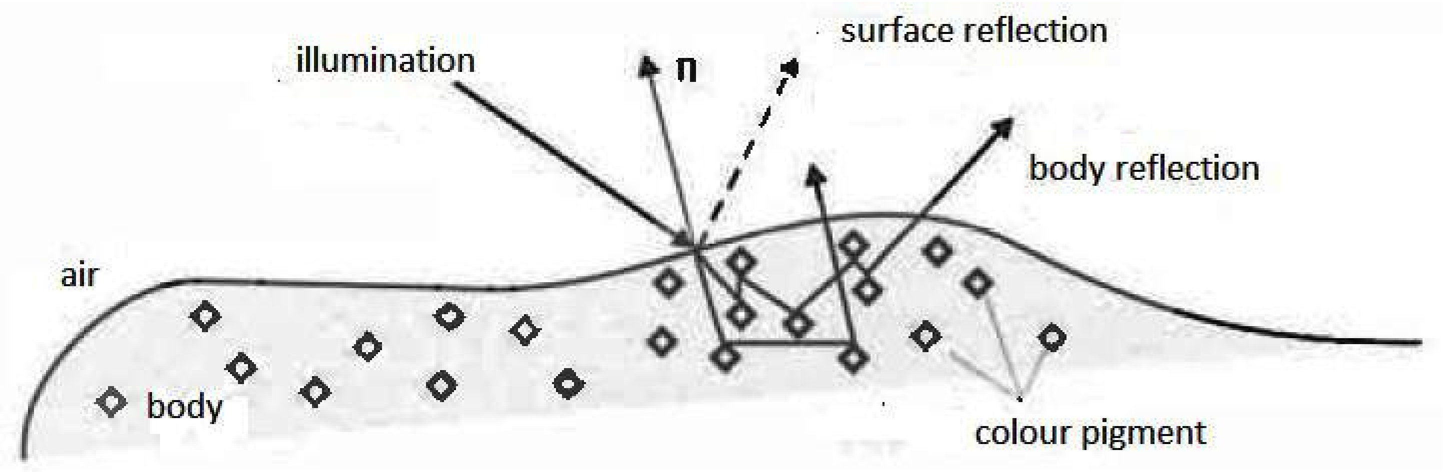
Image Sensing and Acquisition

Depending on the nature of the source, illumination energy is reflected from, or transmitted through, objects.



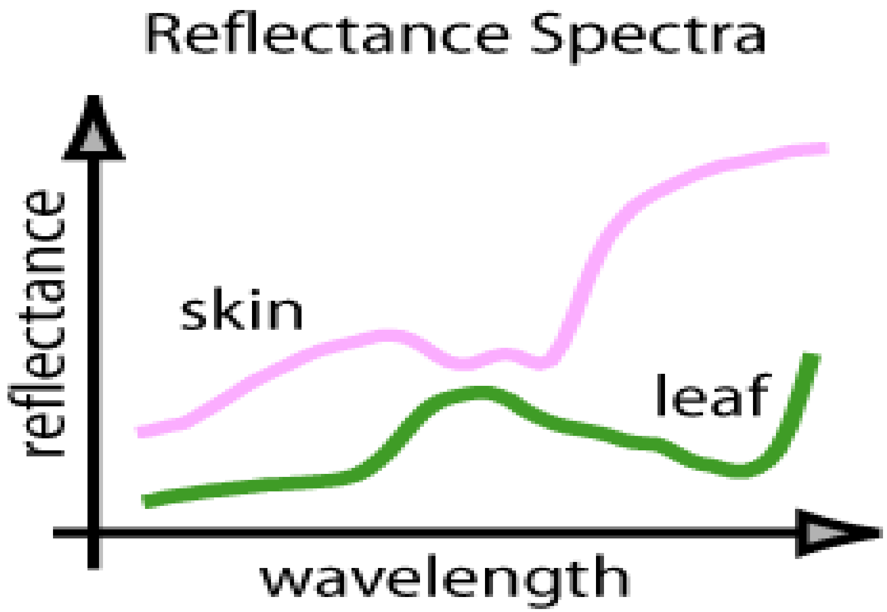
Surface reflection

Observed colour of objects is caused by certain wavelength absorptions by pigment particles in dielectrics.



Reflectance spectrum of a surface

Colour of a surface depends on
the reflectance spectrum r(λ)
and on
the illuminance spectrum i(λ)



reflectance spectra of human skin and a green leaf.

Reflection of light from a surface R(λ)

The function R(λ) may be characterized by a multiplication of two components illumination i(λ) and reflectance r(λ):

$$R(\lambda) = \text{illumination } i(\lambda) * \text{reflectance } r(\lambda)$$

$$R(\lambda) = i(\lambda) * r(\lambda)$$

r(λ) - reflectance spectrum

i(λ) - illuminance spectrum

Reaction of a photoreceptor

Let:

Ri (λ) be the spectral sensitivity of the sensor,

J(λ) be the spectral density of the illumination,

S(λ) describe how the surface patch reflects each wavelength of the illuminating light.

The spectral response qi of the i-th sensor band, can be modelled by integration over a certain range of wavelengths:

$$q_i = \int_{\lambda_1}^{\lambda_2} I(\lambda)\, R_i(\lambda)\, S(\lambda)\, \mathrm{d}\lambda$$

Multispectral images

Most sensors used for colour capture, e.g., in cameras, do not have accurate information about the colour

the exception is a spectrophotometer

Each spectral band is digitized independently and is represented by an individual digital image function as if it were a monochromatic image.

→ Multispectral image

Multispectral images

Multispectral images are commonly used in remote sensing from satellites, airborne sensors and in industry.

...for instance, the LANDSAT satellite transmits digitized images in five spectral bands from near-ultraviolet to infrared.

Minolta 2600d Photospectrometer

This instrument utilizes the D/8 geometry conforming to CIE No.15 (diffused illumination/8° viewing system) standard.

Colour camera

Three-chip cameras have 3 grey sensors

prism

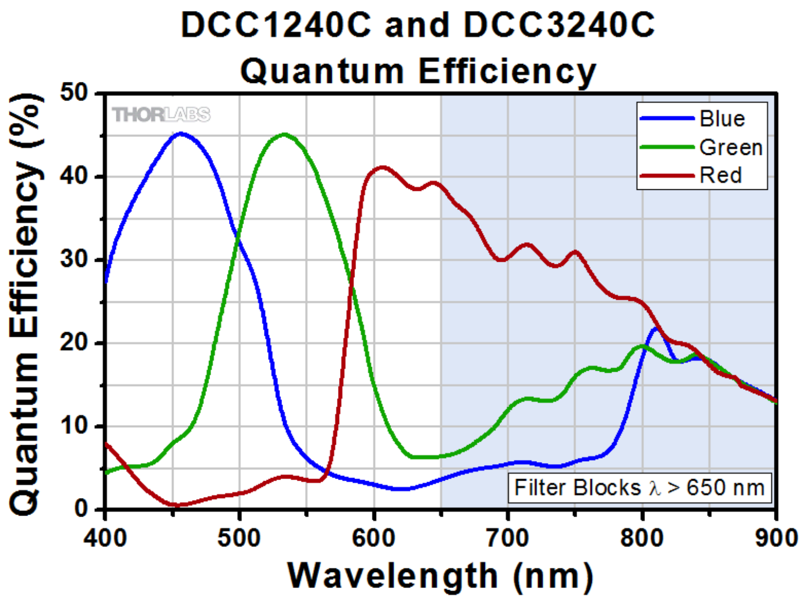
each of the red, green and blue filters covers a complete sensor chip.

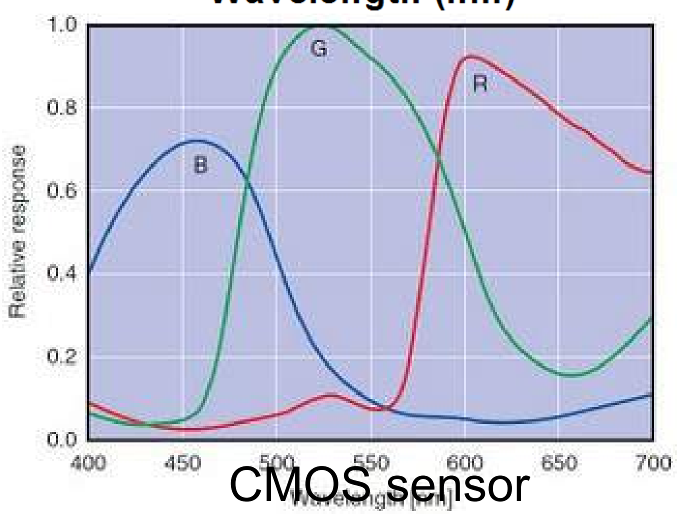
Single-chip colour sensors are conventional sensors to which a colour filter is applied.

Bayer matrix

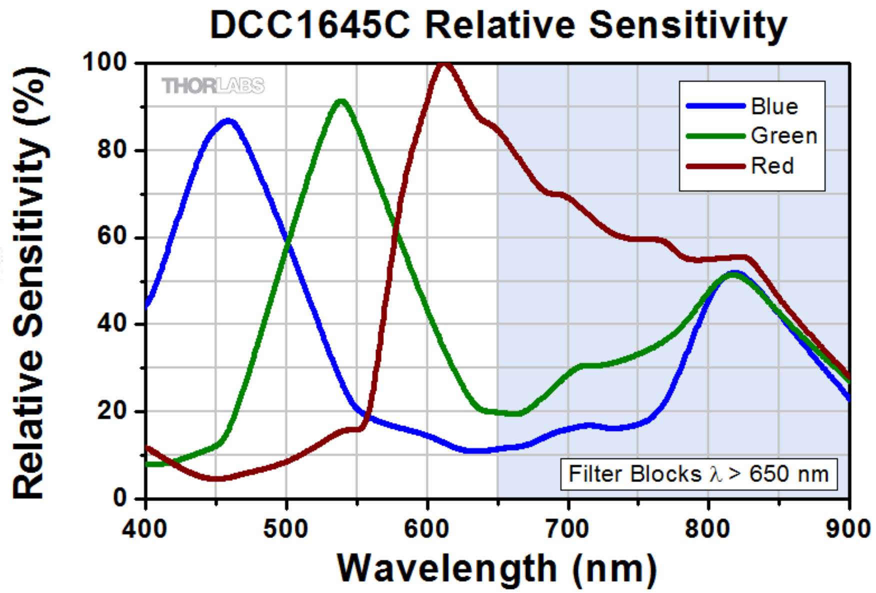
For cost reasons, however, single-chip color cameras are still more widely used than three-chip cameras.

Spectral sensitivity of colour camera





CMOS sensor
SONY camera



Color perceived by a human

Colour of light / Colour perceived

Colour of light arriving at camera depends on

Spectral reflectance of the surface light is leaving

Spectral radiance of light falling on that patch

Colour perceived depends on

Physics of light

Visual system receptors

Brain processing, environment

Colour (perceived)

Color is the perceptual result of light in the visible region of the spectrum, having wavelengths in the region of 400 nm to 700 nm.

Color stimuli are assumed to be uniquely defined by their radiant power spectral distributions of $P(\lambda)$ -

(often in x components each representing a 10 nm(5nm) band).

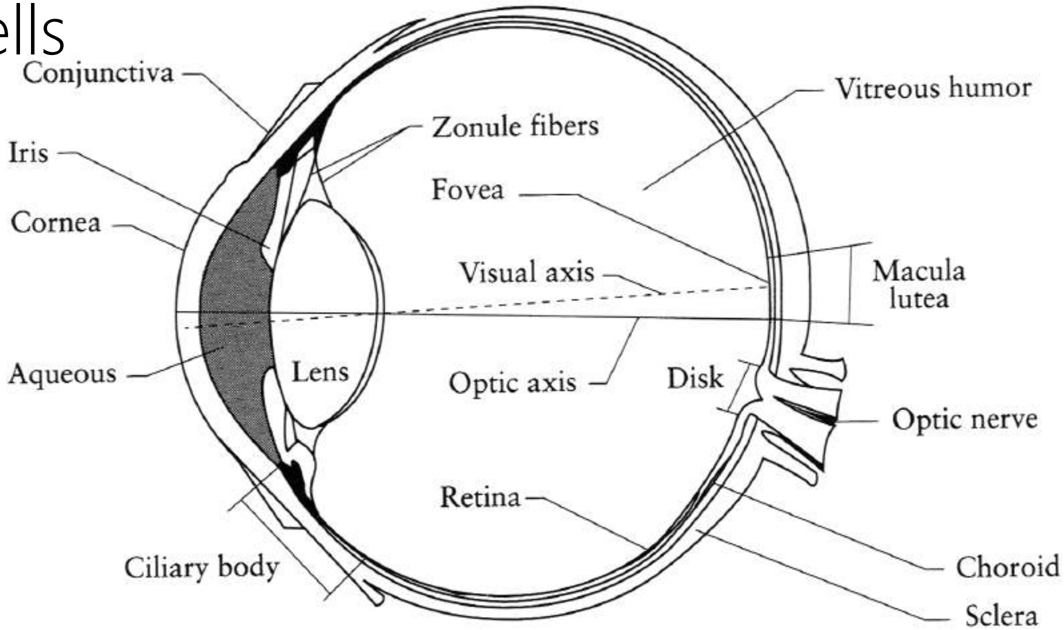
Colour perceived by humans

Human colour perception adds a subjective layer on top of underlying objective physical properties - the wavelength of electromagnetic radiation.

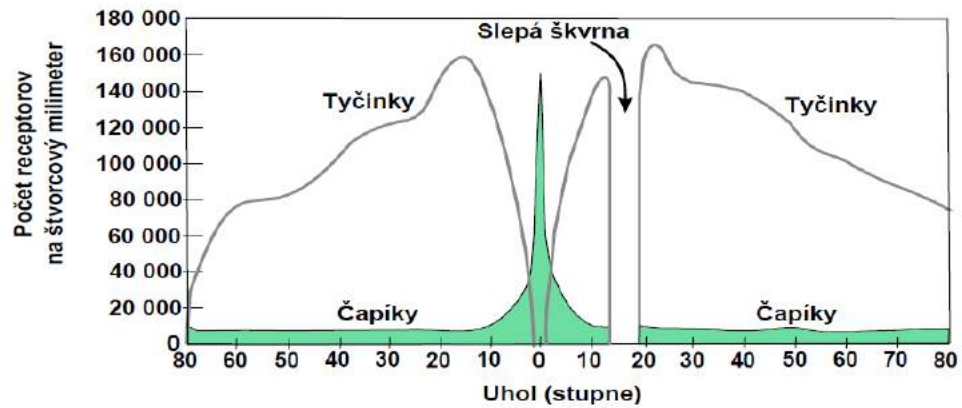
Three types of sensors receptive to the wavelength of incoming irradiation have been established in humans, thus the term trichromacy.

