Machine Vision: Color Image

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It is only after years of preparation that the young artist should touch color,

…. as a means of personal expression.

Henri Matisse

三原色

古诗?

忆江南·江南好

白居易

江南好，

风景旧曾谙。

日出江花红胜火，

春来江水绿如蓝。

能不忆江南？

Preview

Why use color in image processing?

- Color is a powerful descriptor that often simplifies object identification and extraction from a scene.

- Humans can discern thousands of color shades and intensities, compared to about only two dozen shades of gray.

Color image processing is divided into two major areas

- **Full color processing:** The image in question typically are acquired with a full color sensor, such as a color TV camera or color scanner.

- **Pseudo color processing:** The problem is one of assigning a color to a particular monochrome intensity or range of intensities.

- **Full color processing techniques** are now used in a broad range of applications.

Outlines

Focus

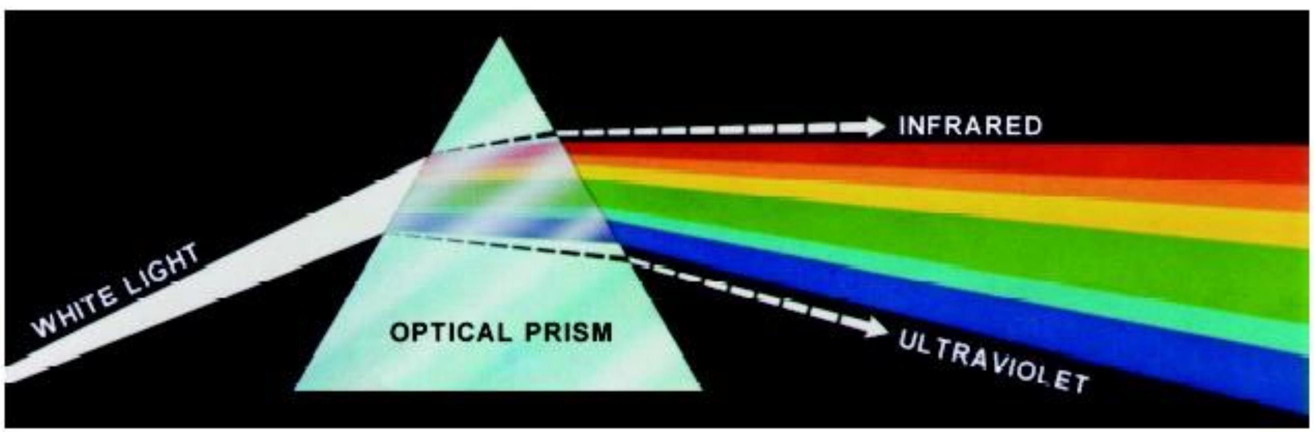
- Color Fundamentals
- Color Models
- Pseudo Color Image Processing
- Basics of Full Color Image Processing
- Color Transformations
- Smoothing and Sharpening

Color Fundamentals

Physical nature of color

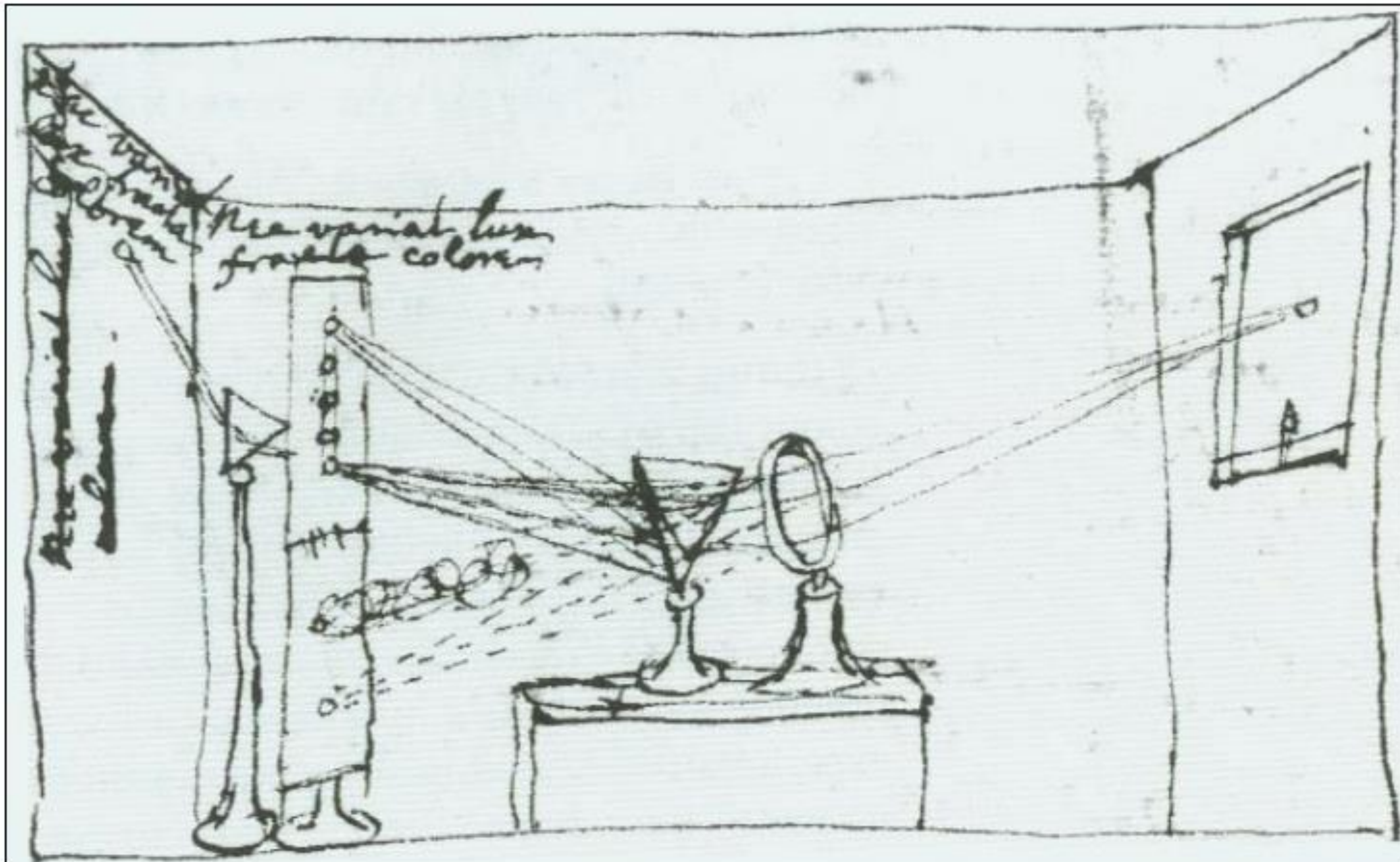
- In 1666, Sir Isaac Newton discovered a continuous spectrum of colors ranging from violet at one end to red at the other.

- The color spectrum may be divided into six broad region: violet, blue, green, yellow, orange, and red.



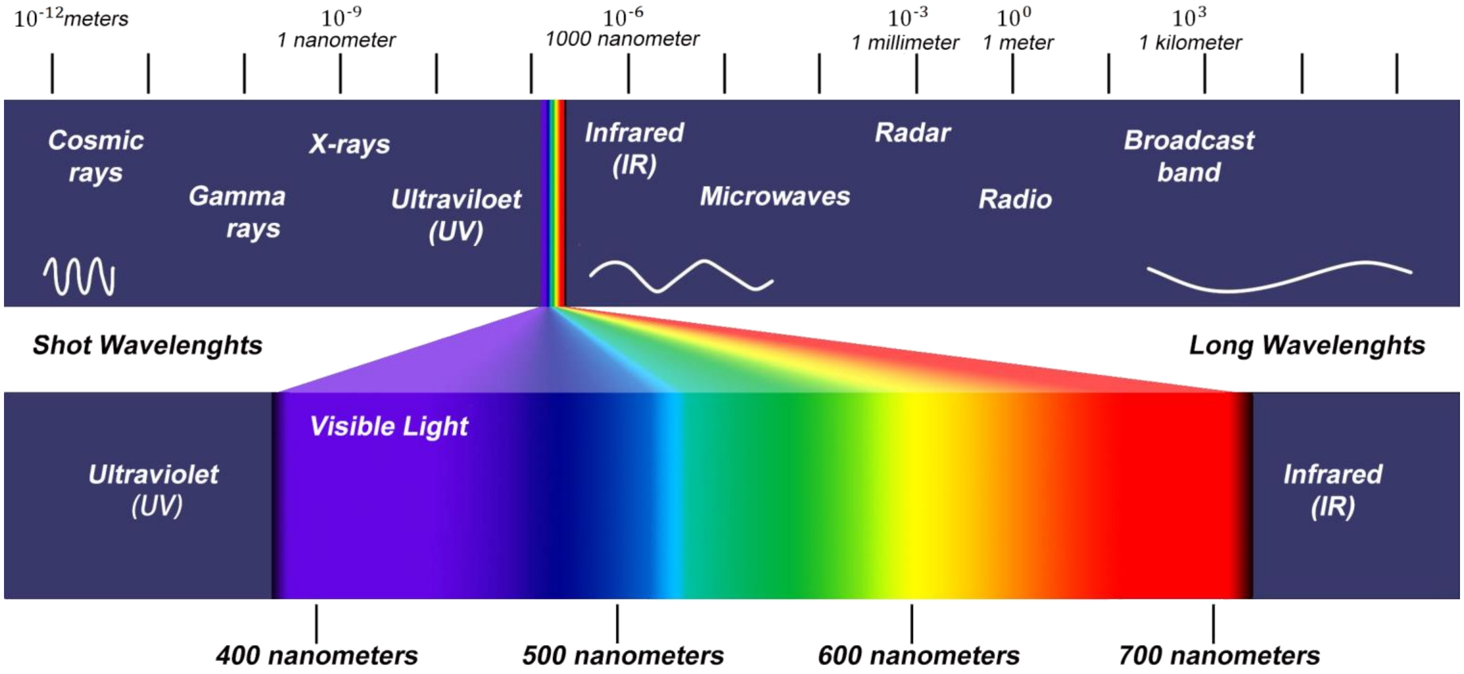
Color spectrum seen by passing white light through a prism.

Newton’s notebook



[Newton, 1666]

Electromagnetic Radiation -Spectrum



Wavelengths comprising the visible range of the electromagnetic spectrum.

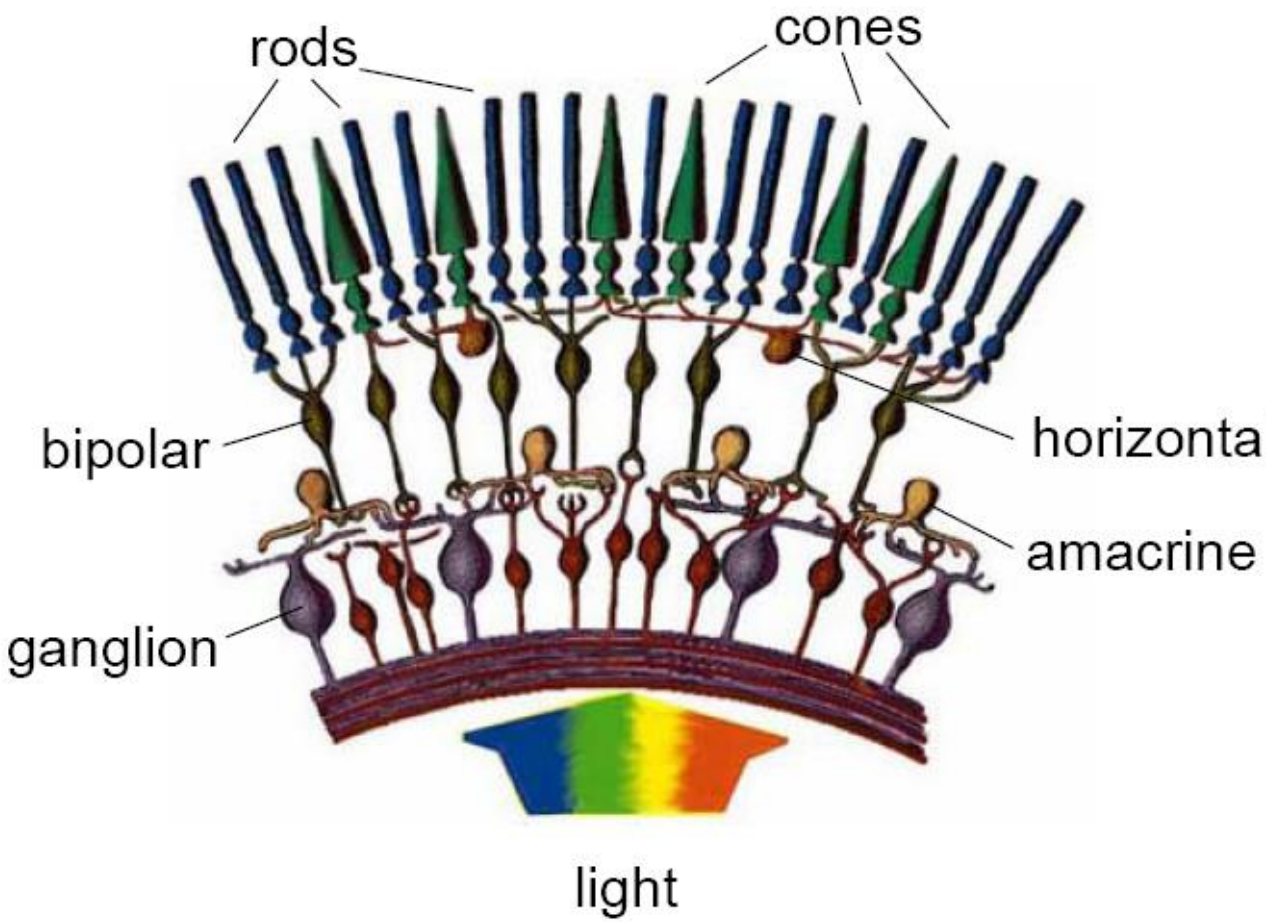
Trichromatic Color Theory

“tri”=three “chroma”=color
color vision is based on three primaries
(i.e., it is 3 dimensional).

