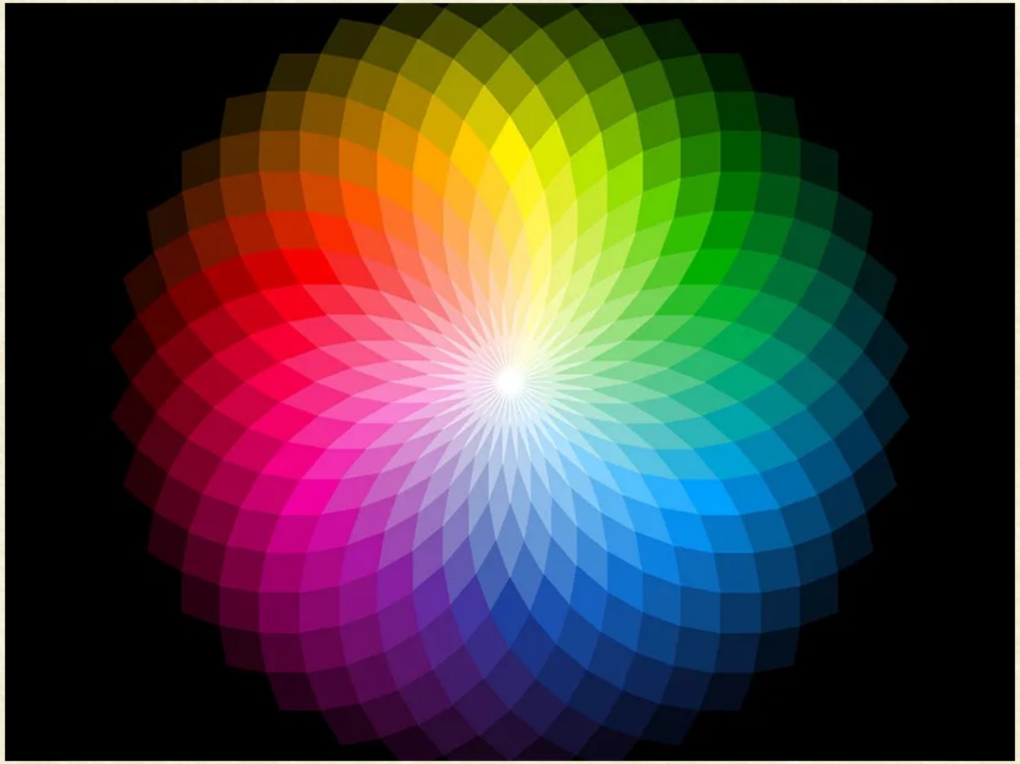
CS7.404: Digital Image Processing

Monsoon 2023: Color in Images



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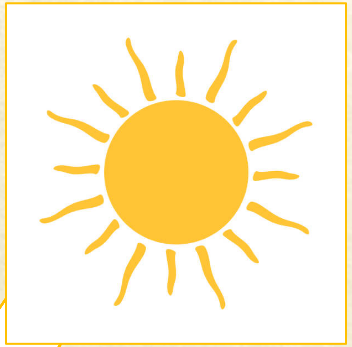
What is Color?

- Physical:

- Physio-psychological:

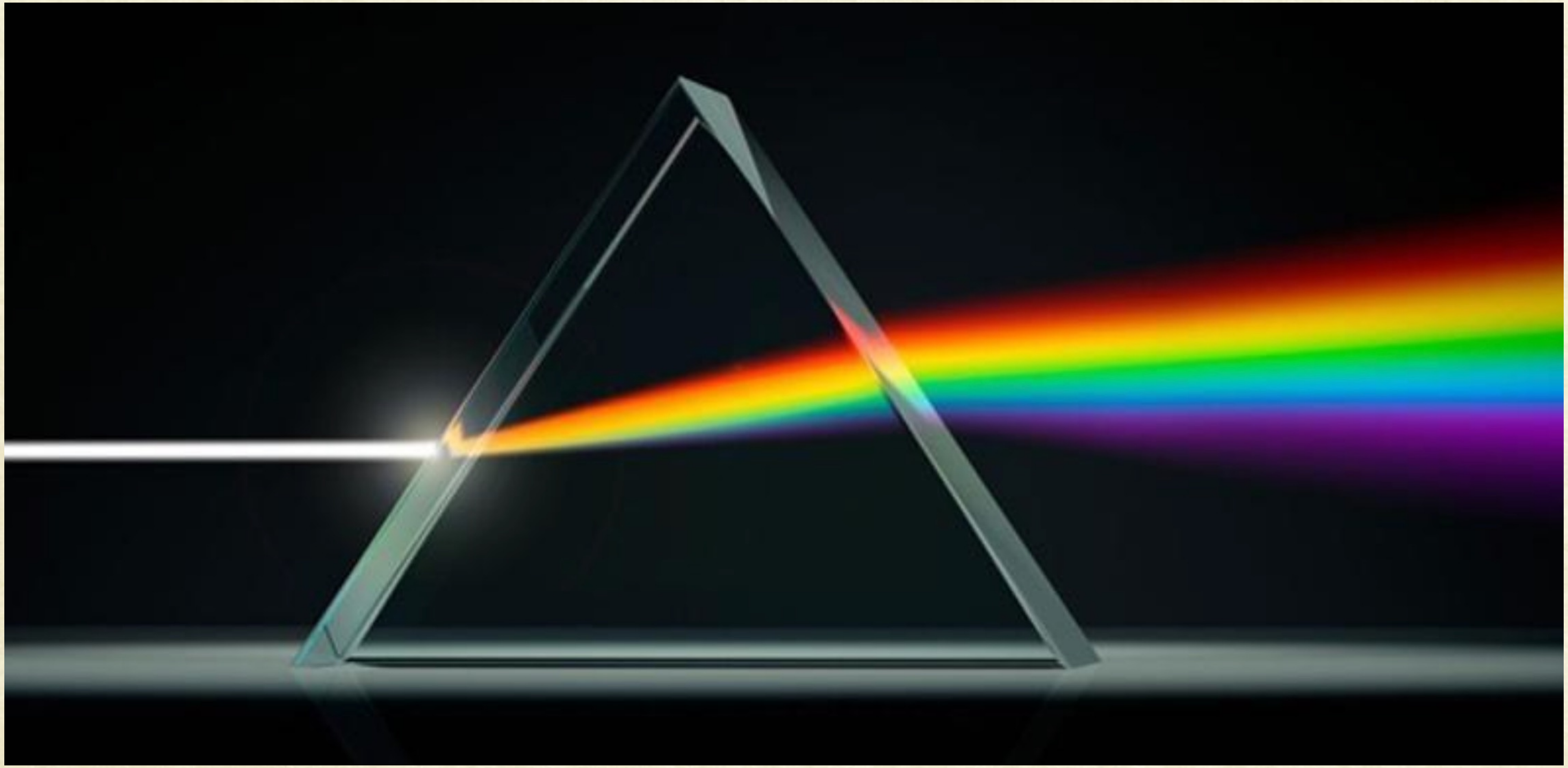
Color as a Physical Phenomenon



- The light falls on a surface
- The surface “reflects” it
- The resulting light falls on the eye

Color as a Physical Phenomenon: The Light

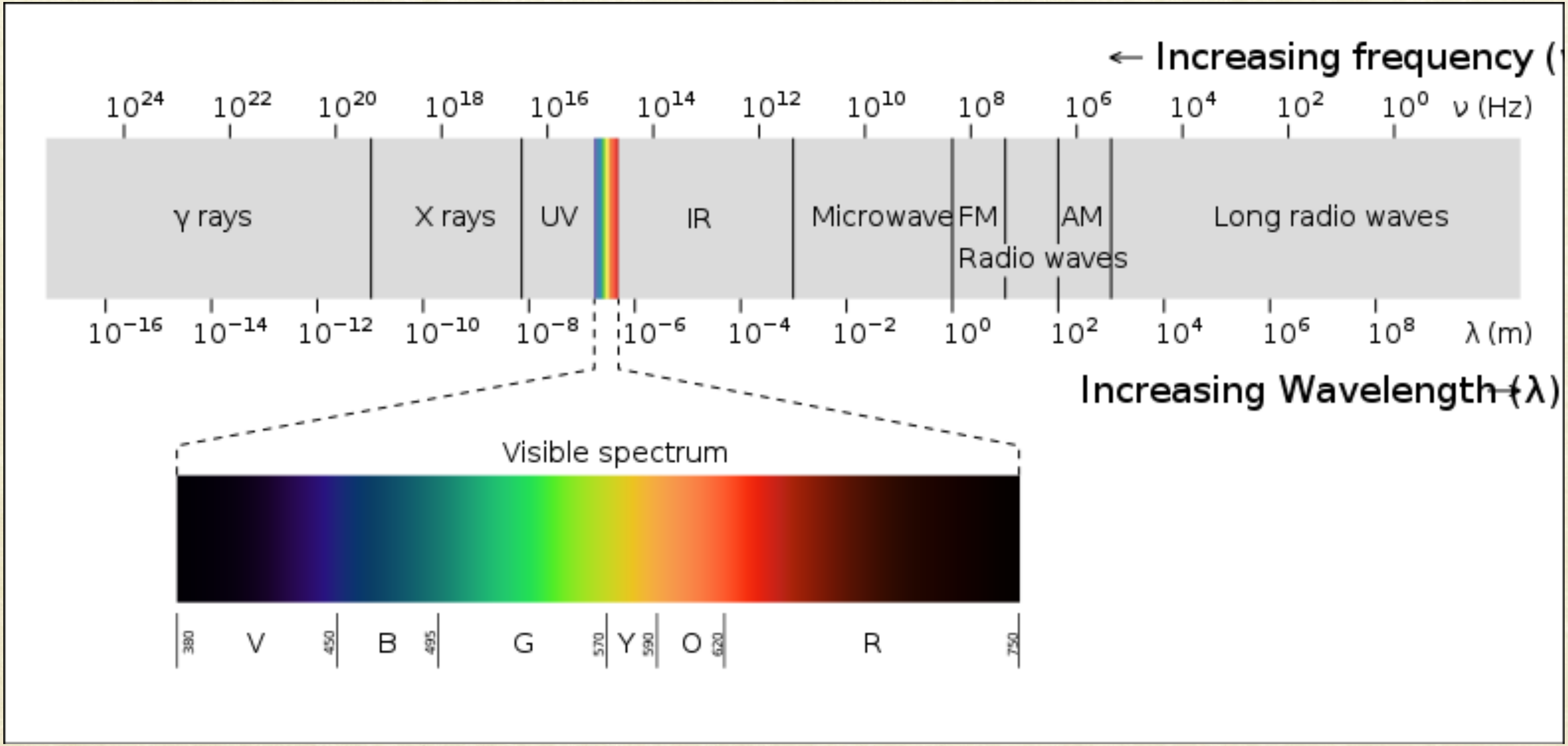
- White light is composed of EMRs of several frequencies.



Red
Orange
Yellow
Green
Blue
Indigo
Violet

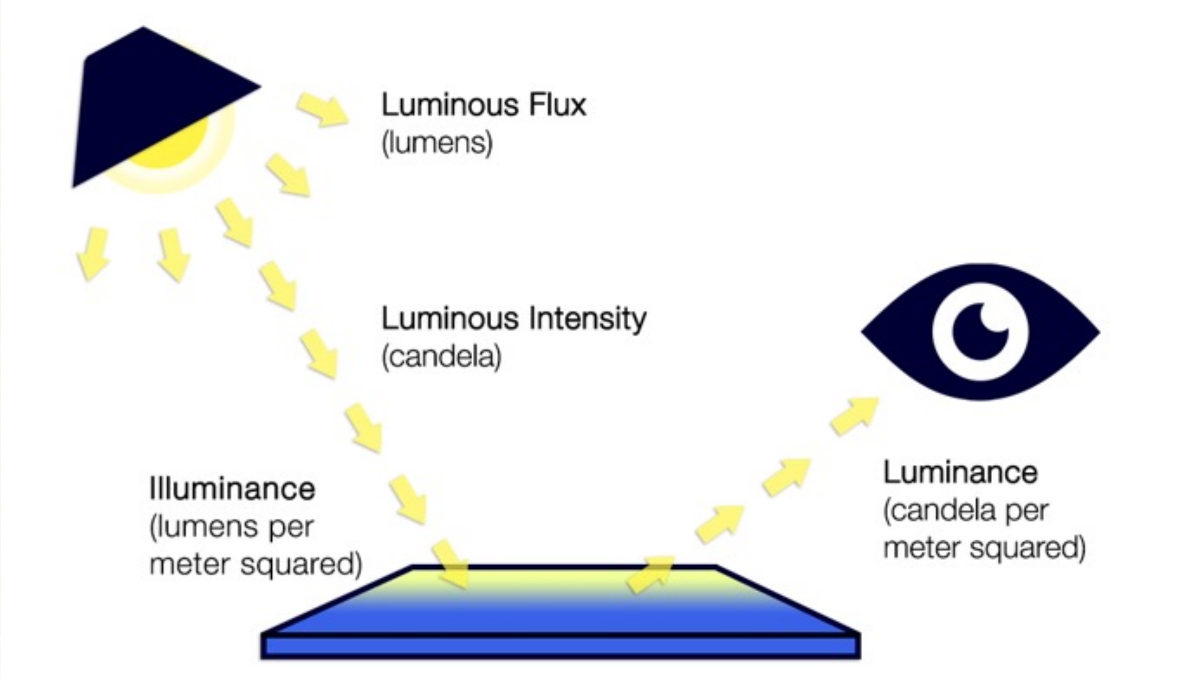
“The **rays** to speak properly are not coloured. In them there is nothing else than a certain Power and Disposition to stir up a Sensation of this or that Colour.” - Isaac Newton, Opticks, 1704

The Light



← Increasing frequency (ν
10^24 10^22 10^20 10^18 10^16 10^14 10^12 10^10 10^8 10^6 10^4 10^2 10^0 ν (Hz)
γ rays
X rays
UV
IR
Microwave
FM
AM
Long radio waves
Radio waves
10^−16 10^−14 10^−12 10^−10 10^−8 10^−6 10^−4 10^−2 10^0 10^2 10^4 10^6 10^8 λ (m)
Increasing Wavelength (λ) →
Visible spectrum
380 V 450 B 495 G 570 Y 590 O 620 R 750

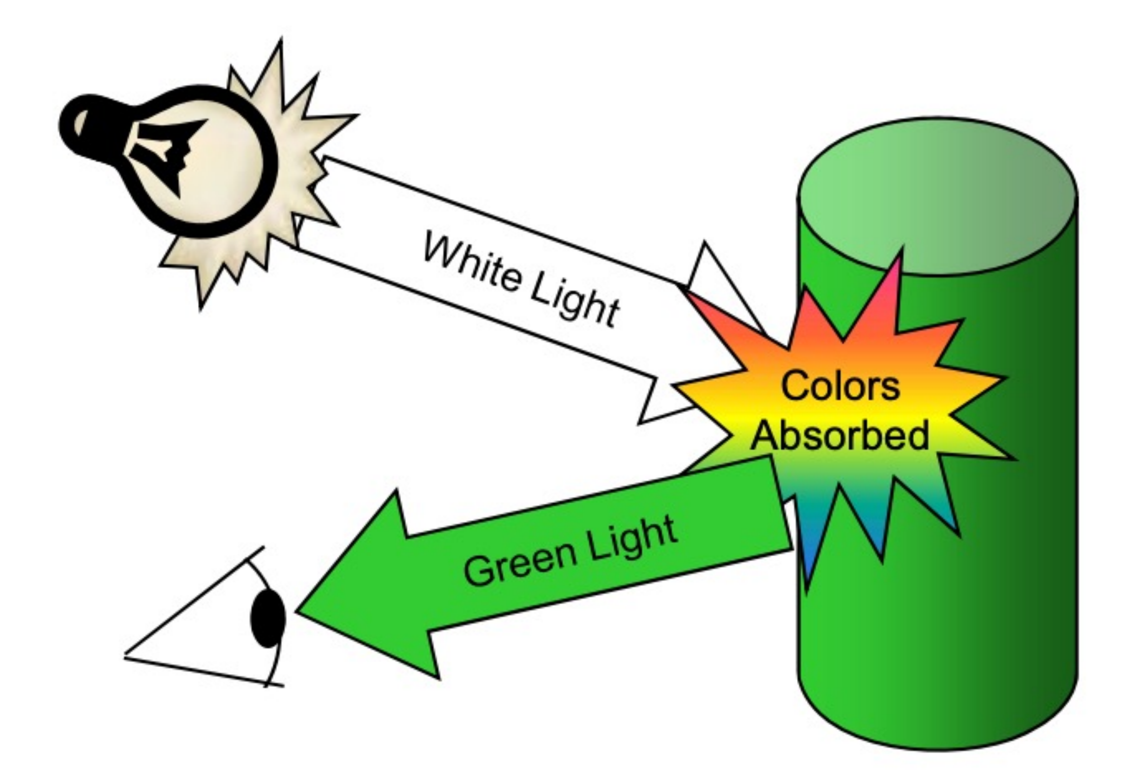
Physical Quantities

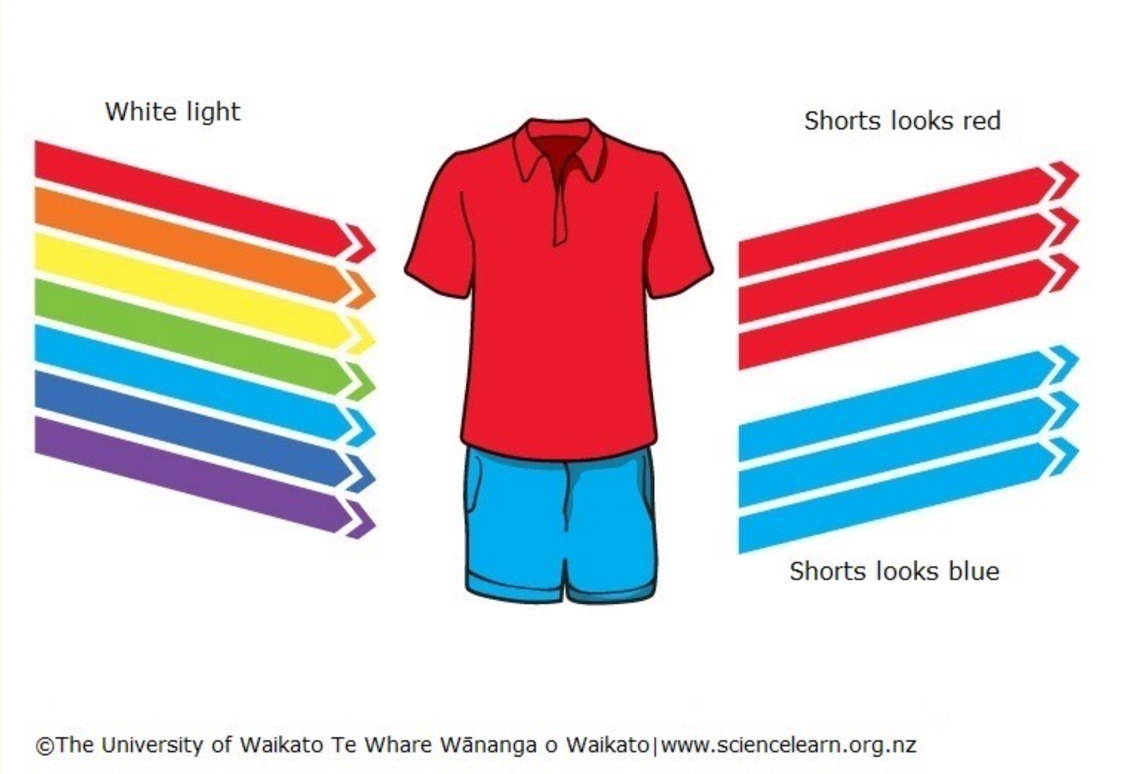


- Radiance: Total amount of energy flow from the light source, measured in watts (W)
- Luminance: amount of energy an observer *perceives* from a light source, measured in candela/m^2
  - Far infrared light: high radiance, but 0 luminance
- Brightness: subjective descriptor that is hard to measure, (similar to the achromatic notion of intensity)

Physical Phenomenon: The Surface

- Color is determined by nature of light reflected from an object
- e.g., green object reflects light from 500-570nm wavelength, and absorbs other wavelengths



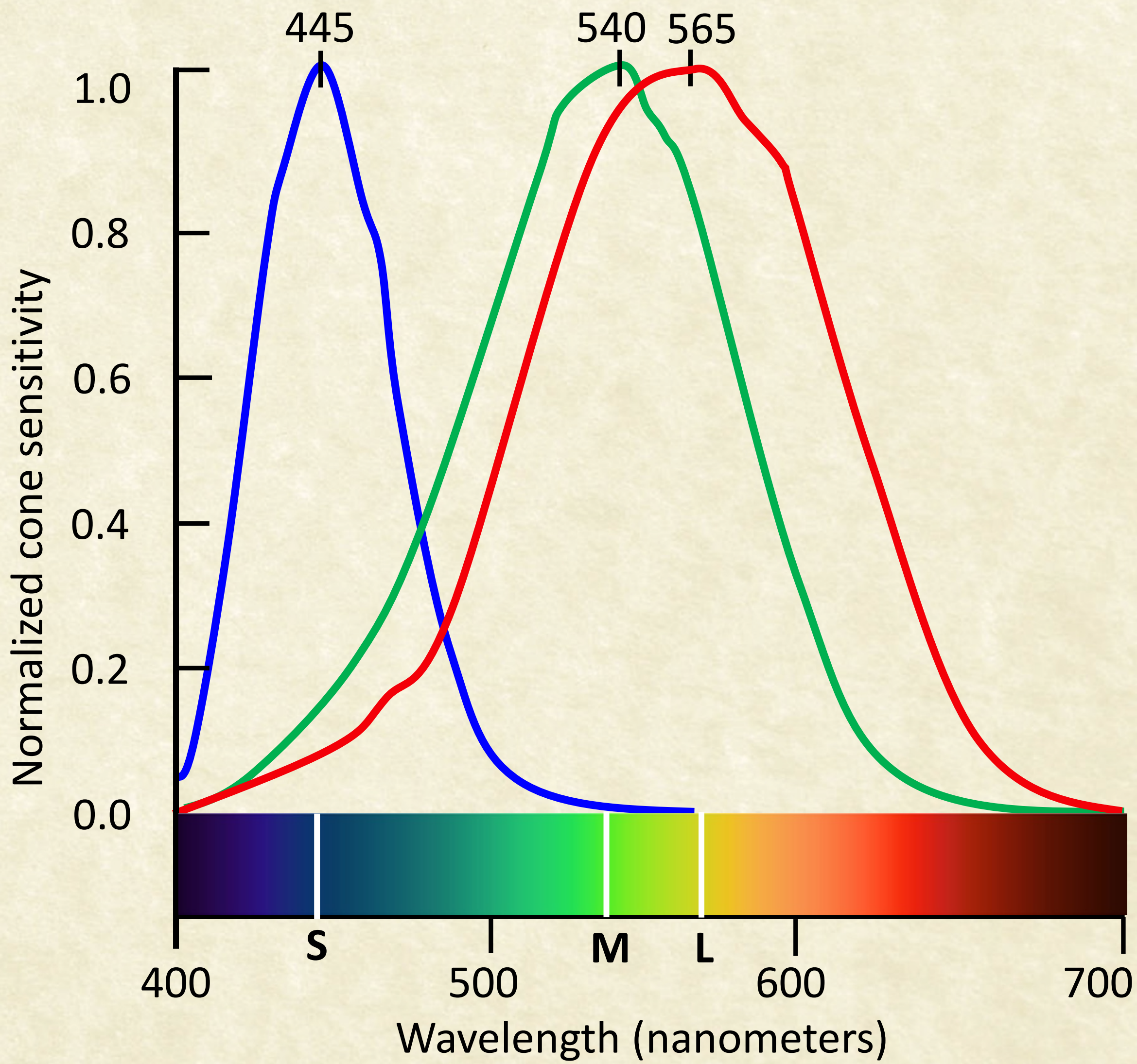


Courtesy: CNikou

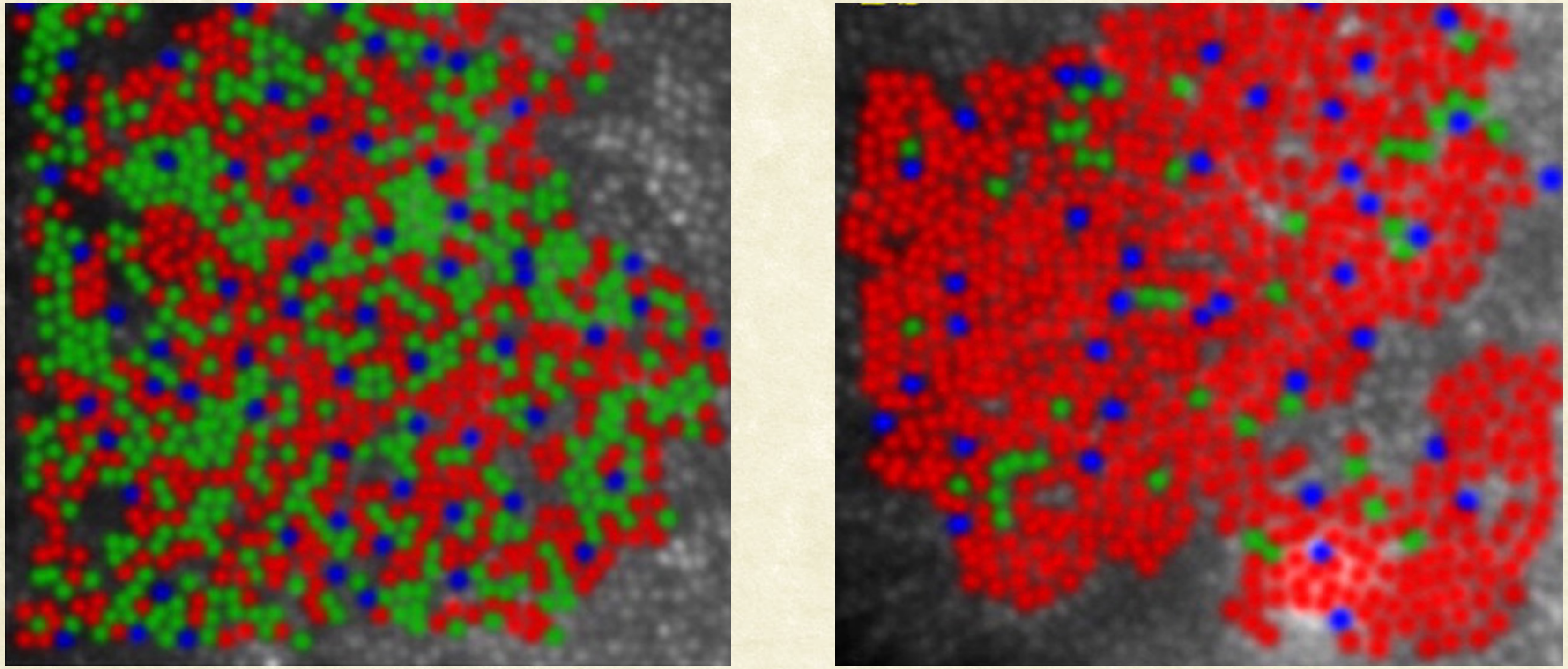
Physical Phenomenon: The Eye

- Cones are active under high light levels.
  They are responsible for photopic vision.
- Three cone types are sensitive to Short (S), Medium (M) and Long (L) wavelengths.

