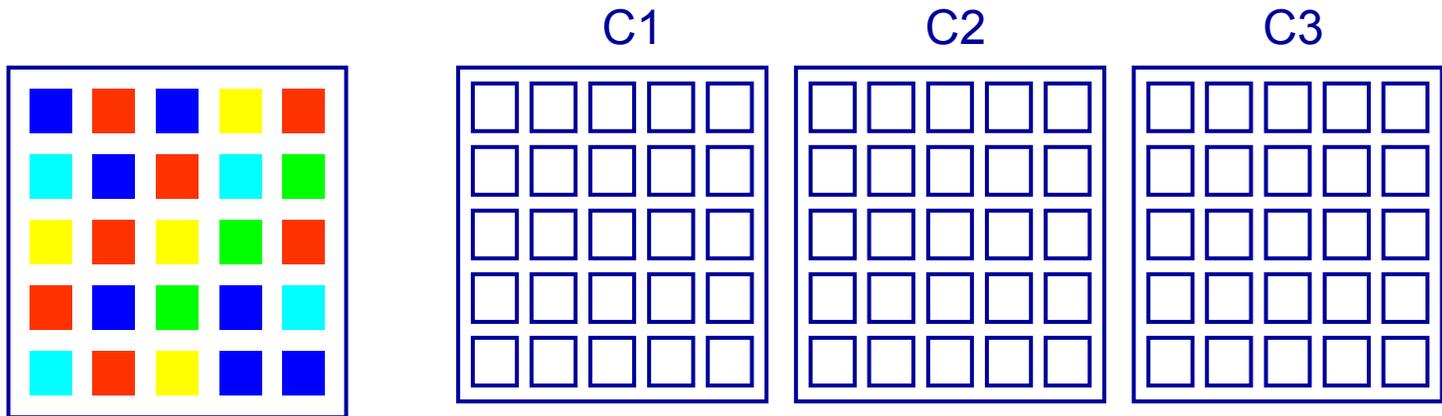


Color imaging

Color images



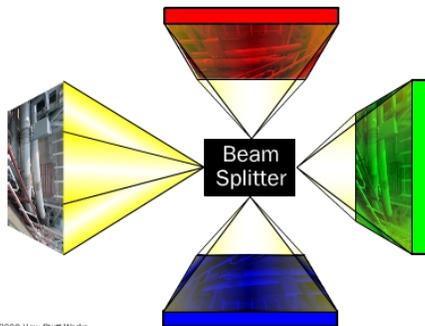
- Each colored pixel corresponds to a *vector* of three values $\{C1, C2, C3\}$
- The characteristics of the components depend on the chosen *colorspace* (RGB, YUV, CIE Lab,..)

Digital Color Images

- $x_R[n_1, n_2]$

$$x_G[n_1, n_2]$$

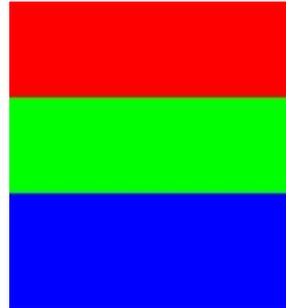
$$x_B[n_1, n_2]$$



© 2000 How Stuff Works



Color channels



Red



Green



Blue

Color channels



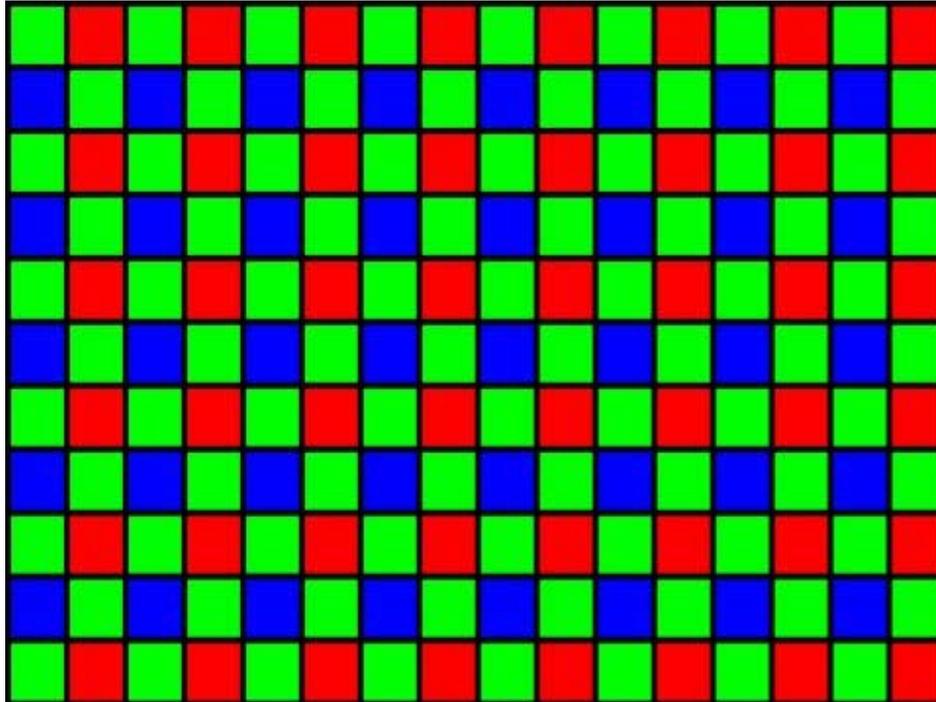
Red

Green

Blue



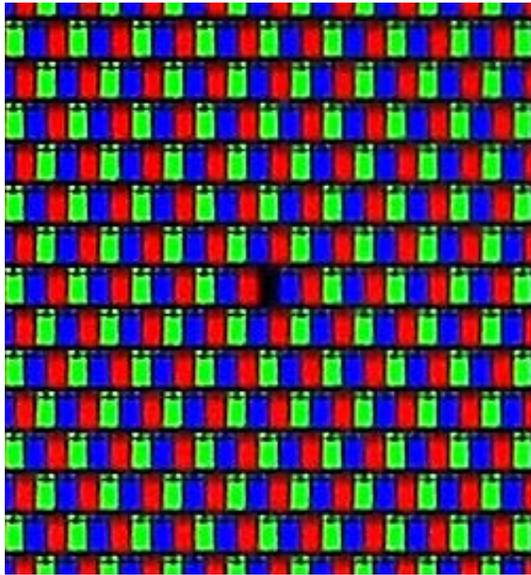
Bayer matrix



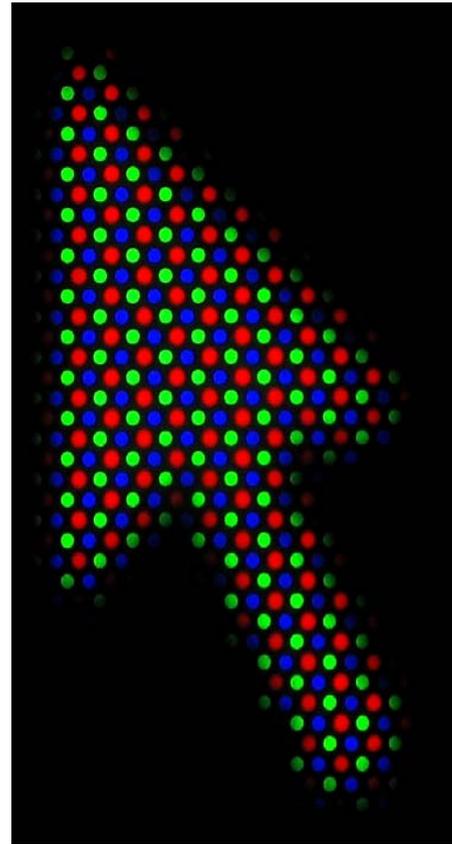
Typical sensor topology in CCD devices. The green is twice as numerous as red and blue.

Displays

LCD



CRT



Color imaging

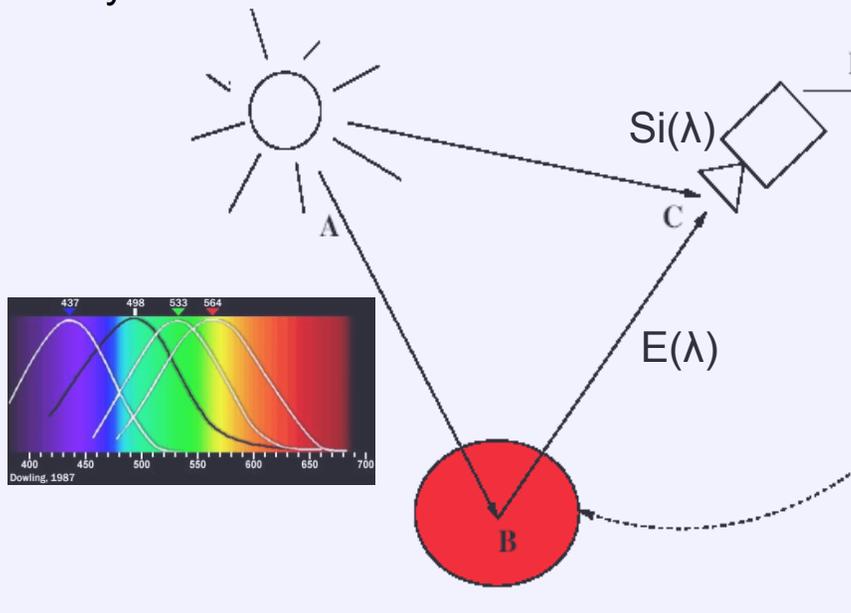
- Color reproduction
 - Printing, rendering
- Digital photography
 - High dynamic range images
 - Mosaicking
 - Compensation for differences in illuminant (CAT: chromatic adaptation transforms)
- Post-processing
 - Image enhancement
- Coding
 - Quantization based on color CFSs (contrast sensitivity function)
 - Downsampling of chromatic channels with respect to luminance

Color science

- Color vision
 - *Seeing* colors
 - Foundations of color vision
 - Trichromatic model
- Color naming
 - *Attaching labels* to colors
- Colorimetry & Photometry
 - *Measuring* colors: radiometric & photometric units
- Applications
 - Image rendering, cross-media color reproduction, image analysis, feature extraction, image classification, data mining...

What is color? qui

Physics

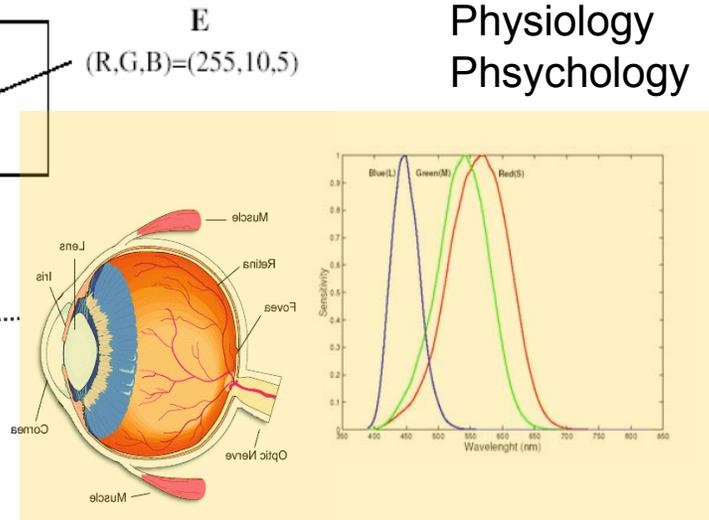


$$C_i = \int_{\lambda} E(\lambda) S_i(\lambda) d\lambda$$

$S_i(\lambda)$: sensitivity of the i^{th} sensor

$E(\lambda)$: Spectral Power Distribution (SPD) of the diffused light

Physiology
Psychology

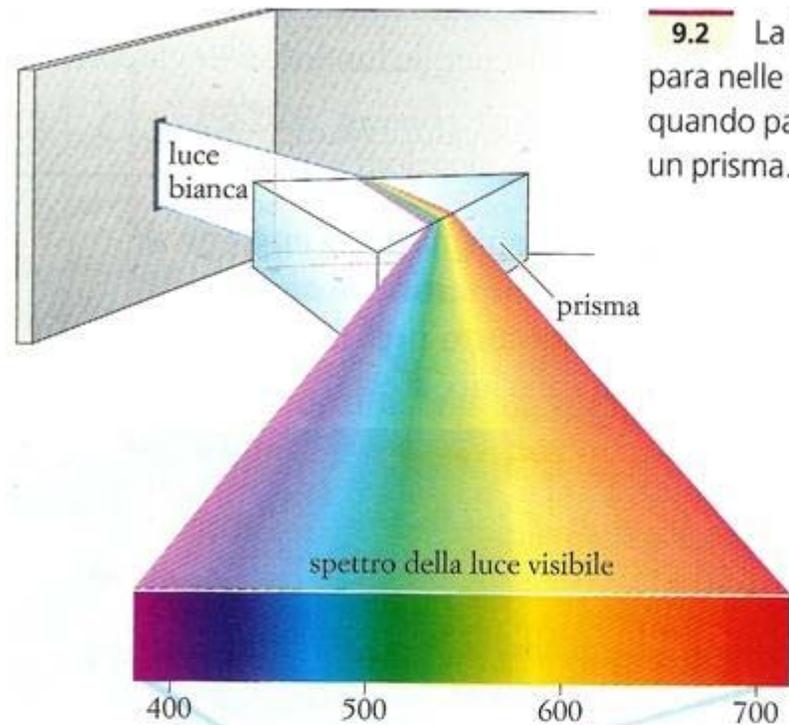


Color
representation

Modeling

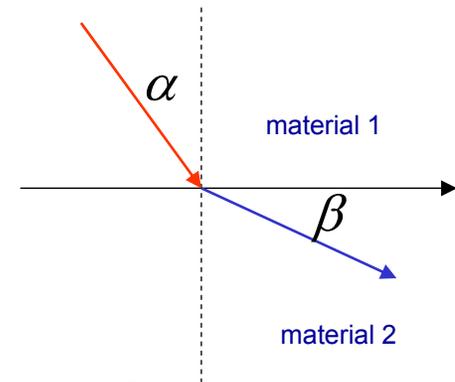
Color
perception

Newton's prism

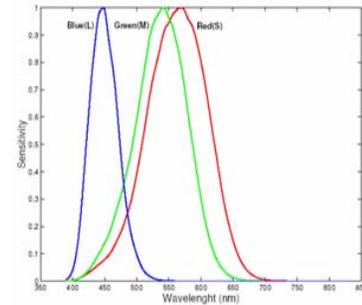
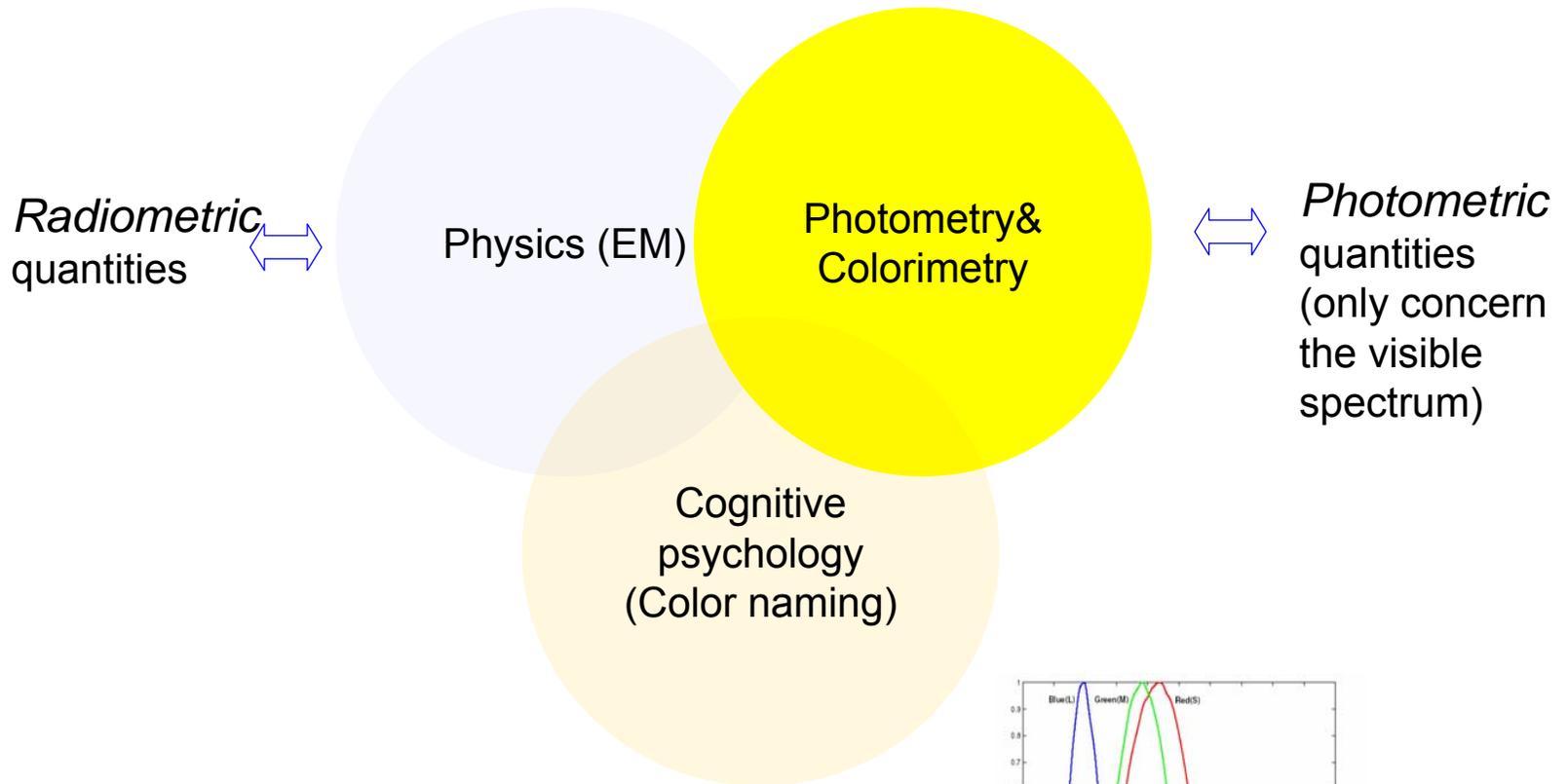


