Digital Image Processing

16 November 2006

Dr. ir. Aleksandra Pizurica
Prof. Dr. Ir. Wilfried Philips

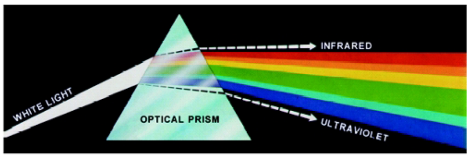
Aleksandra.Pizurica @telin.UGent.be
Tel: 09/264.3415

UNIVERSITEIT GENT
Telecommunicatie en Informatieverwerking

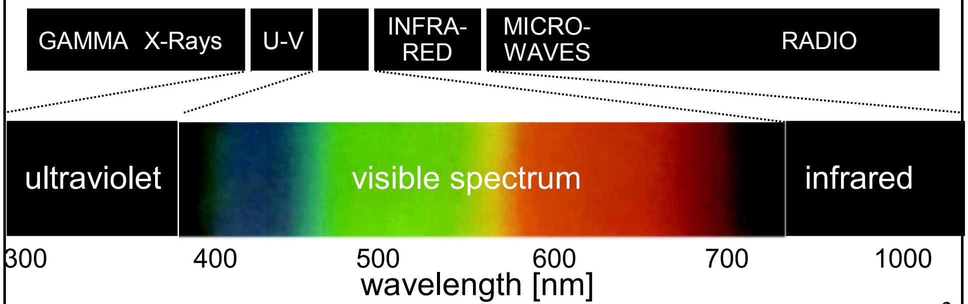
INSTITUUT VOOR PERMANENTE VORMING

Colors and their synthesis

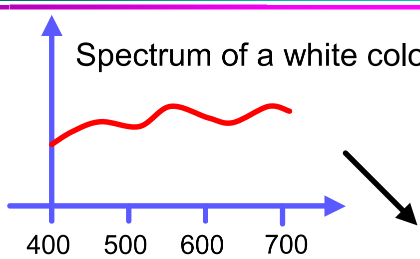
Color Fundamentals



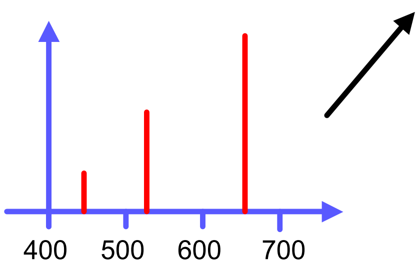
Isac Newton discovered in 1666 that when a sunlight passes through an optical prism the emerging beam is composed of a continuous spectrum ranging from red to violet



Remainder: Color Metamerism

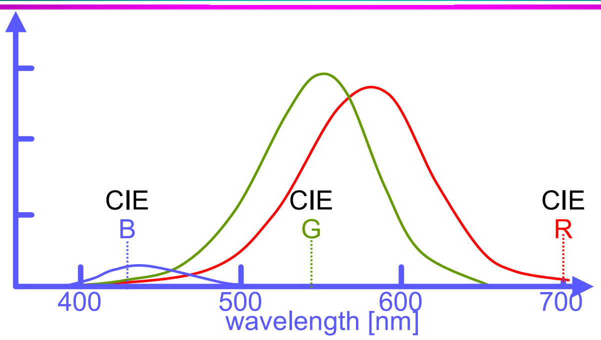


Metamers: light sources of different spectral characteristics but of the same color impression



A well chosen mixture of three monochromatic sources is perceived as a light of the same white color

CIE primary colors



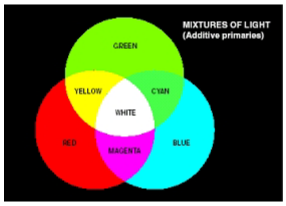
Due to these absorption characteristics of the human eye, colors are seen as variable combinations of the so-called PRIMARY COLORS: red (R), green (G) and blue (B)