  The color names for these cones are not very accurate.



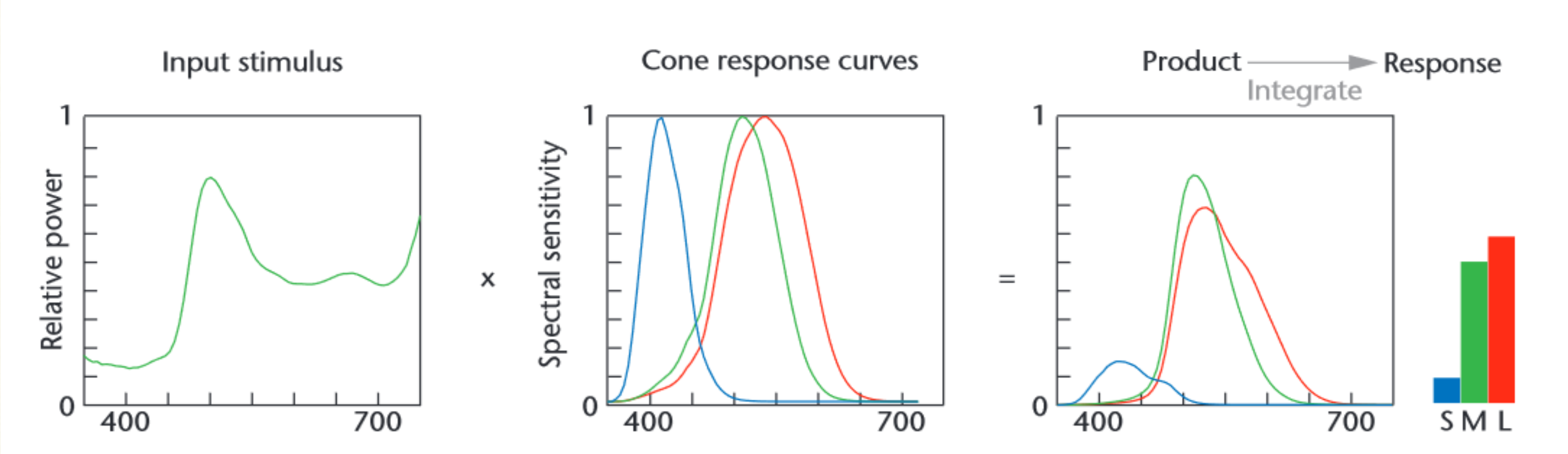
The Eye: Cone distribution



- Near-fovea images of two different human subjects: colors indicate L (red), M (green), and S (blue) cones.
- Remarkably, both subjects have normal color vision !!!

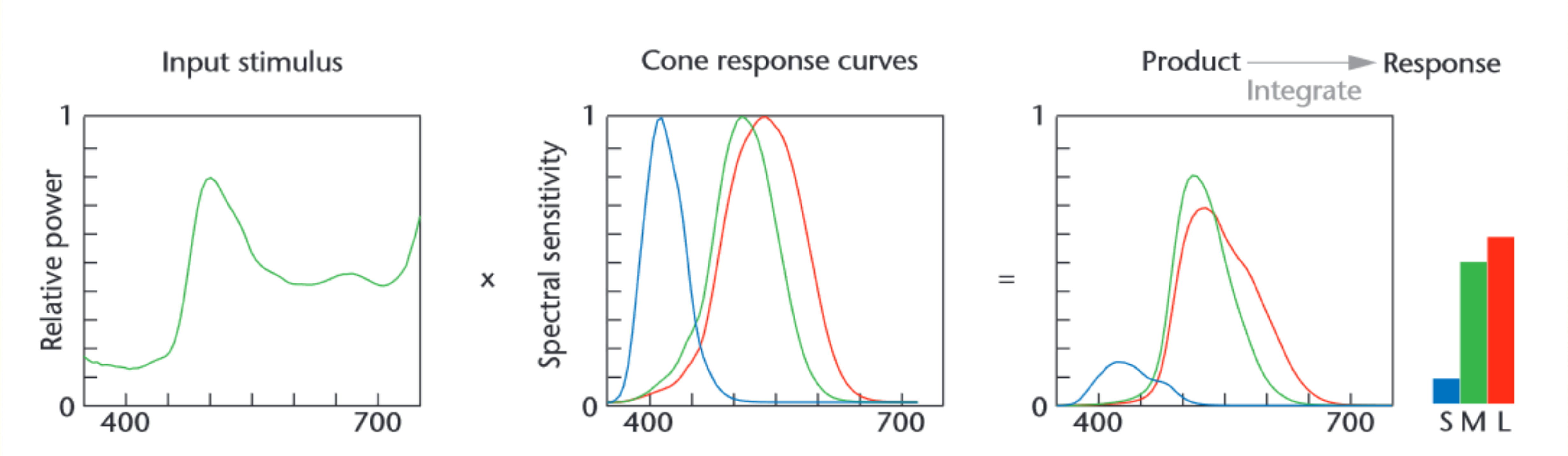
Image Courtsey: Hofer et al.

The Eye: Color signal to the brain



- Note that intensity is a weighted function of their r, g, and b values.
- The human eye does not weight each component equally.
  - $Intensity = 0.299 \times \boldsymbol{Red} + 0.587 \times \boldsymbol{Green} + 0.144 \times \boldsymbol{Blue}.$

Psychological Phenomenon: The Brain



- The perception of color is an entirely arbitrary creation of our nervous system. It is not contained in the wavelengths themselves (remember the remark of Isaac Newton).

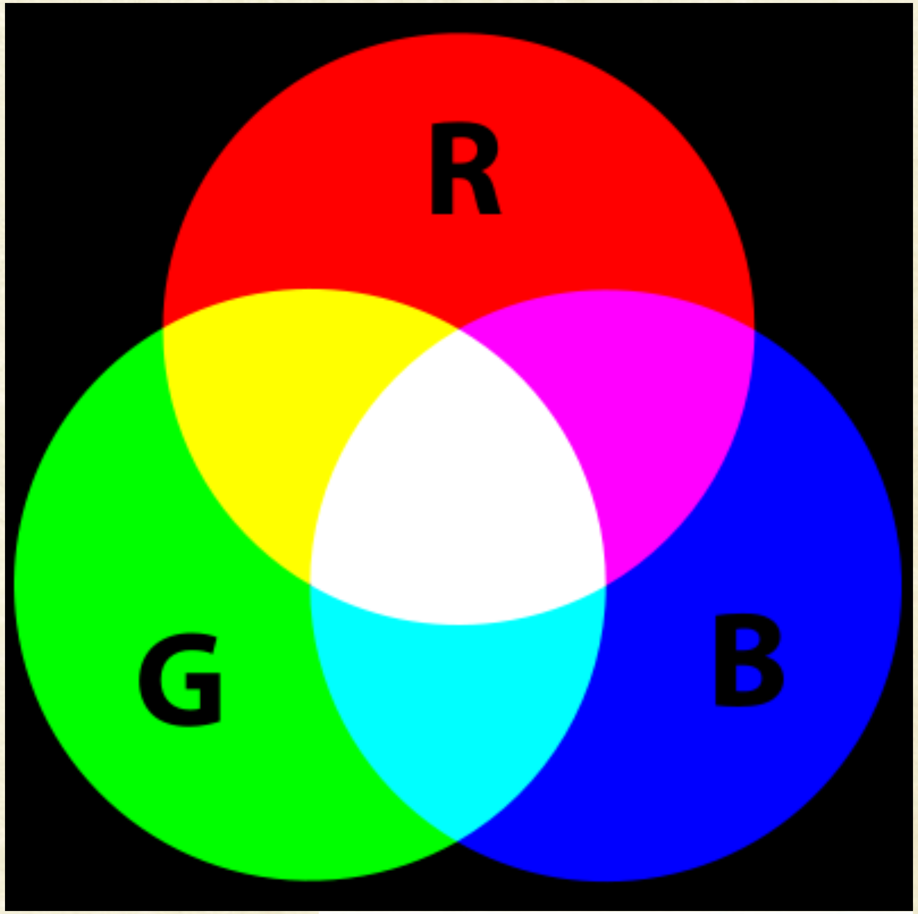
Tetrachromats:

- People with 4 different cones

Mantis shrimp
12 primary color receptors

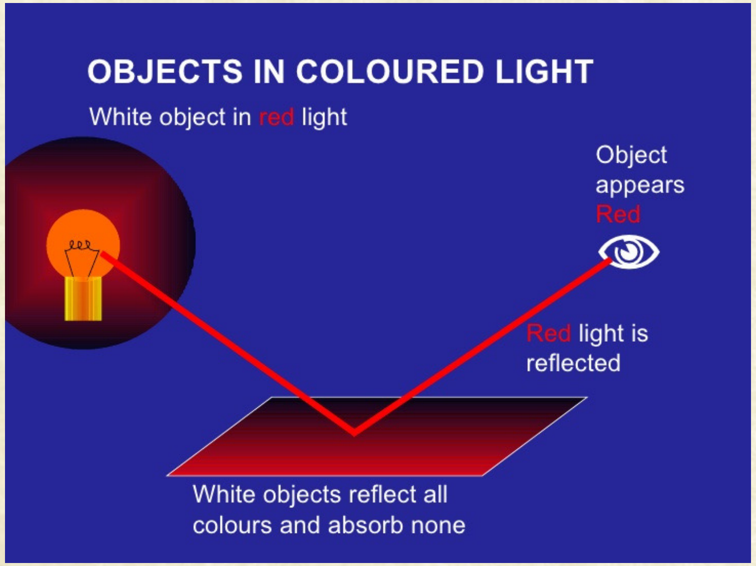
Primary Colors (color as three numbers)

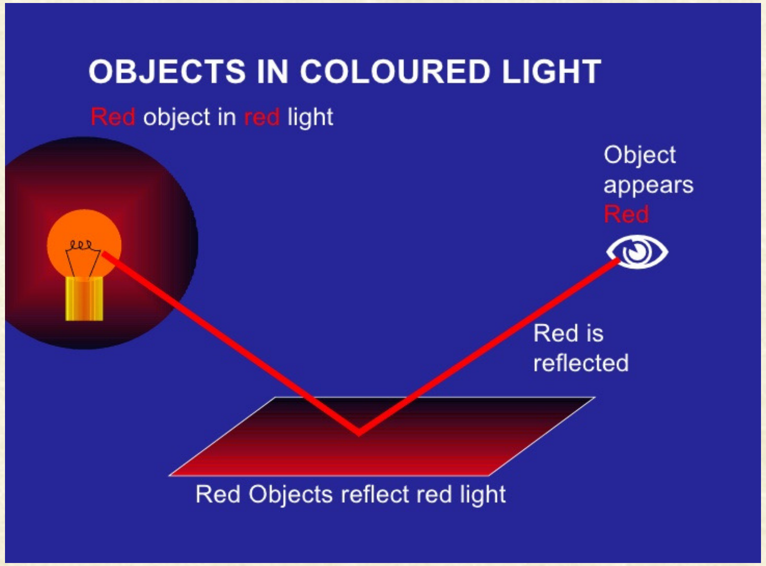
- Additive (CRT displays, projectors etc.)
  - Combining red, green and blue light produces lighter colors, offering a good contrast to dark screens.
  - (Usually) Combined on a surface which reflects all light that falls on it
  - Easy to get **black** – don’t shine any light (CRT)

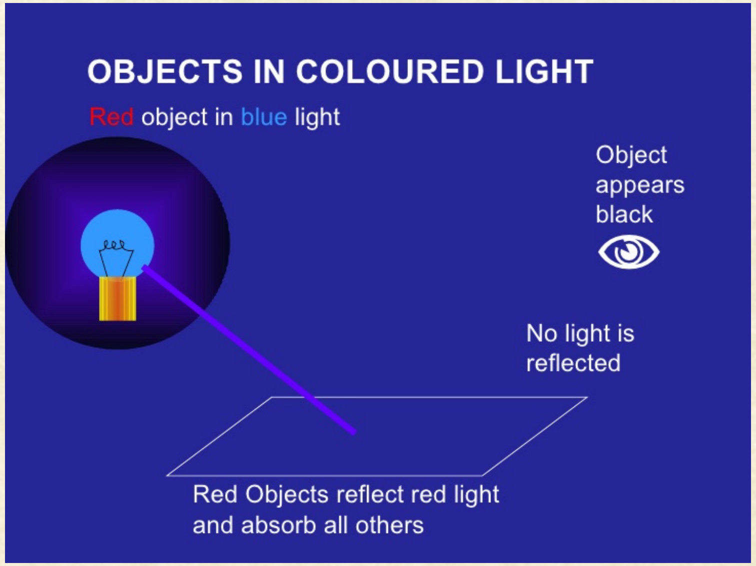


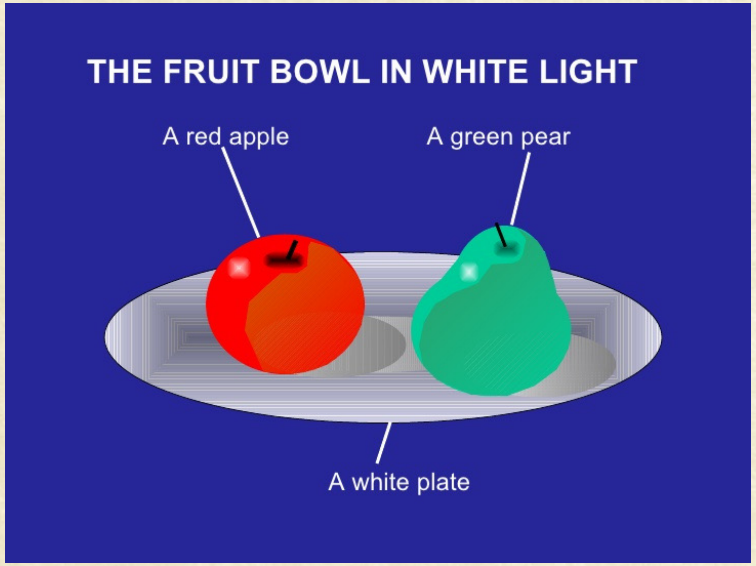
Magenta = Red + Blue
Cyan = Blue + Green
Yellow = Green + Red

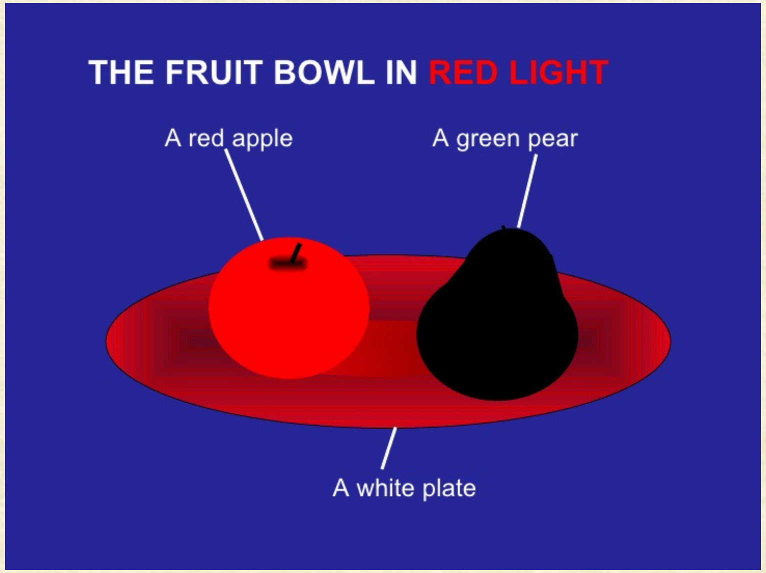
Perceived Color = f(Light, Object)

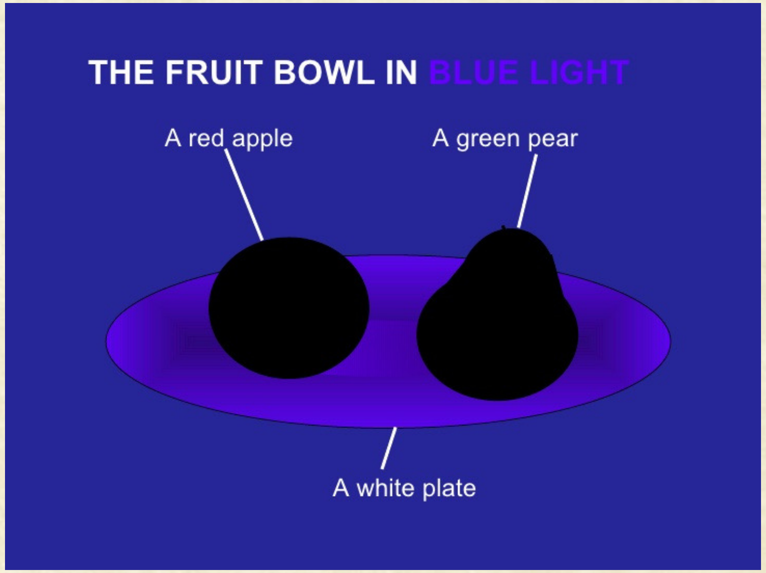












R,G,B Channels of an Image

Full color

Red

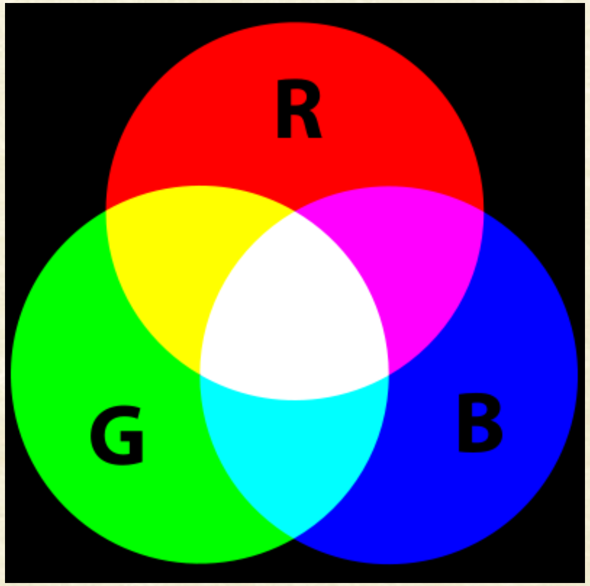
Green

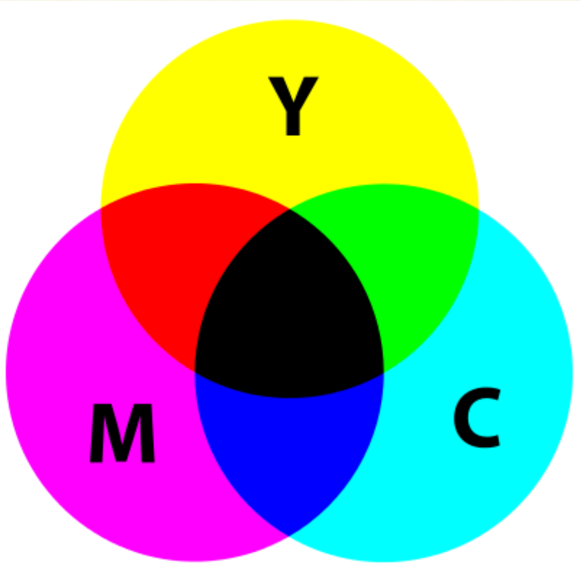
Blue

R,G,B Channels of an Image

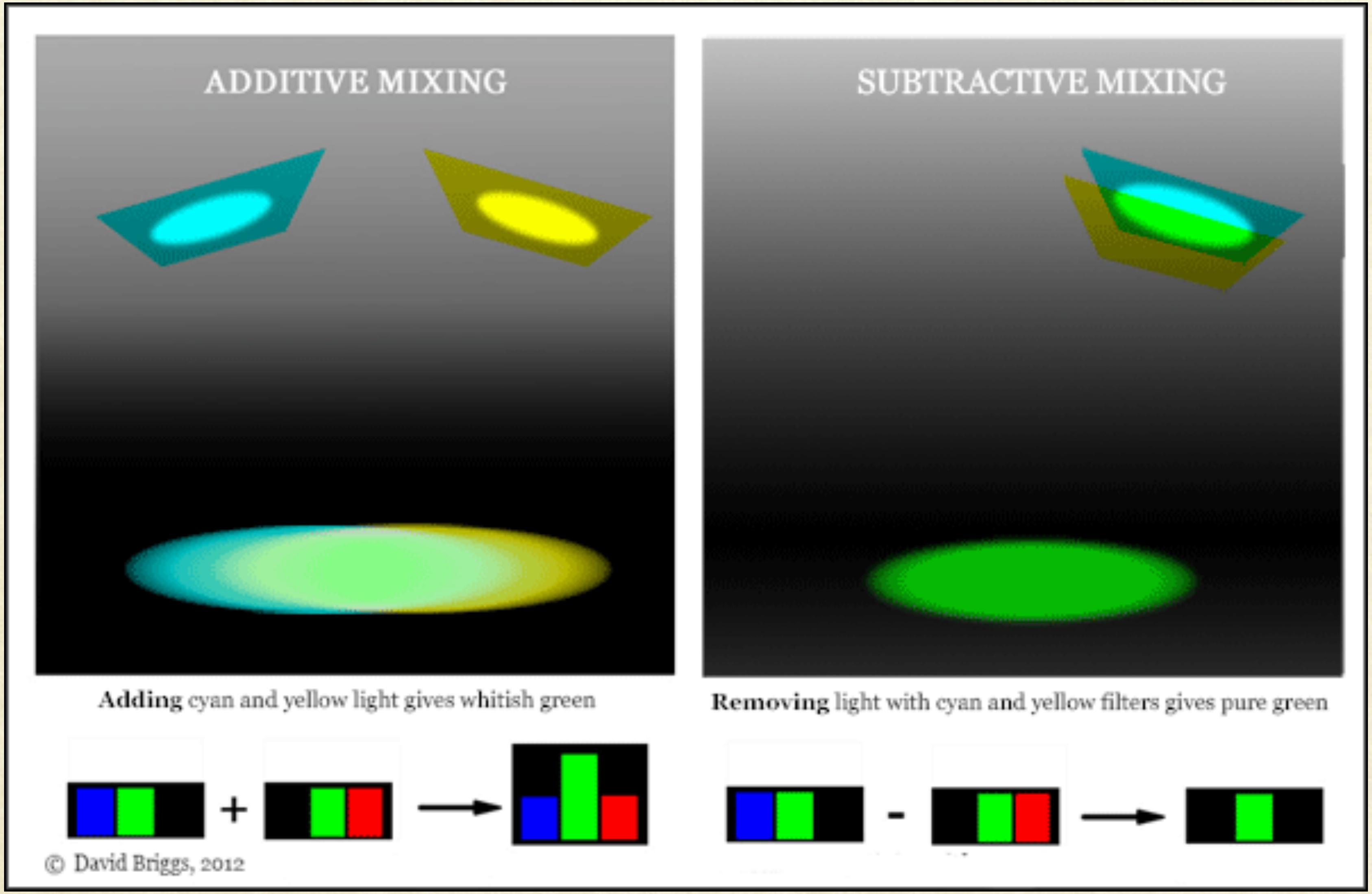
Primary Colors

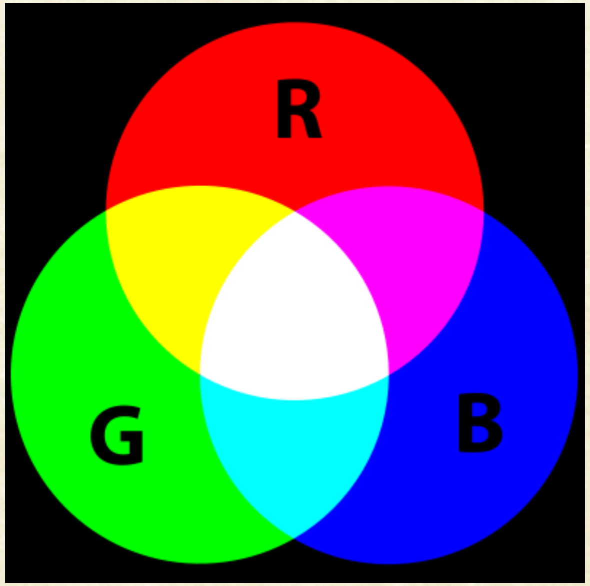
- Subtractive (Painting, printing, etc.)
  - Prevent certain wavelengths from being reflected
  - Starting with white paper, each added colored ink "subtracts" available color from the starting medium.
  - For pure white , leave the paper unprinted (nothing can be whiter than the paper it is printed upon).