9.2 La luce bianca si separa nelle sue componenti quando passa attraverso un prisma.

$$\sin \alpha = n(\lambda) \sin \{\beta(\lambda)\}$$

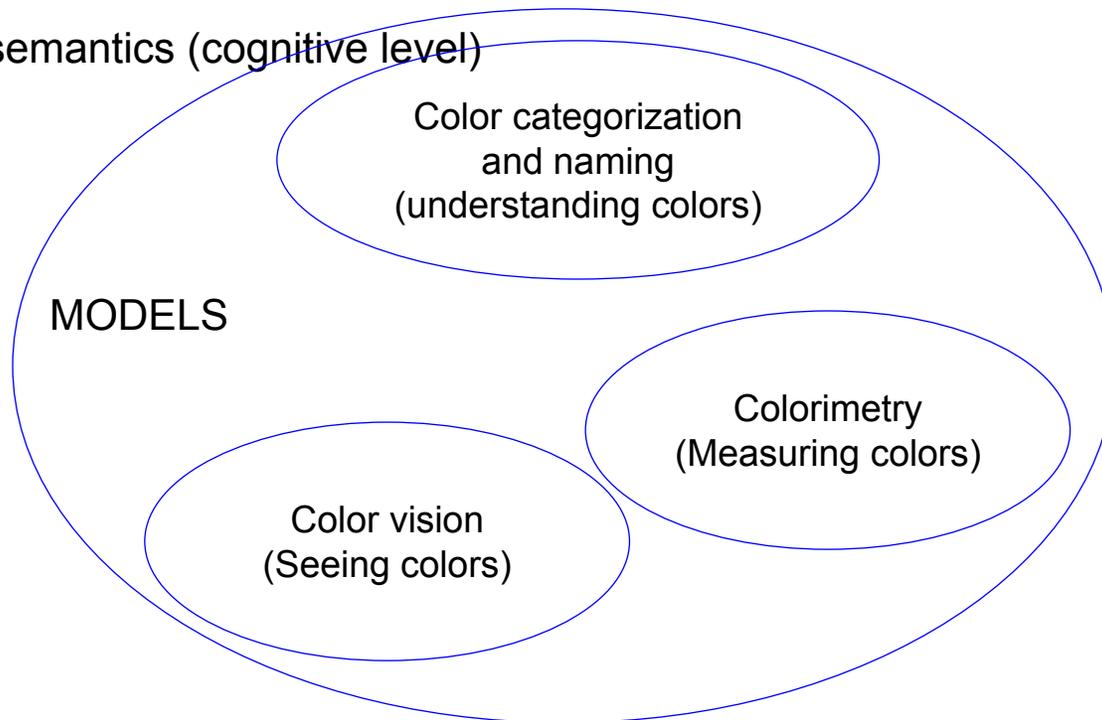


What is color?

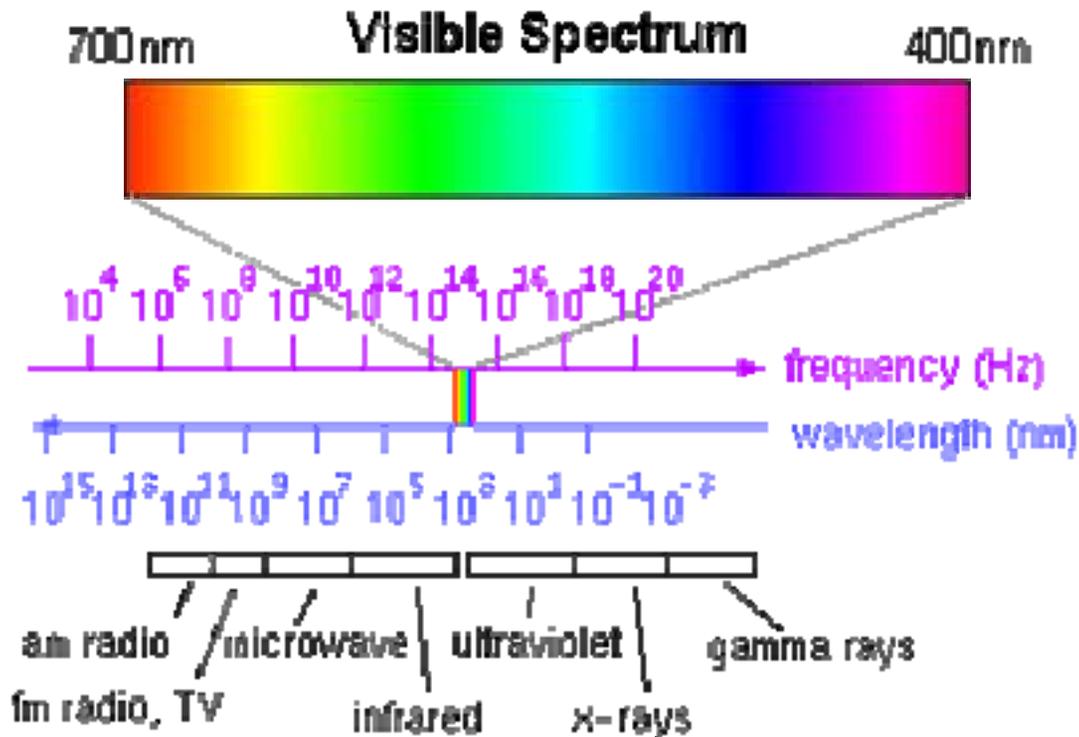


Color

- Human vision
 - Color encoding (receptor level)
 - Color perception (post-receptoral level)
 - Color semantics (cognitive level)
- Colorimetry
 - Spectral properties of radiation
 - Physical properties of materials

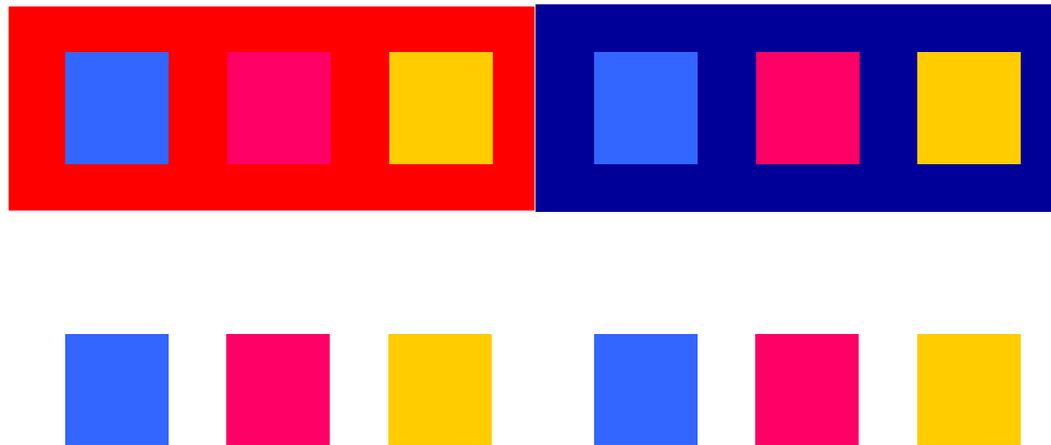


The physical perspective



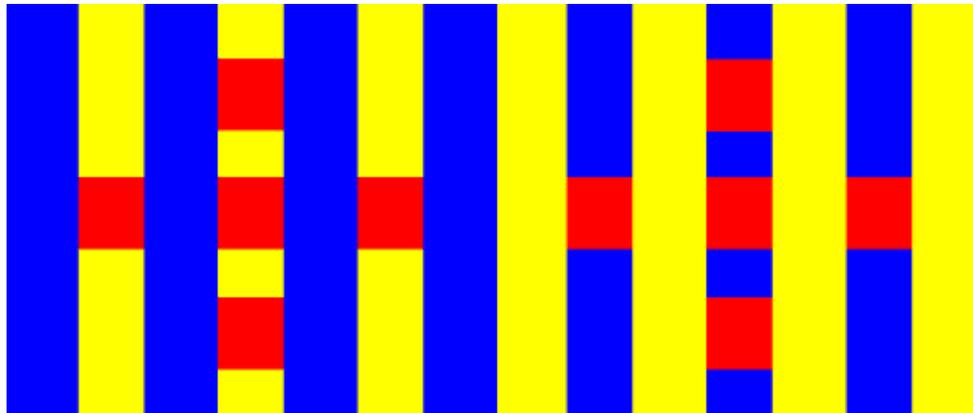
The perceptual perspective

Simultaneous contrast



Color

- Chromatic induction



Basic quantities

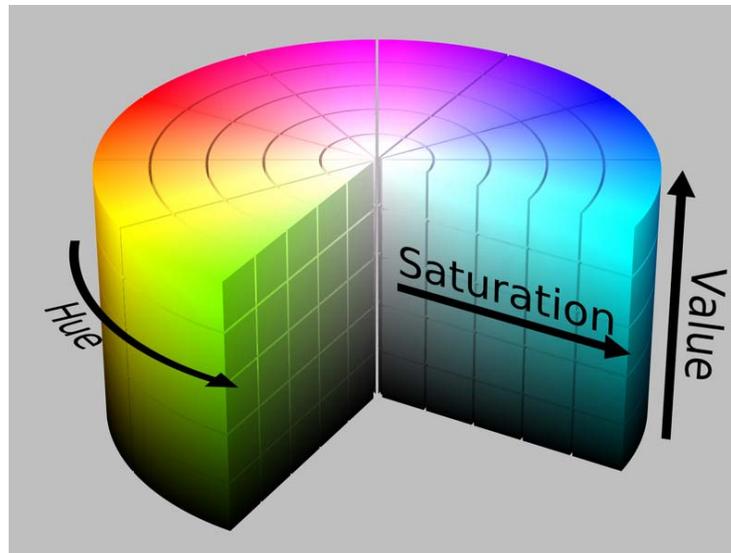
- Radiance: total amount of energy that flows from the light source
 - measured in Watts [W] by a radiometer
- Luminance: measure of the amount of light emitted by the source that a person *perceives*
 - measured in lumens [lm]
 - it is assessed by “weighting” the light emitted by the source by the absorption curves of the “standard subject”
- Brightness: psychological quantity that is impossible to measure “objectively”. It embodies the achromatic notion of “intensity”

Color models

- A color model is a 3D *unique* representation of a color
- There are different color models and the use of one over the other is problem oriented. For instance
 - RGB color model is used in hardware applications like PC monitors, cameras and scanners
 - CMY color model is used in color printers
 - YIQ model in television broadcast
 - In color image manipulation the two models widely used are HSI and HSV
 - *Uniform* color models (CIELAB, CIELUV) are used in color imaging
- [Gonzalez Chapter 6]

Color models

- User-oriented color models
 - Emphasize the intuitive color notions of brightness, hue and saturation
 - HSV (Hue, saturation, Value)
 - HSI (Hue, Saturation, Intensity)
 - HSL (Hue, Saturation, Lightness)



Color models

- Device-oriented color models
 - The color representation depends on the device.
- Concerns both acquisition and display devices
 - Acquisition
 - The value of the color numerical descriptors depend on the spectral sensitivity of the camera sensors
 - Display
 - A color with given numerical descriptors appears different if displayed on another device or if the set-up changes
 - In RGB for instance, the R,G and B components depend on the chosen red, green and blue primaries as well as on the reference white
 - Amounts of ink expressed in CMYK or digitized video voltages expressed in RGB
 - RGB, Y'CbCr, Y'UV, CMY, CMYK
 - Towards device independence: sRGB

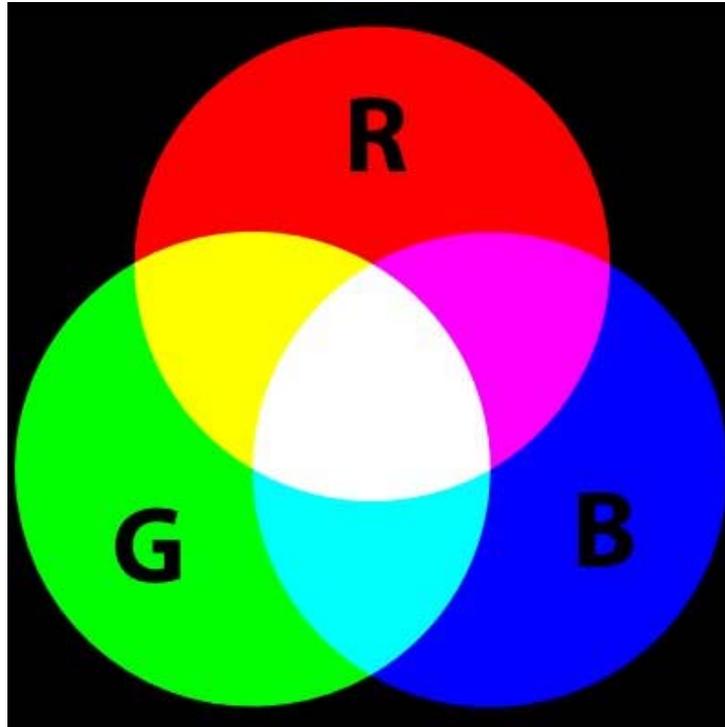
Color models

- Colorimetric color models
 - Based on the principles of trichromacy
 - Allow to predict if two colors match in appearance in given observation conditions
 - CIE XYZ
 - Perceptually uniform color models (CIELAB, CIELUV)

Device-oriented color models

RGB color model

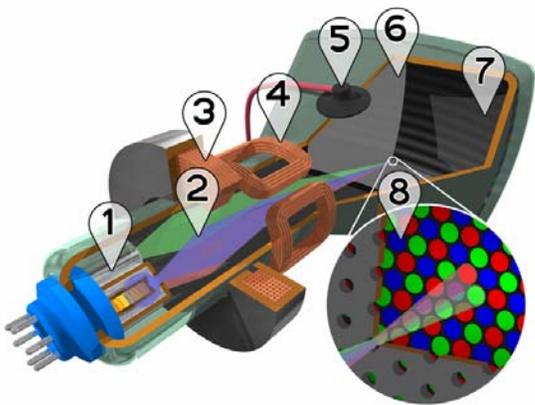
- Additive color model
 - The additive reproduction process usually uses red, green and blue light to produce the other colors



RGB displays

- Each pixel on the screen is built by driving three small and very close but still separated RGB light sources.
- At common viewing distance, the separate sources are indistinguishable, which tricks the eye to see a given solid color.
- All the pixels together arranged in the rectangular screen surface conforms the color image.

