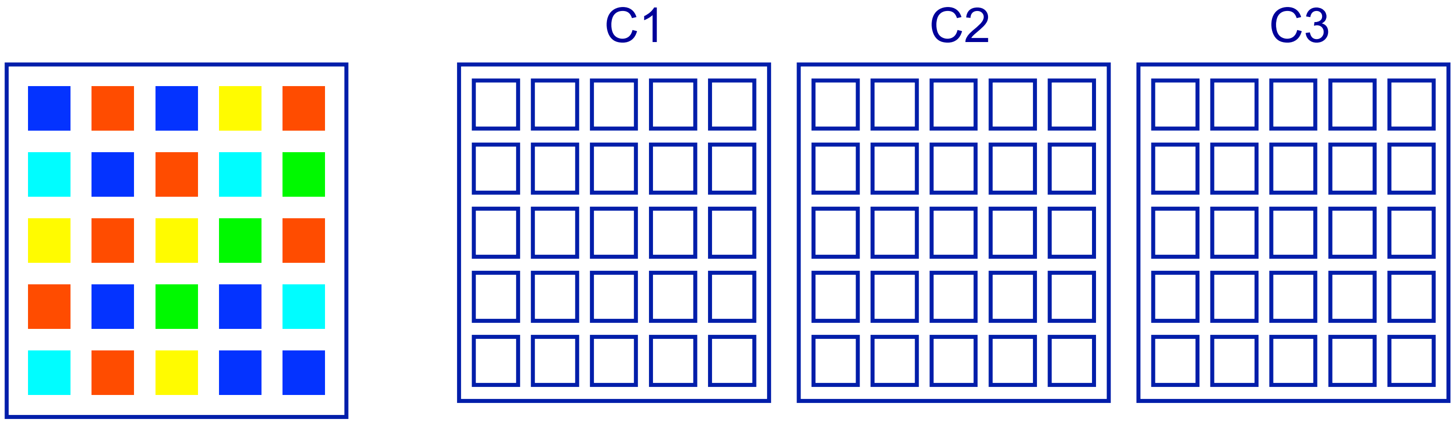
Color image processing

Color images



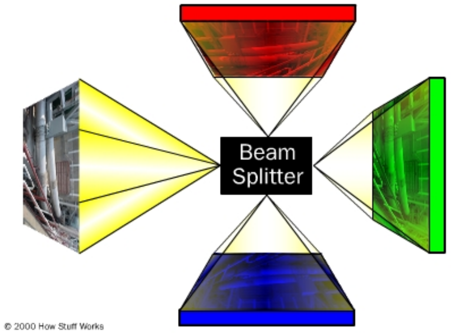
- Each colored pixel corresponds to a *vector* of three values {C1,C2,C3}
- The characteristics of the components depend on the chosen *colorspace* (RGB, YUV, CIELab,..)