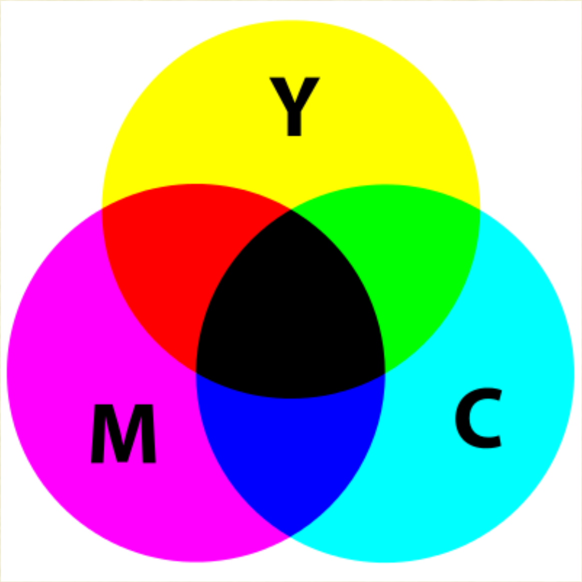




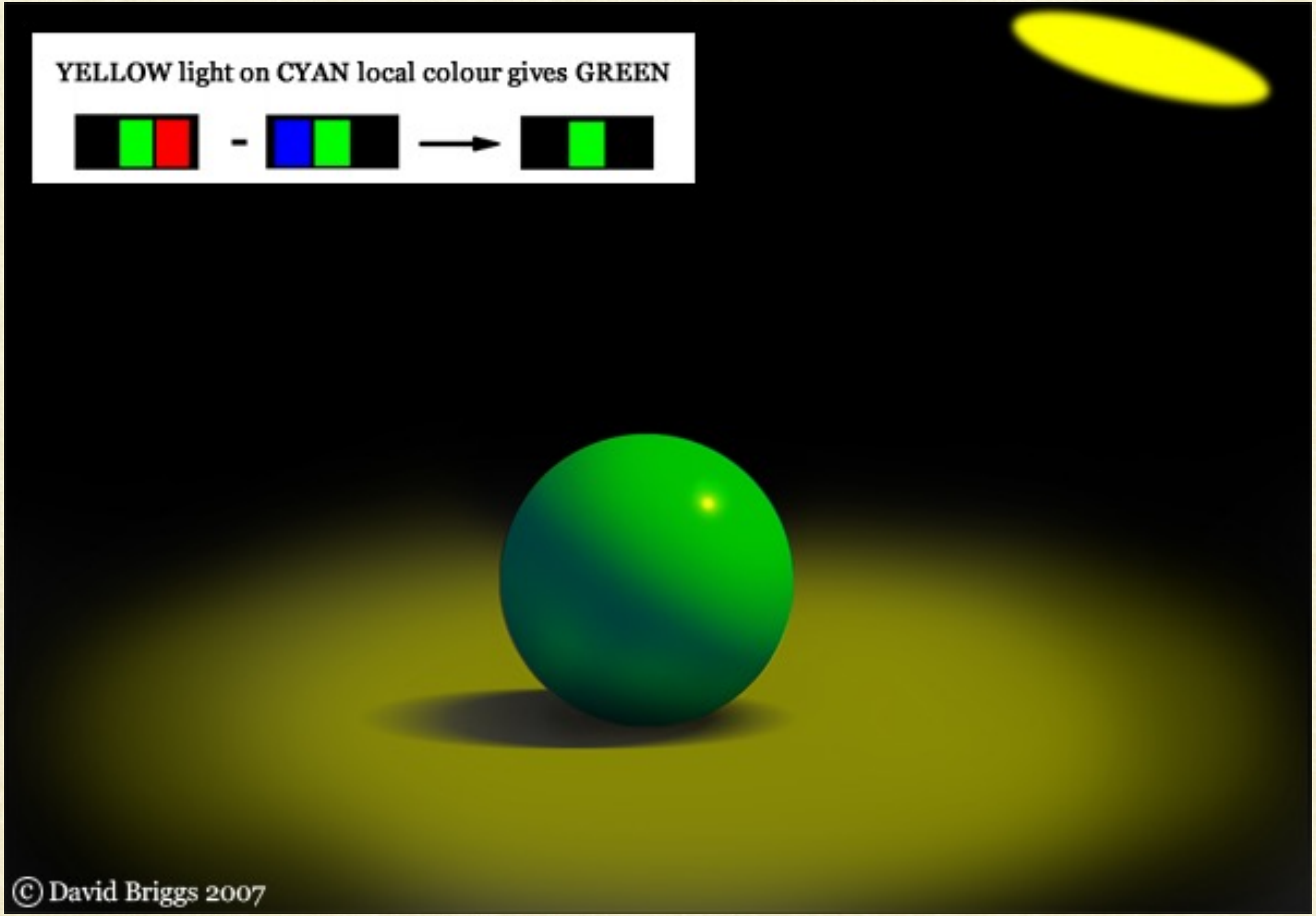
RGB vs CMY


ADDITIVE MIXING
SUBTRACTIVE MIXING
Adding cyan and yellow light gives whitish green
Removing light with cyan and yellow filters gives pure green
+
-
© David Briggs, 2012

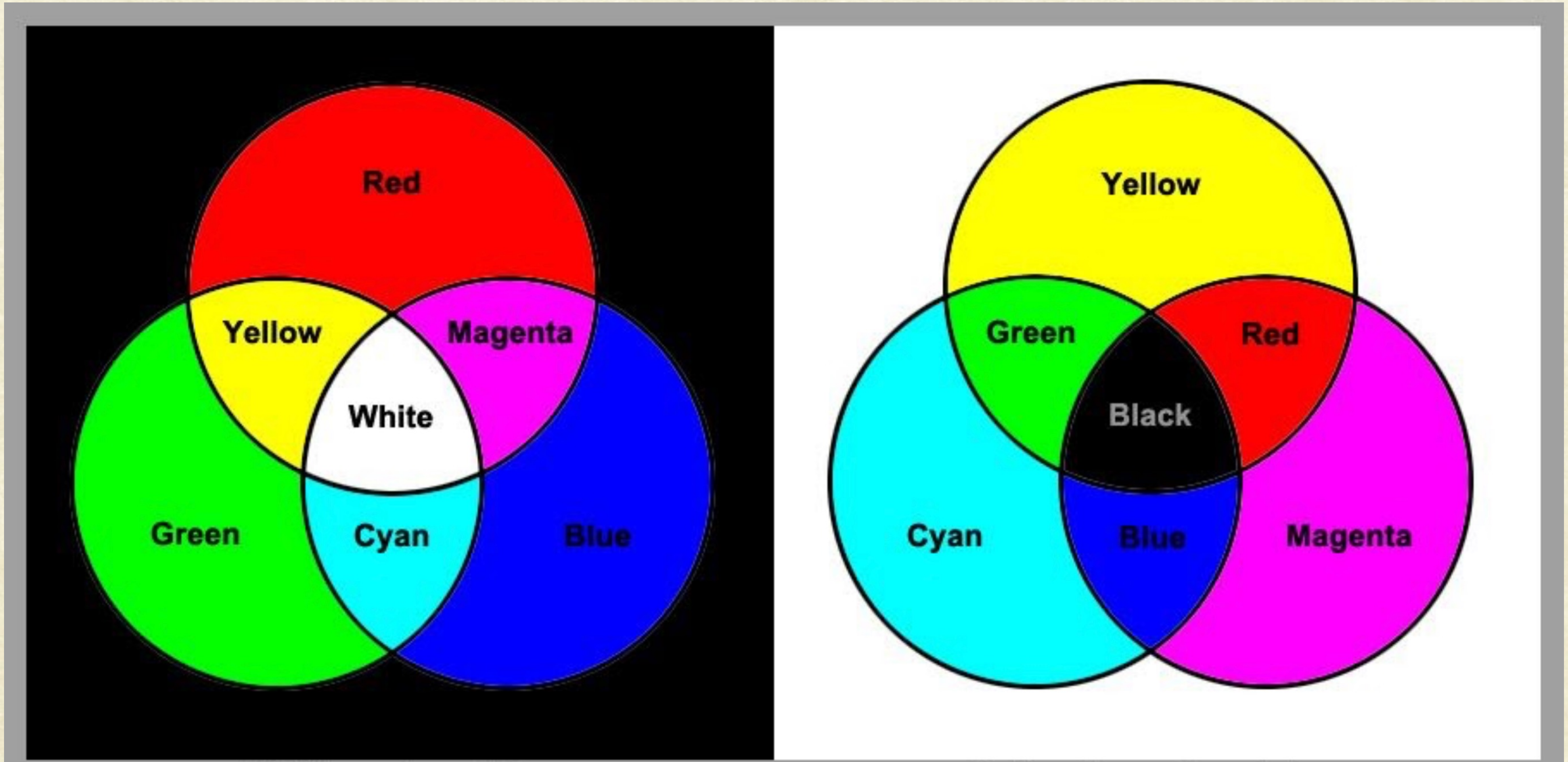

R
G
B


Y
M
C

Objects in Colored Light



Additive vs. Subtractive color mixing



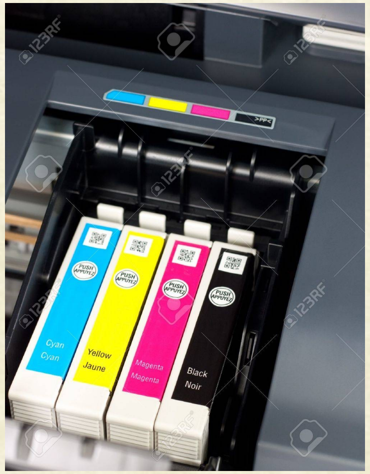
Additive color mixing

Subtractive color mixing

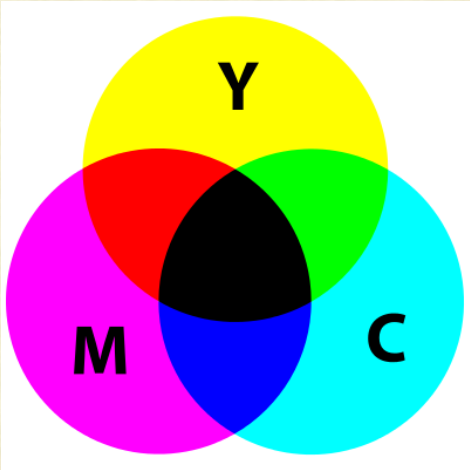
Magenta = Red + Blue
Cyan = Blue + Green
Yellow = Green + Red

Magenta = White - Green
Cyan = White - Red
Yellow = White - Blue

Why CMYK in Printing?

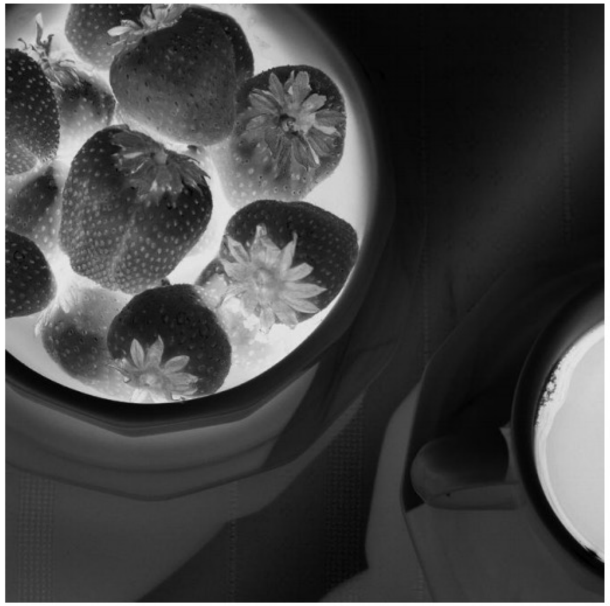


- Color pigments absorb specific wavelenths.
- CMY cover most lighter color ranges quite easily compared to RGB.
- BUT CMY by itself will not be able to create very deep dark colors (e.g. “true black,”)
- Black (designated “K” for “key color”) is added to CMY to achieve a much wider range of colors.

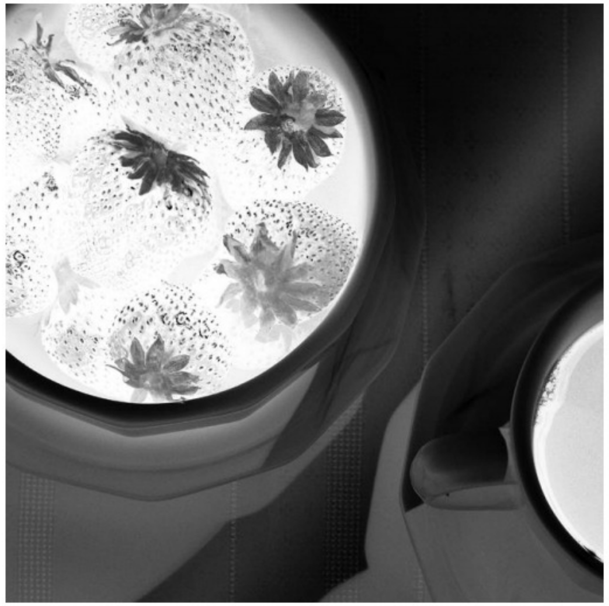


CMYK

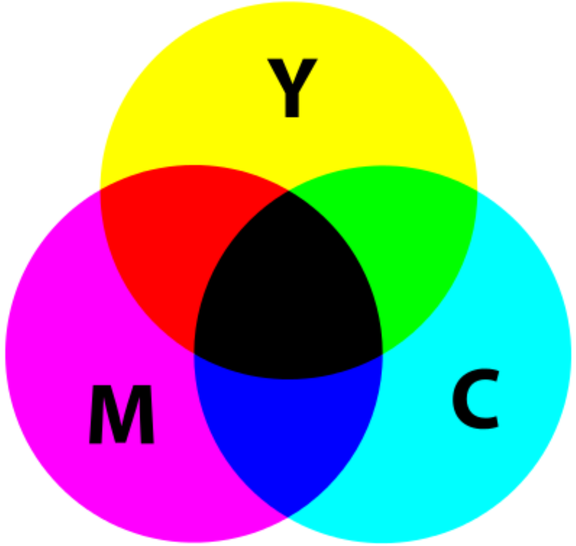
Full color

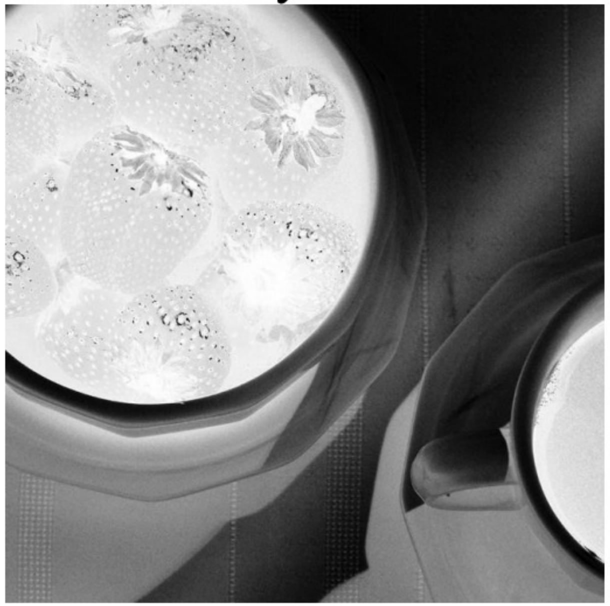


Cyan

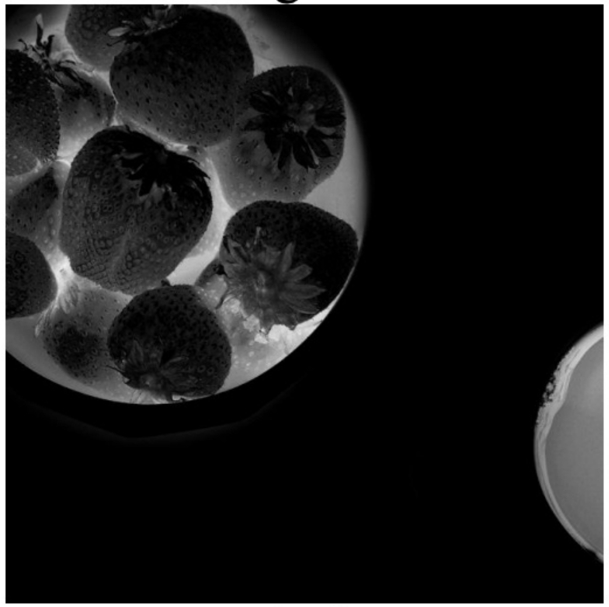


Magenta



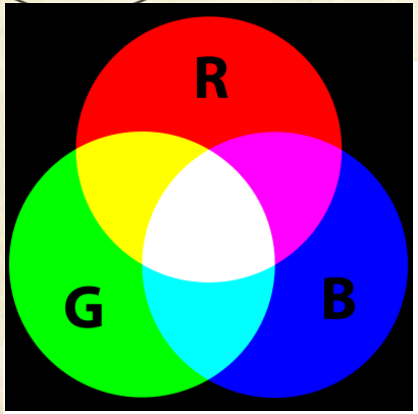


Yellow

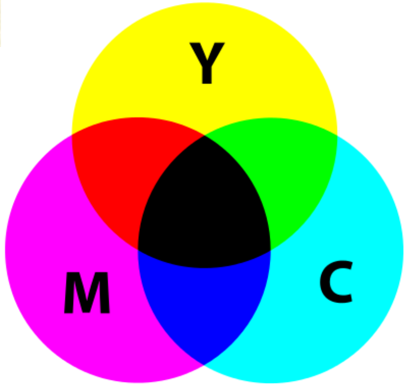


Black

RGB to CMY



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

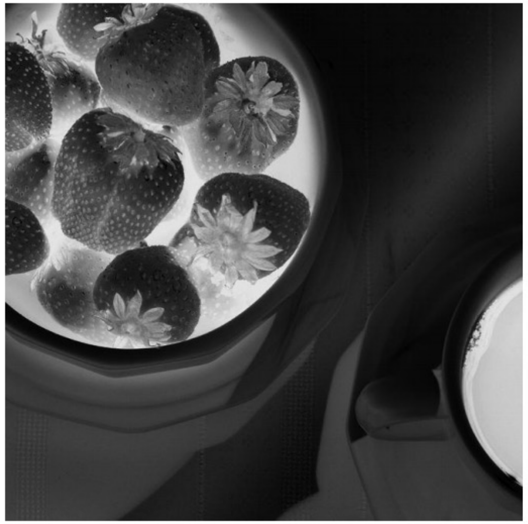


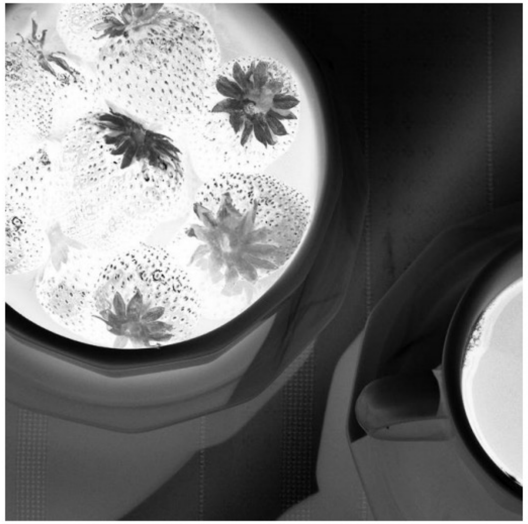

Full color

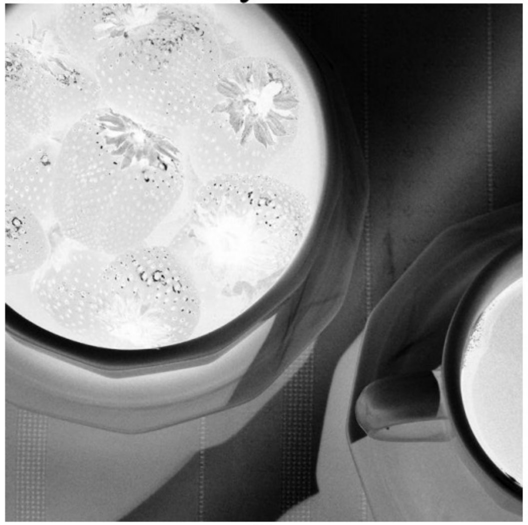

Red

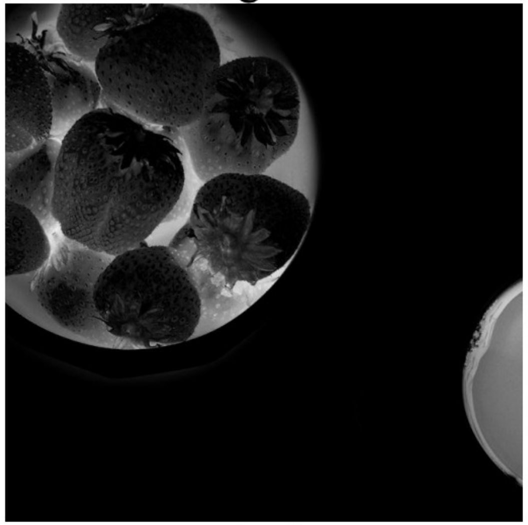

Green


Blue


Cyan

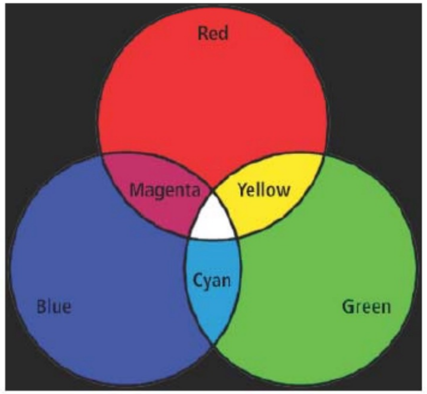

Magenta


Yellow

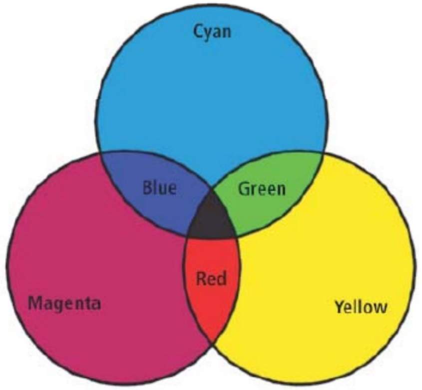

Black

Additive and Subtractive Color Spaces

Original | Red Band | Green Band | Blue Band



Magenta = Red + Blue
Cyan = Blue + Green
Yellow = Green + Red

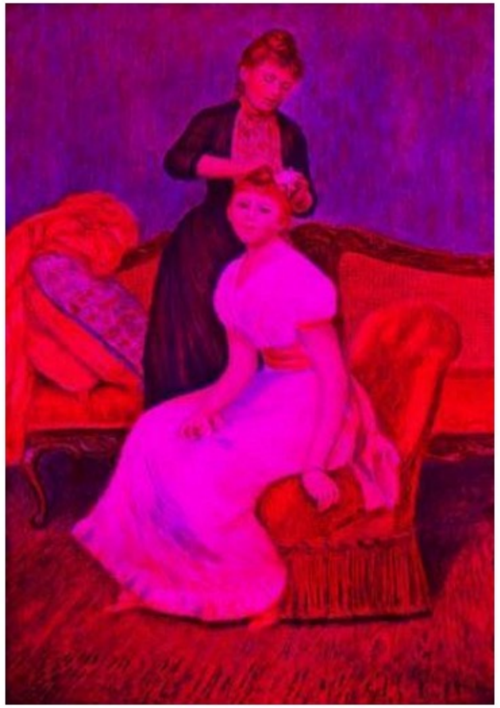


Magenta = White - Green
Cyan = White - Red
Yellow = White - Blue

Cyan

No Red

Magenta

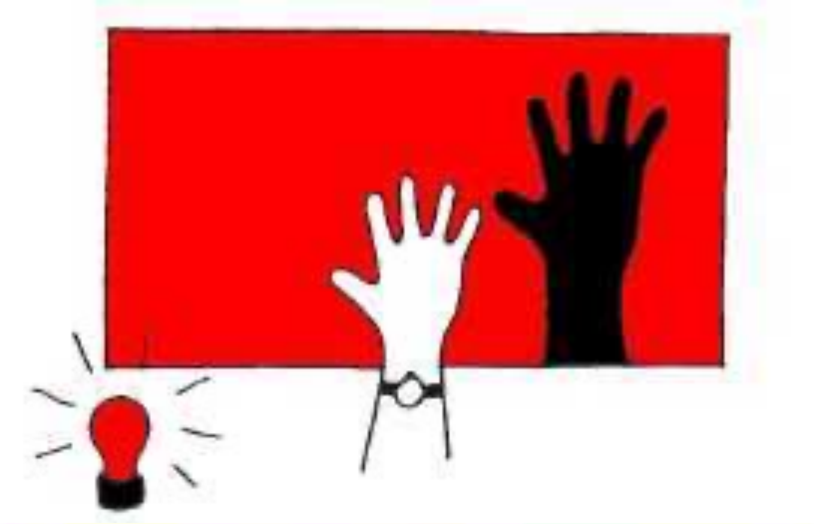


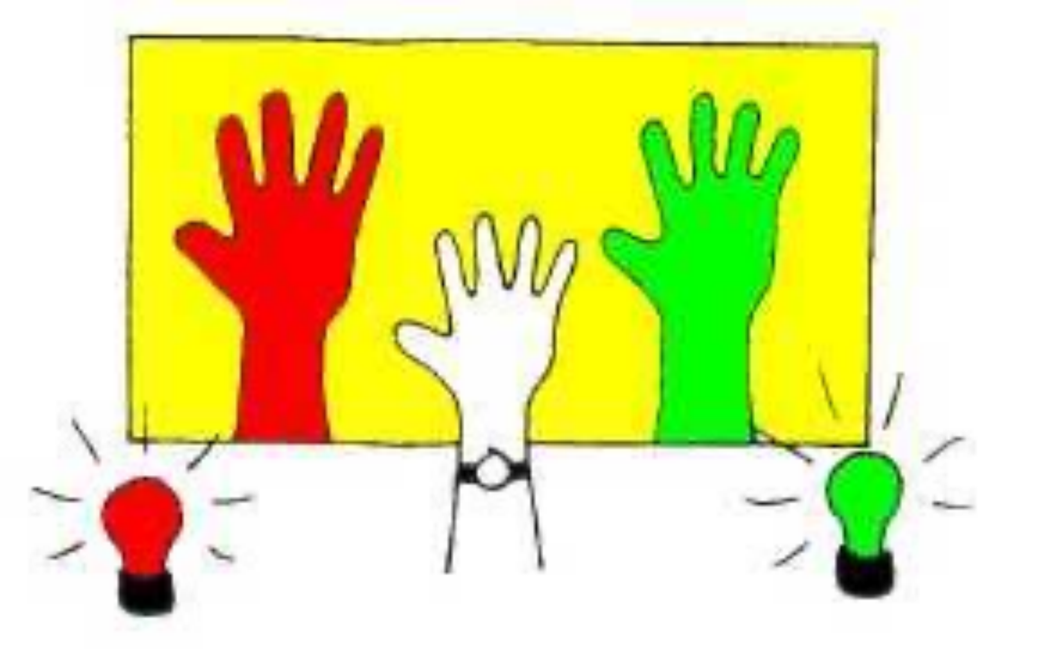
No Green

Yellow

No Blue

RGB vs. CMY



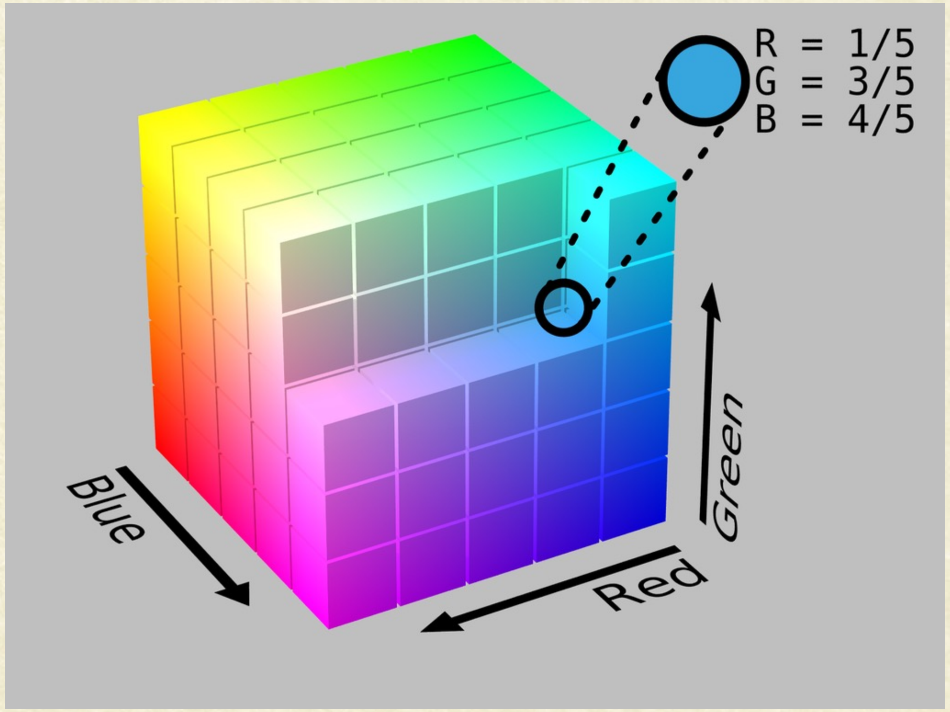


Color Models

- RGB
- HSI / HSY
- CIE LAB

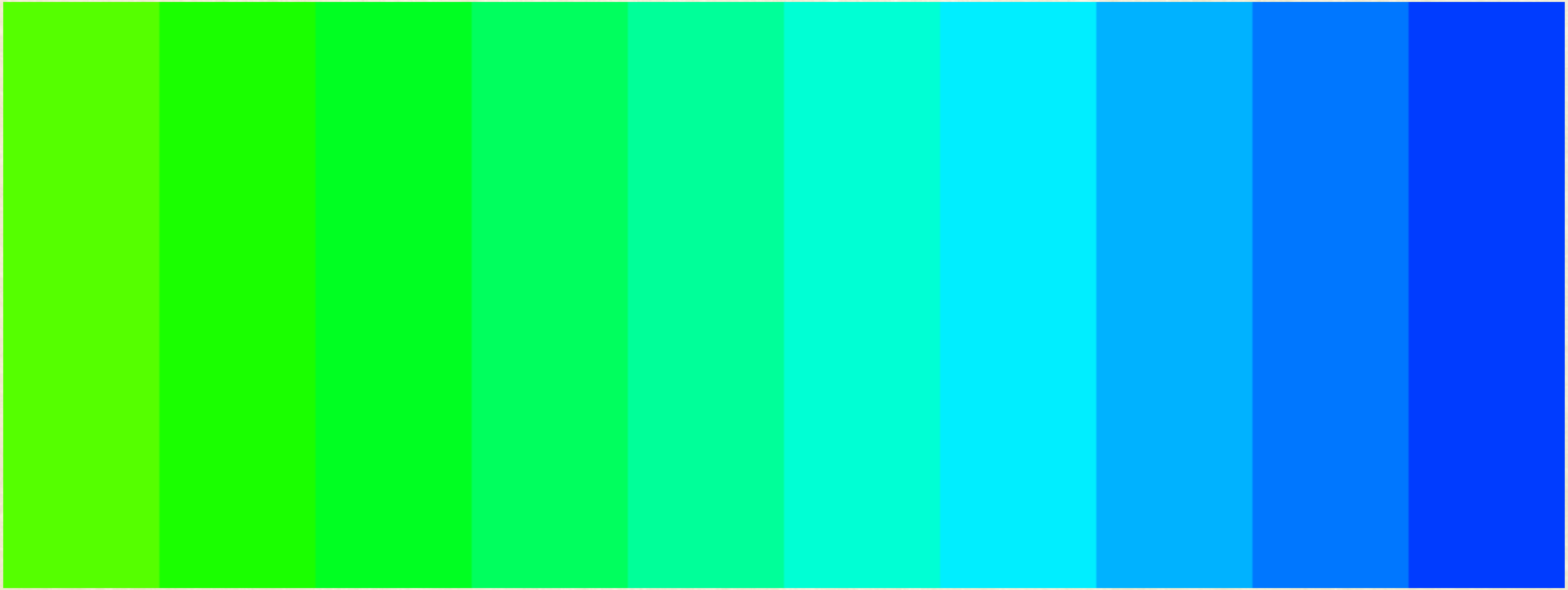
RGB color space

- Primary colors
- Additive color model $f(x, y) = \alpha_1 R + \alpha_2 G + \alpha_3 B$
- Perceptually non uniform