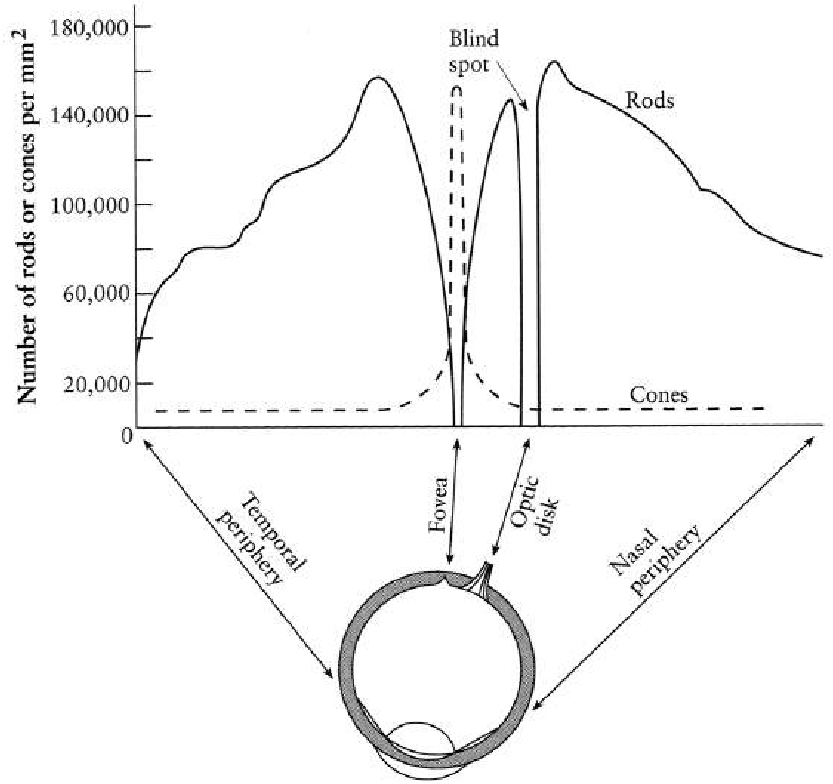
The Eye

The human eye is like a camera!
Iris - colored annulus with radial muscles
Pupil - the hole (aperture) whose size is controlled by the iris
Lens - changes shape by using ciliary muscles (to focus on objects at different distances)
Retina - photoreceptor cells



Photoreceptors in human eye
Rods & Cones





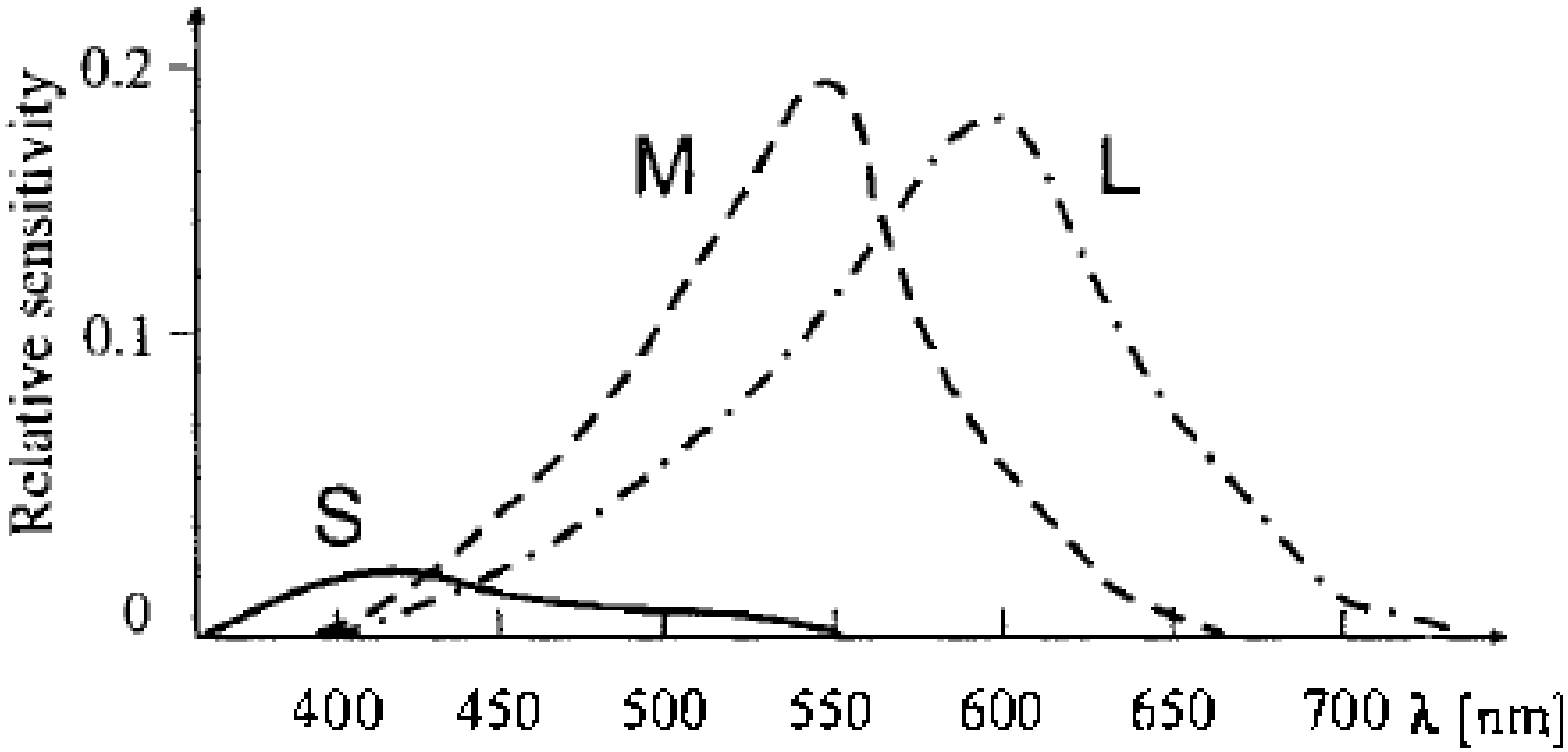
Cones

- cone-shaped
- less sensitive
- operate in high light
- color vision

Rods

- rod-shaped
- highly sensitive
- operate at night
- gray-scale vision

Relative sensitivity of S ,M, L cones of the human eye



Trichromacy

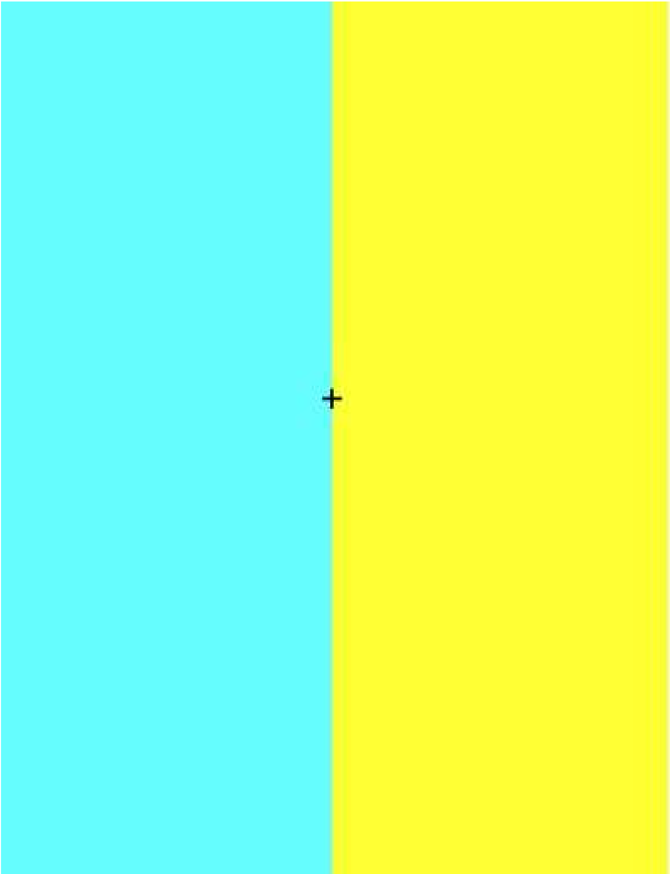
Experimental facts:

- Three primaries will work for most people if we allow subtractive matching; "trichromatic" nature of the human visual system
- Most people make the *same* matches for a given set of primaries (i.e., select the same mixtures)

• Color matching experiments imply that three good primaries are sufficient.

Chromatic adaptation

If the visual system is exposed to a certain illuminant for a while, color system starts to adapt / skew.



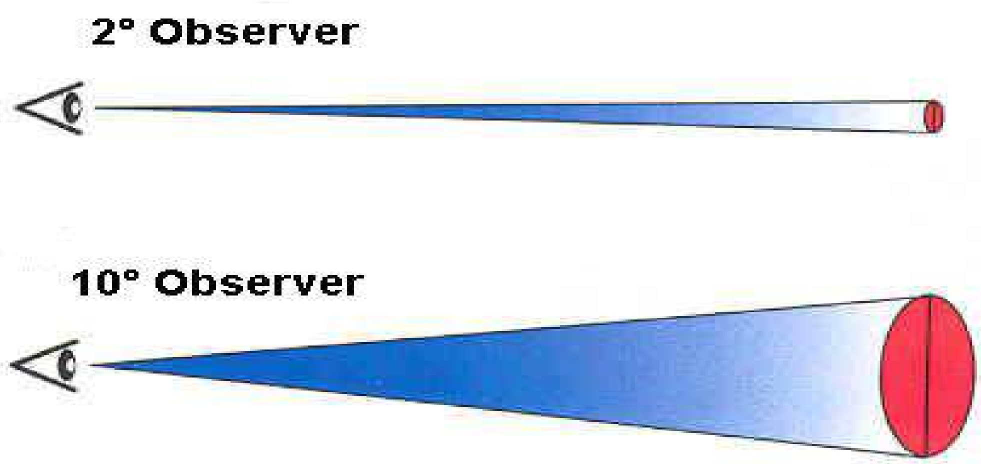
CIE Colorimetric System

Commission Internationale de l 'Eclairage

Commission Internationale de l'Eclairage CIE Colorimetric System

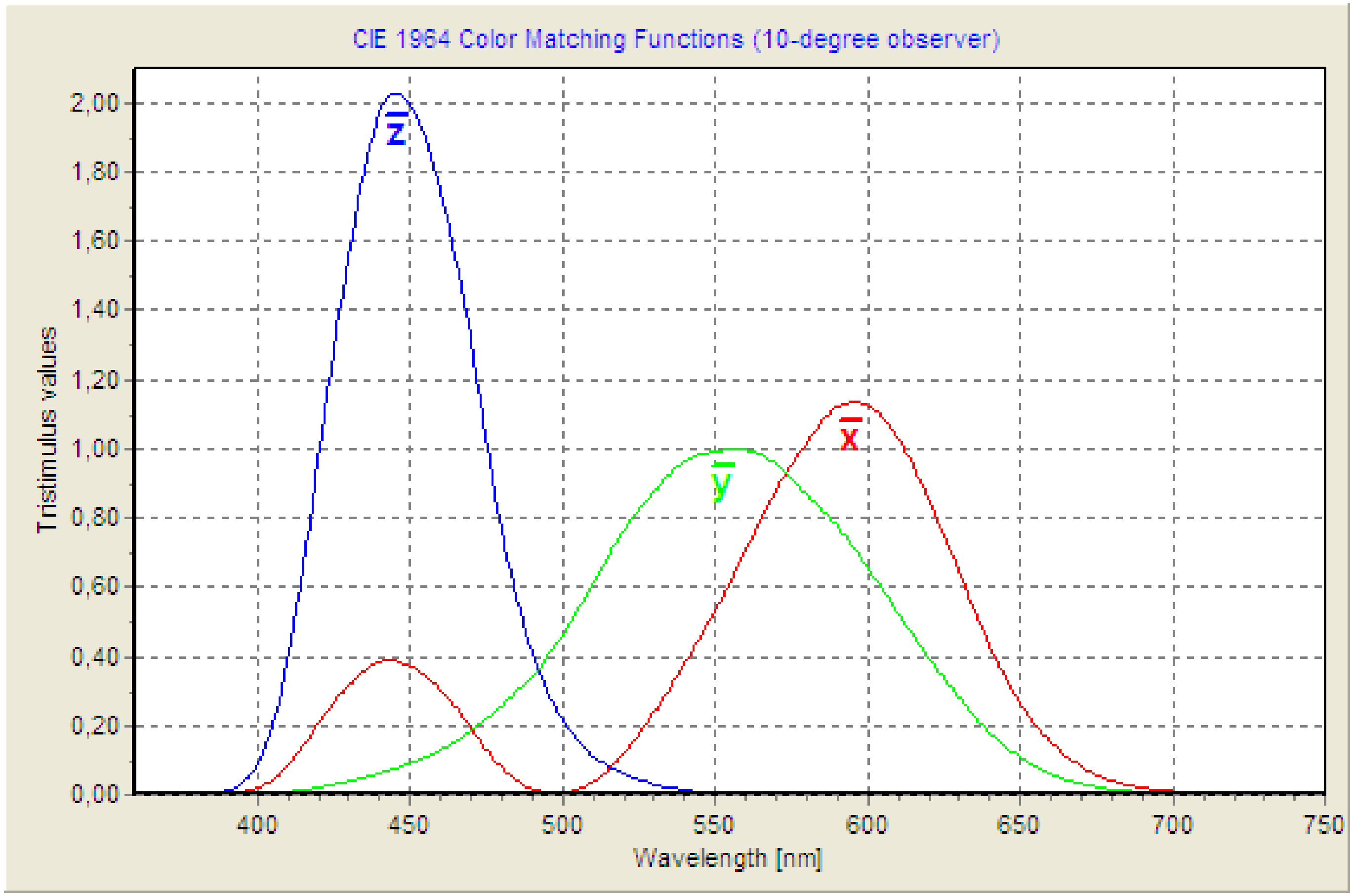
Standard Colorimetric Observer (model of human colour perception):

1931 (2°), 1964 (10°)

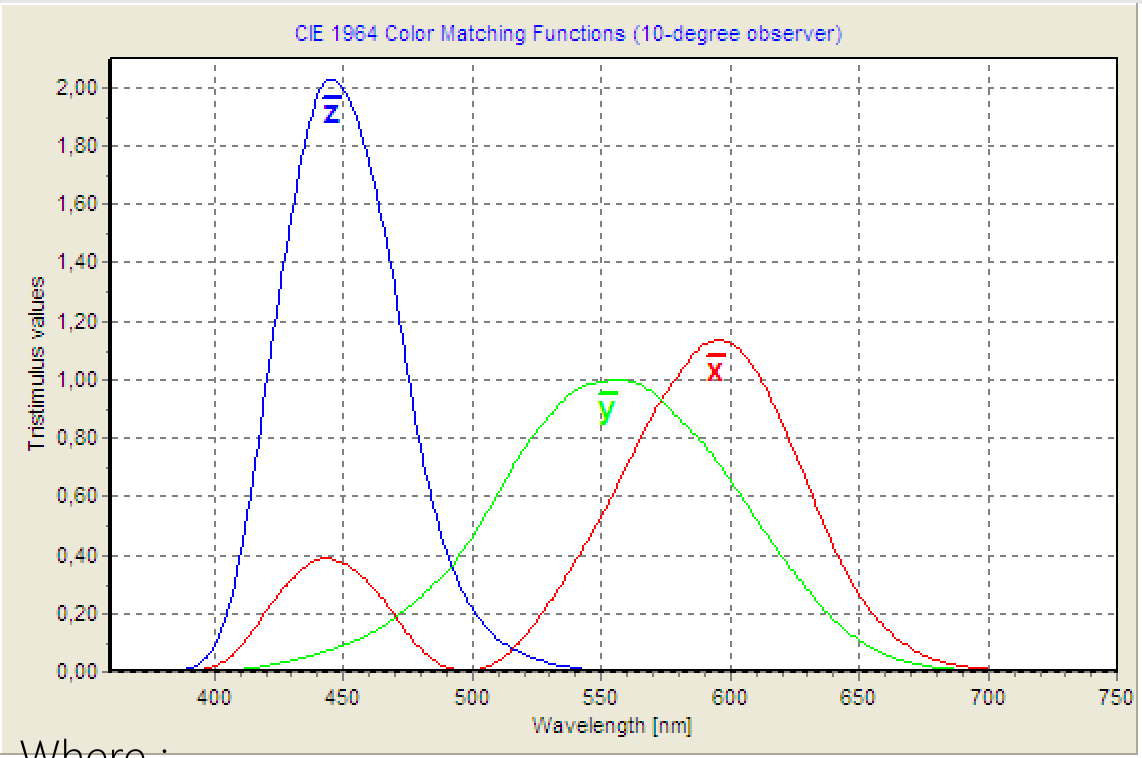


CIE colour matching functions standard colorimetric observer

$x_{10}(\lambda)$, $y_{10}(\lambda)$, $z_{10}(\lambda)$ are colour matching functions that define the CIE 1964 standard colorimetric observer



