University of Osnabrück, Institute of Cognitive Science

Computer Vision

6 − Color

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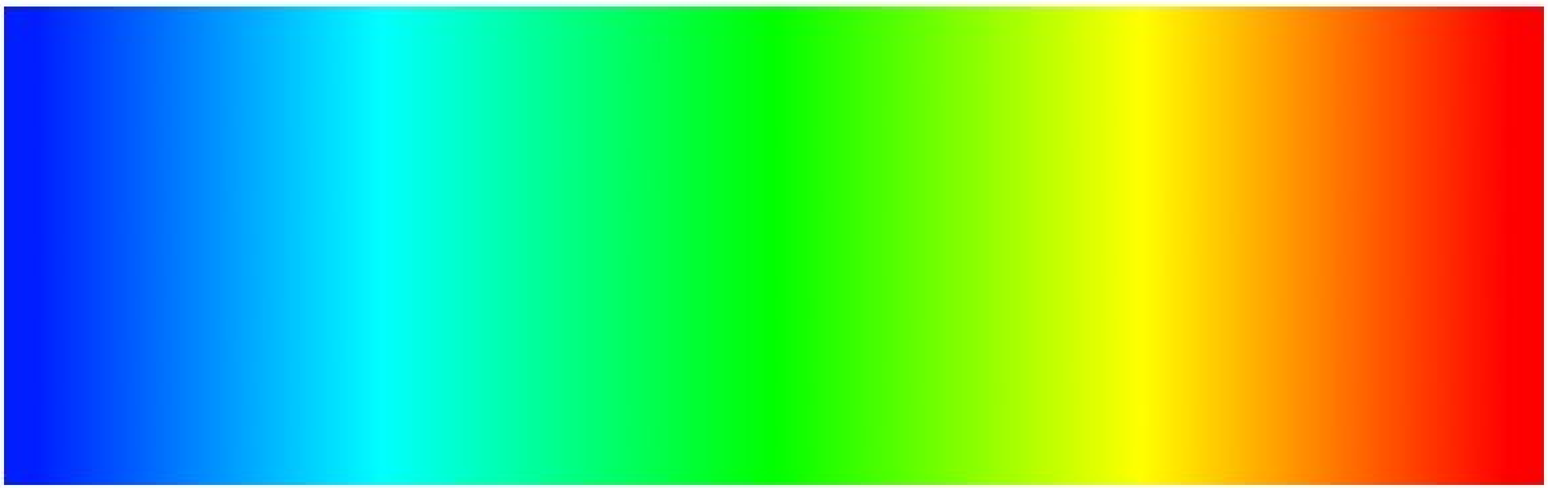
Survey

- Visible spectrum
- Human eye
- Color spaces
- CIE color space
- RGB color space
- CMYK color space
- XYZ color space
- HSV color space
- Lab color space

Visible spectrum

Visible range of the electromagnetic spectrum about 380-780nm



Reflected light

Light reflected by a body

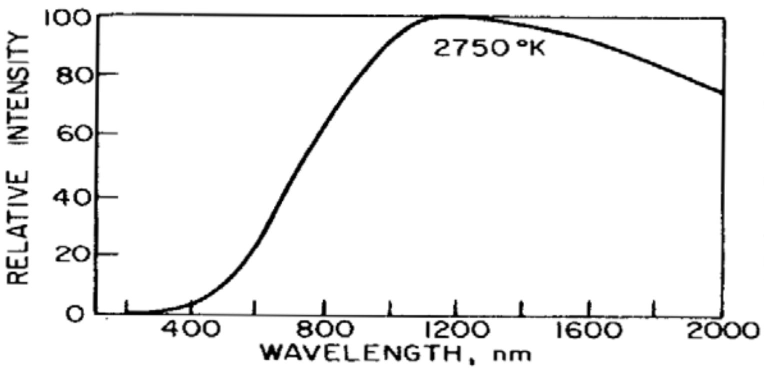
- consists of different wavelengths,
- which are reflected independent of each other.

Which wavelengths are reflected depends on

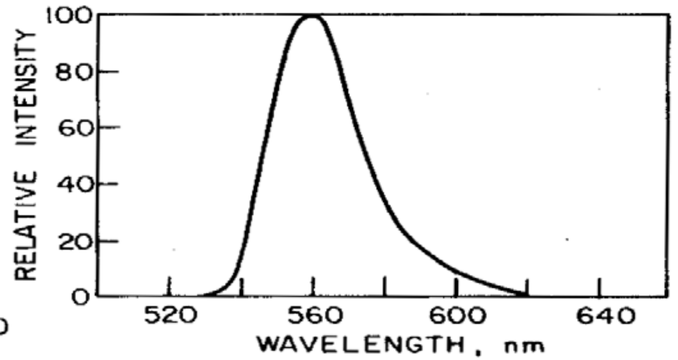
- the incoming spectrum,
- absorption / reflection of the body.

Light sources

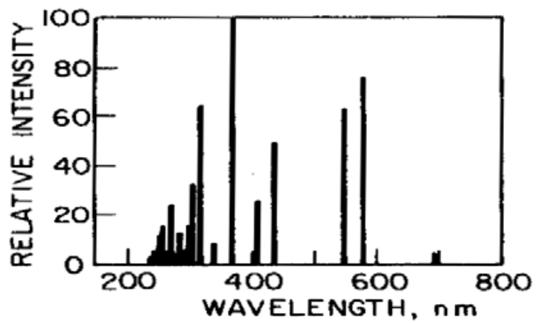
- Light can be produced by different physical processes.
- This causes highly different spectra.
- In particular, there are *continuous* spectra and *line* spectra.



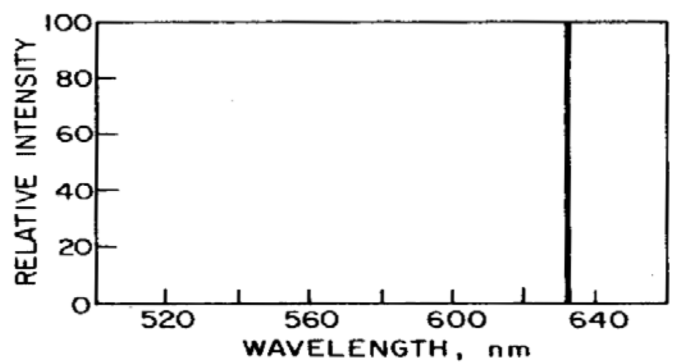
(*b*) Tungsten lamp



(*c*) Light-emitting diode



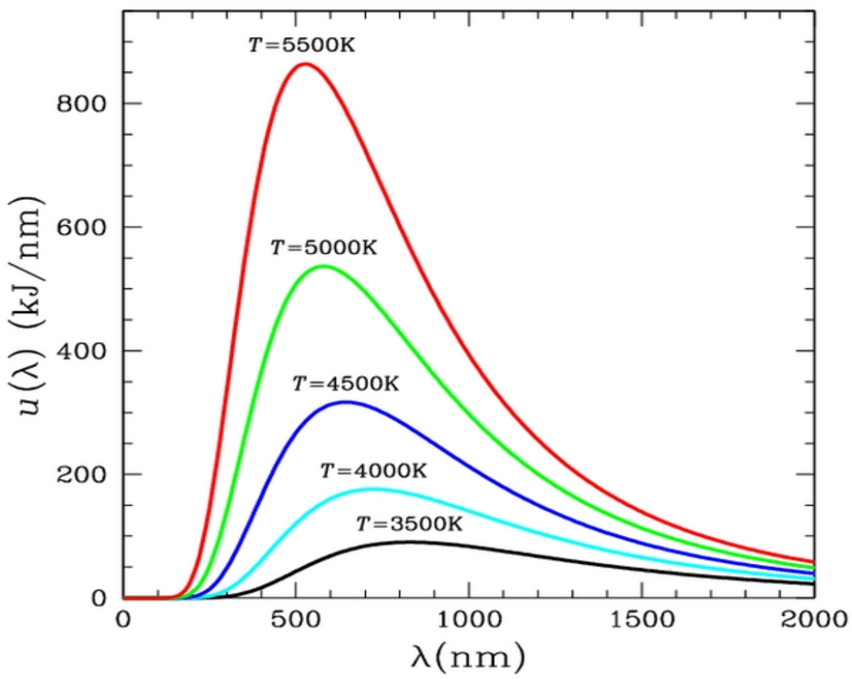
(*d*) Mercury arc lamp



(*e*) Helium–neon

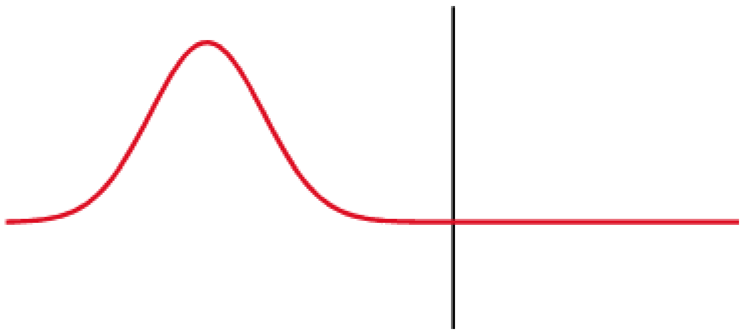
Black body:

