Imagery numérique

Lecture 2

The HVS perception and color

Content of course

Semester 1

Lecture 1: Introduction to image processing

Lecture 2: The HVS perception and color

Lecture 3: Image acquisition and sensing

Lecture 4: Histograms and point operations

Lecture 5: Geometric operations

Lecture 6: Spatial filters

Lecture 7: The 2D Discrete Fourier Transform

Lecture 8: Frequency domain filtering, sampling and aliasing

Lecture 9: Unitary Image Transforms

Lecture 10: Edge detection

Lecture 11: Edge linking and line detection

Lecture 12: Thresholding

Lecture 13: Morphological image processing

Lecture 14: Object and feature detection

Content of course

Semester 2 (tentative for now!)

Lecture 15: Lossless image coding

Lecture 16: Lossy image compression

Lecture 17: Image restoration

Lecture 18: Reconstrcution from parallel projections

Lecture 19: Fan beam corrections

Lecture 20: Dithering and halftoning

Lecture 21: Digital watermarking

Lecture 22: Image blending (or digital forensics)

Lecture 23: Photomontage and inpaining

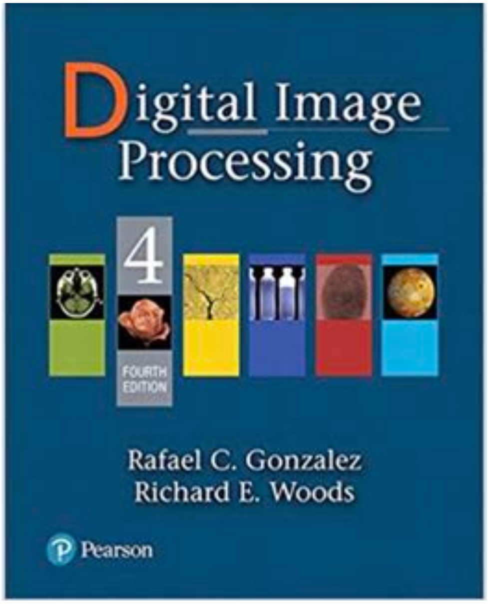
Lecture 24: Image retargeting

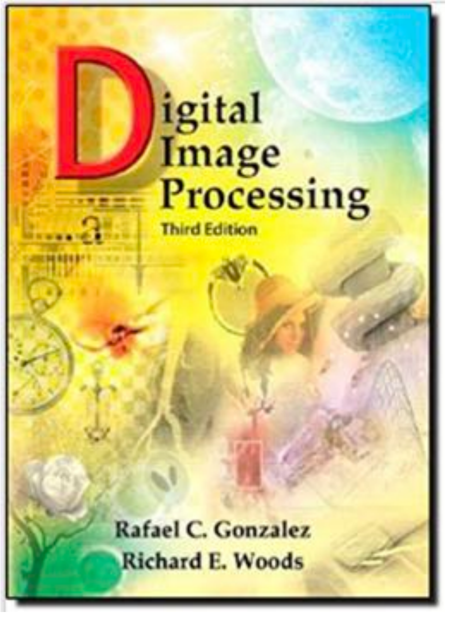
Lecture 25: Active shape models

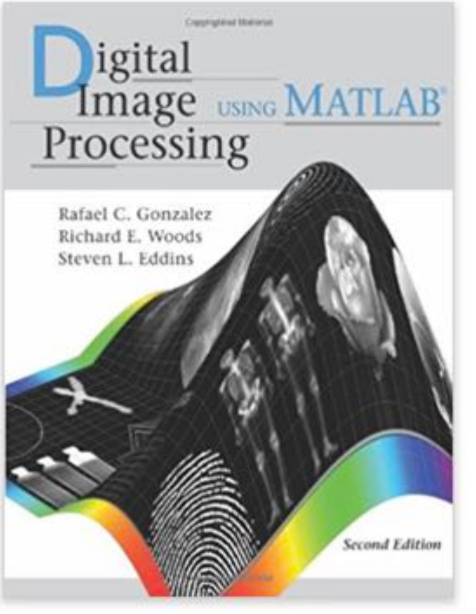
Lecture 26: Sparse modeling and compressive sensing

Lecture 27: Machine learning based applications

Recommended books







YouTube lectures

Intro to Digital Image Processing (ECSE-4540) Lectures, Spring 2015

by Prof. Rich Radke from Rensselaer Polytechnic Institute

Recommended books

- B.A. Wandell, Foundations of Vision, Sinauer Associates, Inc., 1995.
- A. K. Jain, Fundamentals of Digital Image Processing, Prentice-Hall,1989.

Copyright notice

This course uses in part some materials from previously mentioned recommended sources.

Content of this lecture

In this lecture we will consider:

- Perceived information attributes (light, luminance, brightness, contrast)
- Optical properties of the Human Visual System (HVS)
- Standardization and color systems
- Image quality (fidelity) criteria

Introduction

- Why is it important to know the features of the Human Visual System (HVS)?

  1. To develop measures of image fidelity and quality
  2. To design the algorithms matched with these measures
  3. To exploit the knowledge of the HVS for:
     - Efficient processing algorithms such as: compression, denoising, restoration, watermarking, recognition, etc.
     - Hardware parts:
       - sensors
       - displays
       - printers
     - New imaging technologies linking bio-inspired image processing with machine learning and artificial intelligence

Perceived information attributes

Light is the electromagnetic radiation that stimulates our visual response.

Gonzalez at al, p. 44

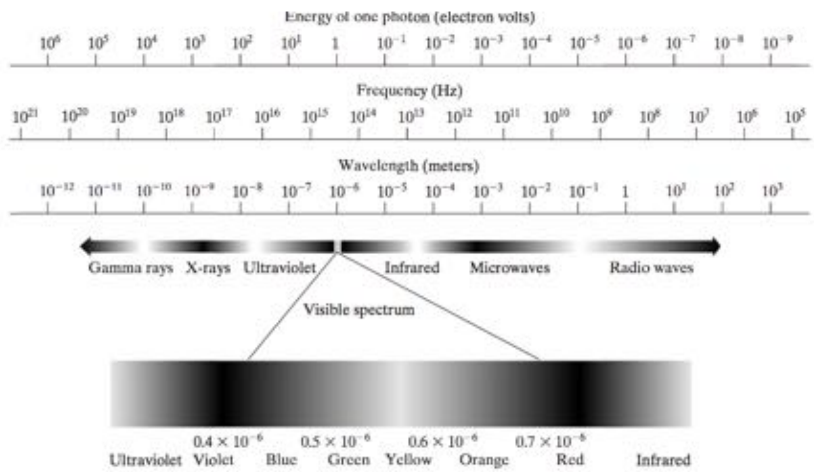
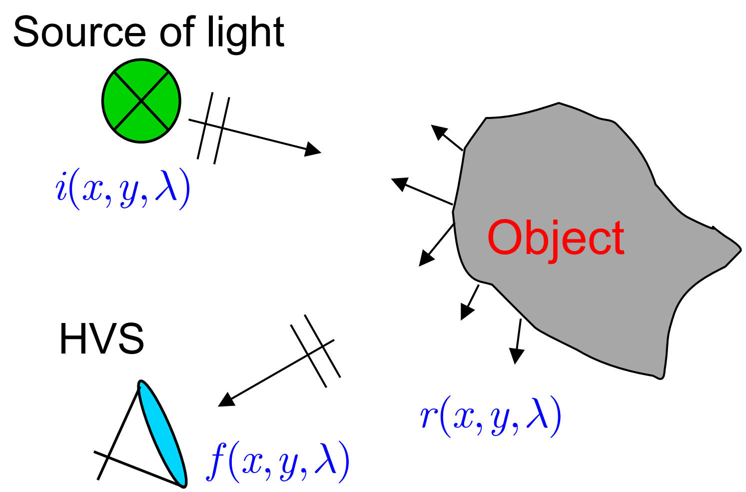