CIE XYZ color space



$$X_{10} = k_{10} \int_{\lambda} P_{\lambda} x_{10}(\lambda) d\lambda$$

$$Y_{10} = k_{10} \int_{\lambda} P_{\lambda} y_{10}(\lambda) d\lambda$$

$$Z_{10} = k_{10} \int_{\lambda} P_{\lambda} z_{10}(\lambda) d\lambda$$

$$k_{10} = \frac{100}{\int_{\lambda} P_{\lambda} y_{10}(\lambda) d\lambda}$$

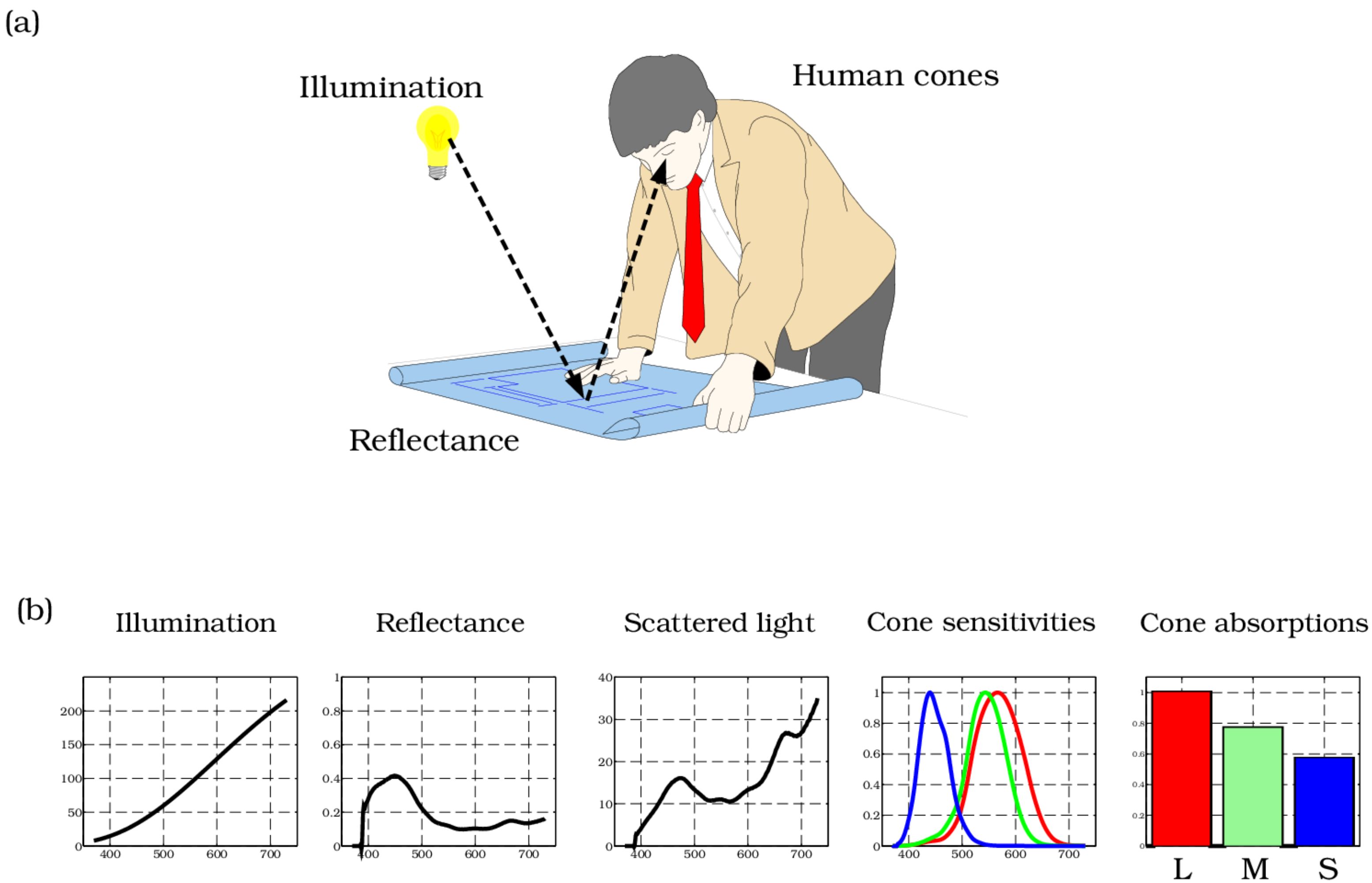
Where :

X10, Y10, Z10 denotes the tristimulus values in the CIE 1964,

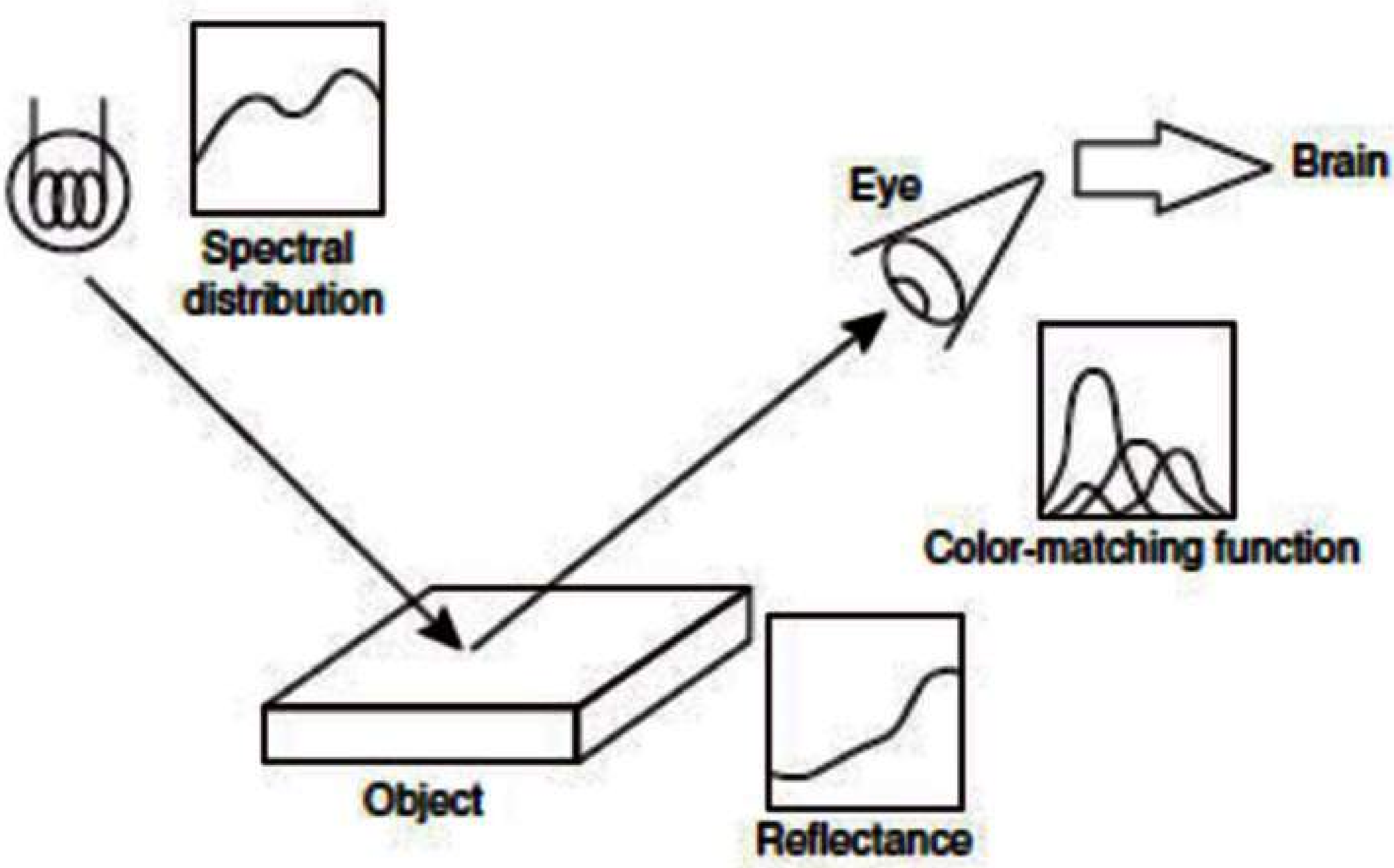
P λ denotes the monochromatic component of given color stimulus with radiant power distribution P λ d λ

x10(λ), y10(λ), z10(λ) are color matching functions that define the CIE 1964 standard colorimetric observer

Color perception model



Color perception model



Color perception model – CIE XYZ color space

$$X = k \sum_{\lambda=380}^{780} S(\lambda)\beta(\lambda)\bar{x}(\lambda)\Delta\lambda,$$

$$Y = k \sum_{\lambda=380}^{780} S(\lambda)\beta(\lambda)\bar{y}(\lambda)\Delta\lambda,$$

$$Z = k \sum_{\lambda=380}^{780} S(\lambda)\beta(\lambda)\bar{z}(\lambda)\Delta\lambda.$$

S(λ) spectral power distribution of the illuminant

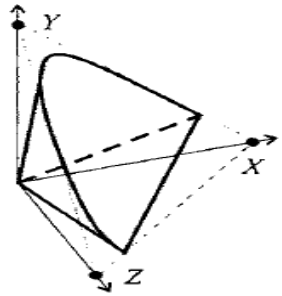
β(λ) spectral reflectance factor of the object

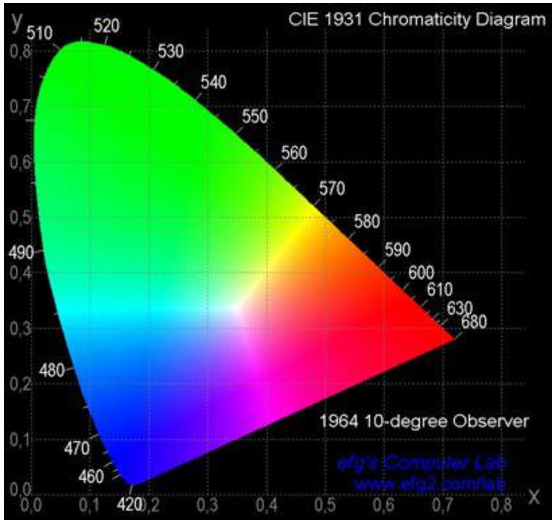
Colour matching functions: $\overline{x_{10}}(\lambda)\ \overline{y_{10}}(\lambda)\ \overline{z_{10}}(\lambda)$

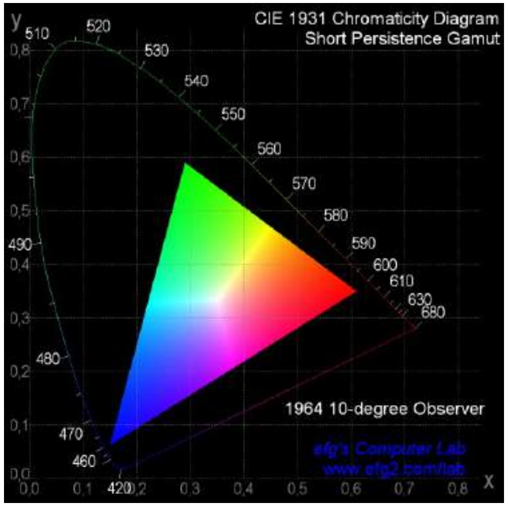
CIE Chromacity coordinates

Normalized tristimulus values, called chromaticity coordinates, are calculated based on the primaries as follows:

CIE chromaticity diagram:



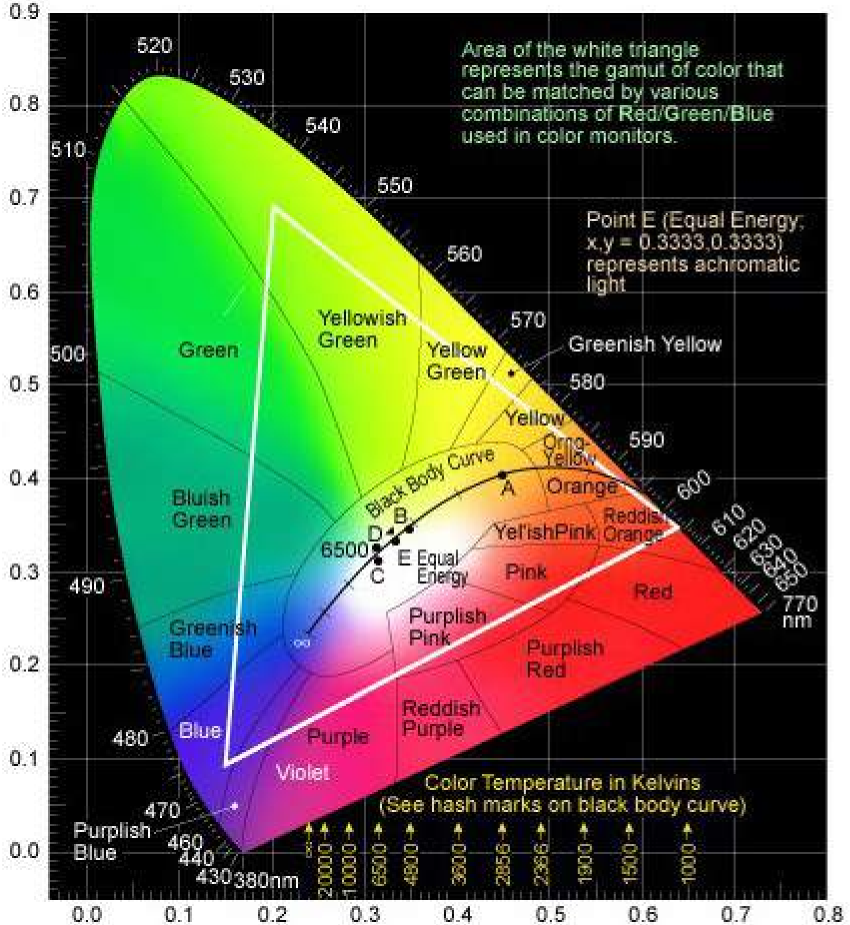




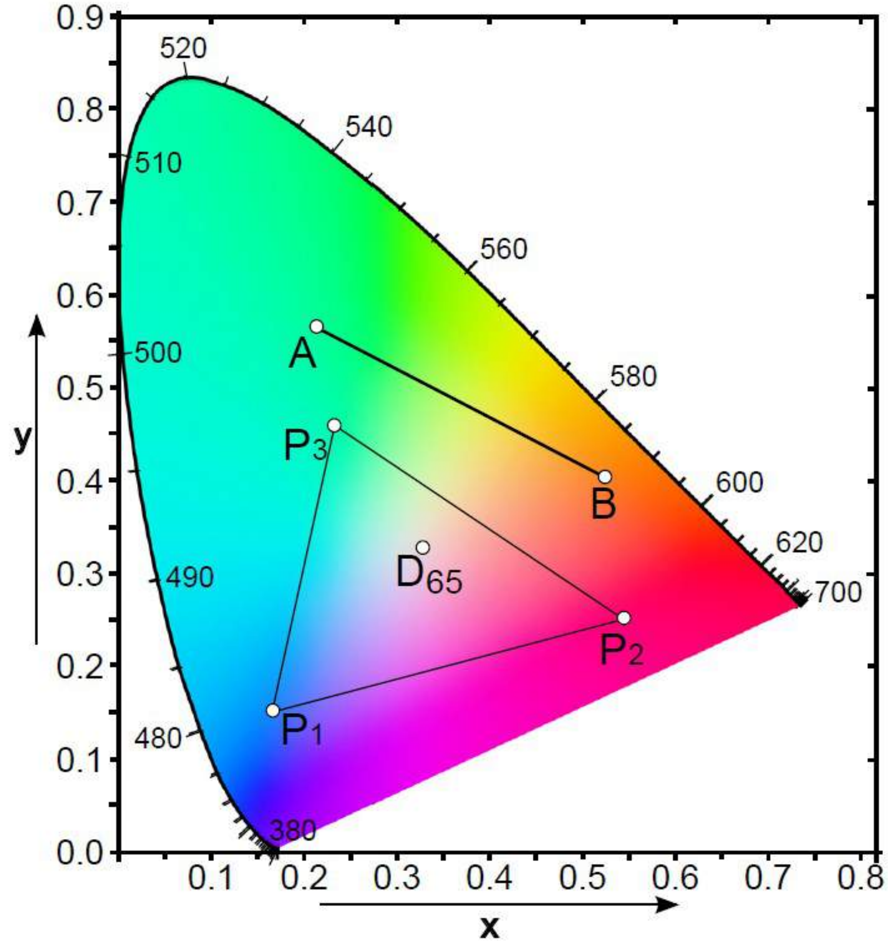
$$x_{10} = \frac{X_{10}}{X_{10}+Y_{10}+Z_{10}}$$