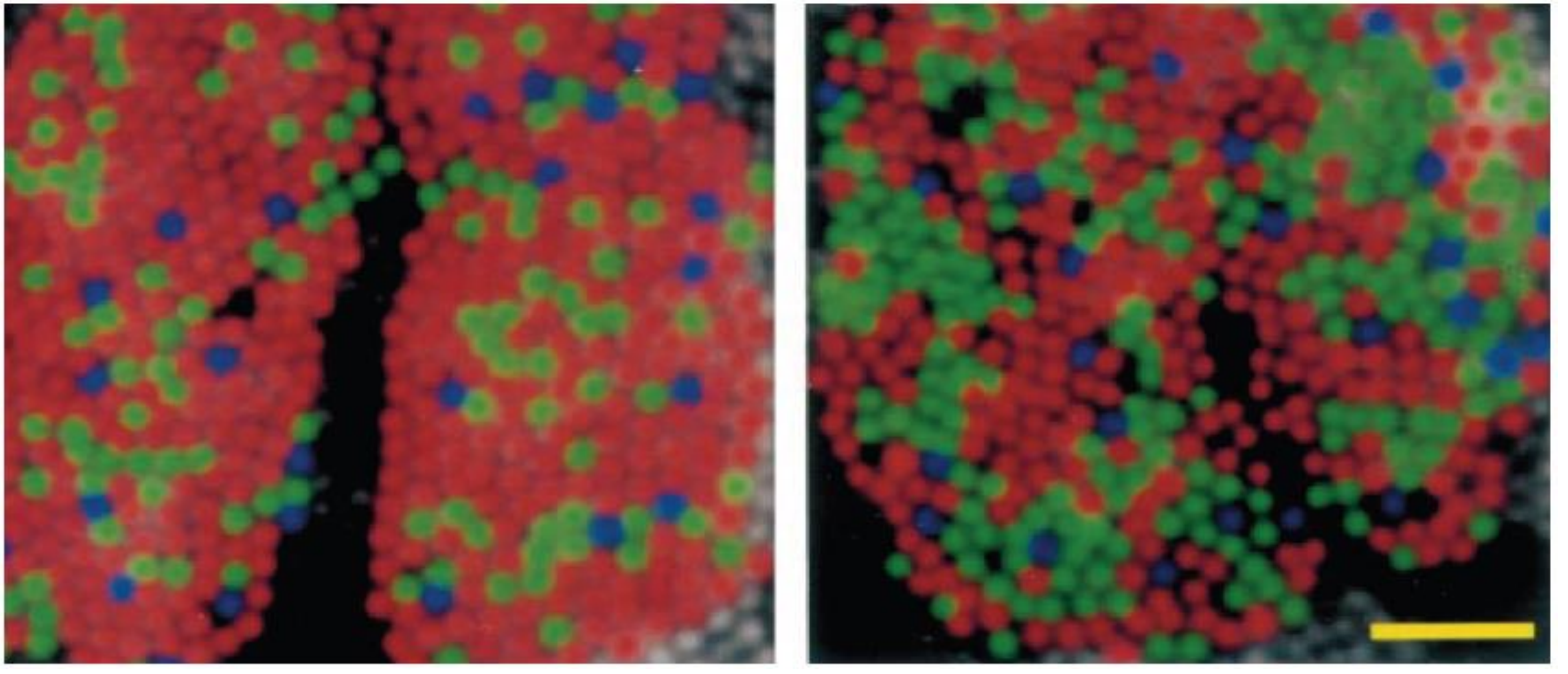
Thomas Young (1773-1829) -
A few different retinal receptors operating with different wavelength sensitivities will allow humans to perceive the number of colors that they do. Suggested 3 receptors.

Helmholtz & Maxwell (1850) -
Color matching with 3 primaries.

The Human Retina



Retinal Photoreceptors



Pseudo-color image of nasal retina, 1 degree eccentricity, in two male subjects, scale bar 5 arcmin of visual angle.

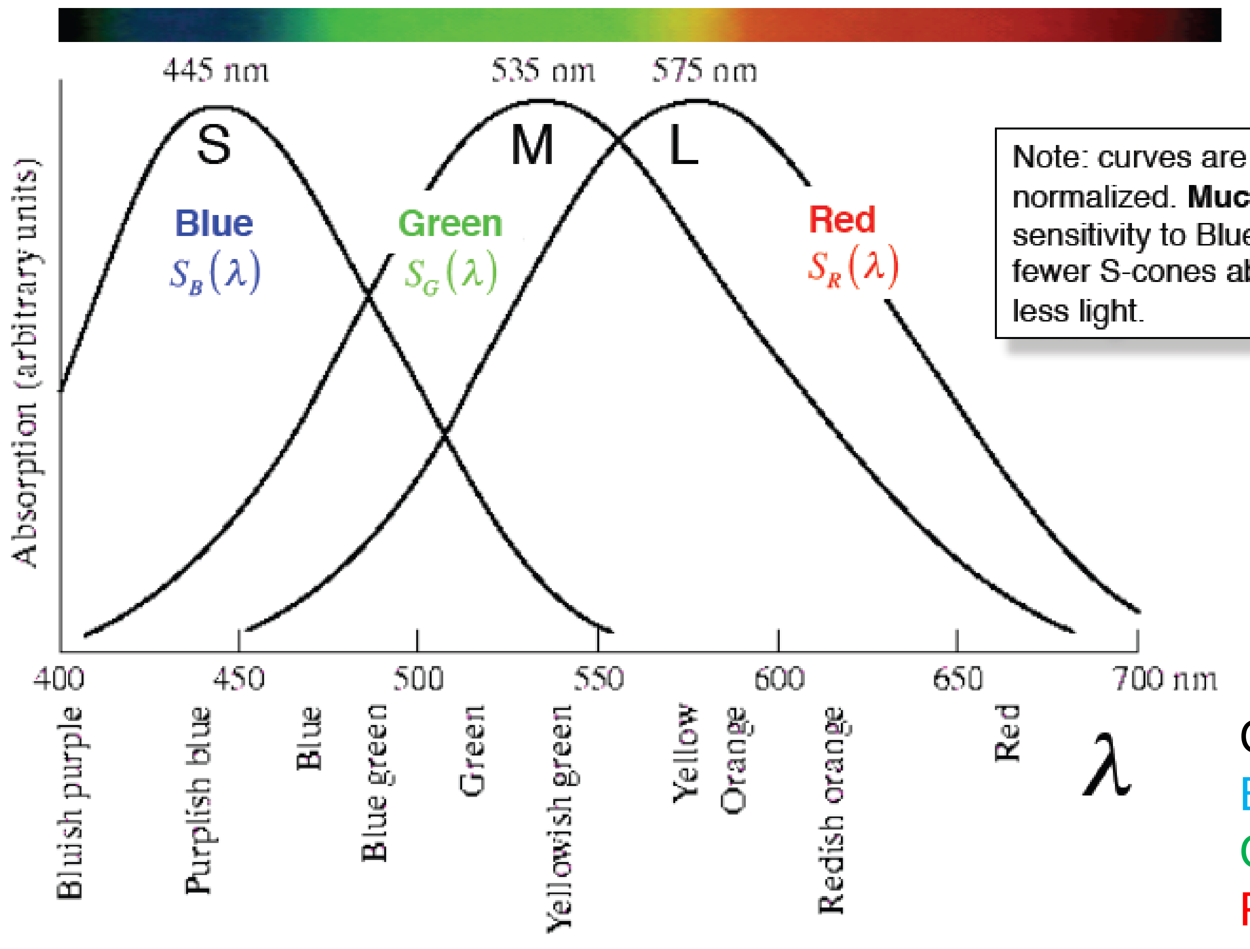
[Roorda, Williams, 1999]

Retinal Photoreceptors

Cones:

- High illumination levels (Photopic vision)
- 6-7 million cones in each eye.
- Only cones in fovea (aprox. 50,000).
- Density decreases with distance from fovea.
- 3 cone types differing in their spectral sensitivity: L , M, and S cones.
- Approximately 65% of all cones are sensitive to red light, 33% to green, 2% to blue but the most sensitive

Retinal Photoreceptors



Note: curves are normalized. **Much** lower sensitivity to Blue, since fewer S-cones absorb less light.

CIE standard:

B=435.8nm

G=546.1nm

R= 700nm

Color Models

Why ?

- the leaf is green
- tangerine is orange
- leaf can change its color

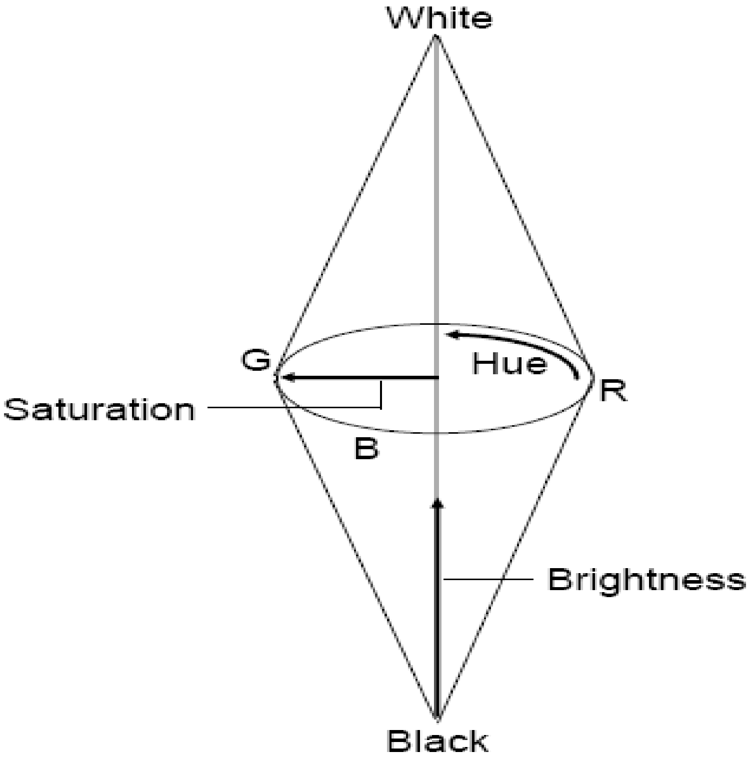
The Characteristics of Color

- Three characteristics to distinguish one color from another:
  - **Brightness** embodies the chromatic notion of intensity (black, grey, white ....)
  - **Hue** is an attribute associated with the dominant wavelength in a mixture of light waves (red, green, yellow, blue ...)
  - **Saturation** refers to the relative purity or the amount of white light mixed with a hue. (pink, bright red, ...)

Hue and saturation taken together are called *chromaticity*.

A color may be characterized by its *brightness* and *chromaticity*.

The Characteristics of Color



Tristimulus Values and Trichromatic Coefficients

Tristimulus values

The amount of red, green, and blue needed to form any particular color, denoted by *X*, *Y*, *Z* respectively.

Trichromatic coefficients

The *trichromatic* coefficients of a color are defined as

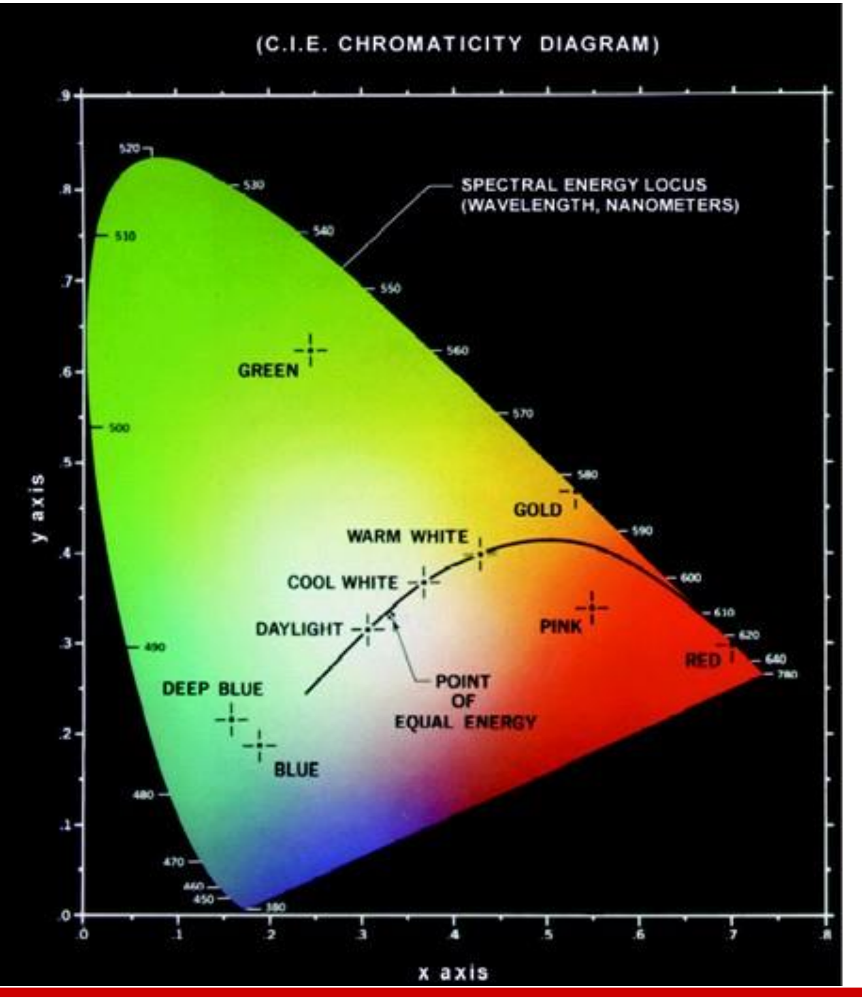
$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z}$$

and

$$x + y + z = 1$$

For any wavelength of light in the visible spectrum, the needed tristimulus values can be obtained from tables (Poynton [1996])

CIE Chromaticity diagram



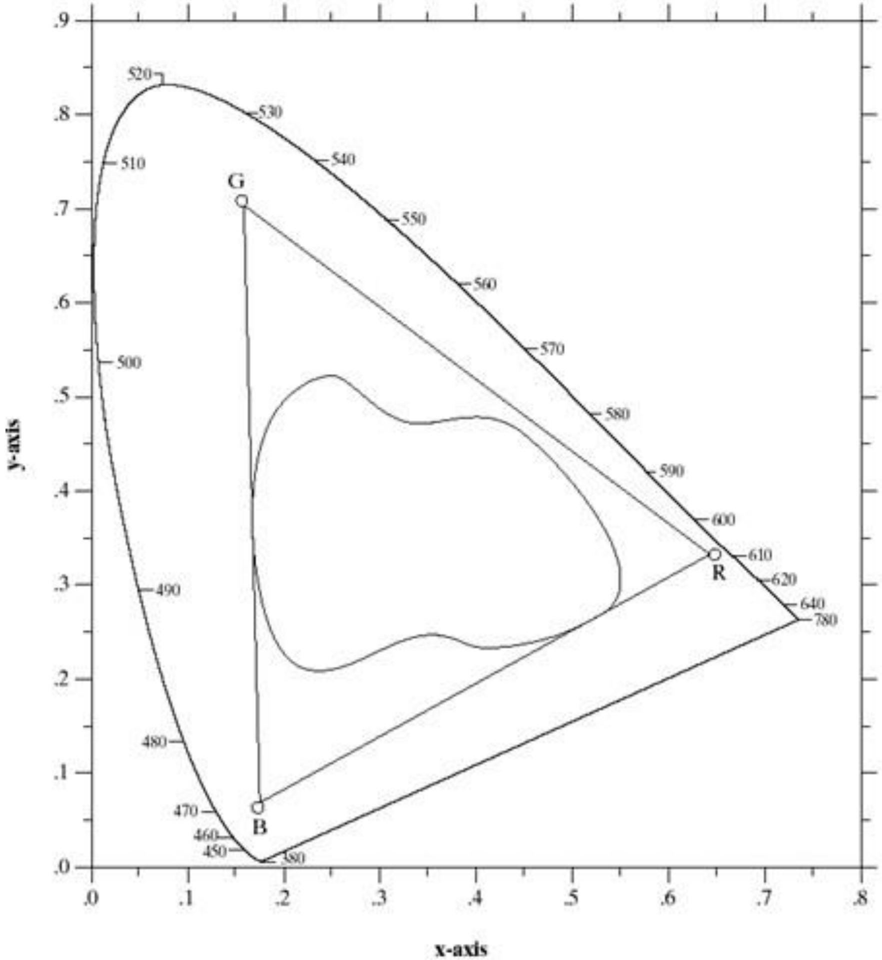
GREEN:

x: 25% (r)

y: 62% (g)

Z = 1-x-y=13%

CIE Chromaticity diagram



Typical color gamut of color monitors (triangle) and color printing devices (irregular region)

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Color Models

- RGB

  (red, green, blue ---- monitor/video camera)