- Idealized light source
- Total absorption of electromagnetic waves
- Emission of thermal radiation according to Planck’s law



From light to stimuli

- Light source:
  - Sun, bulb, neon lamp, laser, …; light reflected by other objects
  - Result: incident spectrum $E(\lambda)$
- Reflection on object:
  - Reflection / absorption / transmission depends on material, wavelength and angle of incidence
  - Reflection properties summarized as coefficient $r(\lambda)$
  - Transmission properties summarized as coefficient $t(\lambda)$

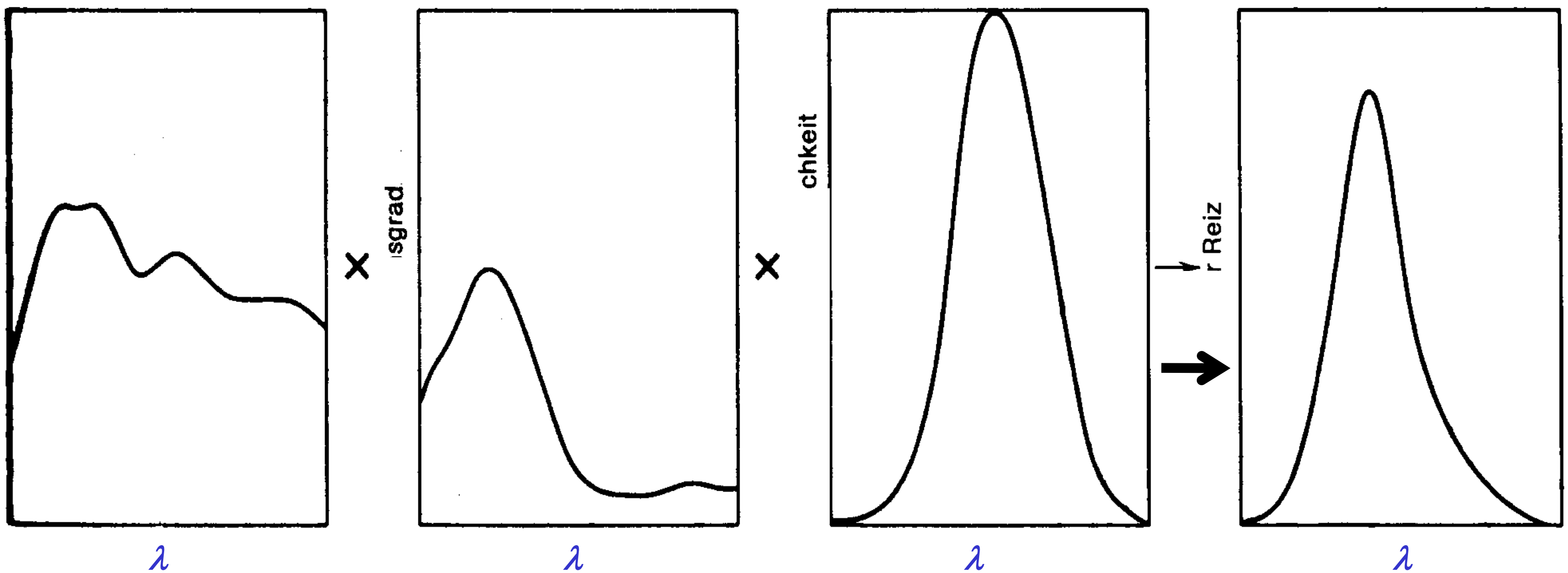


[WOA]

- Resulting reflected spectrum:

$$C(\lambda) = E(\lambda) \cdot r(\lambda)$$

From incident light to stimulus



Incoming spectrum $E(\lambda)$

Reflection coefficient $r(\lambda)$

Relative receptor sensitivity $\varphi(\lambda)$

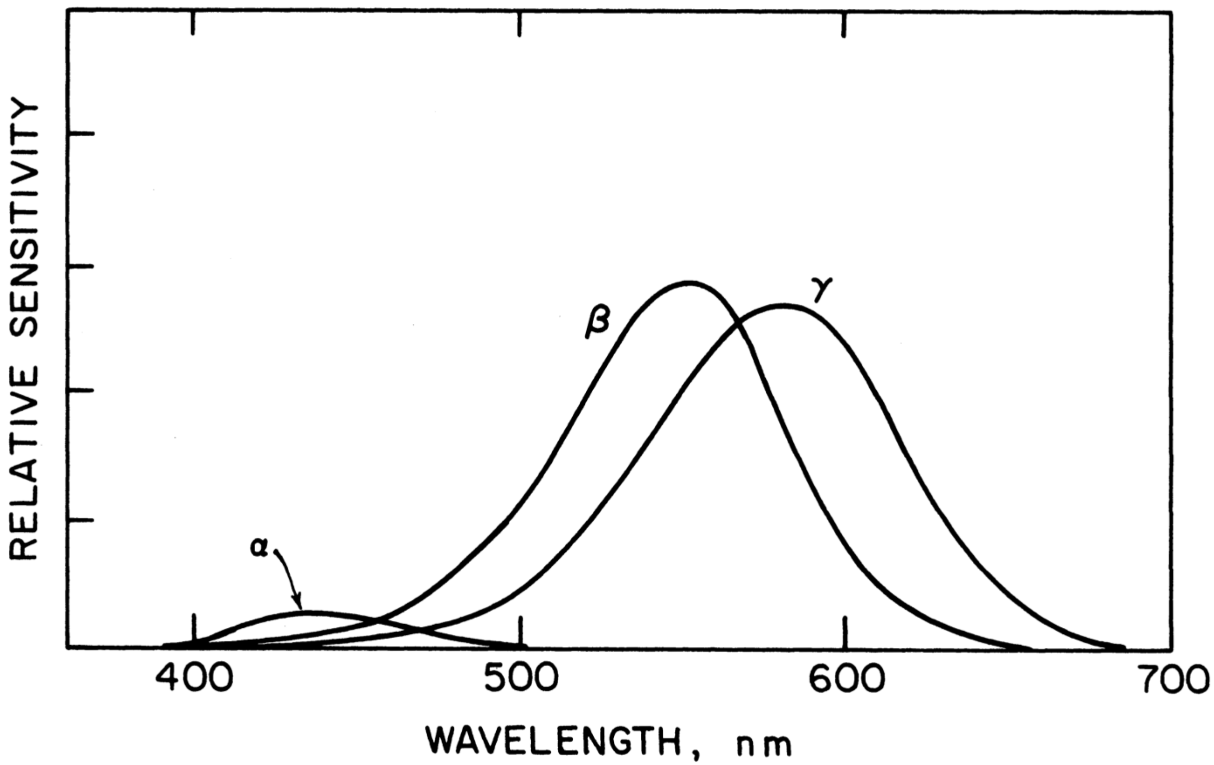
Stimulus: $\int C(\lambda) \cdot \varphi(\lambda)$

Reflected spectrum
$C(\lambda) = E(\lambda) \cdot r(\lambda)$

Color vision in the human eye

- Three types of cones for color vision:
  - **S**(hort) for blue
  - **M**(iddle) for green – yellow
  - **L**(ong) for yellow – red
- Overlapping areas of sensitivity
- Particularly high sensitivity in range between 530 – 560 nm
- Rods (490-495nm) do not contribute to color vision
- Most birds are *tetrachromats* (additional ultraviolet receptors)
- Some humans might be tetrachromats (receptor between M and L) [JH], but it is unclear if an additional stimulus can be processed

Sensitivities



Color perception in the eye

- Stimulus of cones:

$$e_i = \int \varphi_i(\lambda) \cdot C(\lambda)\, d\lambda$$

  $\varphi_i(\lambda)$ is the sensitivity of the receptors $i \in \{S, M, L\}$

- Continuous spectrum is reduced to just three values (*tristimulus values*)
  - “Infinite dimensionality” → $\mathbb{R}^3$
  - *Metamerism:*
    - Different spectra can cause the same color tristimulus values.
    - Two colors of objects are a metameric match if they appear the same under a certain spectrum but different under another.
    - So metameric color match ≠ spectral color match !