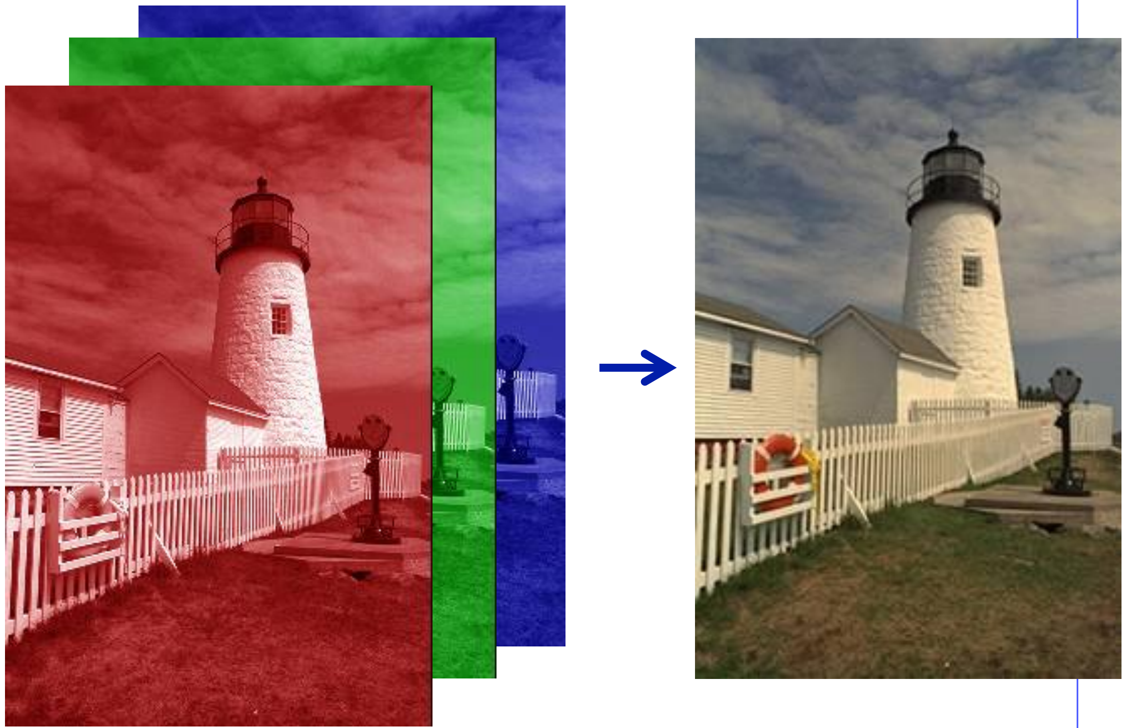
Digital Color Images

- $x_R[n_1, n_2]$

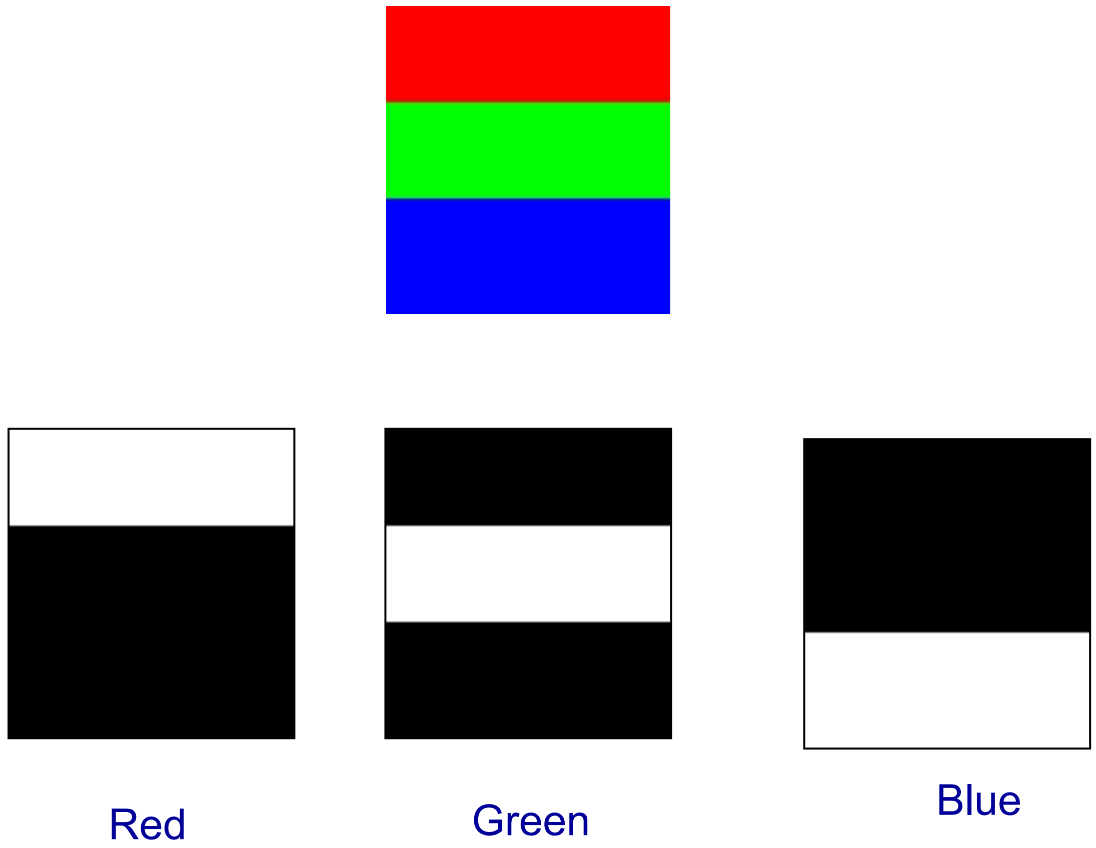
  $x_G[n_1, n_2]$

  $x_B[n_1, n_2]$





Color channels



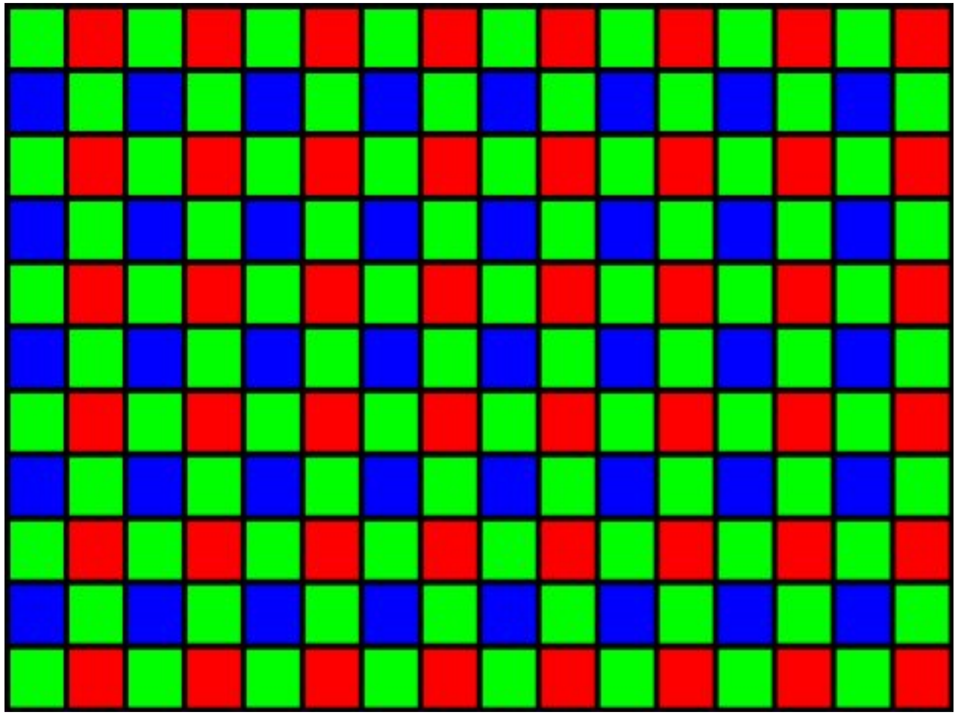
Color channels

Red

Green

Blue

Bayer matrix



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

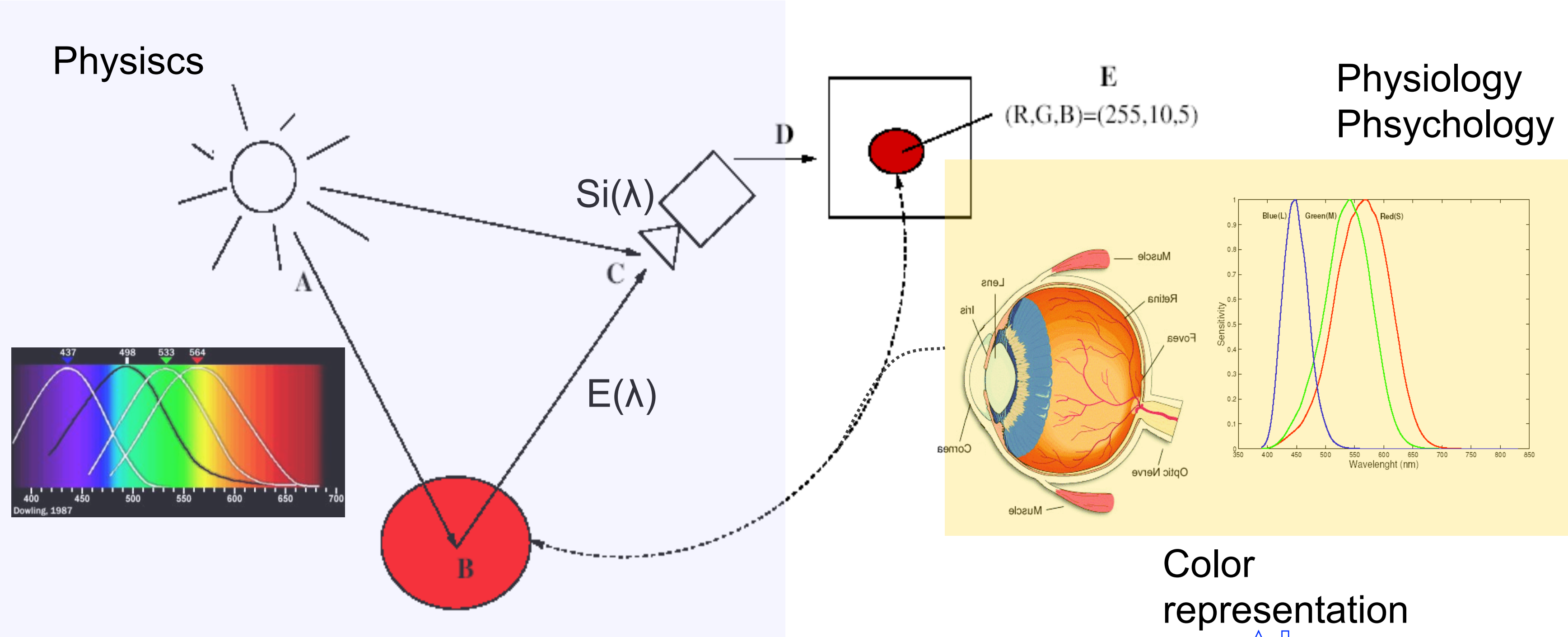
Color imaging

- 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?



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

$S_i(\lambda)$: sensitivity of the i^{th} sensor
$E(\lambda)$: Spectral Power Distribution (SPD) of the diffused light

Color representation

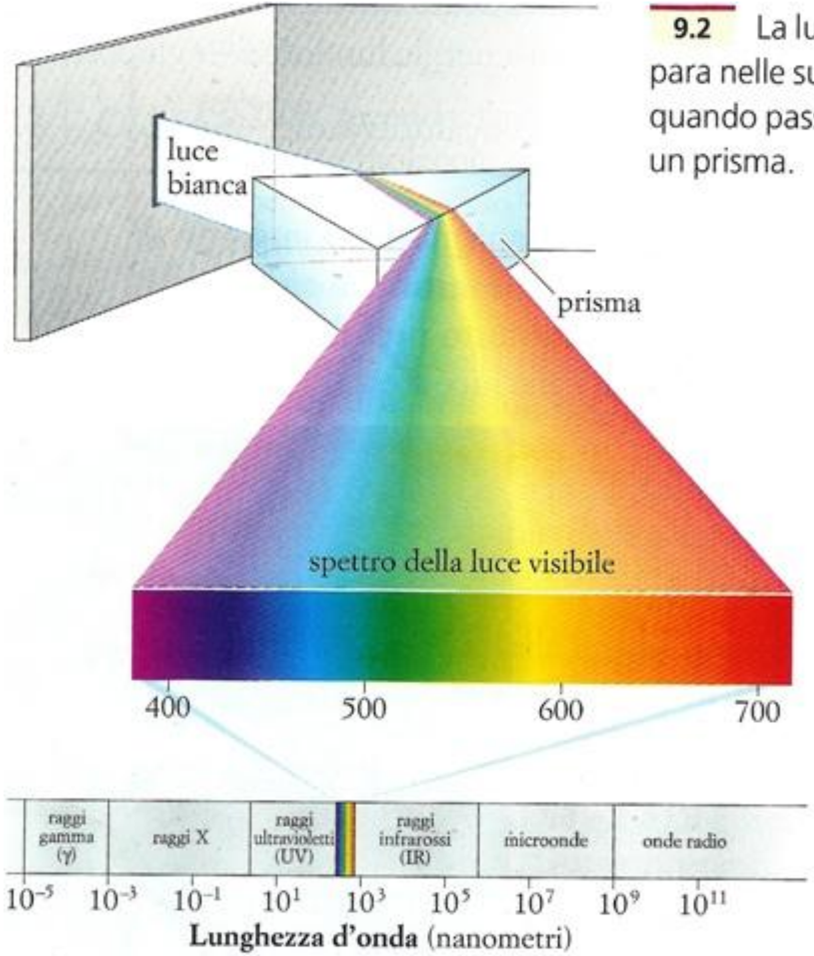
⇧⇩

Modeling

⇧⇩

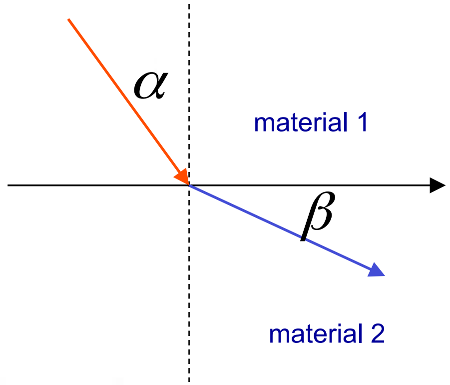
Color perception

Newton’s prism



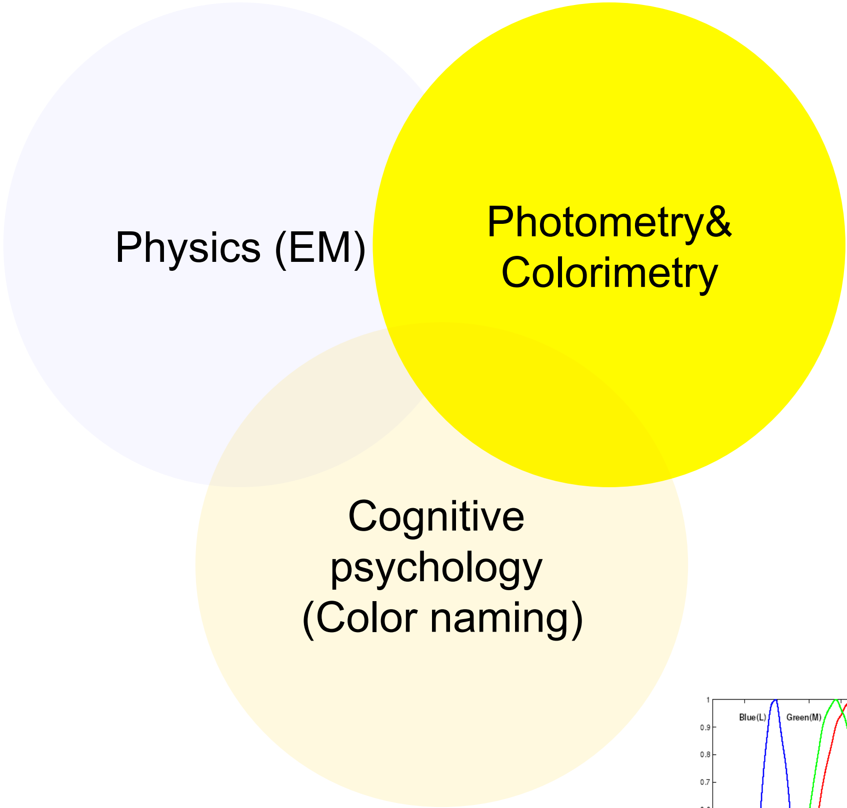
9.2 La luce bianca si separa nelle sue componenti quando passa attraverso un prisma.

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

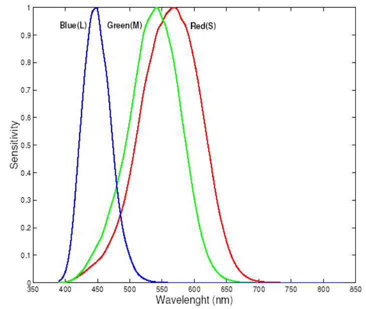


What *is* color?

Radiometric quantities ⇔

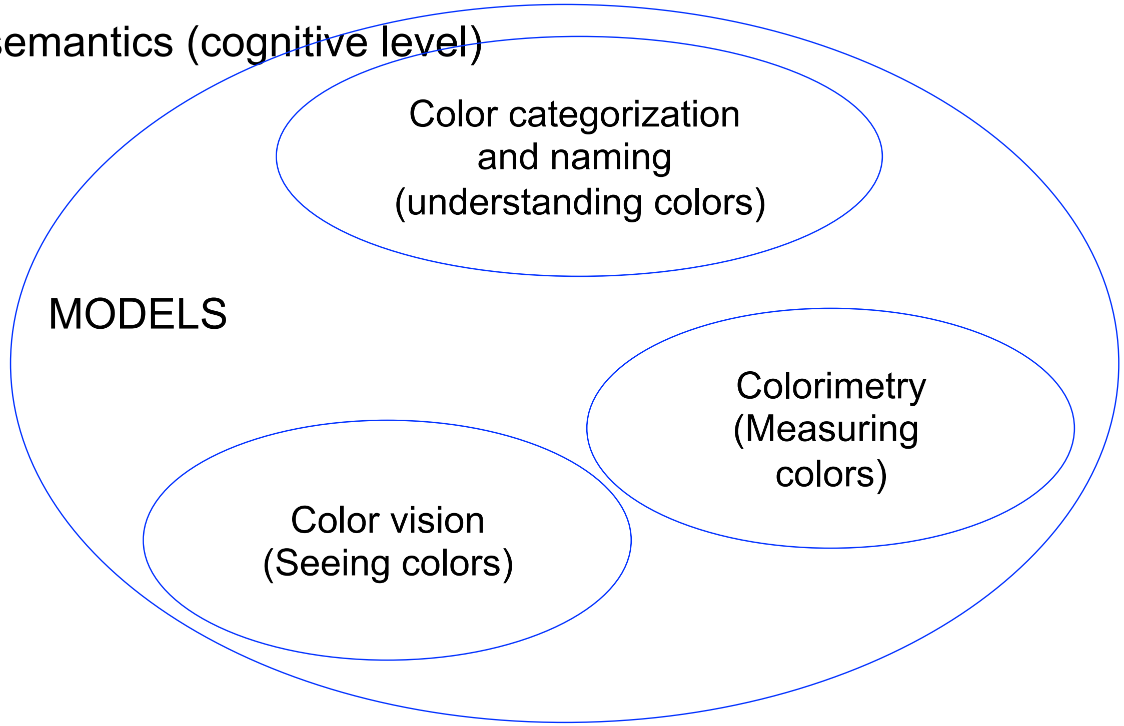


⇔ *Photometric* quantities (only concern the visible spectrum)