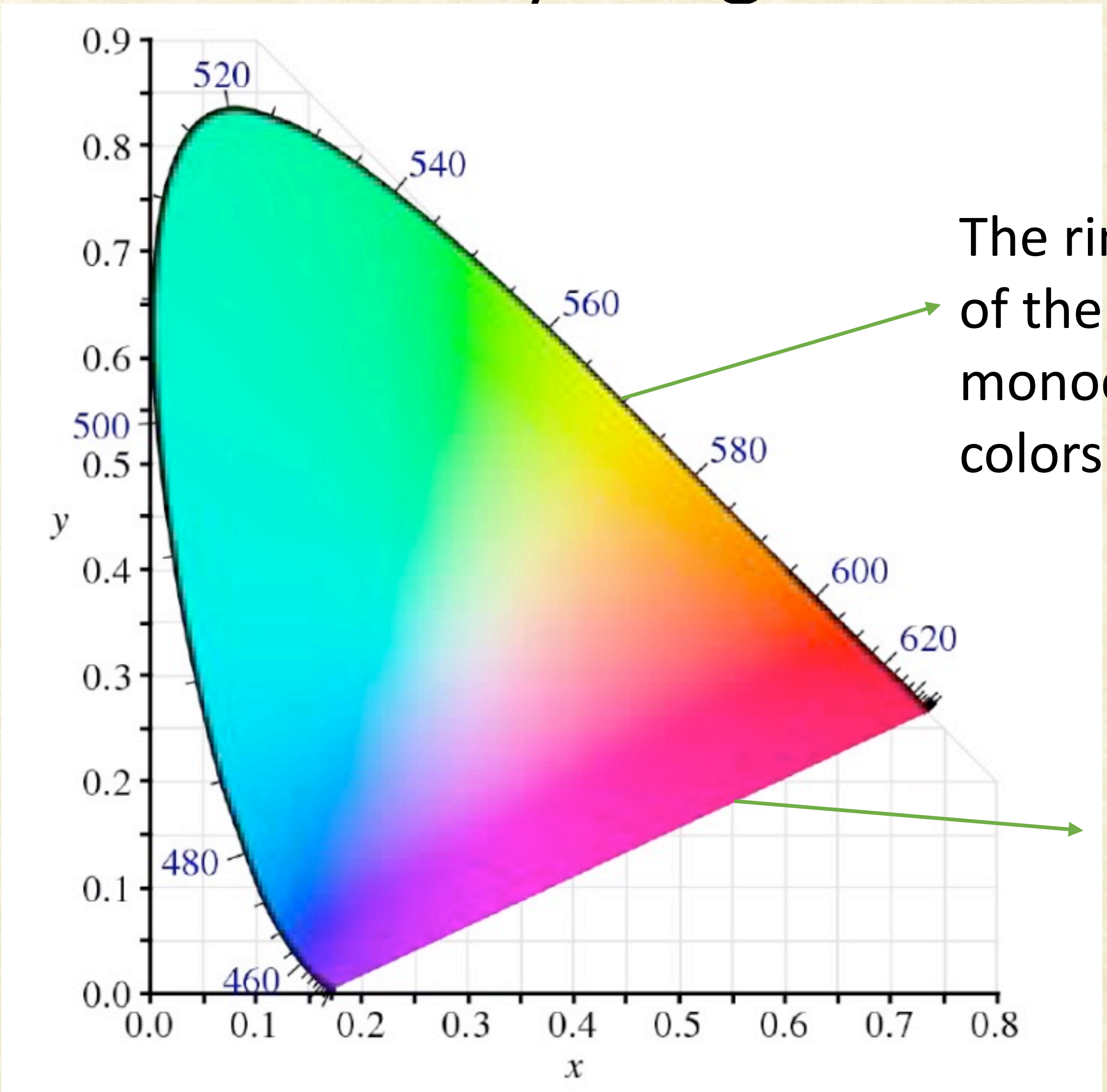
Courtesy: wikipedia

RGB : Non-Uniform Perceptual Space



CIE 1931 (x,y) chromaticity diagram

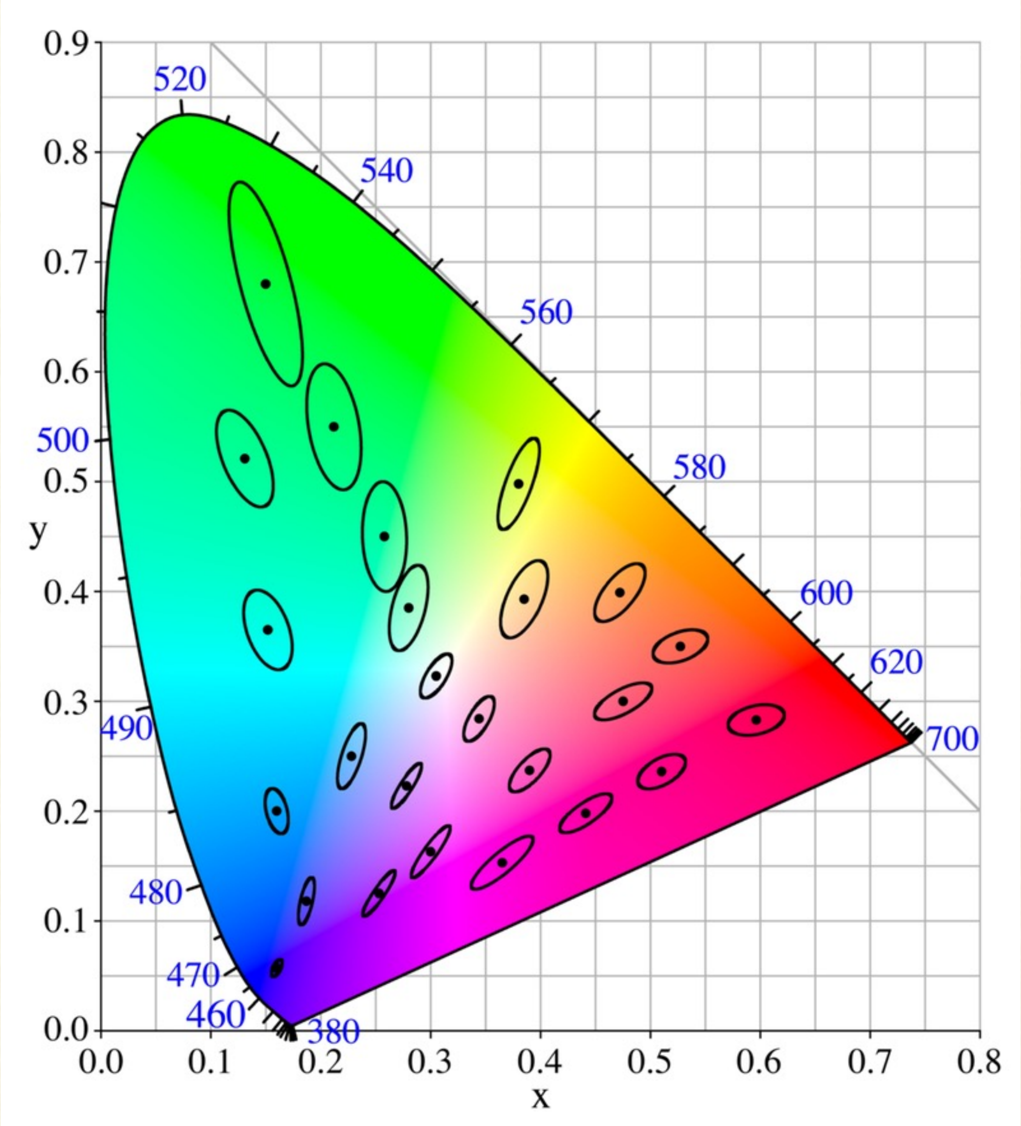
- Created by the International Commission on Illumination (CIE) in 1931
- Y x y: Luminance + the two most distinctive chrominance components
- Helps separate luminance and chromaticity
- A convenient representation for color values



The rim represents all of the pure monochromatic colors

Purple Line

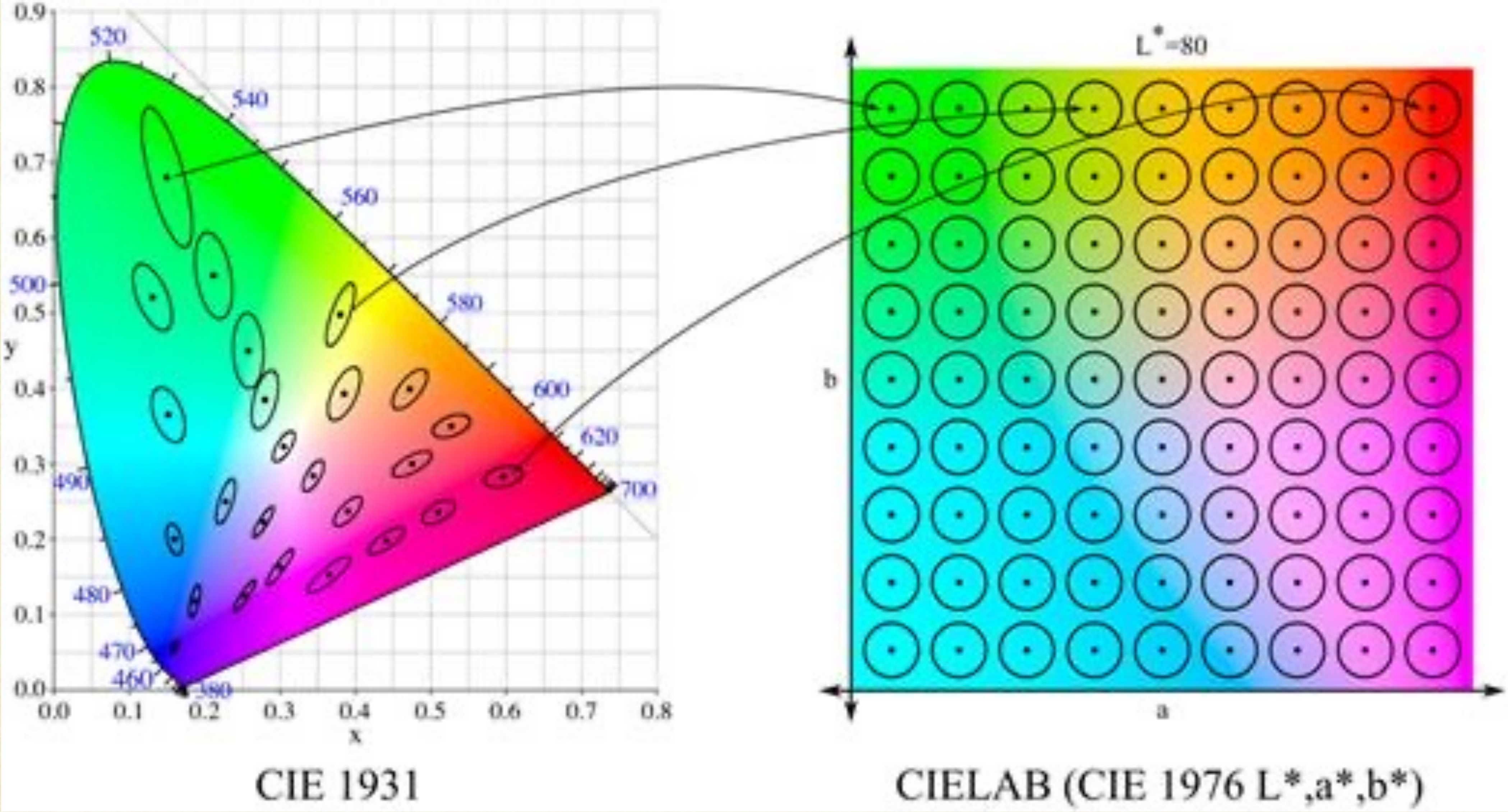
McAdam Ellipses



- **McAdam ellipses** refer to the region on a chromaticity diagram which contains all colors which are indistinguishable, to the average human eye, from the color at the center of the ellipse
- The contour of the ellipse represents the just noticeable differences of chromaticity

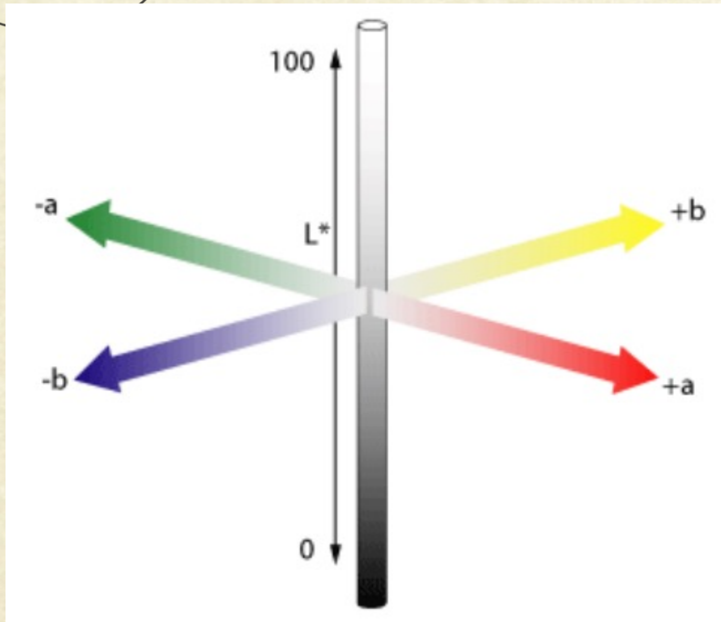
courtesy: wikipedia

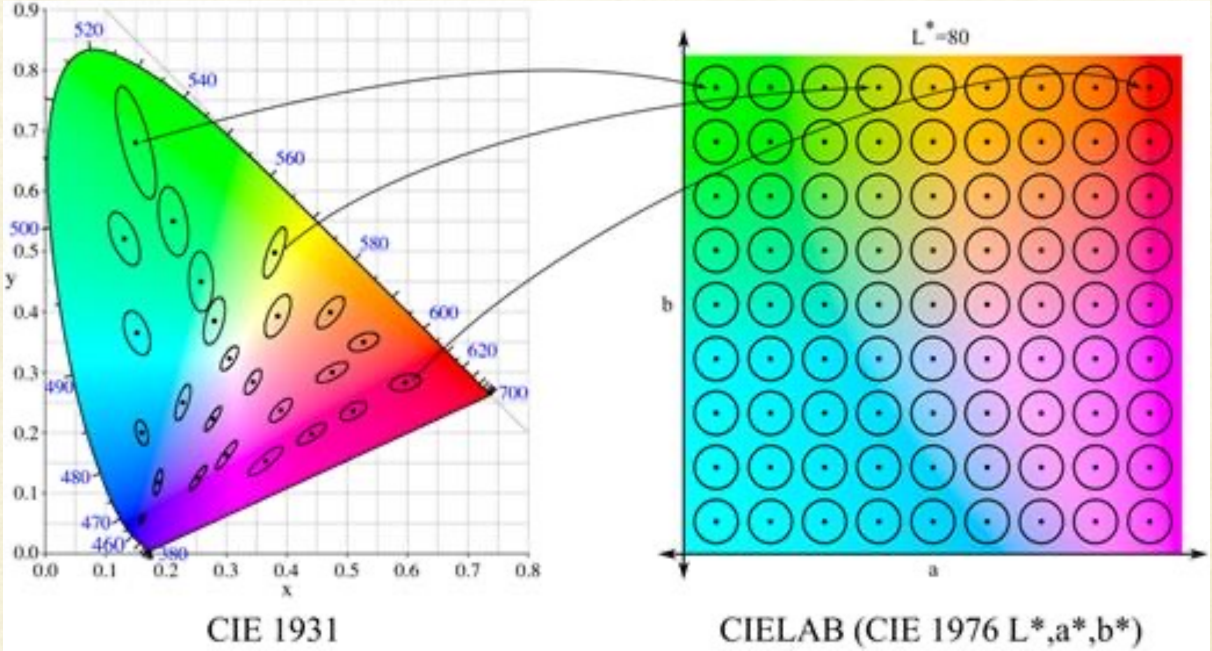
CIE Lab color space



Ideal scenario

CIE Lab color space





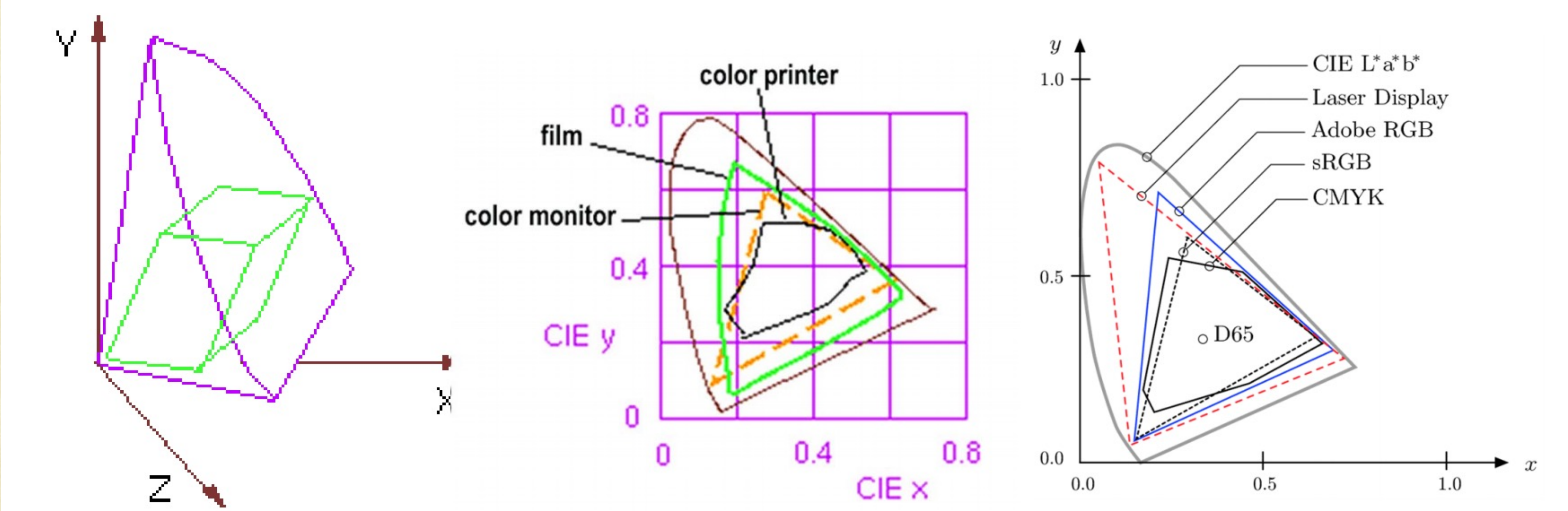
Components:

- Luminosity L
- Color components
  - a* : color hue, saturation along green-red axis
  - b* : color hue, saturation along blue-yellow axis

- Makes changes in CIE space linear with respect to human perception
- Popular in high-quality photographic applications

Color Gamuts of Devices

- The RGB color cube sits within the CIE color space
- CIE chromaticity diagram is useful to compare the gamut of various devices
  - e.g., compare color printer and monitor color gamuts.

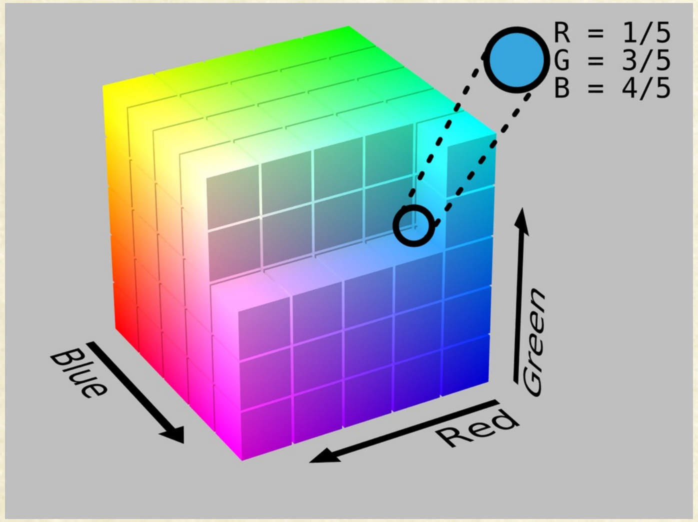


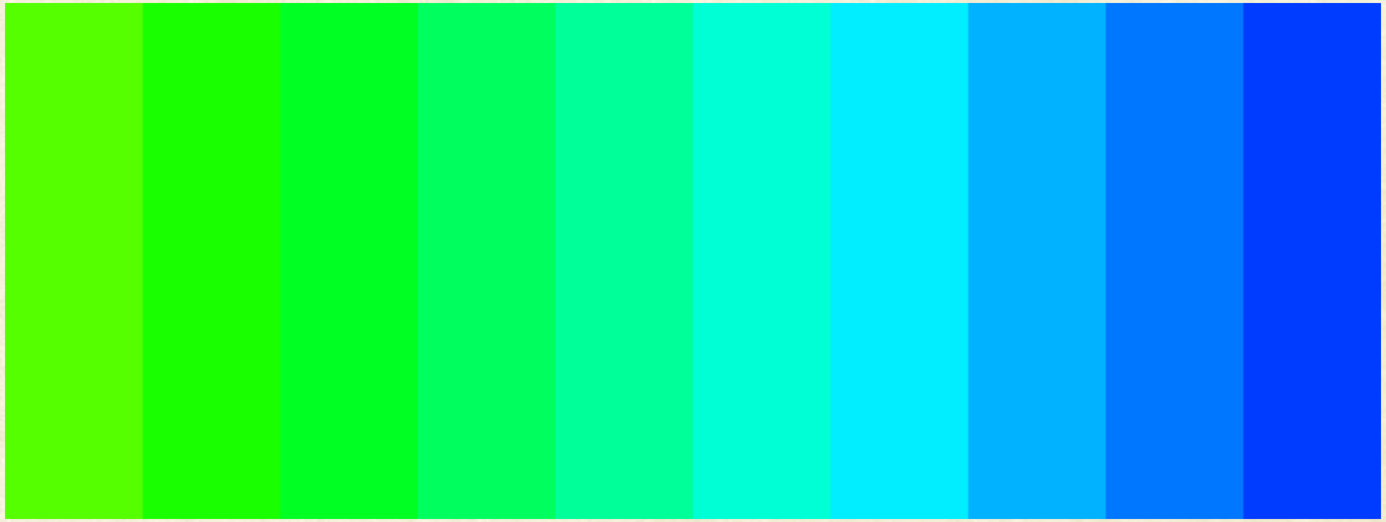
Measuring Color Differences

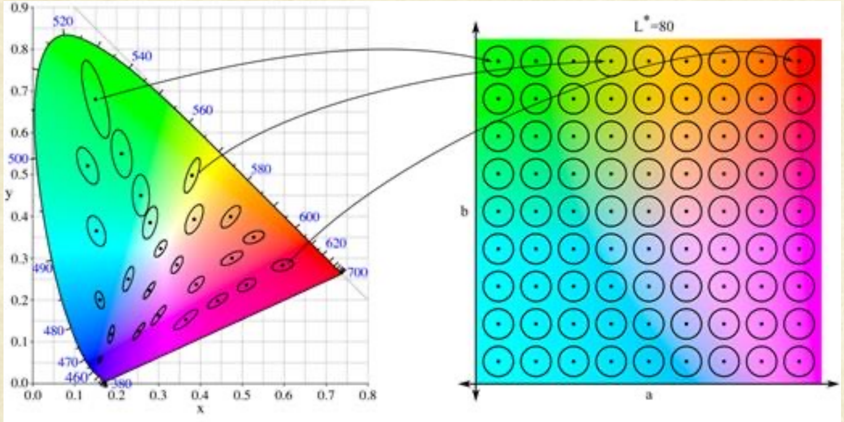
- Due to its uniformity with respect to human perception, the differences between colors in L*a*b* color space can be determined as **Euclidean distance**.

$$
\begin{aligned}
\mathrm{ColorDist}_{\mathrm{Lab}}(\mathbf{C}_1, \mathbf{C}_2) &= \|\mathbf{C}_1 - \mathbf{C}_2\| \\
&= \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}
\end{aligned}
$$