$$y_{10} = \frac{Y_{10}}{X_{10}+Y_{10}+Z_{10}}$$

CIE Chromacity coordinates Chromaticity diagram

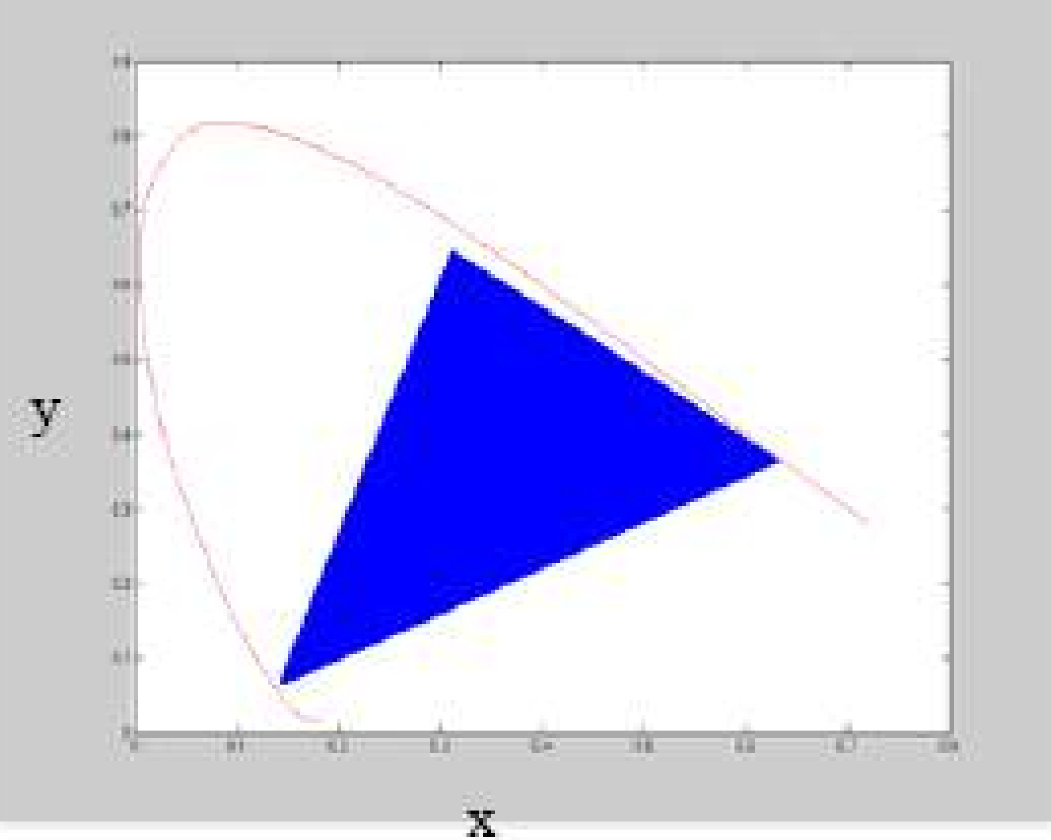


Chromaticity diagram

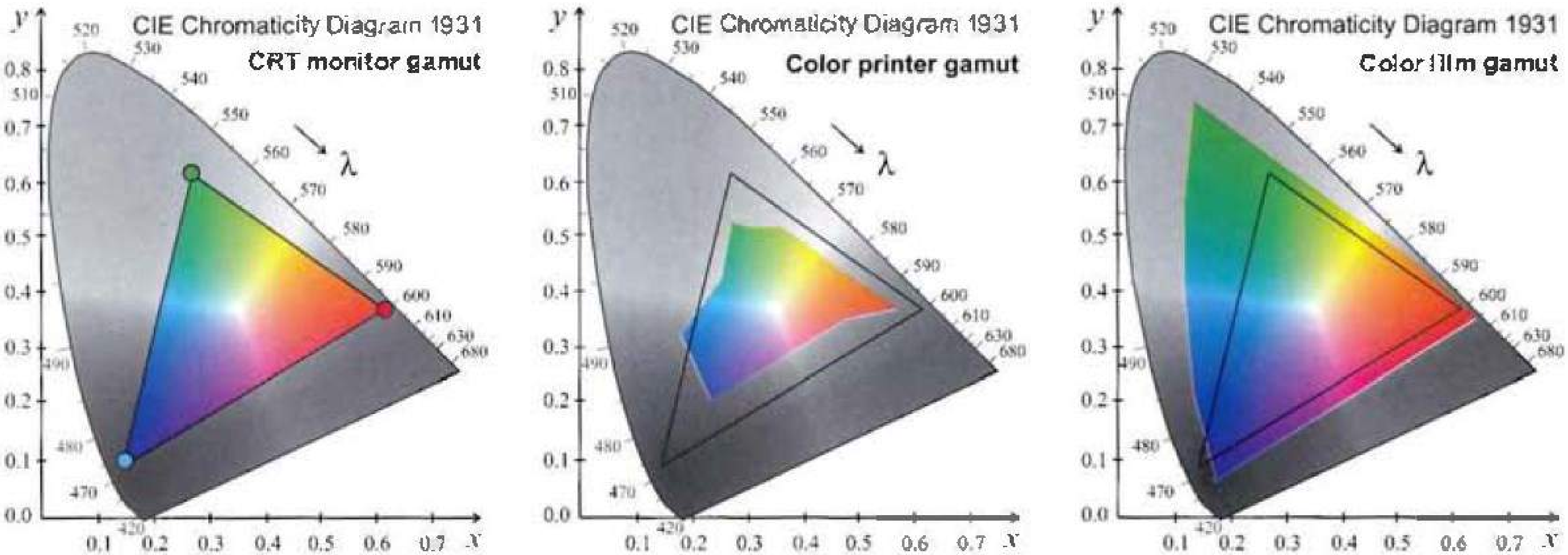


Chromaticity diagram & Gamut of camera

The blue triangle in the Figure restricts the range of colors which can be reproduced by a RGB camera.



Gamuts of three typical display devices



(a) CRT monitor (b) printer (c) film

Color matching

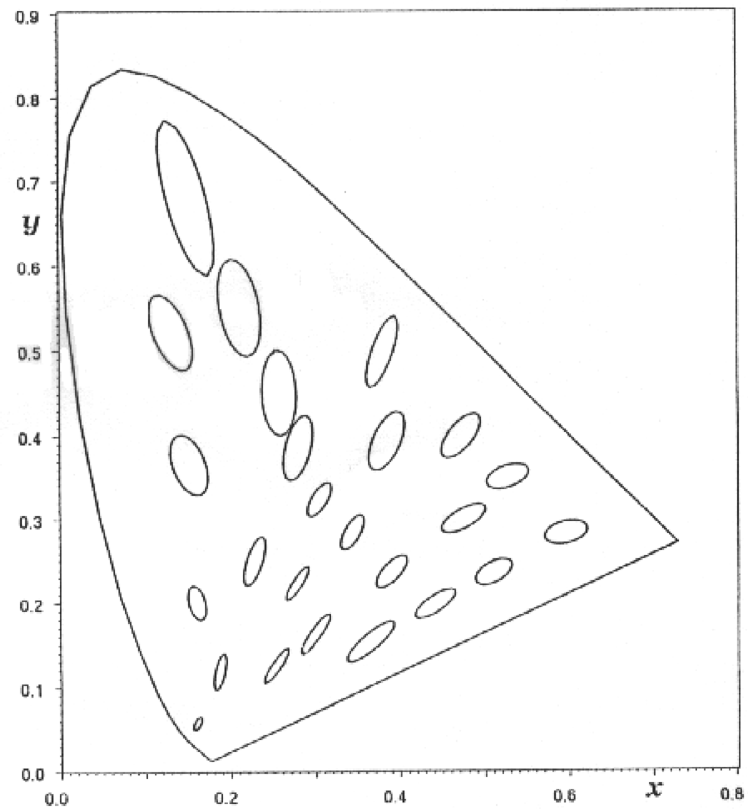
Color matching

Matching two light patches to complete colour match:

lightness, hue and saturation.

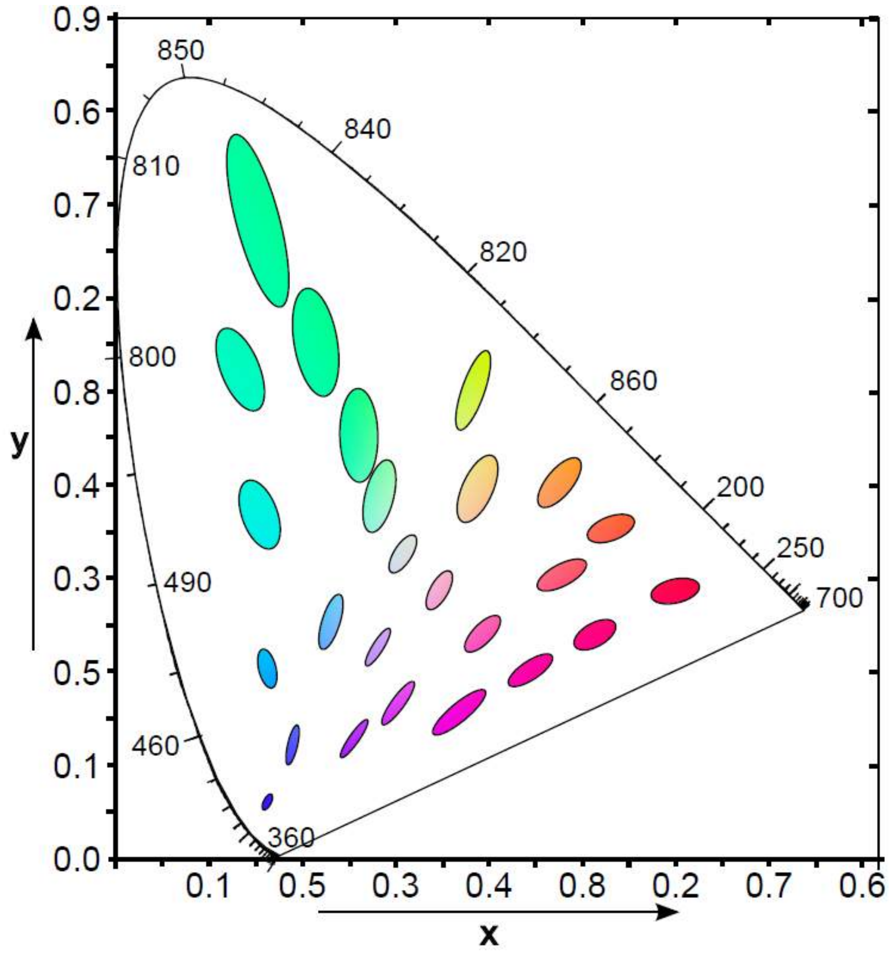
Color differences

For the fovea vision, related to a visual field of 2º, the non uniformity of the chromatic scale has been measured by MacAdam and is graphically represented by ellipses on the chromaticity diagram.



MacAdam ellipses on the CIE 1931 chromaticity diagram magnified 10 times

MacAdam ellipses



Uniform color space CIE L*a*b*

Absolute value of the L*a*b* euclidean colour differences corresponds to the human perception of the colour differences

Definition:

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16 \quad if \quad \frac{Y}{Y_n} > 0.008856$$

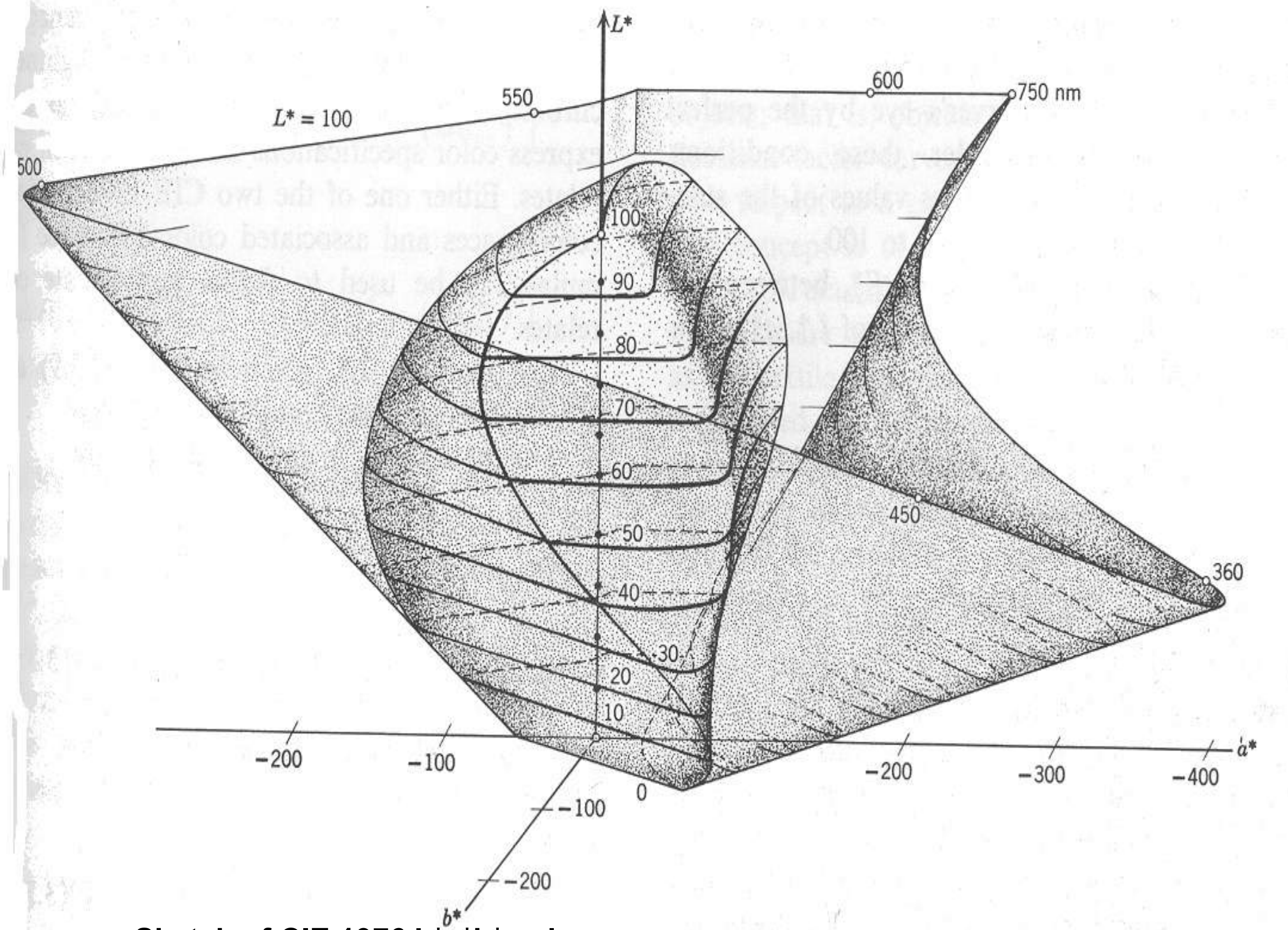
$$L^* = \quad 903.3\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} \qquad if \quad \frac{Y}{Y_n} \leq 0.008856$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}}\right]$$

where [Xn,Yn,Zn] is the white reference point.

Uniform color space
CIE L*a*b*



Sketch of CIE 1976 L*a*b* color space

Colour Differences

The total colour difference ΔE*uv between two color stimuli, each given in terms of L*,a*,b*, is calculated from:

CIE 1976 (L*a*b*) colour difference formula

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

Metamerism

Object-colour stimuli of different spectral radiant power distributions and the given observer judges the two stimuli to be in complete colour match.

The colour match cannot be expected to remain a colour match if the illuminant is changed to another one of different spectral radiant power distribution

Common CIE Illuminants

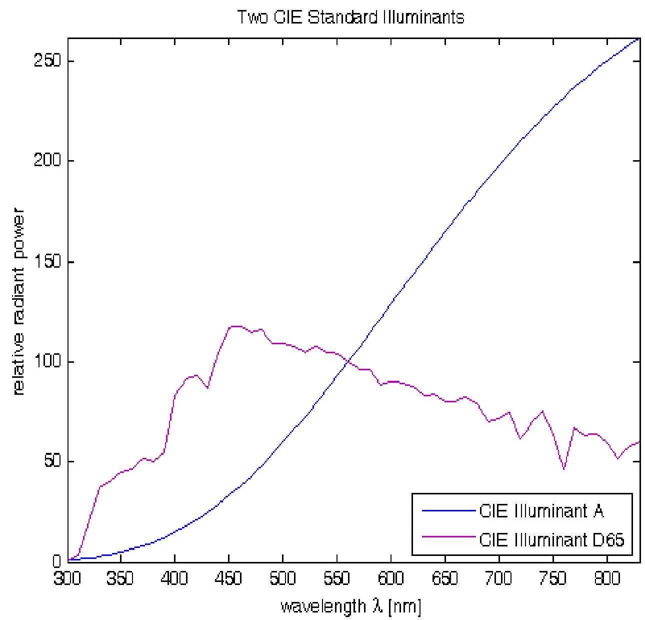
CIE standard illuminant A

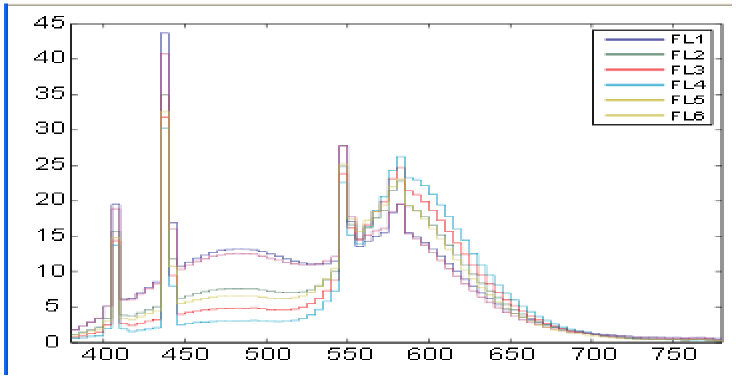
tungsten-filament lighting. Its relative spectral power distribution is that of a Planckian radiator at a temperature of approximately 2 856 K.