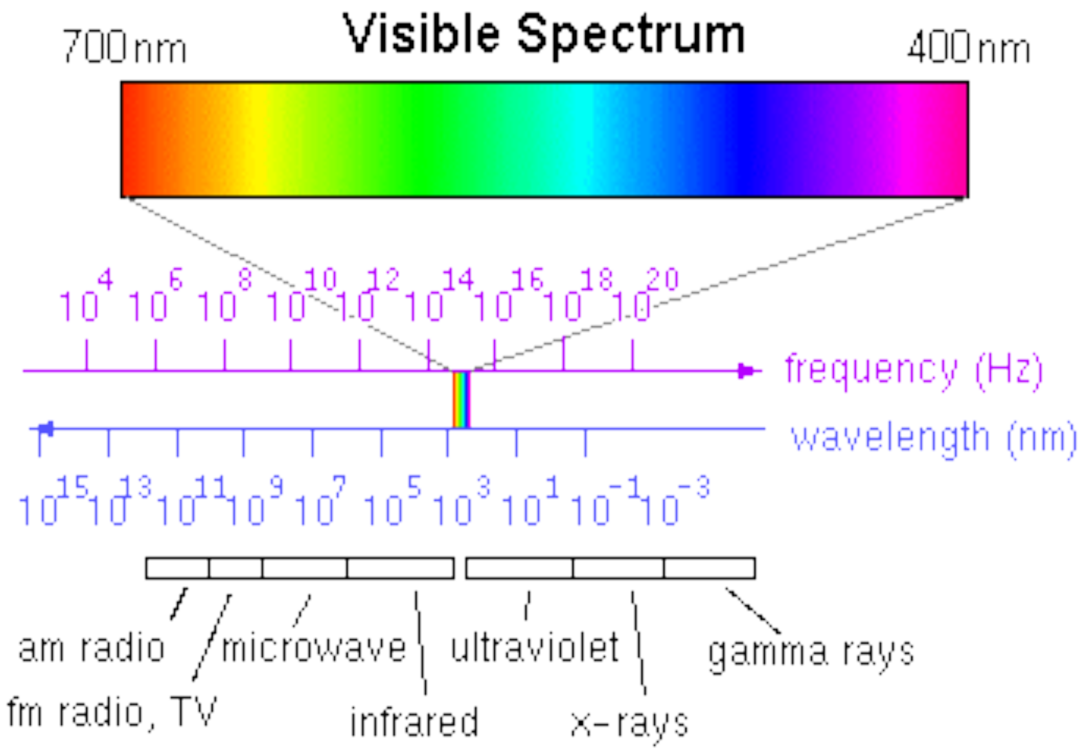


Color

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

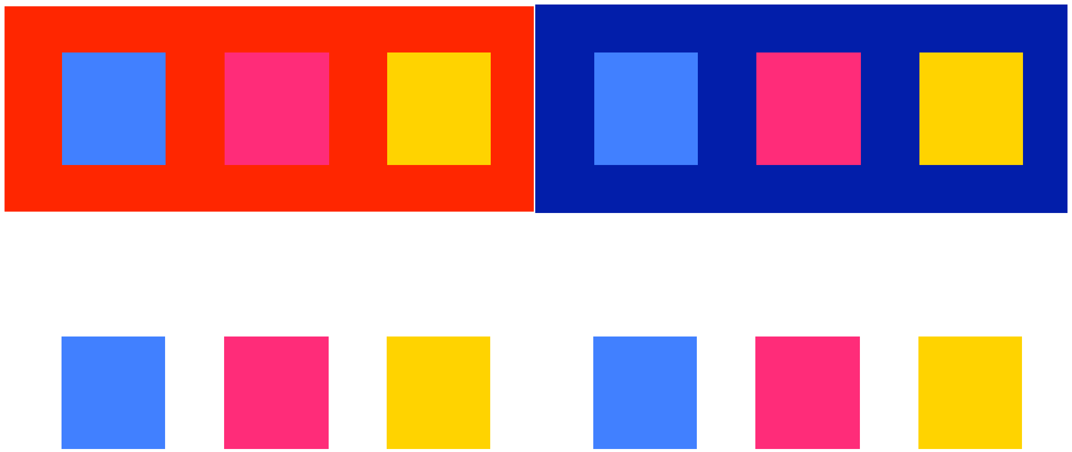


The physical perspective



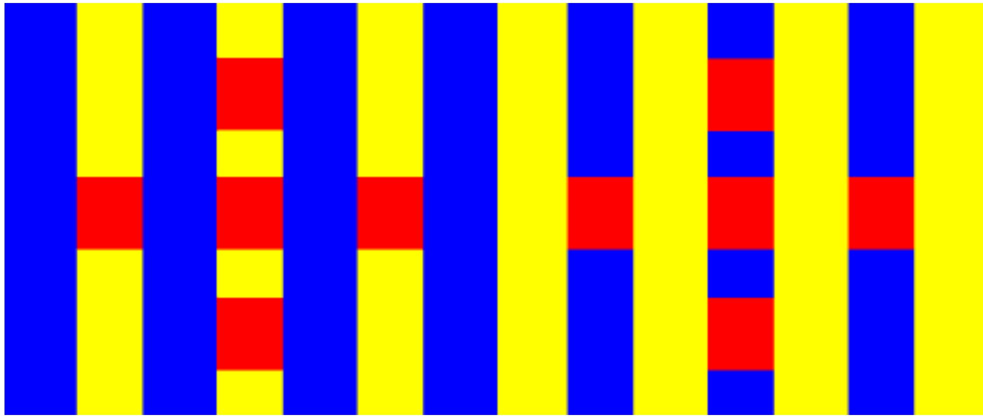
The perceptual perspective

Simultaneous contrast



Color

- Chromatic induction



Basic quantities

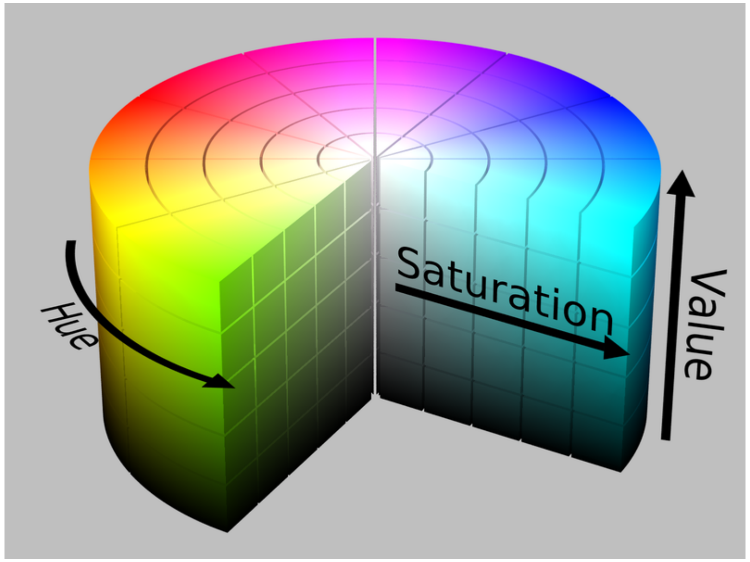
- **Radiance**: total amount of energy that flows from the light source
  - Physical quantity
  - measured in Watts [W] by a radiometer
- **Luminance**: measure of the amount of light emitted by the source that a person *perceives*
  - *Perceptual* quantity
  - measured in lumens [lm]
  - it is assessed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

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

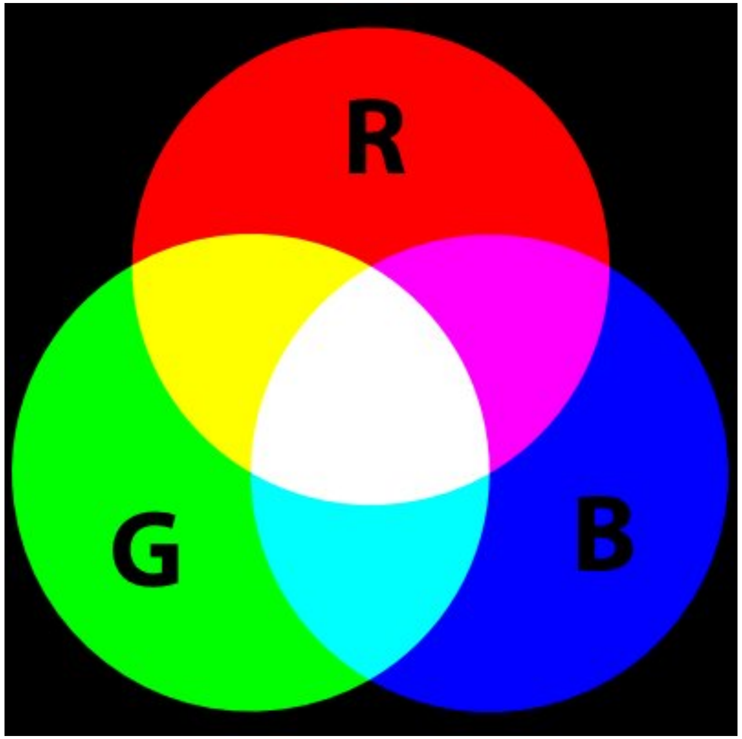
Color models

- 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

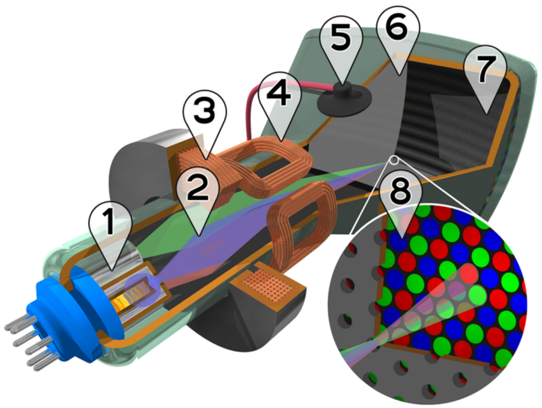
- Additive color model
  - The additive reproduction process usually uses red, green and blue light to produce the other colors



