Lecture 7:
# Colour Perception and Colour Spaces

Contents

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Motivation

◆ Colour perception has direct consequences w.r.t. algorithms for processing colour images and colour image sequences.

◆ Colour is even more important in computer graphics than in image processing.

◆ Understanding the mechanisms of colour perception is also indispensible for calibrating scanners, colour monitors, colour printers and digital cameras.

◆ has led to a complex research area on its own:
colour science, colour vision

◆ highly interdisciplinary:
influences from physics, biology, psychology, physiology, electrical engineering, computer science, and mathematics

◆ Many brilliant minds have done research on this topic over the centuries (but not always successful):
Newton, Goethe, Graßmann, Maxwell, Helmholtz, Schrödinger.

◆ Often the correctness or incorrectnes of these theories has only been verified by experiments in recent decades.

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Physical Background

λ in m
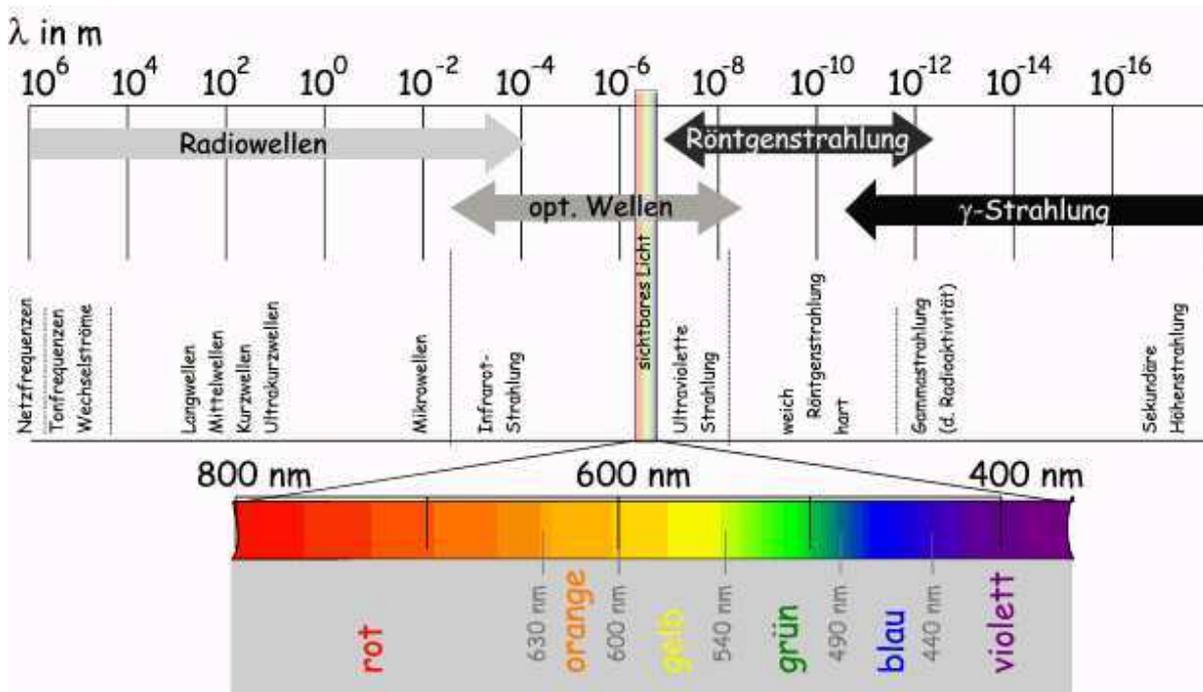
Visible light constitutes only a small part of the entire electromagnetic spectrum. **Source:** www.roro-seiten.de/physik/lk12/emwellen/elektromagnetisches_spektrum.html

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The Visible Spectrum

◆ Electomagnetic waves propage with the speed of light ($c = 299,792,458$ m/s in vacuum). If ν denotes their frequency, their *wave length* λ is defined via $c = \lambda\nu$.

◆ (Visible) light consists of electromagnetic waves with wave length λ between 380 and 780 nm (nanometers, $1\mathrm{nm} = 10^{-9}\mathrm{m}$).

◆ Light is emitted from atoms when outer electrons change their orbits and loose energy.

◆ Light is only a very small fraction of the electromagnetic spectrum.