CRT



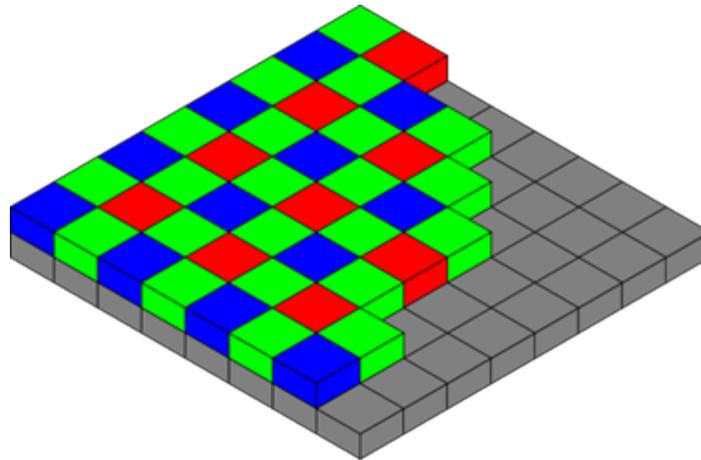
LCD



Close-up of red, green, and blue LEDs that form a single pixel in a large scale LED screen

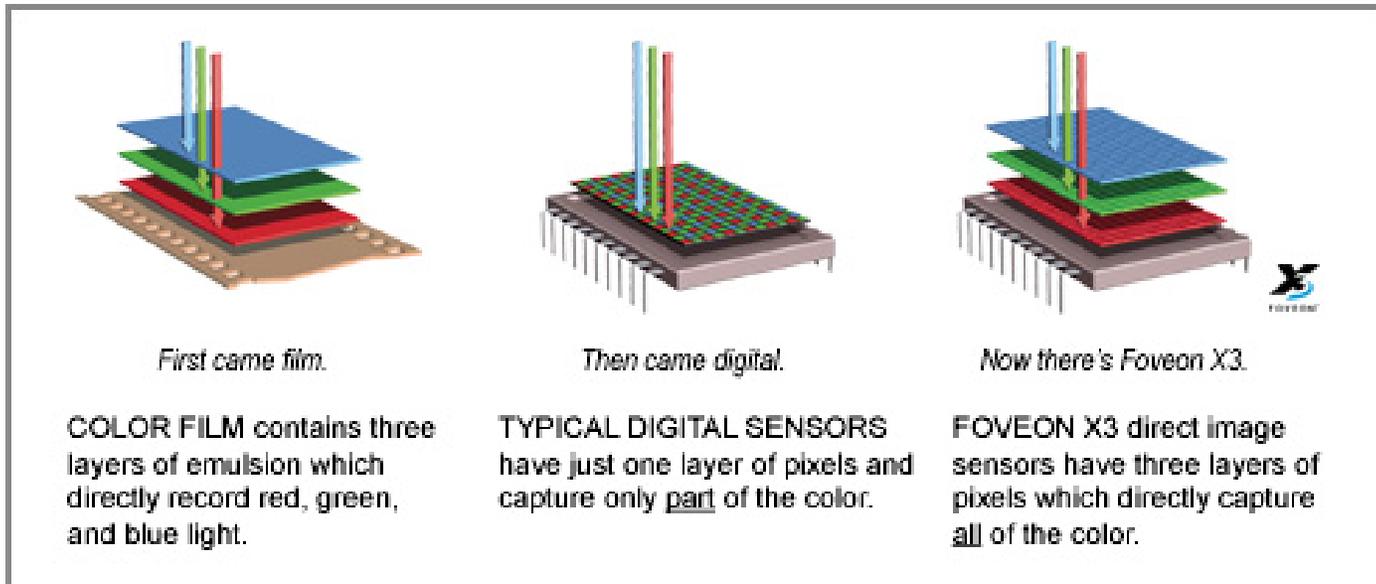
RGB digital cameras

- CCD camera sensor with Bayer array
 - Only one color channel is recorded in each physical location (pixel)
 - Twice as many green sensors than red and blue
 - Demosaicing is needed to recover full size images for the three color channels



RGB digital cameras

- CCD cameras with full color sensors
 - The three color channels are recorded in each physical location (pixel)

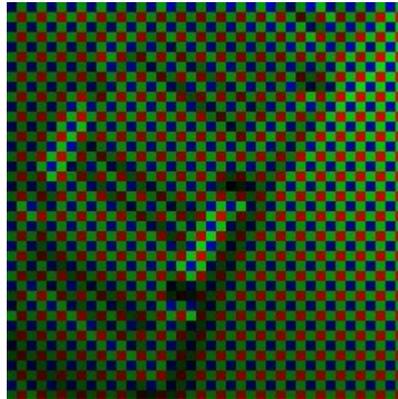


RGB digital cameras

Full color sensors



Image as seen through a Bayer sensor

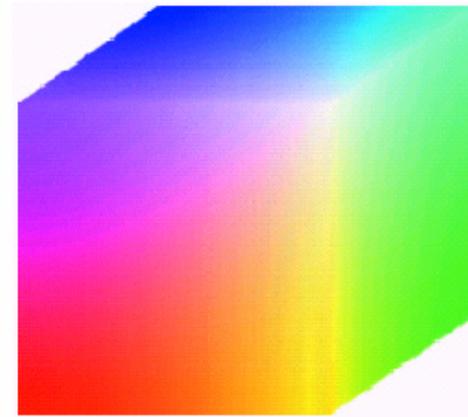
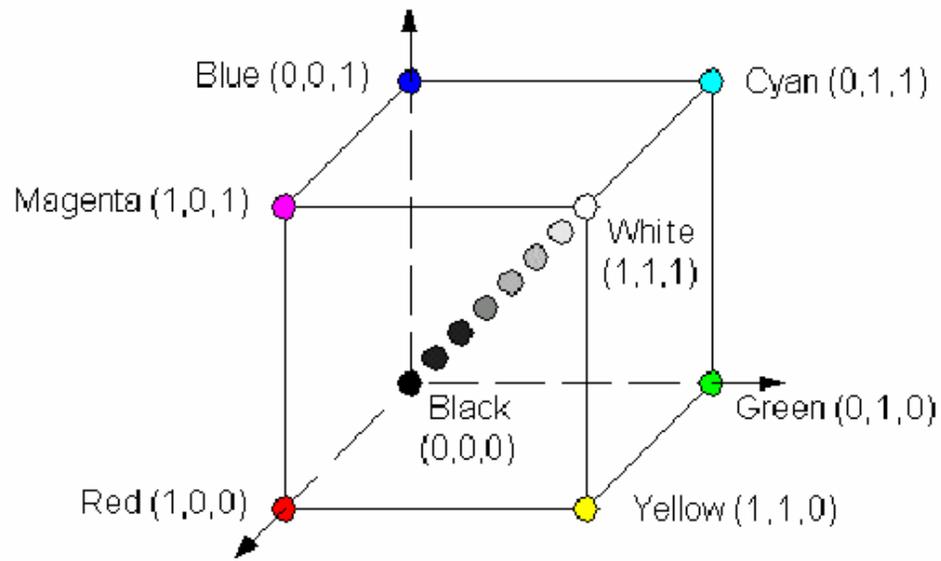


Reconstructed image after demosaicing



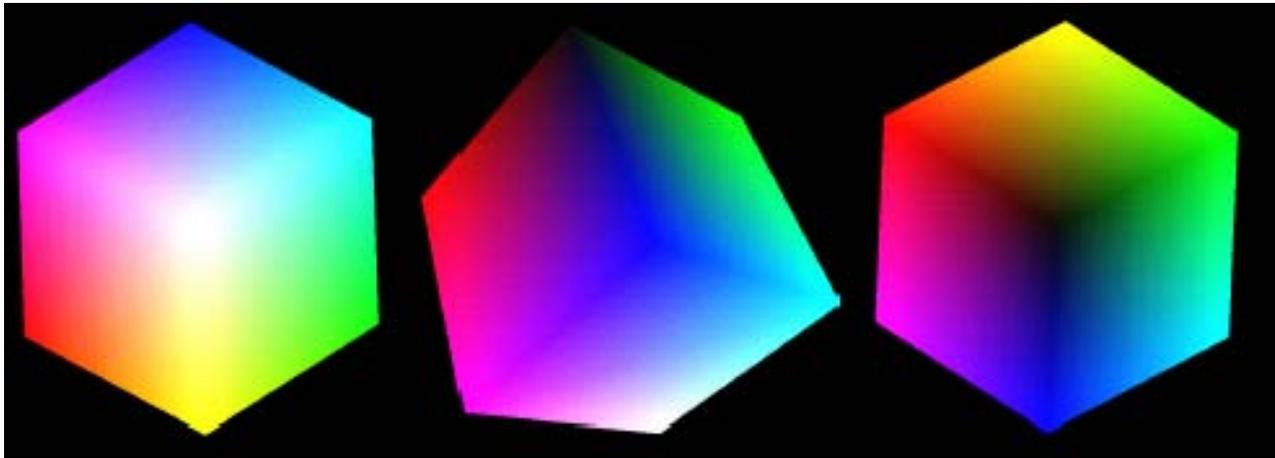
JPEG compression was added to the images

RGB model

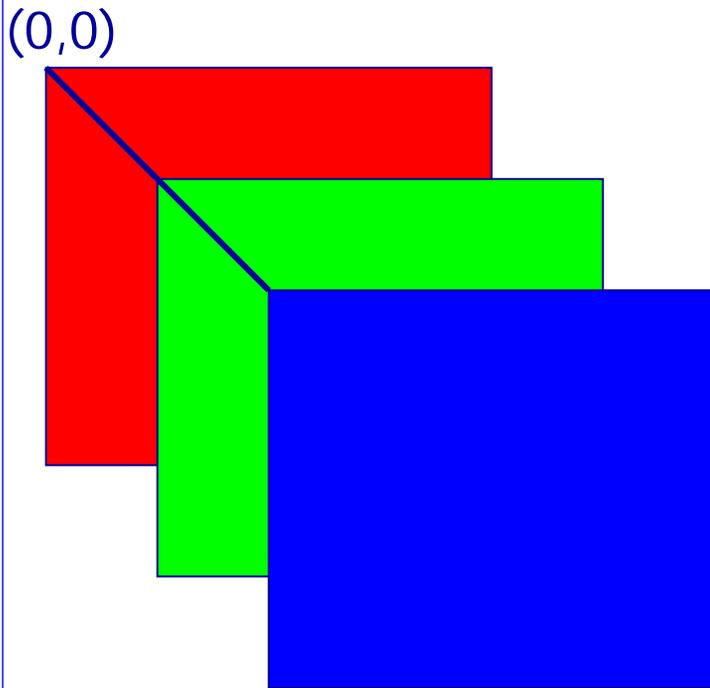


RGB model

- Normalized values in $[0,1]$ (chromaticity coordinates) may be convenient for some applications
- For a given device, the set of manageable colors lies inside the RGB cube



RGB model



A single pixel consists of three components.

| | | |
|-----|-----|----|
| 128 | 251 | 60 |
|-----|-----|----|



Final pixel in the image

If R,G, and B are represented with 8 bits (24-bit RGB image), the total number of colors is $256^3=16,777,216$

Exemple RGB

Original Image



G-Component



R-Component



B-Component



False colors are used to represent the color channels, which all consists of gray values in the range [0,255]

Color channels



Red

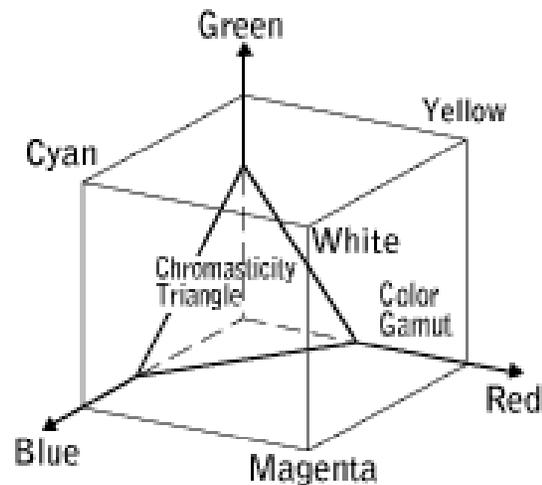
Green

Blue



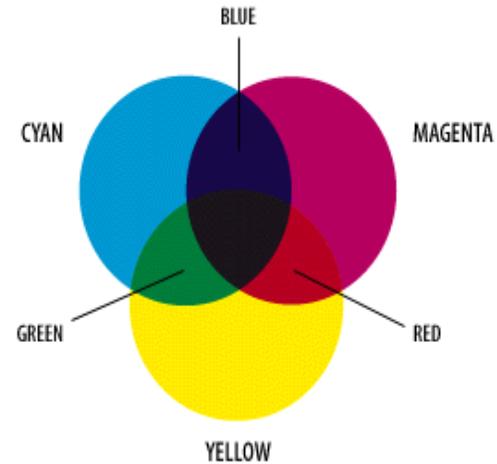
Device-oriented color models: CYM(K)

- Cyan, Yellow and Magenta are the “secondary” colors of light or the “primary” colors of pigments
- Model of “color subtraction”
- Used in printing devices

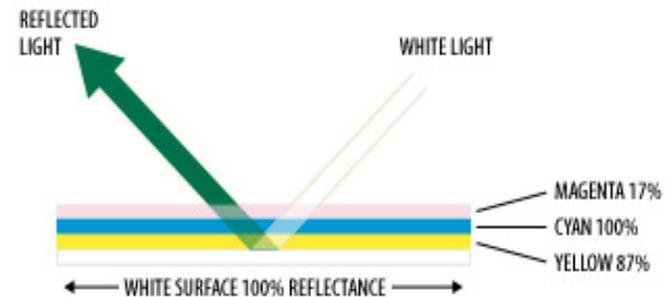


CMY(K)

- *Color subtraction*
 - Cyan, Magenta, Yellow filters
 - The Y filter removes B and transmits the R and G
 - The M filter removes G and transmits R and B
 - The C filter removes R and transmits G and B
 - Adjusting the transparency of these filters the amounts of R, G and B can be controlled



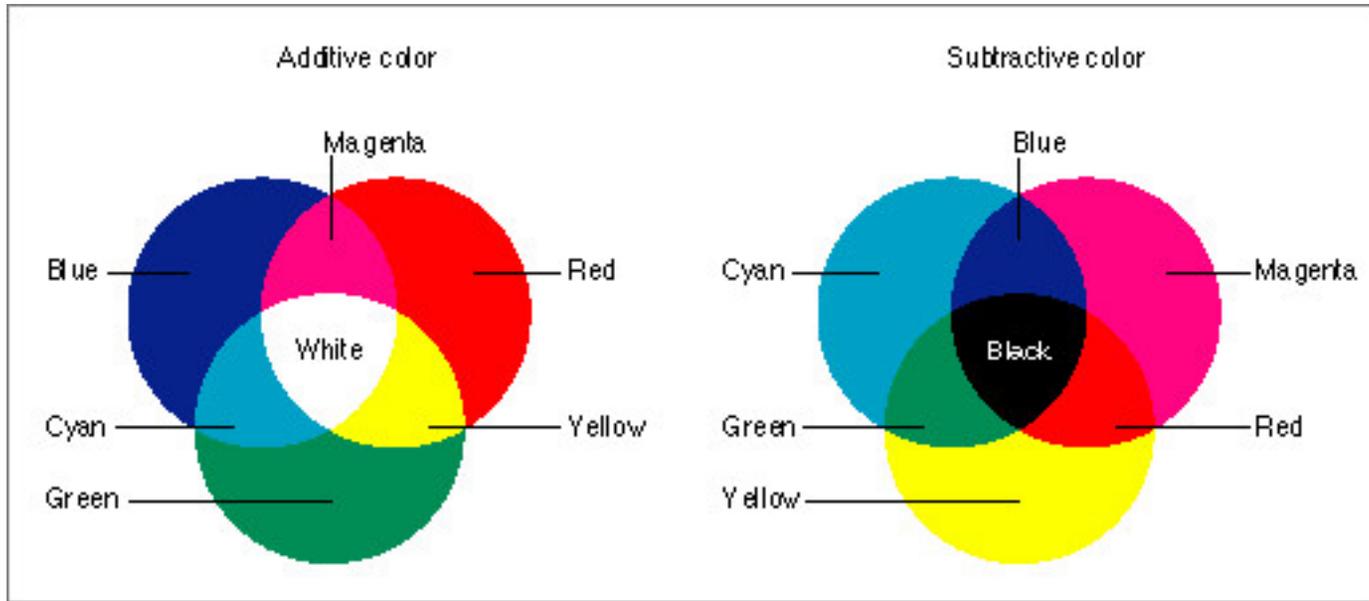
cyan=white-red
magenta=white-green
yellow=white-blue



CMY model

- CMY (Cyan, Magenta, Yellow)
- Used in printing devices
- Subtractive color synthesis
- CMYK: adding the black ink
 - Equal amounts of C,M and Y should produce black, but in practice a dark brown results. A real black ink is then added to the printer

CYM(K)



- cyan (C) absorbs red
- magenta (M) absorbs green
- yellow (Y) absorbs blue

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

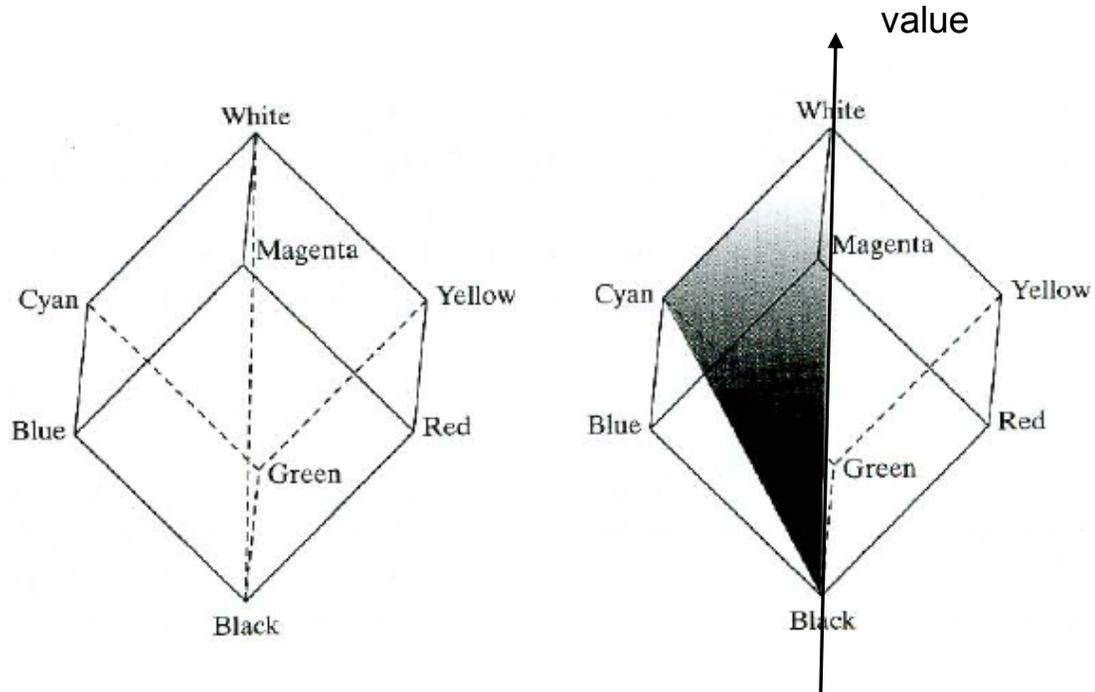
CMY(K) model

- Red, Green, Blue are the primary colors of light
- Cyan, Magenta, Yellow are the
 - Secondary colors of light
 - Primary colors of pigments
- When a cyan-colored object is illuminated with white light, no red light will be reflected from its surface! *Cyan subtracts red!*
- *The pigment when illuminated with white light absorbs its complementary color and reflects the others*

User-oriented CM

- Color is encoded in a way that is most “natural” to humans for describing colors
- Based on the decoupling of chromatic and achromatic information
 - One of the three axis represents the “value” or “intensity on the black-white axis” of the color
 - “dark-” or “bright-” ness of the color
 - The other two independent variables represent
 - Hue, which “qualifies” the color as belonging to a category (ex: red, green)
 - Saturation, or colorfulness, expressing how far the color is from neutral gray
 - Can be thought of as a deformation of the RGB cube