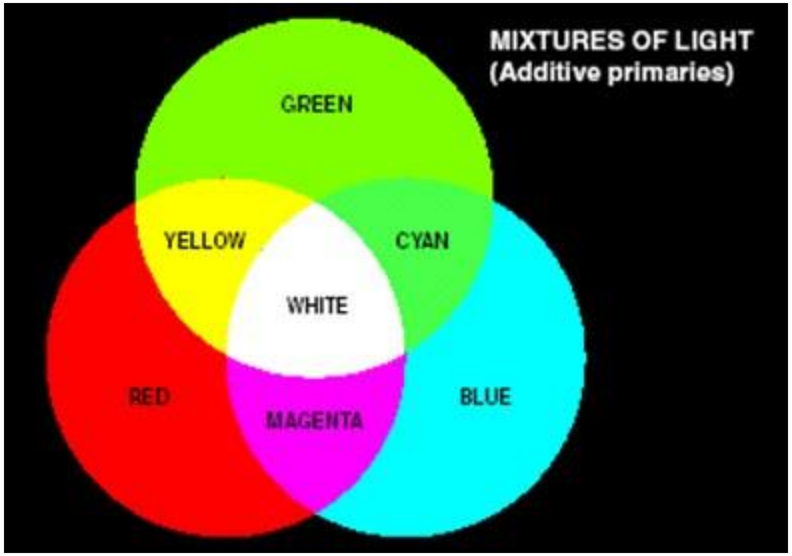
- CMY/ CMYK

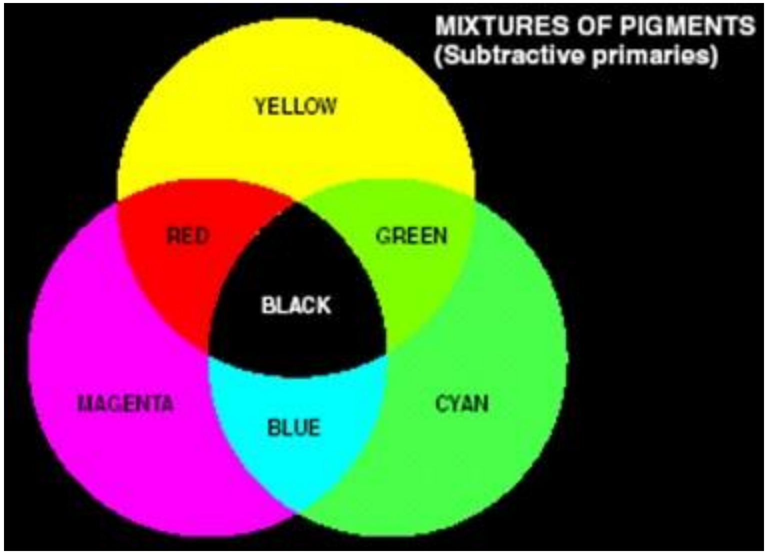
  (cyan, magenta, yellow ---- color printer)

- HSI

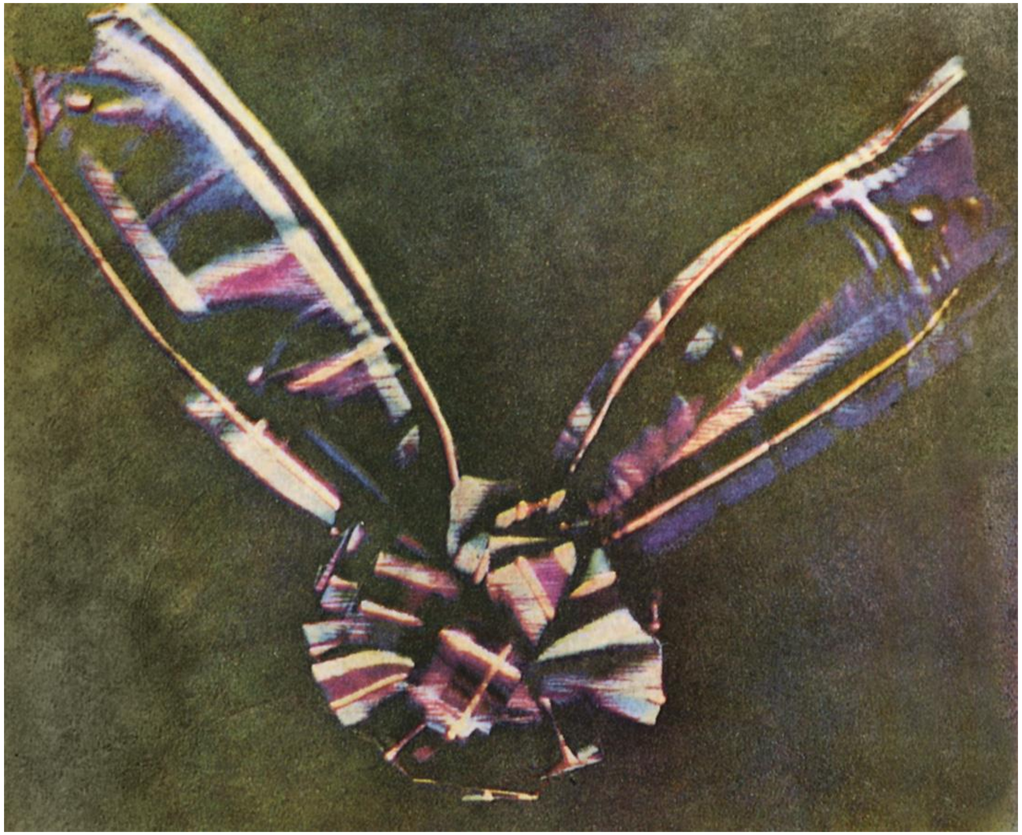
  (Hue, Saturation, Intensity ---- human perception)

Primary and secondary colors of light and pigment





RGB Images



The first permanent color photograph, taken by J.C. Maxwell in 1861
using three filters, specifically red, green, and violet-blue.

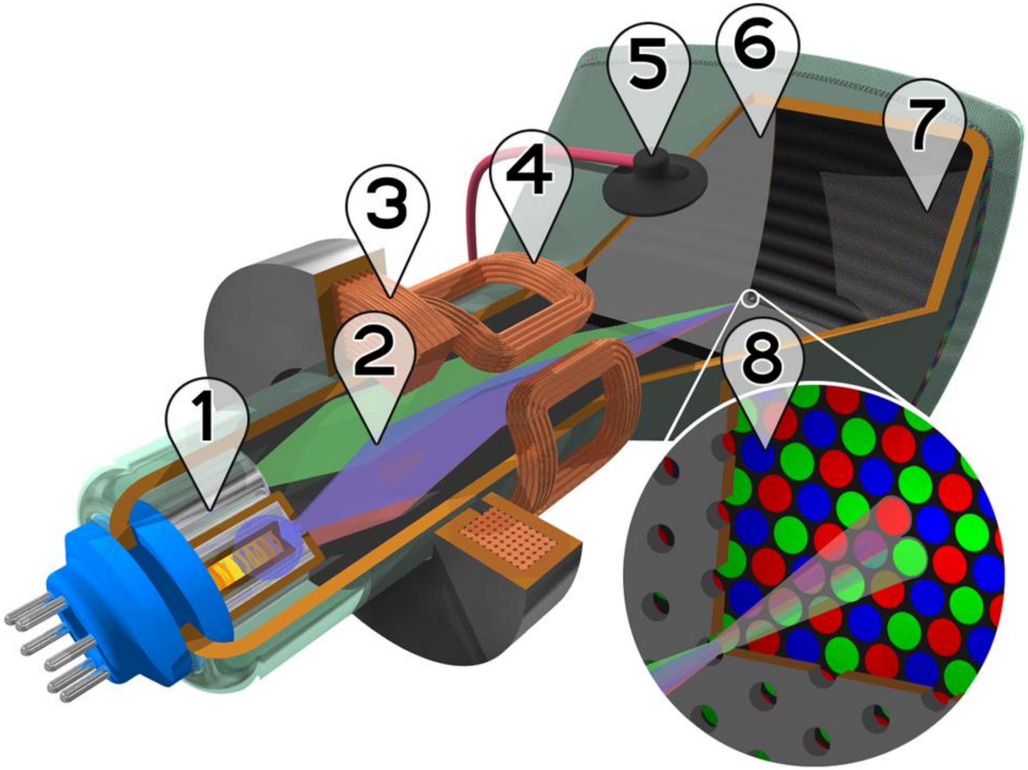
RGB Images

A picture of Mohammed Alim Khan (1880-1944), Emir of Bukhara, taken in 1911. This is an early color photograph taken by Sergei Mikhailovich Prokudin-Gorskii as part of his work to document the Russian Empire. Three black-and-white photographs were taken through red, green and blue filters. The three resulting images were projected through similar filters. Combined on the projection screen, they created a full-color image.

RGB

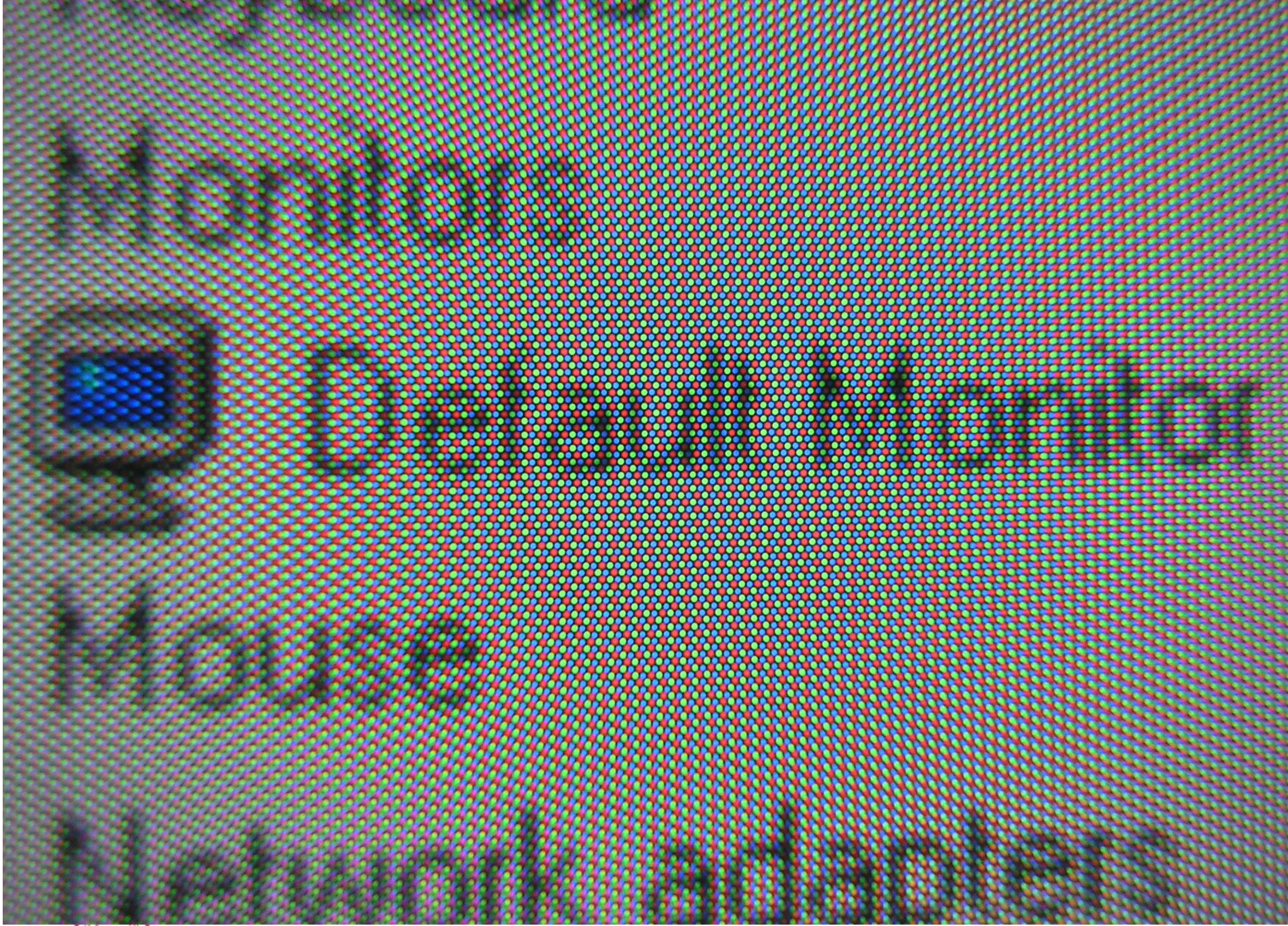

Additív színkeverés CD-tokokkal
Additive color mixing
with CD covers

RGB

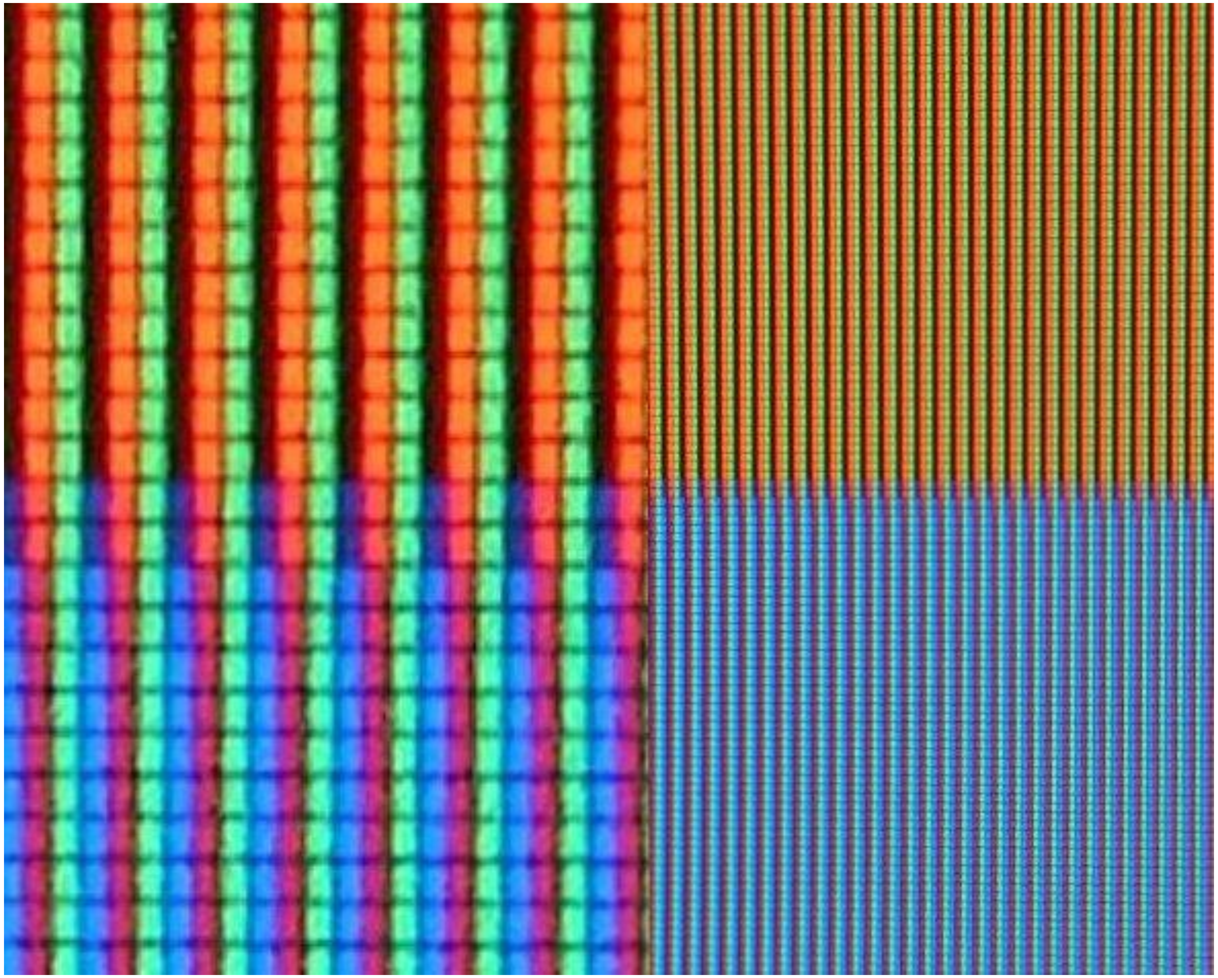


Cutaway rendering of a color CRT:

1. Electron guns
2. Electron beams
3. Focusing coils
4. Deflection coils
5. Anode connection
6. Mask for separating beams for red, green, and blue part of displayed image
7. Phosphor layer with red, green, and blue zones
8. Close-up of the phosphor-coated inner side of the screen



RGB phosphor dots in a CRT monitor



RGB sub-pixels in an LCD TV (on the right: an orange and a blue color; on the left: a close-up)

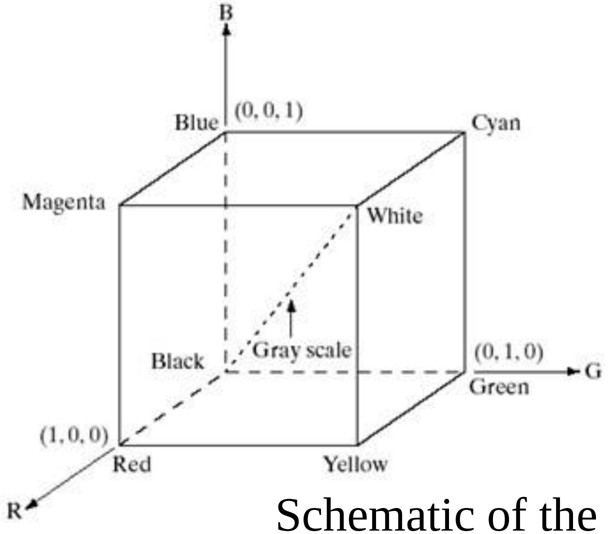
RGB

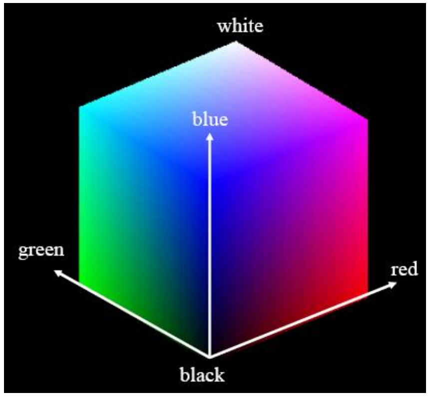
pixel depth:

The number of bits used to represent each pixel in RGB space

Full color image:

is used to denote a 24-bits RGB color image. The total number of colors in a 24-bit RGB image is 16,777,216.