CIE (*Commission Internationale de l'Eclairage – The International Commision on Illumination)* established in 1931 the following primars: B=435.8 nm G=546.1nm R=700nm

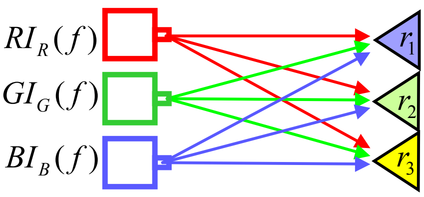
Additive color mixing

Superposition of primary colors
Typically in TV monitors

R, G, B primary colors
C, M, Y secondary colors



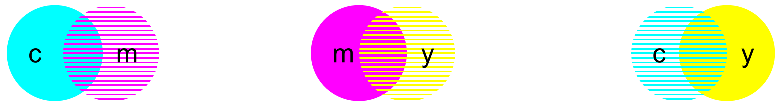
Output signals from the eye cones: $r_i = \int S_i(f) I(f)\, df$ (before "log")



$$= \int S_1(f)\left(RI_R(f) + GI_G(f) + BI_B(f)\right) df$$
$$= \int S_2(f)\left(RI_R(f) + GI_G(f) + BI_B(f)\right) df$$
$$= \int S_3(f)\left(RI_R(f) + GI_G(f) + BI_B(f)\right) df$$

$I_R(f)$, $I_G(f)$ en $I_B(f)$ – spectra of the primary colors

Subtractive color mixing



$I(f) = S_C^c(f) S_M^m(f) W(f)$ $\quad$ $I(f) = S_M^m(f) S_Y^y(f) W(f)$ $\quad$ $I(f) = S_C^c(f) S_Y^y(f) W(f)$

Output spectrum: $I(f) = S_C^c(f) S_M^m(f) S_Y^y(f) W(f)$

filters $\quad$ (white) light source

In subtractive color mixing, color pigments filter out a part of the white light

- cyan filter: passes green and blue, absorbs red
- magenta filter: passes red and blue, absorbs green
- yellow filter: passes green and red, absorbs blue

Multiplicative process: de transmission spectra are (frequency dependent) attenuation factors that are multiplied

De attenuation increases with the depth of c, m en y ink layers

Color synthesis: summary

Additive color mixing:

- Creating colors by superposition of light source
- Spectrum is the sum of the spectra of the light sources
- Example: TV-monitors

Subtractive color mixing:

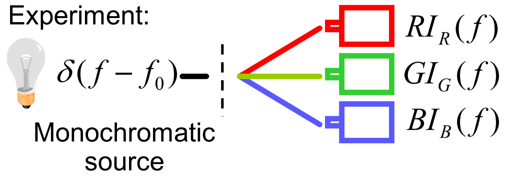
- Creating colors by filtering out parts of the white light spectrum using successive filters
- Multiplicative process (the resulting light spectrum is the product of the transmission spectra of the filters (and the spectrum of the white light)
- Examples: photography, printing

Remarks:

- Typical printing procedures are hybrid (subtractive/additive) and use additional inks (e.g., black – CMYK system)

The color correction functions

Experiment:



1. Adjust R, G, B to produce the same color impression
2. Define: $r(f_0)=R$, $g(f_0)=G$, $b(f_0)=B$
3. Repeat for other f_0

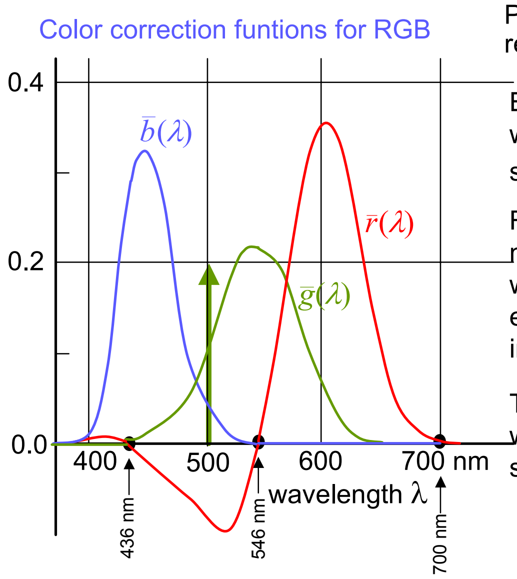
$r(f)$, $g(f)$ en $b(f)$ are color correction functions