FIGURE 2.10 The electromagnetic spectrum. The visible spectrum is shown zoomed to facilitate explanation, but note that the visible spectrum is a rather narrow portion of the EM spectrum.



Visible range of human eye:

350 nm < λ > 780 nm

Light received from the object:

$$f(x,y,\lambda) = r(x,y,\lambda)i(x,y,\lambda)$$

Reflectivity   Incident light

Reminder

milli-meters = mm = 10^{-3} m

microns = μm = 10^{-6} m

nano-meters = nm = 10^{-9} m

$$f\lambda = c$$

$$E = hc / \lambda$$

f = frequency in Hertz (Hz = $^1/_{sec}$)

λ = wavelength in meters (m)

c = the speed of light (299792458 $^m/_s$)

E= energy of electron (e Volts)

h= Plank's constant

Image formation model

Notations: for a given wavelength λ

$f(x,y)$ denotes images as two-dimensional (2D) functions

f intensity value $(f \geq 0)$

(x,y) spatial coordinates

$$0 < f(x,y) < \infty$$

$$f(x,y) = i(x,y)r(x,y)$$

$0 < i(x,y) < \infty$ *is illumination* – the amount of source illumination incident on the scene being viewed

$0 < r(x,y) < 1$ *is reflectance* – the amount of illumination reflected by the objects in the scene

Image formation model - optical systems

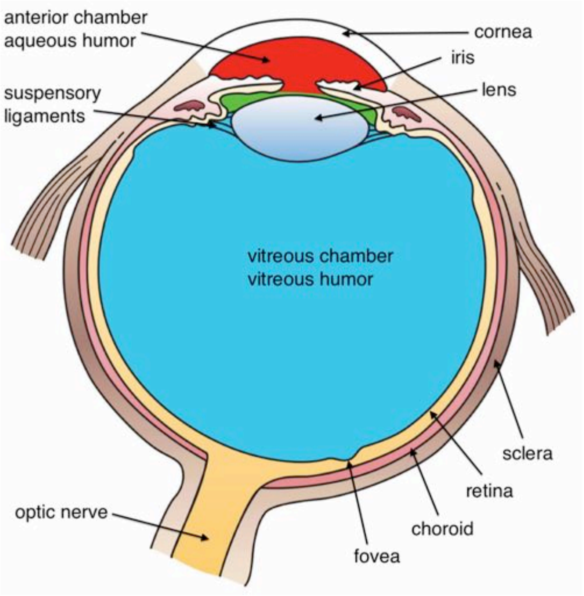
Conditions	$i(x, y), \mathrm{lm/m^2}$
Clear sunny day (on the natural surface)	90K
Cloudy day	10K
Indoors (commercial office)	1K
Full moon (no clouds)	0.1

Surfaces	$r(x, y)$
Snow	0.93
Flat white wall	0.80
Stainless steel	0.65
Black velvet	0.01

The human eye

Retina contains two types of photoreceptors :

- 100 millions of *rods* (dark environment)
- 6.5 millions of *cones* (well-lighted environment, high resolution and color vision)



https://en.wikipedia.org/wiki/Fovea_centralis

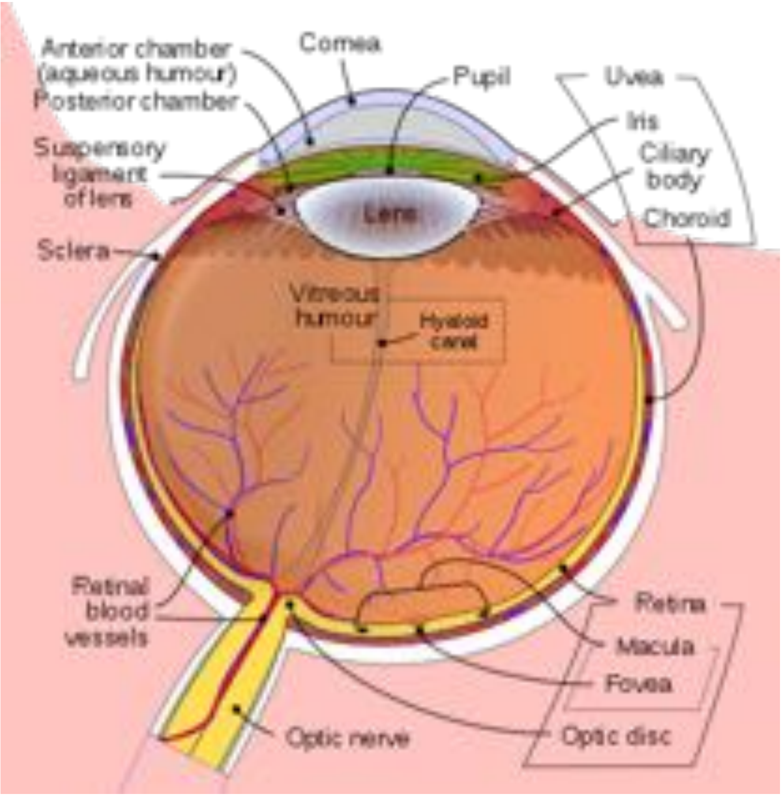
Cones are mostly packed in Fovea.