◆ But: The visible range of the electromagnetic spectrum is (still) the main range in which the sun rays can pass the atmosphere

◆ The visible range is not the same for all animals:

- Insects can perceive ultraviolet light very well.
- Humans whose eye lenses have been removed by a surgeon do also perceive ultraviolet light down to 300 nm.

Physical Background (3)

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◆ The visible spectrum contains seven colours:
red, orange, yellow, green, blue, indigo, violet
(with decreasing wave length or increasing frequency).
Memory hook: "**R**ichard **O**f **Y**ork **G**ave **B**attle **I**n **V**ain".

◆ Pure spectral colours can be found in rainbows or when light rays pass through a prism.

◆ Colours that we usually perceive are a mixture of numerous frequencies.

◆ In practise it is too cumbersome to store all frequencies of a perceived colour.
Is there a more compact representation?
To understand this, we have to make some biological considerations.

Biological Background (1)

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Biological Background

Day Vision and Night Vision

◆ The human retina (Netzhaut) consists of two classes of photo receptors:

- 120 million *rods (Stäbchen)*, distributed over the whole retina.
  Multiple rods are connected to a single nerve.

- 6 million *cones (Zapfen)*, mainly in the centre of the retina.
  Each cone is connected to its own nerve end.

◆ For night vision, rods dominate *(scotopic vision)*.
Very sensitive, but allows only poor sharpness and no colour perception:
"Bei Nacht sind alle Katzen grau." ("At night all cats are grey.")

◆ Daylight vision is dominated by cones *(photopic vision)*.
Low sensitivity, but very good perception of sharpness and colours.
Humans can distinguish about 40 different greyscales, but 2 million colours.

We now focus on photopic vision.

Biological Background (2)

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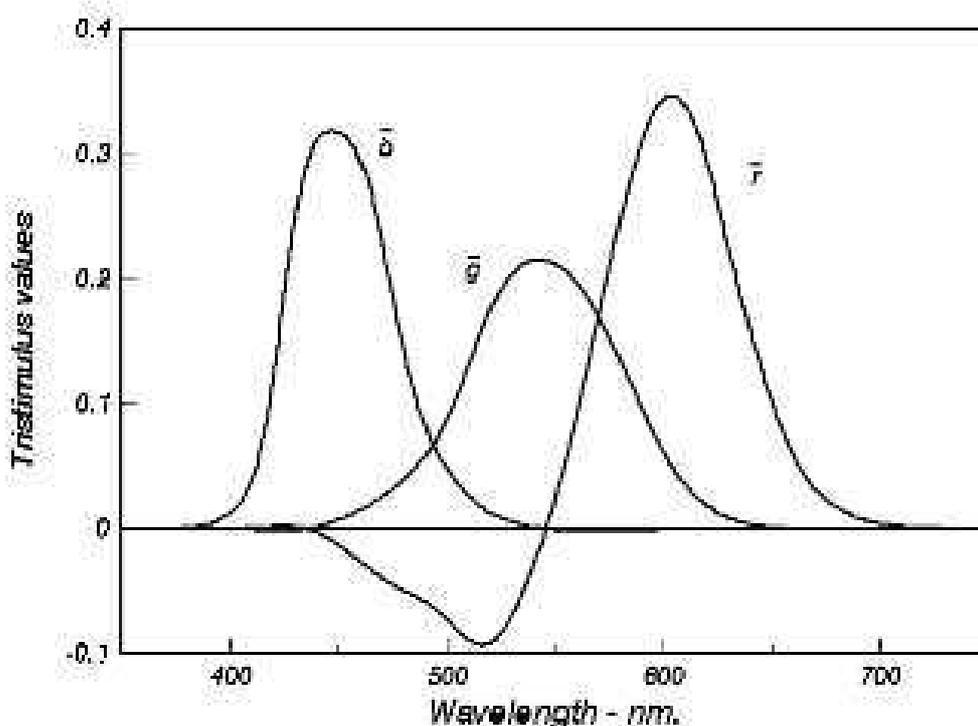19 20
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Tricolour Imaging

◆ Humans have three different types of cones being sensitive to different frequency ranges: *red*, *green* and *blue*.
The sensistivity characteristics are almost identical for all humans.