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

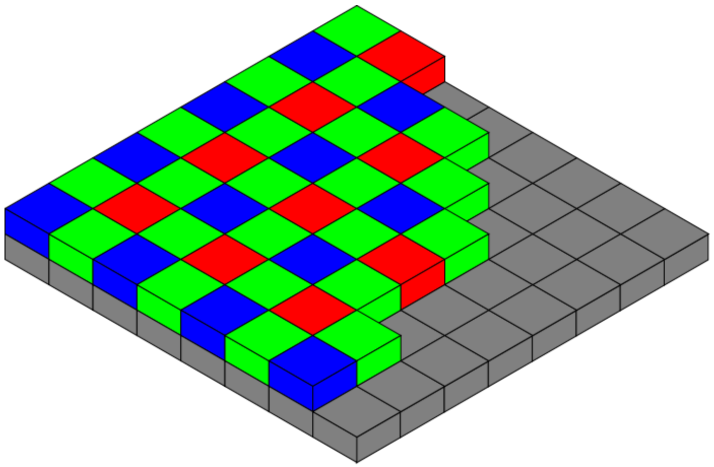


LCD

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

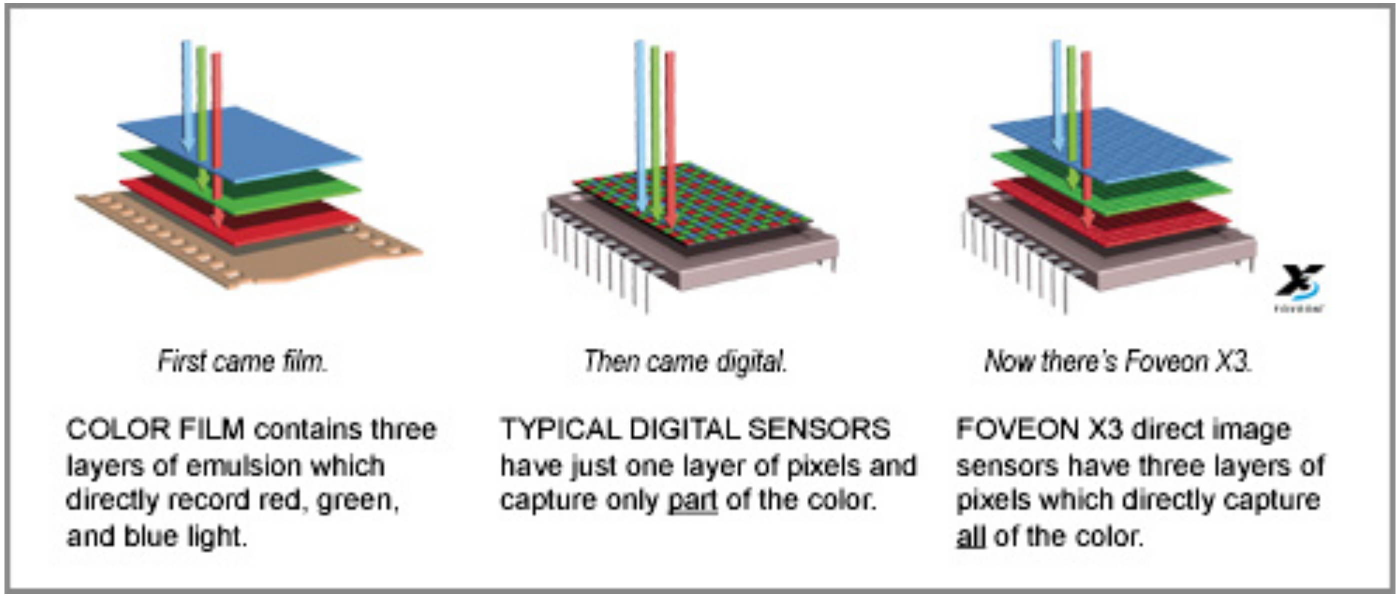
RGB digital cameras

- 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

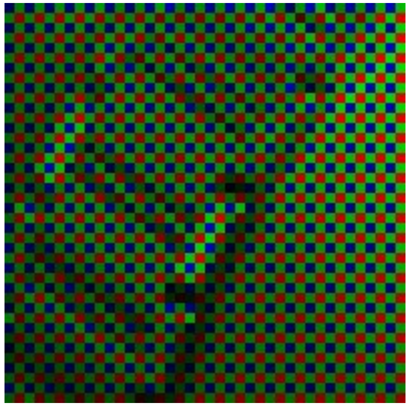
- CCD cameras with full color sensors
  - The three color channels are recorded in each physical location (pixel)



RGB digital cameras

Full color sensors

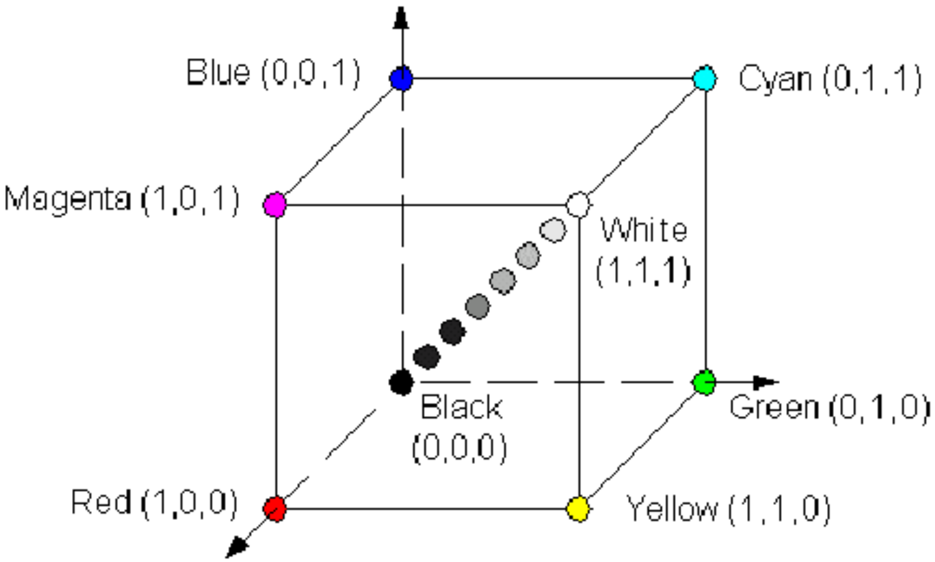
Image as seen through a Bayer sensor

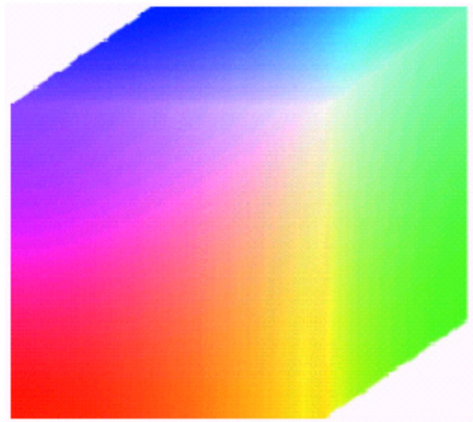


Reconstructed image after demosaicing

JPEG compression was added to the images

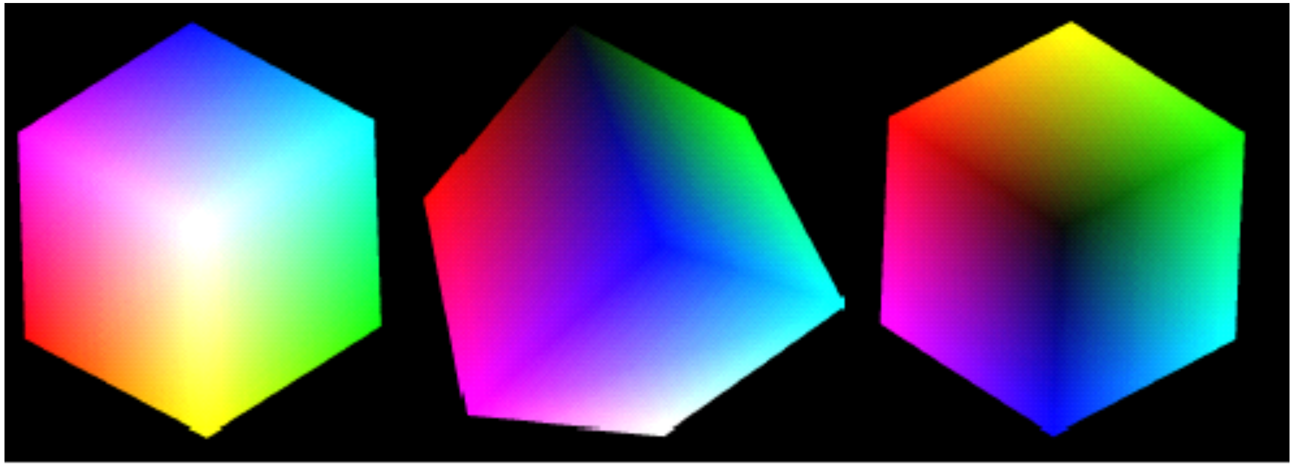
RGB model


Blue (0,0,1)
Cyan (0,1,1)
Magenta (1,0,1)
White
(1,1,1)
Black
(0,0,0)
Green (0,1,0)
Red (1,0,0)
Yellow (1,1,0)

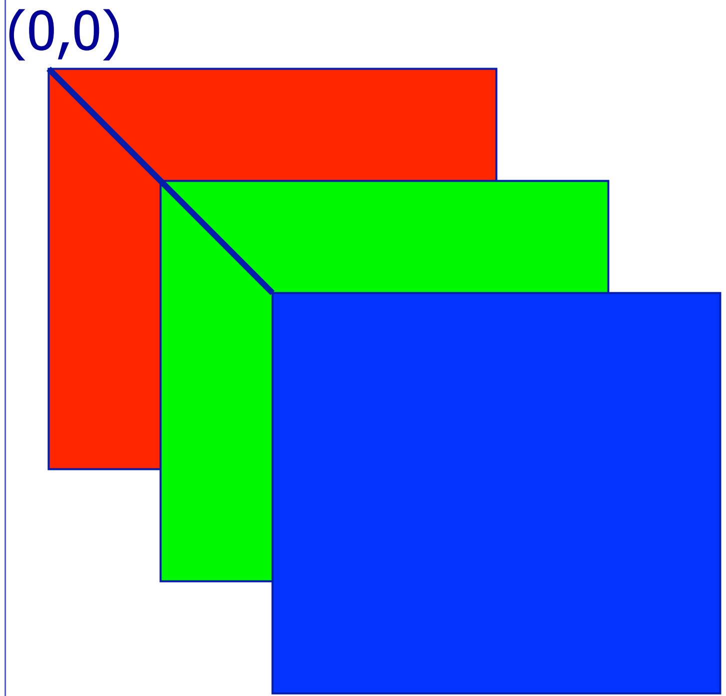


RGB model

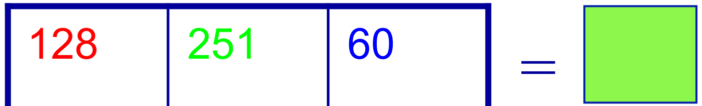
- Normalized values in [0,1] (chromaticity coordinates) may be convenient for some applications
- For a given device, the set of manageable colors lies inside the RGB cube



RGB model



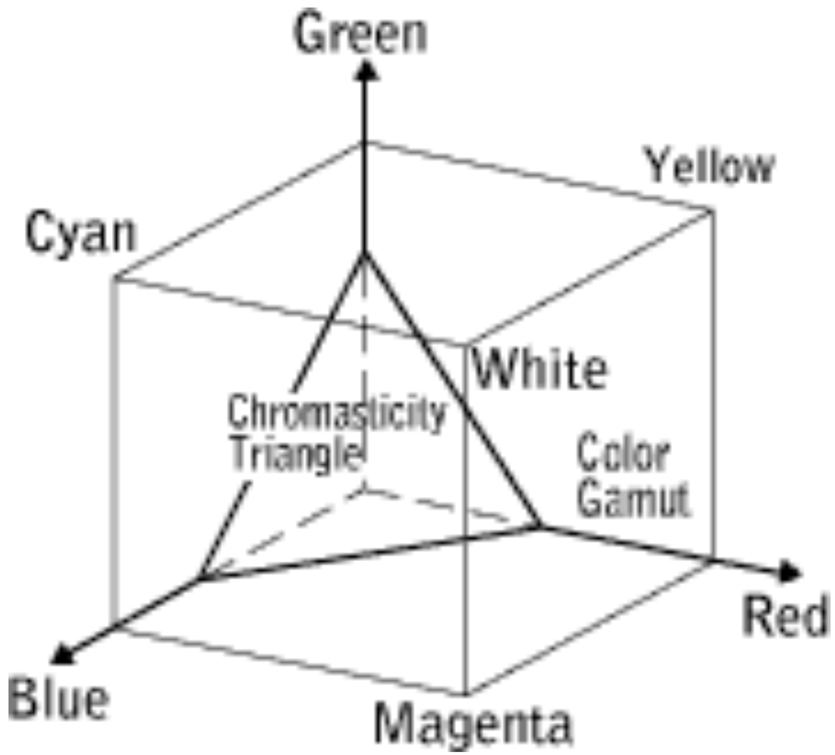
A single pixel consists of three components.



