Lecture 3:
Foundations III: Colour Perception and Colour Spaces

Contents

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Motivation

- Human colour perception has inspired many computer methods 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 useful for calibrating hardware such as scanners and colour monitors.
- 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 colour (but not always successful): e.g. Newton, Goethe, Graßmann, Maxwell, Helmholtz, Schrödinger.
- Often the correctness or incorrectness of these theories has only been verified by experiments in recent decades.

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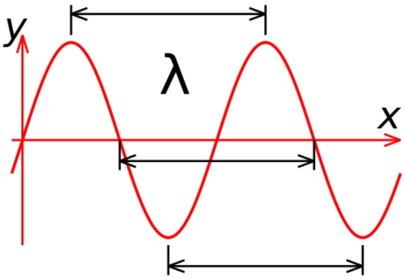
Physical Background



The wavelength λ is the distance between two consecutive points with the same phase. Source: `http://en.wikipedia.org/wiki/Wavelength`.

- Electromagnetic waves propagate with the speed of light ($c = 299,792,458$ m/s in vacuum). If ν denotes their frequency, their *wavelength* λ is defined via $c = \lambda\nu$.
- (Visible) light consists of electromagnetic waves with wavelengths λ between 380 and 750 nm (nanometers, 1 nm $= 10^{-9}$ m).
- It is emitted from atoms when outer electrons change their orbits and lose energy.
- Visible light constitutes only a small fraction of the electromagnetic spectrum.

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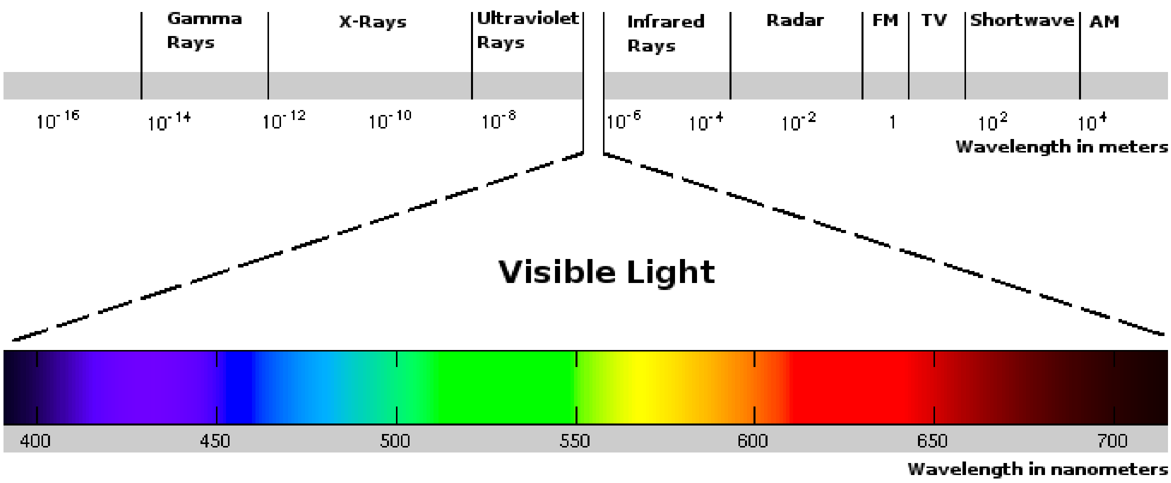

Visible light constitutes only a small part of the electromagnetic spectrum. Author: N. Khan.

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Physical Background (3)

- However, the visible range of the electromagnetic spectrum is the main range in which the sun rays can pass the atmosphere.
- The visible range is not exactly 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.
- The visible spectrum contains seven colours:
  red, orange, yellow, green, blue, indigo, violet
  (with decreasing wavelength or increasing frequency).
- Memory hook: "**R**ichard **O**f **Y**ork **G**ave **B**attle **I**n **V**ain".
- Pure spectral colours consisting of a single frequency are the exception:
  They exist e.g. in rainbows, in light rays that pass through a prism, and in lasers.
- The colours we usually perceive are a mixture of numerous frequencies.
- However, biological and technical systems do not exploit the full richness of this spectral composition: They use a more compact representation.
- To understand this, let us analyse the biology of colour perception.