◆ The visual impression created by a colour is characterised by its impact on the three types of cones, i.e. by three constants *(tristimulus values).*

◆ For an object emitting a spectral density curve $\varphi(\lambda)$, the CIE proposed formulas for approximating the tristimulus response (with suitable normalisation constant k, and nonnegative functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$):

$$X = k \int_{380}^{780} \varphi(\lambda)\,\bar{x}(\lambda)\,d\lambda,$$

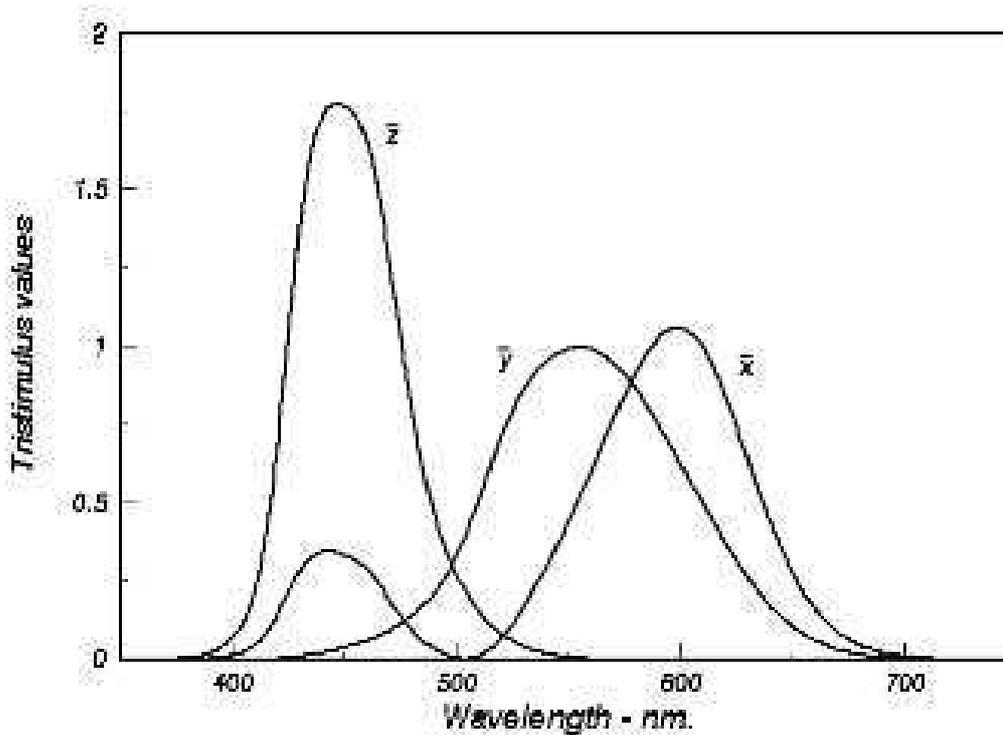$$Y = k \int_{380}^{780} \varphi(\lambda)\,\bar{y}(\lambda)\,d\lambda,$$

$$Z = k \int_{380}^{780} \varphi(\lambda)\,\bar{z}(\lambda)\,d\lambda$$

Biological Background (3)

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Spectral sensitivity of the human eye. Curves measured by the CIE in 1931. Source: `www.research.ibm.com/image_apps/colorsci.html`

Biological Background (4)

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Normalised spectral curves by the CIE. They are supposed to approximate the spectral sensitivities, while permitting only nonnegative weights. Source: `www.research.ibm.com/image_apps/colorsci.html`

Biological Background (5)

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Metamerism (Metamerie)

◆ While every colour leads to unique tristimulus values, the inverse is not true: Two colours with different spectral composition can create the same tristimulus values. They are indistinguishable for humans *(metameric colours)*.

◆ Metamerism is the reason why two clothes that seem to have the same colour in the store, appear to have differing colours at home (under different illumination conditions):

- The spectral density curve of the reflected light depends on the spectral power distributions of the illumination source and the reflectance properties of the clothes.
- Different spectral density curves can create the same tristimulus values (in the store).
- At home, another illumination source creates density curves that are no longer perceived as metameric.

◆ Colours that are metameric for humans may be distinguishable by some animals e.g. birds (`http://www.iitp.ru/projects/posters/meta/`).

Biological Background (6)

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Colour Preception in Animals

◆ It is claimed that the reptile ancestors of mammals already had three colour receptors.

◆ The first mammals were active at night, so there was no need for good colour preception. Only two receptors (blue and yellow) evolved.