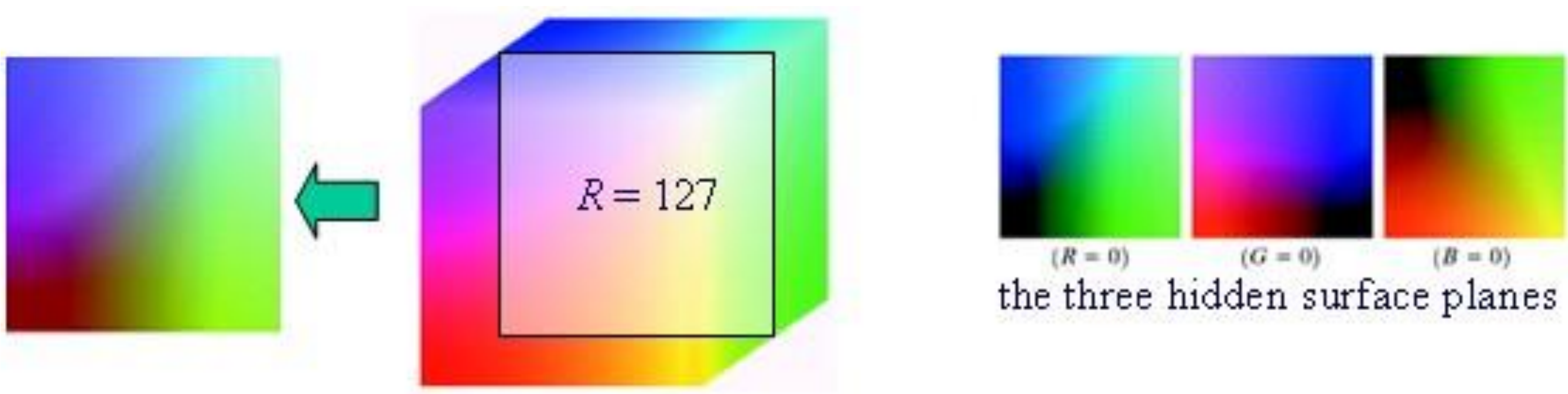




Schematic of the RGB color cube

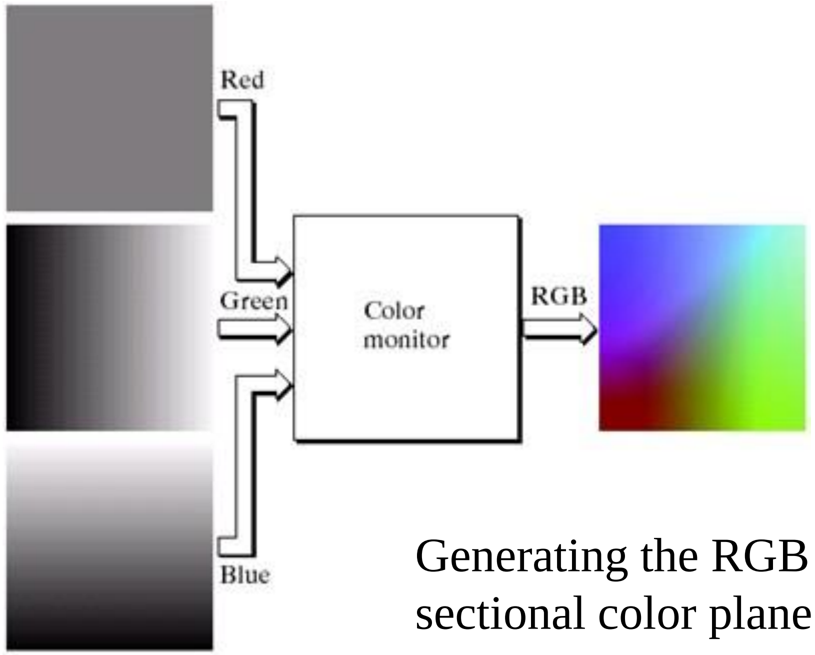
RGB 24-bit color cube

RGB



A convenient way to view these colors is to generate color planes (face or cross sections of the cube). This is accomplished simply by fixing one of the three colors and allowing the other two to vary.

RGB



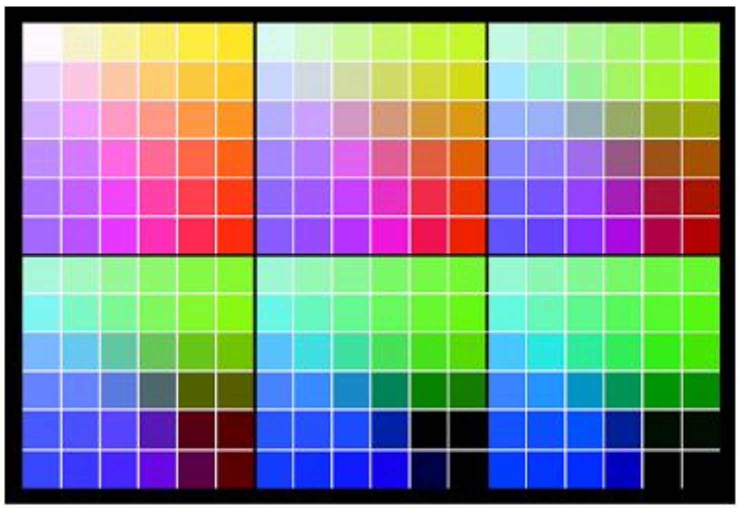
Generating the RGB image of the cross-sectional color plane (127, G, B).

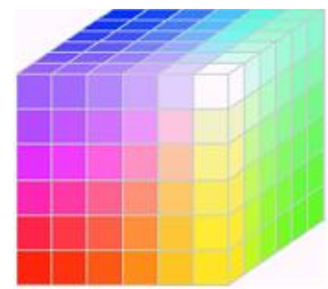
Safe RGB Colors

Valid values of each RGB component in a safe color

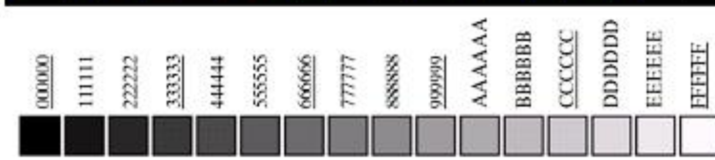
Number System	Color Equivalents					
Hex	00	33	66	99	CC	FF
Decimal	0	51	102	153	204	255

The 216 safe colors





The safe color cube



All possible gray colors in the 256 RGB system

CMY & CMYK

Printer colors:

Cyan = removes red

Magenta = removes green

Yellow = removes blue

Black = removes all

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

C + M + Y = K (black)

- Using three inks for black is expensive
- C+M+Y = dark brown not black
- Black instead of C+M+Y is crisper with more contrast.

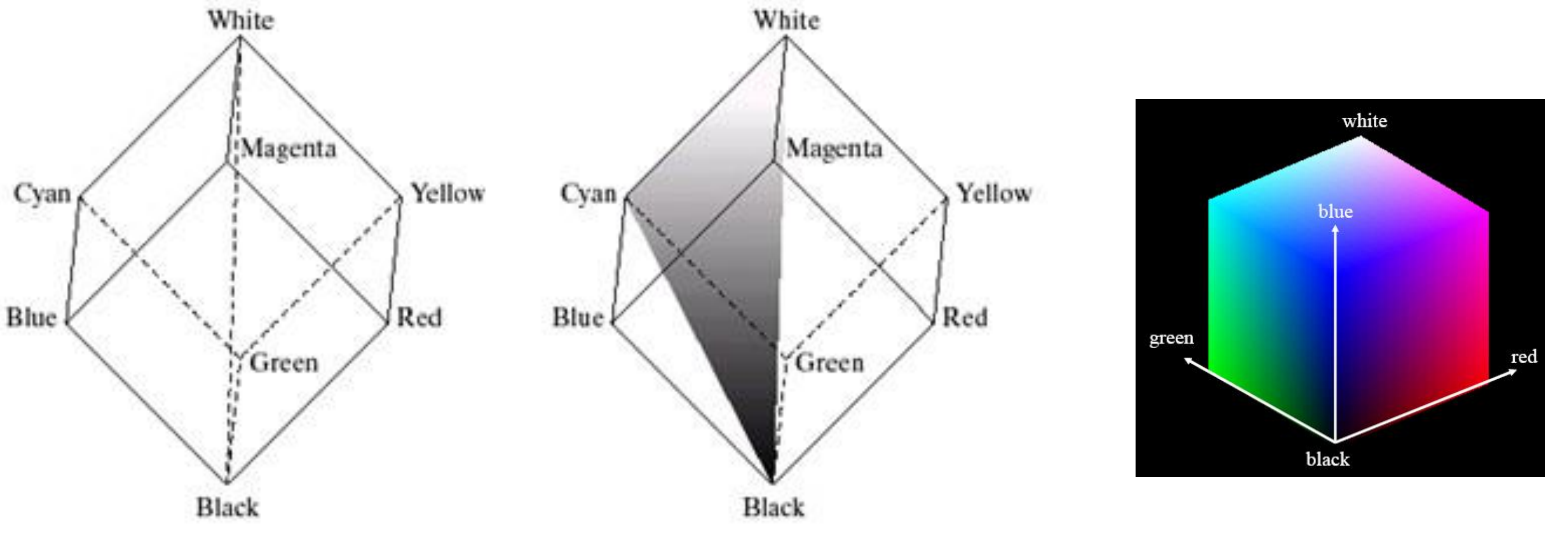
HSI

- RGB is useful for hardware implementations and is serendipitously related to the way in which the human visual system works.
- However, RGB is not a particularly intuitive way in which to describe colors.
- Rather when people describe colors they tend to use **hue**, **saturation** and **brightness.**
- RGB is great for color generation, but HSI is great for color description.

HSI

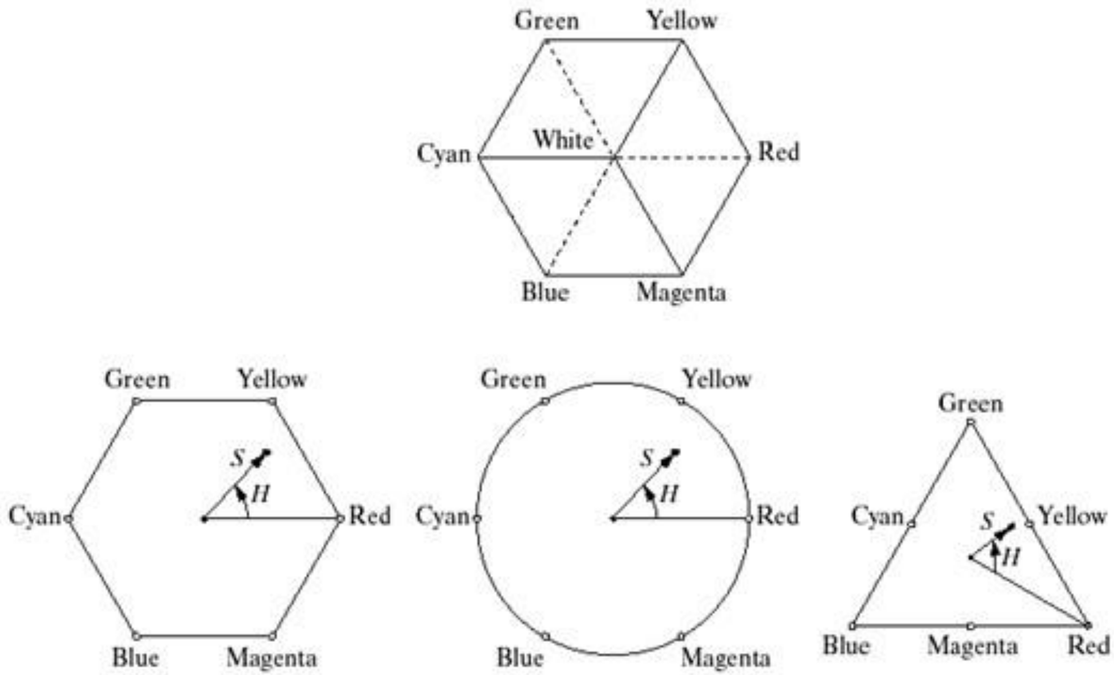
- Three characteristics to distinguish one color from another:
  - **Hue** is an attribute associated with the dominant wavelength in a mixture of light waves
    (red, green, yellow, blue ...)
  - **Saturation** refers to the relative purity or the amount of white light mixed with a hue.
    (pink, bright red, ...)
  - **Intensity:** Brightness is nearly impossible to measure because it is so subjective. Instead we use intensity. Intensity is the same chromatic notion that we have seen in grey level images.
    (black, grey, white ....)