Biological Background (1)

Biological Background

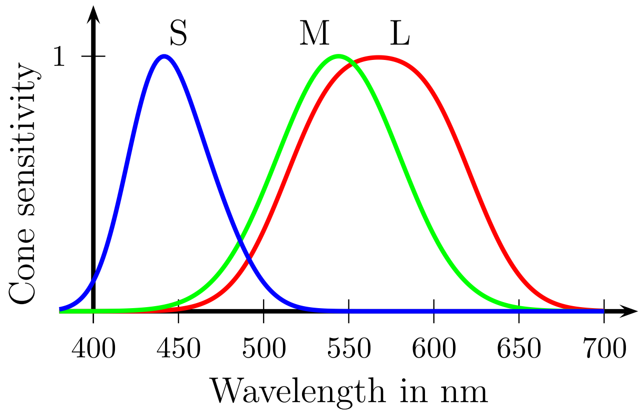
Day Vision and Night Vision

- 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.
  Very sensitive, but allows only poor sharpness and no colour perception:
  "Bei Nacht sind alle Katzen grau." ("At night all cats are grey.")
- Day vision is dominated by cones.
  Low sensitivity, but very good perception of sharpness and colours.
  Humans can distinguish ca. 40 different greyscales, but ca. 2 million colours!
  (These numbers may vary depending on the experimental setting.)

We now focus on day vision.

Tricolour Imaging

- Humans have three different types of cones (L, M, S).
  They are sensitive to different frequency ranges: *red*, *green*, and *blue*.
- The sensistivity characteristics are almost identical for all humans.



Normalised spectral sensitivity of the three cone types in the human eye.
Author: M. Mainberger.

- 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)*.
- The tristimulus value Q_i of a cone of type i = 1, 2, 3 for L-, M-, and S-cones, respectively, is given by

$$Q_i \;=\; \int C(\lambda)\, R_i(\lambda)\, d\lambda$$

  where
  - λ denotes the wavelength,
  - $C(\lambda)$ is the incoming stimulus (product of illuminant and reflectance),
  - $R_i(\lambda)$ is the spectral sensitivity of cone i.
- Representing a colour with a complicated spectral composition by only three constants is a very compact description that reduces the information content.
- Let us now study what is ignored by this tristimulus representation.

Biological Background (4)

Metamerism (Metamerie)

- While every colour leads to unique tristimulus values, the inverse is not true: Colours with different spectral composition can create the same tristimulus values. In this case, they are indistinguishable for humans *(metameric colours).*
- Metamerism is the reason for the following observation:
  - In the store two clothes may have the same colour.
  - At home their colour appearance differs.
- Explanation:
  - The spectral density curve of the reflected light depends on two things:
    - the spectral power distributions of the illumination source
    - the reflectance properties of the clothes
  - In the store, different spectral density curves can create the same tristimulus values.
  - 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://cool.iitp.ru/projects/posters/meta/index.html`).

Biological Background (5)

Colour Perception in Animals

- Presumably the reptile ancestors of mammals had already three colour receptors.
- The first mammals were active at night.
  So there was no need for good colour perception.
  Only two receptors (yellow and blue) evolved.
- Most mammals still use only two receptors and are not very colourful (unlike some fish, birds, and insects).
- 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.
  Therefore, some monkeys are the most colourful mammals.
- Some fish and all birds active during the day even have four receptors: red, green, blue, ultraviolet.
- A few animals have even more receptors.

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

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The King of Colour Perception

Mantis shrimps (Fangschreckenkrebse) possess one the most complex colour vision systems of all animals. Some species have 12 different narrowband photoreceptors for colour analysis (8 for visible light, 4 for ultraviolet light). They also have 4 receptors for polarised light, and each single eye is capable of trinocular depth perception. For more properties of these highly interesting animals, consult Wikipedia. Photos: Roy Caldwell (left image) and Bob Whorton (right image).