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

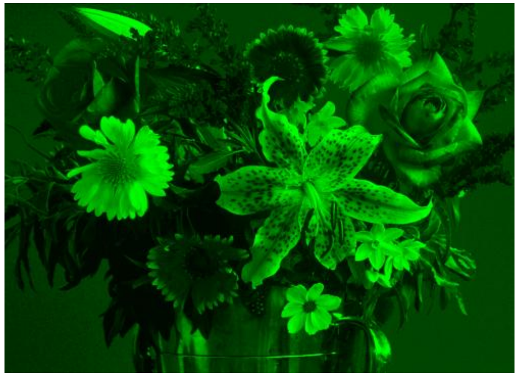
RGB Color Space



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

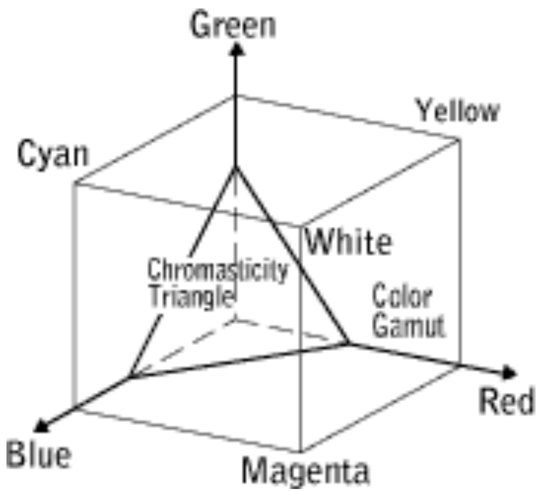
Red

Green

Blue

Device-oriented color models: CYM(K)

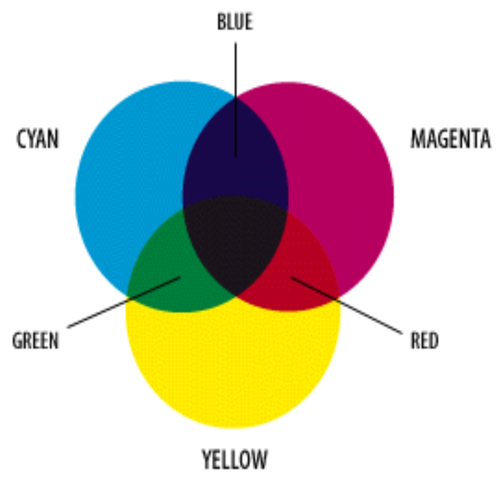
- Cyan, Yellow and Magenta are the “secondary” colors of light or the “primary” colors of pigments
- Model of “color subtraction”
- Used in printing devices

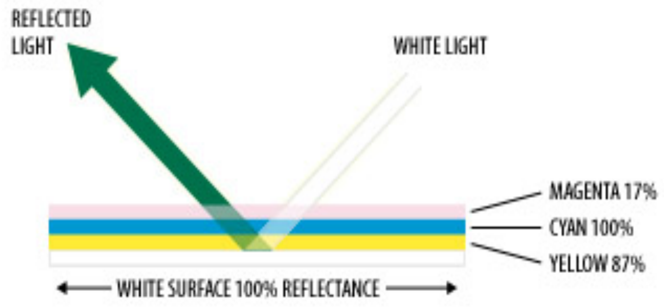


CMY(K)

- Color *subtraction*
  - Cyan, Magents, Yellow filters
    - The Y filter removes B and transmits the R ang 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

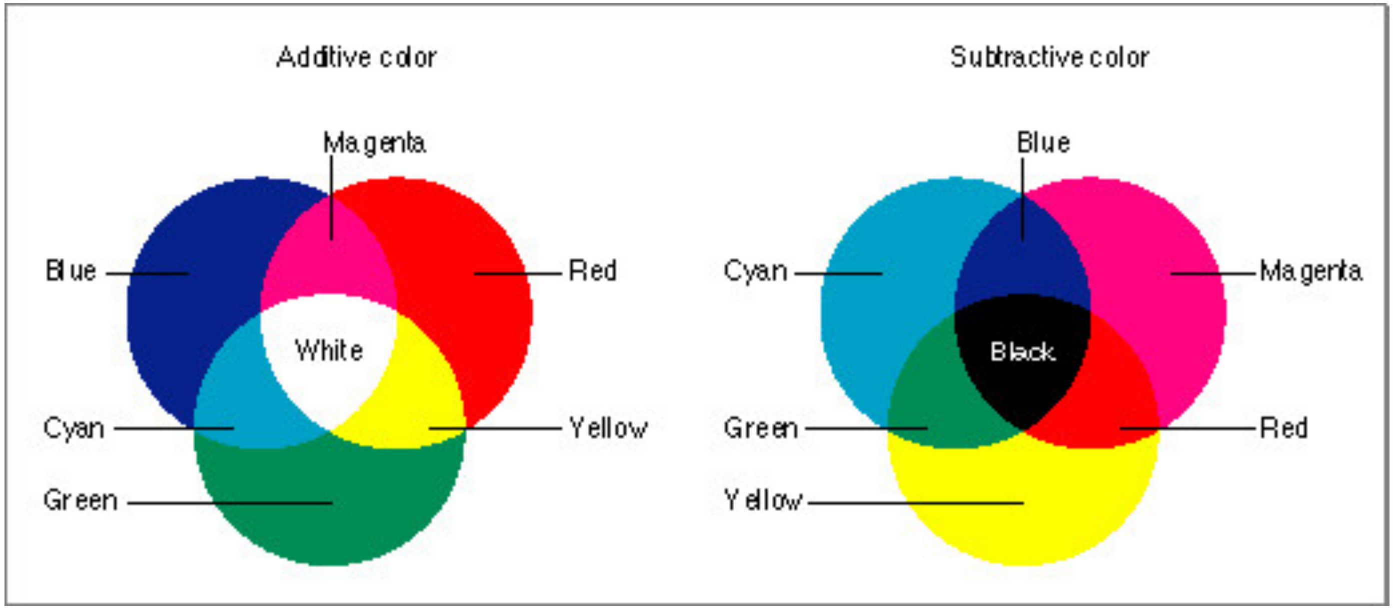




CMY model

- CMY (Cyan, Magenta, Yellow)
- Used in printing devices
- Subractive 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 **blu**

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

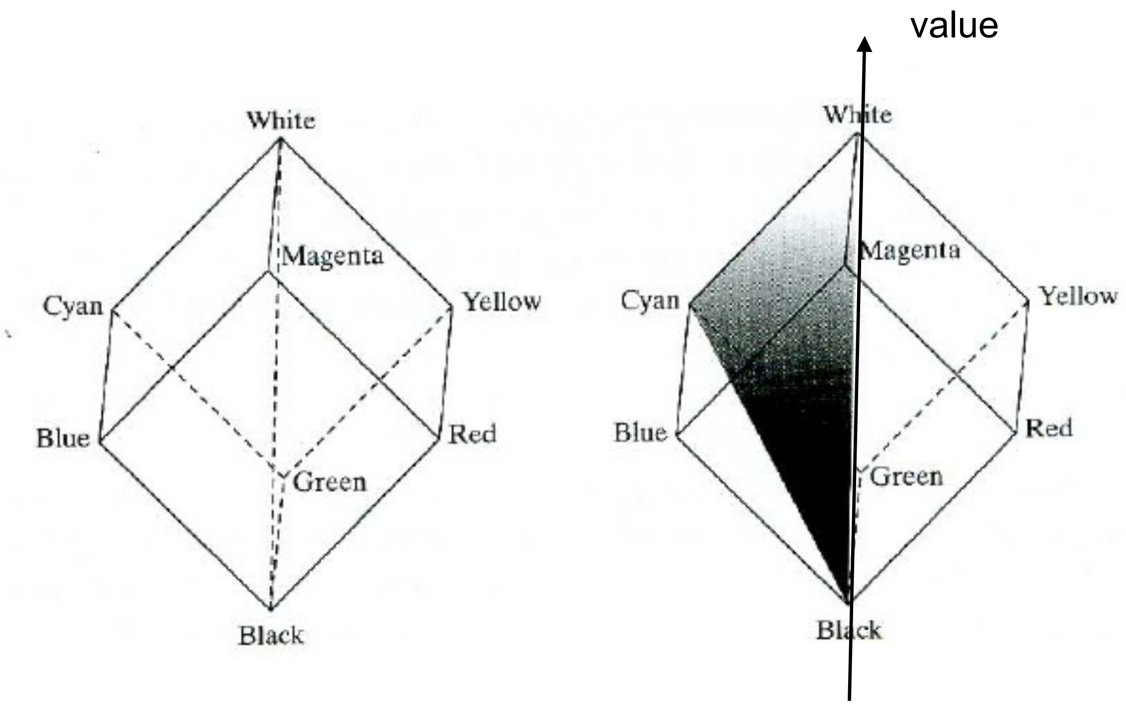
CMY(K) model

- 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



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

User-oriented CM

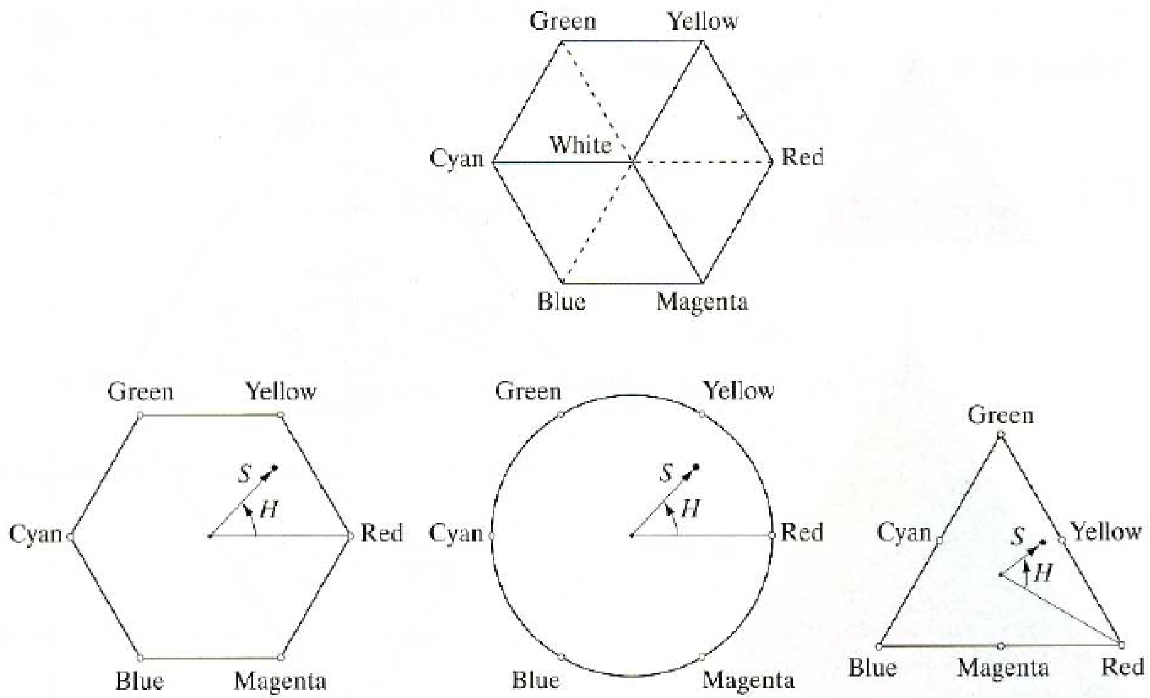
- HSV (Hue, Saturation, and Value). Sometimes variations include HSB (Brightness), HSL (Lightness/Luminosity), HSI (Intensity)
  - The *hue* of a color places it on the color wheel where the color spectrum (rainbow) is evenly spaced
  - The *saturation or chroma* of a hue defines its intensity
    - 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 cromaticity information!
2. Hue and saturation can be accessed independently from illumination