Color spaces

- We need coordinate systems to describe *perceived* colors
- Commonly three coordinates
- Different underlying color models:
  - Technical and physical models
    - Basis consists of *primary colors*, mixing of which allows to span a useful range of colors
    - For example RGB, CMYK
  - Perception oriented models, e.g.
    - Basis consists of quantities that make sense on a semantic level: *HSV* (hue, saturation, value)
    - Coordinates are chosen such that distance in the color space matches perceived difference: *Lab*

Color spaces

In principle, each color C can be obtained by mixing suitable primary colors P_1, P_2, P_3 :

$$C = xP_1 + yP_2 + zP_3$$

- Coefficients must be positive:

$$0 \leq x, y, z \leq 1.$$

- Orthogonality of primary colors would be nice: One primary color should cause stimuli on only *one* receptor type.

- As this is impossible in practice, some perceivable colors can not be realized by the primaries.

Color spaces

- Provided are three primary colors P_1, P_2, P_3.
- A primary is defined as a certain light source.
- Color is specified by a triple (x,y,z) : $C = xP_1 + yP_2 + zP_3$.
- Colors of identical intensity are in a plane (e.g. $x+y+z=1$).
- Position on this plane can be described by just *two* coordinates.
- Transformation to new coordinates (x',y',z') where z' depends on the other two:

$$x' = \frac{x}{x+y+z}$$

$$y' = \frac{y}{x+y+z}$$

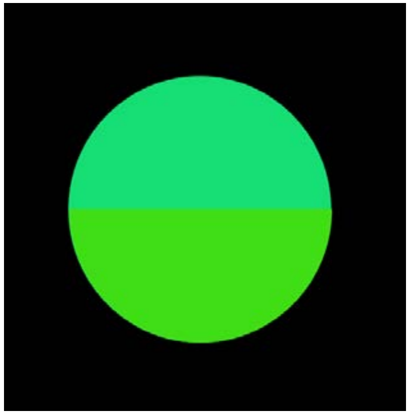
$$z' = 1 - x' - y'$$

CIE RGB color space

CIE is an RGB color space developed in the 1920ies by David Wright and John Guild for the *Commission internationale de l'éclairage.*

Aim: Find the relation

physical light → perceived color.



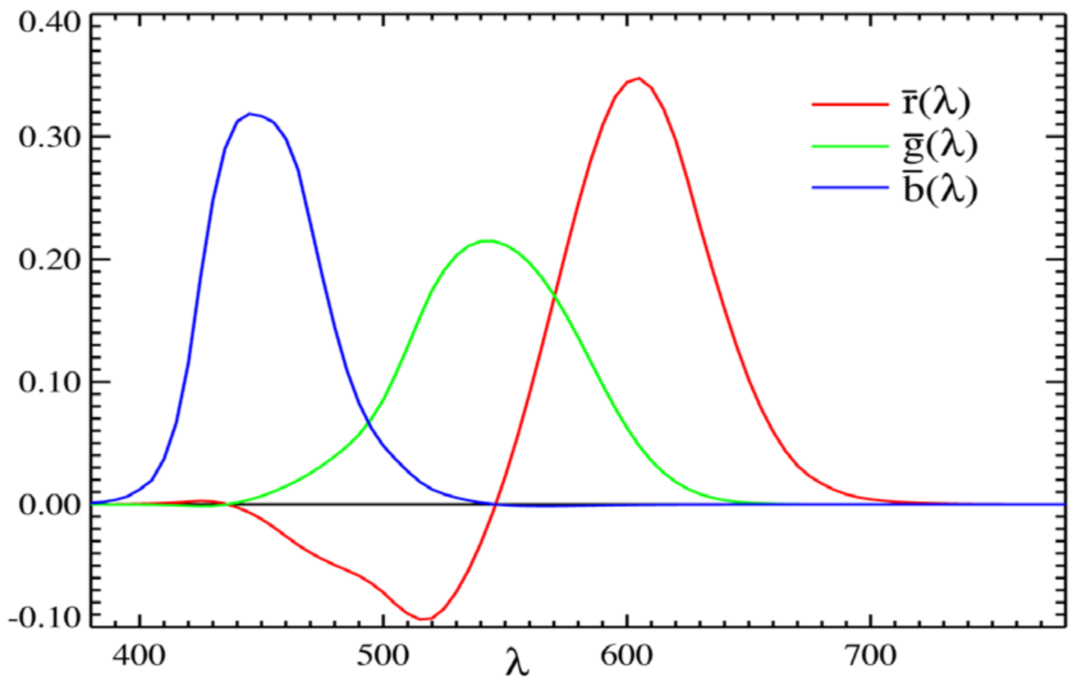
Experimental setup:

- A *test color* is presented in the upper half of the screen.
- Below a color is *mixed additively* by a test person who adjusts the intensities of three given monochromatic primary colors to achieve a match.
- If this is impossible, the intensity of one primary color in the *upper* half may be increased.
- This corresponds to a negative coefficient of the primary color in the *lower* half.

Color matching functions

If the test color is monochromatic, the required brightness of the primary colors can be plotted ("*color matching functions*"). Negative values indicate adding a primary to the test color.

Amplitudes of the primaries required to mix the test color

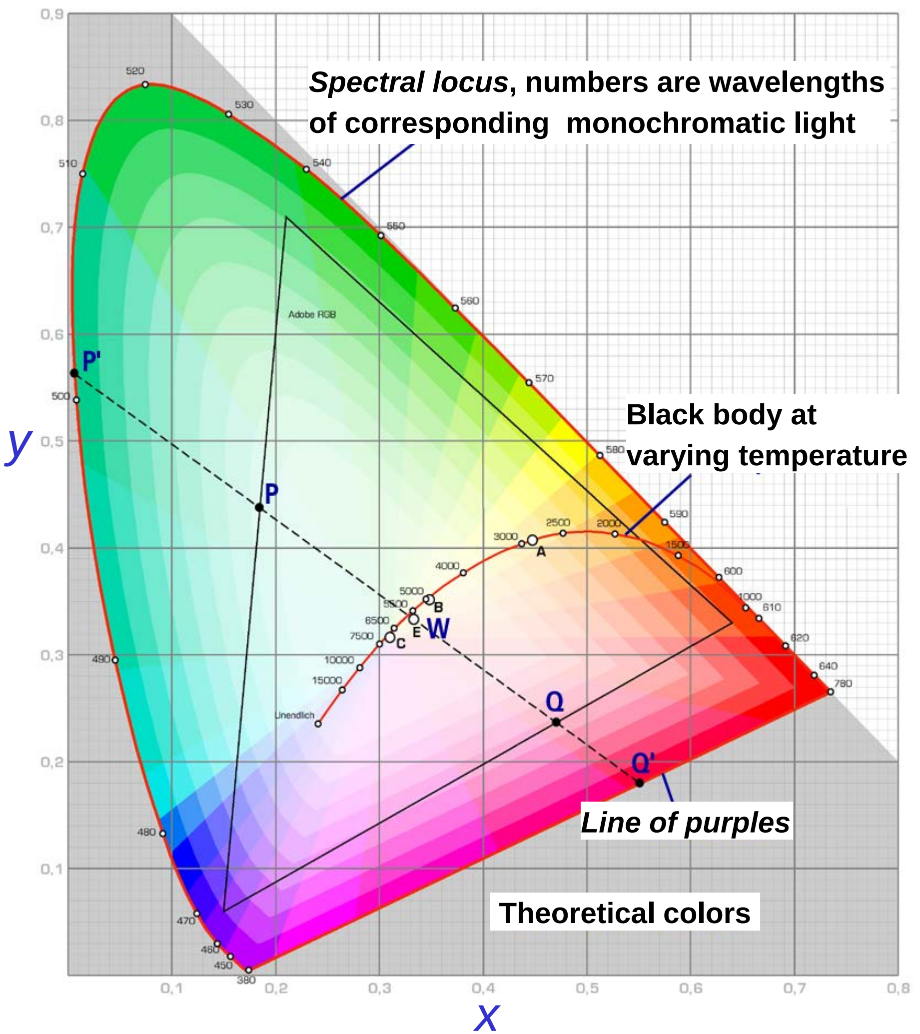


Wavelength of the monochromatic test color

Standard CIE RGB color matching functions are obtained using primaries of 435,8 and 546,1 nm (mercury vapor lines) and 700 nm.