◆ 35 million years ago, monkeys acquired a third receptor. The resulting distinction between red and green allowed them to discriminate between mature and unmature fruits.

◆ Other mammals only use two receptors and are not very colourful (unlike some fish, reptiles, birds, bees and butterflies)

◆ Therefore, some monkeys are the most colourful mammals.

◆ Some fish and all birds active during the day even have four receptors: ultraviolet, blue, green, red.

Colours are no objective physical reality. Colour perception is a biologically useful interpretation of the physically existing wavelength spectrum.

Biological Background (7)

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Graßmann's Laws of Additive Colour Blending (1853)

1. Colour perception is a three-dimensional process that can be blended in an additive way from three independent colour components.

2. Two colours with equal appearance combined with a third colour gives mixtures of equal appearance. Thus the appearance of a colour matters, not its spectral composition.

3. There are continuous transitions between all colours.

These laws laid the foundations of the RGB colour representation in monitors. What we see are mixtures of colours.

In 1931, the CIE has defined three wavelengths as *primary colours (Primärfarben)*: $R_s = 700$ nm (red), $G_s = 546,1$ nm (green) and $B_s = 435,8$ nm (blue).

In 1975, Kranz has further formalised Graßmann's ideas to an axiomatic for additive colour blending: (`www.zwisler.de/scripts/farbwahr/node3.html`).
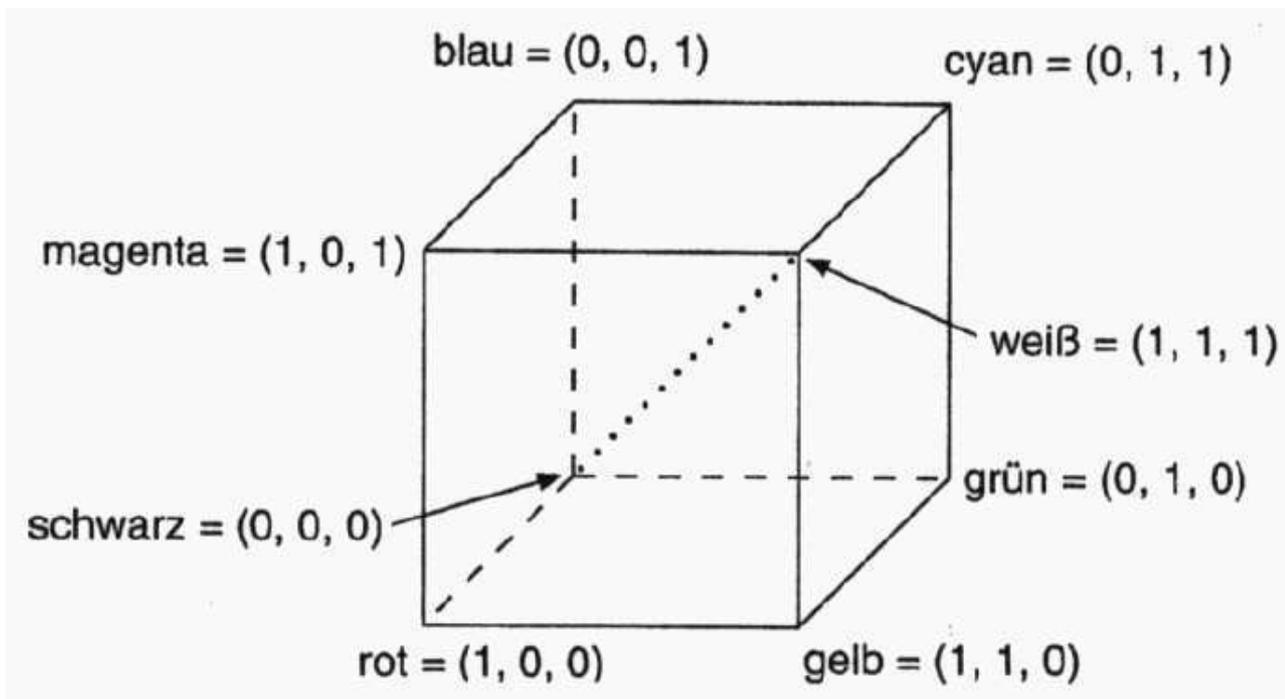
Technical Colour Spaces (1)

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Technical Colour Spaces

The RGB Model

♦ The RGB model is the most important technical colour space. It is used for digital cameras, scanners and colour monitors.