HSI

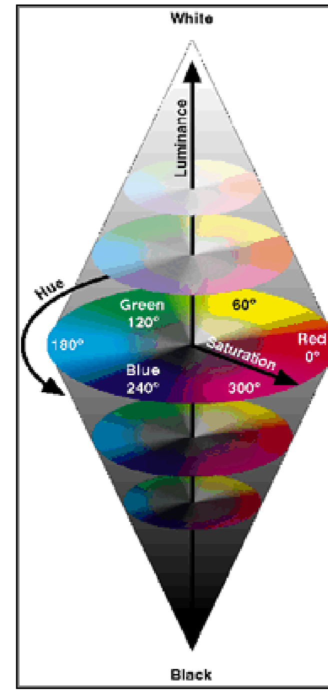


Conceptual relationships between the RGB and HIS color models

HSI

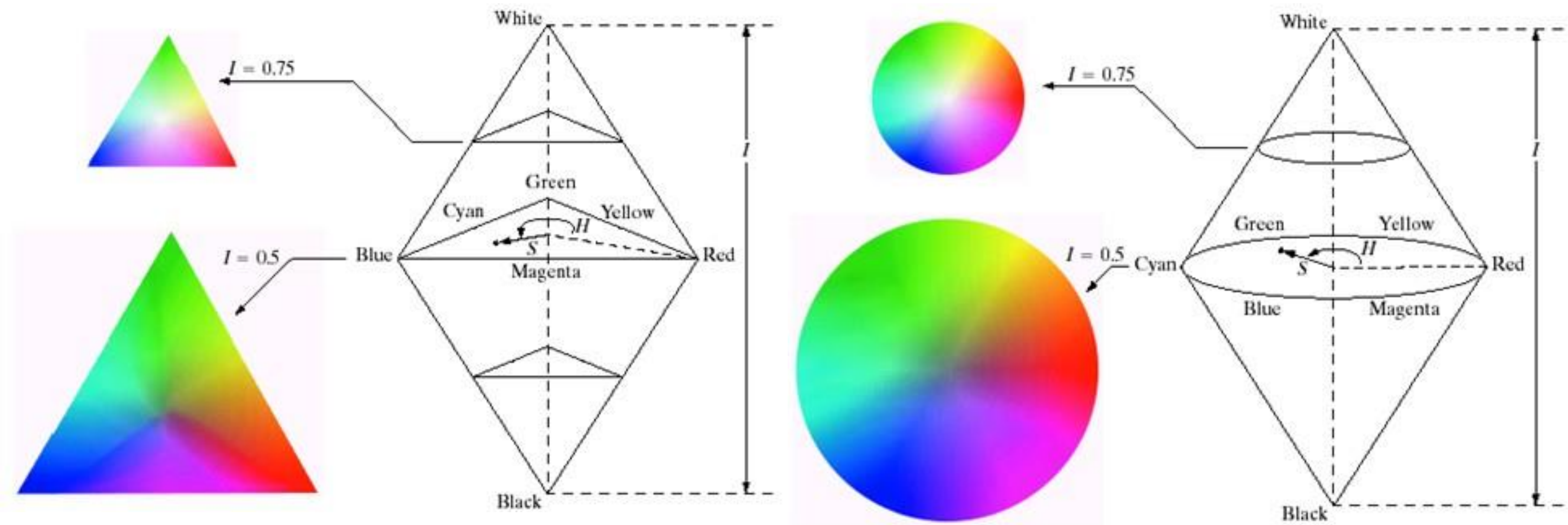


Hue and saturation in the HSI color model.



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 - example



The HSI color model based on triangular and circular color planes

The triangles and circles are perpendicular to the vertical intensity axis.

Converting From RGB To HSI

Given a color as R, G, and B its H, S, and I values are calculated as follows:

RGB values have been normalized to the range [0, 1]

$$H = \begin{cases} \theta & \text{if } B \le G \\ 360 - \theta & \text{if } B > G \end{cases}$$

Hue can be normalized to the range [0, 1] by dividing by 360°.

with

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

The saturation component S is given by

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

The intensity component I is defined by

$$I = \frac{1}{3}(R+G+B)$$

Converting From HSI To RGB

Given a color of HSI in the interval [0, 1], it's R, G, and B values are calculated as follows:

- *RG sector* ($0^o \leqq H < 120^o$):

$$B = I(1-S)$$

$$R = I\left[1+\frac{S\cos(H)}{\cos(60^\circ - H)}\right]$$

$$G = 3I-(R+B)$$

- *GB sector* ($120^o \leqq H < 240^o$): first subtract 120^o from H, then

$$H = H - 120^o$$

$$R = I(1-S)$$

$$G = I\left[1+\frac{S\cos(H)}{\cos(60^\circ - H)}\right]$$

$$B = 3I-(R+G)$$

Converting From HSI To RGB (cont')

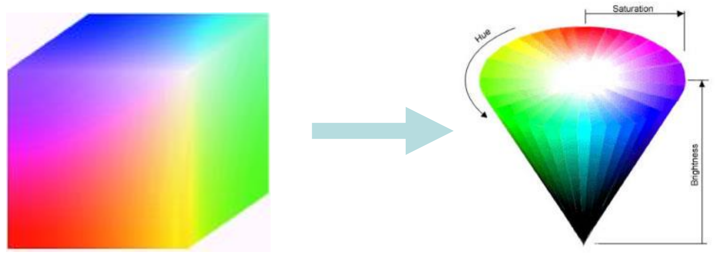
- *BR sector* ($240^o \leqq H < 360^o$): first subtract 240^o from *H*, then

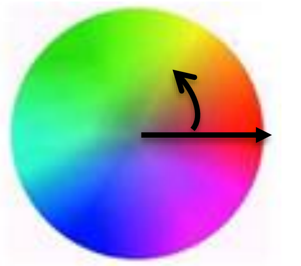
$$H = H - 240^o \qquad G = I(1 - S)$$

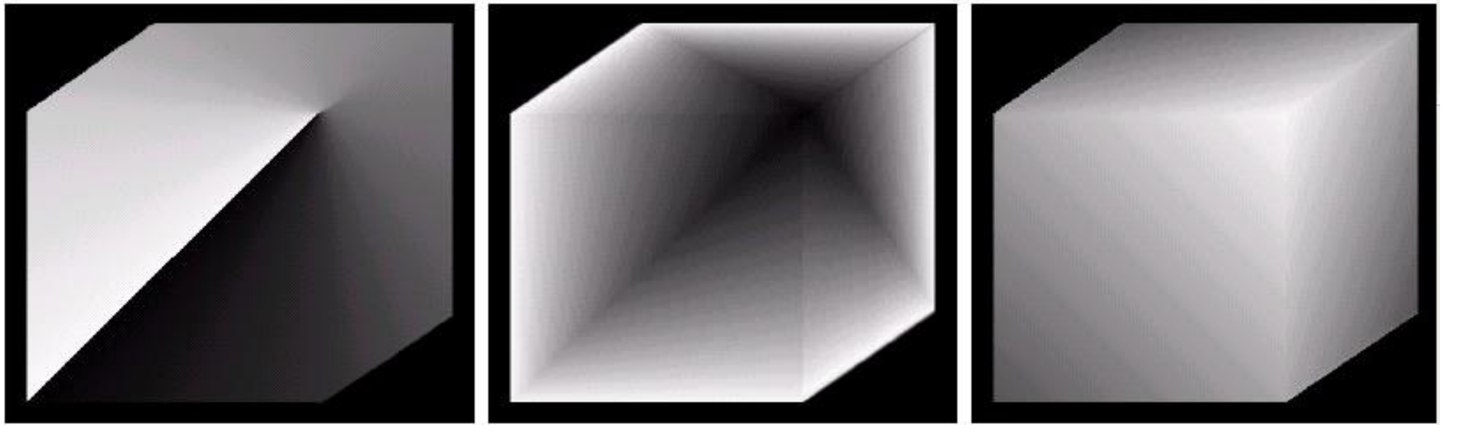
$$B = I\left[1 + \frac{S\cos(H)}{\cos(60^\circ - H)}\right]$$

$$R = 3I - (G + B)$$

HSI & RGB





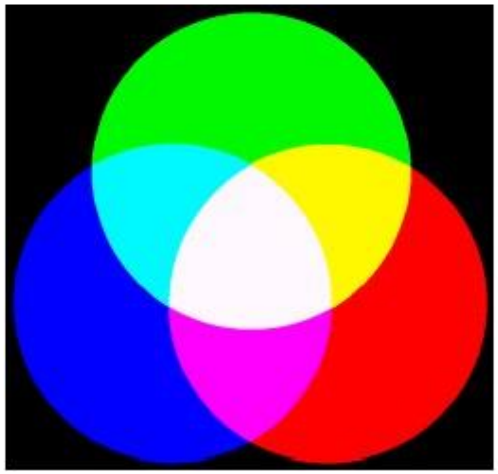


Hue Saturation Intensity

The most distinguishing feature is the discontinuity in value along a 45^{o} line in the front (red) plane of the cube in the hue image. This is the 0^{o} - 360^{o} line of the hue.

Manipulating Images In The HSI Model

RGB

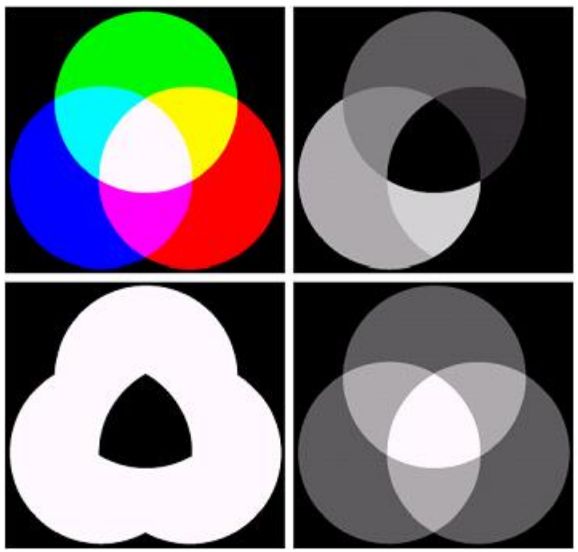


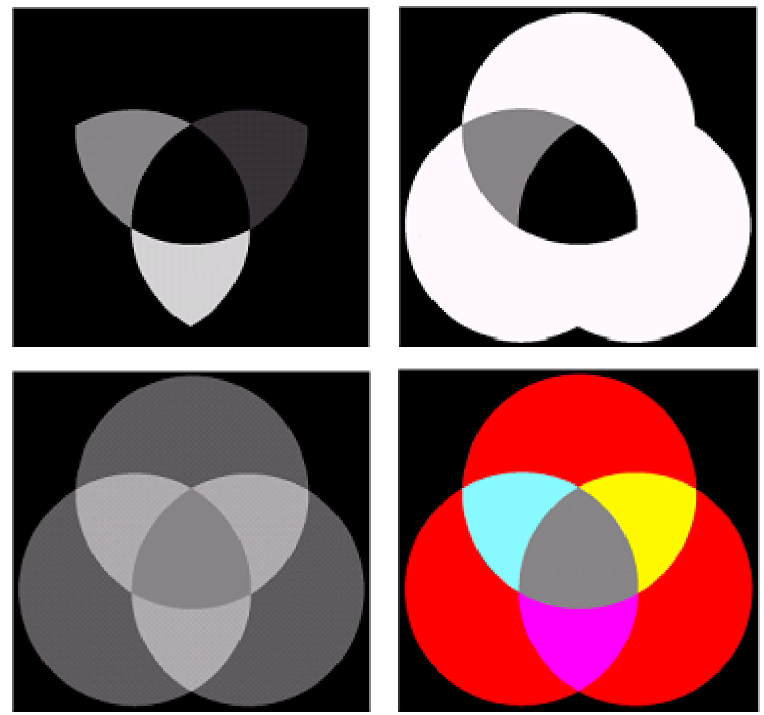
Hue

Saturation

Intensity

Manipulating Images In The HSI Model



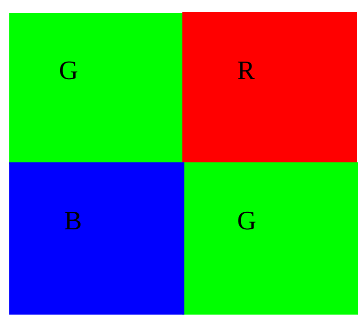


These result illustrate clearly the power of the HSI color model in allowing *independent* control over hue, saturation, and intensity, quantities with which we are quite familiar when describing colors.

题：考察下面的一幅500x500的彩色图像，其中的方块部分分别为纯的红、绿和蓝色。

1. 如果将此图像转换到HSI空间，对H分量图像用一个25x25的算术平均掩模进行处理，再转换回到RGB空间，得到的结果将是怎么样的？

2. 采取上面同样的步骤，只是这次处理的是S分量，结果又会怎样？



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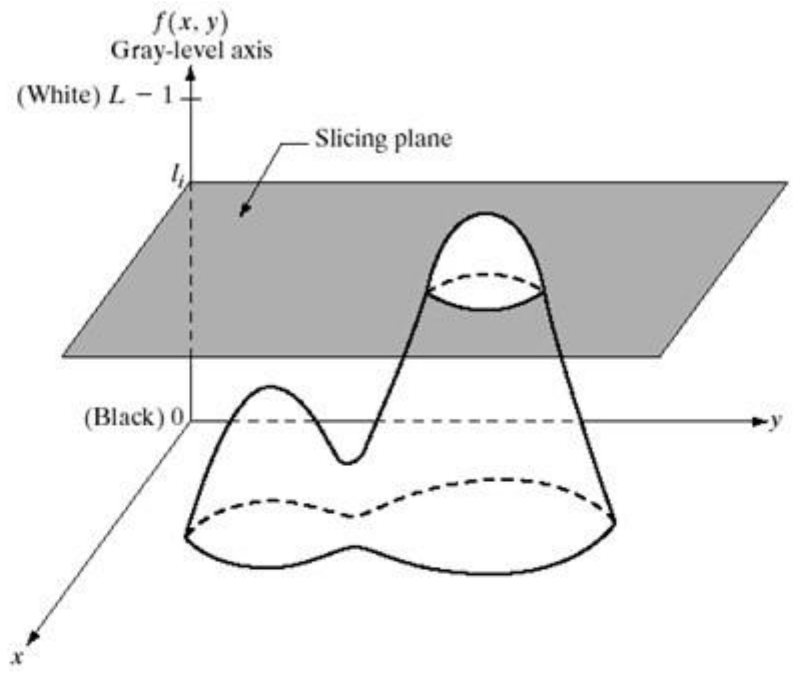
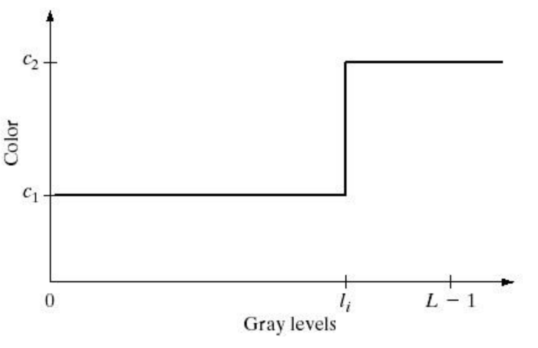
Pseudo color Image Processing

- The principal use of pseudocolor is for human visualization and interpretation of gray-scale events in an image or sequence of images.
- One of the principal motivations for using color is the fact that humans can discern thousands of color shades and intensities, compared to only two dozen or so shades of gray.
- The process is to assign colors to monochrome images.

Intensity Slicing





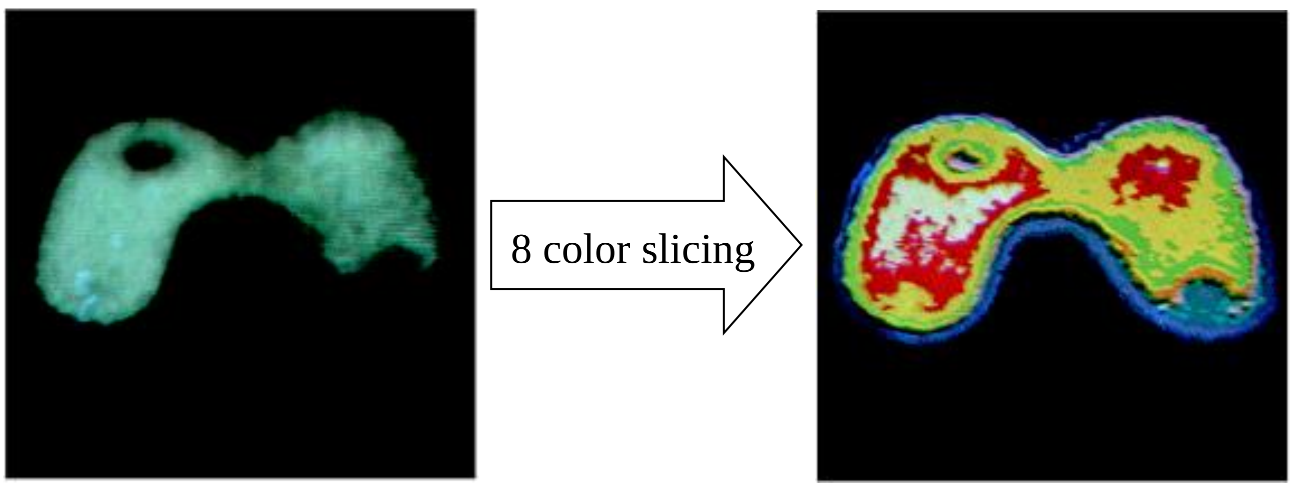
An alternative representation of the intensity-slicing technique

Geometric interpretation of the intensity-slicing technique.