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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.
- Colour impressions are created by the colour that is added to a *black* background.
- uses three primary colours that are motivated from trichromatic vision:

  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 $(0, 0, 0)$.
- Thus, the RGB model is an *additive model*.
- Every colour has a *complementary colour (Komplementärfarbe)*, such that adding them gives white. The complementary colour is at the opposite side of the cube.
- Most digital colour images are in RGB format.
  Often the range $[0, 1]^3$ is replaced by the bytewise coded range $[0, 255]^3$.

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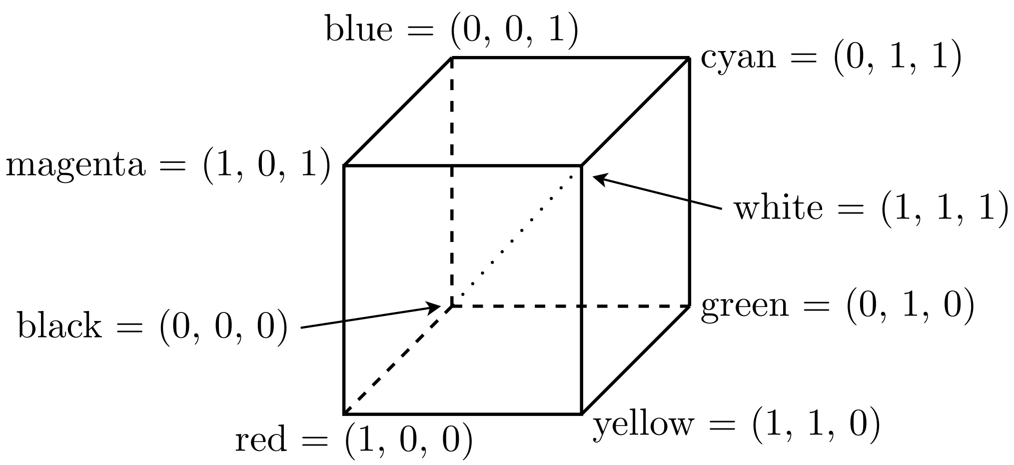
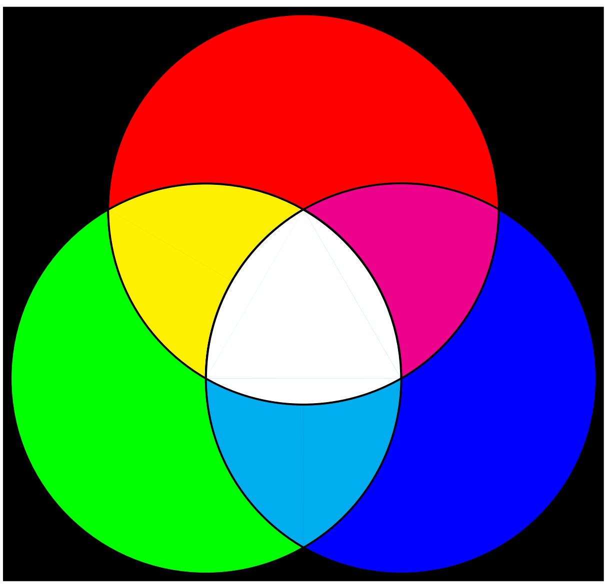
Technical Colour Spaces (2)



RGB colour cube. The diagonal between black and white yields the greyscales. Author: M. Mainberger.