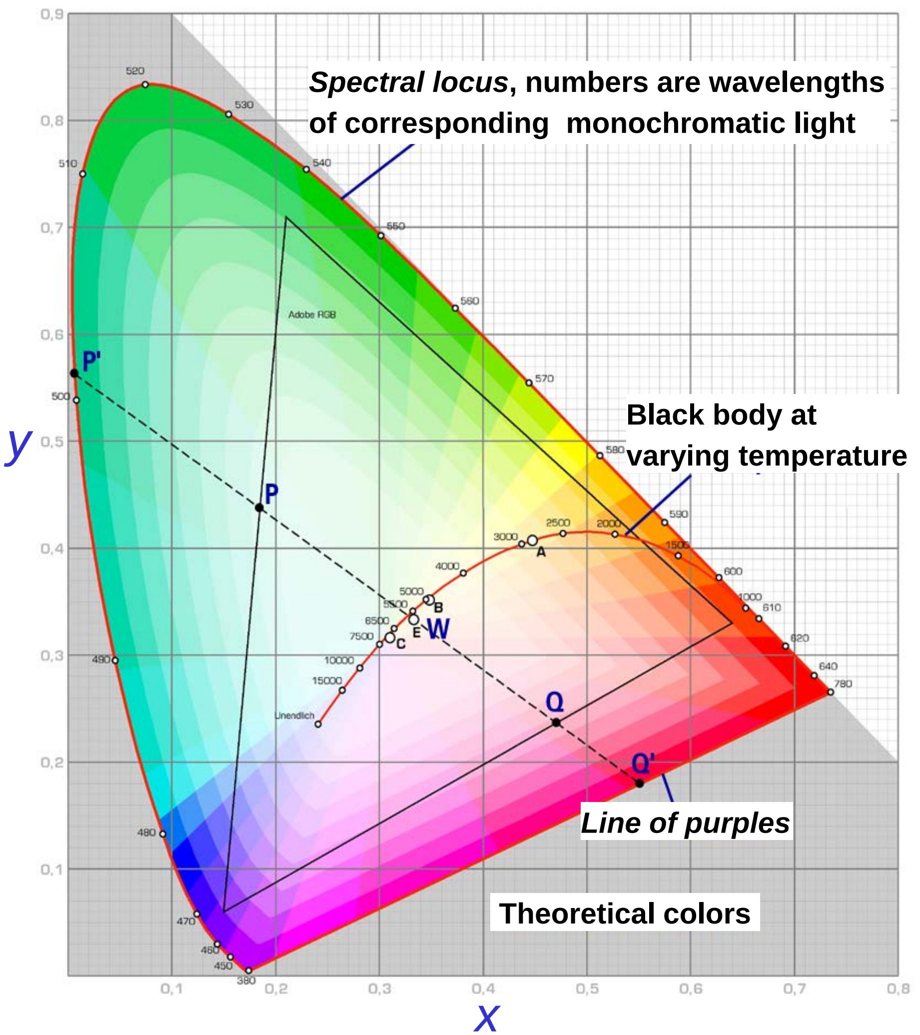
CIE chromaticity diagram

- *x* = red primary,
  y = green primary,
  z = 1–*x*–*y* = blue primary.
- Represents all visible chromaticities.
- “Pure” colors (i.e., with highest saturation) are on the *spectral locus*.
- *Line of purples* is the connecting line of the ends of the spectral locus, representing those perceivable colors of maximum saturation which are not spectral colors. Perception on the line of purples can not be caused by monochromatic light but a mixture of red and blue.



CIE chromaticity diagram

- *P* is the white point, defined by *x* = *y* = *z* = 1/3.
- Colors on the line from *W* to *P'* have the same chroma.
- *P'* and *Q'* are opponent colors.
- Real devices (projector, screen) can display only colors within the triangle, which arises from the definition of an RGB space. The triangle shown here is just an example.
- The colors used here are meant to provide some insight, they are not precisely the colors used in the experiments (otherwise, nothing should be visible outside the triangle using a projector or screen).



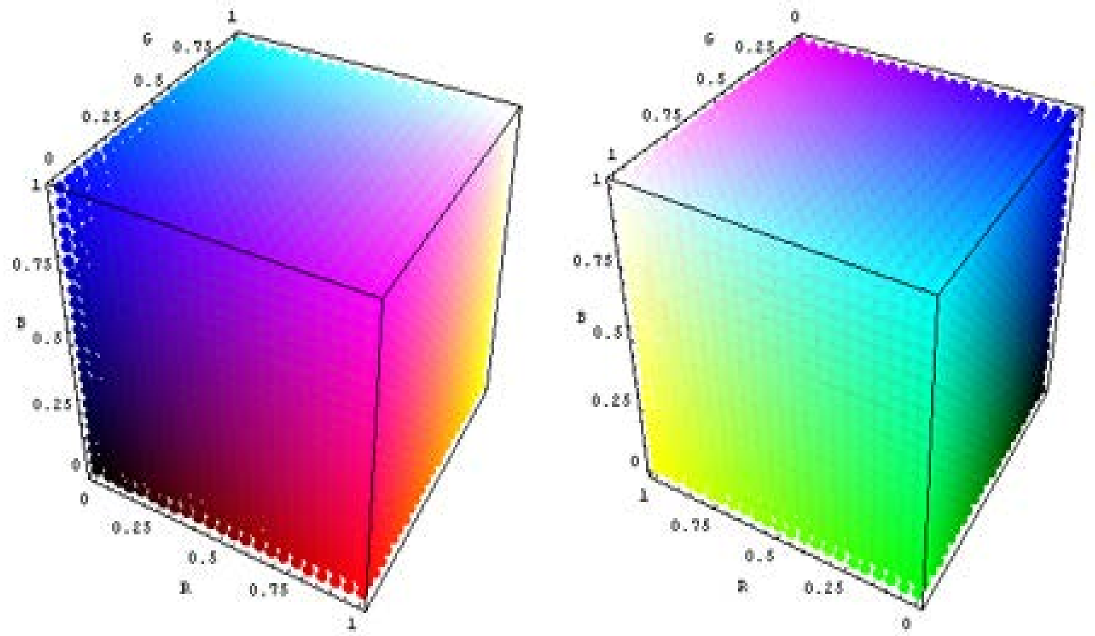
RGB color space

- Primary colors based on CIE-experiments
  - Red (700 nm)
  - Green (546.1 nm)
  - Blue (435.8 nm)
  - R,G values are zero at 435.8 nm, G,B values are zero at 700 nm, etc.

- Normalized with respect to energy:

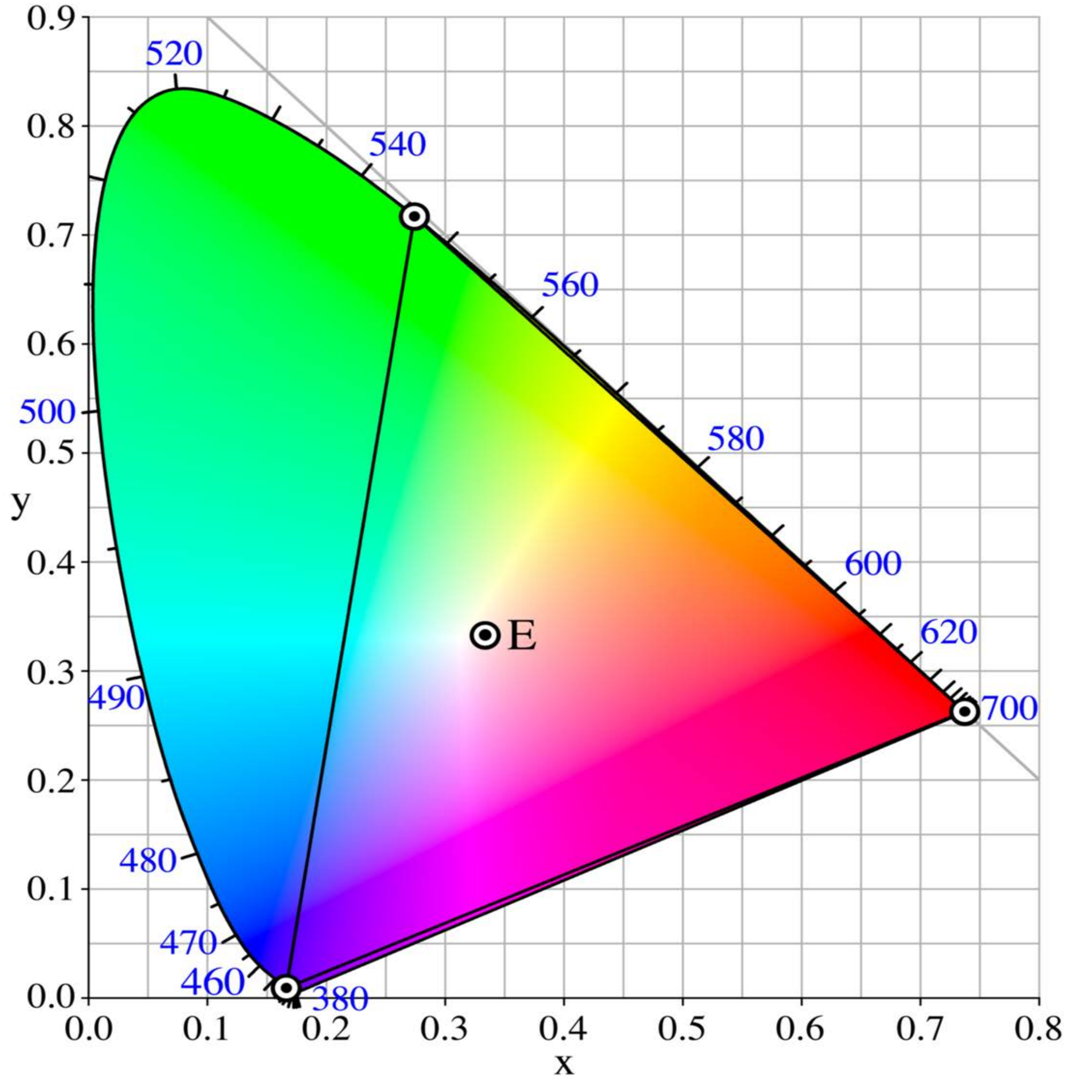
$$\int r(\lambda)\, d\lambda = \int g(\lambda)\, d\lambda = \int b(\lambda)\, d\lambda$$