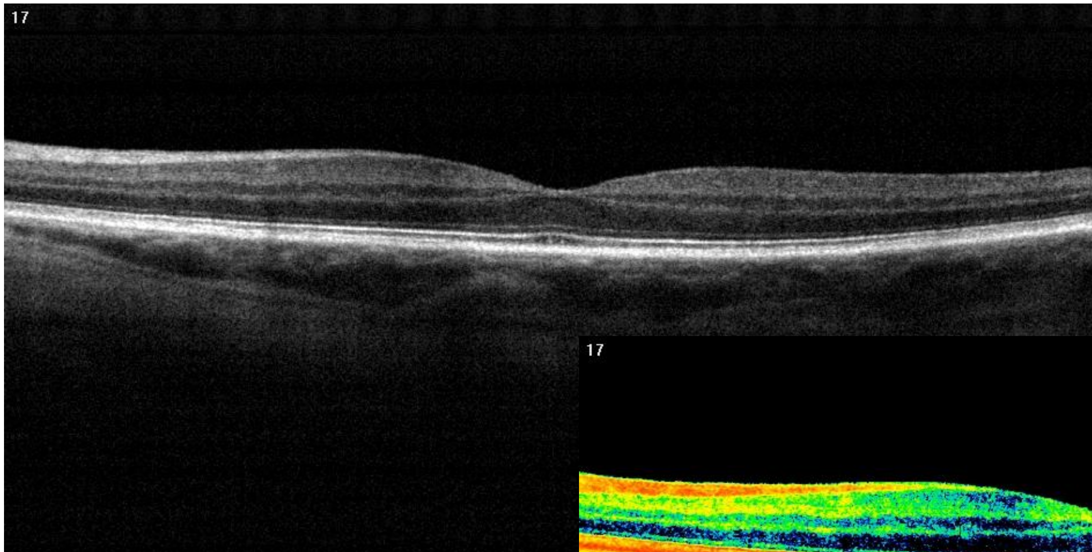
$$f(x,y) = c_k \quad \text{if} \quad f(x,y) \in V_k$$

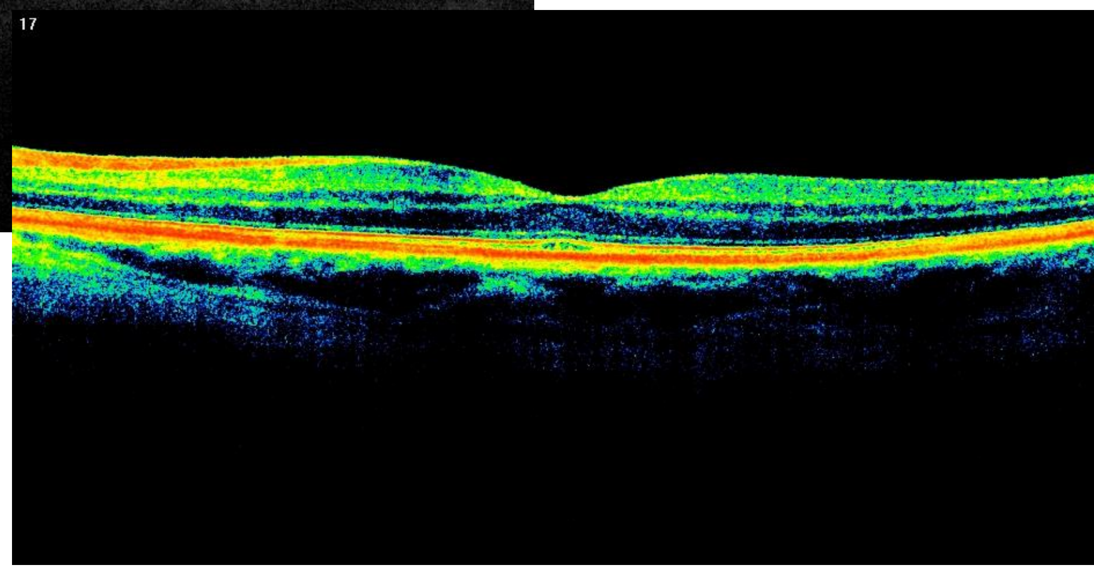
Intensity Slicing - example

Regions that appear of constant intensity in the monochrome image are really quite variable as shown by the various colors in the sliced image – *pseudocolor image*.



Intensity Slicing - example

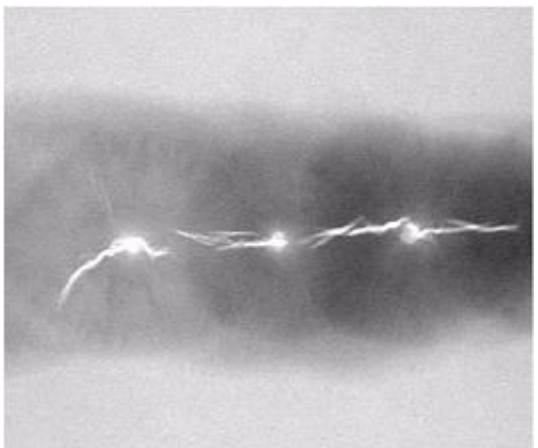




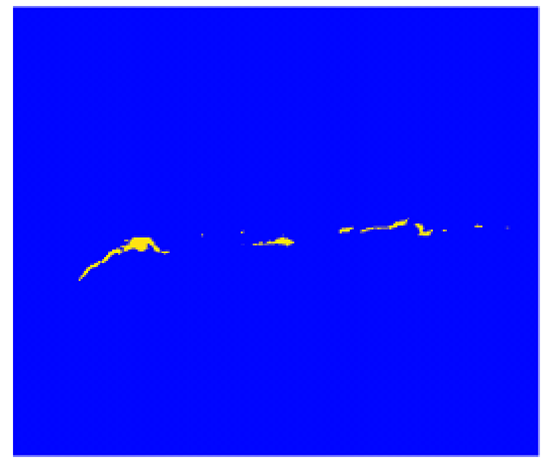
Retina OCT image

Intensity Slicing - example

Intensity slicing assumes a much more meaningful and useful role when subdivision of the gray scale is based on physical characteristics of the image.



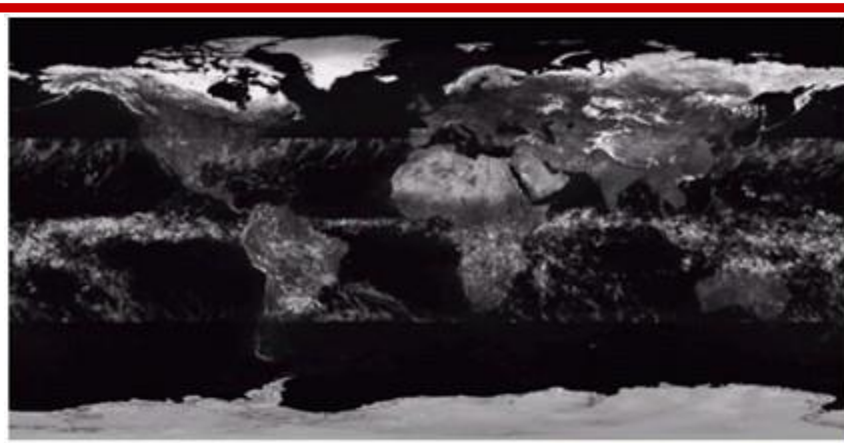
2 color slicing



The X-rays saturates the imaging sensor when through a porosity or crack, thus give the gray levels of value 255 or a little less.

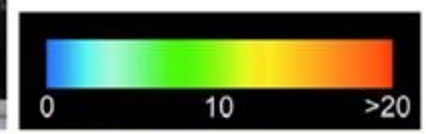
Human error rates would be lower if images were displayed in this form instead, especially when numerous images are involved.

Intensity Slicing - example

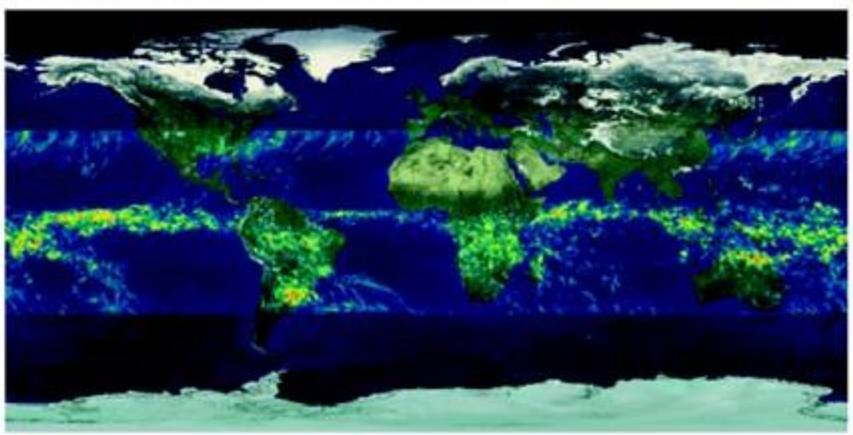


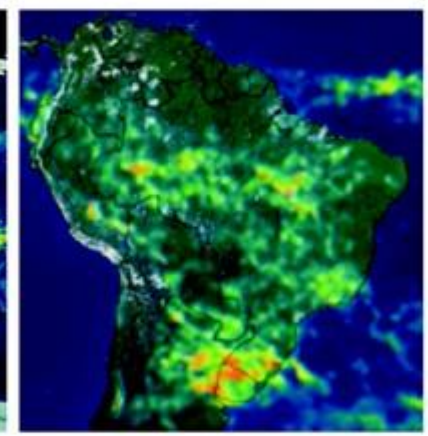
The TRMM satellite image of rain-fall levels in the tropical regions of the Earth. (a precipitation radar, a microwave imager, a visible and infrared scanner)

In the monitored area, the gray levels correspond directly to rainfall



inches



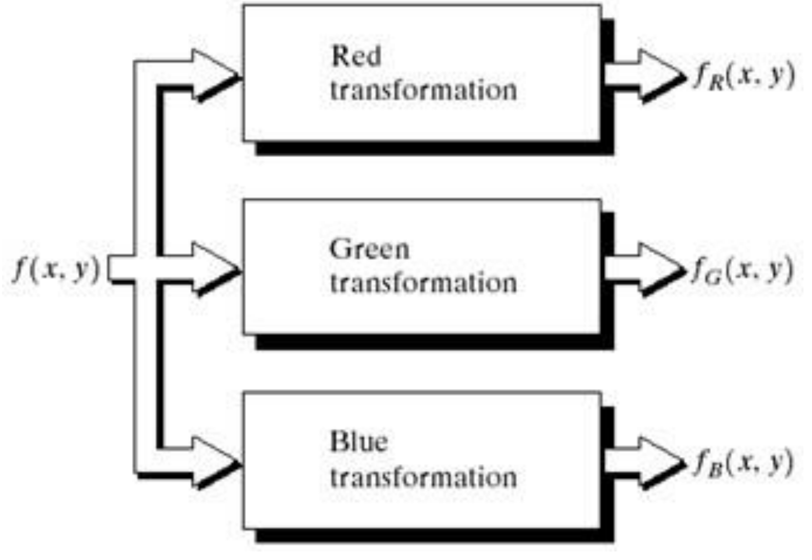


a b
c d

(a) Gray-scale image in which intensity (in the lighter horizontal band shown) corresponds to average monthly rainfall. (b) Colors assigned to intensity values. (c) Color-coded image. (d) Zoom of the South America region.

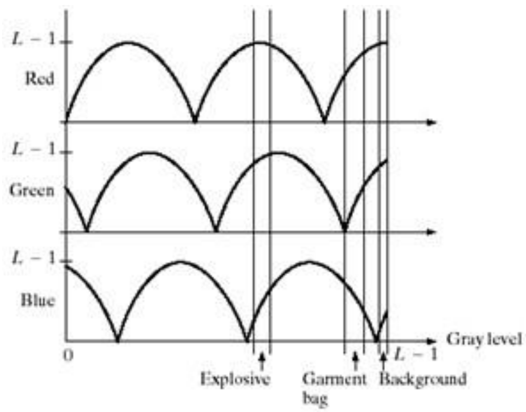
Gray Level to Color Transformations

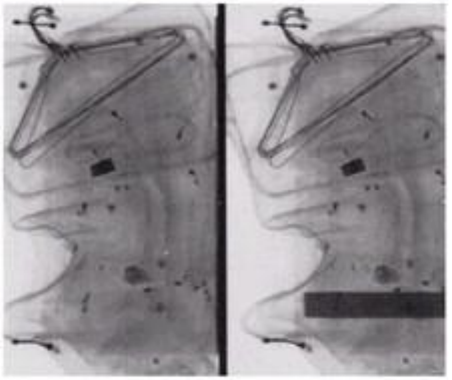
Intensity slicing ---- the gray-level-to-color transformation is a piecewise function.
A more general approach would give the technique considerable flexibility

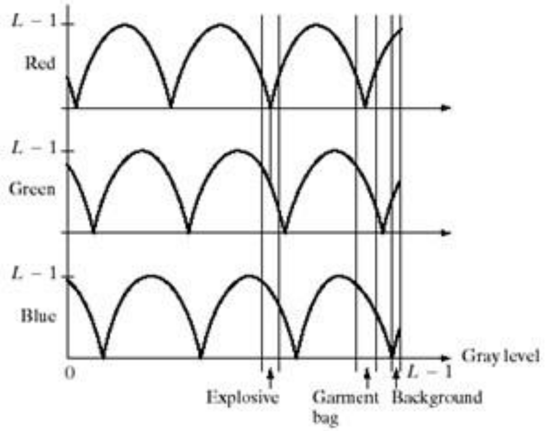


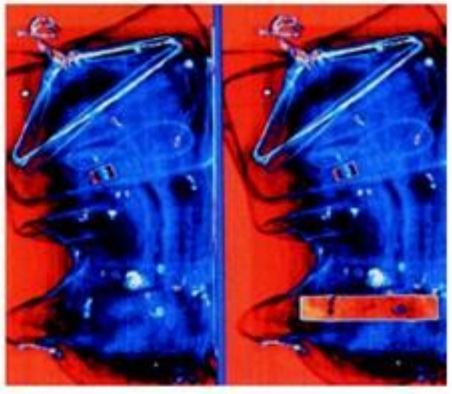
Functional block diagram for pseudocolor image processing. f_R, f_G, and f_B are fed into the corresponding red, green, and blue inputs of an RGB color monitor.