Perceptually Uniform Color Spaces





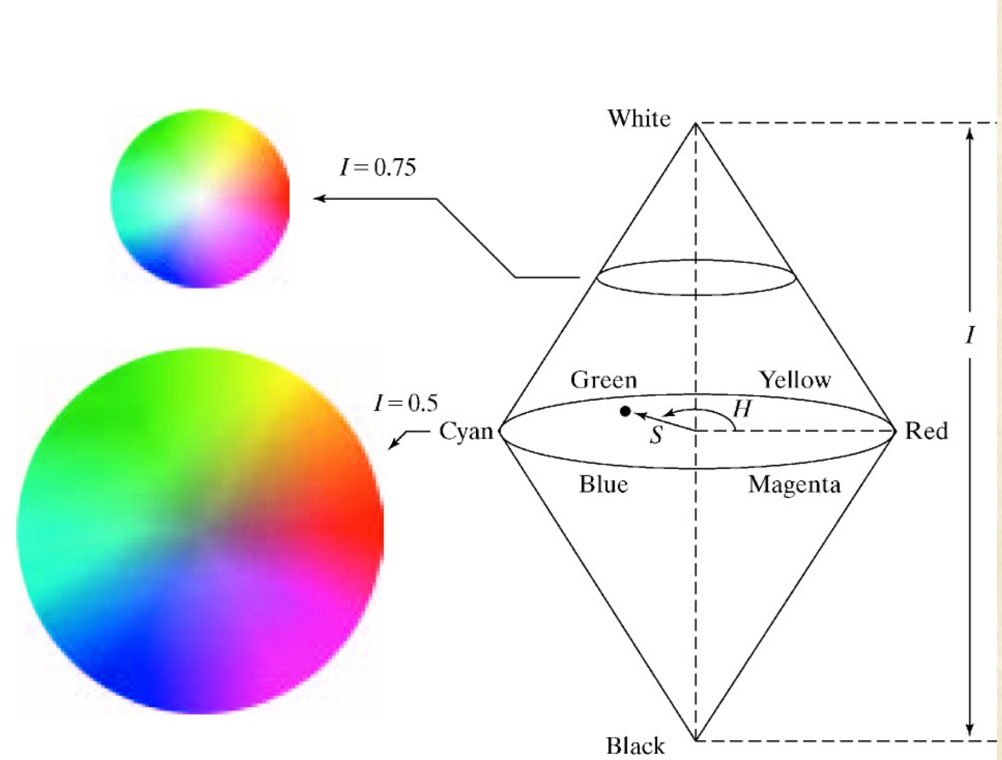


CIE 1931 CIELAB (CIE 1976 L*,a*,b*)

https://matplotlib.org/3.1.1/tutorials/colors/colormaps.html

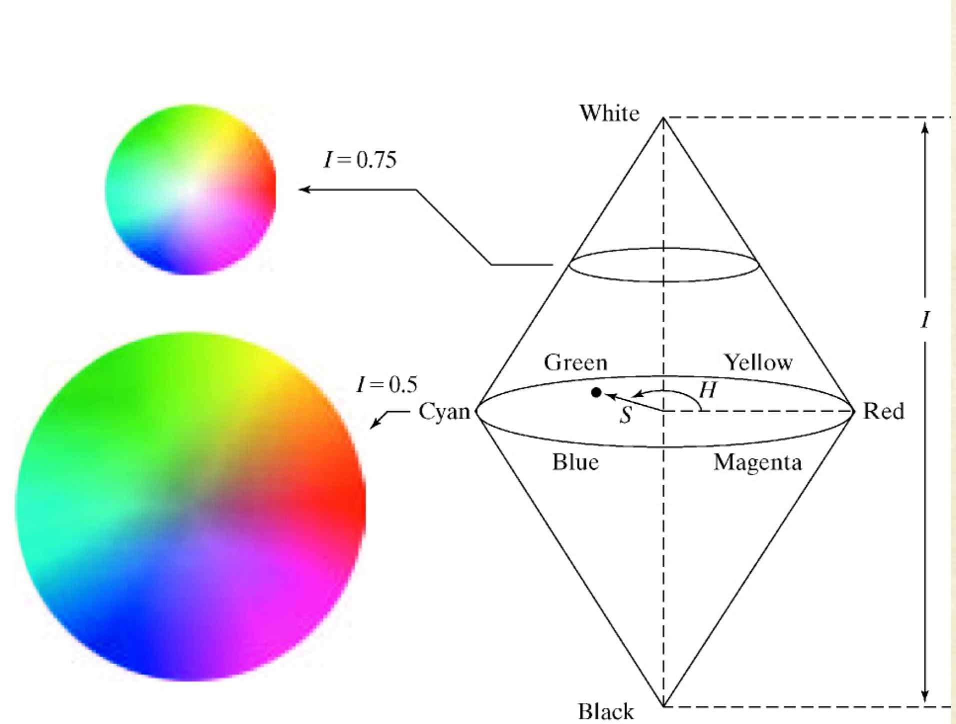
HSI color space

- Hue (H):
  - Dominant colour perceived by an observer
  - When we call an object red or orange, we refer to its hue.
- Saturation (S):
  - Amount of white light mixed with a hue
  - Pure colors are fully saturated.
    - Pink (red+white) is less saturated.
- Brightness (I) : achromatic notion of intensity



HSI color space

- **HUE**
  - A subjective measure of color
  - Average human eye can perceive ~200 different colors
- **Saturation**
  - Relative purity of the color. Mixing more "white" with color reduces its saturation.
  - Pink has the same **hue** as **red** but less **saturation**
- **Intensity**
  - The brightness or darkness of an object



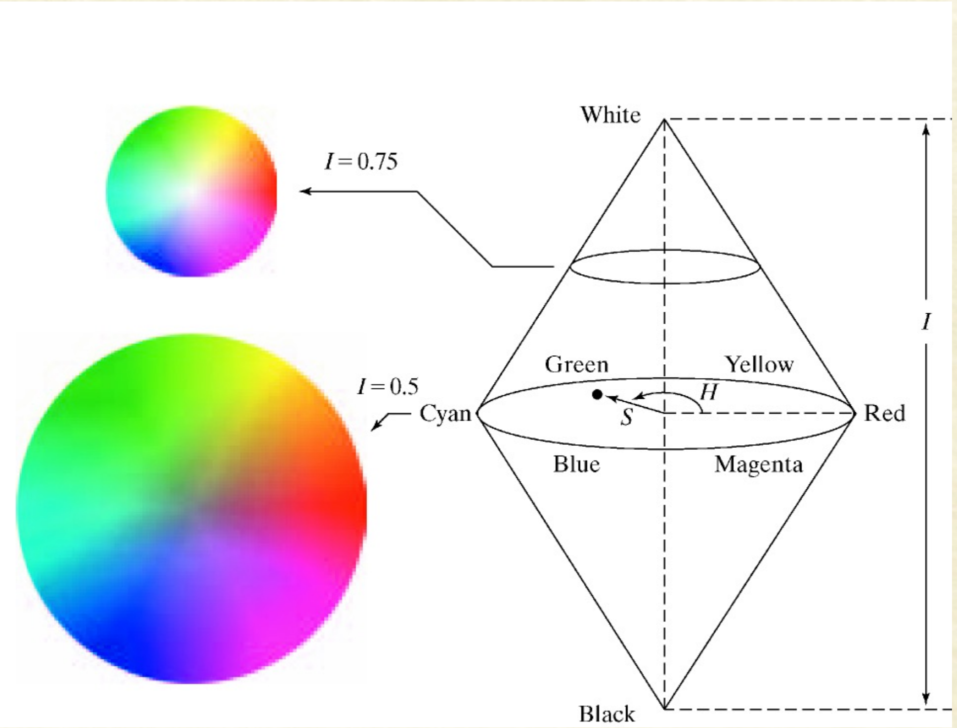
RGB : great for color generation
HSI : great for color description

HSI color space

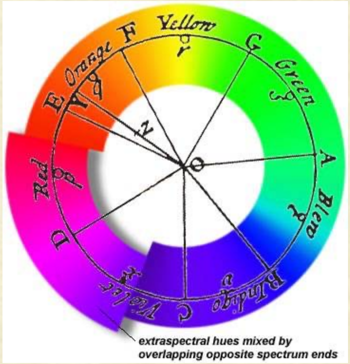
- **Hue** is defined as an angle
  - 0 degrees is **RED**
  - 120 degrees is **GREEN**
  - 240 degrees is **BLUE**

Saturation = % of distance from center : [0,1]

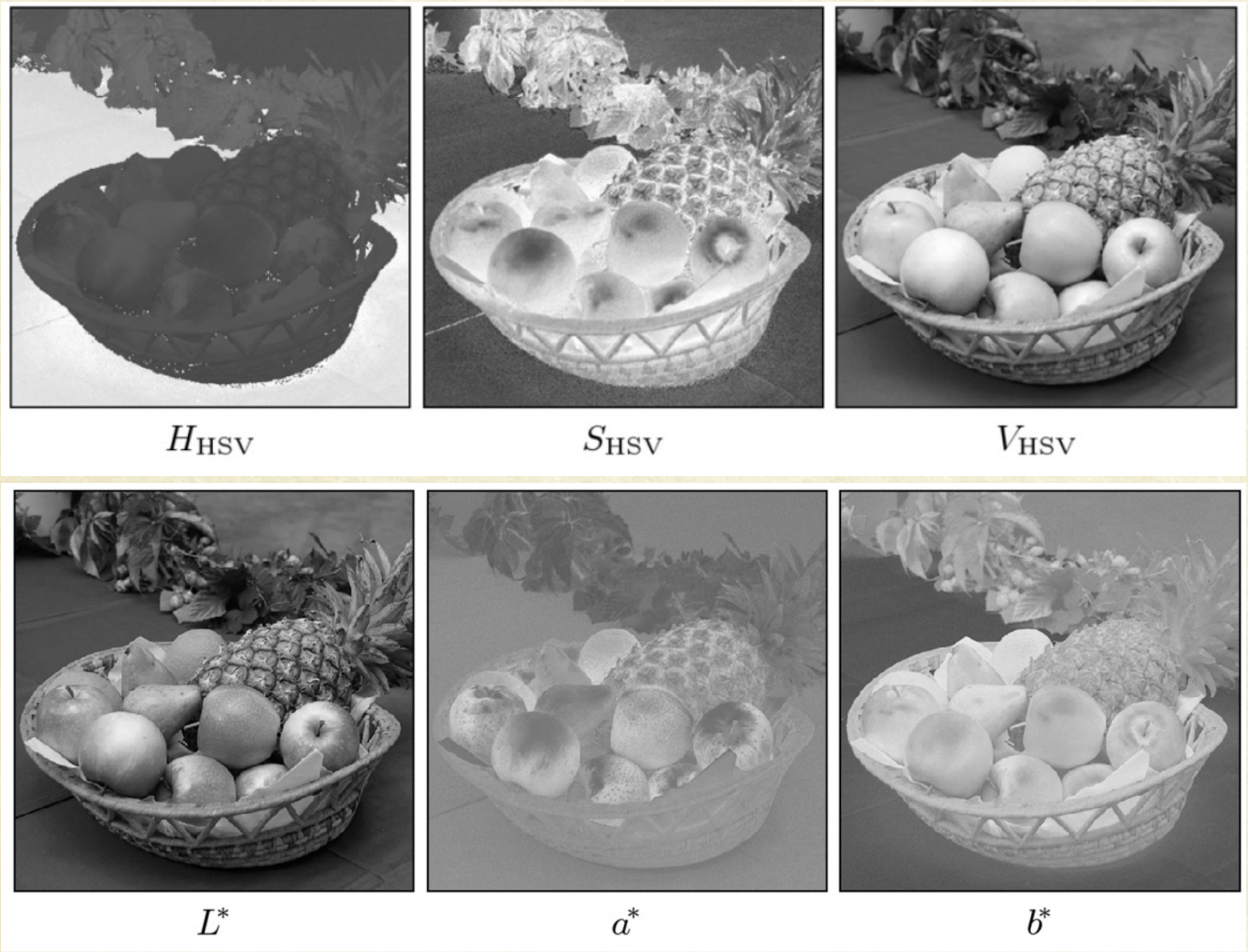
- **Intensity** is denoted as the distance “up” the axis from black.
  - Values range from 0 to 1

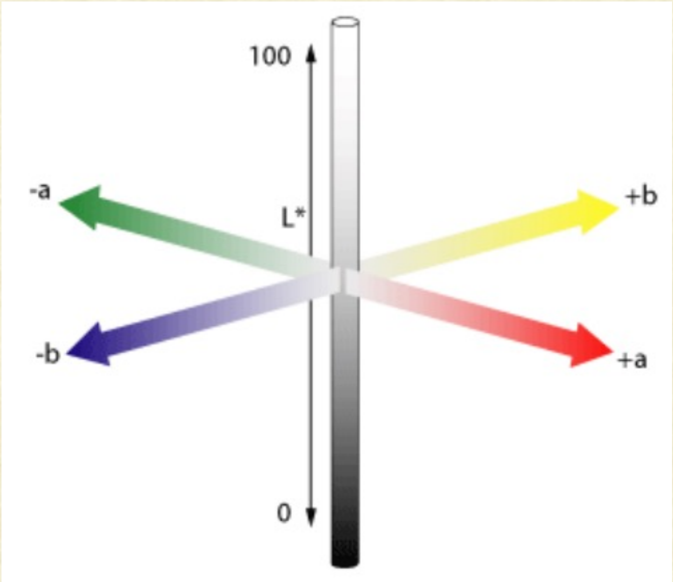


RGB : great for color generation
HSI : great for color description

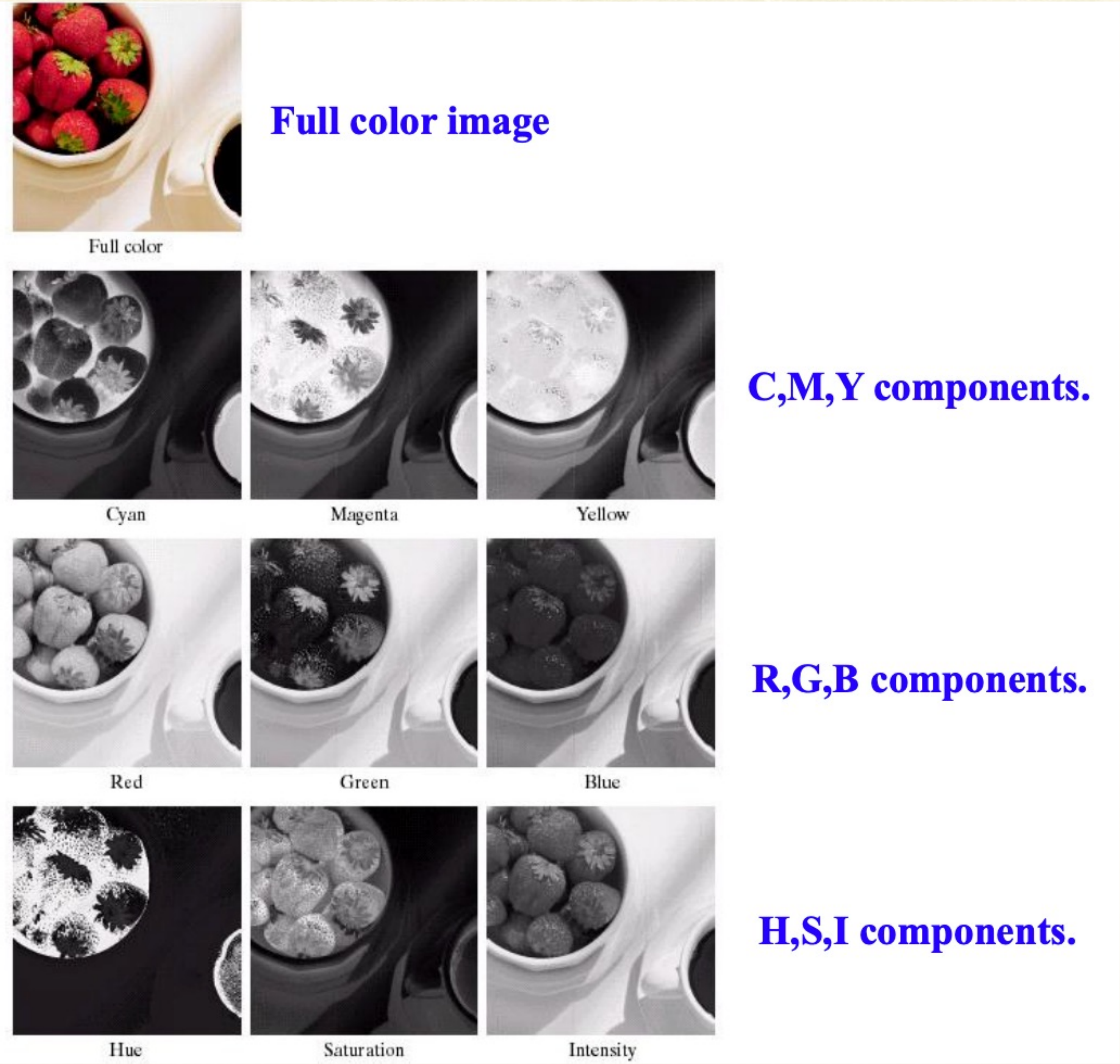


HSI vs Lab





- CMY vs RGB vs HSI



Coloring Mughal-e-Azam

- The colourisation team spent 18 months developing software for colouring the frames, called "Effects Plus".
- Designed to accept only those colours whose hue would match the shade of grey present in the original film. This ensured that the colours added were as close to the real colour as possible.
- The authenticity of the colouring was later verified when a costume used in the film was retrieved from a warehouse, and its colours were found to closely match those in the film.
- Every shot was finally hand-corrected to perfect the look. The actual colourisation process took a further 10 months to complete. (cost: Rs. 2 to 10 cr)

Mayabazar (1957), colorized (2007)

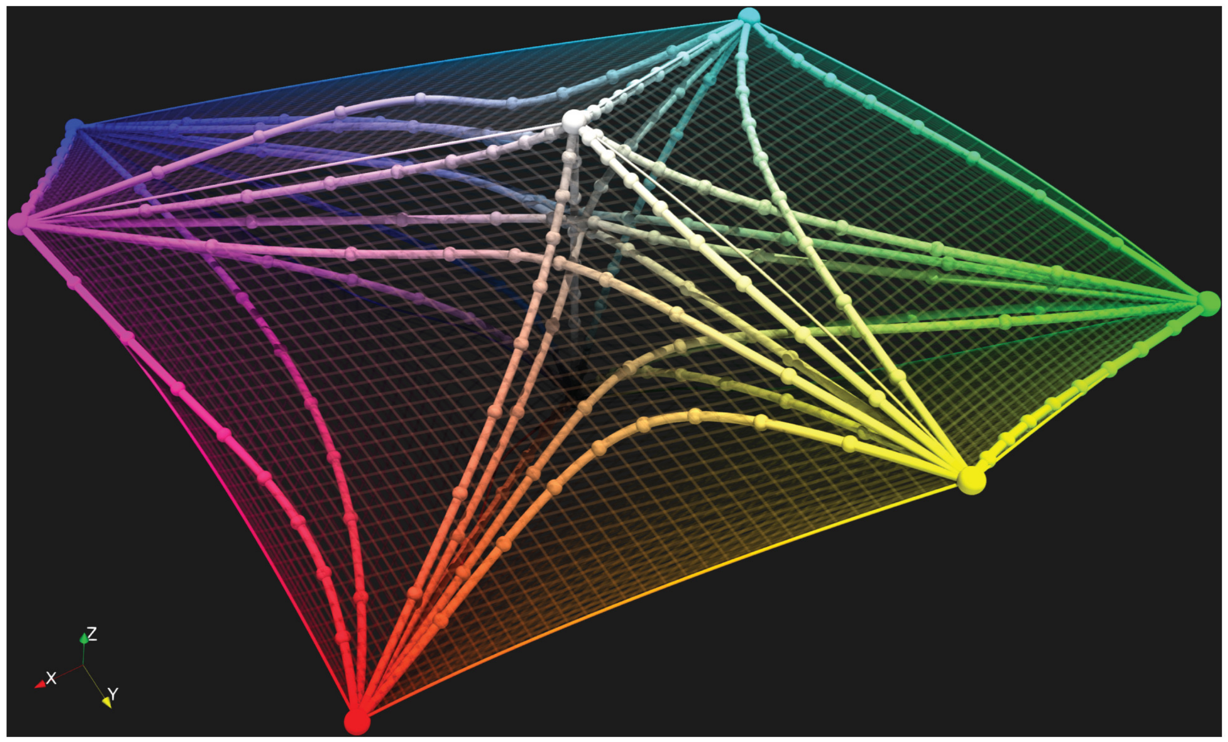
The Film Heritage Foundation announced in March 2015 that they would be restoring *Mayabazar*, along with a few other Indian films from 1931 to 1965, as a part of their restoration projects carried out in India and abroad in accordance with international parameters. **The foundation opposed digital colourisation, stating that they "believe in the original repair as the way the master or the creator had seen it"**

Errors in Perceptual Color Space

- Roxana Bujack, Emily Teti, Jonah Miller, and Terece L. Turton, "The non-Riemannian nature of perceptual color space", Proceedings of the National Academy of Sciences, (April 2022), DOI: 10.1073/pnas.2119753119.

- Shows that the perceptual color space is probably non-Riemannian:

$$\Delta E(A,B) + \Delta E(B,C) > \Delta E(A,C)$$

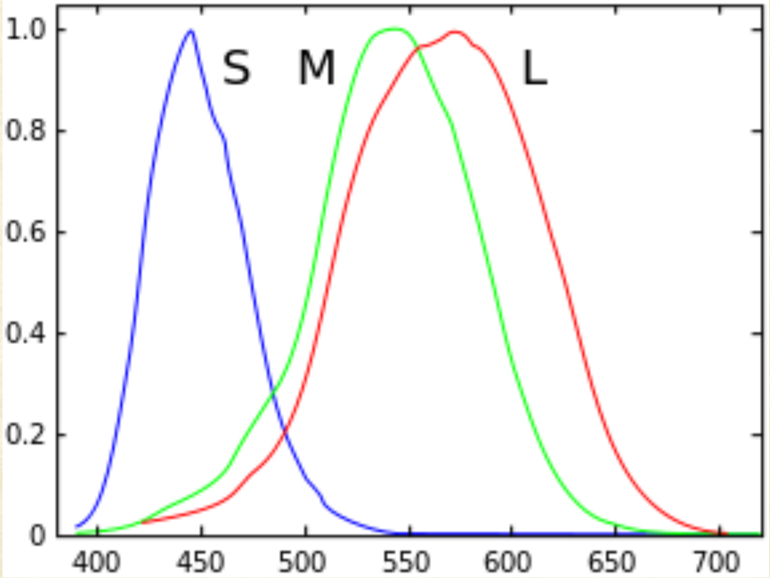


Geodesics in CIE Lab color space: Known since 2000

LMS color space

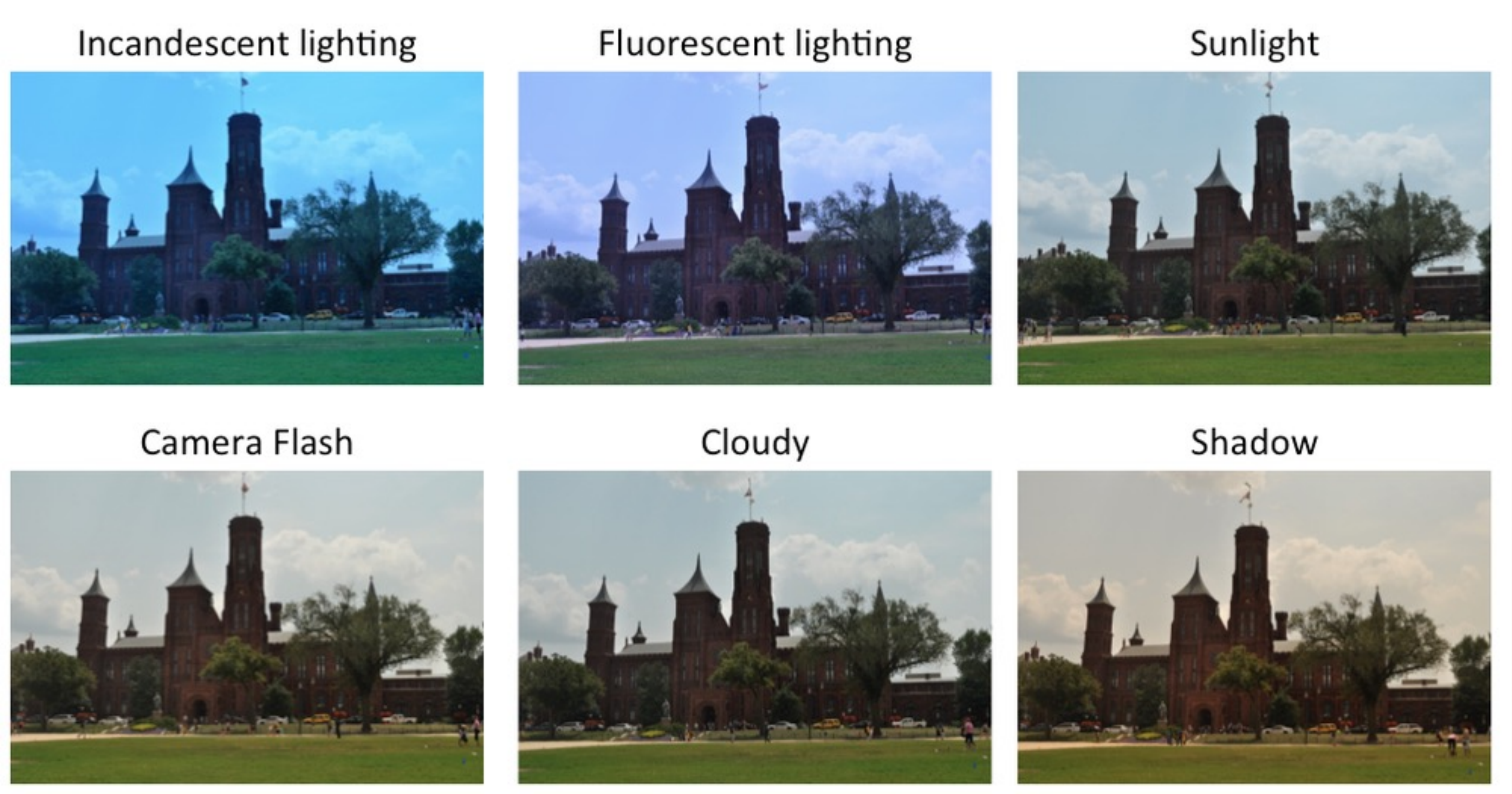
- Used when performing chromatic adaptation (estimating appearance of a sample under a different illuminant)
- Also useful in the study of color blindness, when one or more cone types are defective.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$



Color Image Processing

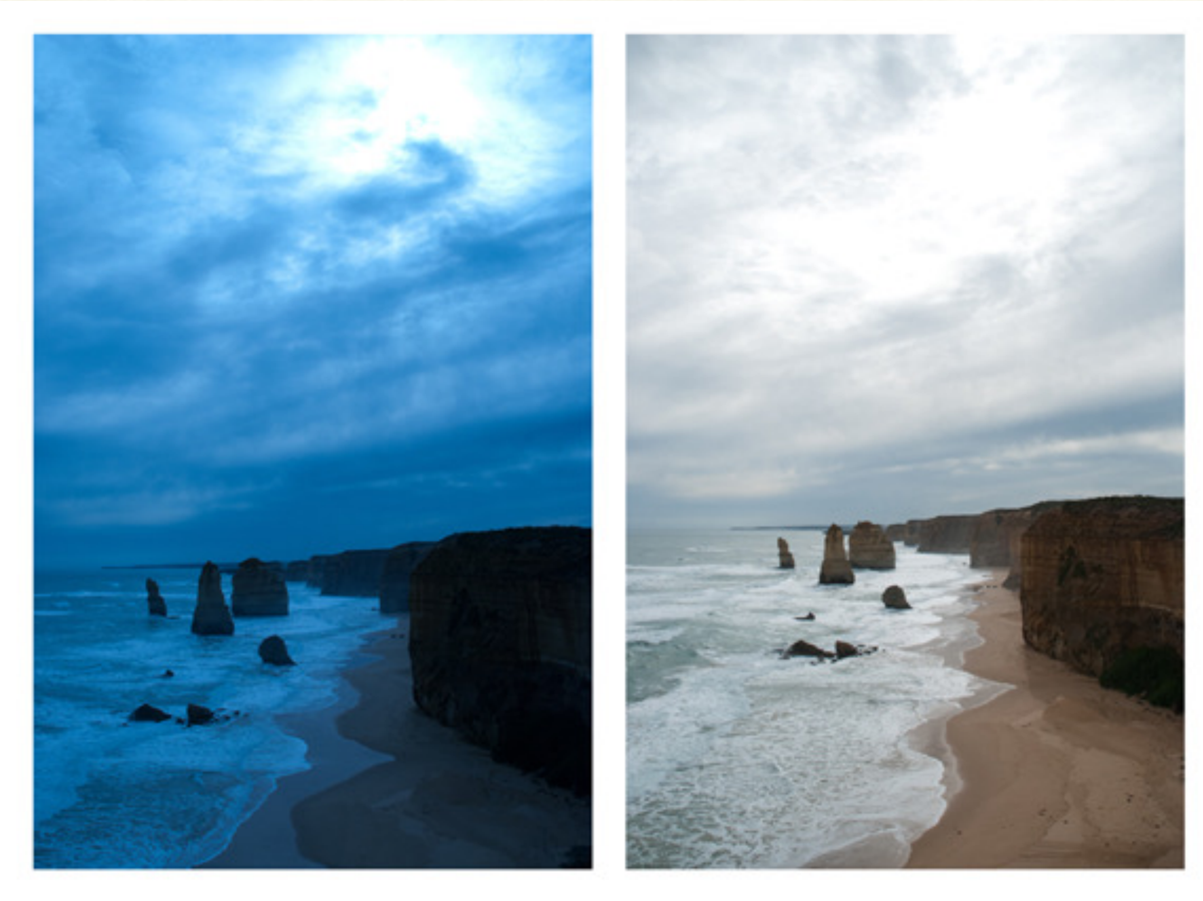
White Balancing



courtesy: seventhgrove.com

White Balancing

Courtesy: wahlmanphotography.com



Courtesy: wallcreations.com.au

White Balancing

White Balancing

- Use reference cards
  - White, 50% gray, etc.