Technical Colour Spaces (3)



Additive colour blending in the RGB model. It is used e.g. for monitors. Author: M. Mainberger

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The CMY Model

- used by printers and copiers that place colour pigments on *white* paper
- Colour impressions are determined by the colour that is subtracted (absorbed) from white light.
- Thus, in contrast to the additive RGB model, the CMY model is *subtractive*.
- uses complementary colours to red, green, and blue:
  cyan (C), magenta (M), and yellow (Y)
- A full combination of the primary colours C, M, Y creates black.
  (In the RGB model, a full combination of the primary colours R, G, B gives white.)
- formula for going from RGB to CMY:

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

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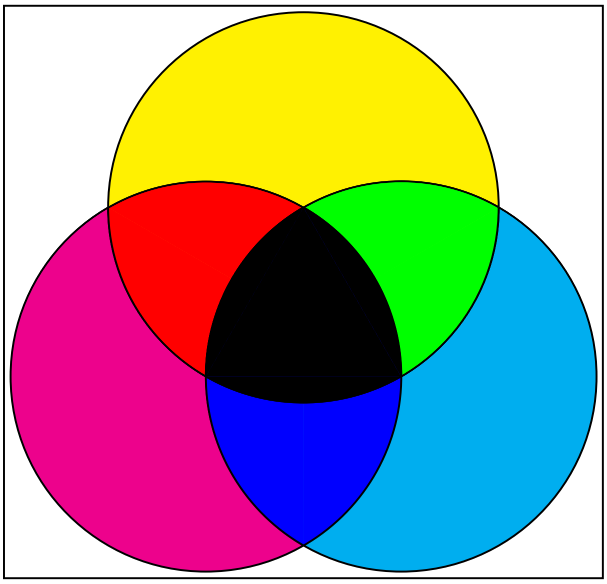


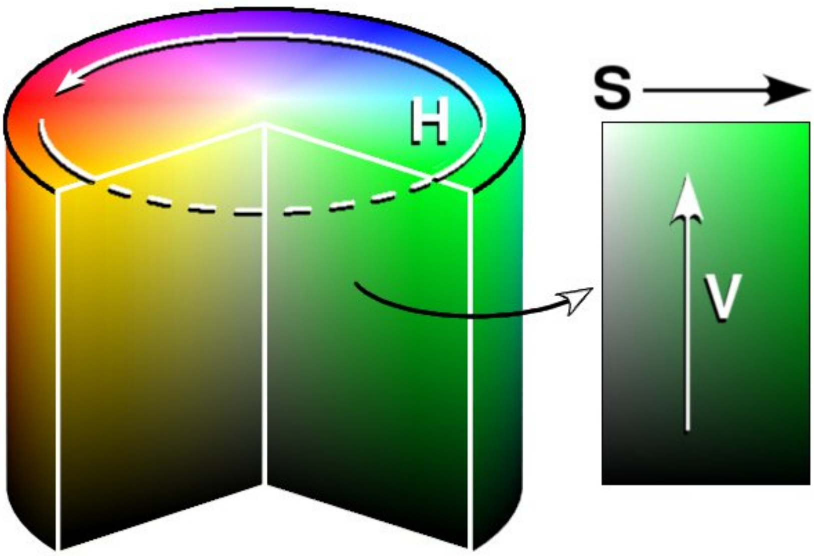
Subtractive colour blending in the CMY model. This is frequently used e.g. in printers. Author: M. Mainberger.

The CMYK Model

- modification of the CMY model that uses black (K) as additional fourth colour
- useful for colour printers that print large amounts of text in black
- The transition from CMY to CMYK is given by

$$\begin{aligned} K &\leftarrow \min(C, M, Y) \\ C &\leftarrow C - K \\ M &\leftarrow M - K \\ Y &\leftarrow Y - K \end{aligned}$$

The HSV Model



The HSV colour space uses a cylindrical polar coordinate system with hue, saturation, and value as coordinates. Source: `http://de.wikipedia.org/wiki/HSV-Farbraum`.