Color spaces: RGB



RGB color cube (from different viewpoints)

RGB color space in CIE color space

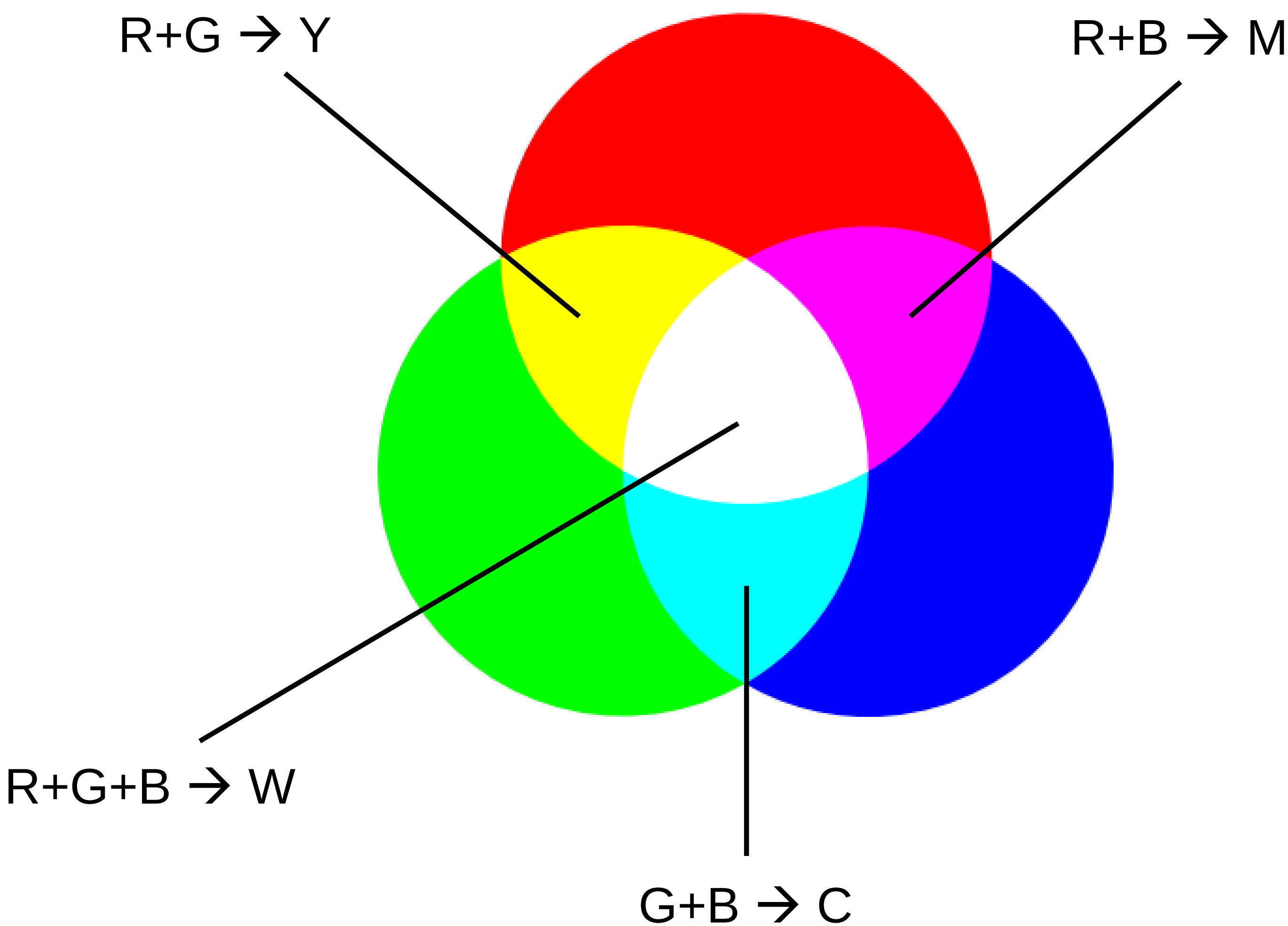


RGB color space

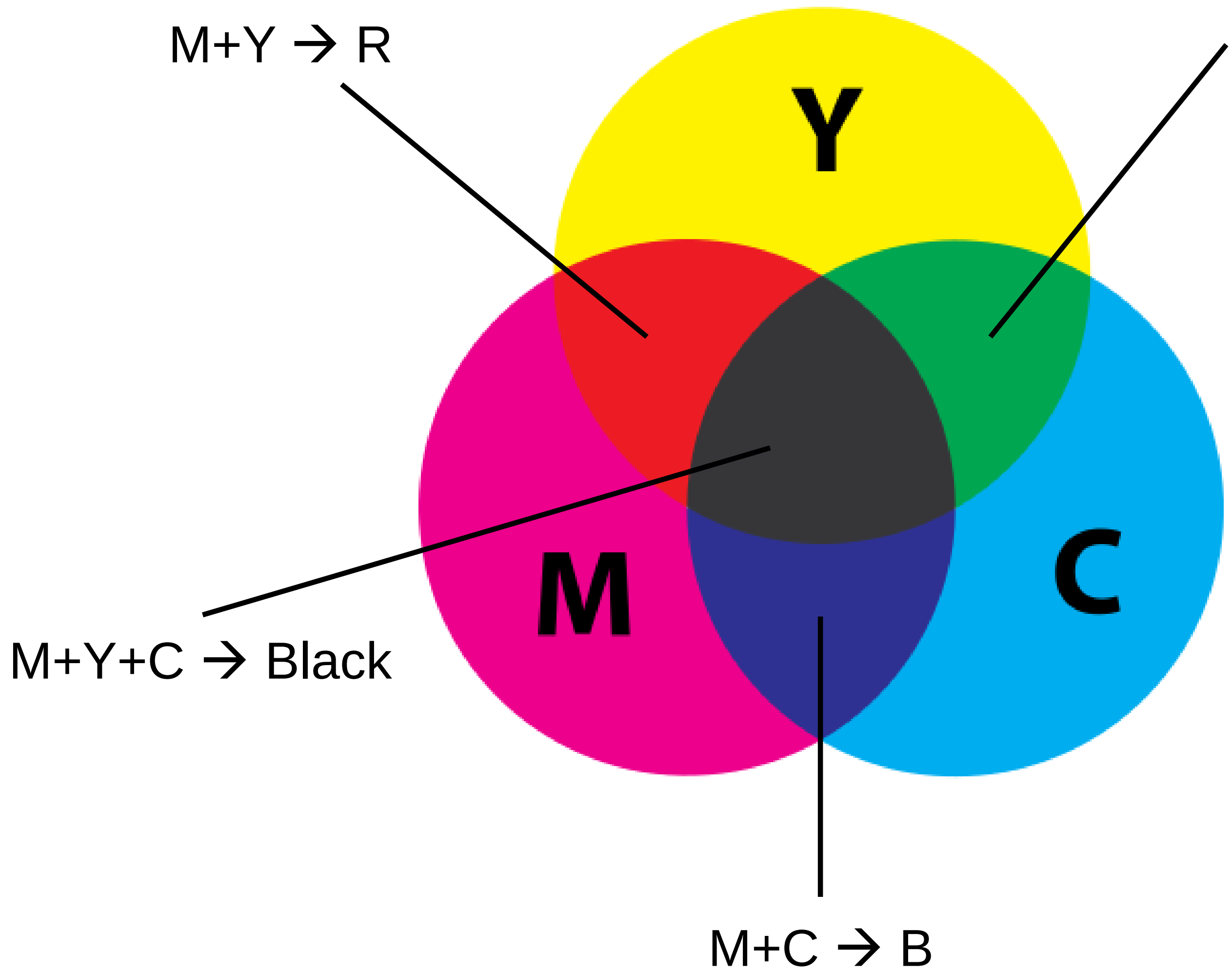
There are several RGB color spaces based on different primary colors for various applications:

NTSC-RGB:	For TV (USA)
EBU-RGB:	For TV (EU)
CCIR-RGB:	International Telecommunications Union
SMPTE-RGB:	Society of Motion Picture and Television Engineers
Adobe RGB:	Optimized to represent CMYK colors on a screen

Additive color mixing



Subtractive color mixing



Y+C → G

I.e.,

- Y absorbs the blue of C.
- C absorbs the red of Y.
- What remains is the green of Y and C.