User-oriented CM



User-oriented CM

- HSV (Hue, Saturation, and Value). Sometimes variations include HSB (Brightness), HSL (Lightness/Luminosity), HSI (Intensity)
 - The *hue* of a color places it on the color wheel where the color spectrum (rainbow) is evenly spaced
 - The *saturation or chroma* of a hue defines its intensity
 - Decreasing the saturation via a contrast control adds gray.
 - The value of a hue defines how bright or dark a color is
- They all are effectively the RGB space twisted so that the *neutral diagonal becomes the lightness axis*, the *saturation the distance from the central lightness axis* and the *hue the position around the center*.
- The only difference between these models is the measurement of saturation, or the strength of the colour

HSI (HSV, HSL) Color Space

- Recall:
 - **Hue** is color attribute that describes a pure color
 - **Saturation** gives the measure to which degree the pure color is diluted by white light.
- 1. Intensity (Value or Lightness) component I (V,L), is decoupled from the chromaticity information!
- 2. Hue and saturation can be accessed independently from illumination

HSI

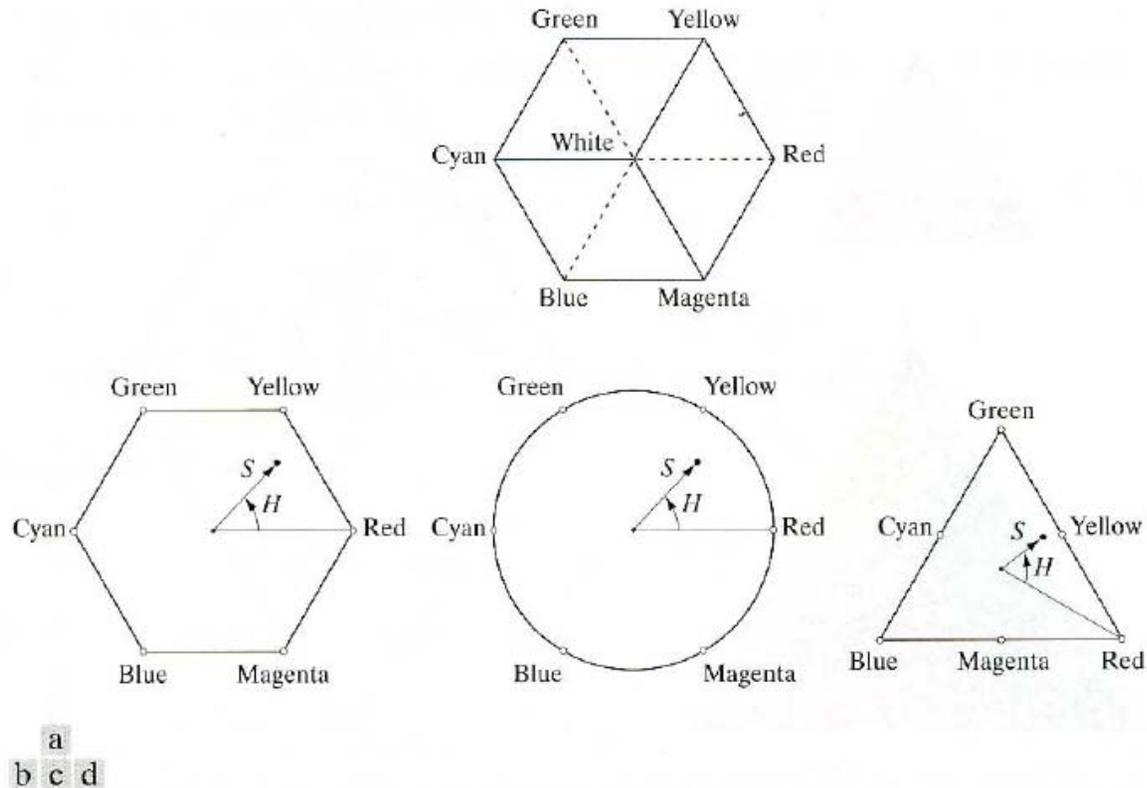
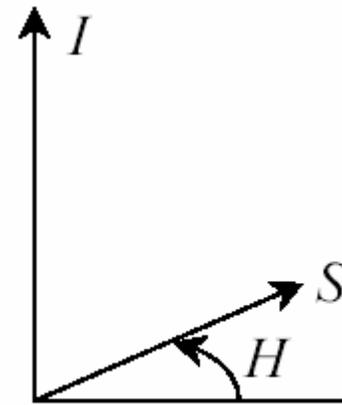


FIGURE 6.13 Hue and saturation in the HSI color model. The dot is an arbitrary color point. The angle from the red axis gives the hue, and the length of the vector is the saturation. The intensity of all colors in any of these planes is given by the position of the plane on the vertical intensity axis.

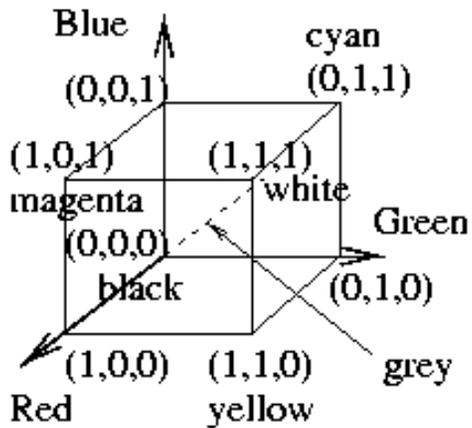
HSI model

- Two values (H & S) encode *chromaticity*
- Convenient for *designing* colors
- Hue H is defined by an angle between 0 and 2π :
 - “red” at angle of 0;
 - “green” at $2\pi/3$;
 - “blue” at $4\pi/3$
- Saturation S models the *purity* of the color
 - S=1 for a completely pure or saturated color
 - S=0 for a shade of “gray”

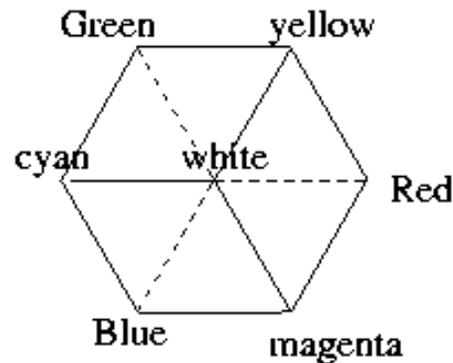


Color hexagon for HSI (HSV)

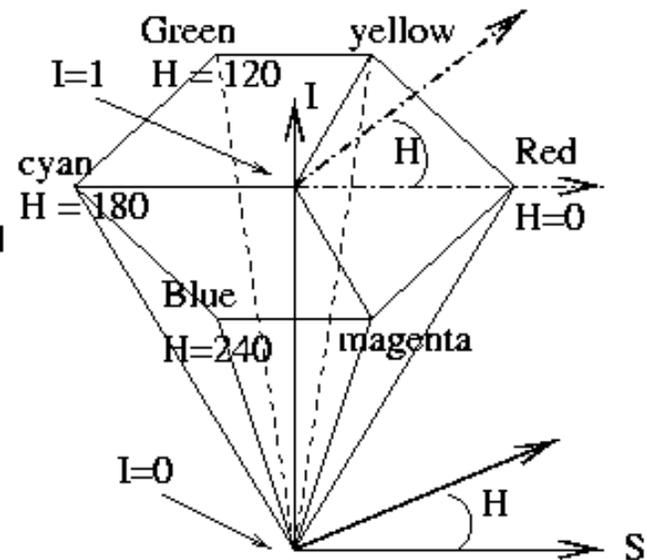
- Color is coded relative to the diagonal of the color cube. Hue is encoded as an angle, saturation is the relative distance from the diagonal, and intensity is height.



(a) RGB color cube

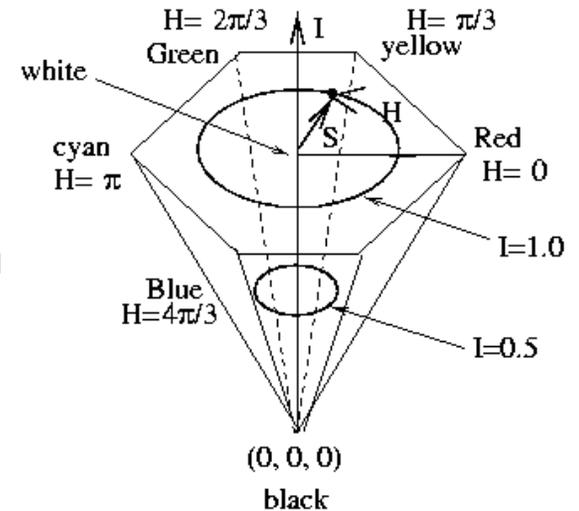
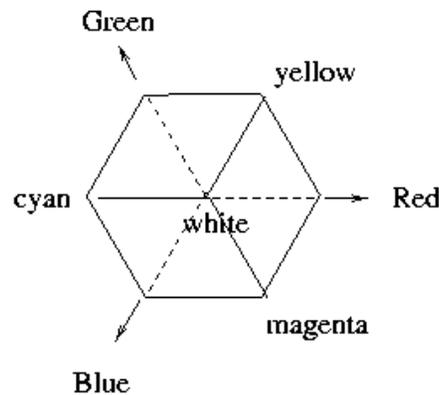
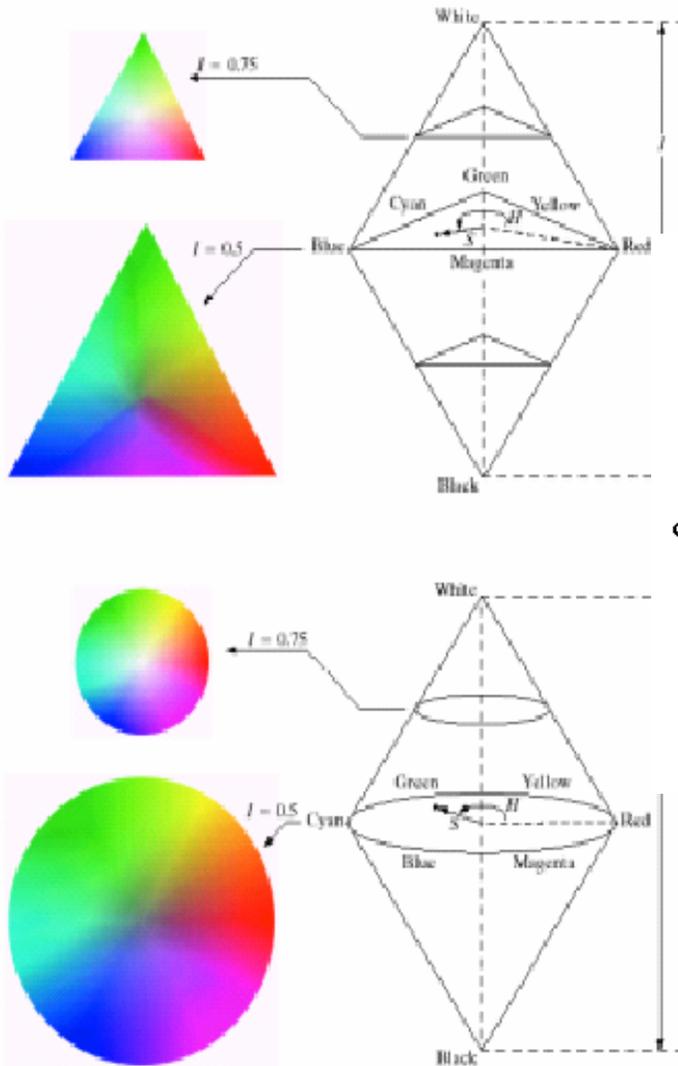


(b) view on diagonal from white to black



(c) single hexacone HSI model

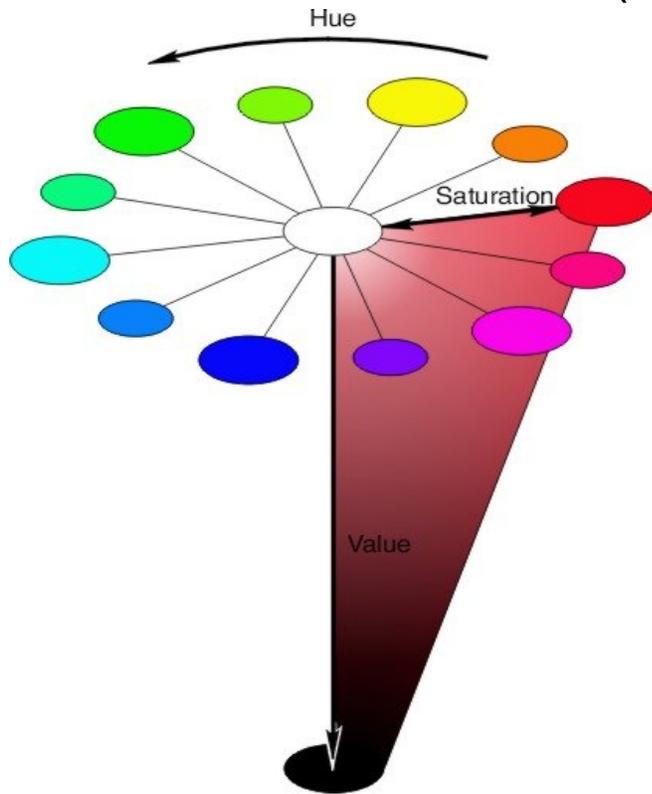
Variations on the theme



The shape on the plane does not matter because the one can always be related to the other by a geometric transformation

HSI-like model

- Hue, Saturation, Value (HSV) model

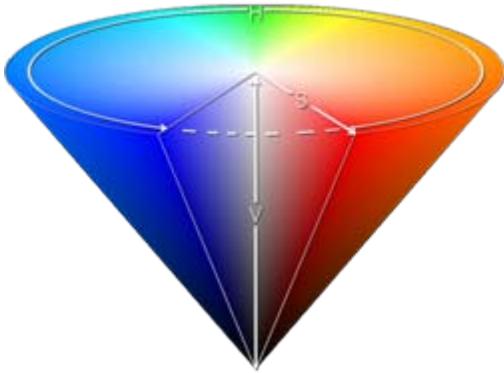


from http://www2.ncsu.edu/scivis/lessons/colormodels/color_models2.html#saturation.

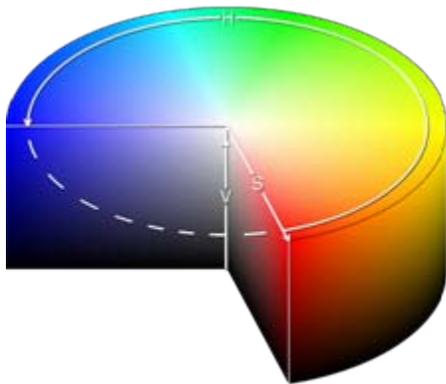
HSV, HSL

Hue, Saturation, Value (Brightness)

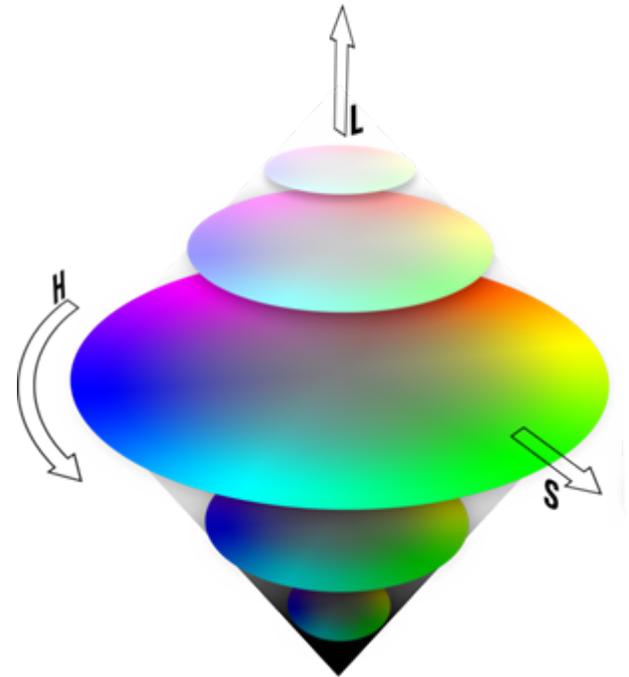
HSV cone



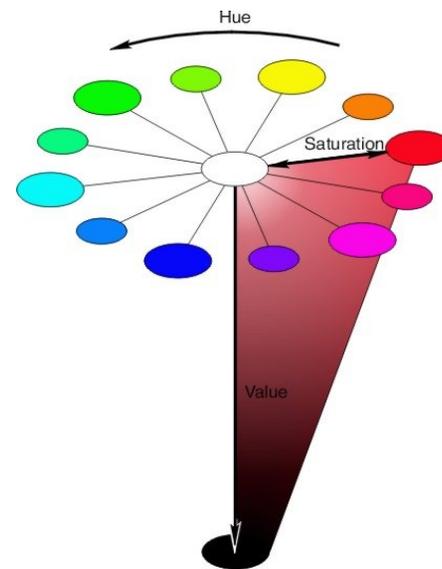
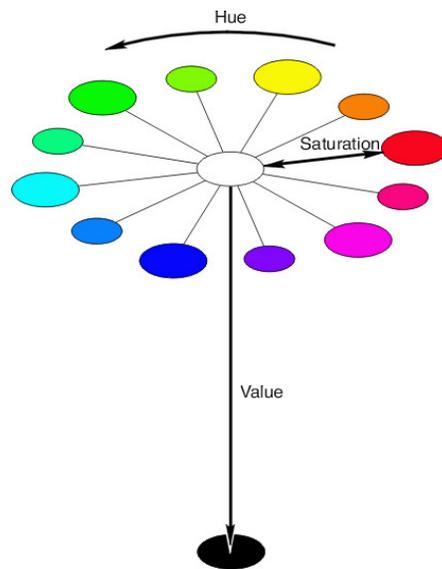
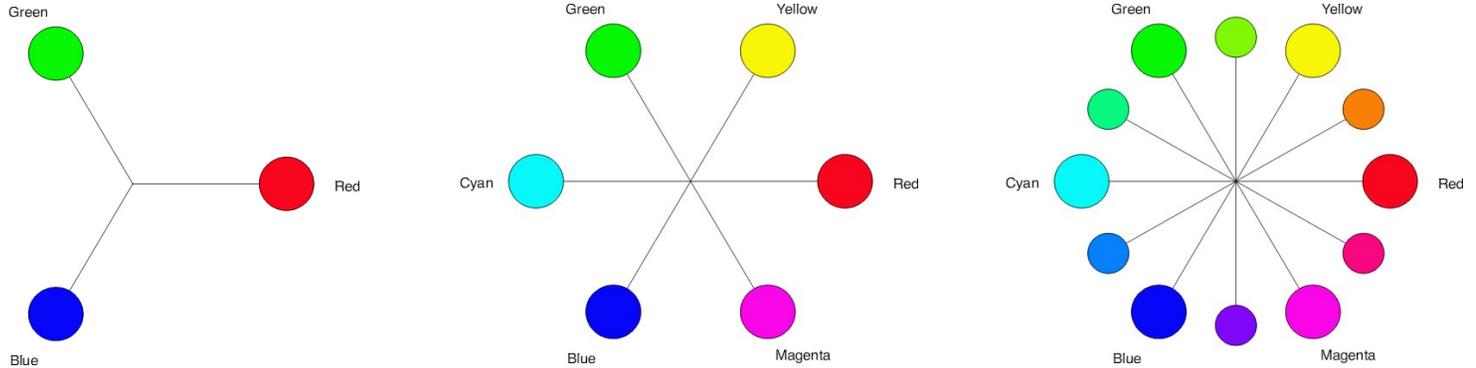
HSV cylinder