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Technical Colour Spaces (8)

Basic Idea

- originally proposed by the painter Albert Henry Munsell in 1905, in order to describe the mixing of colours during painting
- based on a cylindrical polar coordinate system: hue, saturation, and value as coordinates
- *hue (Farbton) H:*
  - polar angle in the horizontal plane
  - red: $0°$; green: $120°$; blue: $240°$
- *saturation (Sättigung) S:*
  - radius in the horizontal plane
  - gives distance of the colour to the nearest grey tone
- *value (Helligkeitswert) V:*
  - vertical axis in the coordinate system
  - defines how dark or bright a colour is

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Technical Colour Spaces (9)

MIA

Conversion from RGB to HSV

- Input: $R, G, B \in [0, 255]$.
- Conversion routine:

$$M := \max(R, G, B)$$
$$m := \min(R, G, B)$$
$$H := \begin{cases} 0°, & \text{if } M = m, \\ 60° \cdot \left(0 + \frac{G-B}{M-m}\right), & \text{if } M = R, \\ 60° \cdot \left(2 + \frac{B-R}{M-m}\right), & \text{if } M = G, \\ 60° \cdot \left(4 + \frac{R-G}{M-m}\right), & \text{if } M = B. \end{cases}$$

If $H < 0°$, then $H := H + 360°$.

$$S := \begin{cases} 0, & \text{if } M = 0, \\ \frac{M-m}{M}, & \text{else.} \end{cases}$$

$$V := \frac{M}{255}$$

- Output: $H \in [0°, 360°)$ and $S, V \in [0, 1]$.

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Technical Colour Spaces (10)

Conversion from HSV to RGB

One can show that this is accomplished by the following algorithm.

- Input: $H \in [0°, 360°)$ and $S, V \in [0, 1]$
- Conversion routine:

$$
\begin{aligned}
k &:= \left\lfloor \frac{H}{60°} \right\rfloor \quad \text{(largest integer} \le \frac{H}{60°}\text{)} \\
f &:= \frac{H}{60°} - k \\
p &:= V(1-S) \\
q &:= V(1-Sf) \\
t &:= V(1-S(1-f))
\end{aligned}
$$

$$
(R,G,B) := \begin{cases}
255\,(V,t,p) & \text{for } k=0 \text{ (between red and yellow),} \\
255\,(q,V,p) & \text{for } k=1 \text{ (between yellow and green),} \\
255\,(p,V,t) & \text{for } k=2 \text{ (between green and cyan),} \\
255\,(p,q,V) & \text{for } k=3 \text{ (between cyan and blue),} \\
255\,(t,p,V) & \text{for } k=4 \text{ (between blue and violet),} \\
255\,(V,p,q) & \text{for } k=5 \text{ (between violet and red).}
\end{cases}
$$

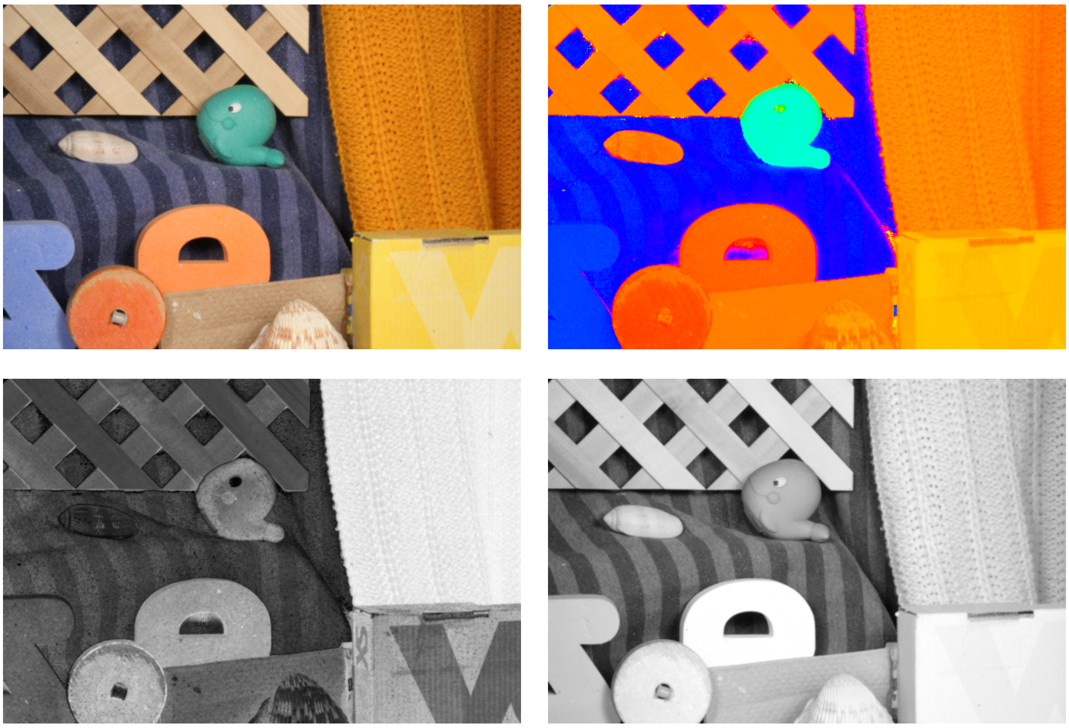
- Output: $R, G, B \in [0, 255]$.