- the values of R, G, en B needed to reproduce the color of spectral (mono-chromatic) light with frequency f
- These values depend on $I_R(f)$, $I_G(f)$ en $I_B(f)$

Importance: using color correction functions we can determine the amount of primars R, G, en B needed to match the color of arbitrary light source of spectrum $I(f)$:

$$R=\int r(f)I(f)\,df \quad G=\int g(f)I(f)\,df \quad B=\int b(f)I(f)\,df$$

Gamut problem with CIE-RGB-primars



Problem: some colors cannot be reproduced

Example: using CIE RGB-primars we cannot match the spectral source with λ=500 nm

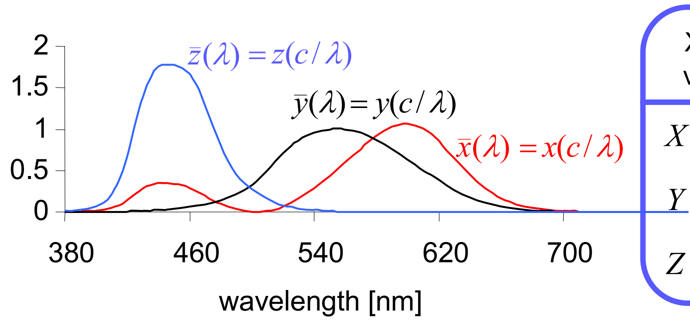
Reason: in order to cause the necessary cone signals we would need R = -0.09, G = 0.09, en B= 0.05 but the negative light intensity cannot be produced

The colors that can be reproduced with a given set of primars form the so-called GAMUT

The XYZ-color space

The CIE defined color correction functions $x(f)$, $y(f)$ en $z(f)$ that comply with the following requirements:

- Can be realized as optical filters $\Leftrightarrow x(f)$, $y(f)$ en $z(f)$ positive for all f
- For uniform white light: $X=Y=Z$ $\Leftrightarrow \int x(f)df = \int y(f)df = \int z(f)df$
- Sources with the same Y are perceived by human eye as equally bright $\Rightarrow$ Y is a luminance measure



XYZ-coördinaten van een bron $I(f)$

$$X = \int x(f)I(f)\,df$$
$$Y = \int y(f)I(f)\,df$$
$$Z = \int z(f)I(f)\,df$$

The CIE-luminance

$Y = \int y(f)I(f)\,df$ is called CIE-luminantie

Remarks:

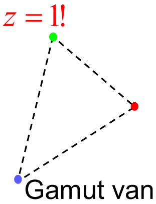
- from the requirements it follows automatically that $y(f)$ is proportional to spectral sensitivity $S_2(f)$ of the "luminance"-cones (those that are sensitive to yellow green – to red)
- log(Y) is proportionl with the perceived brightness I'