♦ motivated from trichromatic vision and Graßmann's laws.

♦ uses 3 primary colours:

red $(R = (1, 0, 0))$, green $(G = (0, 1, 0))$, blue $(B = (0, 0, 1))$.

♦ By adding them, new colours are created. This gives the *RGB cube*. White is in $(1, 1, 1)$, black in $(0, 0, 0)$.

♦ Every colour has a *complementary colour (Komplementärfarbe)*, such that mixing them gives white. The complementary colour is at the opposite side of the cube.

♦ Usually, digital colour images are in RGB format. Often the range $[0, 1]^3$ is replaced by the bytewise coded range $[0, 255]^3$.

Technical Colour Spaces (2)

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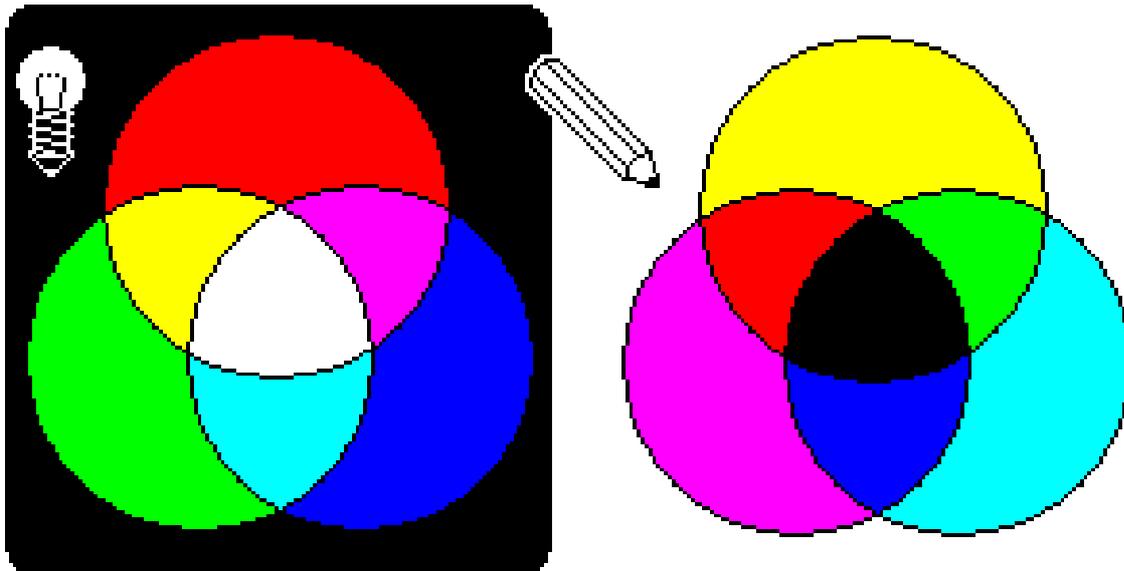
RGB cube. The depicted main diagonal yields the greyscales. Authors: J. D. Foley, A. van Dam, S. K. Feiner, J. F. Hughes, R. L. Phillips (1994).

Technical Colour Spaces (3)

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Left: Additive colour blending. It is used for monitors. **Right:** Subtractive colour blending that is used for printers. Source: `www.khalisi.com/licht/farbspkt.html`

Technical Colour Spaces (4)

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The CMY Model

◆ used by printers and copiers that place colour pigments on white paper

◆ uses complementary colours to red, green and blue: cyan, magenta, and yellow

◆ In contrast to the additive RGB model, the CMY model is subtractive.

◆ Colour impressions are determined by the colour that is subtracted (absorbed) from white light.

◆ Example: Yellow absorbs blue from the white light that is reflected by the paper. Red and green are remaining.

◆ Formula for going from RGB to CMY:

$$\begin{pmatrix} C \\ M \\ Y \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} - \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Technical Colour Spaces (5)

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The CMYK Model

◆ The *CMYK model* uses black (K) as additional fourth colour. This is particularly useful for colour printers that also print large amounts of text in black.