Technical Colour Spaces (11)

Where is the HSV Colour Space Useful?

- HSV can offer advantages when illumination changes appear:
  - Typical changes according to Shafer's dichromatic reflection model:
    - global multiplicative changes: global illumination changes
    - local multiplicative changes: shadow, shading
    - local additive changes: specular highlights
  - The H and S channels are photometric invariants:
    - H is invariant under all these three changes.
    - S is invariant under global and local multiplicative changes.
    - V is not invariant under any of these changes.
- This can be useful in computer vision applications, e.g. motion analysis in videos.
- many closely related colour spaces: HSI, HSB, HCI, HVC, TSD

Technical Colour Spaces (12)



Top left: Colour image, 584×388 pixels. Source: `http://vision.middlebury.edu/flow/data/`. **Top right:** Hue channel H. **Bottom left:** Saturation channel S. **Bottom right:** Value channel V. The shadow of the wheel is only visible in the V channel. Author: H. Zimmer.

Technical Colour Spaces (13)

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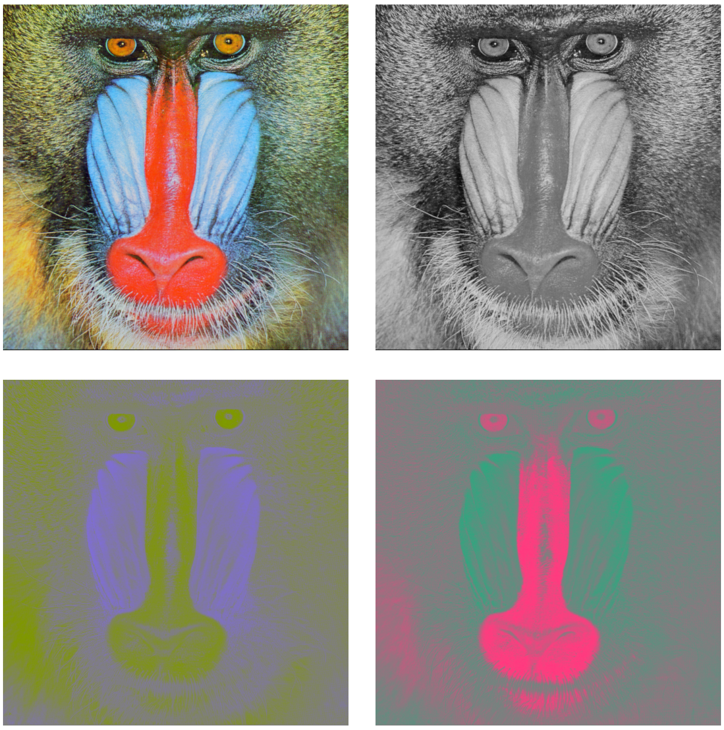
The YCbCr Model

- used in video and digital photography systems
  (digital PAL and NTSC television, JPEG and MPEG compression)
- represents a colour image with the following three channels:
  - The *luma channel* Y is a greyscale version of the colour image.
  - The *chroma channel* C_b measures deviations from grey in blue–yellow direction.
  - The *chroma channel* C_r measures deviations from grey in red–cyan direction.
- Depending on the application, definitions and conversion formulas may vary.
- closely related colour space: YUV

Technical Colour Spaces (14)



Top left: Original image, 512×512 pixels. **Top right:** The luma channel Y contains the luminance information with lots of details. **Bottom left:** Blue–yellow chroma channel C_b. **Bottom right:** Red–cyan chroma channel C_r. Author: M. Mainberger.