Hue, Saturation, Lightness



User-oriented CM: HSV



RGB to HSI

Given an image in RGB color format, the H component of each RGB pixel is obtained using the equation

$$H = \begin{cases} \theta & \text{if } B \leq G \\ 360 - \theta & \text{if } B > G \end{cases} \quad (6.2-2)$$

with

$$\theta = \cos^{-1} \left\{ \frac{\frac{1}{2}[(R - G) + (R - B)]}{[(R - G)^2 + (R - B)(G - B)]^{1/2}} \right\}$$

The saturation component is given by

$$S = 1 - \frac{3}{(R + G + B)} [\min(R, G, B)]. \quad (6.2-3)$$

Finally, the intensity component is given by

$$I = \frac{1}{3} (R + G + B). \quad (6.2-4)$$

RGB 2 HSI

$R, G, B \in \{0, 1\}$

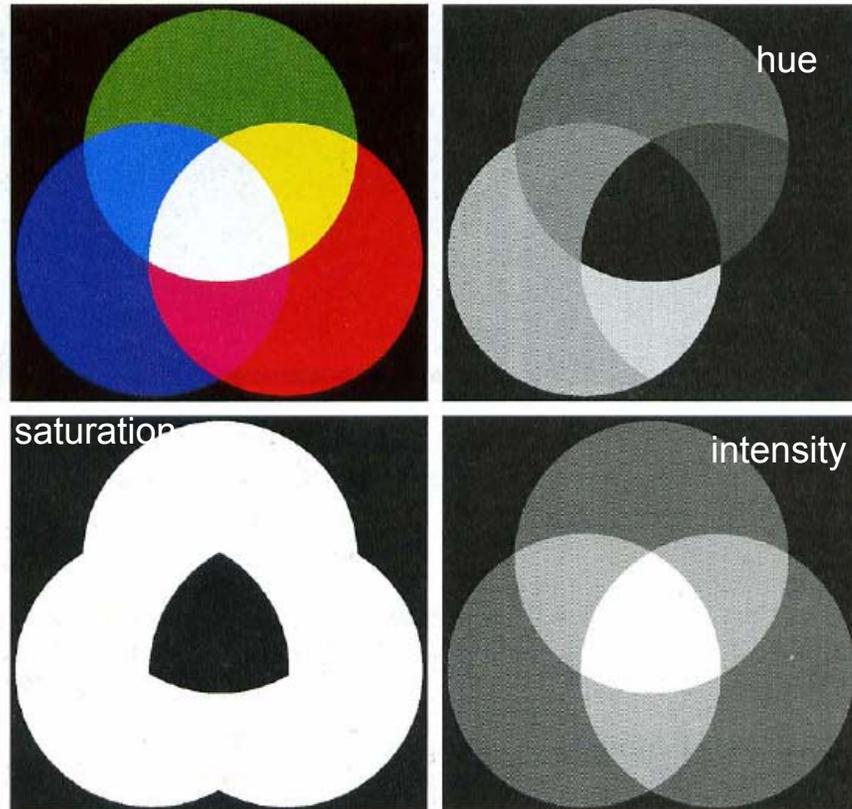
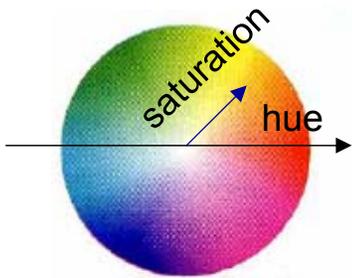
θ is measured counterclockwise from the red axis

H can be normalized to be in $\{0, 1\}$ by dividing by 360

The other values (for chroma and saturation) are in $\{0, 1\}$

The inverse formulas are also defined.

RGB vs HSI



a b
c d

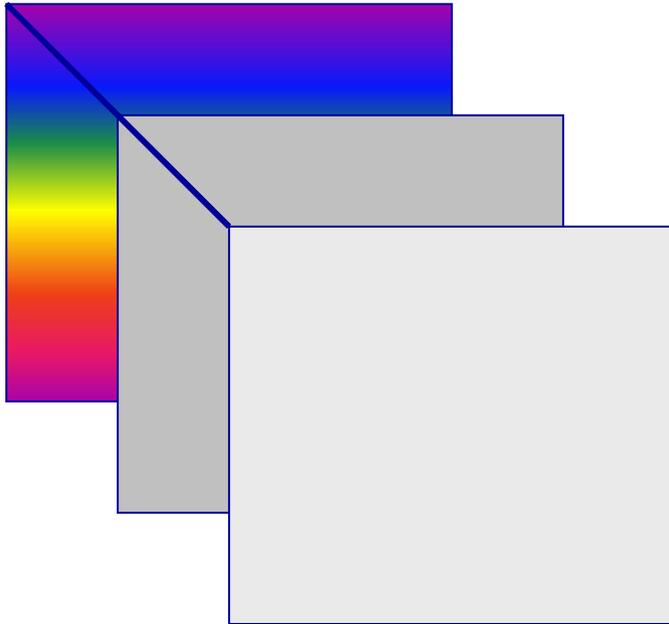
FIGURE 6.16 (a) RGB image and the components of its corresponding HSI image: (b) hue, (c) saturation, and (d) intensity.

User-oriented CM

- Drawbacks
 - Singularities in the transform (such as undefined hue for achromatic points)
 - Sensitivity to small deviations of RGB values near the singularities
 - Numerical instability when operating on hue due to its angular nature

HSI Representation

(0,0)



A single pixel consists of three components.

Each pixel is a **Vector / Array**.

| | | |
|-----|-----|----|
| 128 | 251 | 60 |
|-----|-----|----|

=



Pixel-Vector in
the computer
memory

Final pixel in
the image

Caution! Sometimes pixels are not stored as vectors. Instead, first is stored the complete hue component, then the complete sat., then the intensity.

HSI Examples

Original Image



Hue



Saturation



Intensity



Editing saturation of colors



(Left) Image of food originating from a digital camera;
(center) saturation value of each pixel decreased 20%;
(right) saturation value of each pixel increased 40%.

YUV Color model

- YUV color model “imitates” human vision.
 - Implementation of the opposed channel model, also called luminance / chrominance color spaces
- Historically, YUV color space was developed to provide compatibility between color and black /white analog television systems.
 - YUV color image information transmitted in the TV signal allowed proper reproducing an image contents at the both types of TV receivers, at the color TV sets as well as at the black / white TV sets.
- PAL TV standard
 - YCbCr similar, used in JPEG and MPEG
 - YCbCr color space is defined in the ITU-R BT.601-5 [1] and ITU-R BT.709-5 [2] standards of ITU (International Telecommunication Union).
 - YIQ (similar) used in NTSC

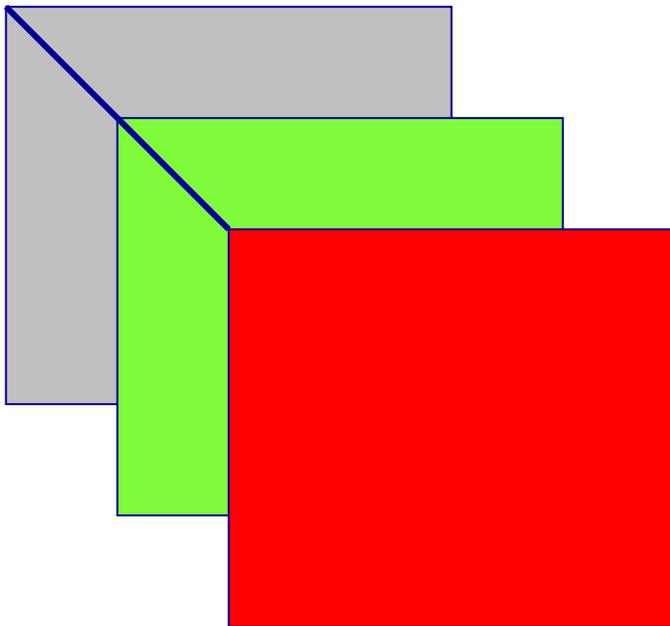
[1] RECOMMENDATION ITU-R BT.601-5, 1982-1995; [2] RECOMMENDATION ITU-R BT.709-5, 1990-2002.

YUV color model

- Color channels
 - Y: luminance
 - UV (Cb, Cr): chrominance. These are often downsampled exploiting the lower cutting frequency and sensitivity of the human visual system with respect to the luminance component
- Conversion formulas from/to RGB are available in the literature and implemented in Matlab

YUV reppresentation

(0,0)



A single pixel consists of three components.

Each pixel is a Vector / Array.

| | | |
|-----|-----|----|
| 128 | 251 | 60 |
|-----|-----|----|



Pixel-Vector in
the computer
memory

Final pixel in
the image

Same Caution as before applies here!

YUV example

Original Image



Y-Component



U-Component



V-Component



YUV possible subsampling patterns

| Sub sampling ratio | Sub sampling pattern | | | | Color component size | | |
|--------------------|----------------------|--------------|-------------|----------|----------------------|-----------|-----------|
| | Uniform | Co site Even | Co site Odd | Centered | Luma Y | Chroma Cb | Chroma Cr |
| 4:4:4 | | | | | 1 | 1 | 1 |
| 4:2:2 | | | | | 1 | 1/2 | 1/2 |
| 4:2:0 | | | | | 1 | 1/4 | 1/4 |

Designation of used symbols are the following:

- position of luma sample only
- position of 2 chroma samples only
- positions of luma and 2 chroma samples are co sited.

YIQ model

- NTSC
- Y is the luminance
- Chromaticity is represented by I and Q
 - in phase and in quadrature components
- RGB2YIQ

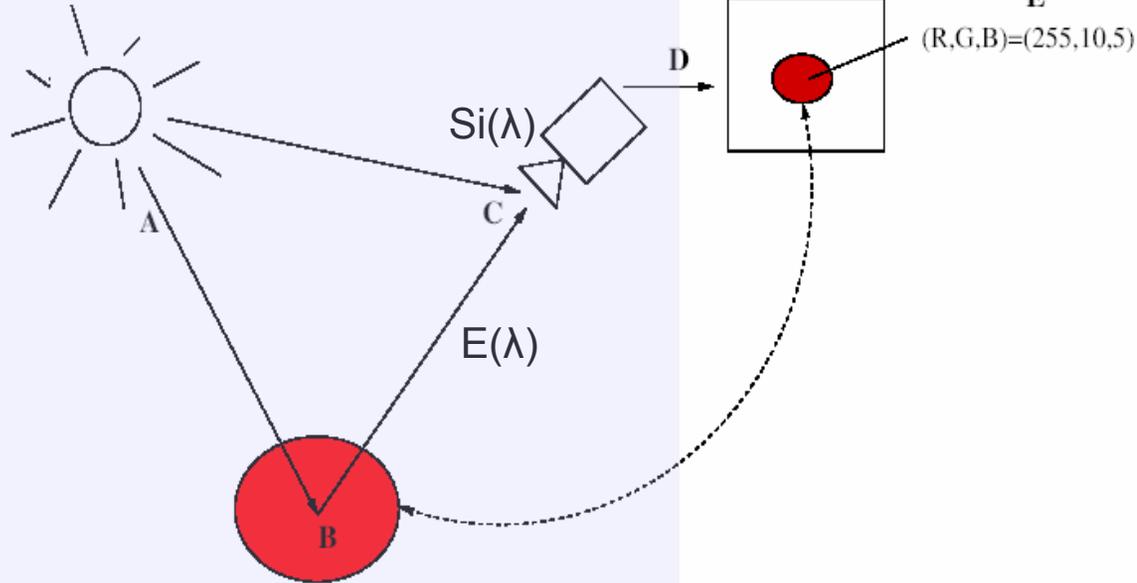
$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.528 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Colorimetric color models

- CIE-RGB
- CIELAB
- CIELUV

RGB color model

Image formation



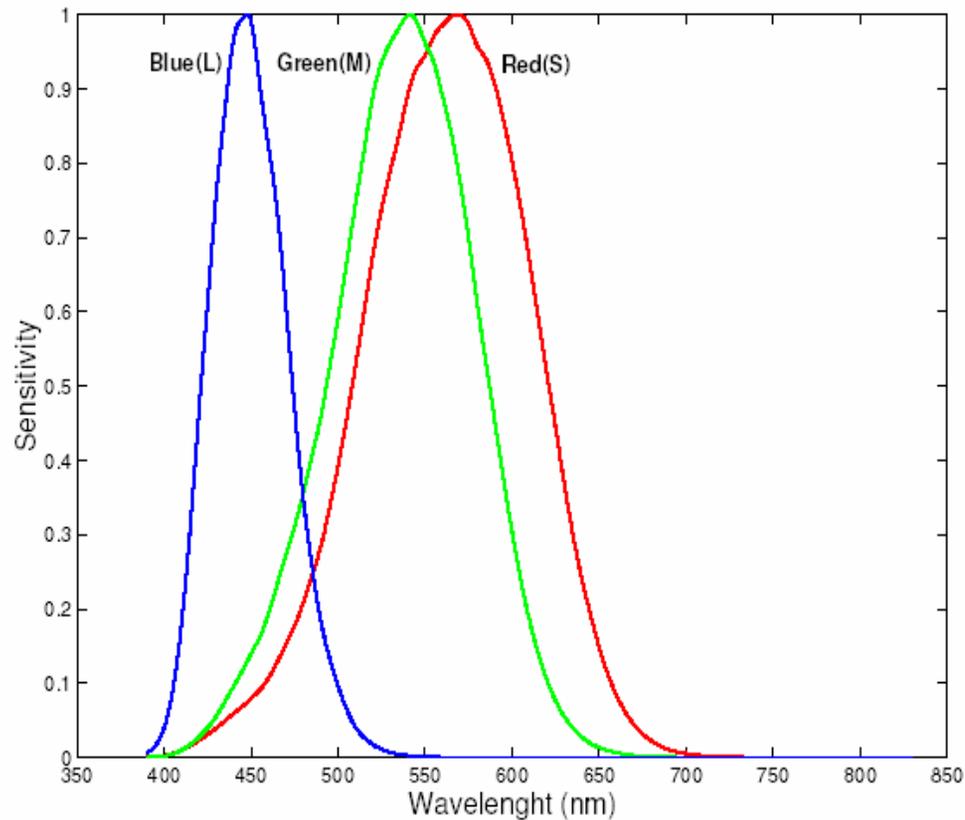
$$C_i = \int_{\lambda} E(\lambda) S_i(\lambda) d\lambda$$