HSI

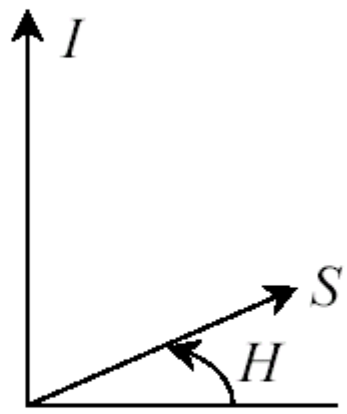


a
b c d

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

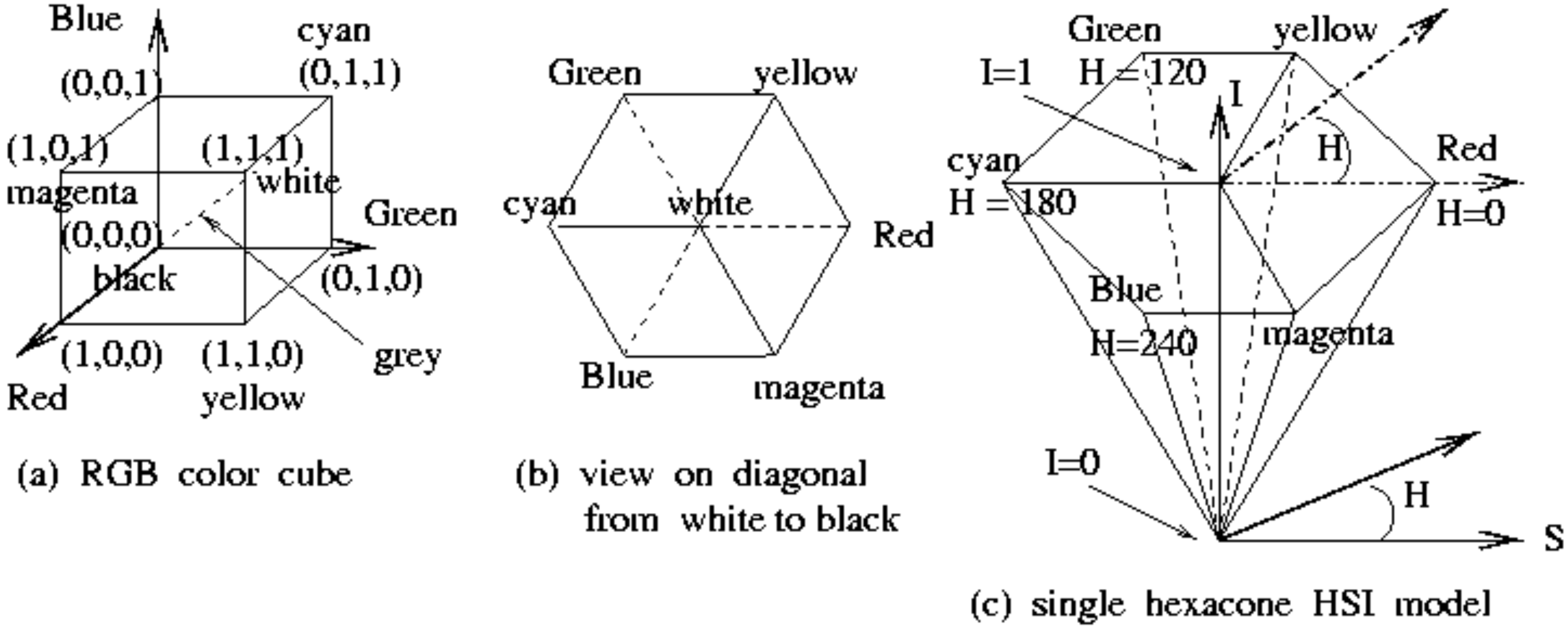
- Two values (H & S) encode *chromaticity*
- Convenient for *designing* colors
- Hue H is defined by and angle between 0 and 2π:
  - "red" at angle of 0;
  - "green" at $2\pi/3$;
  - "blue" at $4\pi/3$



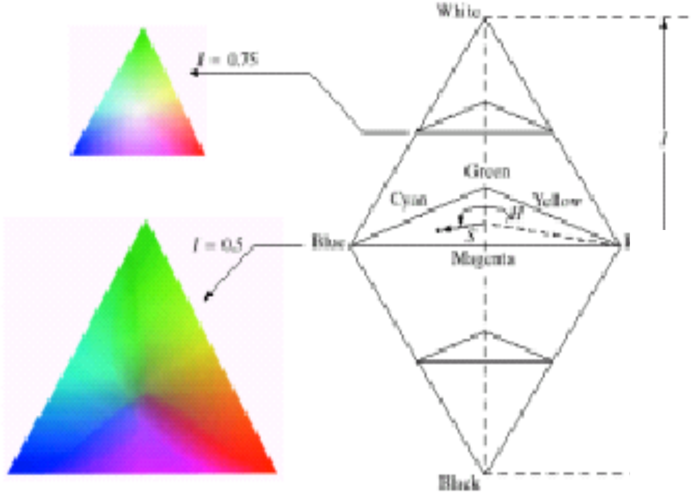
- Saturation S models the *purity* of the color
  - S=1 for a completely pure or saturated color
  - S=0 for a shade of "gray"

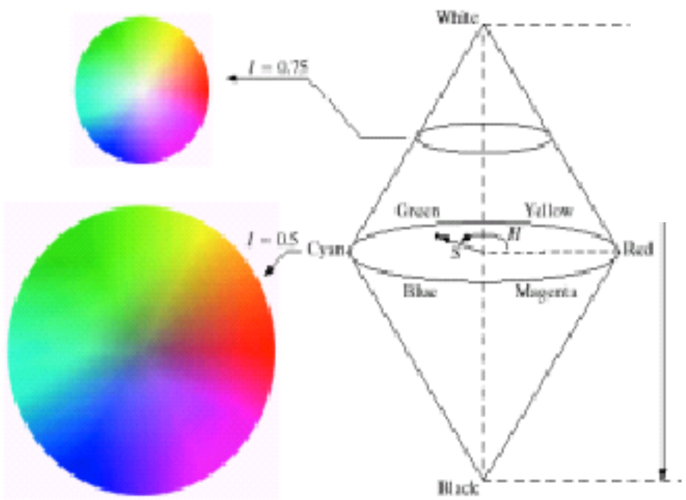
Color hexagon for HSI (HSV)

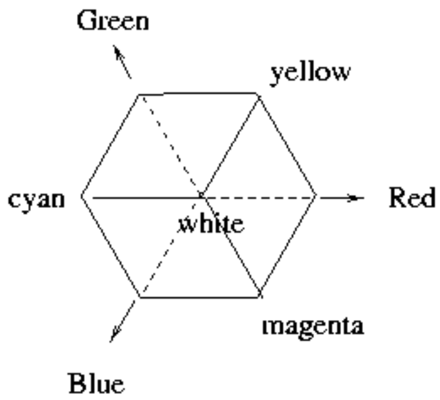
- Color is coded relative to the diagonal of the color cube. Hue is encoded as an angle, saturation is the relative distance from the diagonal, and intensity is height.

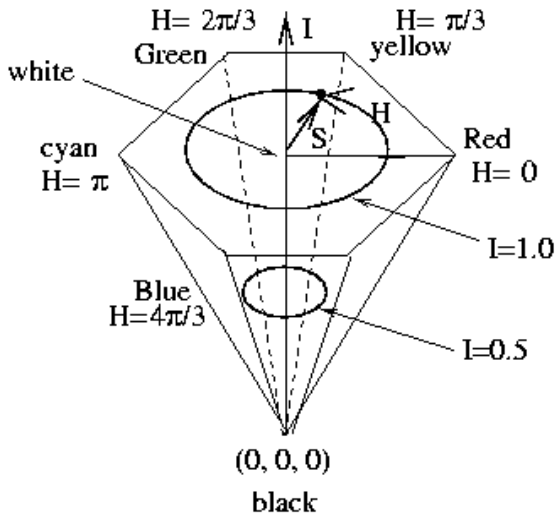


Variations on the theme





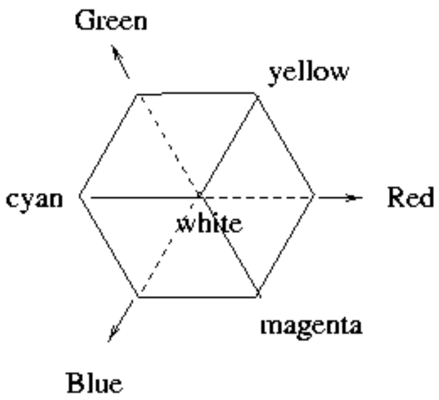


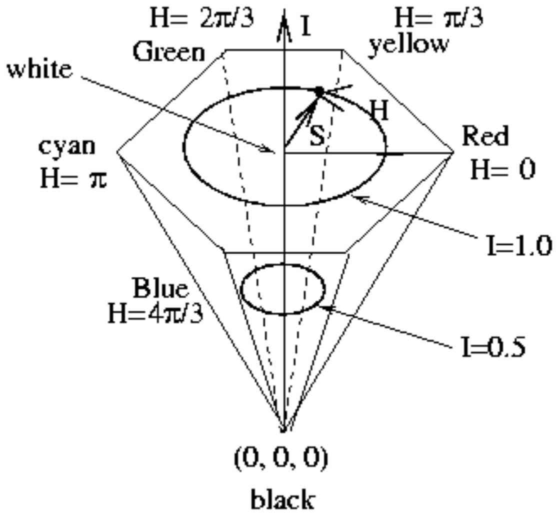


The shape in the plan does not matter because the one can always be related to the other by a geometric transformation

Color hexacone for HSI (HSV)

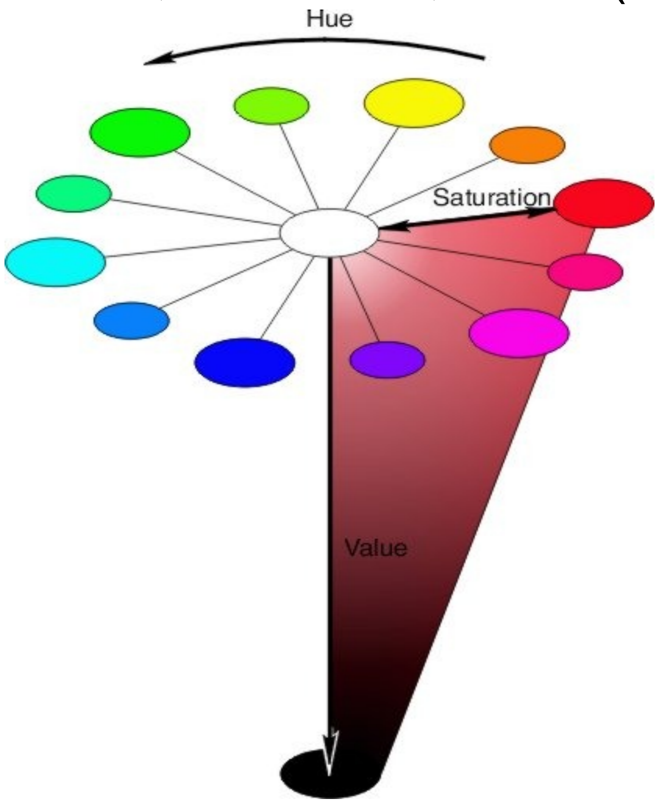
- (Left) Projection of RGB cube perpendicular to the diagonal (0,0,0) – (1,1,1).
- Color names now at vertices of a hexagon.
- Colors in HIS :
  - intensity I is vertical axis
  - hue H is angle with R at 0
  - saturation is 1 at periphery and 0 on I axis