White Balancing

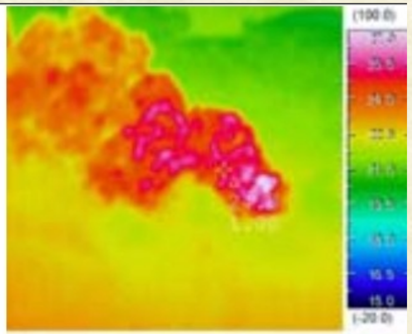
```
im = double(imread('lighthouse.jpg'));

RGBw = [246 169 87];

im1(:,:,1) = im(:,:,1)*255/RGBw(1);
im1(:,:,2) = im(:,:,2)*255/RGBw(2);
im1(:,:,3) = im(:,:,3)*255/RGBw(3);
```

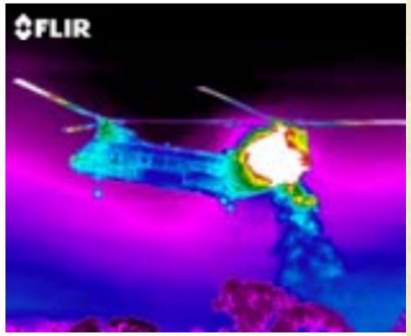
- Von Kries Method
  - White Balancing in LMS color space

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 1/L'_w & 0 & 0 \\ 0 & 1/M'_w & 0 \\ 0 & 0 & 1/S'_w \end{bmatrix} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix}$$

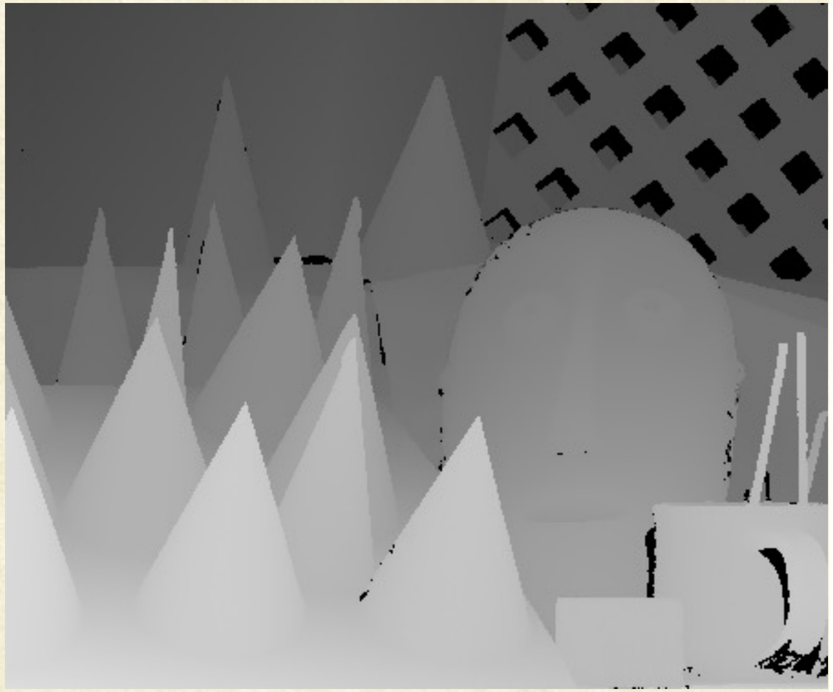
Pseudocoloring of Images

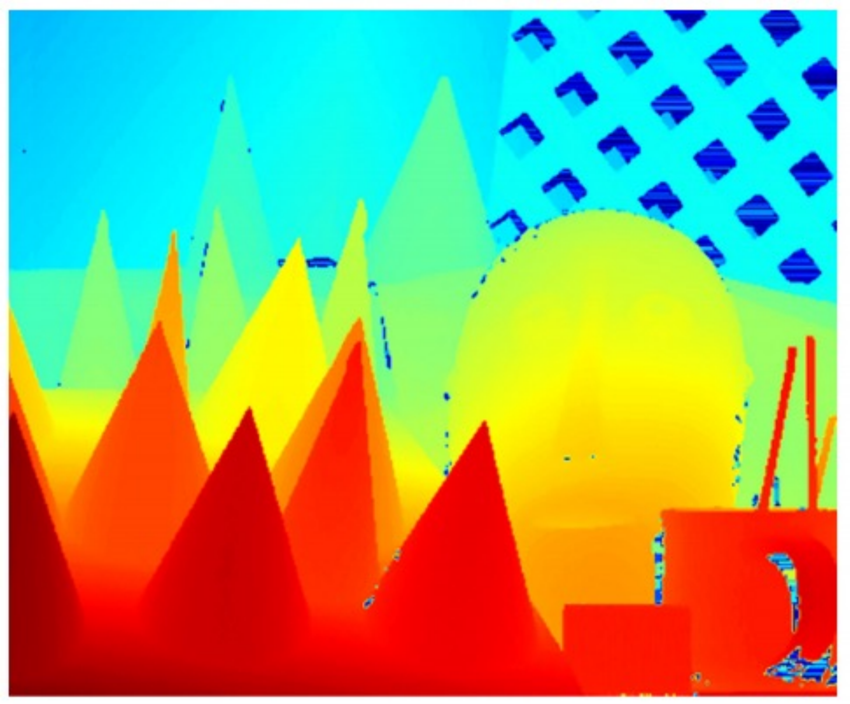
- Pseudocolor (also called false color) image processing consists of assigning colors to grey values based on a specific criterion.
- The principle use of pseudocolor image processing is for human visualisation.
  - Humans can discern between thousands of color shades and intensities, compared to only about two dozen or so shades of grey.





Pseudo color Image Processing

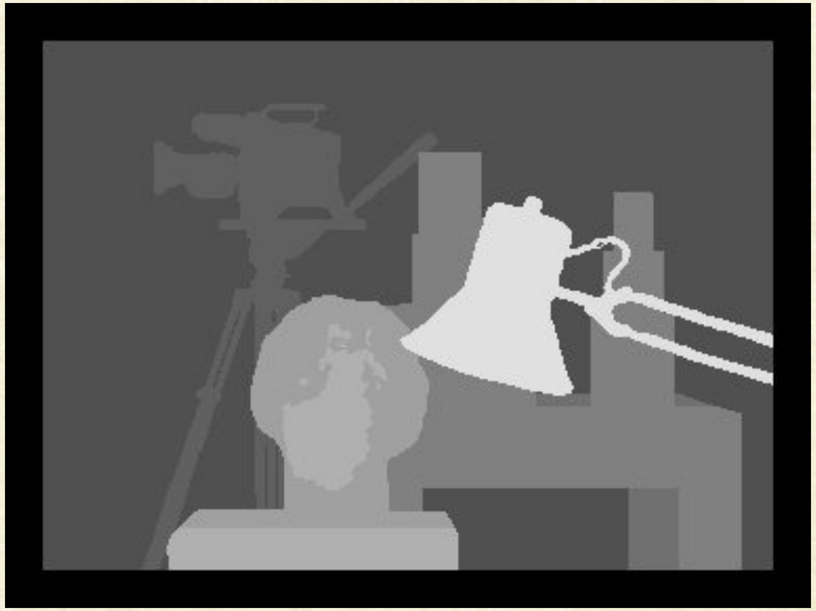




courtesy: middlebury dataset

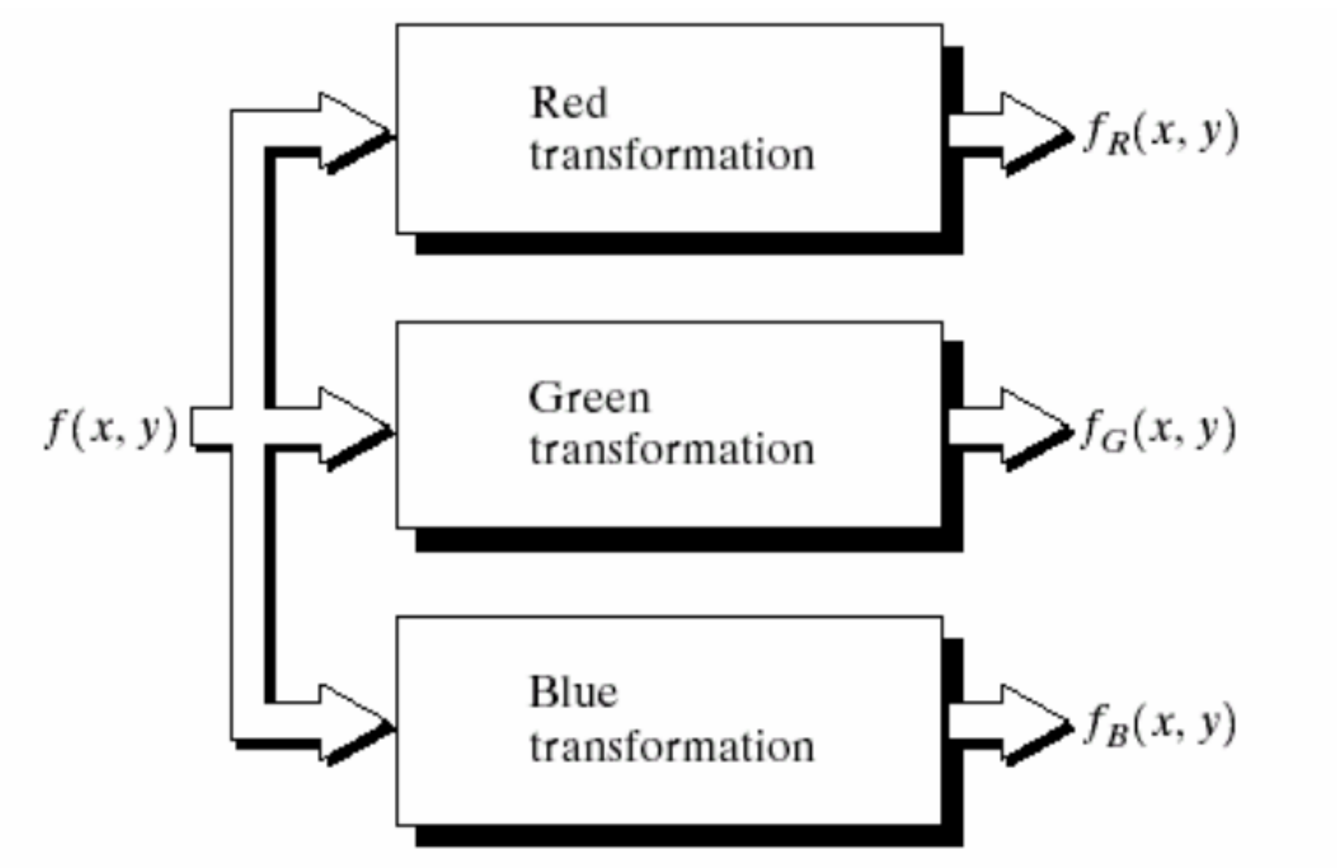
Pseudo color Image Processing

- Colors to indicate Labels

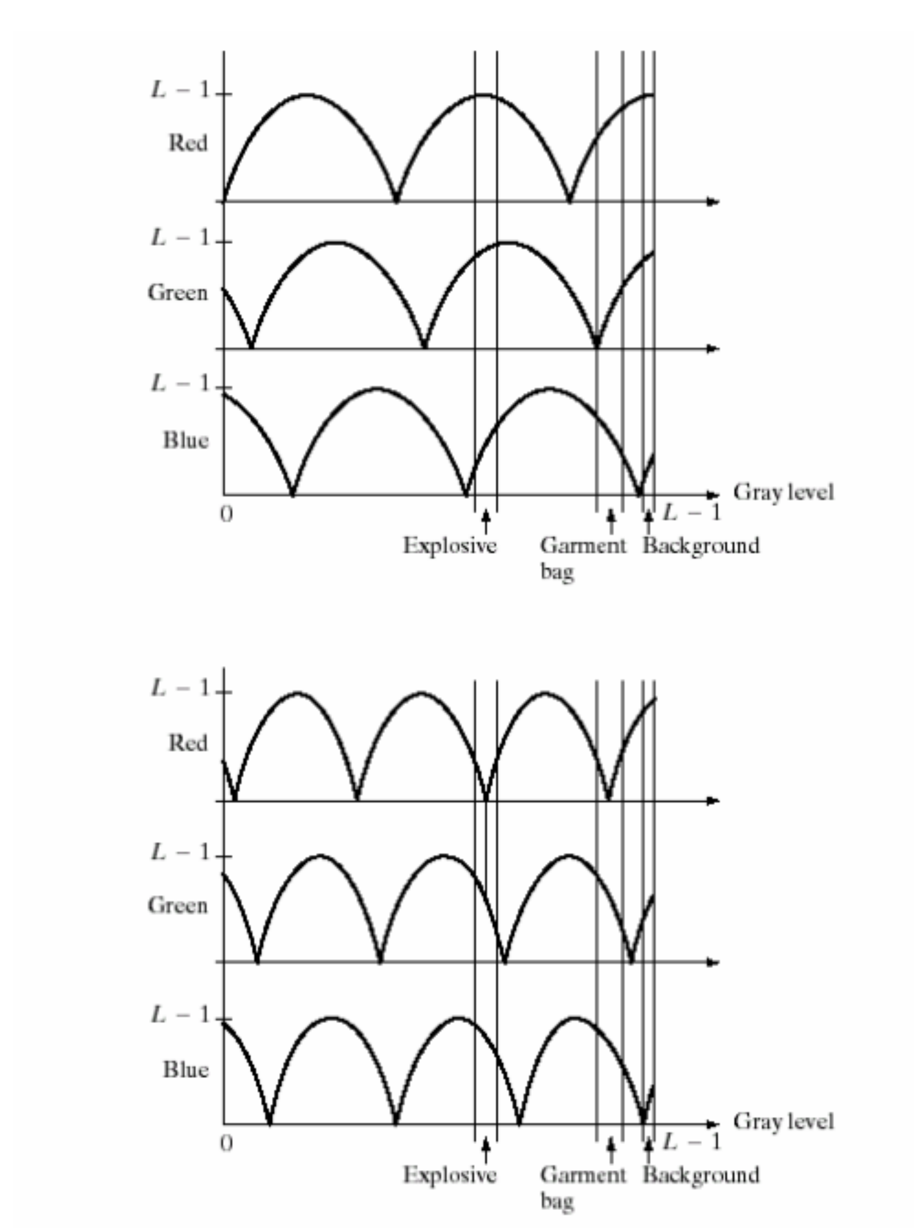

courtesy: middlebury dataset

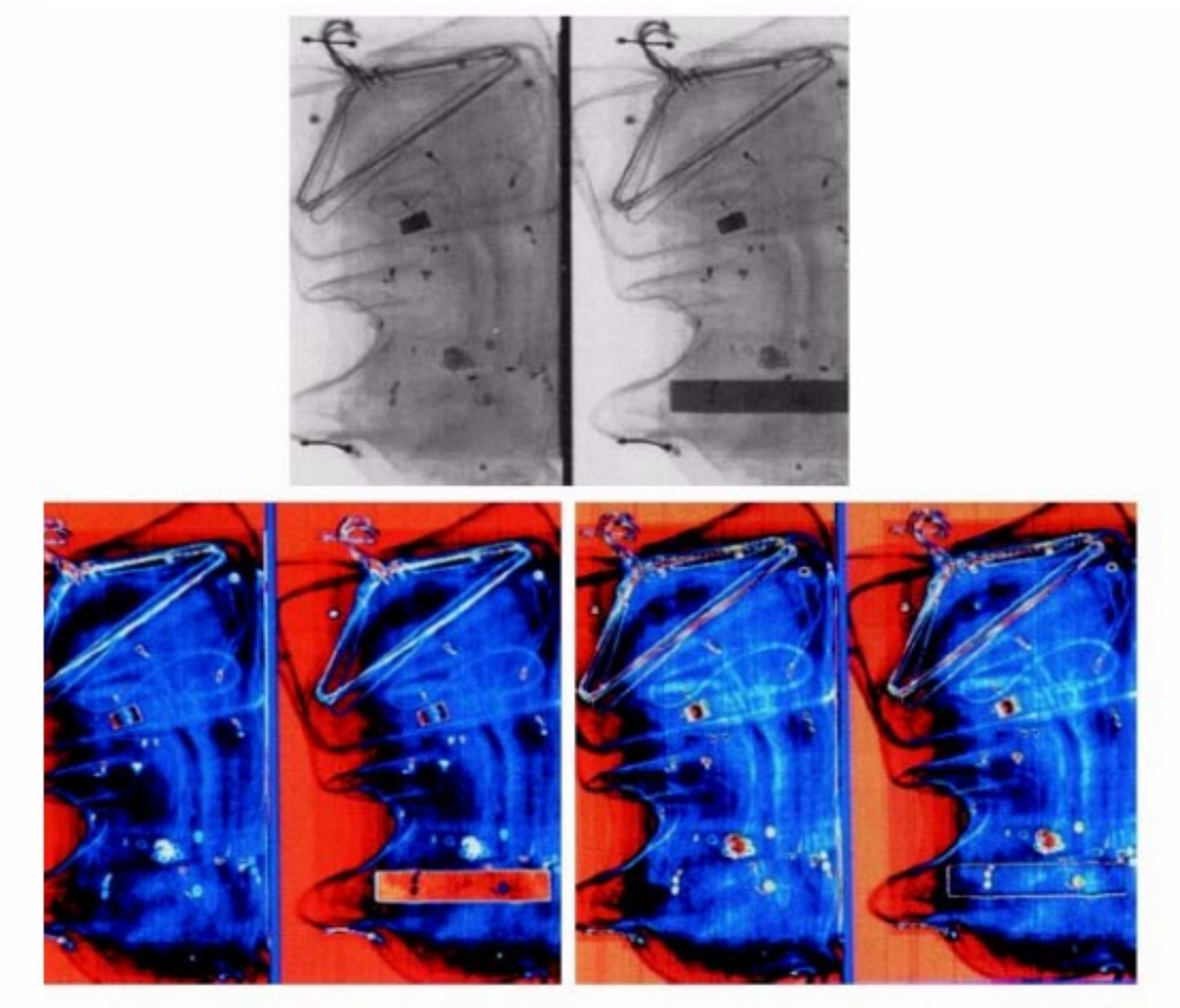
Pseudo color Image Processing (Transformations)



courtesy: Gonzalez and Woods

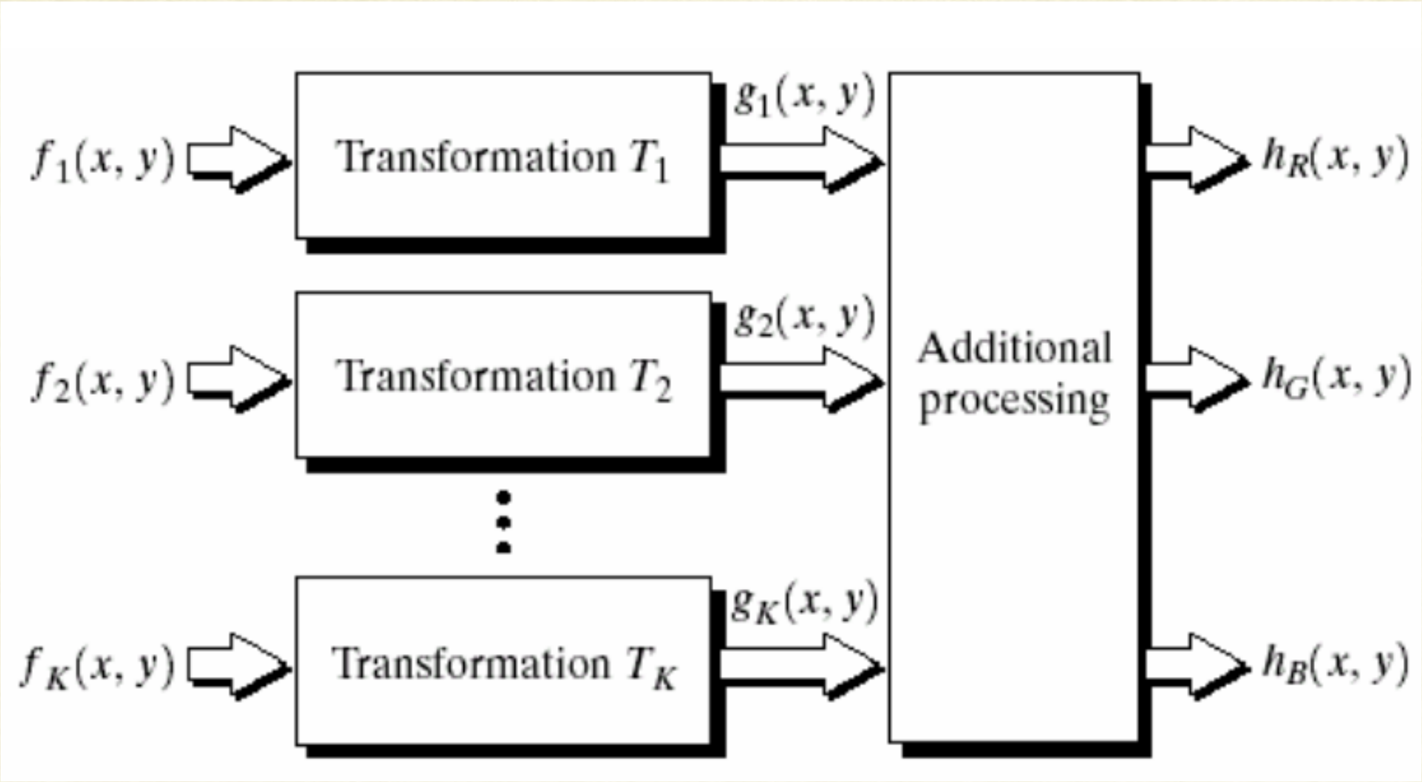
Pseudo color Image Processing (Transformations)