CMYK color space

- RGB color space is well suited, e.g., for computer screens, because the pixels are self-luminous → additive color mixing
- But: RGB is not suited to represent colors of not self-luminous materials, e.g., printed color
- Color printing is based on subtractive mixing of primary colors:
  - Cyan (absorbs red)
  - Magenta (absorbs green)
  - Yellow (absorbs blue)
  - Key (black) (absorbs all)

CMYK color space

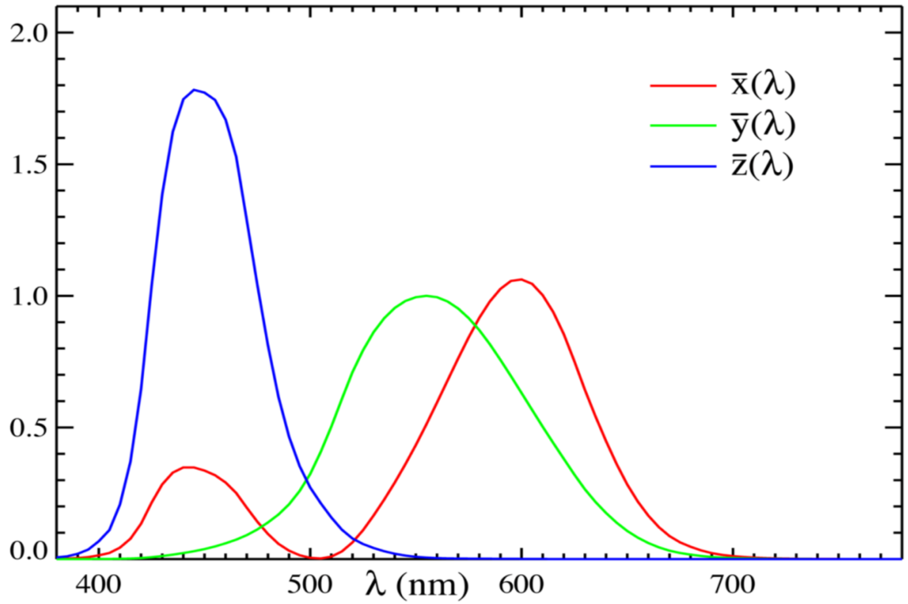
- CMY is complementary to RGB.
- Conversion (where R,G,B and C,M,Y have values $0 – 1$):

$$
\begin{aligned}
C &= 1 - R, & R &= 1 - C, \\
M &= 1 - G, & G &= 1 - M, \\
Y &= 1 - B, & B &= 1 - Y.
\end{aligned}
$$

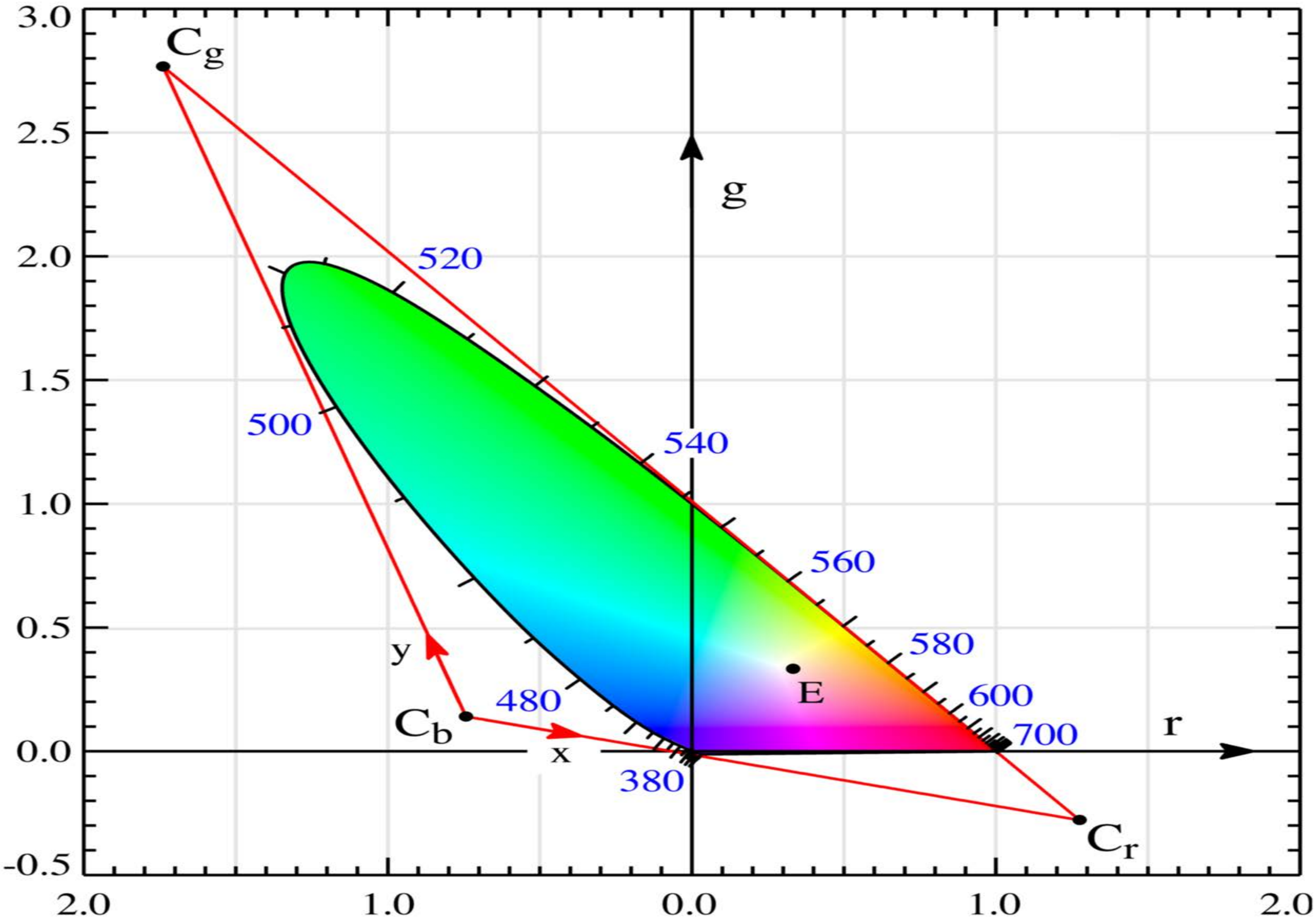
- In principle, K (black) is not necessary, because it can be mixed from C,M,Y.
- In practice, C,M,Y can only mix a dark blue, so black is used in printing as an additional color.
- Further, the above conversion is quite theoretical, since the resulting color impression heavily depends on the interaction of ink with paper.

CIE XYZ color space

- Color matching functions should be > 0 for all wavelengths, ensuring positive coordinates
- Primary colors normalized with respect to energy
- Brightness parameter should match human sensitivity
- XYZ is based on artificial primary colors which can not be represented.