Gray Level to Color Transformations

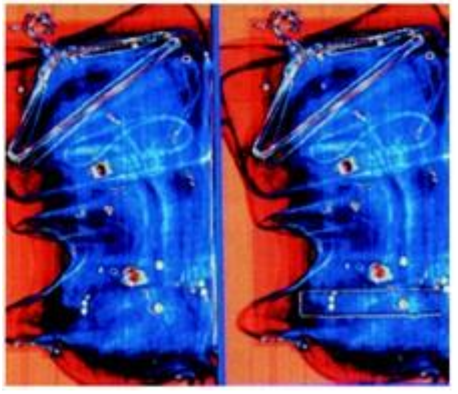








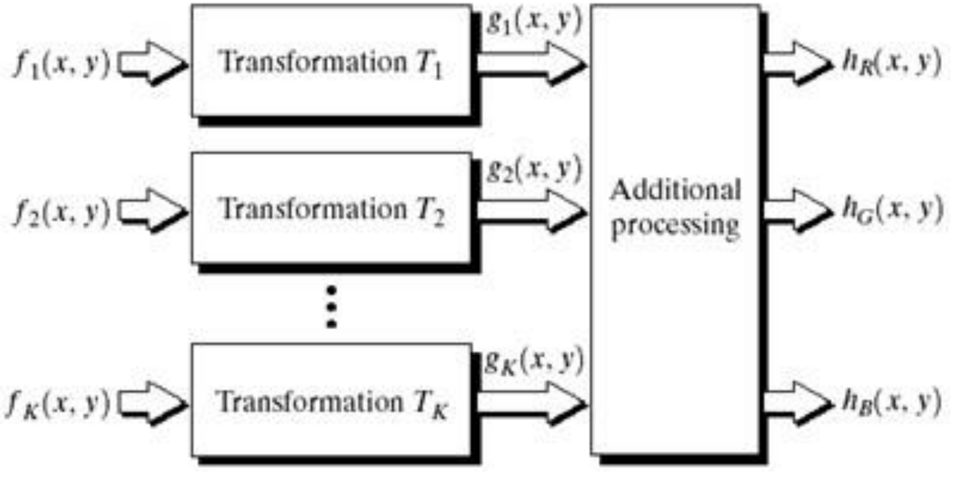
The color enhancement result is much sensitive to the frequency and phase of the sinusoidal function



Color Transformations for Multi-Monochrome Images

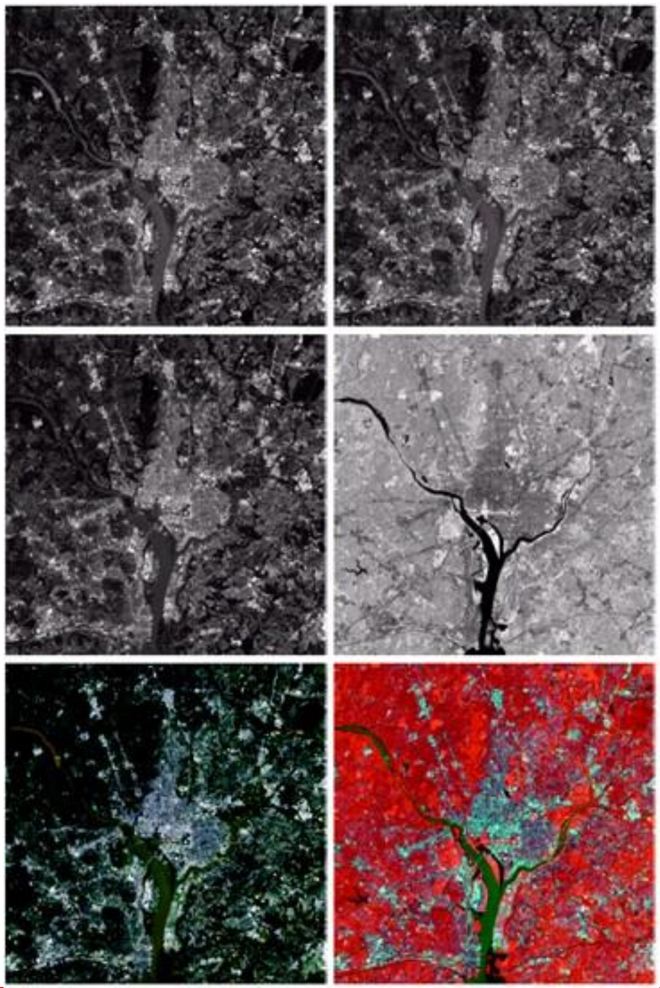
several monochrome image → a single color composite.

Eg. in multi-spectral image processing and image fusion.



A pseudocolor coding approach used when several monochrome images are available.

An Example in Multispectral Image Processing



Band No.	Name	Wavelength (μm)	Characteristics and Uses
1	Visible blue	0.45–0.52	Maximum water penetration
2	Visible green	0.52–0.60	Good for measuring plant vigor
3	Visible red	0.63–0.69	Vegetation discrimination
4	Near infrared	0.76–0.90	Biomass and shoreline mapping
5	Middle infrared	1.55–1.75	Moisture content of soil and vegetation
6	Thermal infrared	10.4–12.5	Soil moisture; thermal mapping
7	Middle infrared	2.08–2.35	Mineral mapping

near infrared

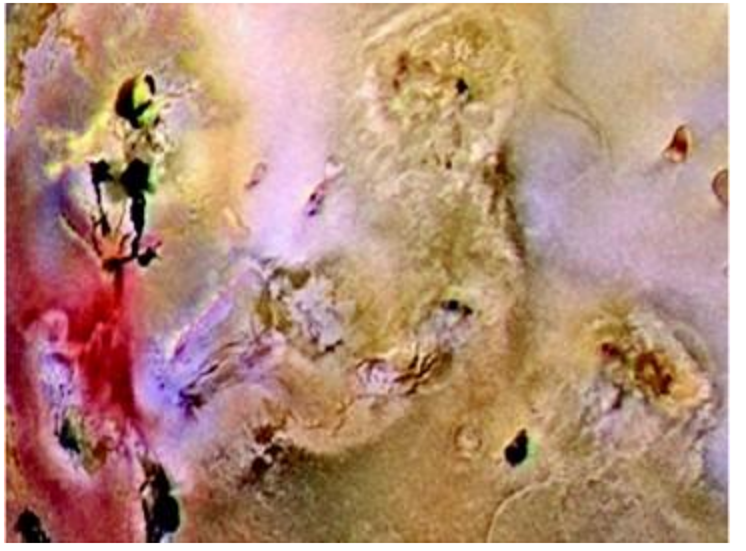
$T = 1$

Noticed color difference in the Potomac river

Using the near infrared instead of the red

An Example in Multispectral Image Processing

Pseudocolor rendition of Jupiter Moon.



A close-up

- The original multispectral images came from several sensors. Some of them are not visible to the eye.
- Such an image conveys the characteristics of the object much more readily than would be possible by analyzing the component images individually

Outlines

Focus

- Color Fundamentals
- Color Models
- Pseudo Color Image Processing
- Basics of Full Color Image Processing
- Color Transformations
- Smoothing and Sharpening

Basics of Full-Color Image Processing

Full-color image processing approaches fall into two major categories:

- process each component image individually and then form a composite processed color image
- work with *color pixels*, which are vectors that have at least three components, directly.

Take RGB system as an example, for a color pixel **c**, we have

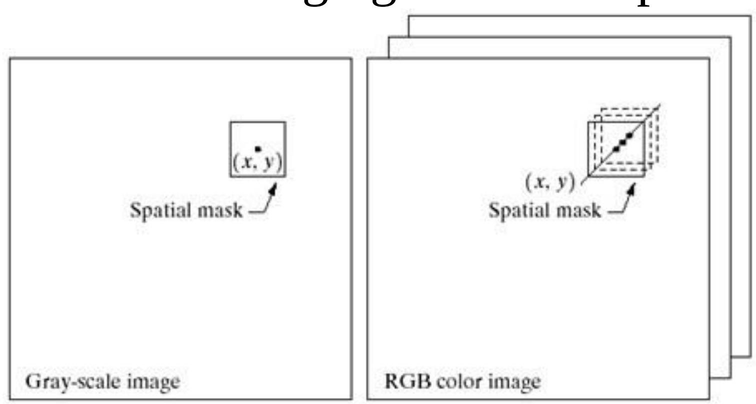
$$\mathbf{c}(x,y)=\begin{bmatrix} c_R(x,y) \\ c_G(x,y) \\ c_B(x,y) \end{bmatrix}=\begin{bmatrix} R(x,y) \\ G(x,y) \\ B(x,y) \end{bmatrix}$$

Basics of Full-Color Image Processing

In order for these two approaches to be equivalent, two conditions have to be satisfied:

- the process has to be applicable to both vectors and scalars
- the operation on each component of a vector must be independent of the other components

The spatial neighborhood averaging is an example of such equivalence.



Spatial masks for gray-scale and RGB color images

Outlines

Focus

- Color Fundamentals
- Color Models
- Pseudo Color Image Processing
- Basics of Full Color Image Processing
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Color Transformations

The formulation

$$g(x, y) = T\left[f(x, y)\right]$$

is denoted to the color transformation (corresponding to gray-level transformation in monochrome images) or processing.

An alternate form is

$$s_i = T_i(r_1, r_2, \ldots, r_n), \quad i = 1, 2, \ldots, n$$

where r_i and s_i are variables denoting the color components of $f(x, y)$ and $g(x, y)$ at any point (x, y), n is the number of color components, and $\{T_1, T_2, \ldots, T_n\}$ is a set of transformation or color mapping functions that operate on r_i to produce s_i.

If RGB color space is selected, then $n = 3$, r_1, r_2, and r_3 denote the red, green, and blue. In CMYK, $n = 4$, and $n = 3$ in HSI.

Color Transformations

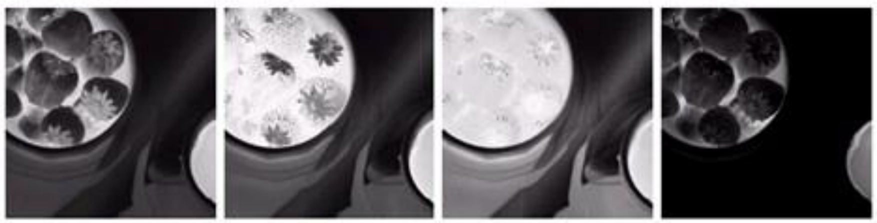
- Color intensity modification
- Color Complements
- Color Slicing
- Tone and color correction

An Example of Color Intensity Modification

Full color

A full-color image and its various color-space components

$$g(x, y) = kf(x, y) \quad 0 < k < 1$$



Cyan Magenta Yellow Black

$$s_i = kr_i + (1 - k) \quad i = 1, 2, 3$$

Red Green Blue

$$s_i = kr_i \quad i = 1, 2, 3$$

Hue Saturation Intensity

$$s_3 = kr_3$$

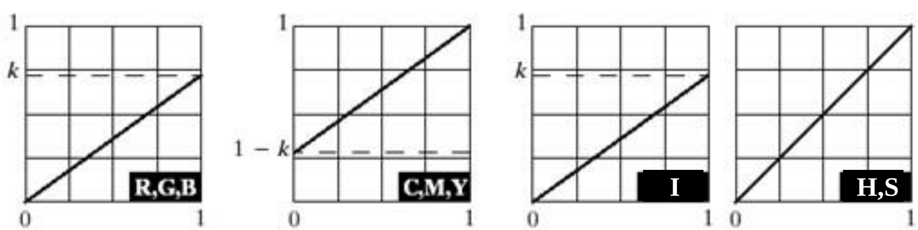
Here, each transformation depends only on one component within its color space

An Example of Color Intensity Modification

Adjusting the intensity of an image using color transformations

Original image

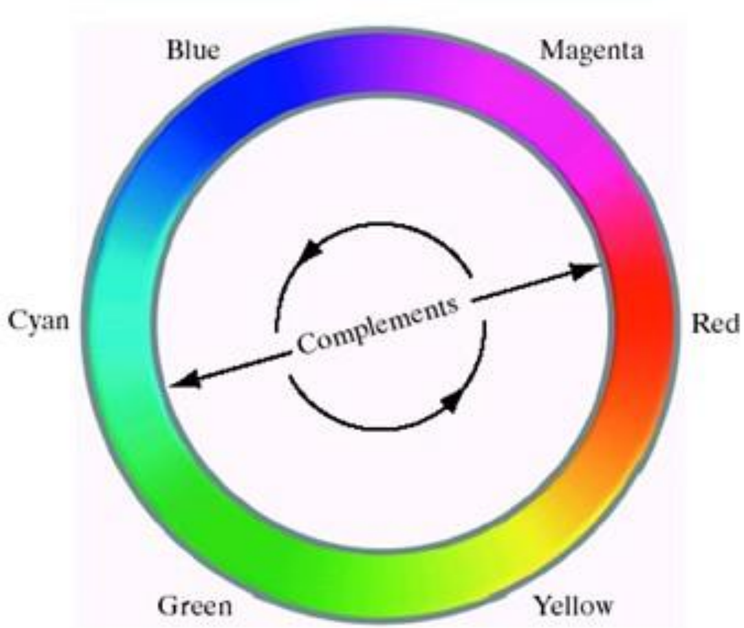
Result of decreasing its intensity by 30% (k =0.7)



The required RGB, CMY, and HSI transformation functions

Color Complements

The hues directly opposite one another on the *color circle* are called ***complements***.

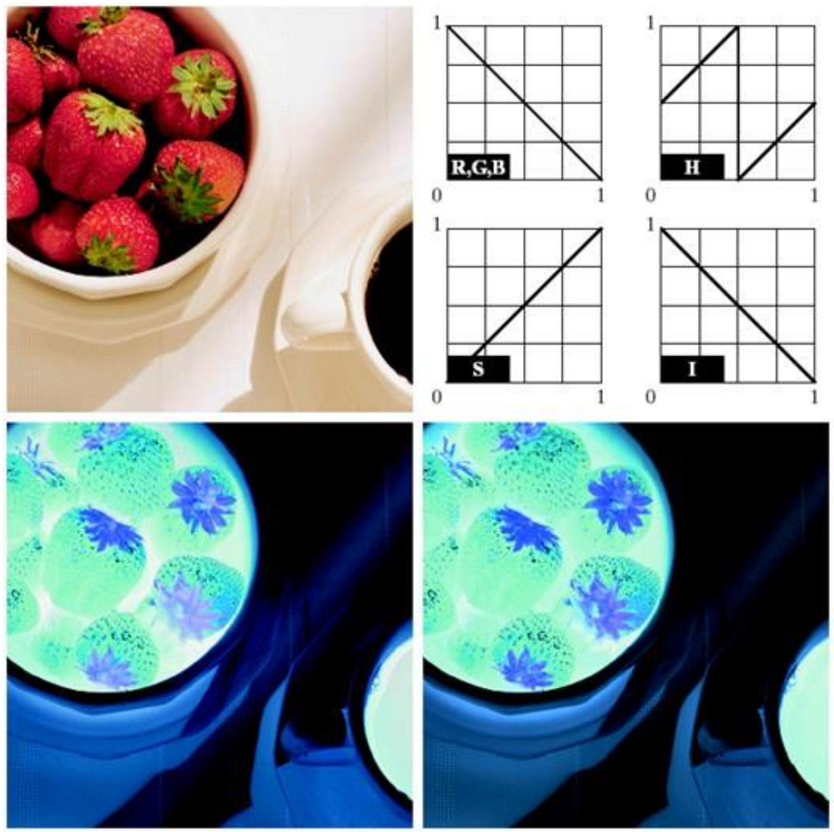


As taking negatives in the gray-scale case, color complements are useful for enhancing detail that is embedded in dark, yet dominant regions of a color image

Color Complements

Color complement transformations

Original image



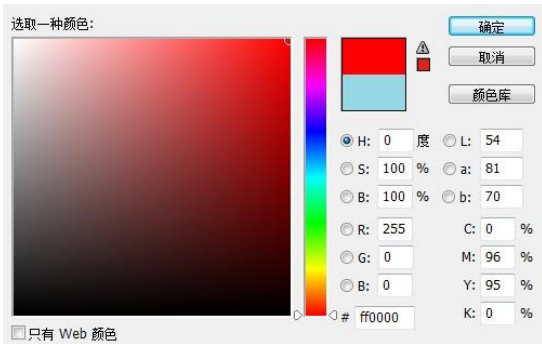
Complement transformation functions

Complement based on the RGB mapping functions

An approximation of the RGB complement using HSI transformations

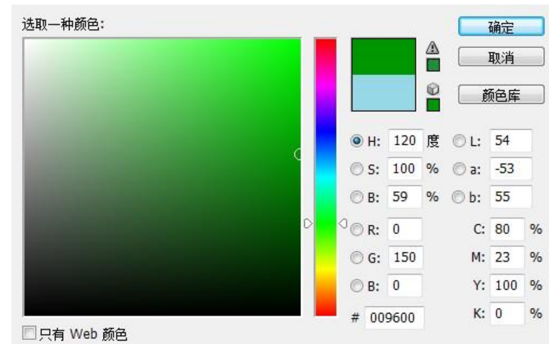
Saturation on Color Complements

(R,G,B) = (1,0,0)



(H, S, I)=(0, 1, 0.33)

(R,G,B) = (0,0.59,0)



(H, S, I)=(0.33, 1, 0.2)

Complements

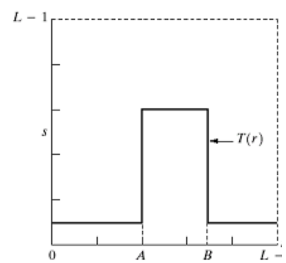
Conclusion:
the same starting saturation resulted in two different "complemented" saturations. Saturation alone is not enough information to compute the saturation of the complemented color.