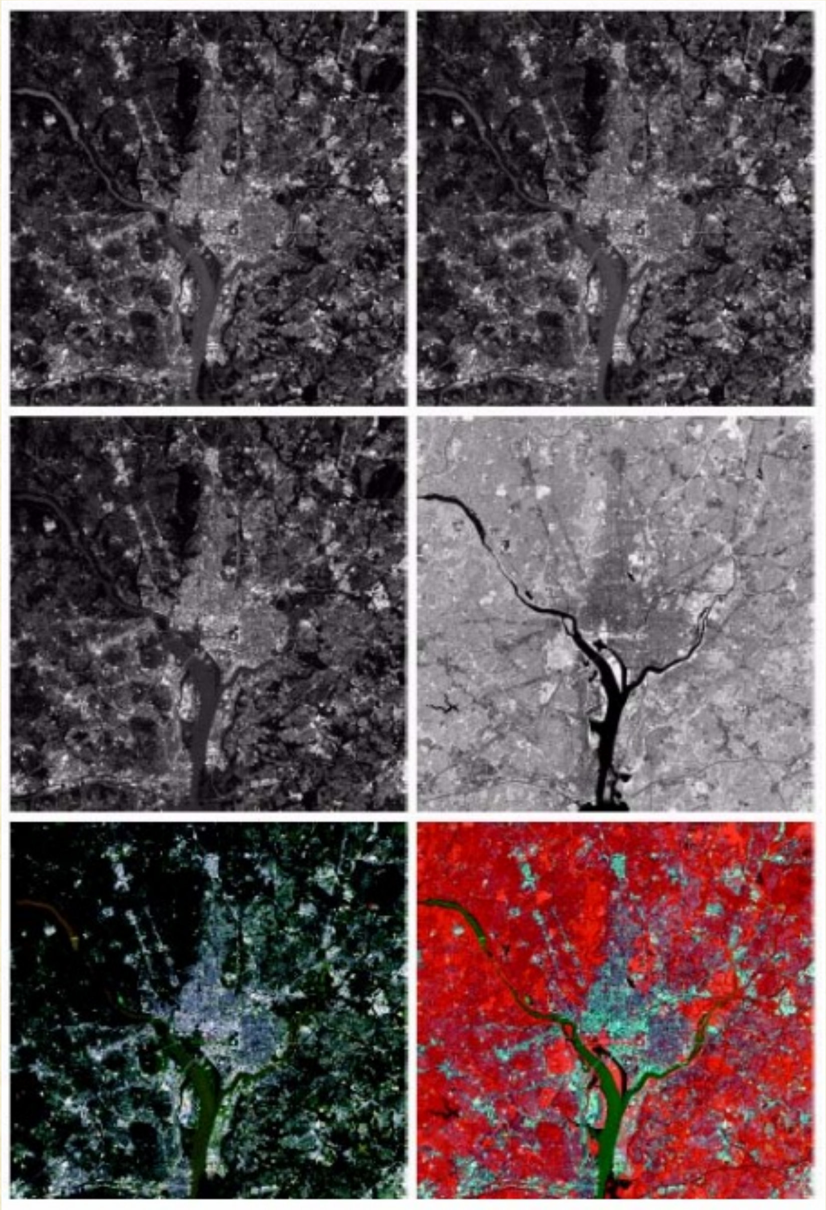




courtesy: Gonzalez and Woods

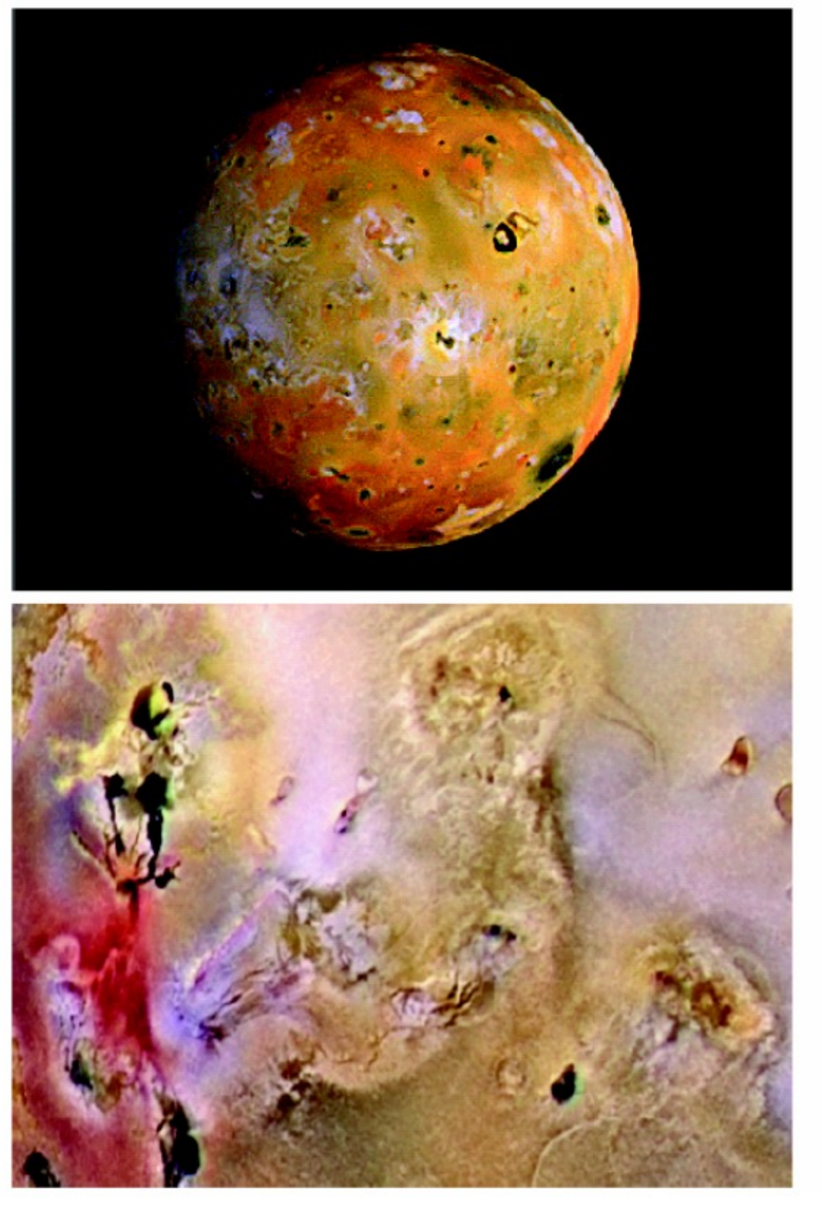
Pseudo color Image Processing (Multi Spectral)





courtesy: Gonzalez and Woods

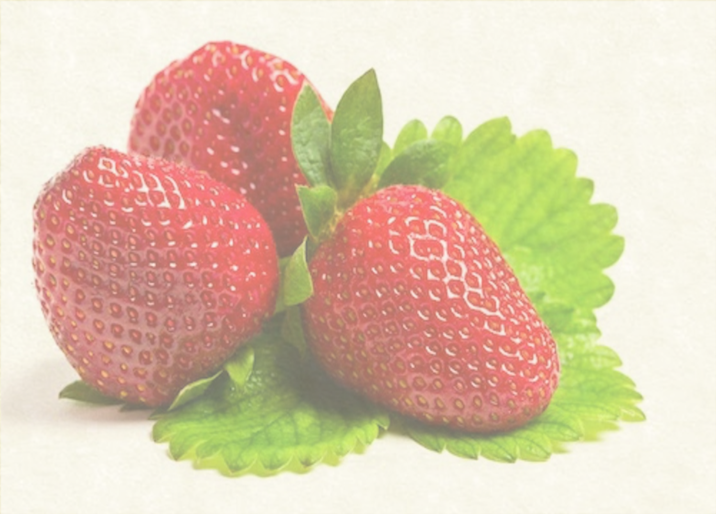
Pseudo color Image Processing (Multi Spectral)



courtesy: Gonzalez and Woods

RGBA space

- A (alpha) for transparency (important in image editing)


$$I_{out} = \alpha I_{foreground} + (1 - \alpha) I_{background}$$

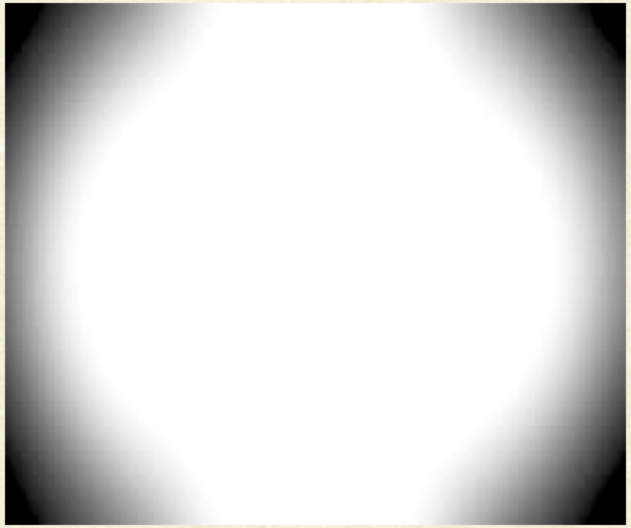
Trending applications: Image enhancement in RGB

Example: Vintage effect or Sepia Toning

outR= (R * .293) + (G *.769) + (B * .210);
outG = (R * .249) + (G *.686) + (B * .188);
outB = (R * .172) + (G *.534) + (B * .151);

Example: Vignetting effect

×



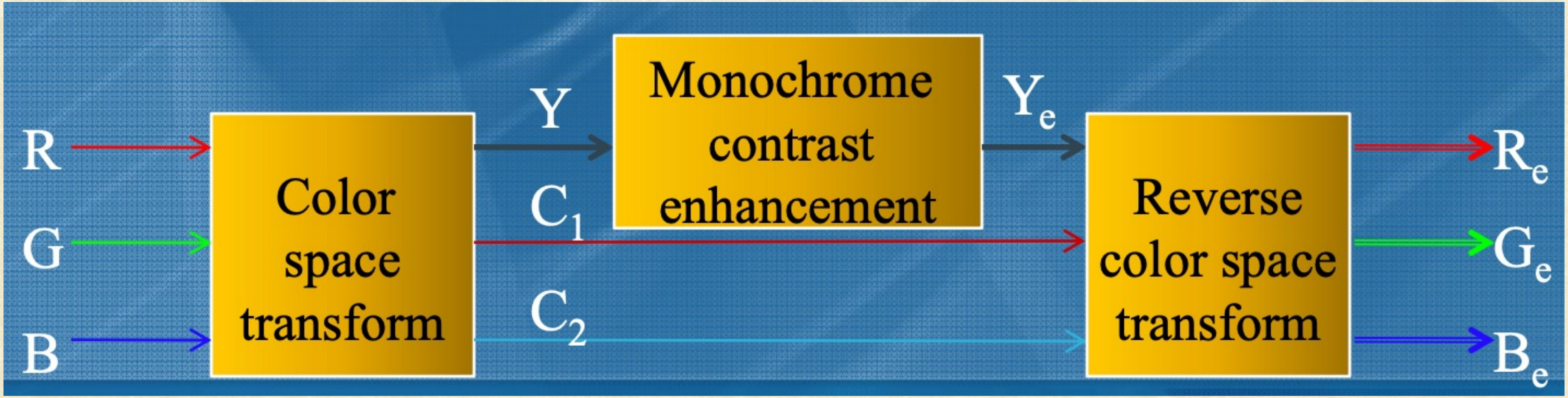
=

```
txt = imread(texture_path);
txt = imresize(txt,[size(out,1) size(out,2)]);
txt = double(rgb2gray(txt))/255;
```

```
out1(:,:,1) = double(out(:,:,1)) .* double(txt);
out1(:,:,2) = double(out(:,:,2)) .* double(txt);
out1(:,:,3) = double(out(:,:,3)) .* double(txt);
```

Contrast Enhancement in Color Image

- Basic (popular) Approach:
  - Human eye is more sensitive to brightness contrast than color contrast
  - Can achieve good contrast enhancement on brightness component alone



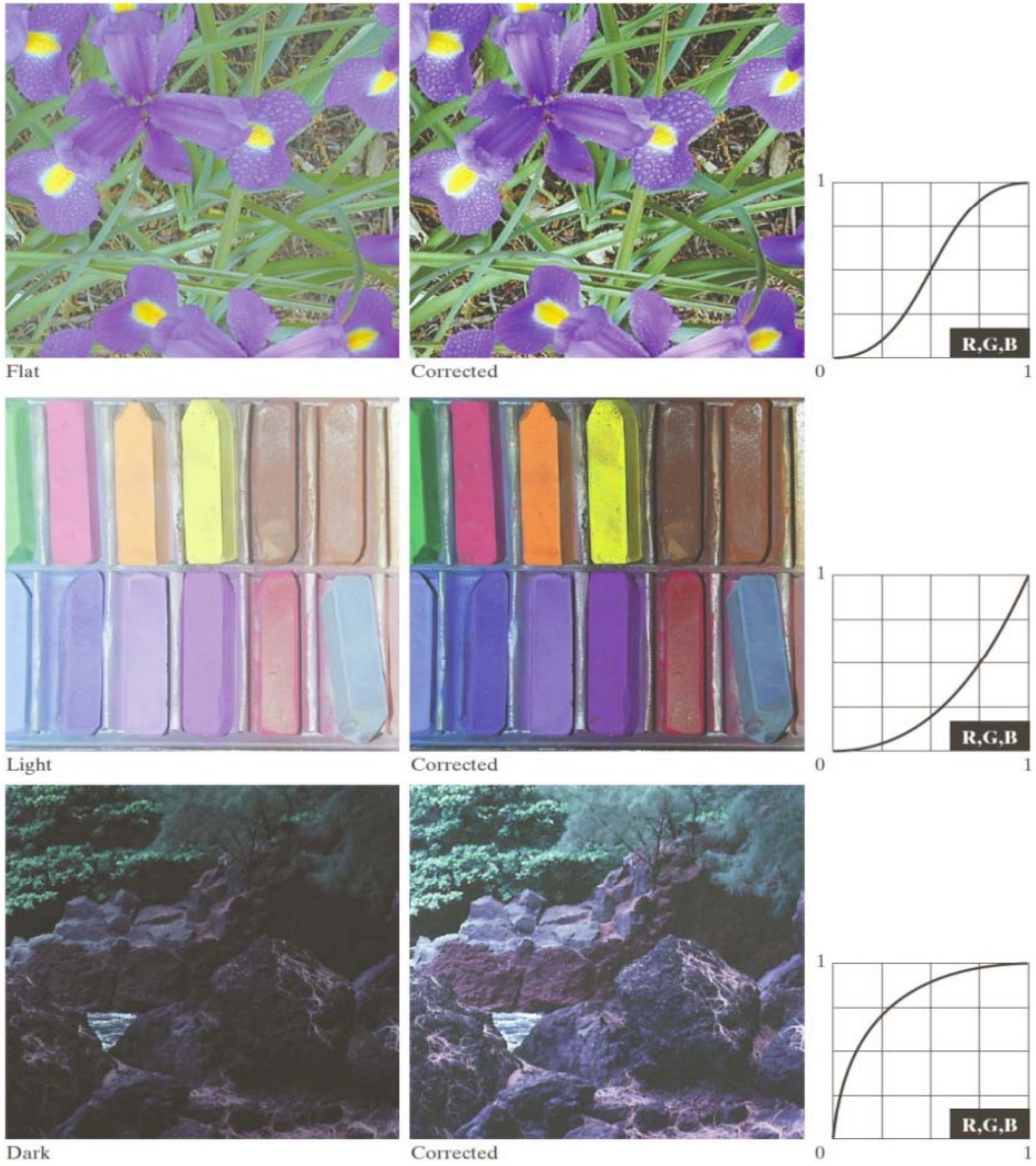
Tone and Color Corrections

$$L^* = 116h(\frac{Y}{Y_W}) - 16$$

$$a^* = 500[h(\frac{X}{X_W}) - h(\frac{Y}{Y_W})]$$

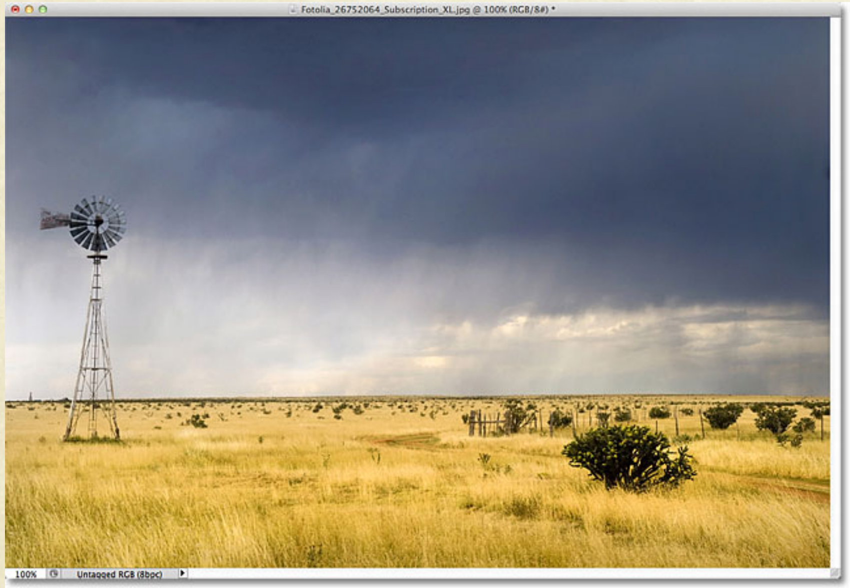
$$b^* = 200[h(\frac{Y}{Y_W}) - h(\frac{Z}{X_W})]$$

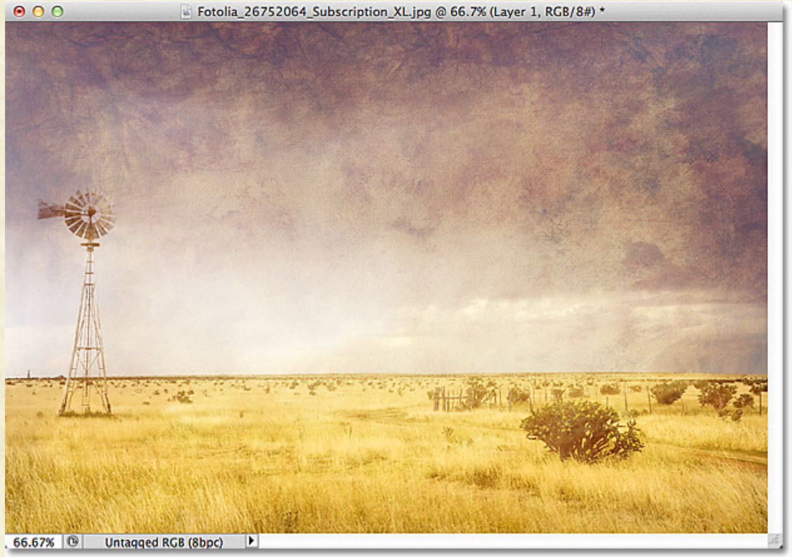
$$h(q) = \begin{cases} \sqrt[3]{q}0.5 & q > 0.008856 \\ 7.787q + 16/116 & q \leq 0.008856 \end{cases}$$



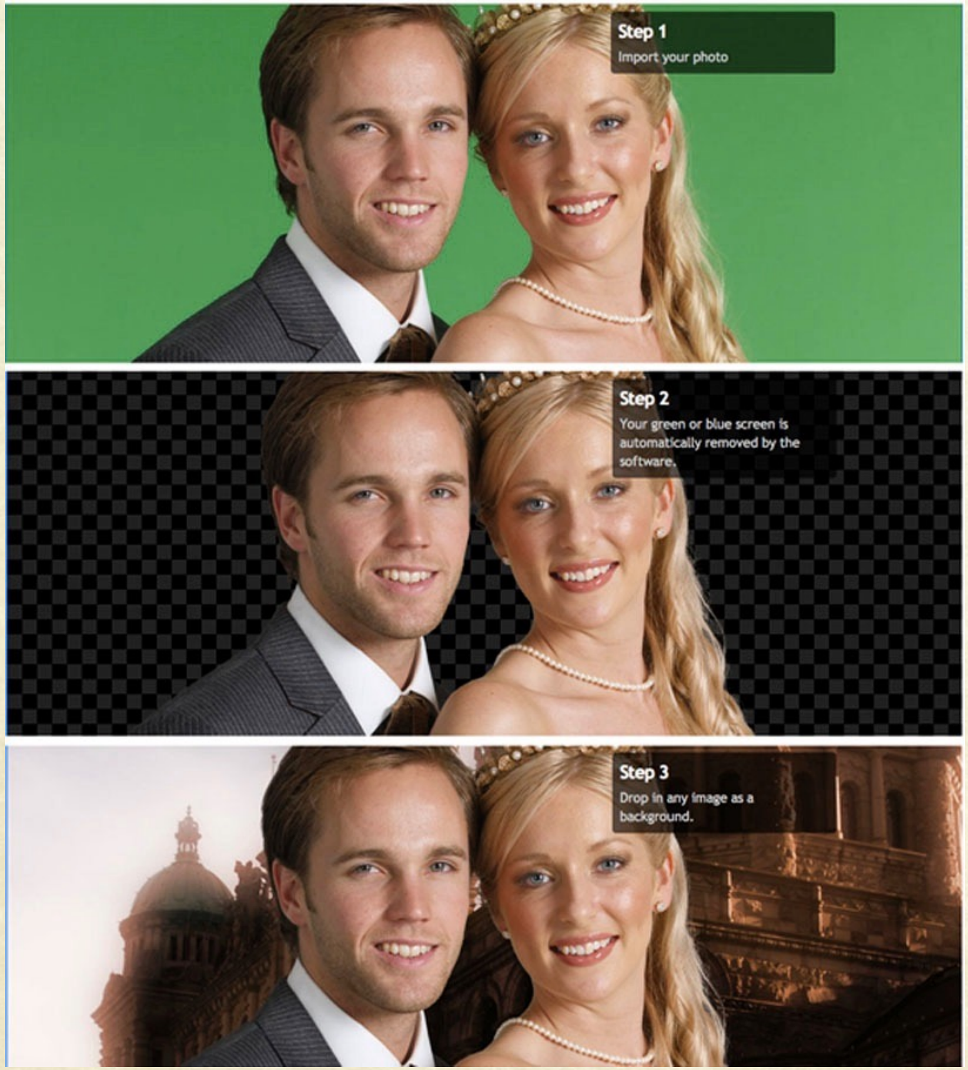
Other such Image Effects

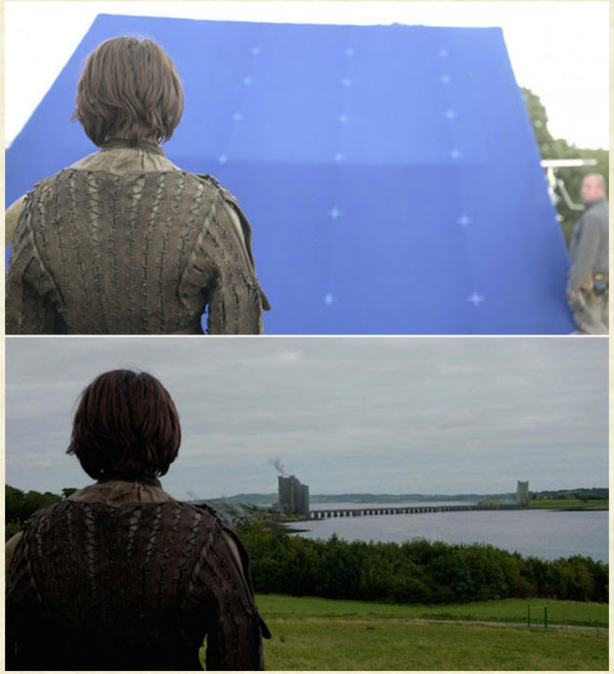
1. Change the transformation matrix, to suit the desired color tones
2. Choose or design different textures and blend them with original image
3. Repeat 1 and 2 in innovative ways