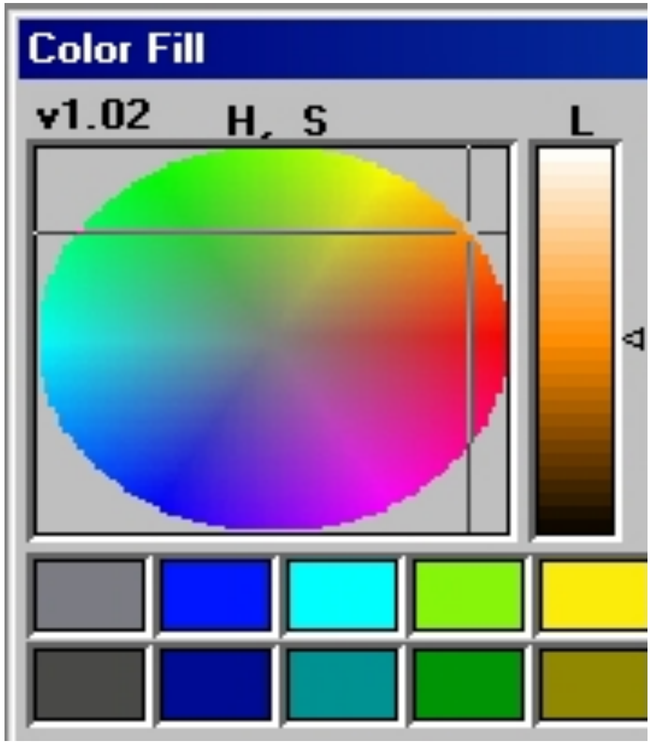




HSI-like model

- Hue, Saturation, Value (HSV) model



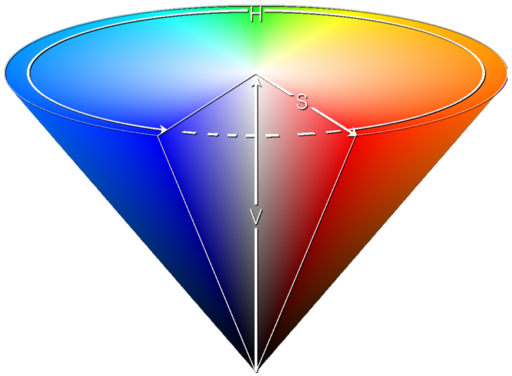


from http://www2.ncsu.edu/scivis/lessons/colormodels/color_models2.html#saturation.

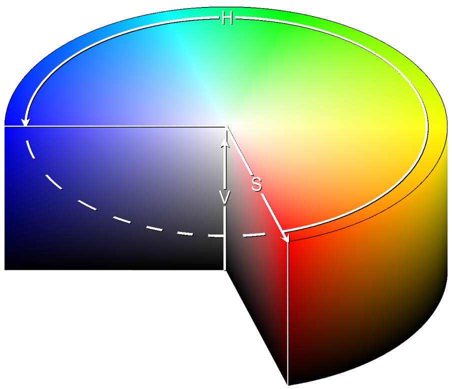
HSV, HSL

Hue, Saturation, Value (Brightness)

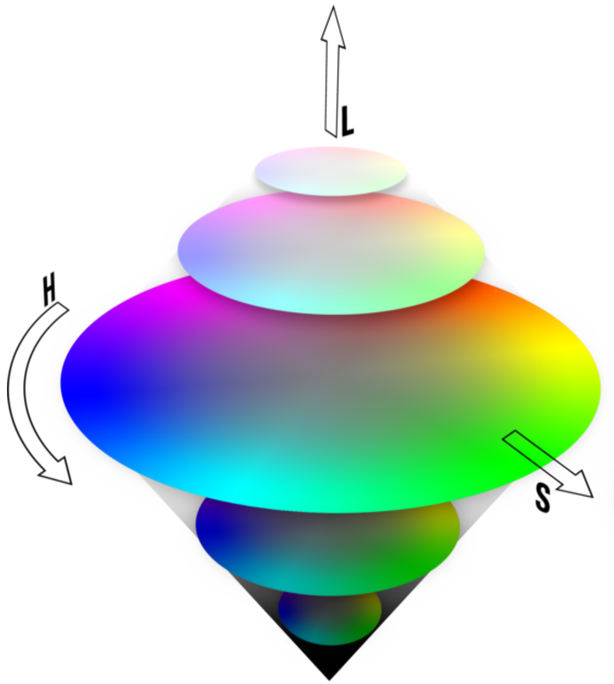
HSV cone



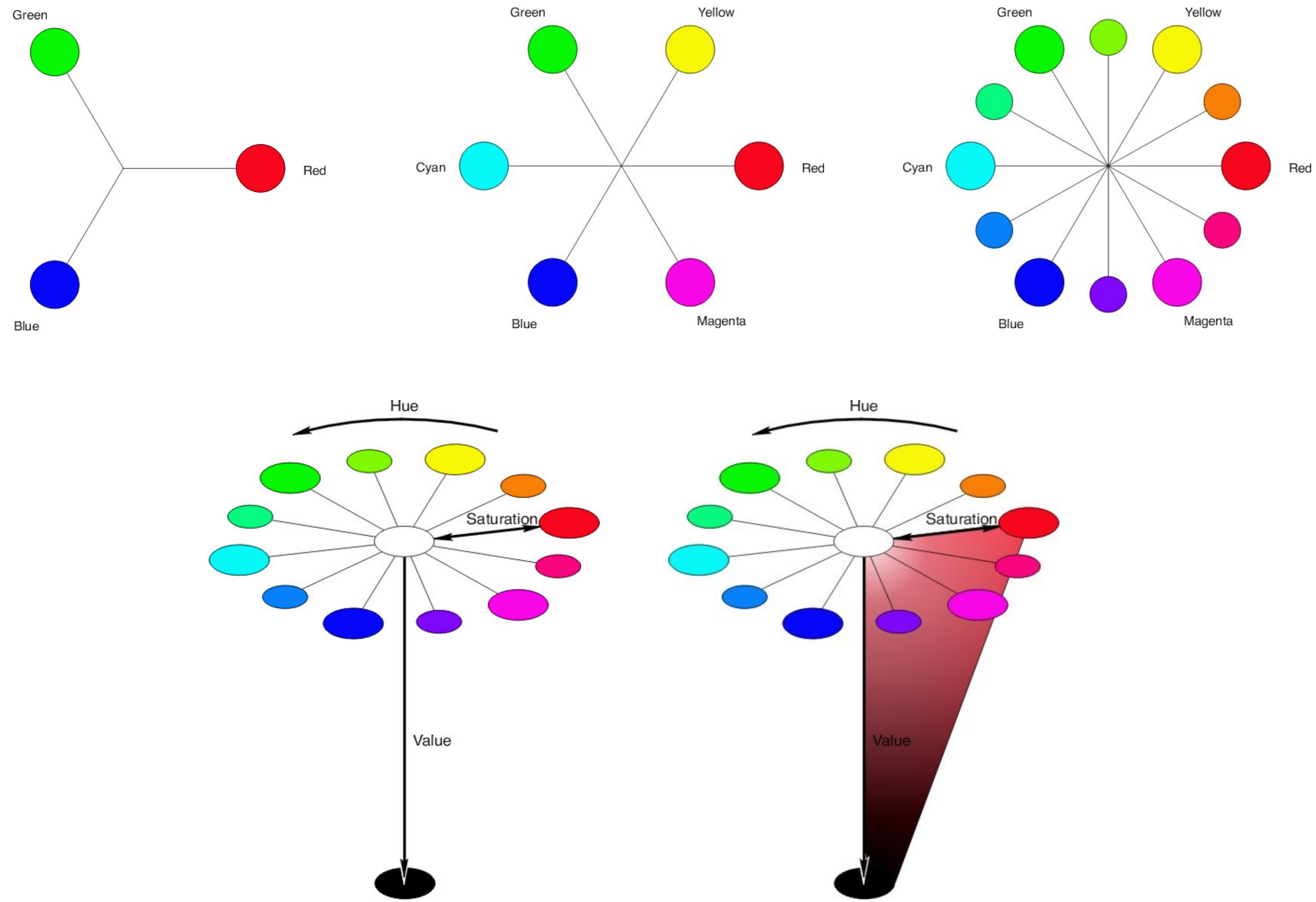
HSV cylinder



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

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

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

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

Finally, the intensity component is given by

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

RGB 2 HSI

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

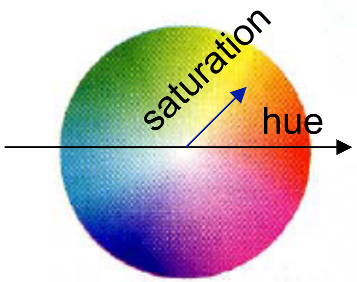
θ is measured conterclockwise from the red axis

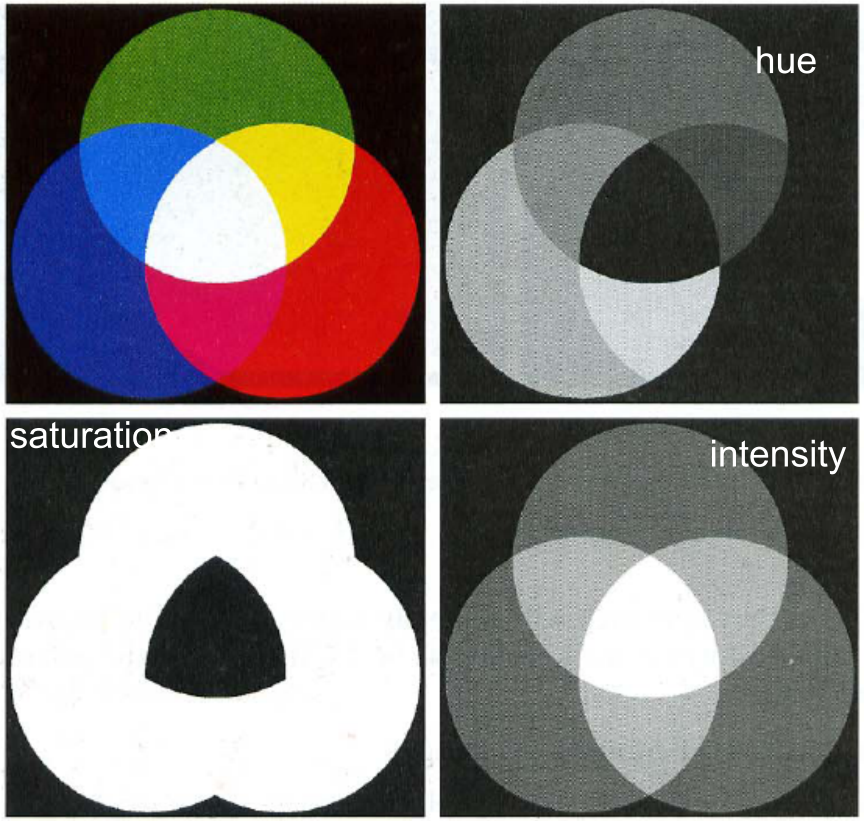
H can be normalized to be in $\{0,1\}$ by dividing by 360

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

The inverse formulas are also defined.