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Technical Colour Spaces (15)

Conversion from RGB to YCbCr

- For an RGB image with range $[0, 255]^3$, one possible conversion formula is

$$\begin{pmatrix} Y \\ C_b \\ C_r \end{pmatrix} = \begin{pmatrix} 0 \\ 127.5 \\ 127.5 \end{pmatrix} + \begin{pmatrix} 0.2990 & 0.5870 & 0.1140 \\ -0.1687 & -0.3313 & 0.5000 \\ 0.5000 & -0.4187 & -0.0813 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}.$$

  The resulting Y, C_b, and C_r values are in the interval $[0, 255]$.

- How can this formula be motivated?
  - The luma channel $Y = 0.299\, R + 0.587\, G + 0.114\, B$ uses different weights: Our visual system is more sensitive to green than to blue.
  - Blue with $(R, G, B) = (0, 0, 255)$ gives $C_b = 255$, and yellow with $(R, G, B) = (255, 255, 0)$ yields $C_b = 0$. The weights are chosen such that $\frac{-0.1687}{-0.3313} = \frac{0.2990}{0.5870}$.
  - Red with $(R, G, B) = (255, 0, 0)$ gives $C_r = 255$, and cyan with $(R, G, B) = (0, 255, 255)$ yields $C_r = 0$. The weights satisfy $\frac{-0.4187}{-0.0813} = \frac{0.5870}{0.1140}$.

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Conversion from YCbCr to RGB

- The previous conversion formula implies the following backtransformation from YCbCr to RGB:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 1.0000 & 0.0000 & 1.4020 \\ 1.0000 & -0.3441 & -0.7141 \\ 1.0000 & 1.7720 & 0.0000 \end{pmatrix} \left(\begin{pmatrix} Y \\ C_b \\ C_r \end{pmatrix} - \begin{pmatrix} 0 \\ 127.5 \\ 127.5 \end{pmatrix} \right).$$

Where is the YCbCr Model Useful?

- The luma channel Y contains many details and should be stored in high resolution.
- Usually the chroma channels C_b and C_r contain less details.
  They can be subsampled without significant visual deterioration.
- This is exploited in the JPEG compression standard (Lecture 8).

Summary

- Visible light consists of electromagnetic waves in the range from 380 to 750 nm.
  Illuminated real objects emit a mixture of different wavelengths.
- Human colour perception is based on three types of cones.
  They are sensitive in different frequency bands.
- Different frequency spectra can create the same colour perception (metamerism).
- The three cone types correspond to the three primary colours red, green, and blue.
  Their additive blend creates other colour impressions.
- A technical realisation of this biological mechanism is the RGB colour space.
  It is a 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 represents colours in a cylindrical polar coordinate system.
  This can be useful when illumination changes appear.
- The YCbCr representation separates luma from chroma information.
  One can subsample the chroma channels without severe visual degradation.

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References

- 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, Fourth Edition, 2007.
  (one of the best chapters on colour in a standard textbook)
- 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)
- T. W. Cronin, J. Marshall: Parallel processing and image analysis in the eyes of mantis shrimps. *Biological Bullentin*, Vol. 200, 177–183, April 2001.
  (describes the fascinating features of the visual system of the mantis shrimp)
- 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 RGB, HSV, and YCbCr
  (a good starting point for these colour spaces)

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Announcements

- The mailboxes for the tutorial groups have been moved to Building E2.5 (cellar, next to Lecture Hall 1).
- The Easter holidays also affect the IPCV class:
  - The forthcoming Friday lecture is moved to Thursday, April 18, 6:15 pm, E1.3, Lecture Hall 001.
  - The deadline for submitting the homework assignments H1 is postponed to Tuesday, April 23, 10 am (before the lecture).

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