CIE standard illuminant D65

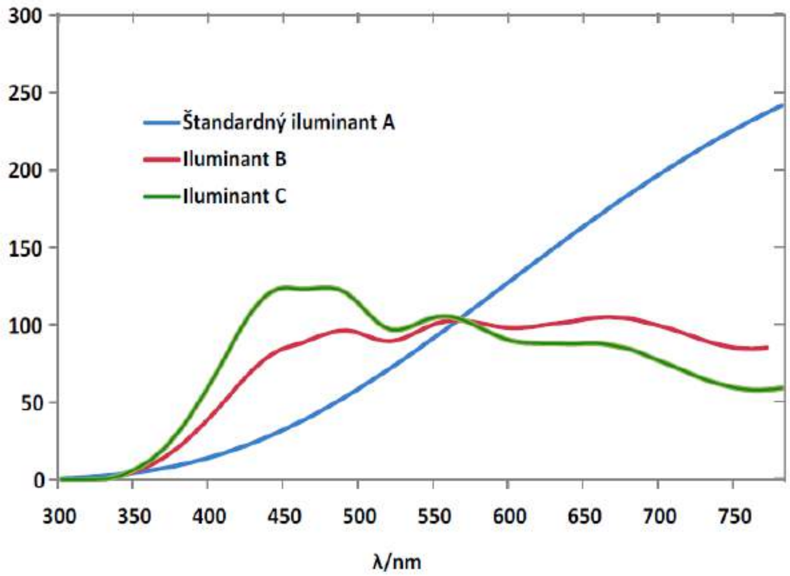
average daylight and has a correlated colour temperature of approximately 6 500 K.

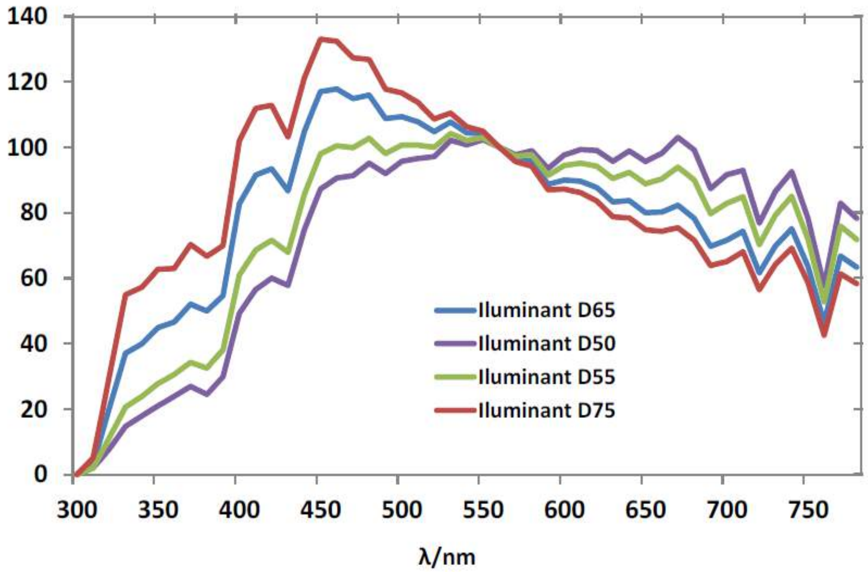
CIE standard illuminant F1–F6 "standard" fluorescent lamps





CIE standard Illuminants





CIE Standard of Reflectance

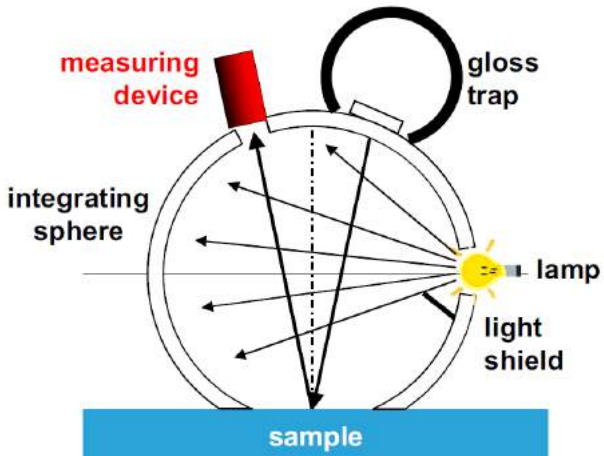
Perfect reflecting diffuser

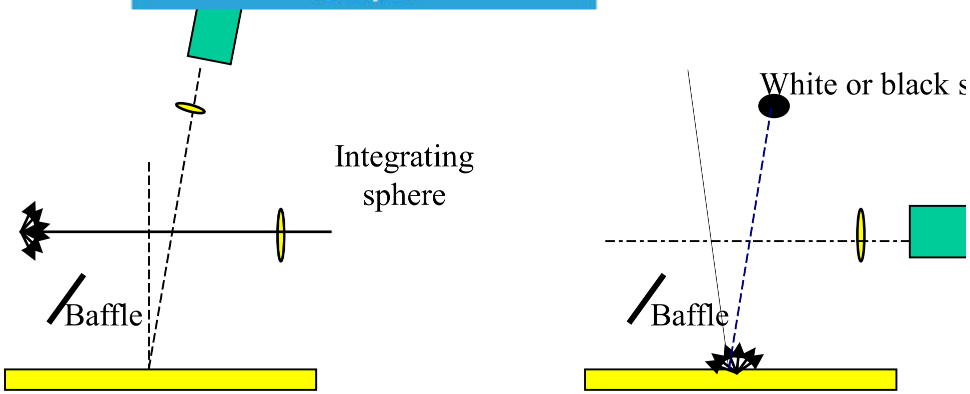
The CIE (1971) recommends the perfect reflecting diffuser with a reflectance equal to unity as the reference for making measurement of reflectance factor.

No material surface has those properties

Secondary standards - white standards

CIE Standard Illuminating and Viewing Conditions

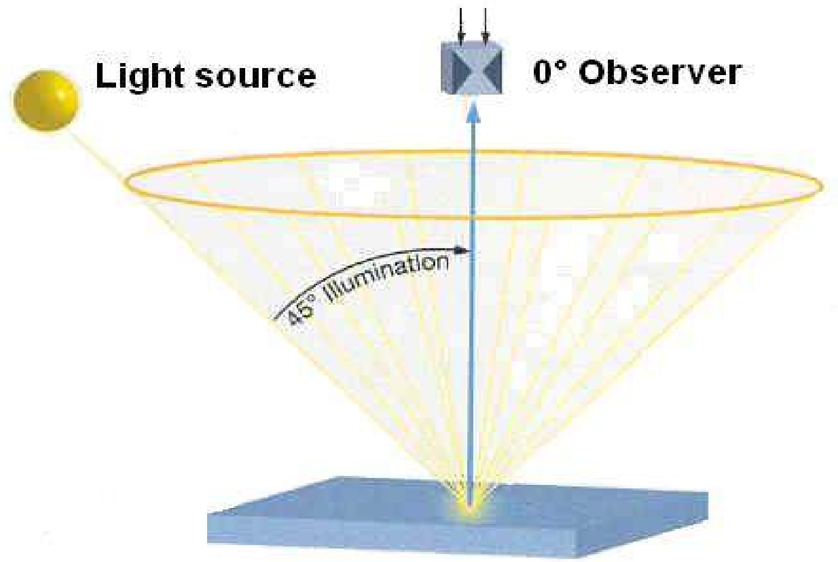




diff./0 0/diff.

d/0, 0/d Viewing Conditions, d= 8°

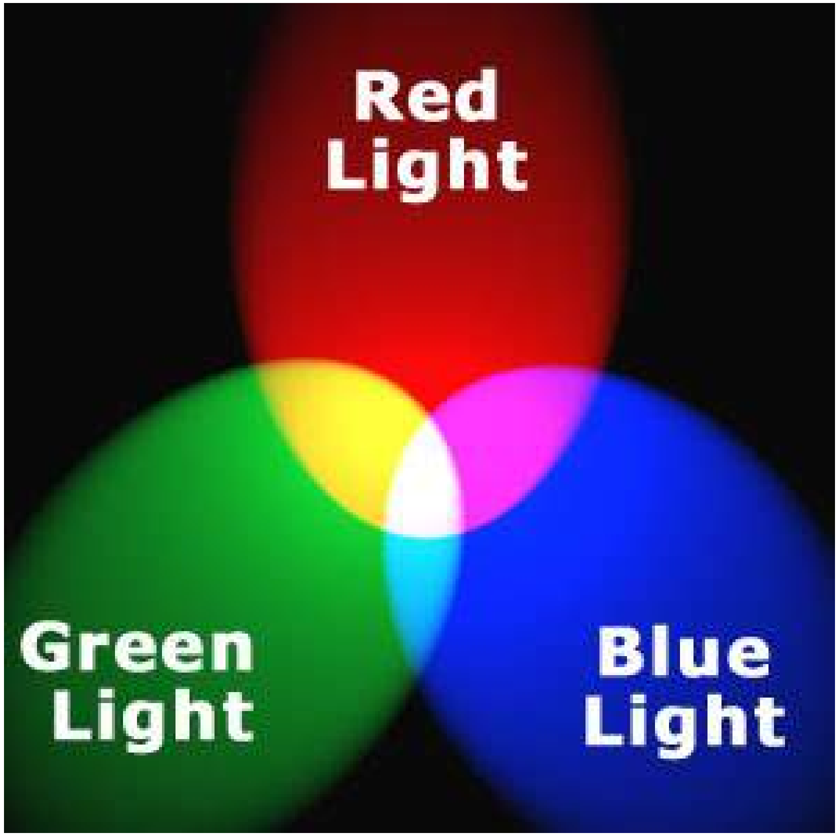
45/0, 0/45 Viewing Conditions



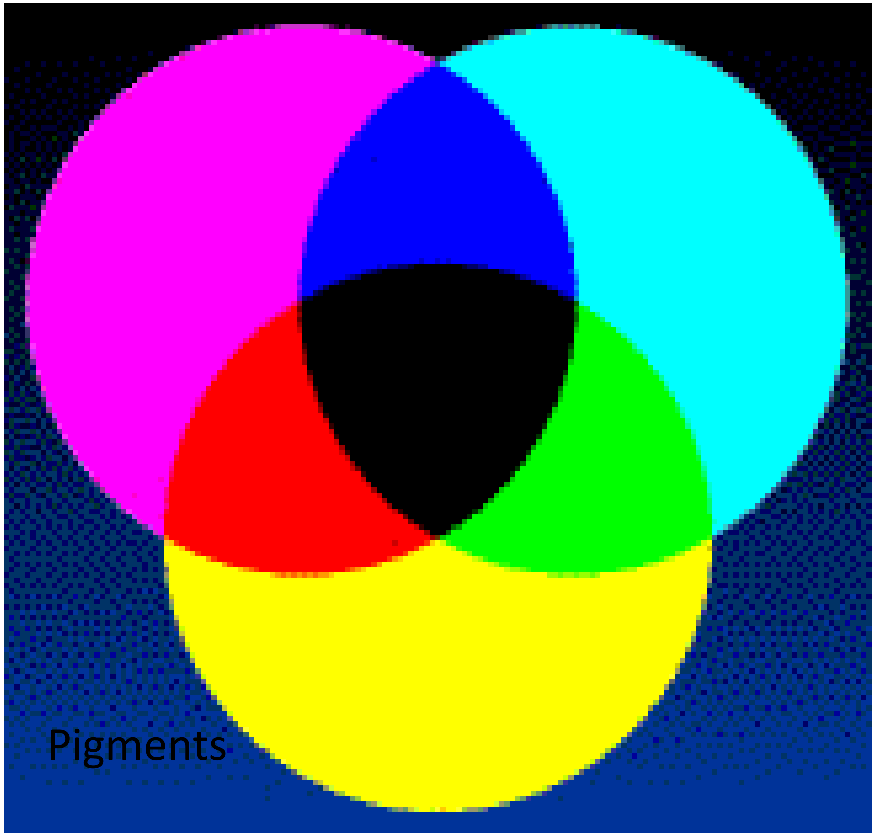
Color spaces

Additive color mixing
Subtractive color mixing

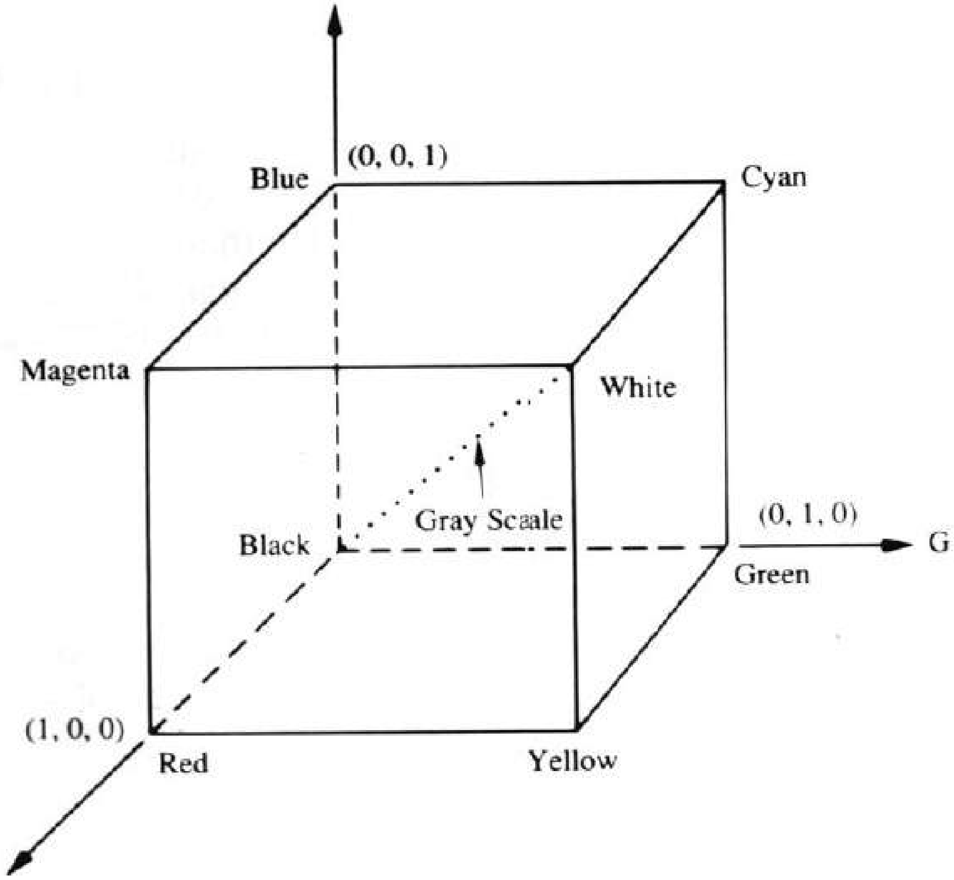
Additive color mixing



Subtractive color mixing



sRGB color spaces



RGB to XYZ – example camera TVI

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.2405 & -1.5372 & -0.4985 \\ -0.9693 & 1.8760 & 0.0416 \\ 0.0556 & -0.2040 & 1.0573 \end{bmatrix} * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