$S_i(\lambda)$: sensitivity of the i^{th} sensor

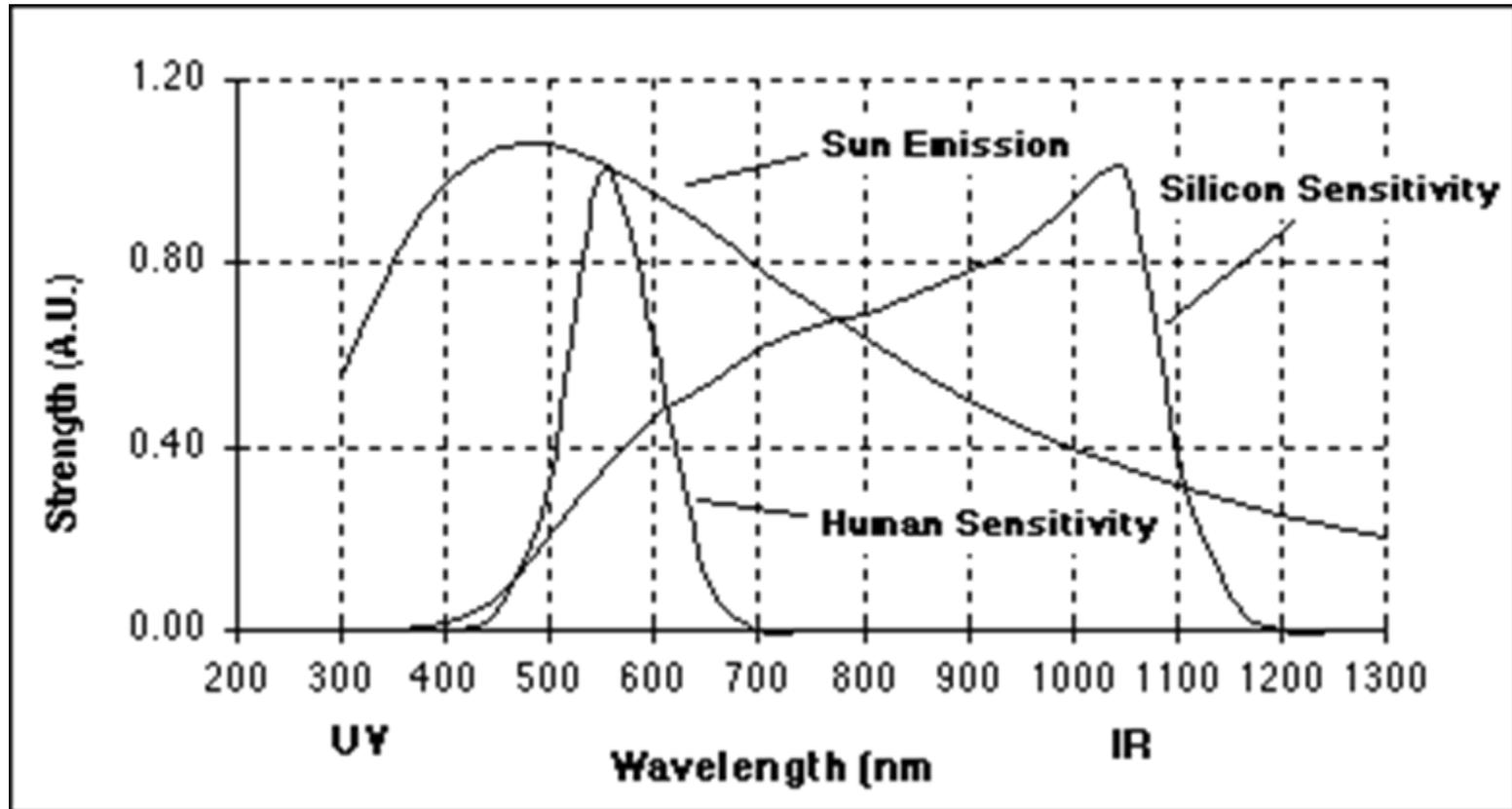
$E(\lambda)$: Spectral Power Distribution (SPD) of the diffused light

Spectral sensitivities

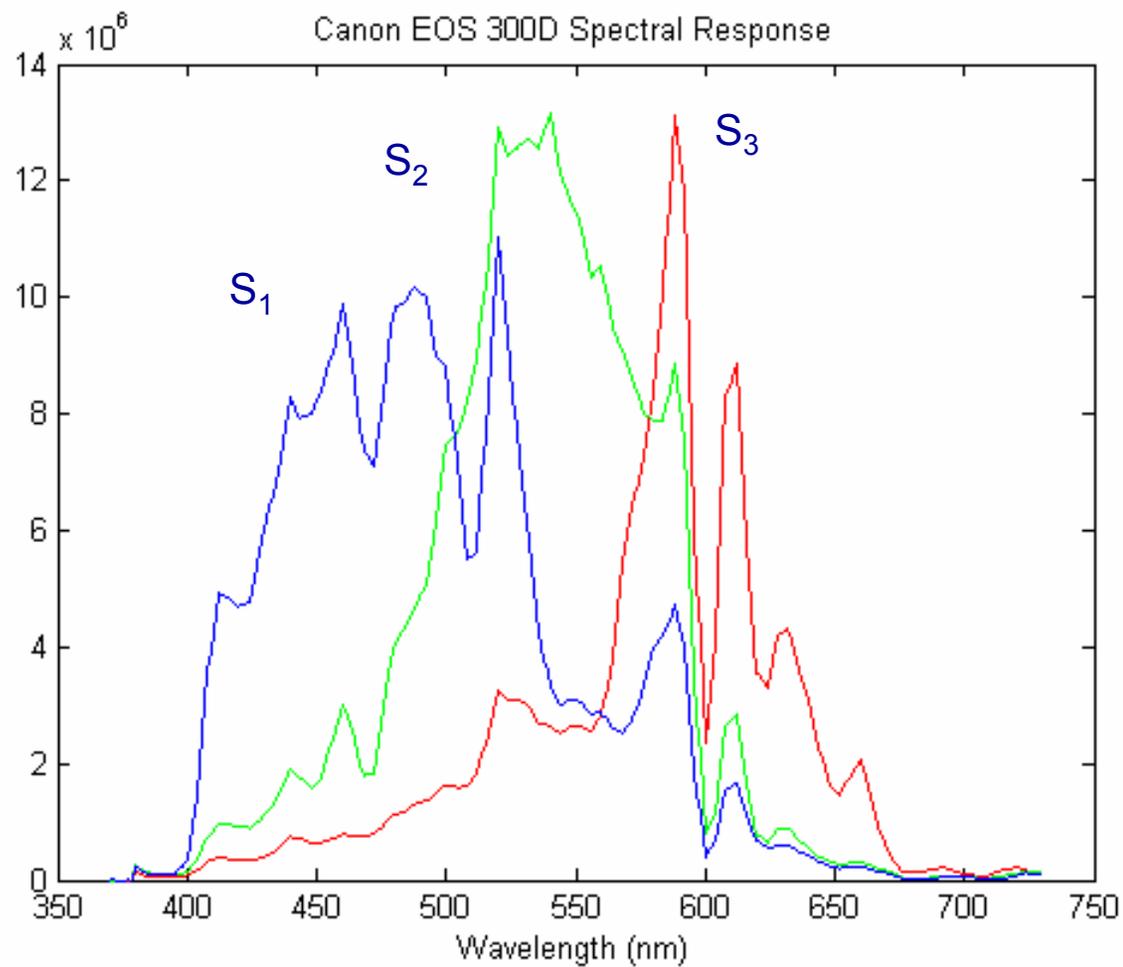
Target: (normalized) spectral sensitivities of the eye



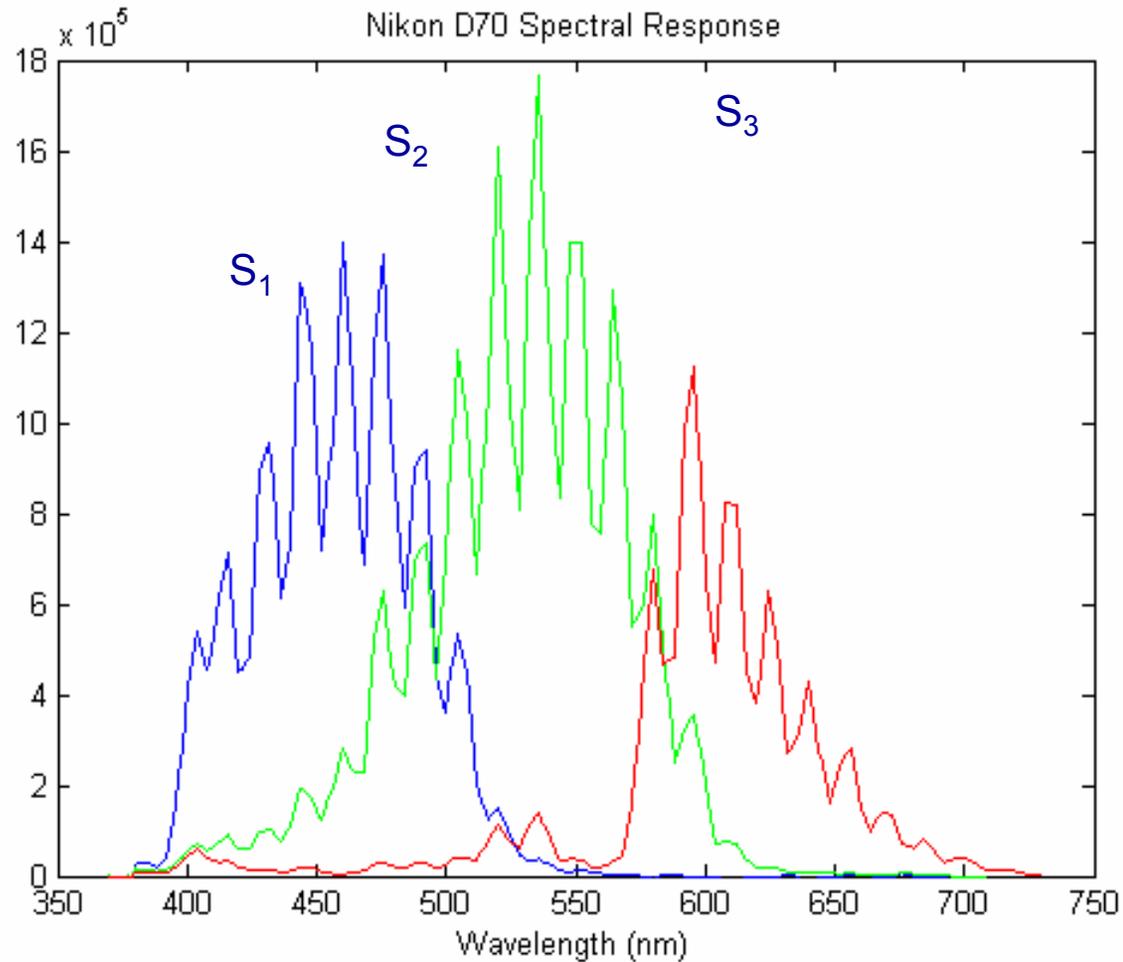
Broad range sensitivity



Sensor sensitivity: Ex. 1



Spectral sensitivity: Ex. 2



RGB model

$$C_i = \int_{\lambda} P(\lambda) S_i(\lambda) d\lambda$$

$P(\lambda)$: PSD (Power Spectral Density of the incident light)

$S_i(\lambda)$: spectral sensitivity of the "red", "green" and "blue" sensors

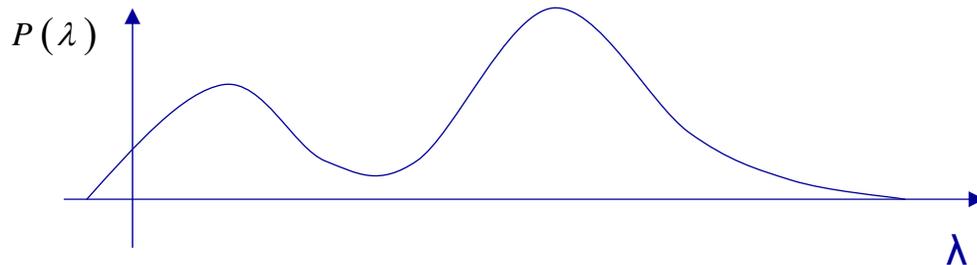
Intensity of the signals recorded by the camera in the three channels

$$R_c = k_1 \int_{\lambda} P(\lambda) S_1(\lambda) d\lambda$$

$$G_c = k_2 \int_{\lambda} P(\lambda) S_2(\lambda) d\lambda$$

$$B_c = k_3 \int_{\lambda} P(\lambda) S_3(\lambda) d\lambda$$

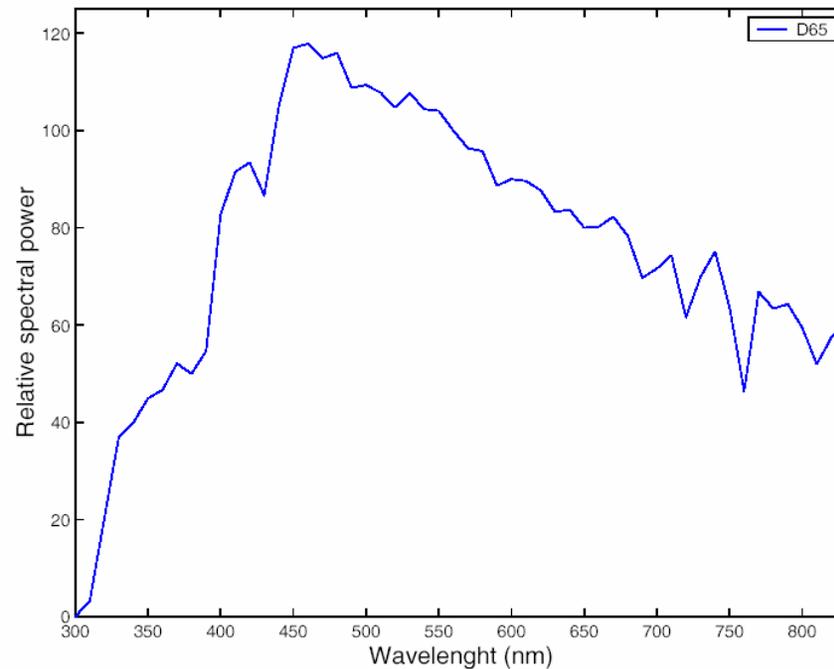
relative to the camera



We need a PSD representing the "white" to calculate k_1 , k_2 and k_3 such that for that PSD ($P(\lambda) = E P(\lambda)$) $R_c = G_c = B_c = 1$ (255). This is called the *reference white*

Reference white

- The reference white is the light source that is chosen to approximate the white light
 - D65, D50



Reference white

- The reference white, $E(\lambda)$, will be given the maximum tristimulus values in all channels ($R_c=G_c=B_c=255$)
- The numerical values of the R,G,B coordinates of a generic PSD $P(\lambda)$ will depend on the choice of $E(\lambda)$
 - We neglect the pedices for easyness of notations

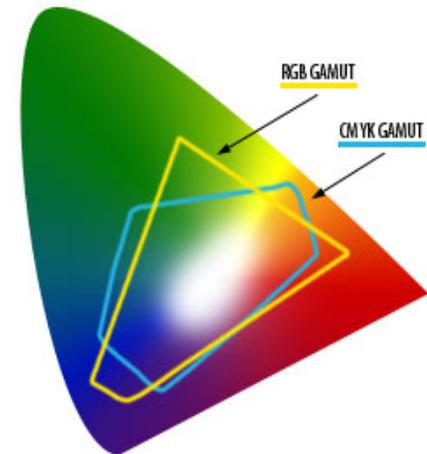
$$R_{Ec} = k_1 \int_{\lambda} E(\lambda) S_1(\lambda) d\lambda = 255$$

$$G_{Ec} = k_2 \int_{\lambda} E(\lambda) S_2(\lambda) d\lambda = 255 \rightarrow k_1, k_2, k_3$$

$$B_{Ec} = k_3 \int_{\lambda} E(\lambda) S_3(\lambda) d\lambda = 255$$

RGB tristimulus values

- The R,G,B coordinates does not have an *absolute* meaning, as their values depend on
 - The spectral sensitivity of the sensors that are used in the capture device
 - The reference white
- Thus, R,G,B values of the *same physical stimulus* (image) acquired with *different cameras* are different, in general
- Gamut: set of colors that is “manageable” by the device
 - Acquisition devices: set of colors that are represented by the device
 - → gamut mapping



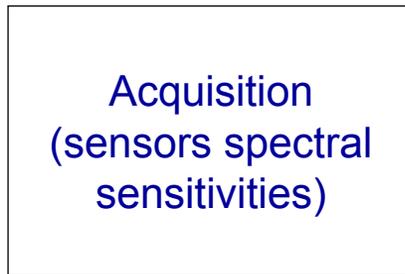
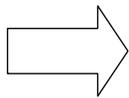
RGB model

- Similar considerations apply to rendering devices: the rendering of a color with given tristimulus coordinates (R,G,B) will depend on
 - The spectral responses of the emitters
 - phosphors for a CRT
 - color filters in a LCD
 - The calibration of the device
 - As for the acquisition devices, the color corresponding to the rendered white must be set
 - To define the entire gamut for a monitor, you only need mark the points on the diagram that represent the colors the monitor actually produces. You can measure these colors with either a colorimeter or a photospectrometer along with software that ensures the monitor is showing 100 percent red for the red measurement, 100 percent green for the green measurement, and 100 percent blue for the blue measurement.
 - The linearity of the monitor transfer function (gamma)

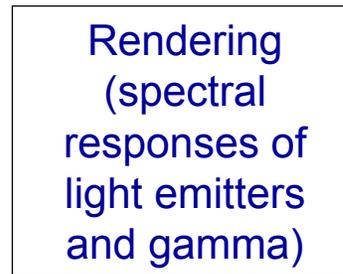
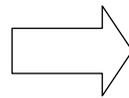
RGB model



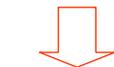
$P(\lambda)$



(R_c, G_c, B_c)