◆ The transition from CMY to CMYK is given by
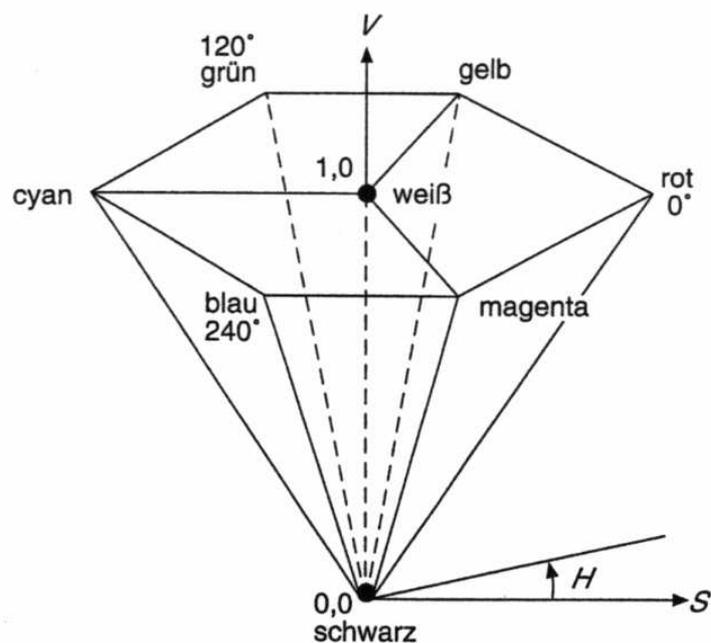
$$
\begin{aligned}
K &\longleftarrow \min(C, M, Y) \\
C &\longleftarrow C - K \\
M &\longleftarrow M - K \\
Y &\longleftarrow Y - K
\end{aligned}
$$

Technical Colour Spaces (6)

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The HSV Model

The HSV colour space. **Authors:** J. D. Foley, A. van Dam, S. K. Feiner, J. F. Hughes, R. L. Phillips (1994).

Technical Colour Spaces (7)

- ◆ has been developed by the painter Albert Henry Munsell in 1905, in order to describe the mixing of colours during painting

- ◆ uses a cylindrical polar coordinate system with hue, saturation and value as coordinates

- ◆ *hue (Farbton) H:*
  - polar angle in the horizontal plane
  - red: 0 degrees; green: 120 degrees; blue: 240 degrees

- ◆ *saturation (Sättigung) S:*
  - radius in the horizontal plane
  - gives distance to the next grey tone
  - ranges between 0 and 1

- ◆ *value (Helligkeitswert) V:*
  - vertical axis in the coordinate system
  - defines how dark or bright a colour is

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Technical Colour Spaces (8)

- ◆ The HSV model allows to modify hue and saturation directly, without affecting the value.

- ◆ Singularities can appear:
  The hue H, for instance, is undefined for greytones.

- ◆ Conversion routines to RGB: see e.g. Foley et al. (1994)

- ◆ closely related colour spaces: HSI, HSB, HCI, HVC, TSD

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Technical Colour Spaces (9)

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The YCbCr Model

◆ used in video and digital photography systems
(digital PAL and NTSC television, JPEG and MPEG compression)

◆ separates the colour image into

- a *luma component Y* that is basically a greyscale version of the colour image
- a *chroma component Cb* that measures deviation from grey in blue–yellow direction
- a *chroma component Cr* that measures deviation from grey in red–cyan direction

◆ The luma channel Y can be stored in high resolution, while the chroma channels Cb and Cr can be subsampled without significant visual deterioration.

◆ For an RGB image with range $[0, 255]^3$ a frequently used conversion is given by

$$
\begin{pmatrix} Y \\ Cb \\ Cr \end{pmatrix} = \begin{pmatrix} 16 \\ 128 \\ 128 \end{pmatrix} + \frac{1}{256} \begin{pmatrix} 65.738 & 129.057 & 26.064 \\ -37.945 & -74.494 & 112.439 \\ 112.439 & -94.154 & -18.285 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}
$$

Technical Colour Spaces (10)