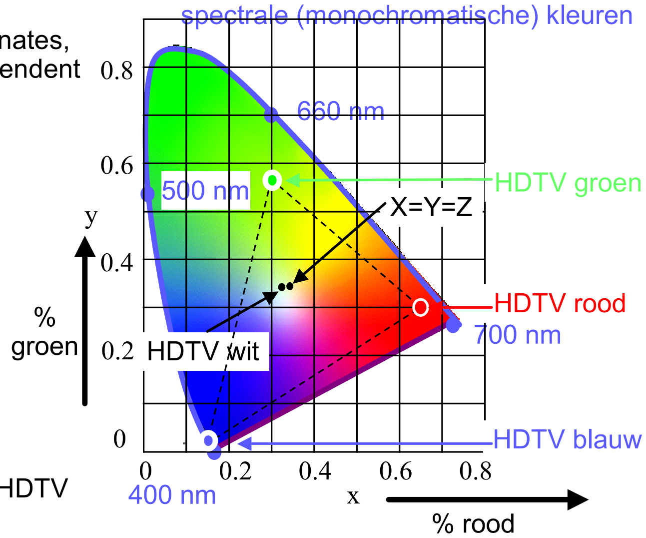
De xyz-kleurencoördinaten

xyz-chromaticity coordinates, are defined to be independent of the intensity:

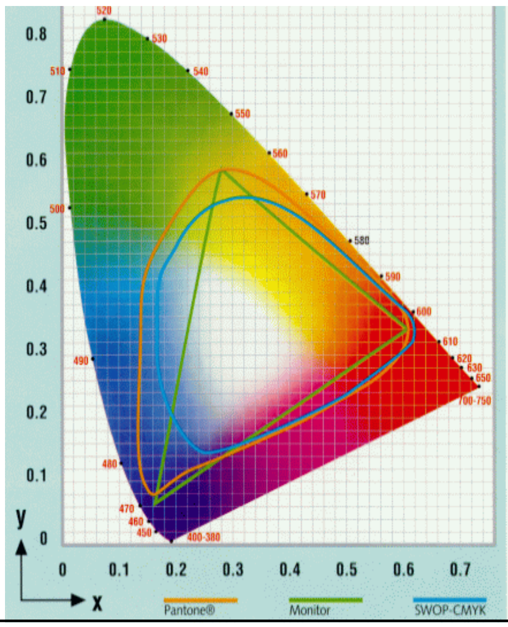
$$x = X/(X+Y+Z)$$
$$y = Y/(X+Y+Z)$$
$$z = Z/(X+Y+Z)$$

$$x + y + z = 1!$$





The xy-color triangle



- Gamut color monitor
- Gamut CMYK-printer
- Pantone colors

Remarks

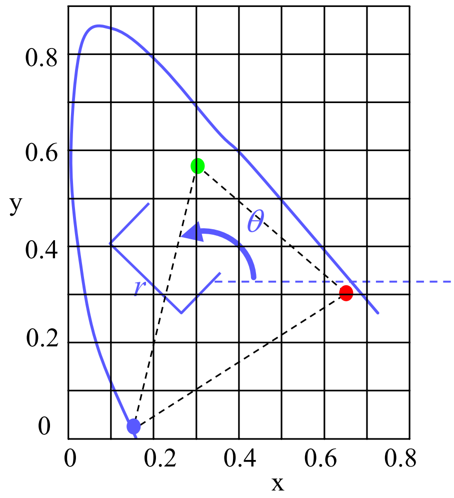
- In printing techniques additional inks are used to increase gamut (pantone, goud,…)
- The spectral colors are on the border.
- The colors in this figure are not entirely correct!

Color tone and saturation (HSV-space)

If the brightness is constant Y the color impression is fully determined by chromatic components x and y

Definitions

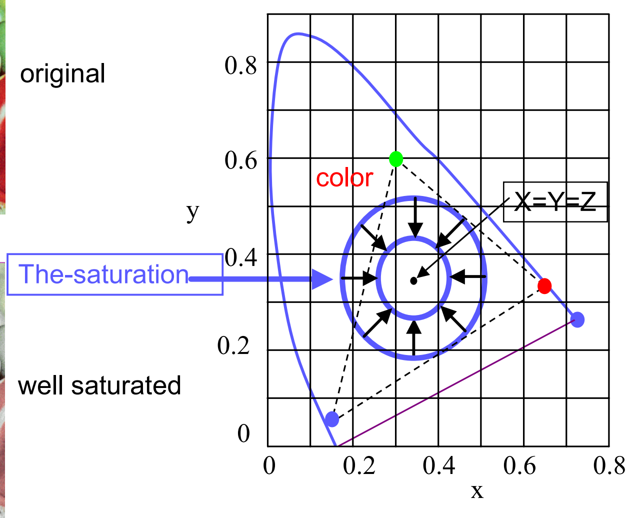
- Value: Brightness: $\approx Y$
- Hue: Color tone: θ
- Saturation: r
  (distance to "white")