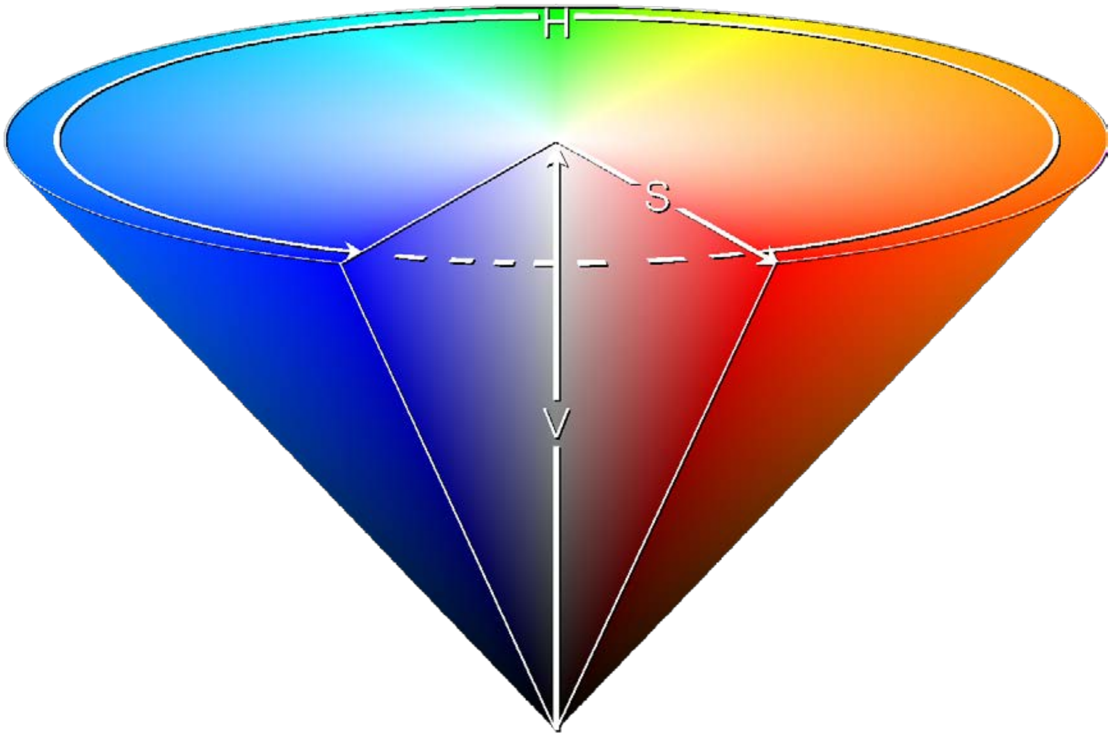
XYZ color space



HSV color space

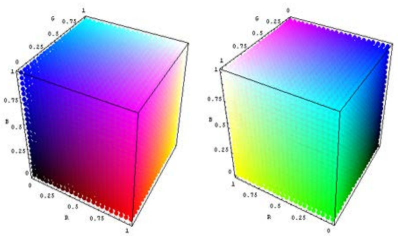
- Based on perception and verbal description of colors
- Colors can be mixed and described using HSV more easily than using primary colors
- Three values:
  - **H**ue = Angle on color circle
    - 0° red
    - 120° green
    - 240° blue
  - **S**aturation:
    - 0% no color
    - 100% pure color
  - **V**alue: Percentage of maximum brightness

HSV color space

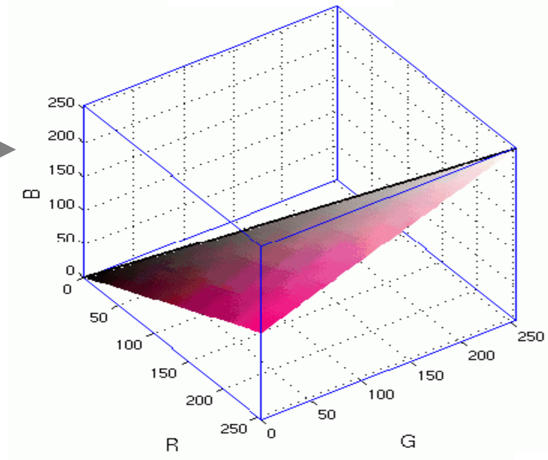


HSV color space as a cone (no embedding in RGB space)

HSV visualized in RGB space

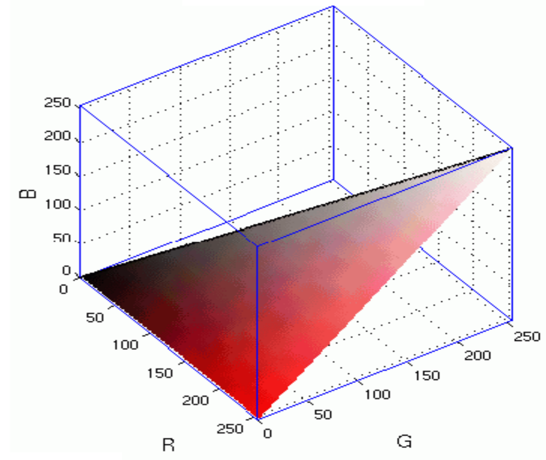


Hue 330°



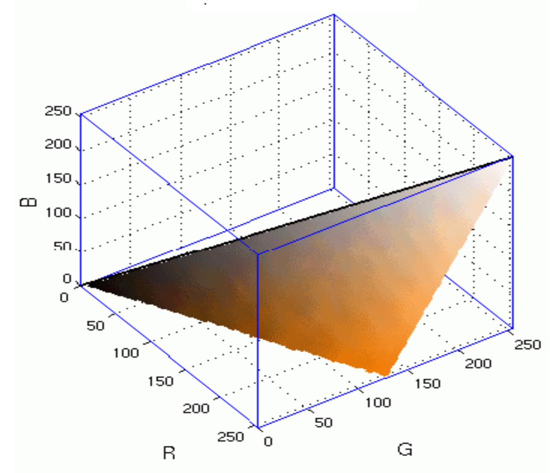
(a)

Hue 0°



(b)

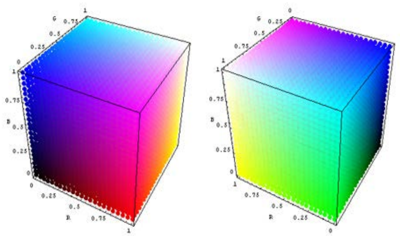
Hue 30°

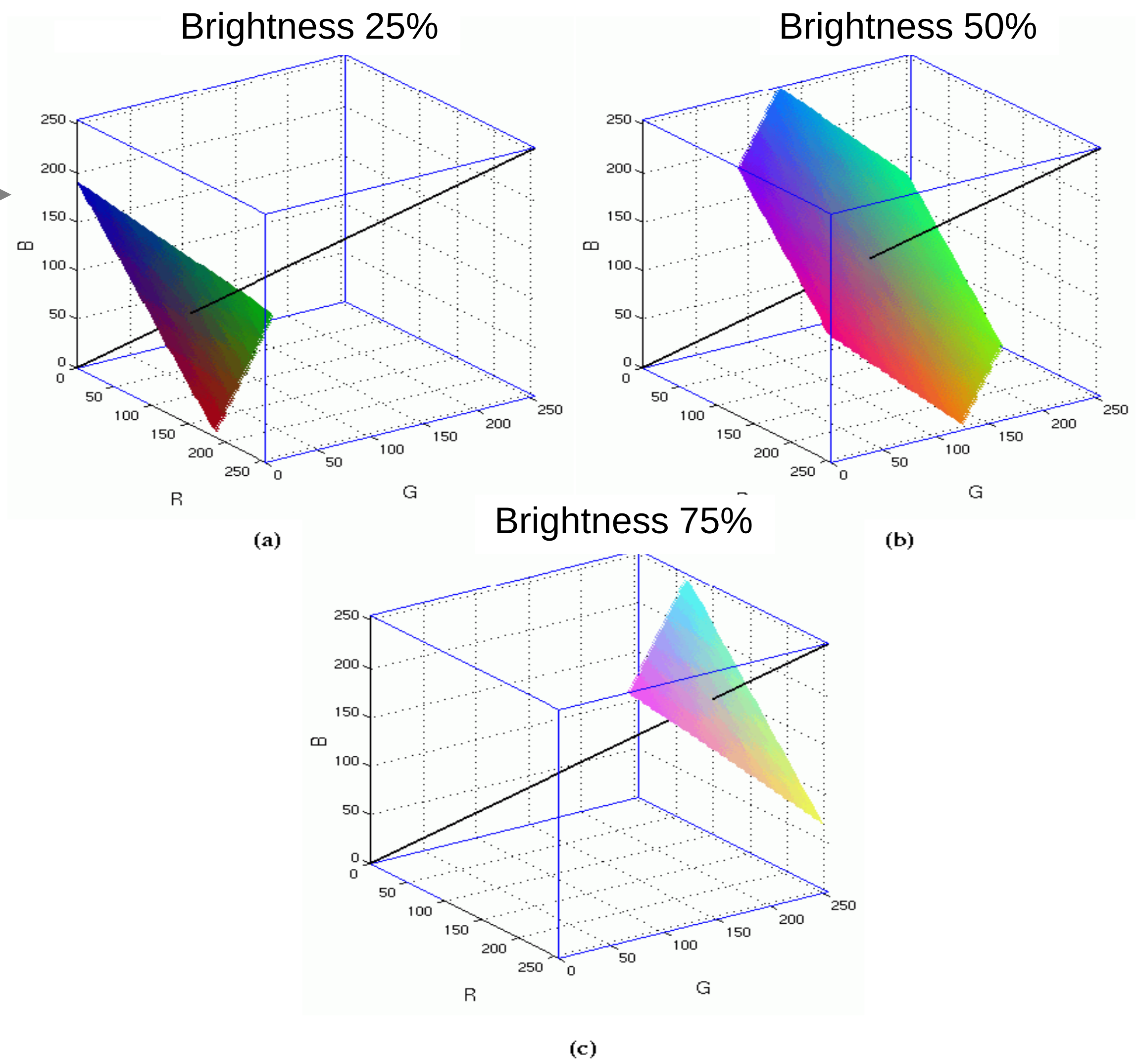


(c)