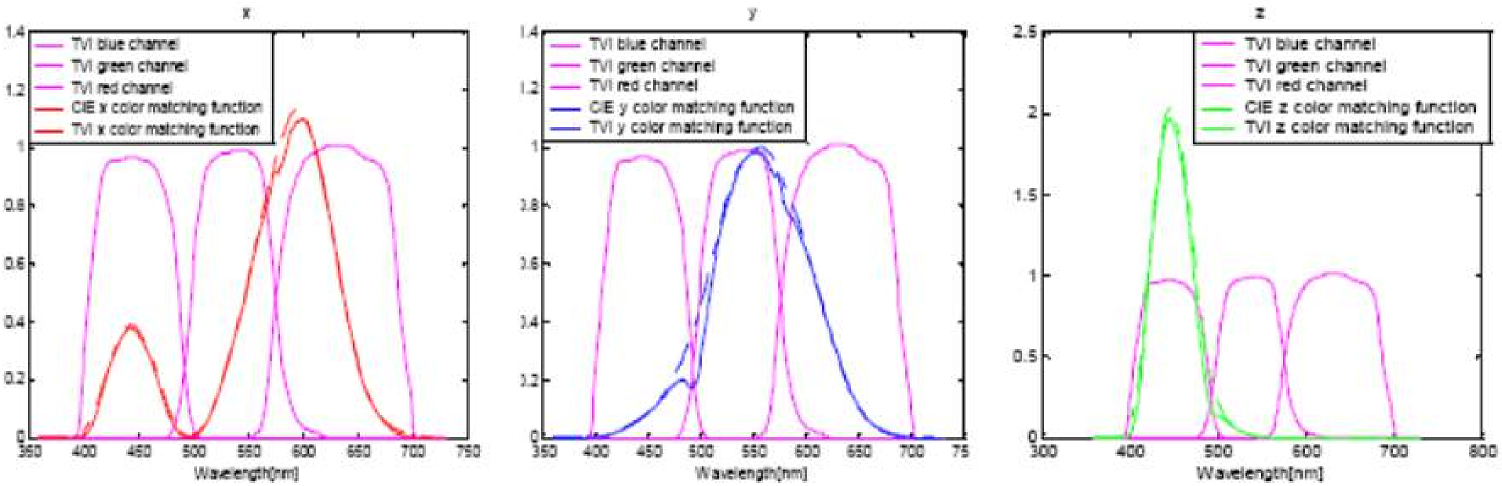


Figure 2.1: **CIE color matching functions compared with the color matching functions calculated for the camera**

RGB to XYZ
variety of definitions

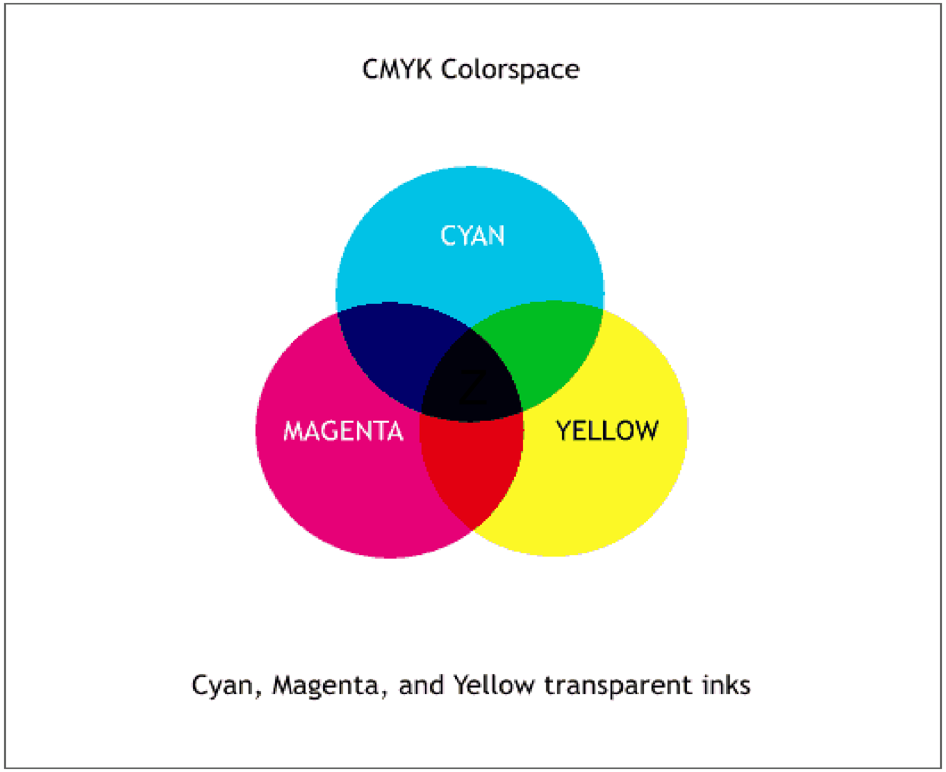
Adobe RGB (1998)	D65	0.5767309 0.1855540 0.1881852 0.2973769 0.6273491 0.0752741 0.0270343 0.0706872 0.9911085	2.0413690 -0.5649464 -0.3446944 -0.9692660 1.8760108 0.0415560 0.0134474 -0.1183897 1.0154096
AppleRGB	D65	0.4497288 0.3162486 0.1844926 0.2446525 0.6720283 0.0833192 0.0251848 0.1411824 0.9224628	2.9515373 -1.2894116 -0.4738445 -1.0851093 1.9908566 0.0372026 0.0854934 -0.2694964 1.0912975
Best RGB	D50	0.6326696 0.2045558 0.1269946 0.2284569 0.7373523 0.0341908 0.0000000 0.0095142 0.8156958	1.7552599 -0.4836786 -0.2530000 -0.5441336 1.5068789 0.0215528 0.0063467 -0.0175761 1.2256959
Beta RGB	D50	0.6712537 0.1745834 0.1183829 0.3032726 0.6637861 0.0329413 0.0000000 0.0407010 0.7845090	1.6832270 -0.4282363 -0.2360185 -0.7710229 1.7065571 0.0446900 0.0400013 -0.0885376 1.2723640
Bruce RGB	D65	0.4674162 0.2944512 0.1886026 0.2410115 0.6835475 0.0754410 0.0219101 0.0736128 0.9933071	2.7454669 -1.1358136 -0.4350269 -0.9692660 1.8760108 0.0415560 0.0112723 -0.1139754 1.0132541
CIE RGB	E	0.4887180 0.3106803 0.2006017 0.1762044 0.8129847 0.0108109 0.0000000 0.0102048 0.9897952	2.3706743 -0.9000405 -0.4706338 -0.5138850 1.4253036 0.0885814 0.0052982 -0.0146949 1.0093968

..and more...

CMY colour model
Cyan, Magenta, Yellow

- subtractive colour mixing which is used in printing processes

CMYK stores ink values for black in addition.



Color Space – YCbCr

Conversion from RGB:

$Y=0.299(R-G) + G + 0.114(B-G)$

$Cb=0.564(B-Y)$

$Cr=0.713(R-Y)$

Advantage: Bandwidth efficiency

Used for: digital video encoding

Axes:

Y: luma

Cb: blue chroma

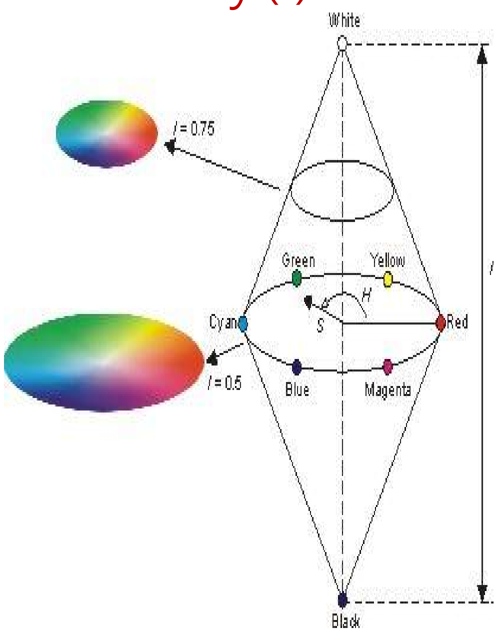
Cr: red chroma

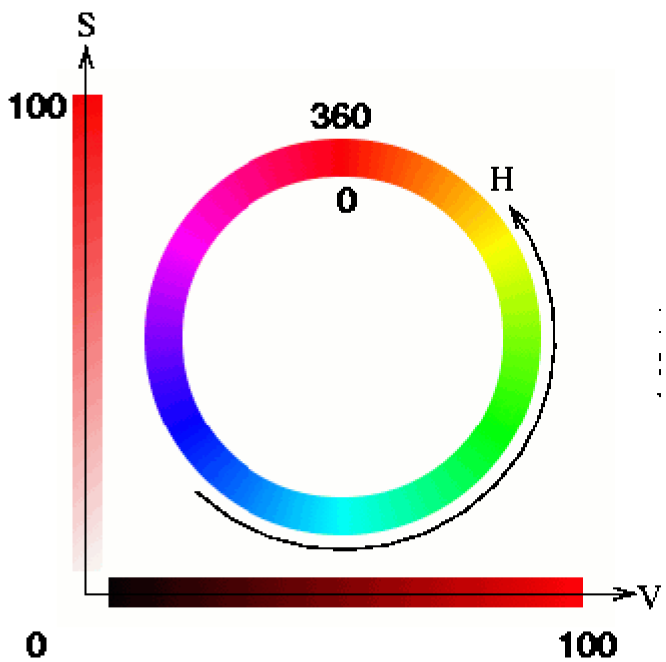
HSI color space

saturation (S) is proportional to radial distance

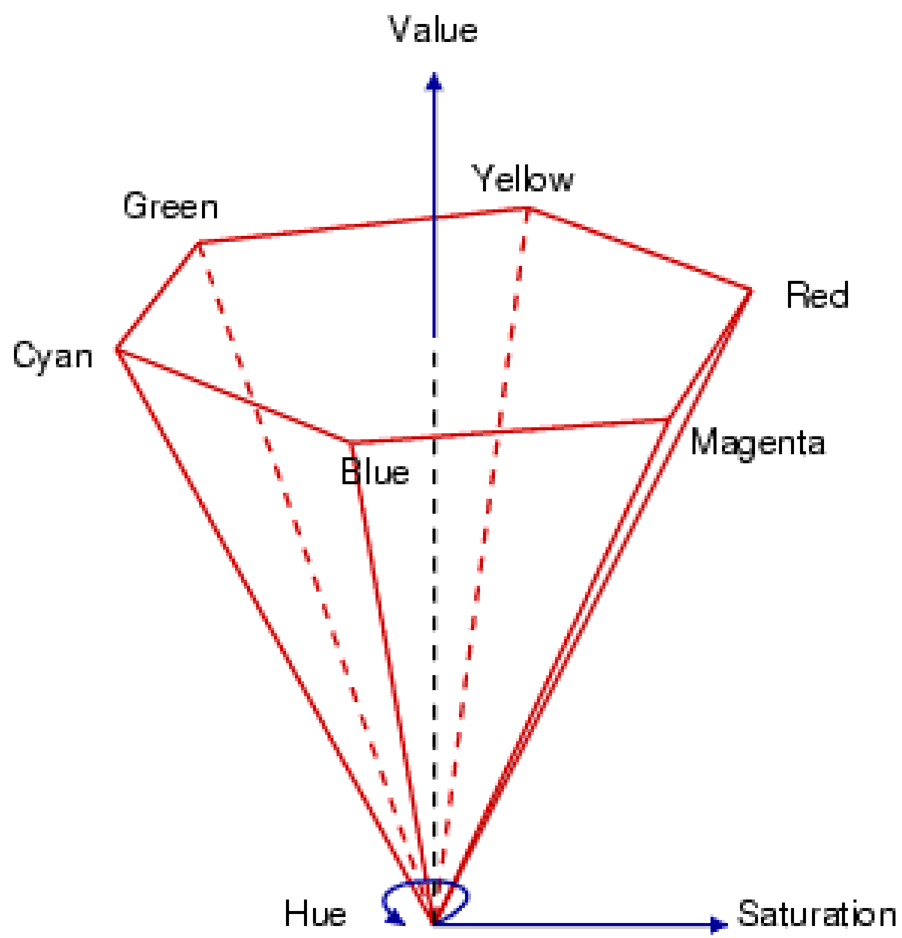
hue (H) is a function of the angle in the polar coordinate system.

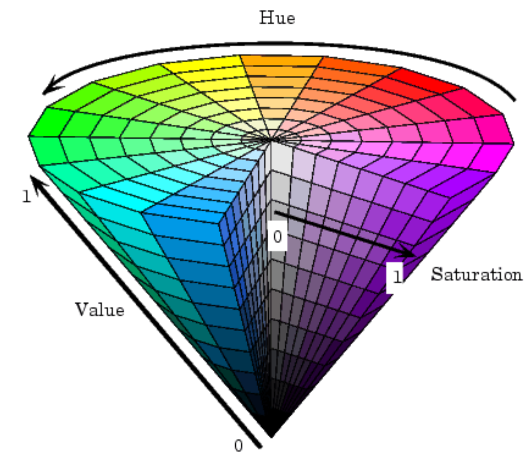
Intensity(I): $I = (R+G+B)/3$

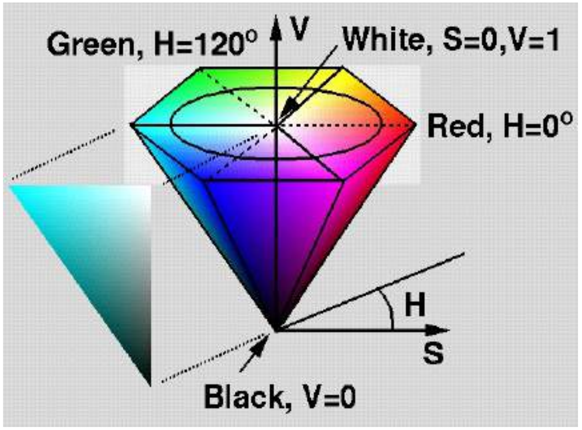




HSV colour space
Hue, Saturation, and Value





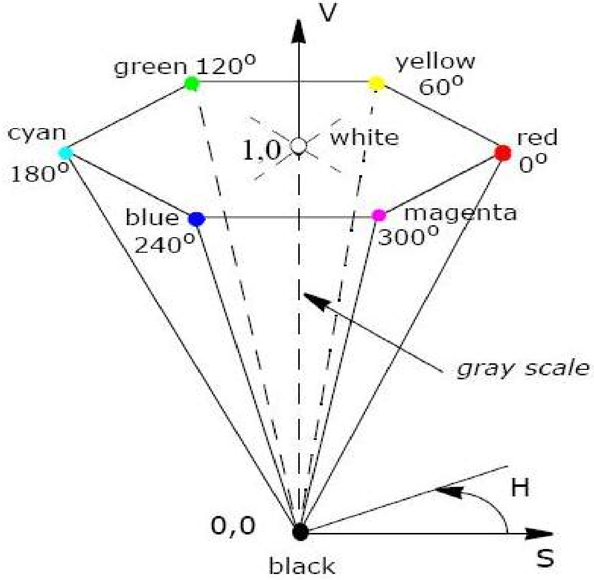


- often used by painters

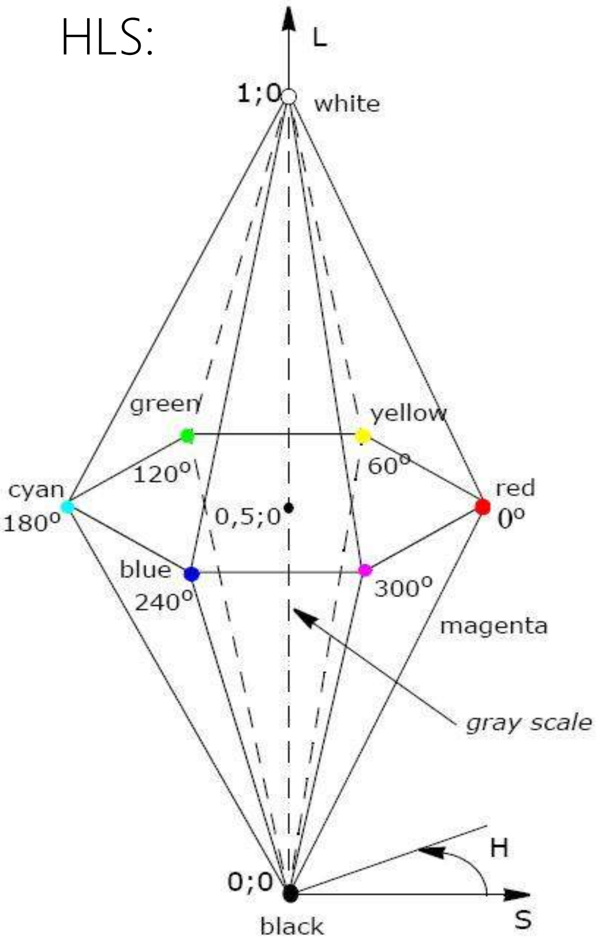
HLS
hue, lightness, saturation

HSV vs. HLS

HSV:



HLS:



Demonstrations tools

ShowImage.exe

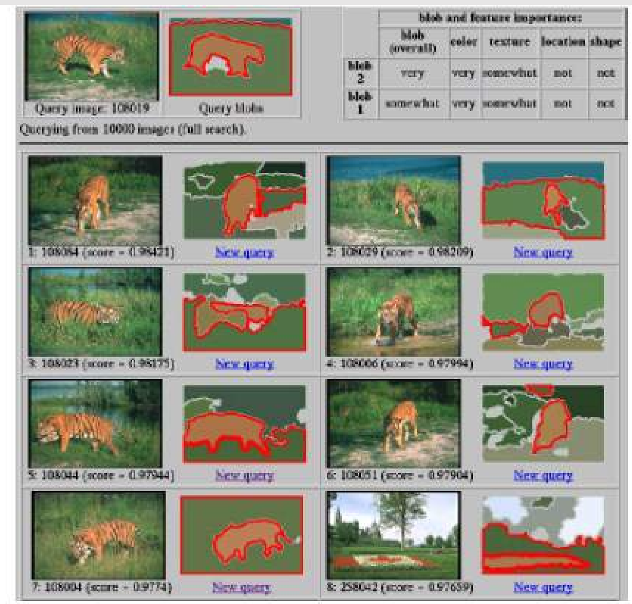
Hsv.exe

Color in Computer vision

examples

Color as a low-level cue for CBIR

Swain and Ballard, [Color Indexing](), IJCV 1991

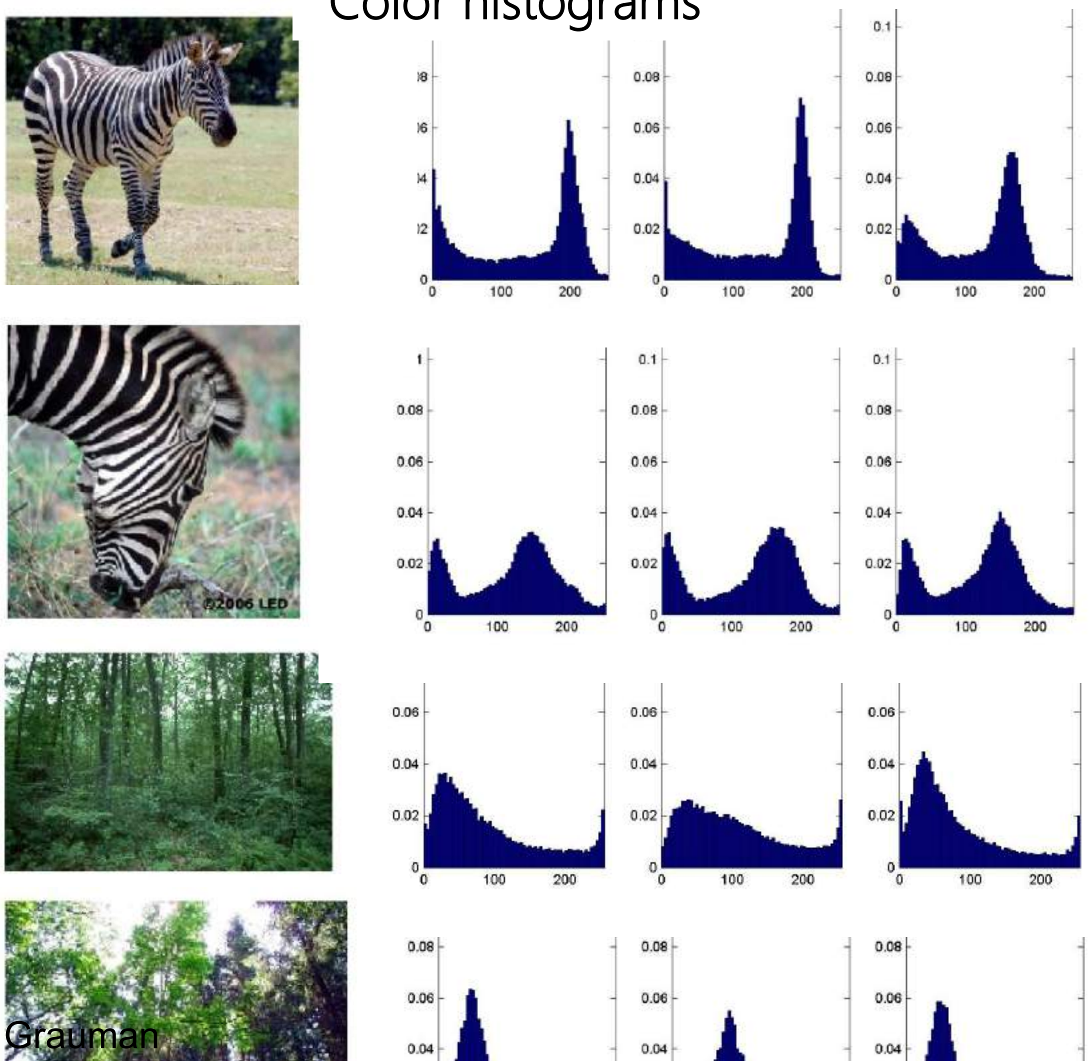


Blobworld system
Carson et al, 1999

Color as a low-level cue for Content-based image retrieval

R G B

Color histograms



- Color histograms: Use distribution of colors to describe image

- No spatial info – invariant to translation, rotation, scale

Kristen Grauman

Color-based image retrieval example

Given collection (database) of images:

- Extract and store one color histogram per image

Given new query image:

- Extract its color histogram
- For each database image:
  - Compute intersection between query histogram and database histogram
- Sort intersection values (highest score = most similar)
- Rank database items relative to query based on this sorted order

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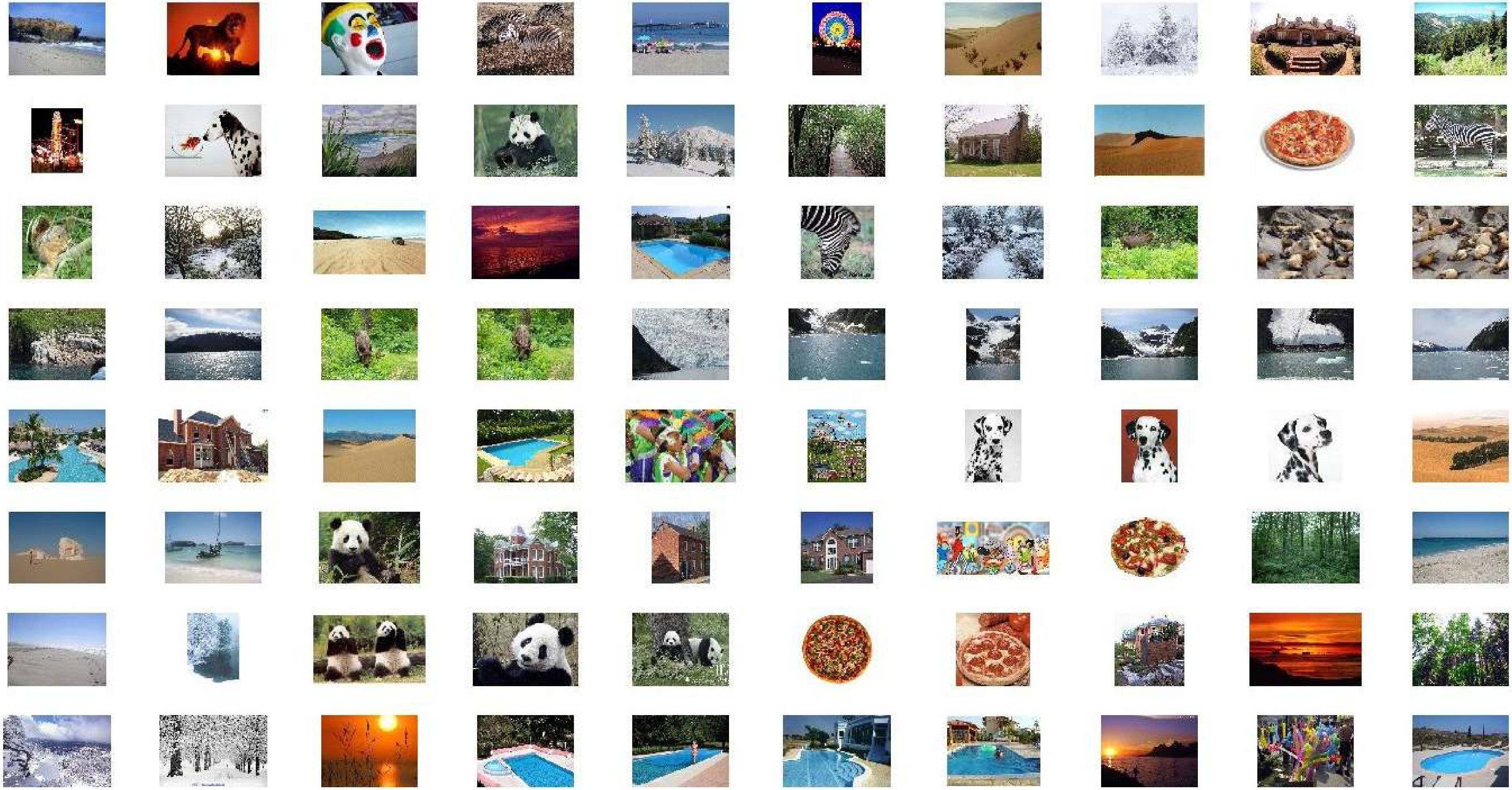
Color-based image retrieval




Example database

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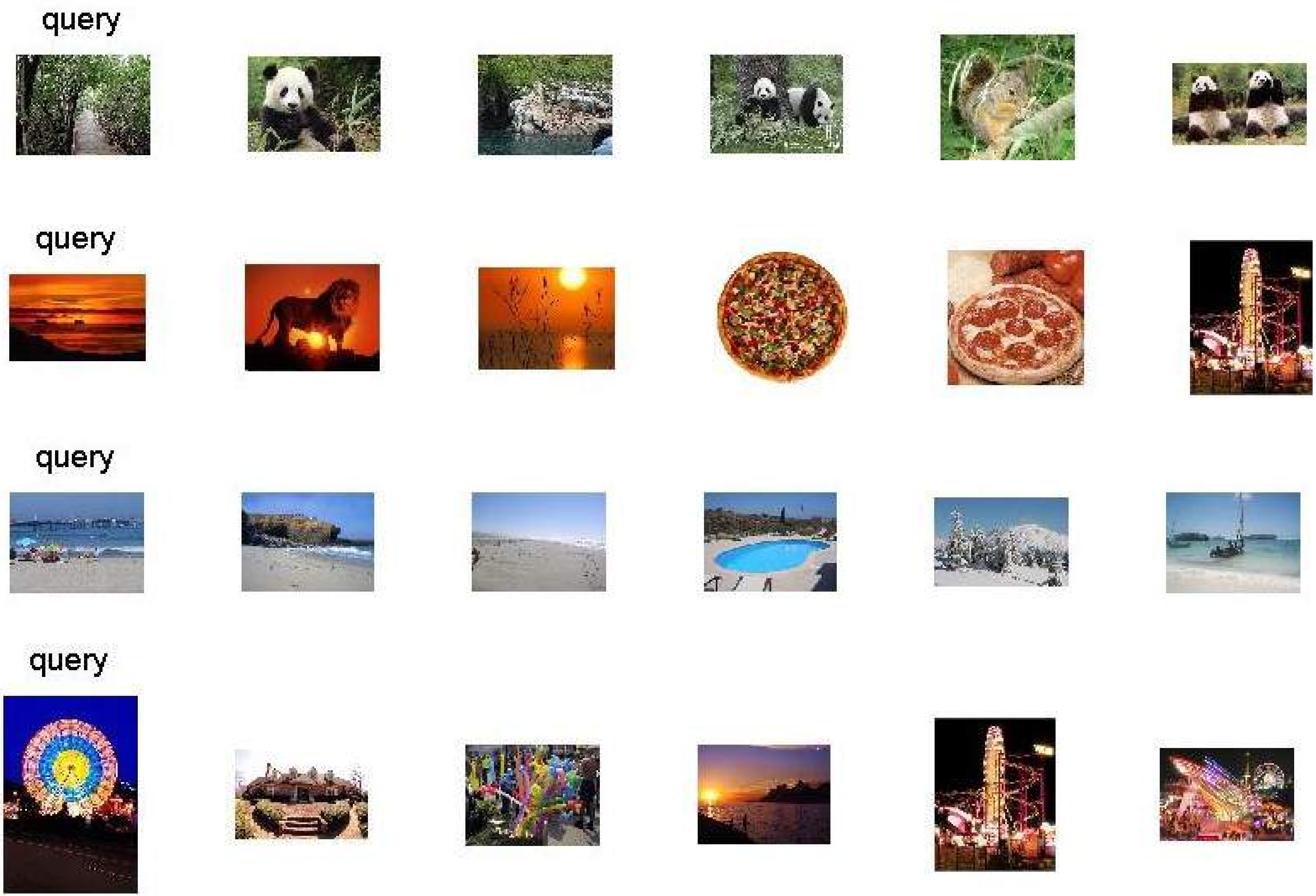
Color-based image retrieval



Example retrievals

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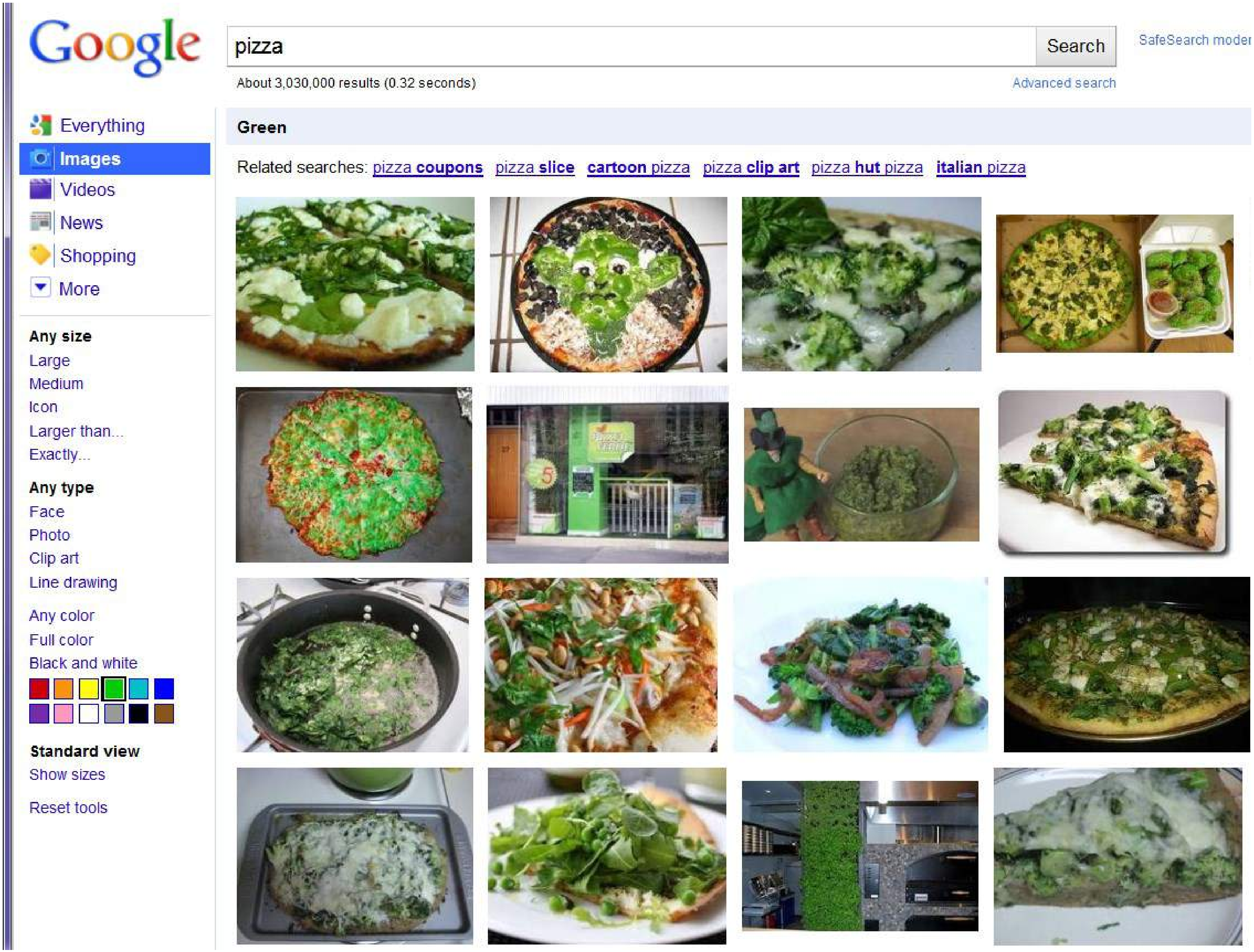
Google
pizza
Search
SafeSearch moder
About 3,030,000 results (0.32 seconds)
Advanced search
Everything
Images
Videos
News
Shopping
More
Green
Related searches: pizza coupons pizza slice cartoon pizza pizza clip art pizza hut pizza italian pizza
Any size
Large
Medium
Icon
Larger than...
Exactly...
Any type
Face
Photo
Clip art
Line drawing
Any color
Full color
Black and white
Standard view
Show sizes
Reset tools