Adapting saturation

original

well saturated

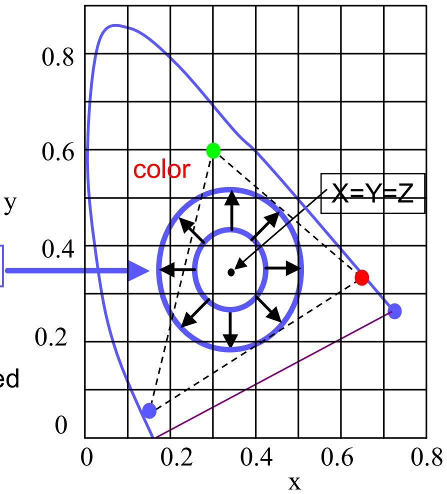


Adapting saturation

original

100% saturated

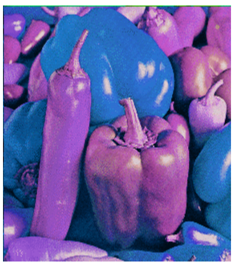
Saturation



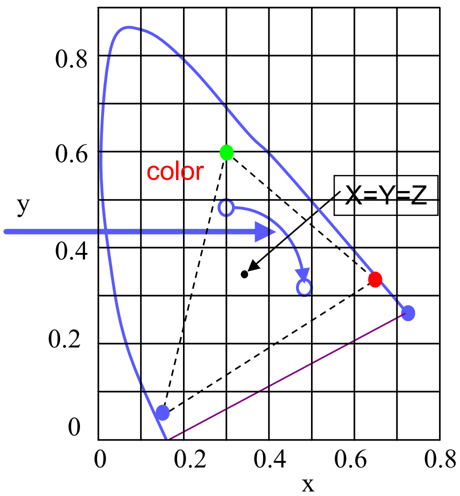
Adapting color tone

original

adapting color tone

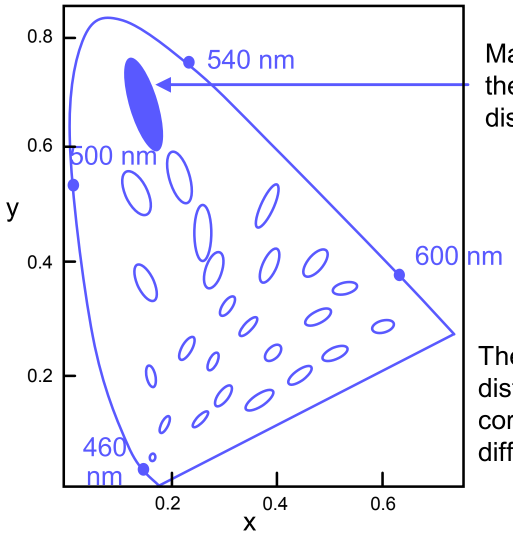


red →cyan



Color tone adaptation corresponds to a rotation

The MacAdam-ellipses



MacAdam-ellipses: colors within these elipses cannot be discriminated

Remark: the actual elipses are much smaller!