$(R_{out}, G_{out}, B_{out})$

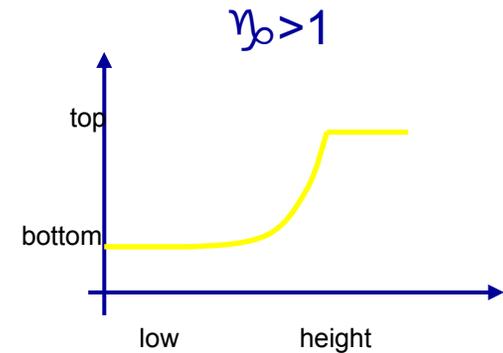
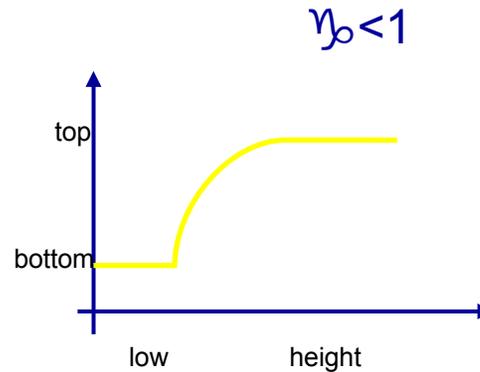
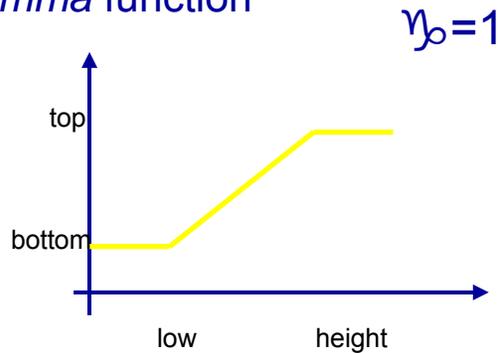


$P_{out}(\lambda)$

$P(\lambda) \neq P_{out}(\lambda)$

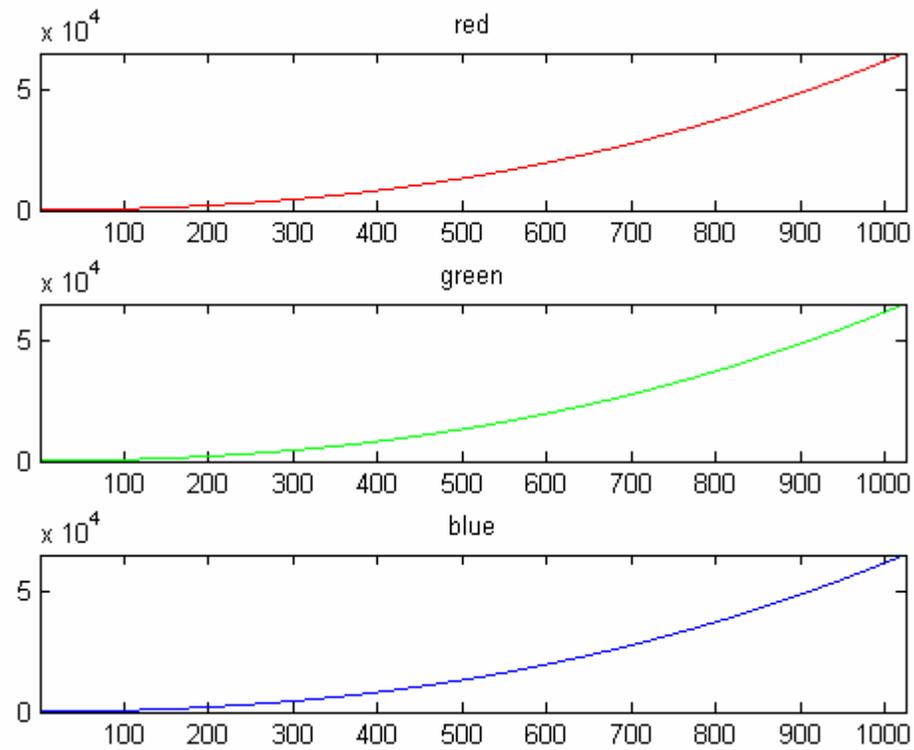
Gamma function

Gamma function



- Typical CRT monitors: gamma=2.2
- The non-linearity of the monitor can be compensated by non-uniform scaling of the RGB coordinates at input (*RGB linearization*)
- This led to the definition of the sRGB color model

sRGB



CIE-RGB

Colorimetric standard observer

RGB standard observer

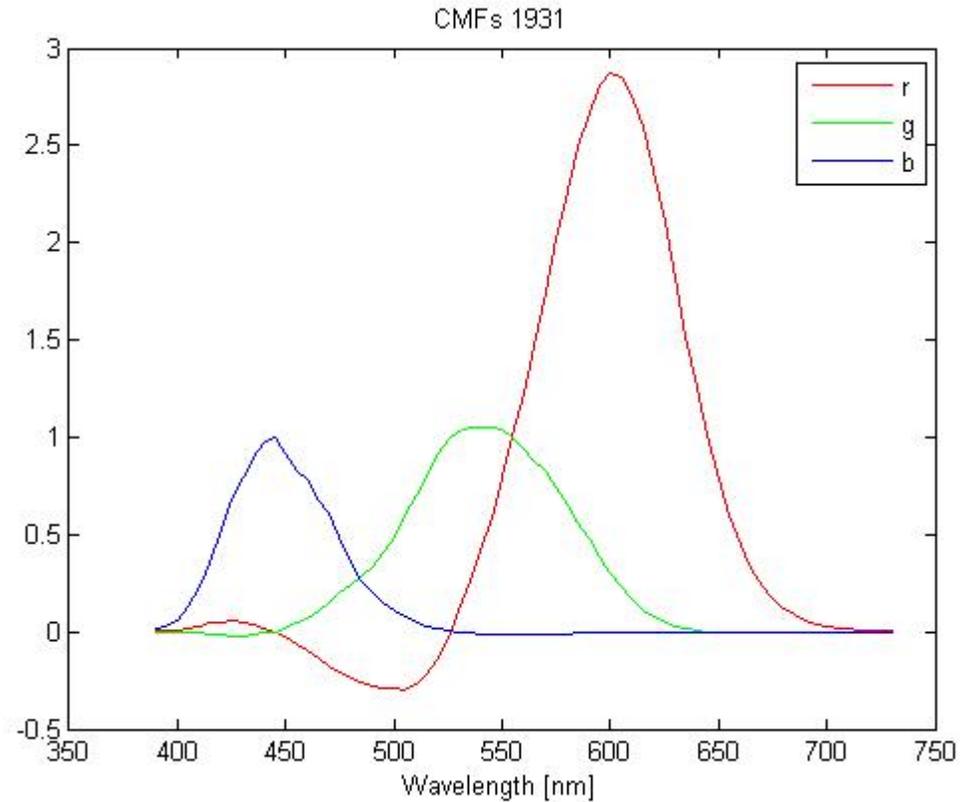
- Spectral sensitivities for the human eye have been measured in reference conditions by a very large number of observers
- Performed by the CIE (Commission Internationale d'Eclairage) standardization committee
- Such curves are called Color Matching Functions (CMFs) after the type of experiment
- The so-derived tristimulus values
 - Are not device dependent
 - Are still relative as they depend on (1) the choice of the red, green and blue monochromatic primaries that were used (2) the reference white and (3) the experimental conditions

CIE - RGB

$$R = \int_{\lambda} P(\lambda) \bar{r}(\lambda) d\lambda$$

$$G = \int_{\lambda} P(\lambda) \bar{g}(\lambda) d\lambda$$

$$B = \int_{\lambda} P(\lambda) \bar{b}(\lambda) d\lambda$$



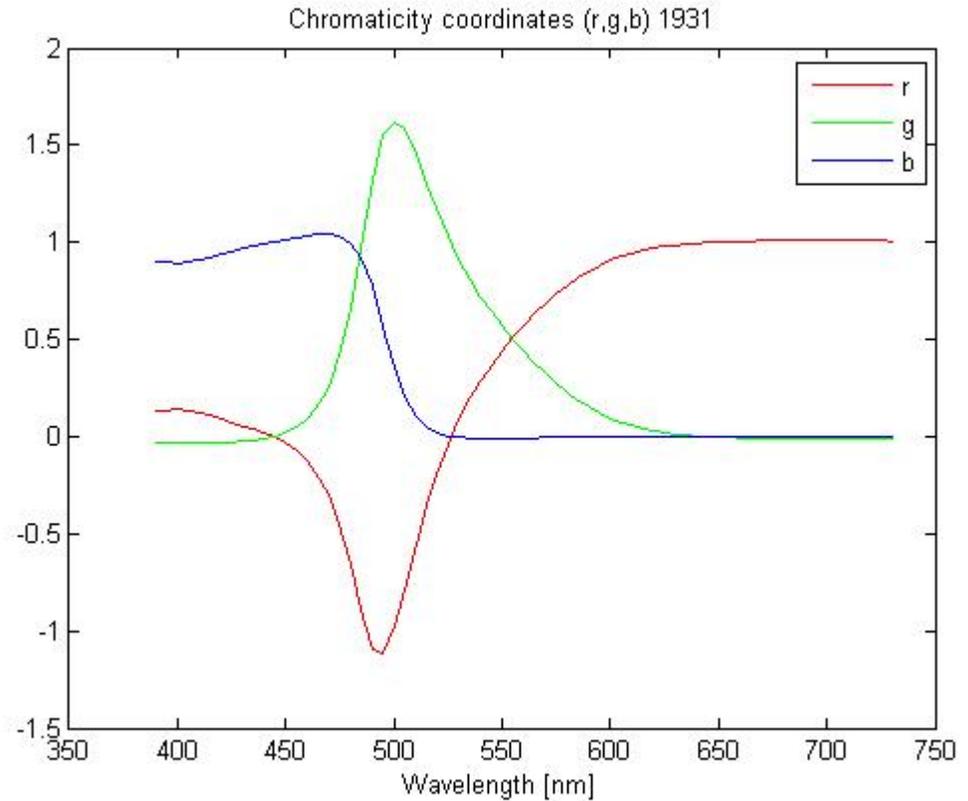
Chromaticity coordinates

$$r(\lambda) = \frac{\bar{r}(\lambda)}{\bar{r}(\lambda) + \bar{g}(\lambda) + \bar{b}(\lambda)}$$

$$g(\lambda) = \frac{\bar{g}(\lambda)}{\bar{r}(\lambda) + \bar{g}(\lambda) + \bar{b}(\lambda)}$$

$$b(\lambda) = \frac{\bar{b}(\lambda)}{\bar{r}(\lambda) + \bar{g}(\lambda) + \bar{b}(\lambda)}$$

$$r(\lambda) + g(\lambda) + b(\lambda) = 1$$



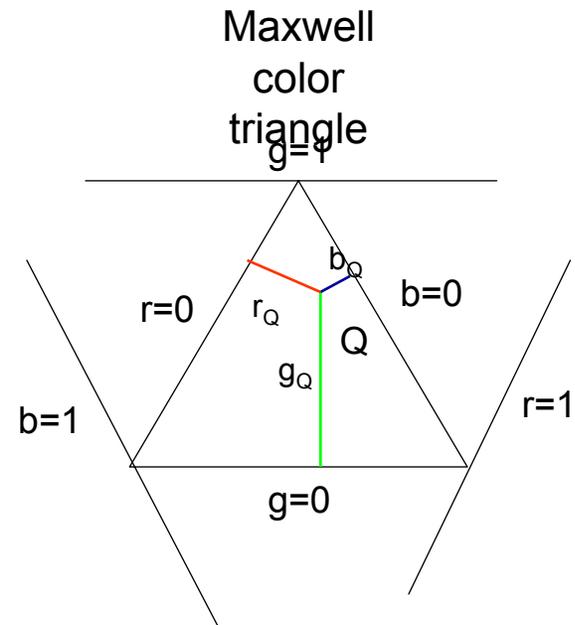
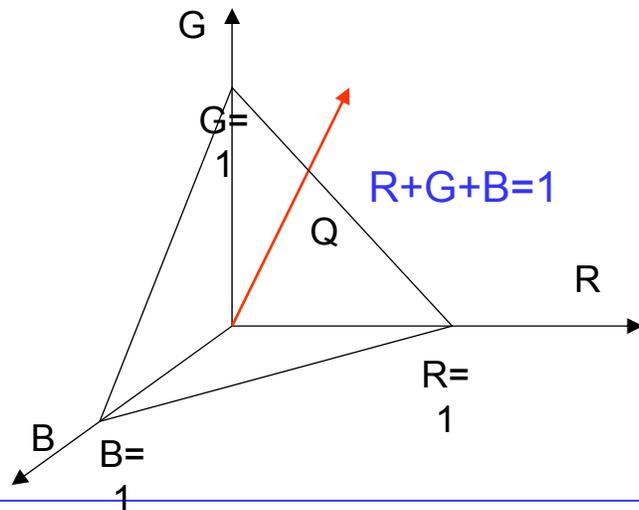
Chromaticity coordinates

Chromaticity coordinates

$$r = \frac{R}{R+G+B}$$

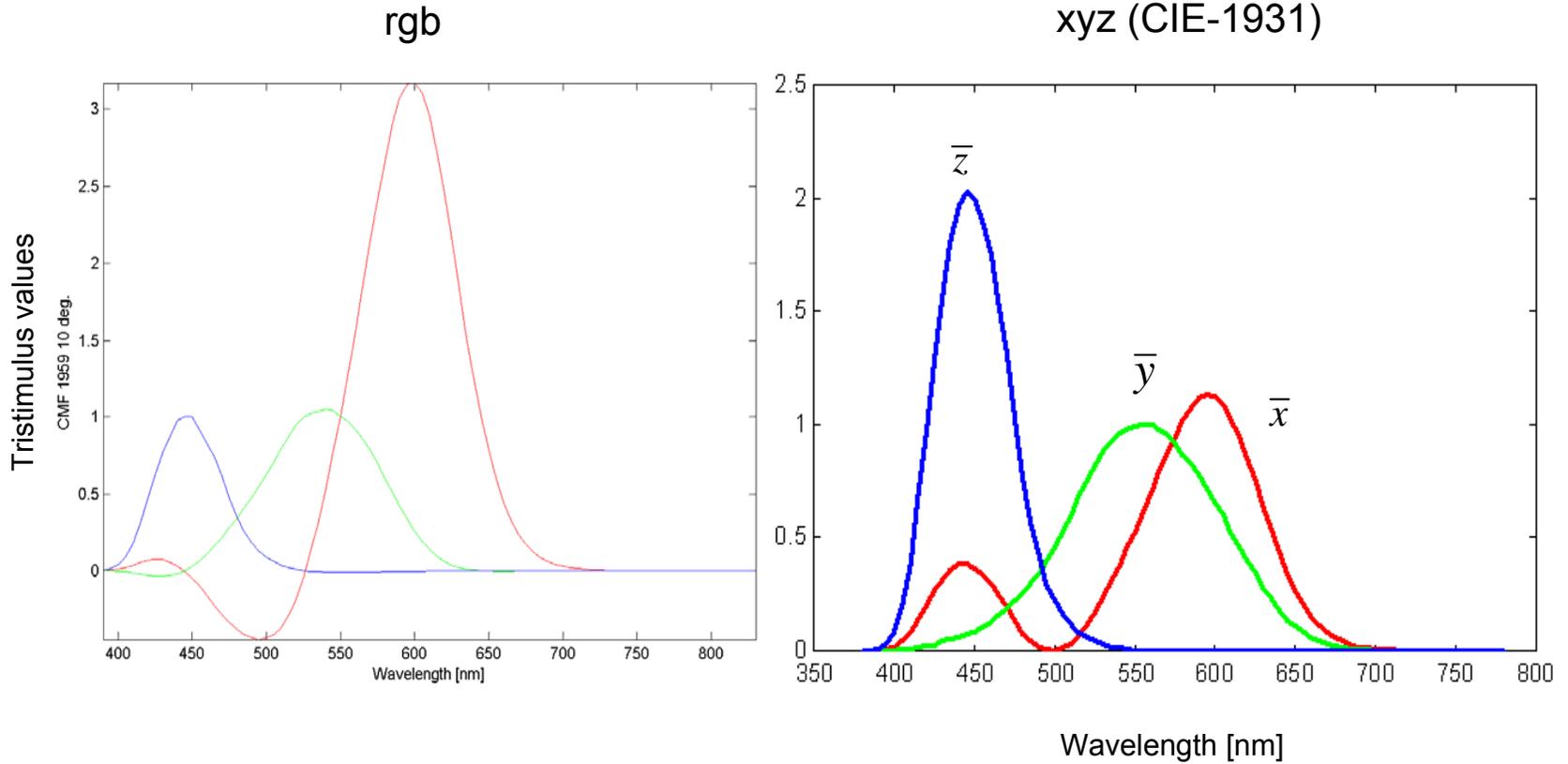
$$g = \frac{G}{R+G+B} \quad \Longrightarrow \quad r+g+b=1$$

$$b = \frac{B}{R+G+B}$$



(*r,g*) specify the *hue and saturation* of the color while the information about the luminance is lost

From rgb to xyz



rgb2xyz

- Chromaticity coordinates

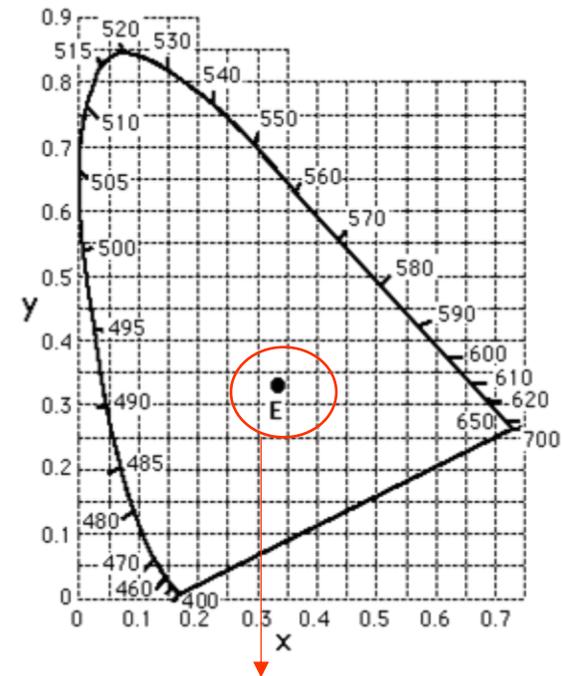
$$x = \frac{0.49r + 0.31g + 0.2b}{0.66697r + 1.1324g + 1.20063b}$$
$$y = \frac{0.17697r + 0.81240g + 0.01063b}{0.66697r + 1.1324g + 1.20063b}$$
$$z = \frac{0.0r + 0.01g + 0.99b}{0.66697r + 1.1324g + 1.20063b}$$