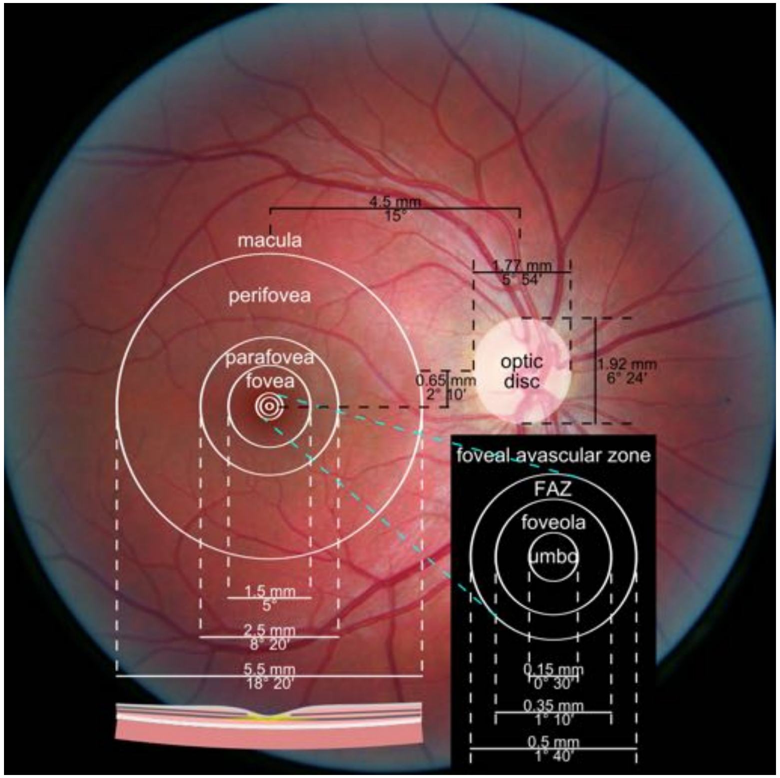
Rods are distributed over all Retina.

Pupil acts as small imaging aperture (size is varying from 2 to 8 mm).

Lens determines the aperture focusing. Iris is the muscle that controls the pupil size.

The human eye





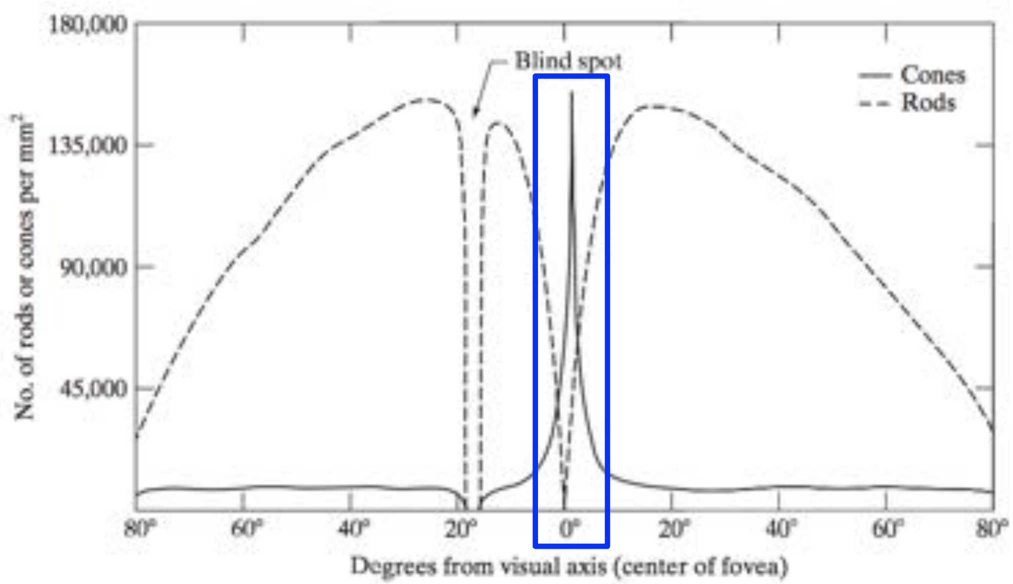
https://en.wikipedia.org/wiki/Fovea_centralis

The human eye

Cones (only bout 6.5 Mio) are responsible for the color vision.

The area of fovea is about 1.5 mm in diameter and about 1.77 mm2 of area.

FIGURE 2.2
Distribution of rods and cones in the retina.



Gonzalez et al, p. 38

The number of cones in fovea is about 265K (individually addressable!)

From the point of view of modern sensors, it is a quite poor concentration of sensitive elements.

Processing of the brain

Image formation in the eye

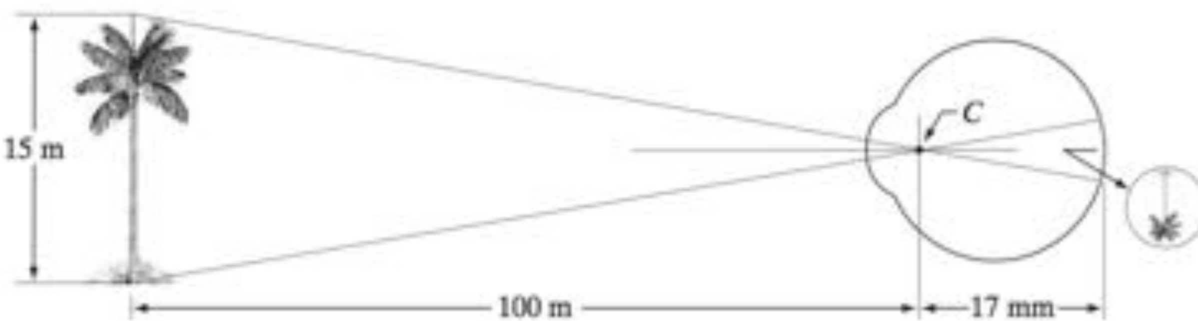
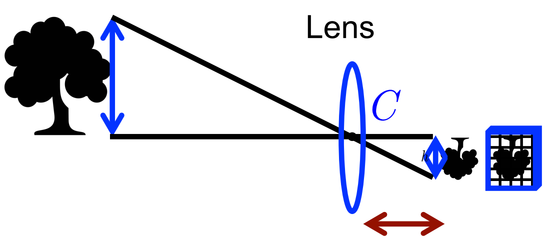


FIGURE 2.3 Graphical representation of the eye looking at a palm tree. Point *C* is the optical center of the lens.

Gonzalez et al, p. 35

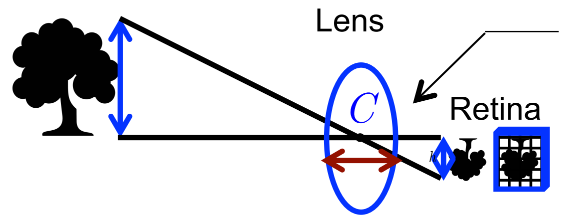
Important difference in focusing:

ordinary camera



To focus - change the distance between the lens and the image plane

the human eye



To focus - change the focal distance by varying the lens

Image formation in the eye

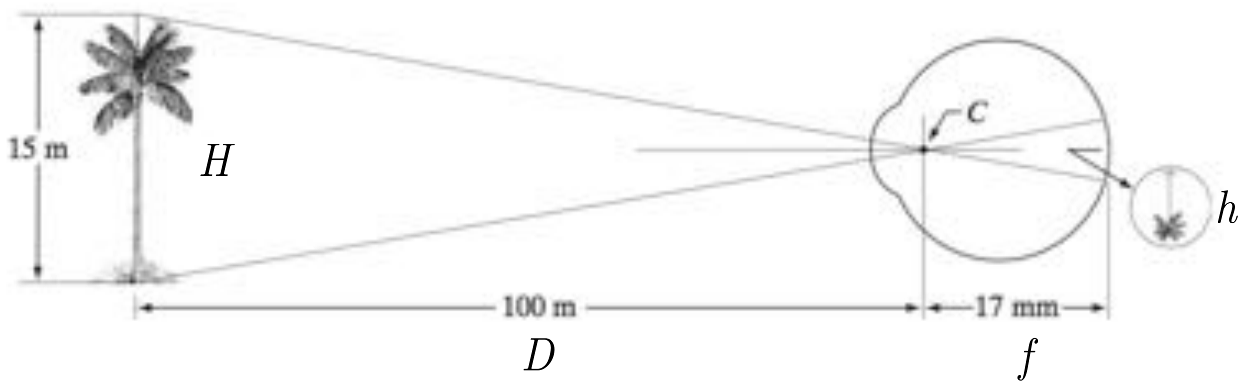
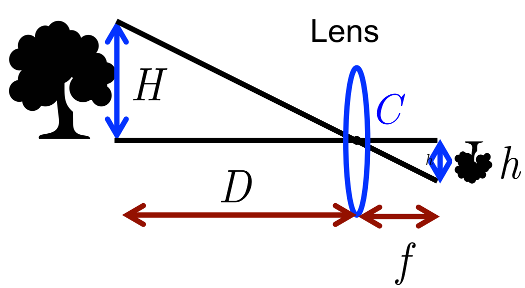


FIGURE 2.3 Graphical representation of the eye looking at a palm tree. Point C is the optical center of the lens.

Gonzalez et al, p. 35

Focal length is in the range 14-17 mm



From similarity of triangles

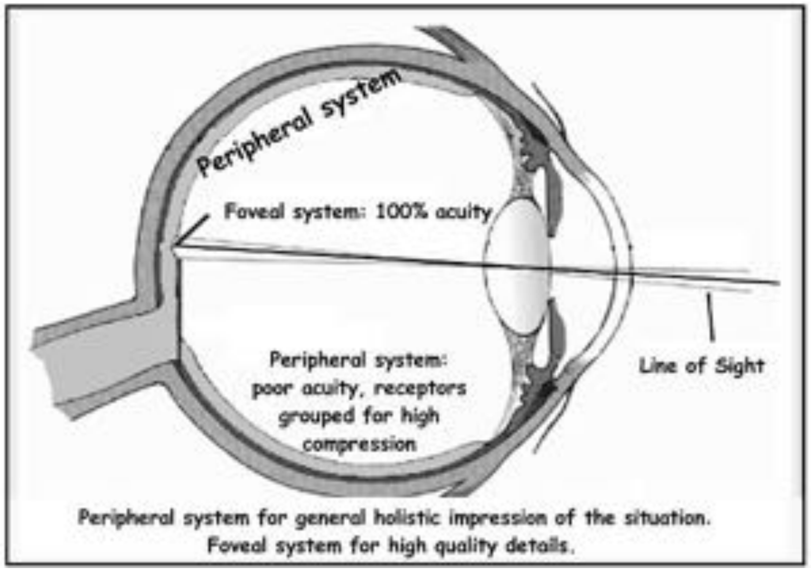
$$\frac{H}{D} = \frac{h}{f} \quad \Rightarrow \quad \boxed{h = f\frac{H}{D}}$$

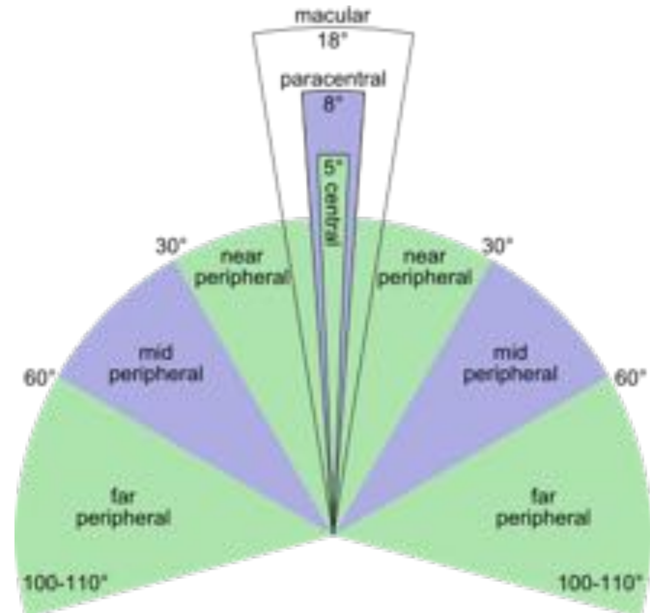
$$h = f\frac{15}{100} = 17 * 0.15 = 2.55mm$$

This is mostly in fovea of diameter 1.5 mm

The human eye

https://en.wikipedia.org/wiki/Peripheral_vision



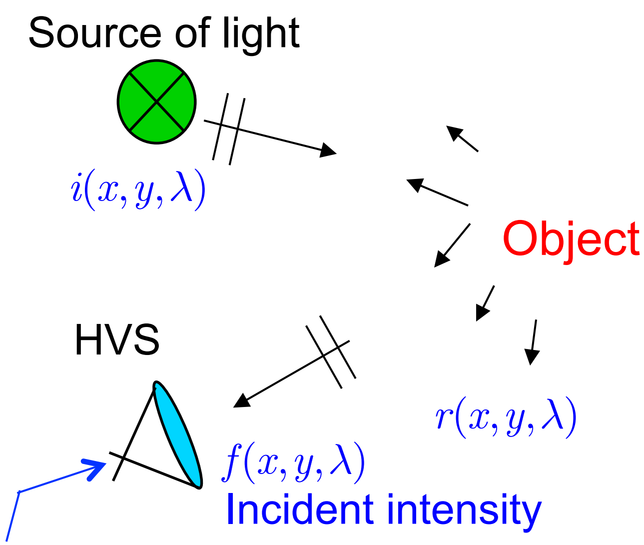


Foveal vision is defined as the central 1.5–2° of the field of vision. Vision within the fovea is generally called **central vision**, while vision outside of the fovea is called **peripheral, or indirect vision**.

Central vision (fovea area) is mostly due to the direct projection onto fovea where we have most of cones packed!

Brightness adaptation and discrimination

The second difference of the HVS and ordinary cameras consists in the way how it perceives the light.



Brightness is a "perceived luminance"

Eye has a huge dynamic range $O\left(10^{10}\right)$.

It means that eye can adapt to a very broad deviation of input light intensity

(the difference in the darkest and lightest intensities).