The xy space is non-uniform. The distance in this space does not correspond with the color differences

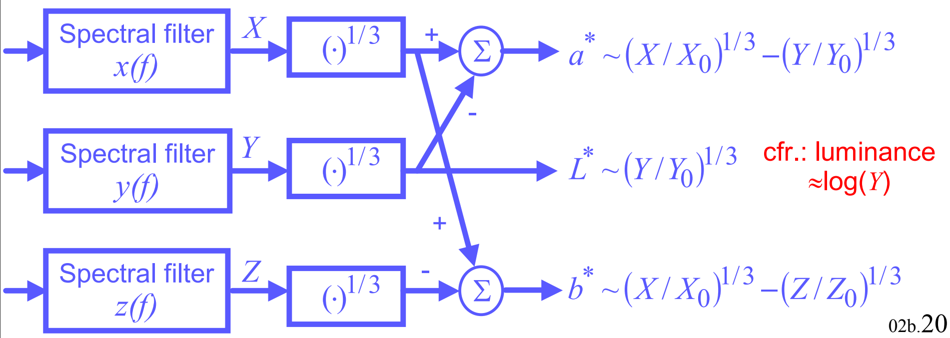
The L*a*b* color space

The $L^*a^*b^*$-space is much more uniform:

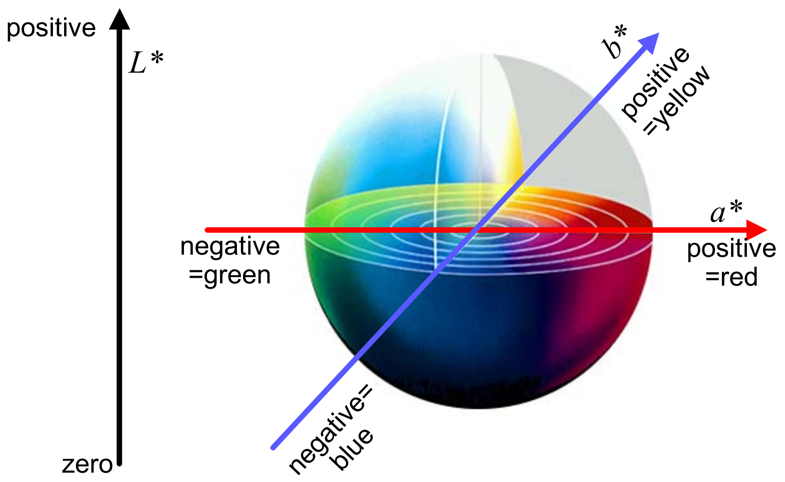
$$L^* = 25(100Y/Y_0)^{1/3} - 16$$
$$a^* = 500\left((X/X_0)^{1/3} - (Y/Y_0)^{1/3}\right)$$
$$b^* = 200\left((X/X_0)^{1/3} - (Z/Z_0)^{1/3}\right)$$

X_0, Y_0 en Z_0 are the XYZ coordinates of a well-defined white light

Approximate formula's!



... The $L^*a^*b^*$ color space...



... ... The $L^*a^*b^*$ color space...

De $L^*a^*b^*$-space is perceptually uniform:

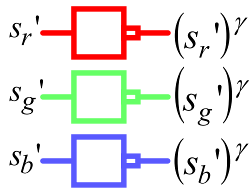
- In the $L^*a^*b^*$ -space the MacAdams-ellipses are circles
- Perceptual difference between two sources: $\sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$

  Difference in intensity: ΔL^*

  Color difference: $\sqrt{(\Delta a^*)^2 + (\Delta b^*)^2}$

  The least perceivable difference in luminance is always $\Delta L^* \approx 1$

Monitors and gamma

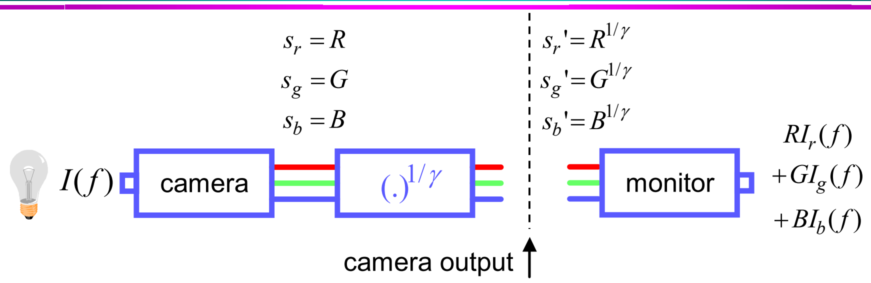


For cathode ray tube monitors intensity to voltage response curve is roughly a 2.5 power function. Monitors, then, are said to have a gamma of 2.5