- Tristimulus values

$$X = \frac{x}{y}V \quad Y = V \quad Z = \frac{z}{y}V$$

luminance

(x,y) chromaticity diagram



reference white

$$x_E = y_E = \frac{1}{3}$$

CIE Chromaticity Coordinates

- (X,Y,Z) tristimulus values

$$X = \int P_{\lambda} \bar{x}(\lambda) d\lambda$$

$$Y = \int P_{\lambda} \bar{y}(\lambda) d\lambda$$

$$Z = \int P_{\lambda} \bar{z}(\lambda) d\lambda$$

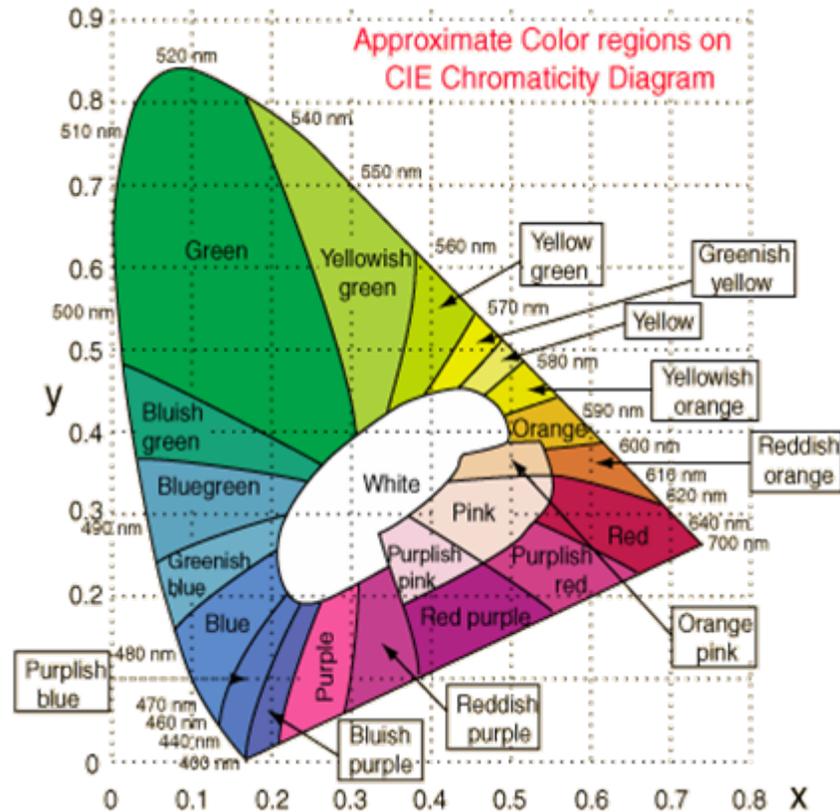
- Chromaticity coordinates

$$x(\lambda) = \frac{\bar{x}(\lambda)}{\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda)}$$

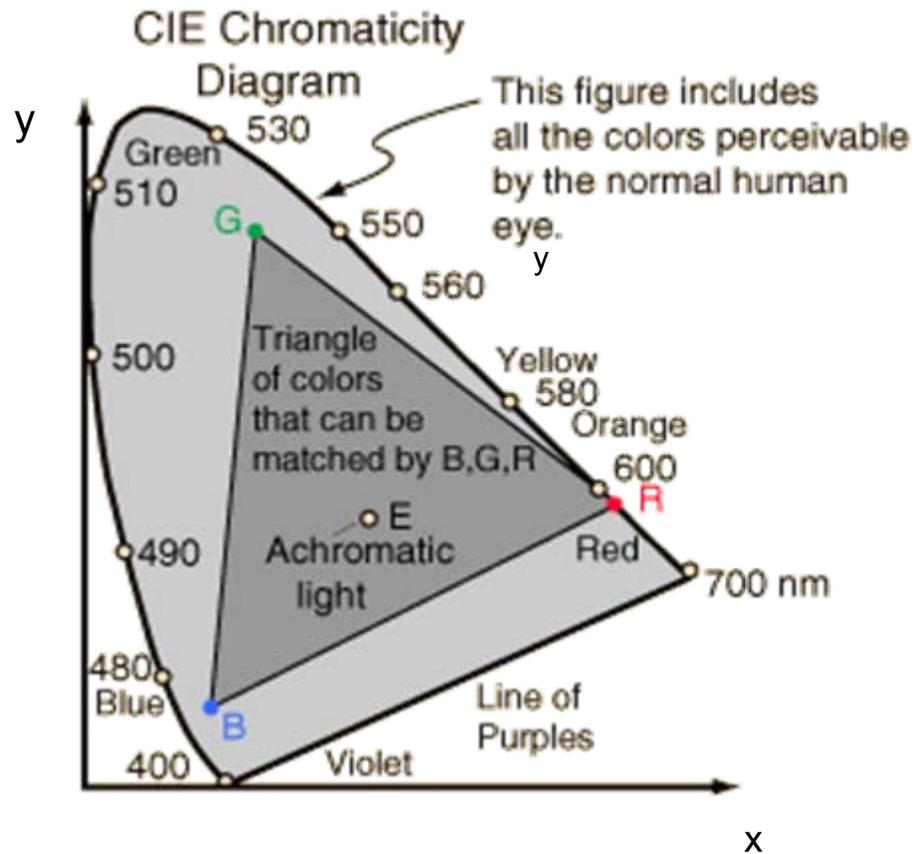
$$y(\lambda) = \frac{\bar{y}(\lambda)}{\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda)}$$

$$z(\lambda) = \frac{\bar{z}(\lambda)}{\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda)}$$

$$x(\lambda) + y(\lambda) + z(\lambda) = 1 \quad \text{x-y chromaticity diagram}$$



Gamut mapping



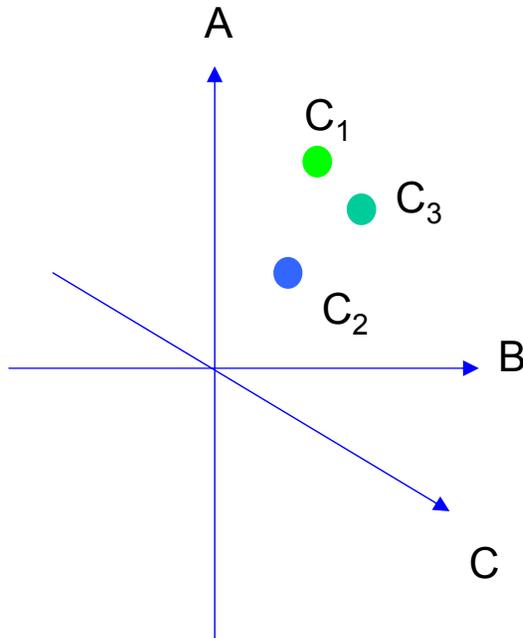
The CIE coordinates provide a device independent framework for performing color related processing

Uniform color scales

Attributes: hue, saturation (chroma), brightness (lightness)

- **Brightness**
 - The attribute of a visual sensation according to which a visual stimulus appears to be more or less “intense”, or to emit more or less light
 - Ranges from “bright” to “dim”
- **Lightness**
 - The attribute of a visual sensation according to which a visual stimulus appears to be more or less “intense”, or to emit more or less light *in proportion to that emitted by a similarly illuminated area perceived as “white”*
 - Relative brightness
 - Ranges from “light” to “dark”
- **Colorfulness**
 - The attribute of a visual sensation according to which a visual stimulus appears to be more or less “chromatic”
- **Chroma**
 - The attribute of a visual sensation which permits a judgment to be made of the degree to which a chromatic stimulus differs from an “achromatic” stimulus *of the same brightness*
- **Saturation**
 - The attribute of a visual sensation which permits a judgment to be made of the degree to which a chromatic stimulus differs from an “achromatic” stimulus *regardless of their brightness*
- Chroma and saturation are often considered as equivalent

Perceptually uniform color models



Perceptual distance:

- Scaling the perceptual similarity among color samples
 - C₁ is most similar to C₃ than it is to C₂

Measurable distance

- Metric in the color space
 - Euclidean distance among the color samples

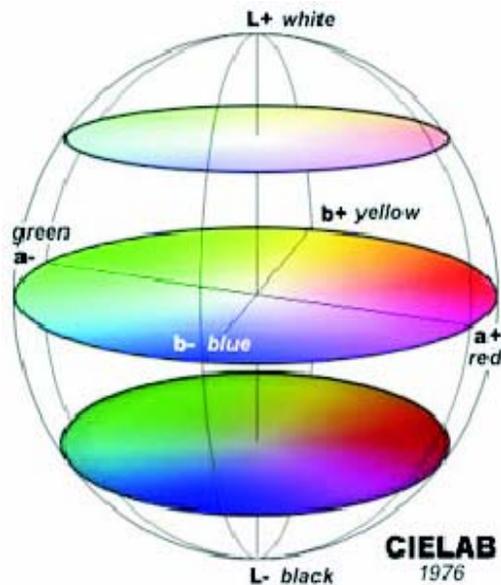
Does the perceptual distance match with the measurable distance among colors?

$$d(C_1C_3) \stackrel{?}{\leq} d(C_1C_2)$$

Color models whose metric is representative of the perceptual distance are *perceptually uniform*

Perceptually uniform Color models: Lab

CIE 1976 L*a*b* (CIELAB)



X_n, Y_n, Z_n : reference white

Tristimulus values for a nominally white object-color stimulus. Usually, it corresponds to the spectral radiance power of one of the CIE standard illuminants (as D65 or A), reflected into the observer's eye by a perfect reflecting diffuser. Under these conditions, X_n, Y_n, Z_n are the tristimulus values of the standard illuminant with $Y_n=100$.

For: $\frac{Y}{Y_n}, \frac{X}{X_n}, \frac{Z}{Z_n} \geq 0.01$

$$L^* = 116(Y/Y_n)^{1/3} - 16$$

$$a^* = 500[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$$

$$b^* = 200[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$$

otherwise

$$L^* = 116 \left[f \left(\frac{Y}{Y_n} \right) - \frac{16}{116} \right]$$

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

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

$$f \left(\frac{Y}{Y_n} \right) = \begin{cases} \left(\frac{Y}{Y_n} \right)^{1/3} & \text{for } \frac{Y}{Y_n} > 0.008856 \\ 7.787 \frac{Y}{Y_n} + \frac{16}{116} & \text{for } \frac{Y}{Y_n} \leq 0.008856 \end{cases}$$

Hint: the diffuse light (★ color) depends on both the physical properties of the surface and the illuminant

Summary

- References
 - B. Wandell, “Foundations of visions”
 - Wyszecki&Stiles, “Color science, concepts, methods, quantitative data and formulae”, Wiley Classic Library
 - D. Malacara, “Color vision and colorimetry, theory and applications”, SPIE Press

Color images

- Different approaches
 - An edge is present iff there is a gradient in the luminance
 - An edge exists if there is a gradient in any of the tristimulus components
 - “Total gradient” above a predefined threshold

$$G(j, k) = G_1(j, k) + G_2(j, k) + G_3(j, k)$$

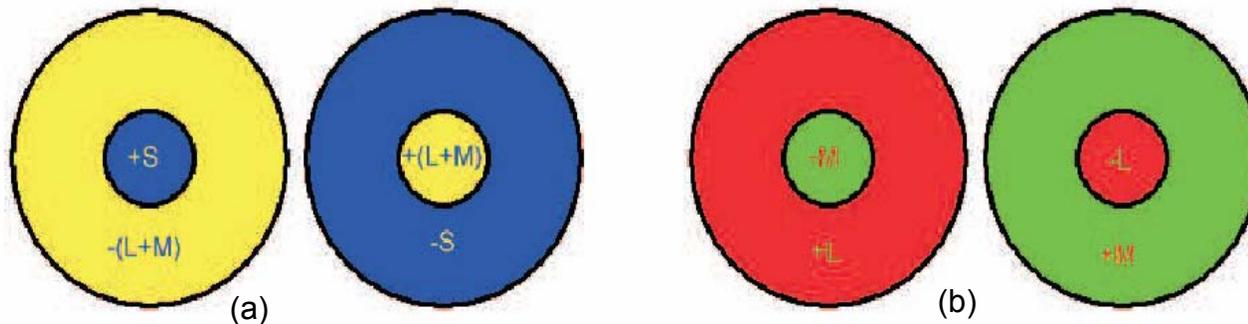
- “Vector sum gradient” above a predefined threshold

$$G(j, k) = \left\{ |G_1(j, k)|^2 + |G_2(j, k)|^2 + |G_3(j, k)|^2 \right\}^{1/2}$$

$G_i(j, k)$: i-th linear or non-linear tristimulus value

Opponent Color Model

- Perception is mediated by *opponent color channels*
 - *Evidences*
 - Afterimages
 - Certain colors cannot be perceived simultaneously (i.e. no *reddish-green* or *bluish-yellow*)

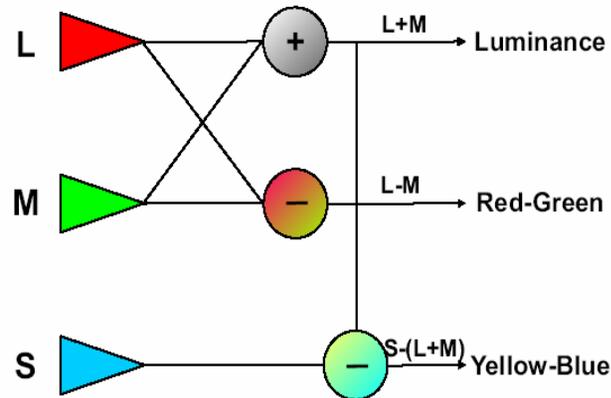


Example of typical center-surround antagonistic receptive fields: (a) on-center yellow-blue receptive fields; (b) on-center red-green receptive fields.

Because of the fact that the L, M and S cones have different spectral sensitivities, are in different numbers and have different spatial distributions across the retina, the respective receptive fields have quite different properties.

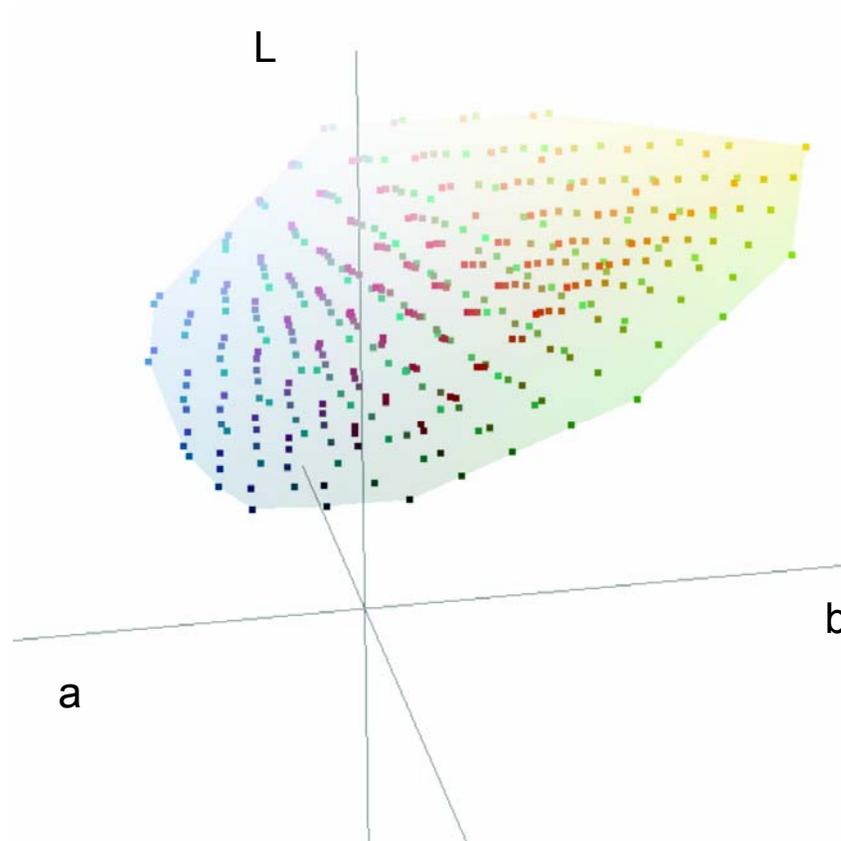
Opponent color channels

Cone interconnections in the retina leading to opponent color channels



- As a convenient simplification, the existence of three types of color receptive fields is assumed, which are called *opponent channels*.
- The black-white or *achromatic* channel results from the sum of the signals coming from L and M cones (L+M). It has the highest spatial resolution.
- The *red-green* channel is mainly the result of the M cones signals being subtracted from those of the L cones (L-M). Its spatial resolution is slightly lower than that of the achromatic channel (L+M).
- Finally the *yellow-blue* channel results from the addition of L and M and subtraction of S cone signals. It has the lowest spatial resolution.

Color representation in Lab



Opponent Colors