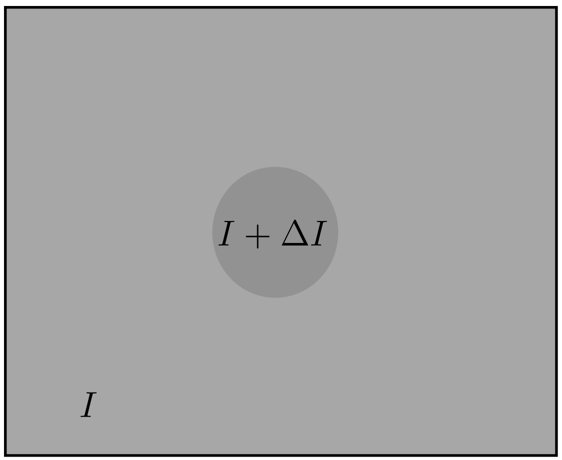
The subjective brightness is logarithmic as a function of incident intensity.

Example: imagine a very good lighted environment. A human eye can perceive many variations in shadow. In contrast, imagine some dark room where you can barely distinguish contours of person or some object even after long time adaptation.

- This process is called **brightness adaptation (iris diameter and receptors)**.

Brightness adaptation: Weber law

Just a noticeable difference



Uniform intensity

ΔI - a small increment of intensity

- The HVS can perceive the small difference in luminance.
- However, the minimum difference that can be perceived depends on the surround luminance (intensity).
- This dependence is known as contrast sensitivity
- Rods and cones have different sensitivity

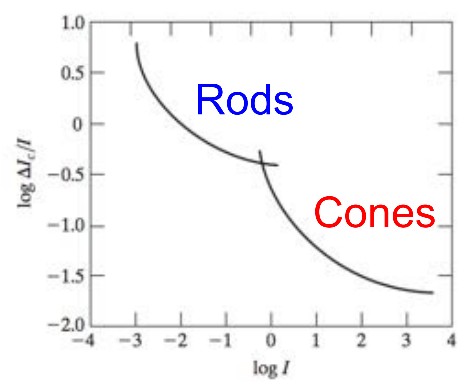


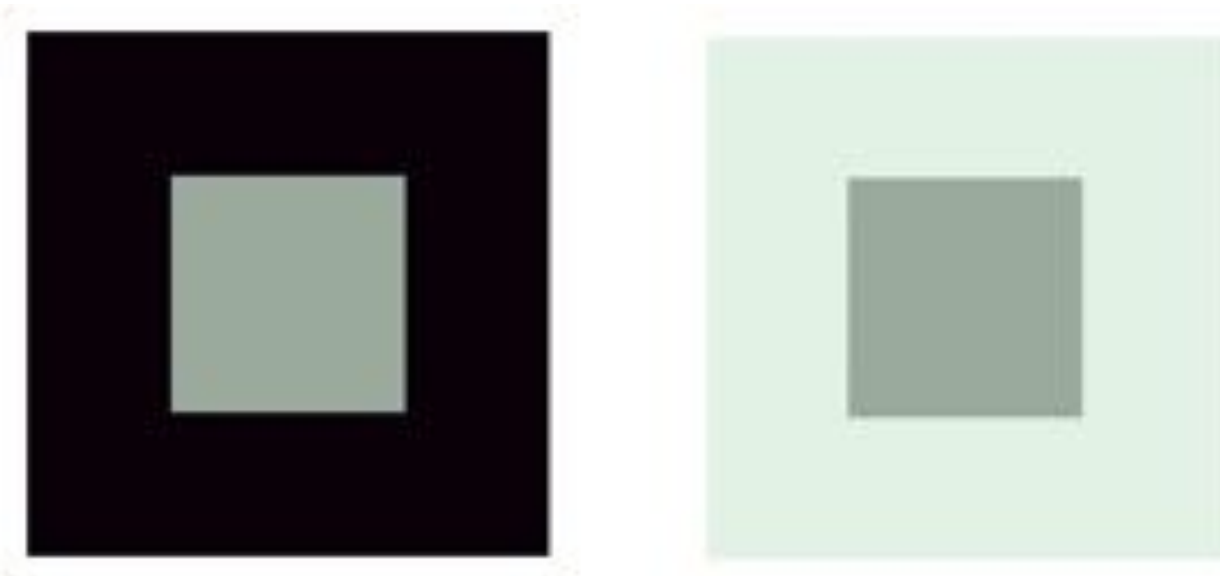
FIGURE 2.6 Typical Weber ratio as a function of intensity.

Gonzalez, p. 41

This curve shows that brightness discrimination is poor (the Weber ratio is large) at low levels of illumination, and it improves significantly (the Weber ratio decreases) as background illumination increases.

Perceived information: Luminance and Brightness

Therefore, **brightness** is a perceived luminance. It depends on luminance of the surround



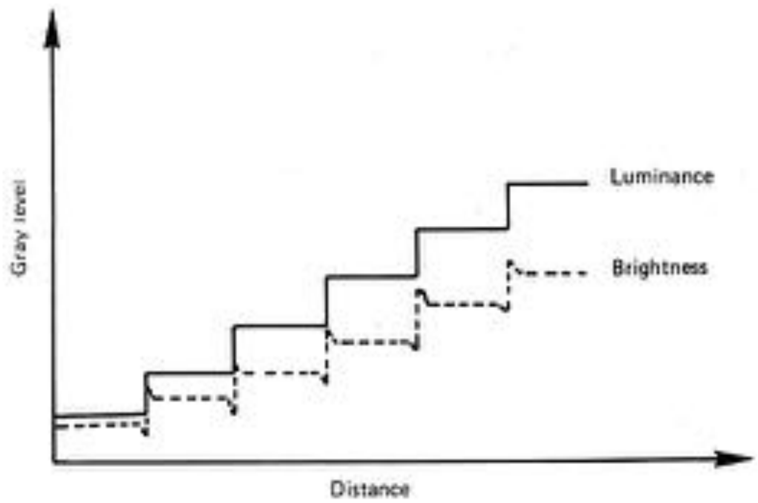
Small squares in the middle have equal luminance but do not appear equally bright.

The human perception is sensitive to luminance contrast rather than the absolute luminance values themselves.

Perceived information: Luminance and Brightness

Conclusion: the perceived brightness is not just a function of input intensity but it has a more complex nature.

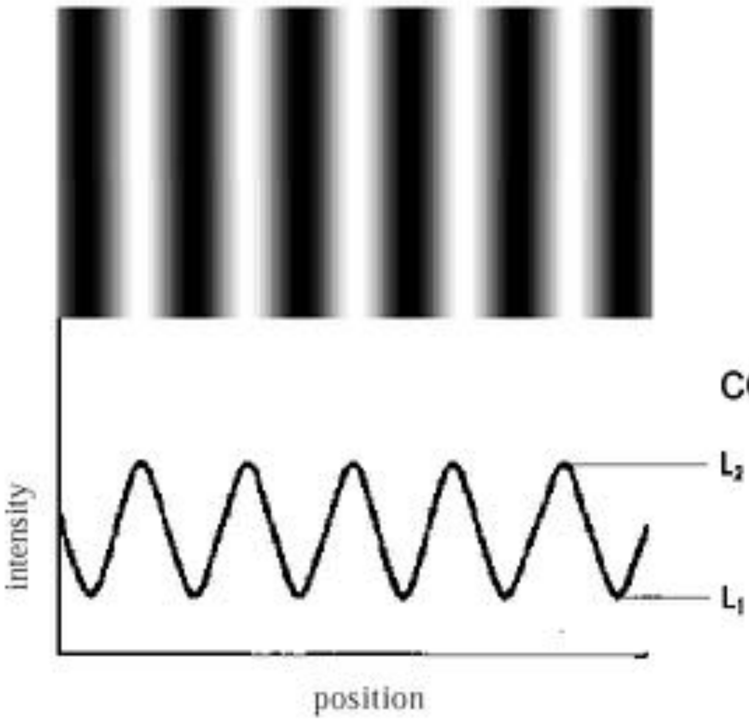
Mach bands – the measure of visual system in spatial domain.