This means that if the monitor receives a signal that a certain pixel should have intensity equal to x, it will actually display a pixel which has intensity equal to $x^{2.5}$

Because the range of voltages x sent to the monitor is between 0 and 1, this means that the intensity value displayed will be less than wanted

Gamma-correction

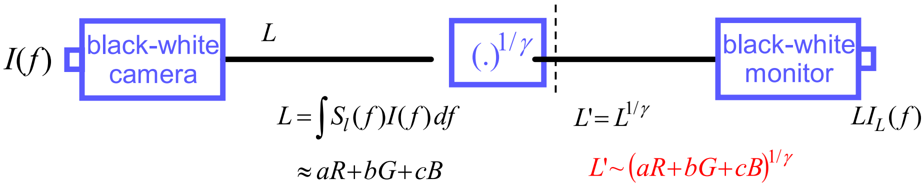


In order to correctly display the image at the monitor, the input signal to the monitor (the voltage) must be "gamma corrected".

Since we know the relationship between the voltage sent to the monitor and the intensity which it produces, we can correct the signal before it gets to the monitor.

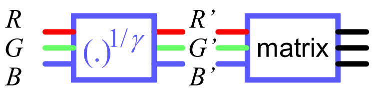
The YUV-kleurenruimte

In black-white TV γ -correction was applied to the intensity signal L



In a color system γ -correction is applied separately to R, G en B:

In order to keep some compatibility with black-white TV now color TV systems send a lluminance signal Y' that is a rough approximation for L'



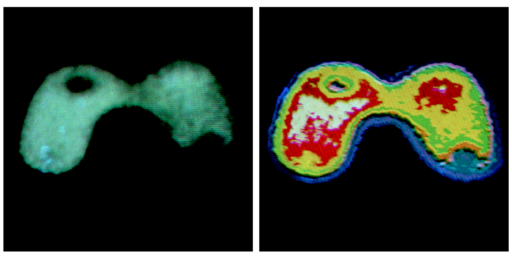
$$Y' = 0.299R' + 0.587G' + 0.114B'$$
$$U' = (B' - Y')/1.772$$
$$V' = (R' - Y')/1.402$$

broadcasted signals

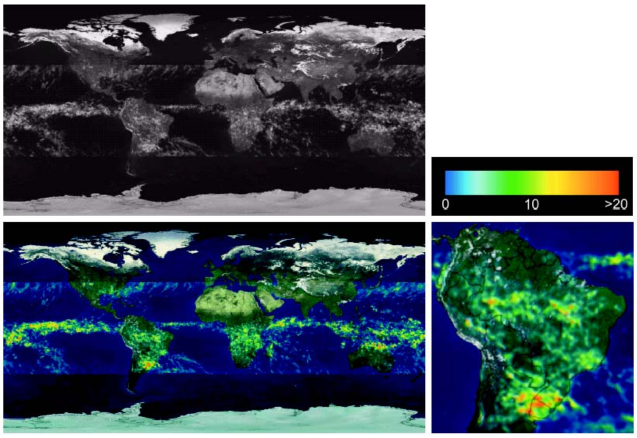
$Y' \neq L'$: the reproduction of intensity on black-white TV is not exact