(H, S, I)=(0.5, 1, 0.66)

(H, S, I)=(0.83, 0.48, 0.8)

Color Slicing

- Like gray-level slicing, the basic idea of color slicing is highlighting a specific range of colors in an image, either to display the colors of interest so that they stand out from the background, or use the region defined by the colors as a mask for further processing.



- The color transformation functions are more complicated than their gray-scale counterparts because a color pixel is an *n*-dimensional quantity.

- The simplest way to "slice" a color image is to map the colors outside some range of interest to a nonprominent neutral color, say, a middle gray or color

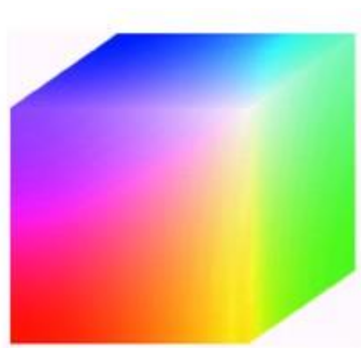
Color Slicing

for a cube with width W

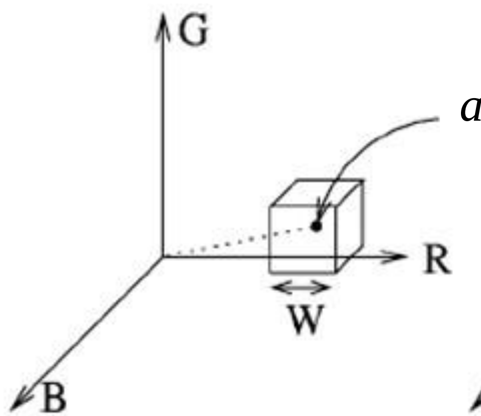
$$s_i = \begin{cases} 0.5 & \text{if } \left[\left| r_j - a_j \right| > \dfrac{W}{2} \right]_{\text{any } 1 \le j \le n} \\ r_i & \text{otherwise} \end{cases} \qquad i = 1, 2, \dots, n$$

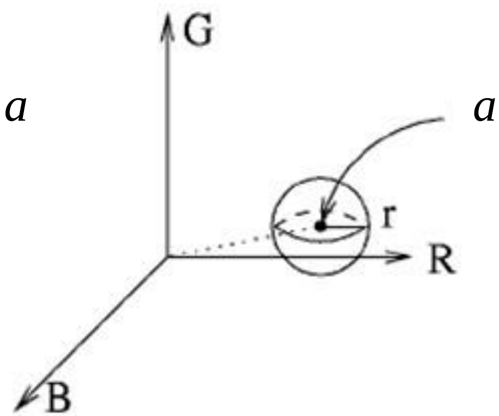
for a sphere with radius R_0

$$s_i = \begin{cases} 0.5 & \text{if } \sum_{j=1}^{n} (r_j - a_j)^2 > R_0^2 \\ r_i & \text{otherwise} \end{cases} \qquad i = 1, 2, \dots, n$$

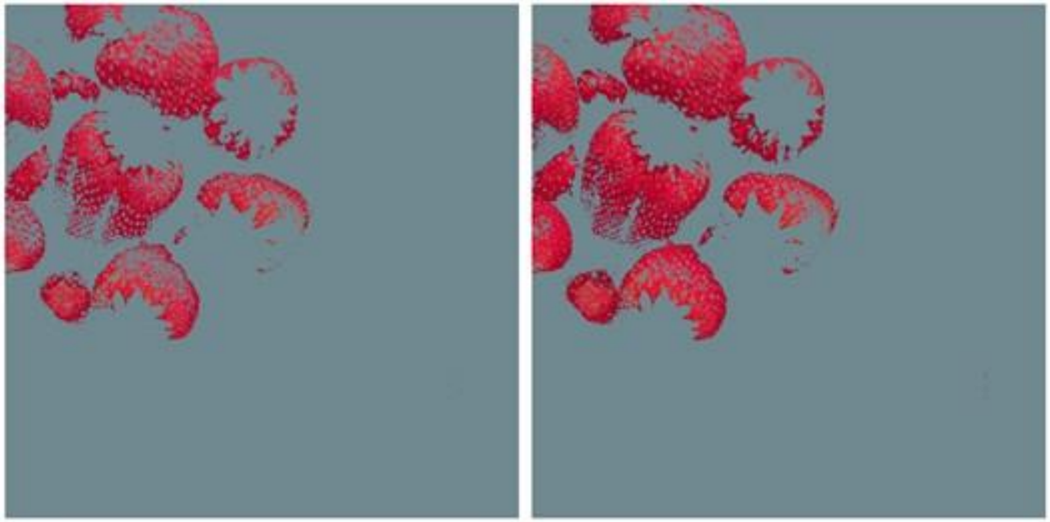


RGB 24bit cube





An Example of Color Slicing



Color slicing transformations that detect (a) reds within an RGB cube of width W = 0.2549 centered at (0.6863, 0.1608, 0.1922). And (b) reds within an RGB sphere of radius 0.1765 centered at the same point. Pixels outside the cube and sphere were replaced by color (0.5, 0.5, 0.5).

- **Color slicing** for separating objects from their surroundings.
- A first step towards image segmentation.

Tone corrections

Tonal corrections for flat, light (high key), and dark (low key) color images, Adjusting the red, green, and blue components equally **does not change the image hues.**

RGB space ?

CMY(K) space ?

HSI space ?

Contrast

Weber contrast

$$\frac{I - I_{\mathrm{b}}}{I_{\mathrm{b}}},$$

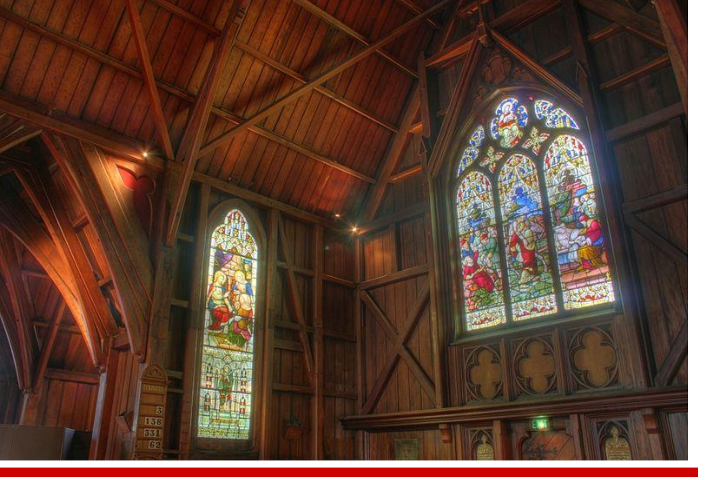
Michelson contrast

$$\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}},$$

RMS contrast

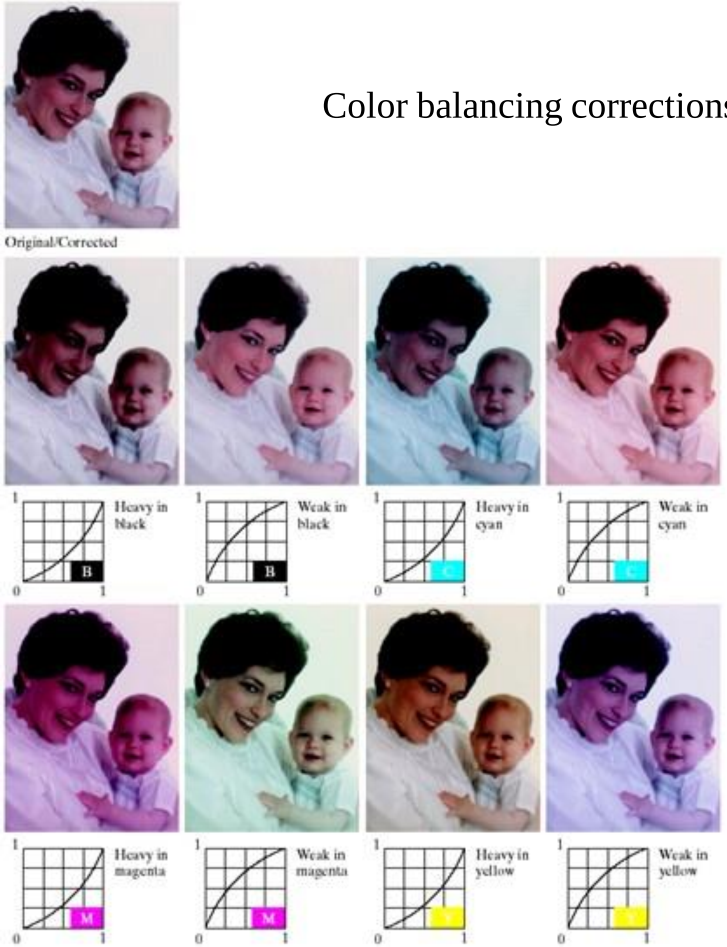
$$\sqrt{\frac{1}{MN}\sum_{i=0}^{N-1}\sum_{j=0}^{M-1}(I_{ij} - \bar{I})^2},$$

Tone mapping

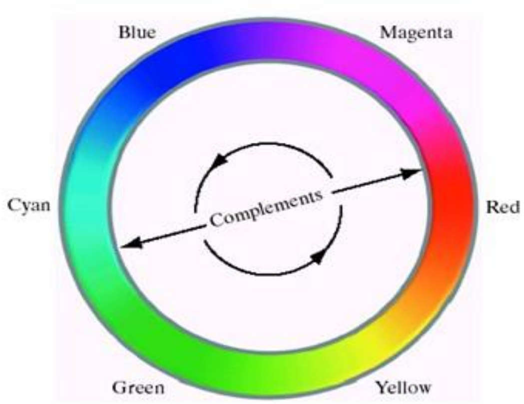


Contrast corrections

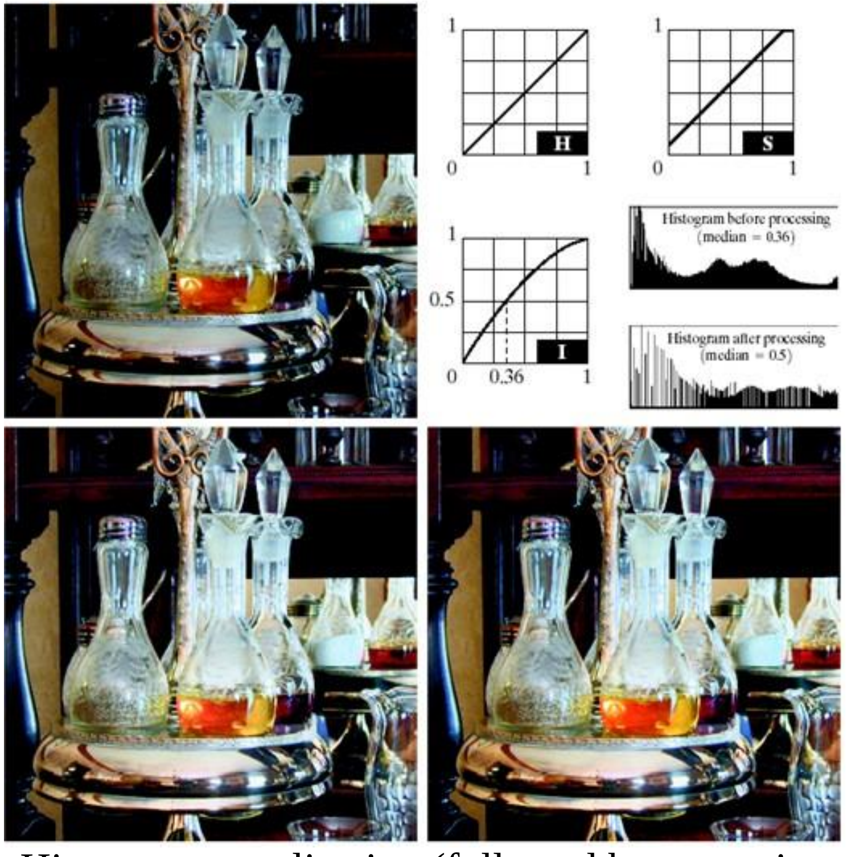
Correction of color balancies



Color balancing corrections for CMYK color images



Histogram Processing



Histogram equalization (followed by saturation adjustment) in the HIS color space.

Intensity equalization process did impact the overall color perception.

Adjustment on saturation subsequent to histogram equalization is common.

Outlines

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Color Image Smoothing

The concept of color image smoothing is the same as in gray-scale image smoothing, except that we must deal with component vectors instead of scalar gray-level values

$$\bar{\mathbf{c}}(x,y) = \frac{1}{K} \sum_{(x,y)\in S_{xy}} \mathbf{c}(x,y)$$

It follows from the definition of $\mathbf{c}(x, y)$ and the properties of vector addition that

$$\bar{\mathbf{c}}(x,y) = \begin{bmatrix} \frac{1}{K} \sum_{(x,y)\in S_{xy}} R(x,y) \\ \frac{1}{K} \sum_{(x,y)\in S_{xy}} G(x,y) \\ \frac{1}{K} \sum_{(x,y)\in S_{xy}} B(x,y) \end{bmatrix}$$

So, color image smoothing by neighborhood averaging can be carried out on a **per-color-plane basis** in RGB space.

Color Image Smoothing

RGB image

R

G

B

Result of smoothing each RGB component image with a 5×5 averaging mask

Color Image Smoothing

H

S

I

Result of smoothing I component image in HSI space with a 5×5 averaging mask

Color Image Smoothing

HSI decouples intensity from color. Suitable for processing only the intensity component of an image.

Result of smoothing each RGB component image with a 5×5 averaging mask

Result of smoothing each I component image in HSI space with a 5×5 averaging mask

Difference between the two results

Color Image Sharpening

Take the Laplacian as the sharpening tool. The Laplacian of a vector is defined as a vector whose components are equal to the Laplacian of the individual scalar components of the input vector. In RGB space,

$$\nabla^2[\mathbf{c}(x,y)] = \begin{bmatrix} \nabla^2 R(x,y) \\ \nabla^2 G(x,y) \\ \nabla^2 B(x,y) \end{bmatrix}$$

Result of processing each RGB channel

Result of processing the intensity component and converting to RGB

Difference between the two results

Noise in Color Images

- The noise models discussed for grayscale images are also applicable to color images.
- However, in many applications, a color channel may be more or less affected than the other channels.
- For instance, using a red color filter in a CCD camera may affect the red component of the image (CCD sensors are noisier at low levels of Images taken from dark illumination).
- We will take a brief look of how noise carries over when converting from one color model to another

Noise in Color Images

Red, green, and blue component images corrupted by additive Gaussian noise of mean 0 and variance 800.

Noise is less noticeable than it is in a grayscale image.

Noise in Color Images

Gaussian noise

$\mu = 0, \sigma^2 = 800$

H S I

HSI components of the noisy color image

- The hue and saturation image are significantly degraded by noise due to the nonlinearity of **cos** and **min** operations.
- The intensity component is smoother than any of the three noisy RGB component images because it is the average of the three components.

Noise in Color Images

RGB image with green plane corrupted by salt-and-pepper noise

H

S

I

- When only one channel is affected by noise, conversion to HIS spreads the noise to all HSI components images.
- This is due to the transformation that makes use of all RGB components to compute each HSI component.

The end