The bars have constant luminance.

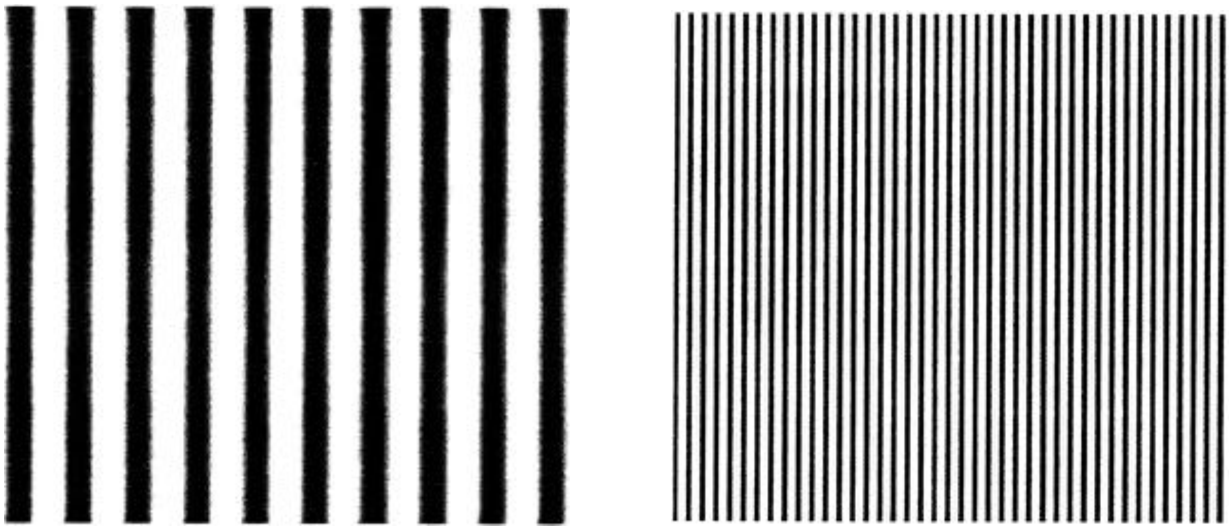
However, the perceived brightness is not uniform along the width of the bar.