Pseudo color images

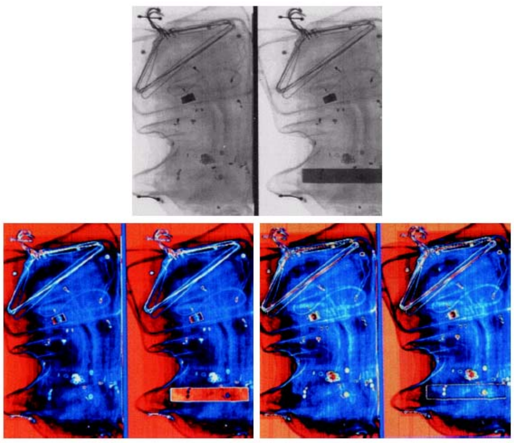
In pseudo color imaging we assign a color to a particular intensity or range of intensities in a gray-scale (monochrome) image



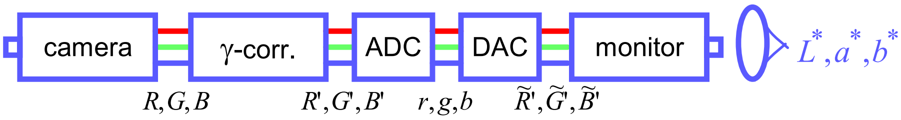
Pseudo color images



Pseudo color images



Digitalisation of greyvalues and color



Quantisation causes errors

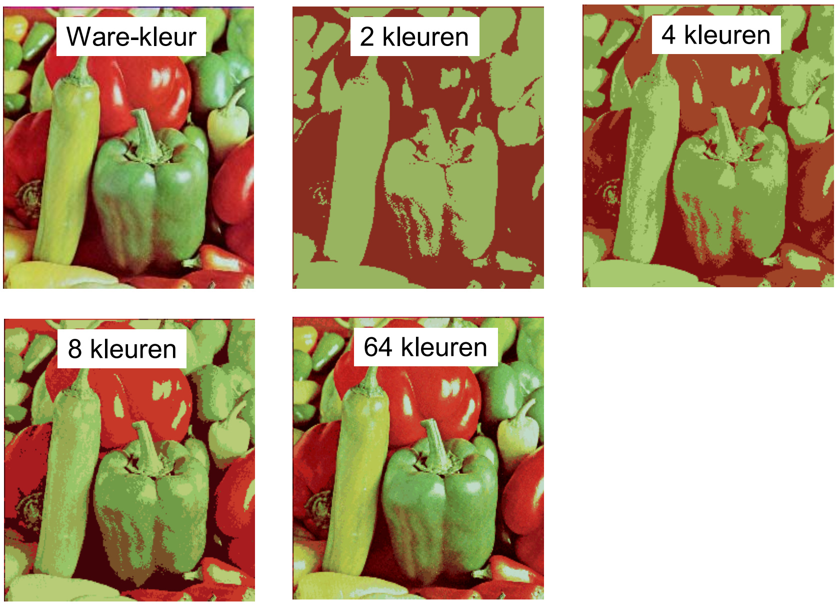
- The perceptual error (measured in Lab space) is not equally big in all positions of the color space
- the maximal perceptual error has to be sdmall enough ⇒ this determins the required bitlength for ADC and DAC
  - 8 bit accuracy is enough for quantisation of γ-corrected signals
  - Quantisation of R, G, B requires a higher accuracy (10 to 12 bit)

Remarks:

- If the images still need to be processed more bits are needed (e.g. 10 to 12 bits for medical images)
- The minimal bit length (for a given "worst-case" perceptual error) is obtained by digitazing in the $L^*a^*b^*$-color space

Color quantisation

Color quantisation : example



Conclusions for image processing

Different reproduction systems have different gamuts

⇒ Realization of all possible colors is never achievable

Digital images are gamma corrected

⇒ The pixel values are hence R'G'B'-values and not RGB-values

Usually the accent is not written

Such images are well displayed on a monitor, but without counter-compensation not on a LCD-display

The colors and intensities have to be evaluated in a perceptually uniform color space

- De $L^*a^*b^*$-space is ideal for this
- However, often used is a representation like $\sqrt{a(\Delta R')^2 + b(\Delta G')^2 + c(\Delta B')^2}$