Planes of constant hue in RGB space

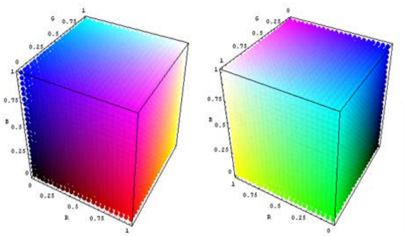
HSV visualized in RGB space

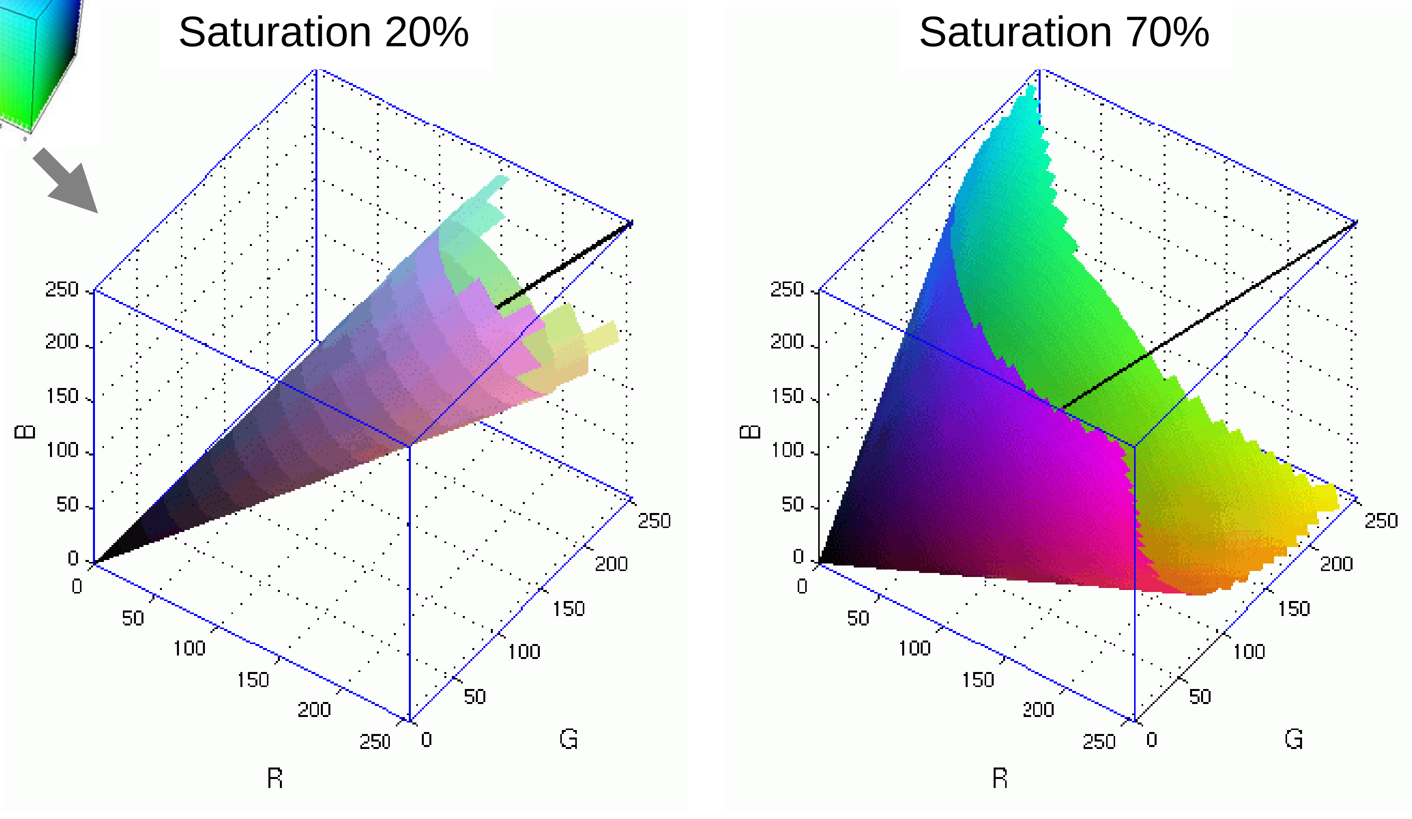




Planes of constant brightness in RGB space

HSV visualized in RGB space





(a) (b)

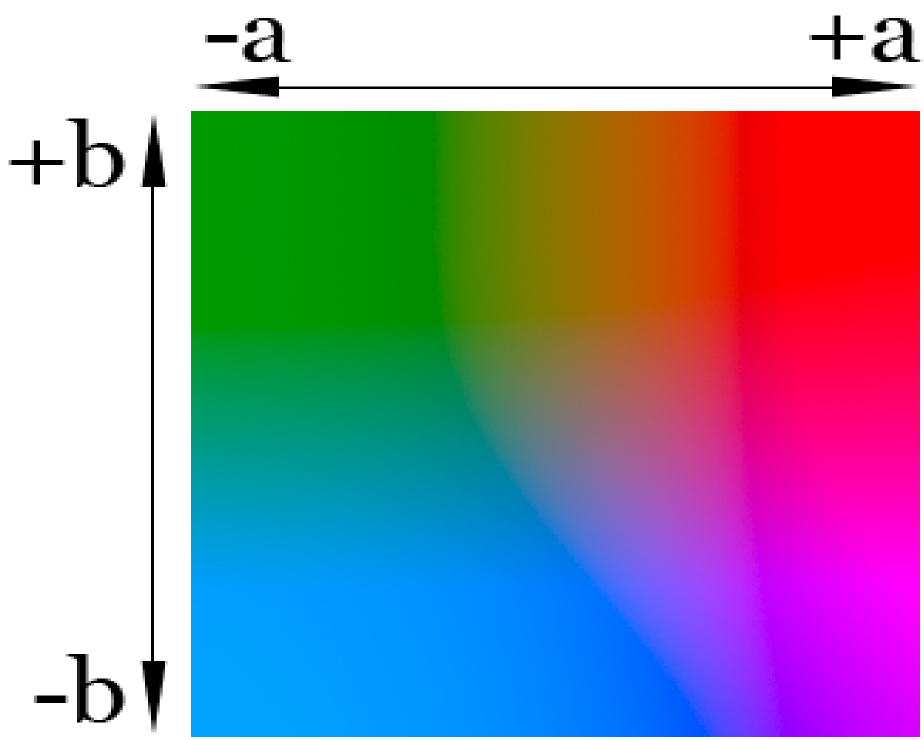
Cones of constant saturation in RGB space

Lab color space

- Based on XYZ color space
- Perceived color distance corresponds to euclidean distance in Lab space
- Comprises all possible colors, including colors that can not be displayed technically .
- Based on *opponent colors*
- Two color coordinates:
  - *a*: green-red
  - *b*: blue-yellow
  - *L*: Luminance
- Color space used by Adobe Photoshop and PostScript Level II.

Lab color space

For constant luminance *L*:



Use of color for CV

- How color is used:
  - Segmentation (= partition image into segments of constant color)
  - Color classification for fast detection of objects, e.g., skin color:
    - Classify color of each pixel as *skin color* / *other color*
    - Find regions of connected skin pixels
    - Further processing only for skin-regions (e.g., face recognition, hand gesture classification)
    - Works only under fixed illumination and in the absence of similar colors (e.g., wood)
  - Classification of regions or even entire images using color histograms (# pixels of each color). Use:
    - Object recognition
    - Image retrieval (search in image databases)

Use of color for CV

- Where color is not in use:
  - Shape recognition
  - in particular, joint recognition of color and shape
- Why color is not used for shape recognition:
  - Humans have better resolution for brightness than for color. Thus technical systems provide less resolution for color, e.g., JPEG .
  - Coloring book theory: Brain processes color and shape along different pathways. First, shape is detected from brightness, and color is filled in by later processing steps. So color is only assigned to already recognized shape. For this reason, technical vision is organized in the same way.
  - Because that’s how we do things.

Use of color for CV

- Why color could be used for shape recognition:
  - No technical reason to treat wavelengths differently or combinations thereof.
  - Statistics of natural images (recorded by standard cameras) show color contributes to structure with about 40%.
  - Coloring book theory questionable: E.g., there are *spatio-chromatic* receptive fields in cortex.

Summary

- Light sources yield continuous spectra or line spectra
- Material properties cause reflection of some wavelengths and absorption or transmission of others
- Eye reduces spectrum to three color stimuli
- CIE conducted experiments to derive color spaces
- Important color spaces:
  - RGB (screen)
  - CMYK (printer)
  - HSV (intuitive interpretation of components)
  - Lab (intuitive interpretation of similarities / distances)
- In CV, color is so far mainly used for low level processing such as segmentation, color classification and color histograms

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