Color-based skin detection

M. Jones and J. Rehg, Statistical Color Models with Application to Skin Detection, IJCV 2002.

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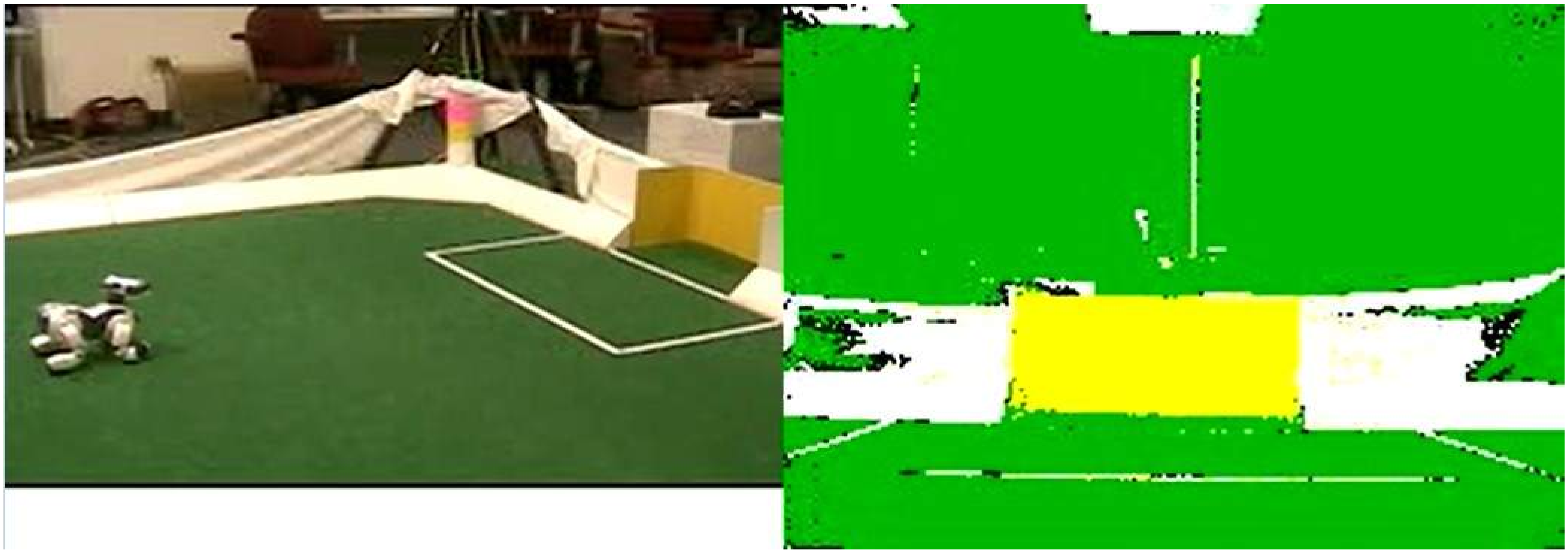
Color-based segmentation for robot soccer



Towards Eliminating Manual Color Calibration at RoboCup. Mohan Sridharan and Peter Stone. RoboCup-2005: Robot Soccer World Cup IX, Springer Verlag, 2006

http://www.cs.utexas.edu/users/AustinVilla/?p=research/auto_vis

Kristen Grauman

Visual Attention and Saliency maps

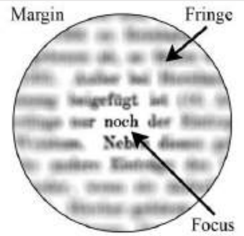
Visual Attention

The main features of attention are:

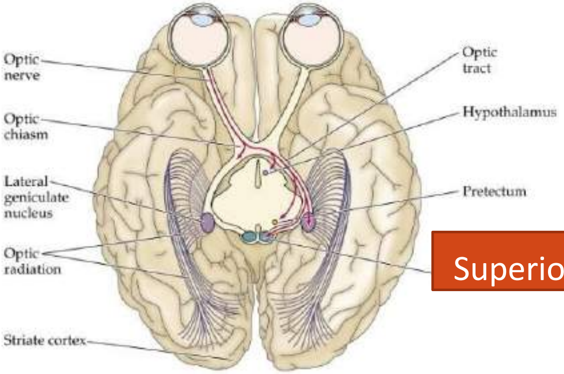
Selection: We focus on several aspects of the environment while ignoring others.

Limitation: The rate of sensorial information processing of the brain is limited.

Visual Attention



- For search of salient parts in image
- It helps us decide where to move and fix the eyes gaze
- Attention by fixation of gaze on the subject
- Attention in the peripheral vision without a moving of the eyes



Superior colliculus

Fixation, Saccade, Smooth pursuit

We distinguish different eye behaviours :

1. Fixation: The pause in a movement when eyes are fixated to the specific position and remain still is called fixation. During the fixation, visual information is taken from the environment. It lasts 200 – 300 msec. However, eyes are not completely still, but they perform micro-movements such as tremor, microsaccades and drifts.

2. Saccade: Saccade is a quick movement from one fixation to another. It is the fastest movement the body can produce. We make approximately 3 saccades per second that last only 30 – 80 msec.

3. Smooth pursuit: Our eyes perform a movement called smooth pursuit when we follow a moving object voluntary.

Bottom-up Attention

stimulus-driven attention.

It is involuntary, rapid and unconscious attention based on visual characteristics of a scene which automatically draw our attention (Goldstein, 2008)2.

Bottom-up attention is related to the term saliency.

Typical bottom-up features involve colour,

contrast, orientation, texture and movement (Wolfe, 2009).

Top-down Attention

goal-driven attention

driven endogenously is guided by prior knowledge, experiences, expectations, tasks or goals.

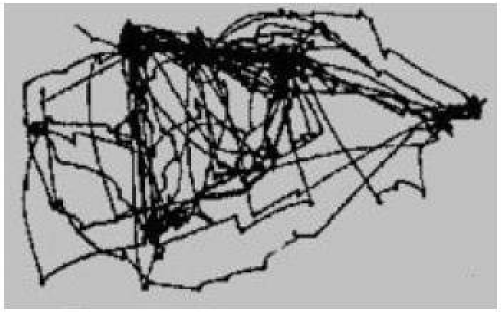
Contrary to the bottom-up approach, top-down attention related to our memory is much slower, voluntary and conscious

Task: find a unicorn!

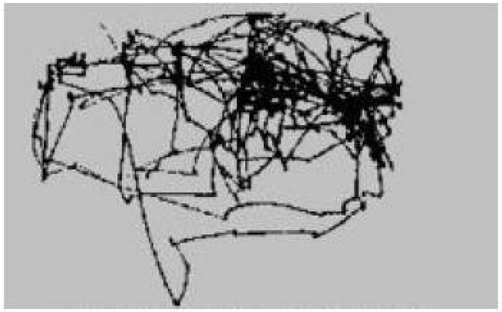
Eye tracking experiment.

Observers view a given image within various tasks

(a) Image used in experiment.

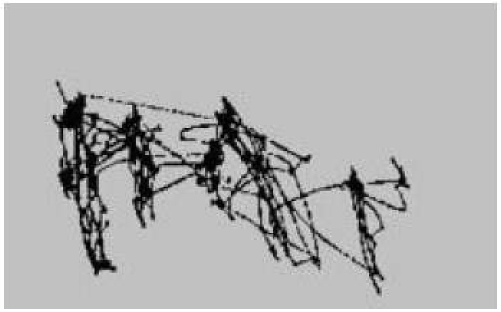


(b) Free exploration.

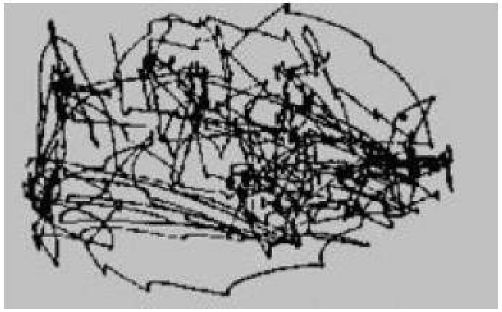


(c) Estimate material conditions of the family.

(d) Estimate family age.



(e) Remember the family members' clothes.



(f) Remember the positions of family members and objects.

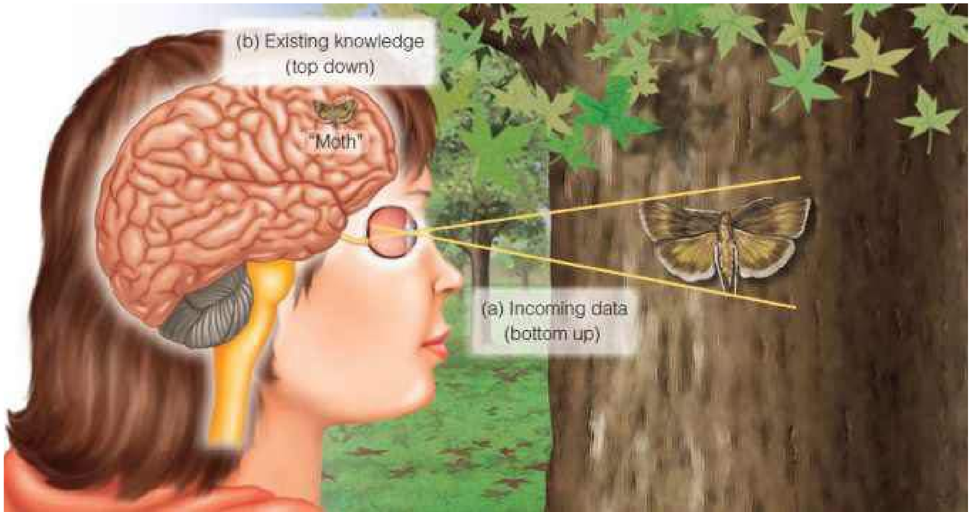
bottom-up and top-down processing.

Perception involves:

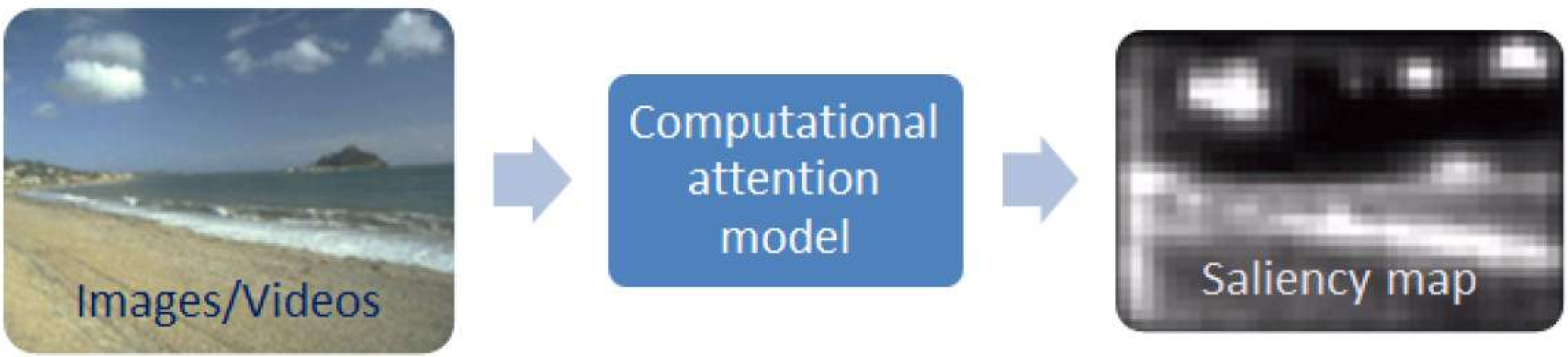
bottom-up and

top-down processing.

Within bottom-up processing basic features of incoming data are analysed. After top-down processing a object is recognised using a prior knowledge.



General process of bottom-up attention model



Overview of attention models

hierarchical (cognitive): hierarchical decomposing of features

Bayesian: combination of saliency and prior knowledge

decision theoretic: discriminant saliency theory

information theoretic: maximisation of information from a given environment

graphical graph-based: computations of saliency

spectral analysis: saliency computation in the frequency domain

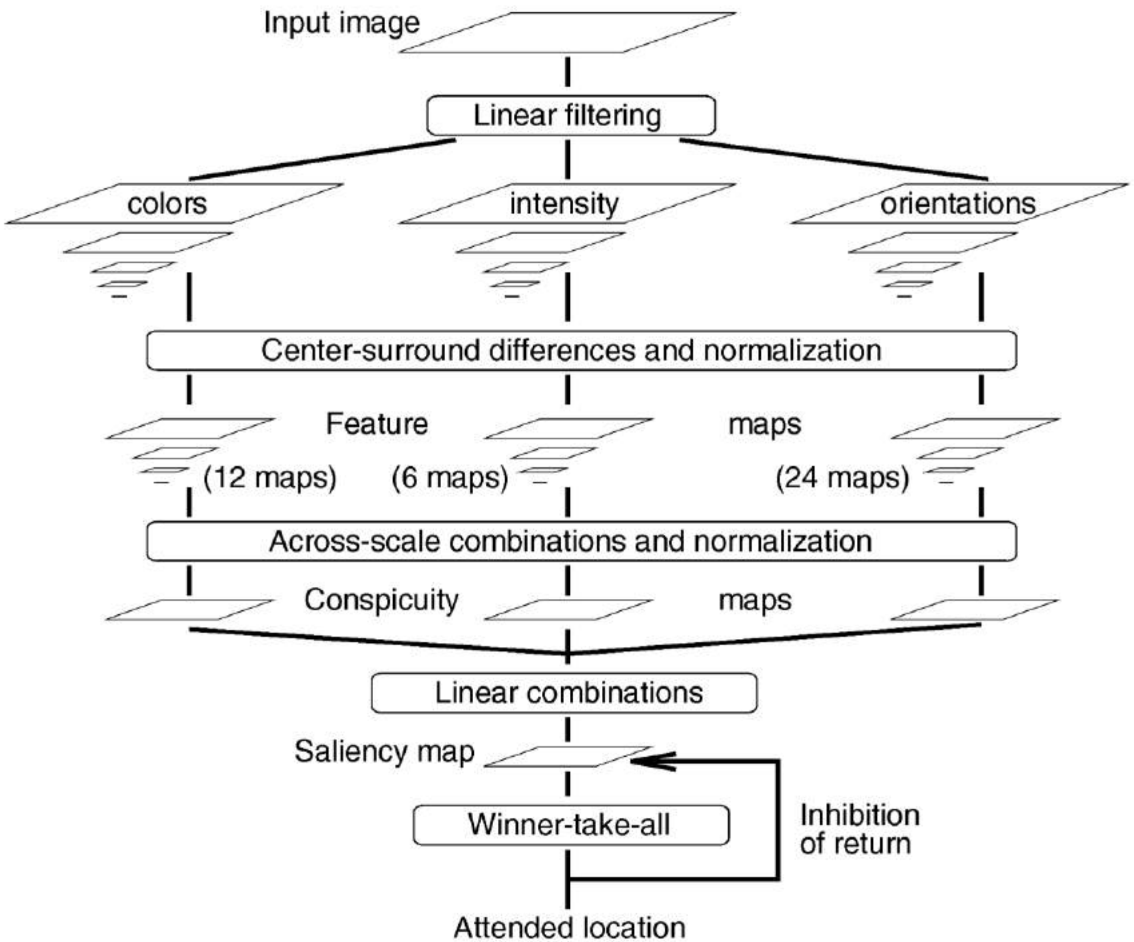
pattern classification: machine learning from salient patterns

reinforcement learning: maximisation of a gained cumulative reward

Itti model - Hierarchical (cognitive) model

biologically inspired models based on hierarchical decomposition
of visual features inspired by Feature Integration Theory (FIT)

- Colour
- Intensity
- Orientation



Itti model adopted for superpixels

Basic units:

superpixels