RGB vs HSI





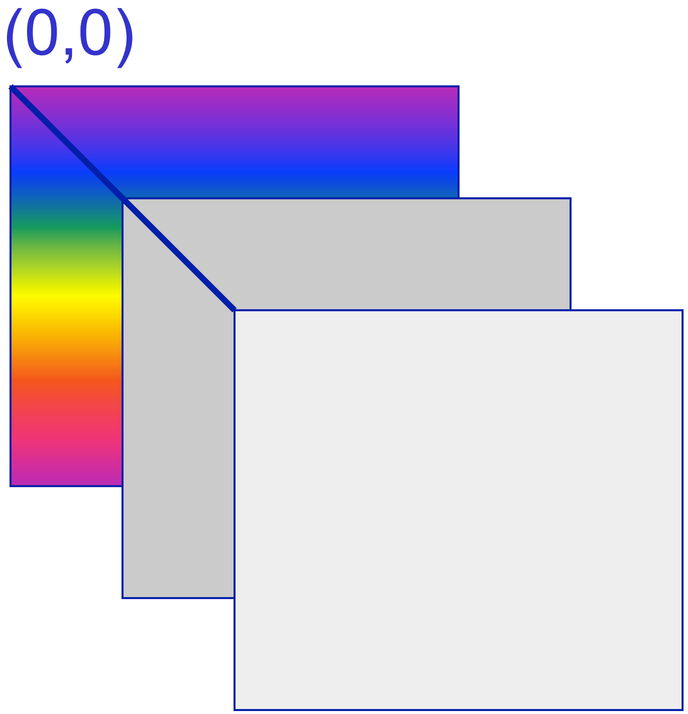
a b
c d

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

User-oriented CM

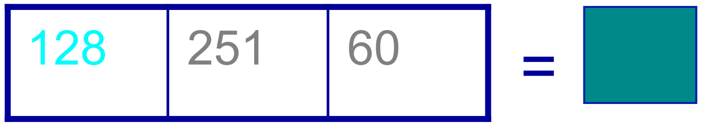
- Drawbacks
  - Singularities in the transform (such as undefined hue for achromatic points)
  - Sensitivity to small deviations of RGB values near the singularities
  - Numerical instability when operating on hue due to its angular nature

HSI Representation



A single pixel consists of three components.

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



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

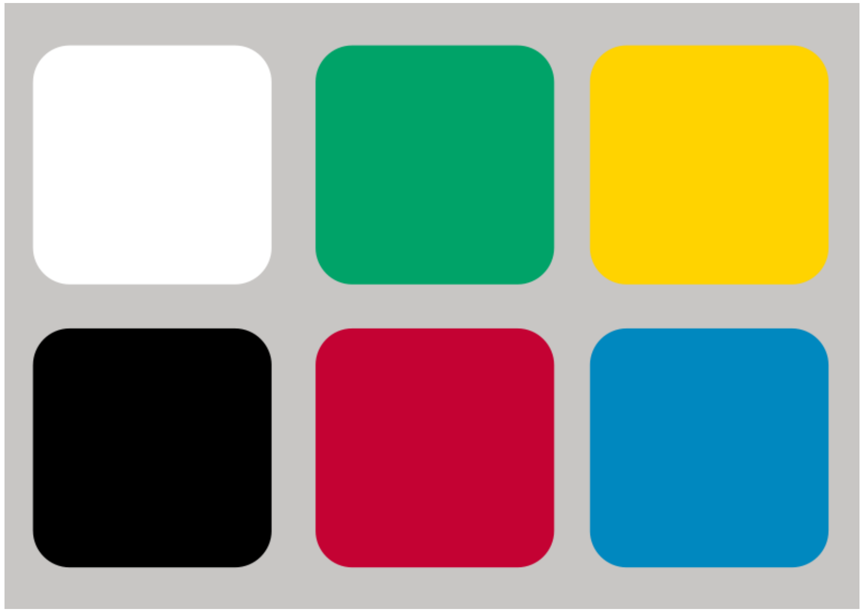
(Left) Image of food originating from a digital camera;

(center) saturation value of each pixel decreased 20%;

(right) saturation value of each pixel increased 40%.

Opposite channels model

- Encode color images taking human perception into account
- RGB -> luminance + 2 chrominances
- Going from Y’ (physical entity) to Y implies a non linear operation



YUV Color model

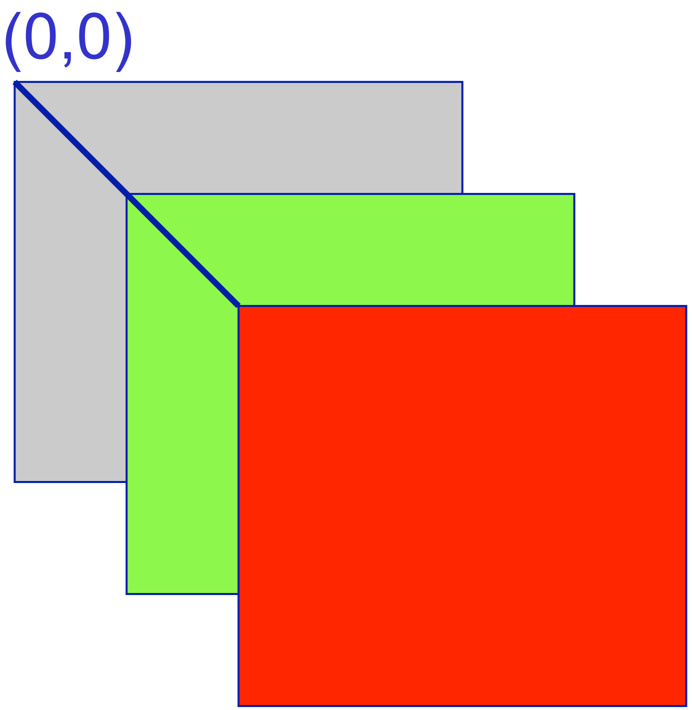
- YUV color model “imitates” human vision.
  - Implementation of the opposed channel model, also called luminance / chrominance color spaces
- Historically, YUV color space was developed to provide compatibility between color and black /white analog television systems.
  - YUV color image information 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.

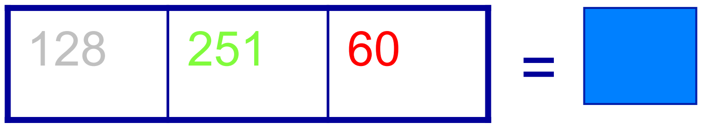
YUV color model

- Color channels
  - Y: luminance
  - UV (Cb, Cr): chrominance. These are often downsampled exploiting the lowers 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



A single pixel consists of three components.
Each pixel is a Vector / Array.



Pixel-Vector in the computer memory

Final pixel in the image

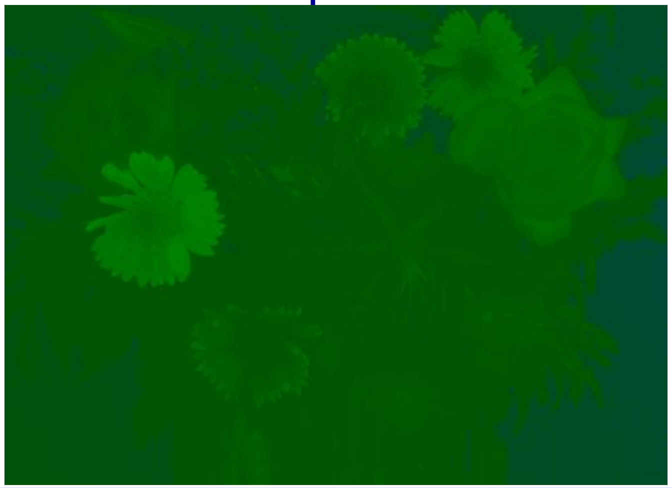
Same Caution as before applies here!

YUV example

Original Image

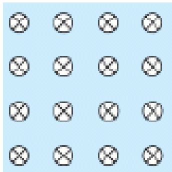
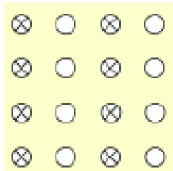
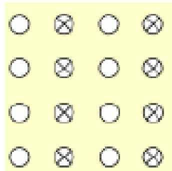
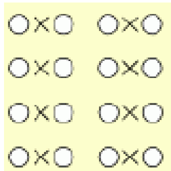
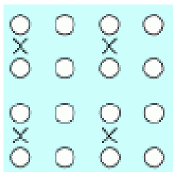
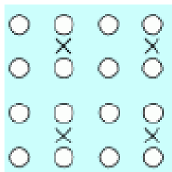
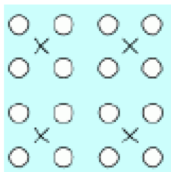
Y-Component

U-Component



V-Component

YUV possible subsampling patterns

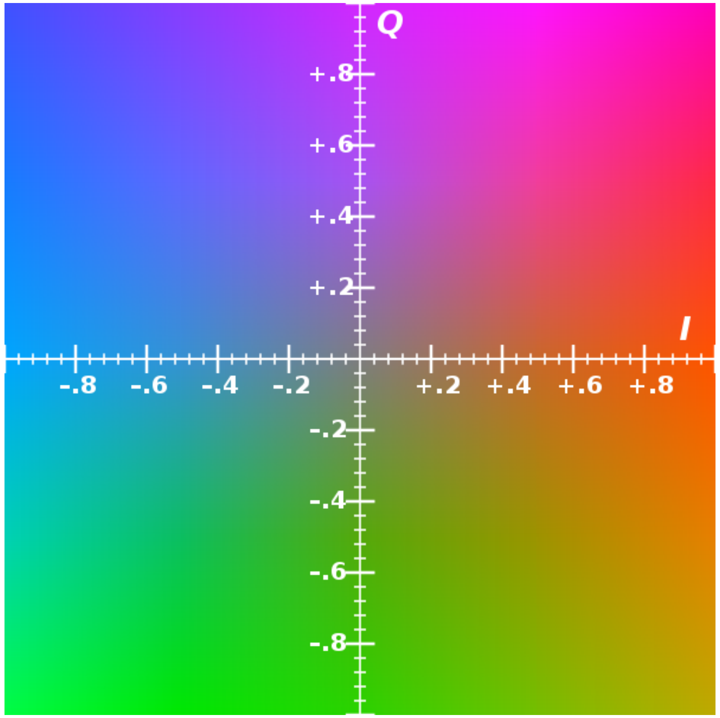
Sub sampling ratio	Sub sampling pattern				Color component size		
	Uniform	Co site Even	Co site Odd	Centered	Luma Y	Chroma Cb	Chroma Cr
4:4:4					1	1	1
4:2:2					1	1/2	1/2
4:2:0					1	1/4	1/4

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 (National Television Color System)
- Y is the luminance, meaning that light intensity is nonlinearly encoded based on gamma corrected RGB primaries



The YIQ color space at Y=0.5. Note that the I and Q chroma coordinates are scaled up to 1.0. See the formulae below in the article to get the right bounds.

YIQ

- 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
- CIE-XYZ
- CIELAB
- CIELUV