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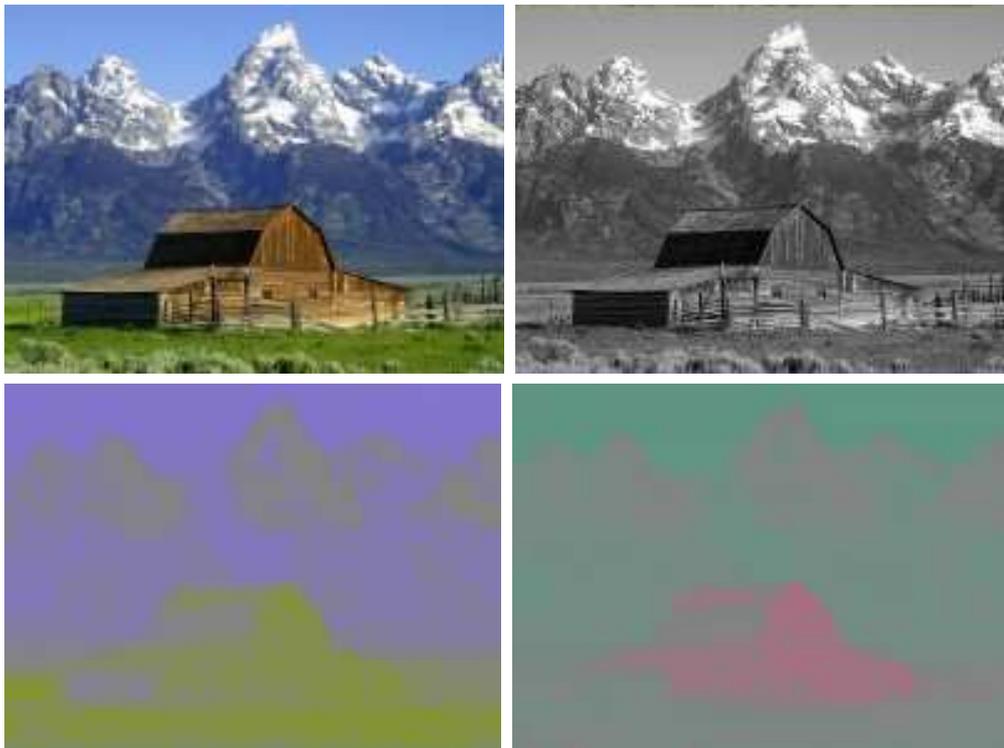
Top left: Original image, 200×149 pixels. **Top right:** The luma channel Y contains the luminance information at a high resolution. **Bottom left:** Blue chroma channel Cb. **Bottom right:** Red chroma channel Cr. **Source:** http://en.wikipedia.org/wiki/YCbCr.

Summary

◆ Visible light consists of electromagnetic waves in the range from 380 to 780 nanometers. Real objects emit a large number of different wavelengths.

◆ Human colour preception is based on three types of cones that are sensitive in different frequency ranges.

◆ Different frequency spectra can create the same colour perception (metamerism).

◆ An additive blending of the three primary colours red, green and blue is used for creating other colours.

◆ This is realised in the RGB colour space which is a very frequently used additive colour space for digital cameras and monitors.

◆ The CMY and CMYK spaces are subtractive colour spaces for printers and copiers.

◆ The HSV colour space is inspired by the mixing of colours during painting.

◆ The YCbCr representation separates luma from croma information and allows to subsample the croma channels without severe visual degradation.

Literature

◆ R. Zwisler: *Farbwahrnehmung*. Universität Regensburg, 1998.
(`www.zwisler.de/scripts/farbwahr/farbwahr.html`)
(exciting and well-written web page of a psychologist)

◆ W. K. Pratt: *Digital Image Processing: PIKS Inside*. Wiley, Third Edition, 2001.
(one of the best chapters on colour in a standard textbook)

◆ J. D. Foley, A. van Dam, S. K. Feiner, J. F. Hughes, R. L. Phillips: *Grundlagen der Computergraphik*. Addison–Wesley, Bonn, 1994.
(computer graphics book with a good chapter on colour)

◆ A. Koschan, K. Schlüns: *Grundlagen und Voraussetzungen für die Digitale Farbbildverarbeitung*. Technischer Bericht 94-14, Fachbereich Informatik, TU Berlin, 1994.
(extended technical report on processing colour images)

◆ G. Wyszecki, W. S. Stiles: *Color Science: Concepts and Methods, Quantitative Data and Formulae*. Wiley, New York, 2000.
(the ultimate reference on colour science)

◆ Wikipedia information on YCbCr:
in English: `http://de.wikipedia.org/wiki/YCbCr-Farbmodell`
in German: `http://en.wikipedia.org/wiki/YCbCr`
(a good starting point for the YCbCr model)