Sine wave grating



$$\text{contrast ratio} = \frac{L_2 - L_1}{L_2 + L_1}$$

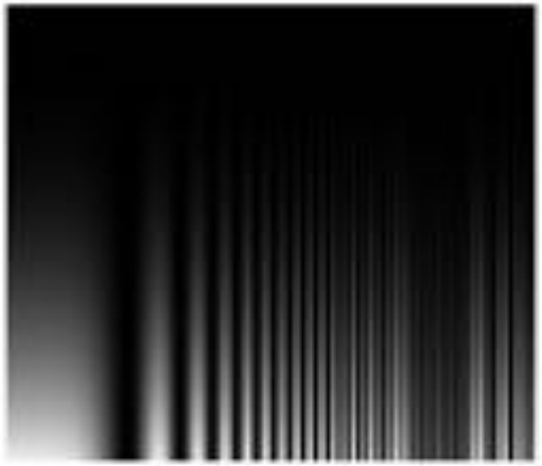
MTF of the visual system

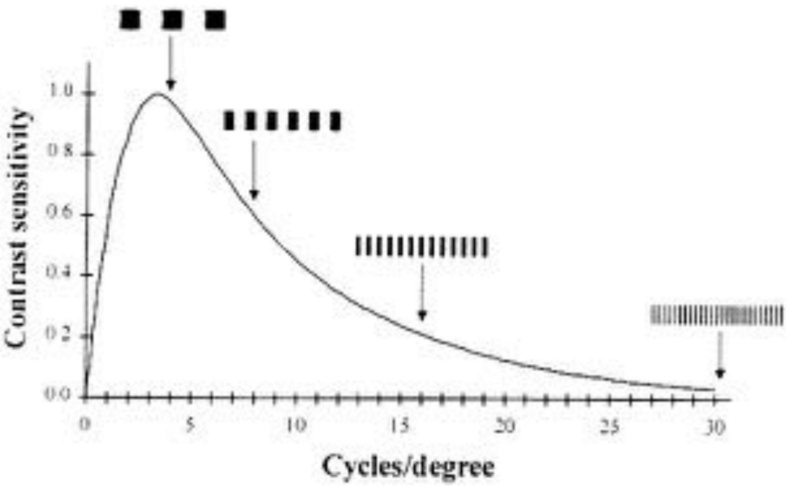


low- and high-frequency pattern

MTF: Modulated Sine Wave Grating

MTF – the measure of visual system in frequency domain





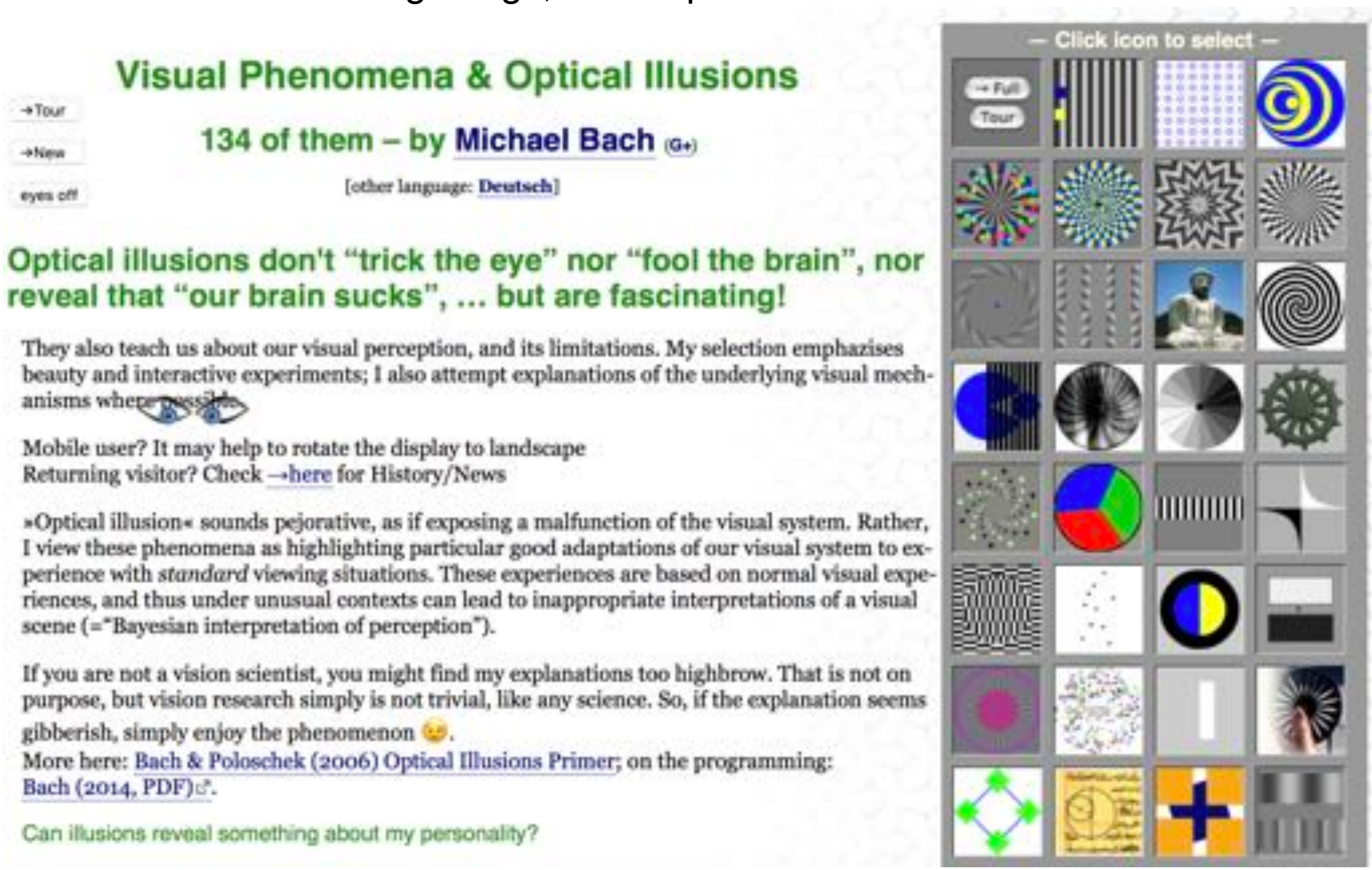
$$H(\xi_1,\xi_2) = H_p(\rho) = A\left[\alpha + \frac{\rho}{\rho_0}\right]\exp\left[-\left(\frac{\rho}{\rho_0}\right)^{\beta}\right]$$

$$\rho = \sqrt{\xi_1^2 + \xi_2^2}\ cycles\ /\ deg$$

(isotropic approximation)

Brightness adaptation and discrimination

To see more interesting things, visit http://www.michaelbach.de/ot/



Brightness adaptation and discrimination

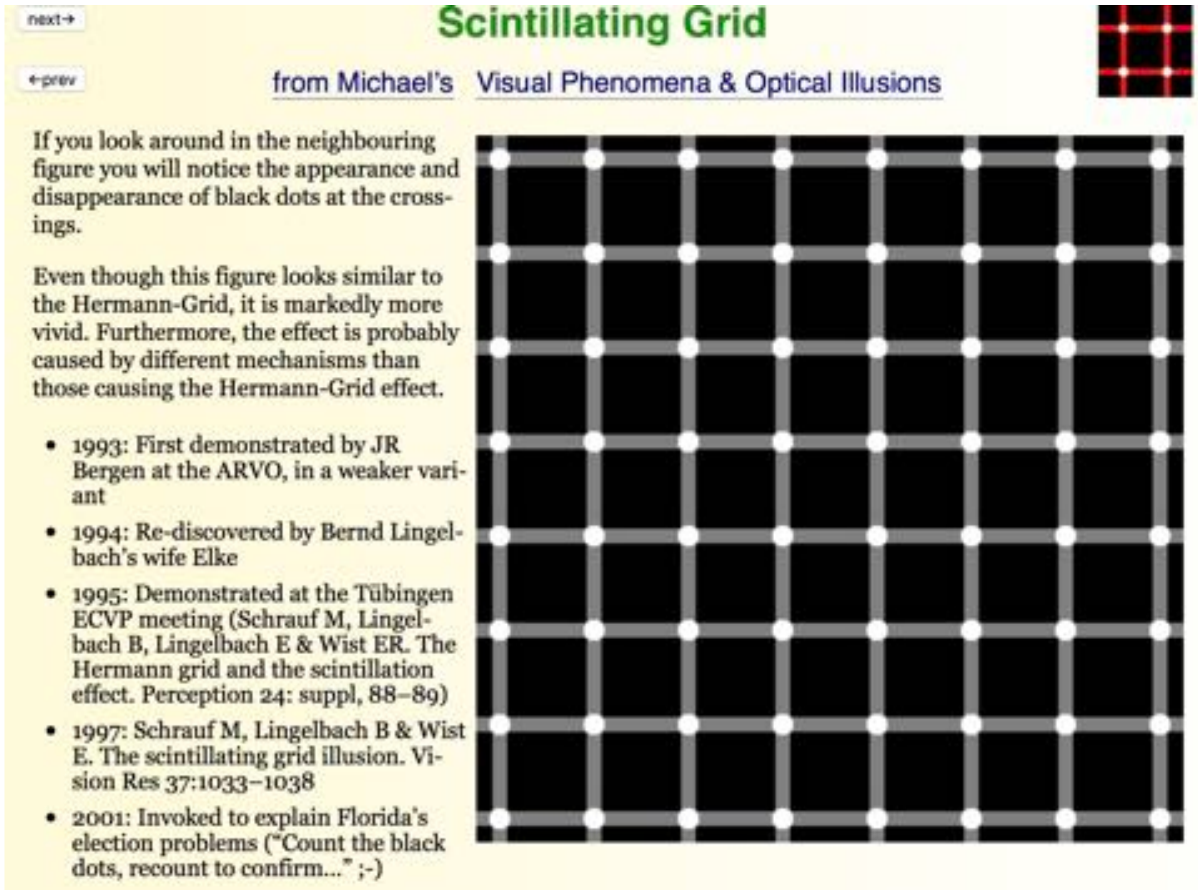
To see more interesting things, visit http://www.michaelbach.de/ot/

Luminance & Contrast

- Hermann's Grid – fleeting luminance illusions
- Hermann's Grid Variant – a new twist, refuting the classical explanation
- Scintillating Grid – strong fleeting luminance illusions
- 12 Vanishing Dots – No variation of the above
- Translational Moiré Patterns
- Rotatory Moiré Patterns
- Pulfrich effect – luminance turning time into displacement → stereo
- Induced grating – classical brightness contrast
- Shaded-diamond illusion – more brightness contrast
- Craik-O'Brien-Cornsweet – collaboration of retina & cortex
- Wertheimer-Koffka-Ring – pitting Gestalt vs. lateral inhibition
- Mach Bands
- Simultaneous Contrast – here dynamic
- Pyramid Illusion – Vasarely revealed
- Munker-White Illusion – contrary to lateral inhibition
- Adelson's »Corrugated Plaid« – context affecting brightness
- Adelson's »Checker Shadow« illusion – more context affecting brightness
- Saccadic Suppression – eye movements interact with visibility
- Contour Adaptation – a new case of contrast gain control
- Contrast Constancy – demonstrating space-average-based contrast gain control
- Contrast Gain Control – demonstrating temporal contrast gain control
- Lazy Shadow – Interaction of luminance & time
- Visual Acuity ↔ Hyperacuity