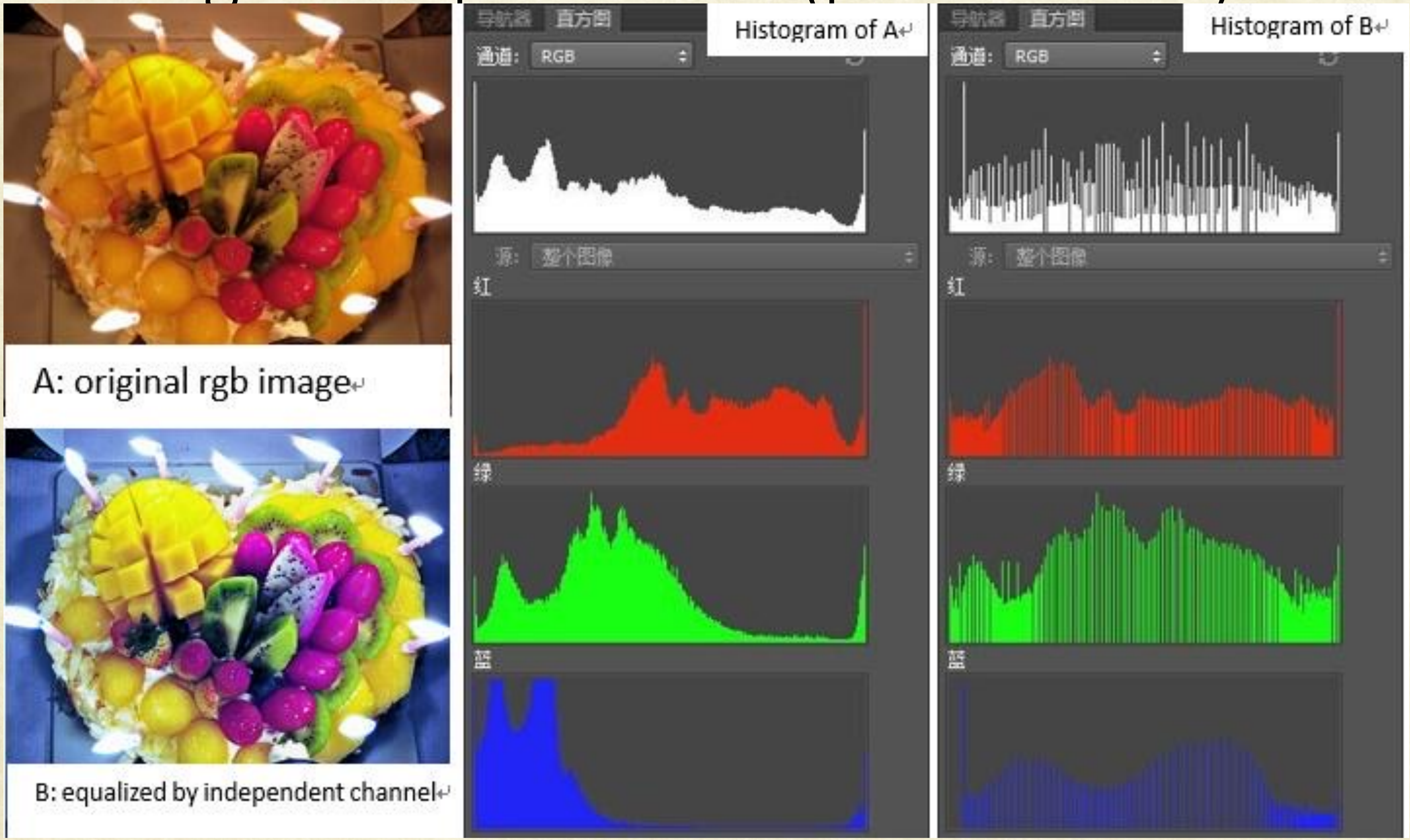


Chroma Keying

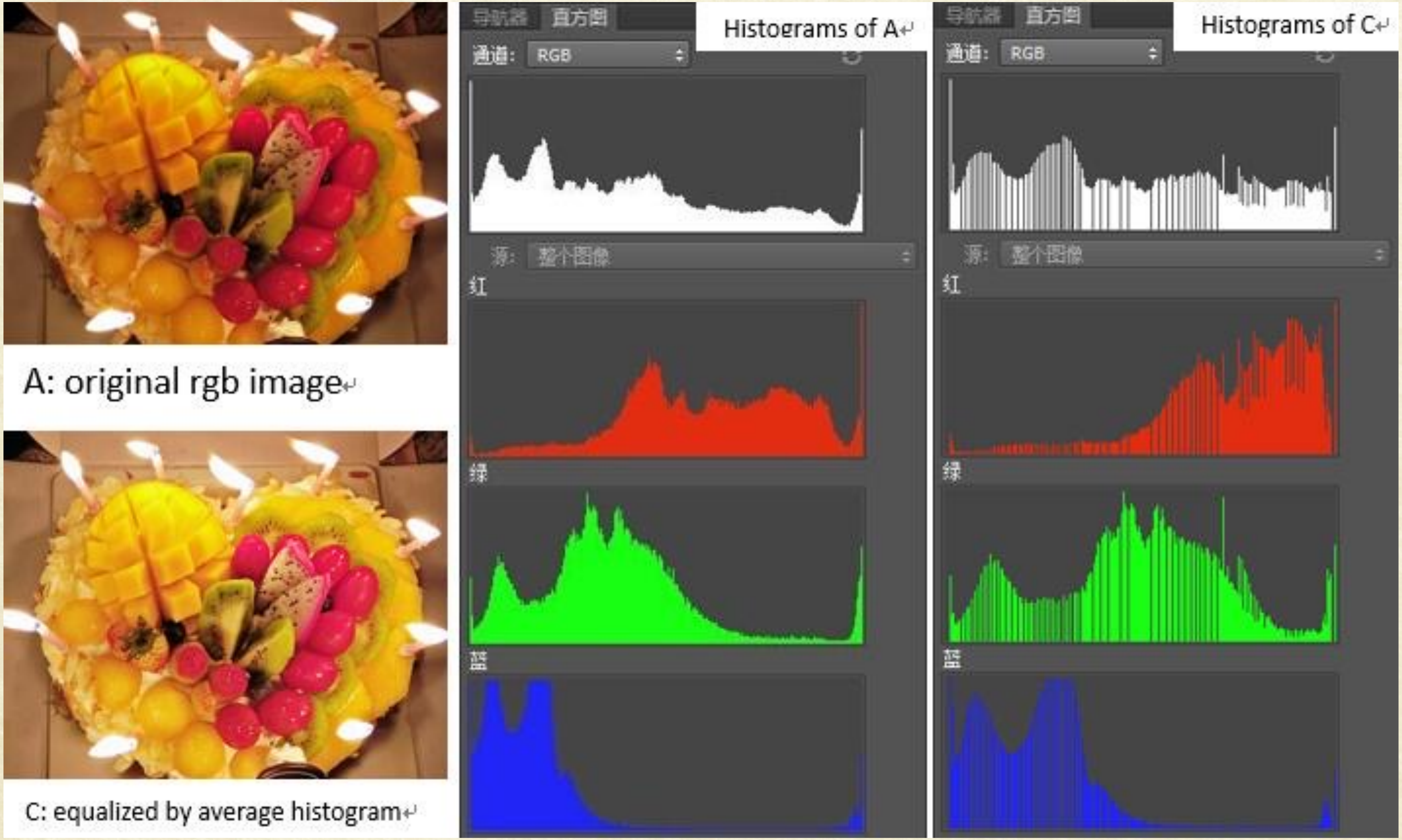




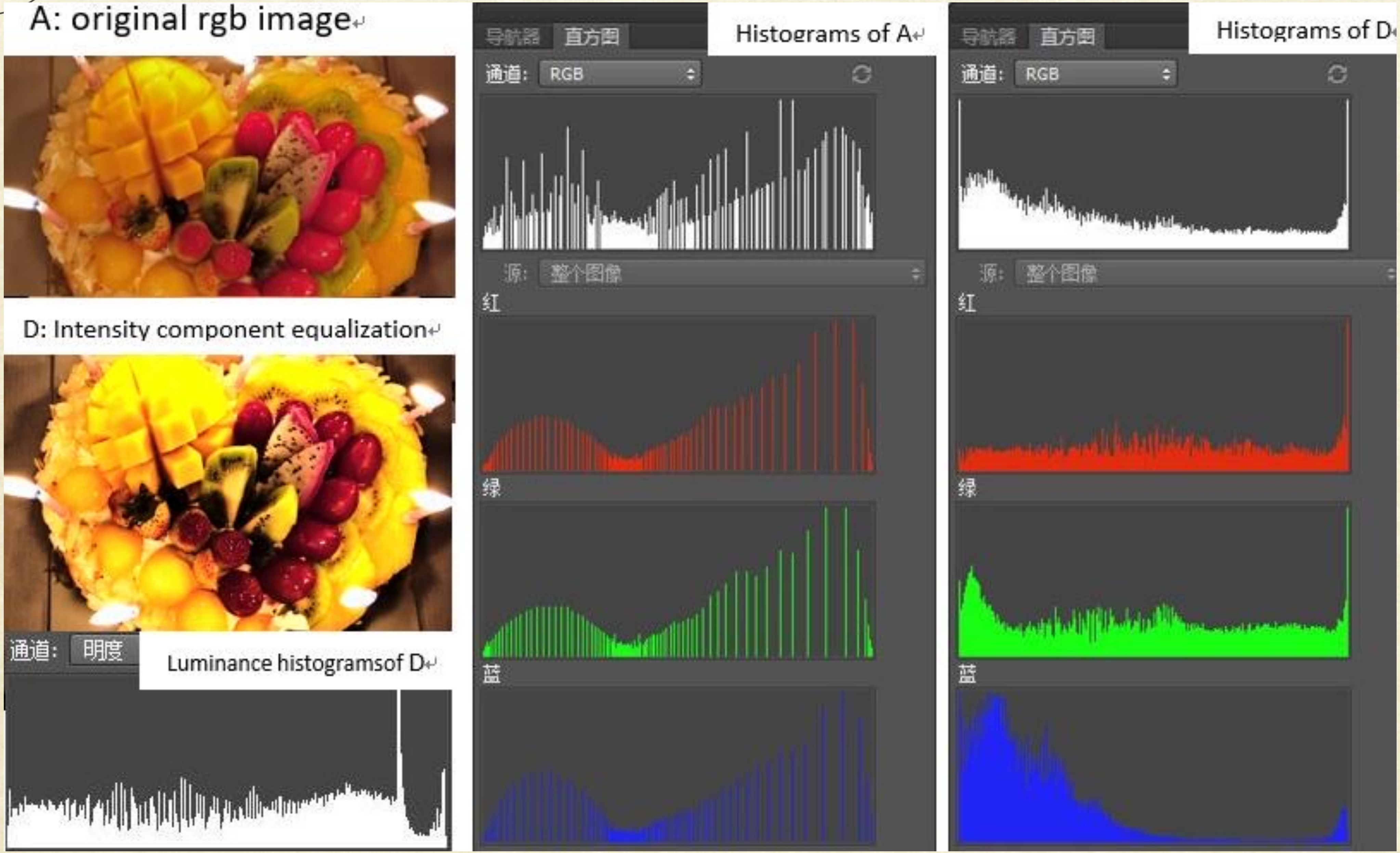
Histogram equalization (per-channel)

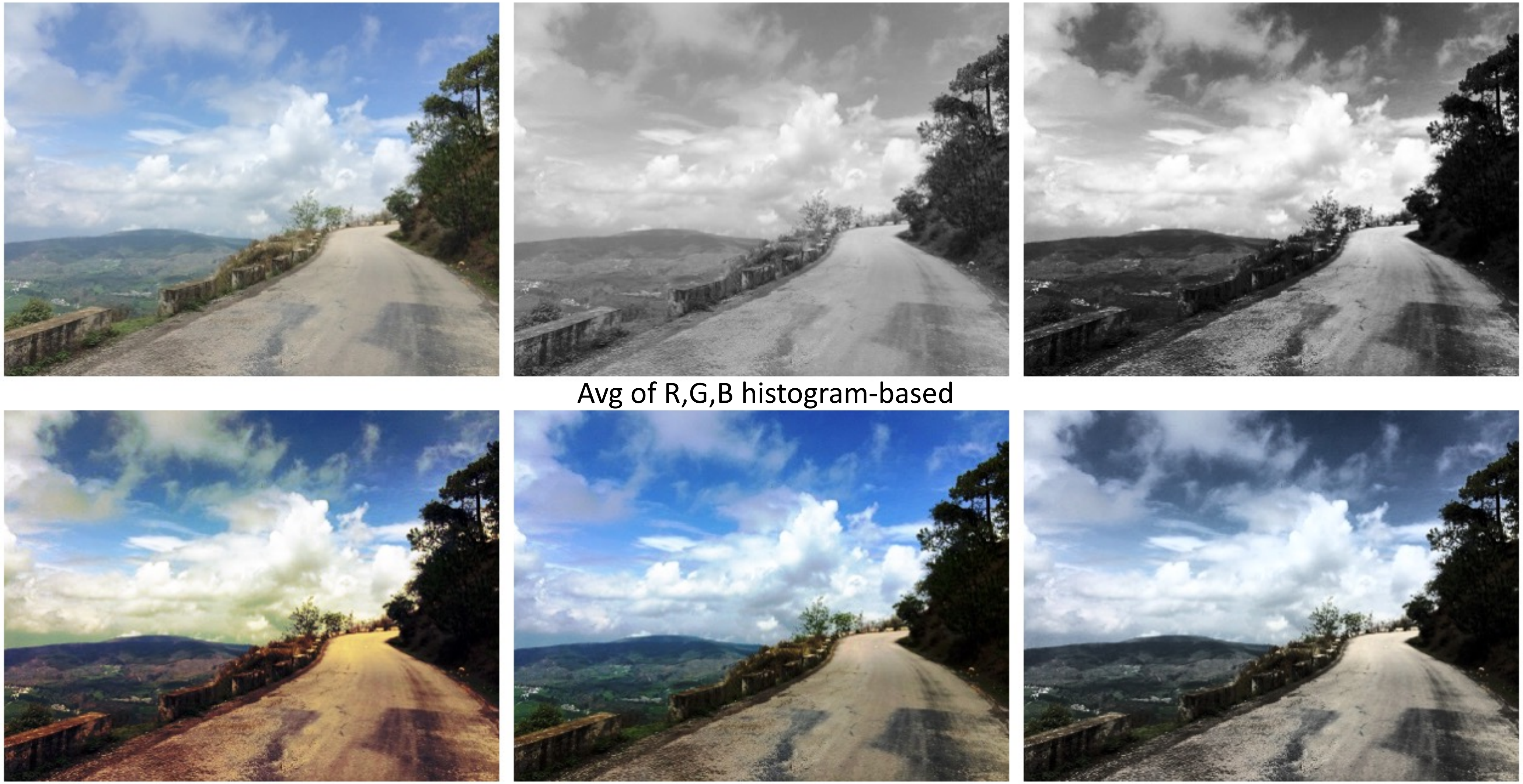


Histogram equalization (ref histogram = average of R,G,B)



Histogram equalization (ref histogram = I of HSI)





Avg of R,G,B histogram-based

Independent

Background and foreground that are both bright.

I of HSI

Avg of R,G,B histogram-based

Independent

Foreground brighter.

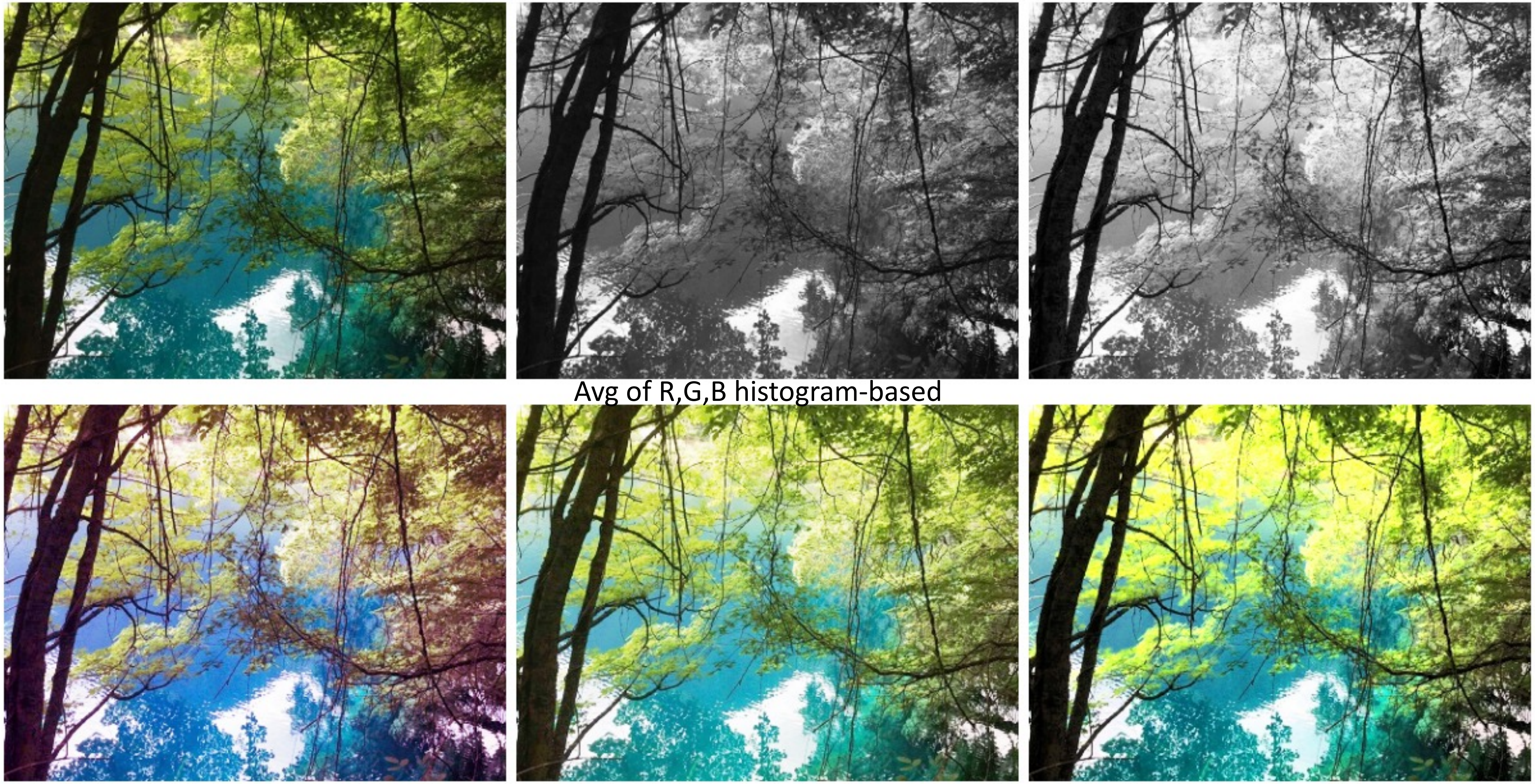
I of HSI

Avg of R,G,B histogram-based

Independent

Lanterns are brighter.

I of HSI



Avg of R,G,B histogram-based

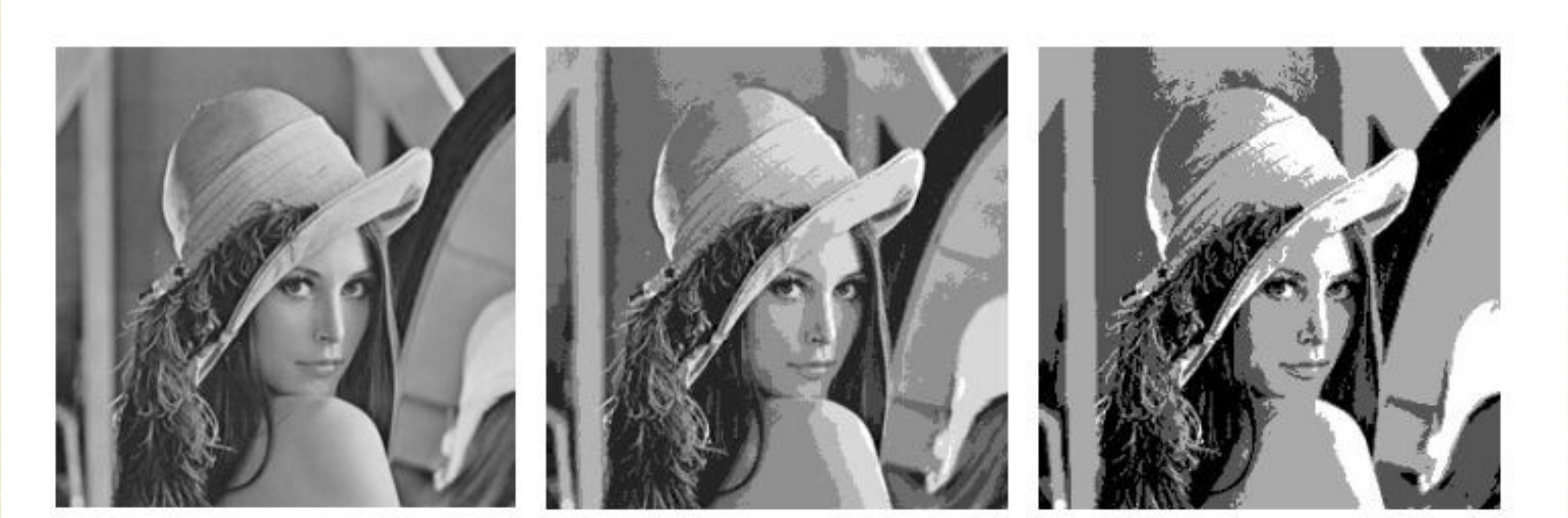
Independent

Local areas are brighter.

I of HSI

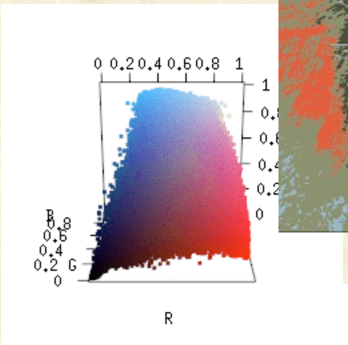

Avg of R,G,B histogram-based
Independent
The grasses are unrealistic and the figure is outlined against the background with white line.
I of HSI

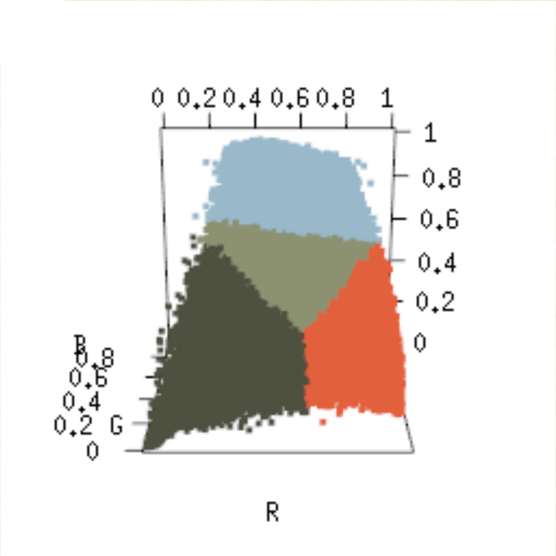
Grayscale Quantization



Original 8 levels 4 levels

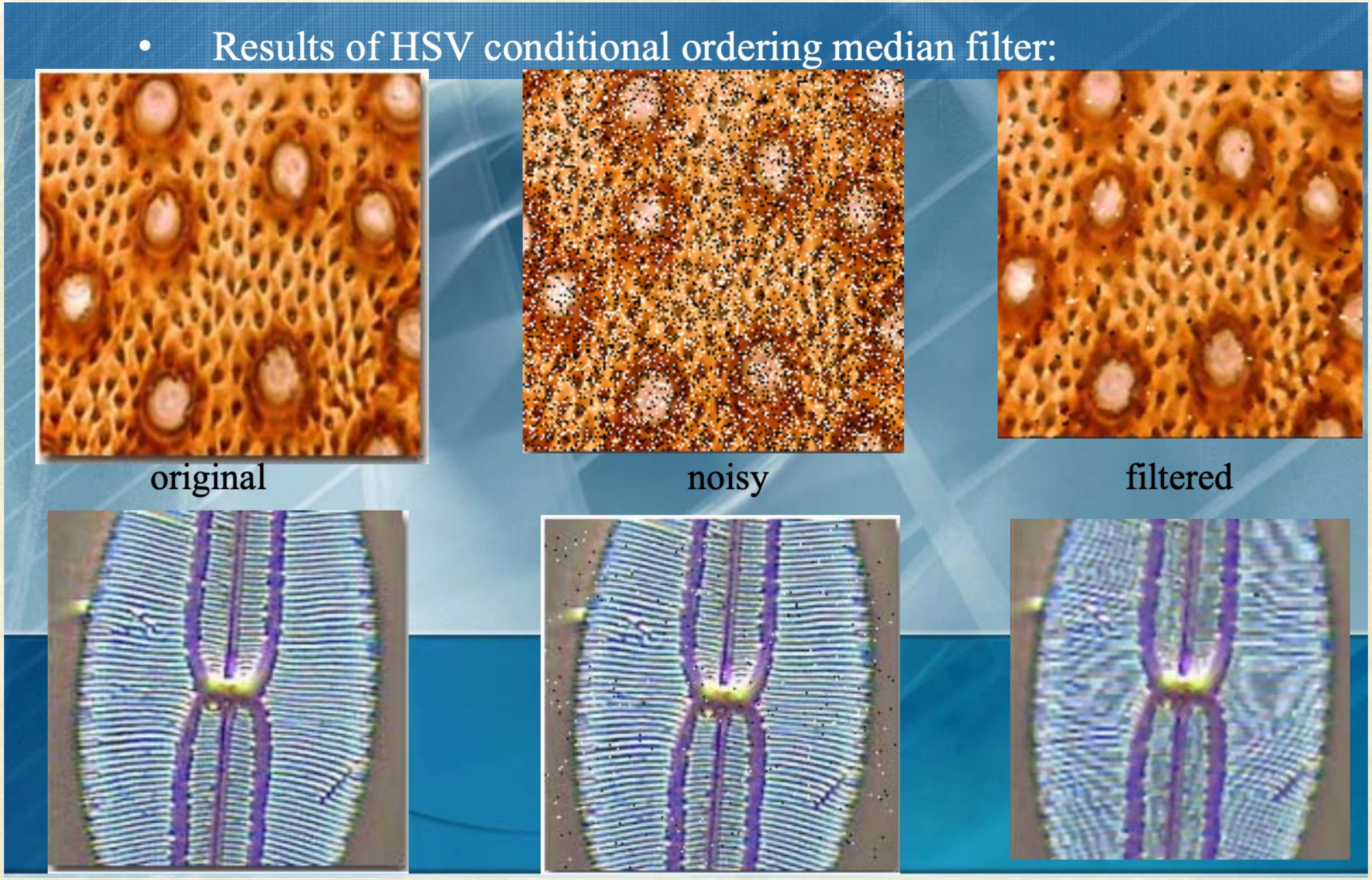
Color Quantization (k-means on RGB)



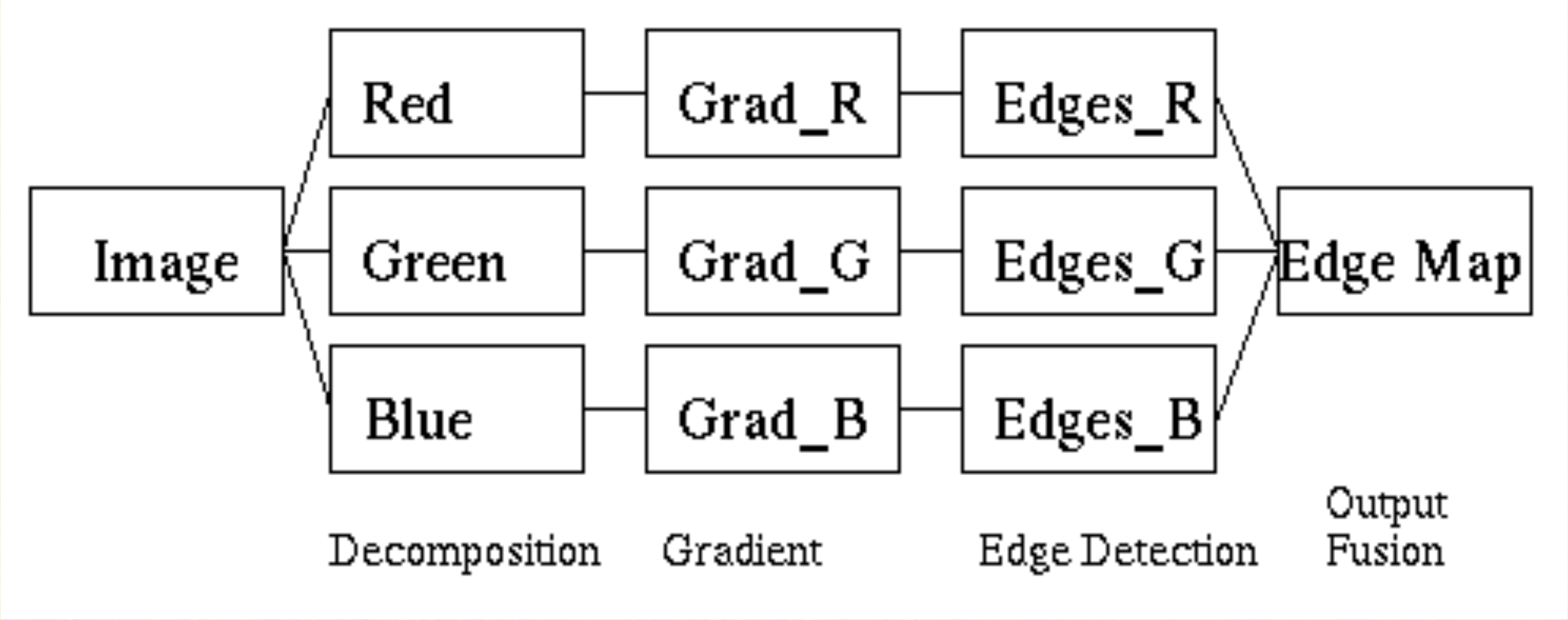


Color Image Filtering

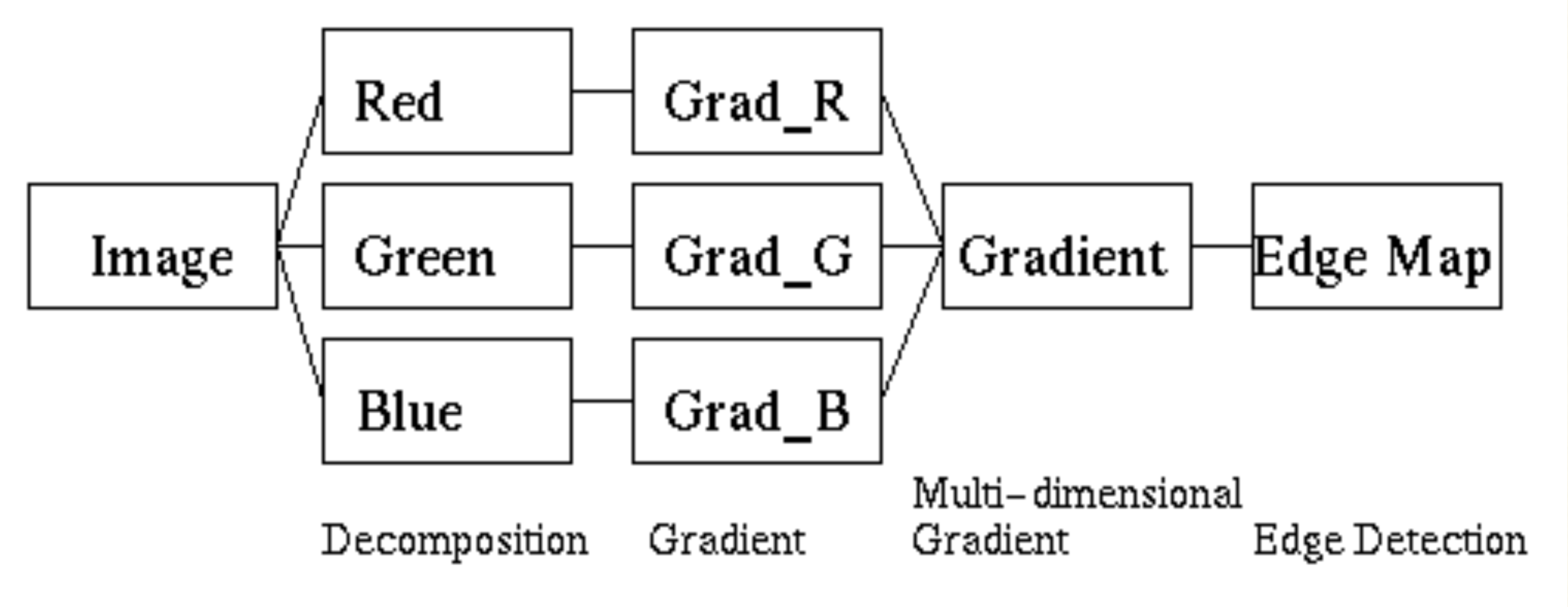
- Median filtering



Color Edge Detection



Color Edge Detection



Edge in Color Images

References

- "Colorimetry", Ohta and Robertson, John Wiley and Sons Ltd
- https://hypjudy.github.io/2017/03/19/dip-histogram-equalization/
- http://www.inf.u-szeged.hu/ssip/2008/presentations2/Gordan_LectureSSIP08.pdf

Questions?