Brightness adaptation and discrimination

To see more interesting things, visit http://www.michaelbach.de/ot/lum-scGrid/index.html



Brightness adaptation and discrimination

To see more interesting things, visit

http://www.michaelbach.de/ot/lum-inducedGrating/index.html

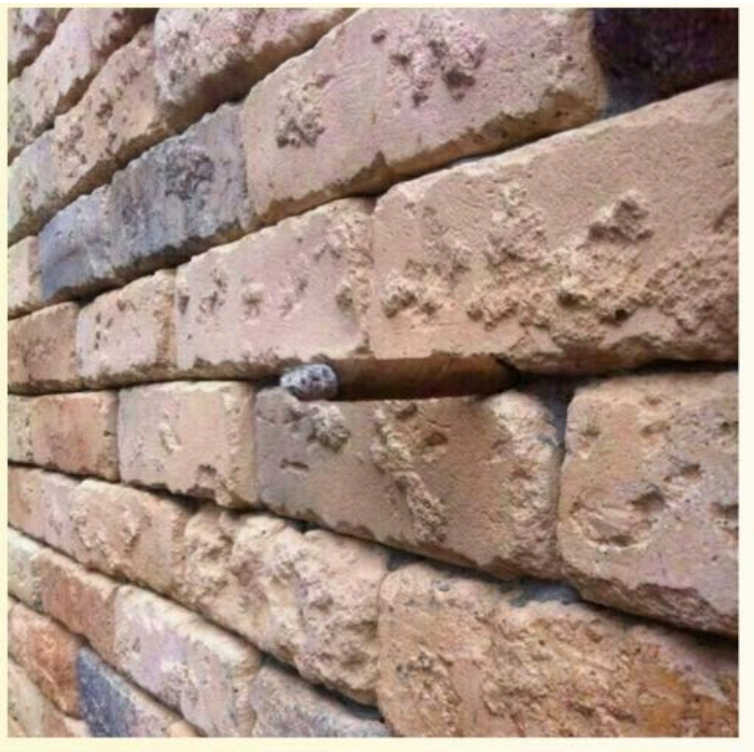
Optical illusions

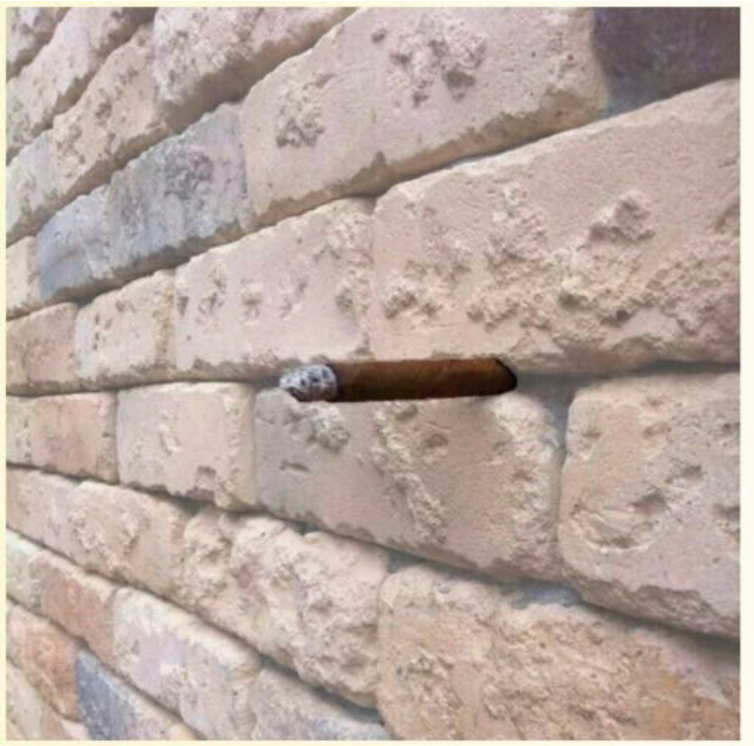
Optical illusion and scene interpretation (try to blur them and see what appear)

http://www.michaelbach.de/ot/cog-blureffects/index.html

Optical illusions

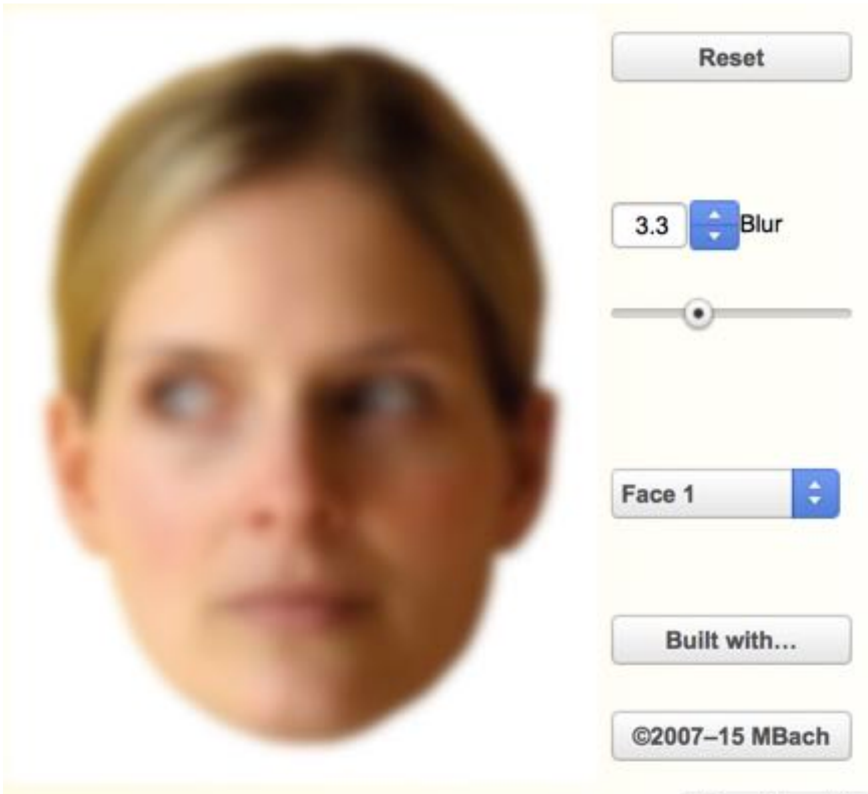
Hidden objects http://www.michaelbach.de/ot/cog-brickWall/index.html





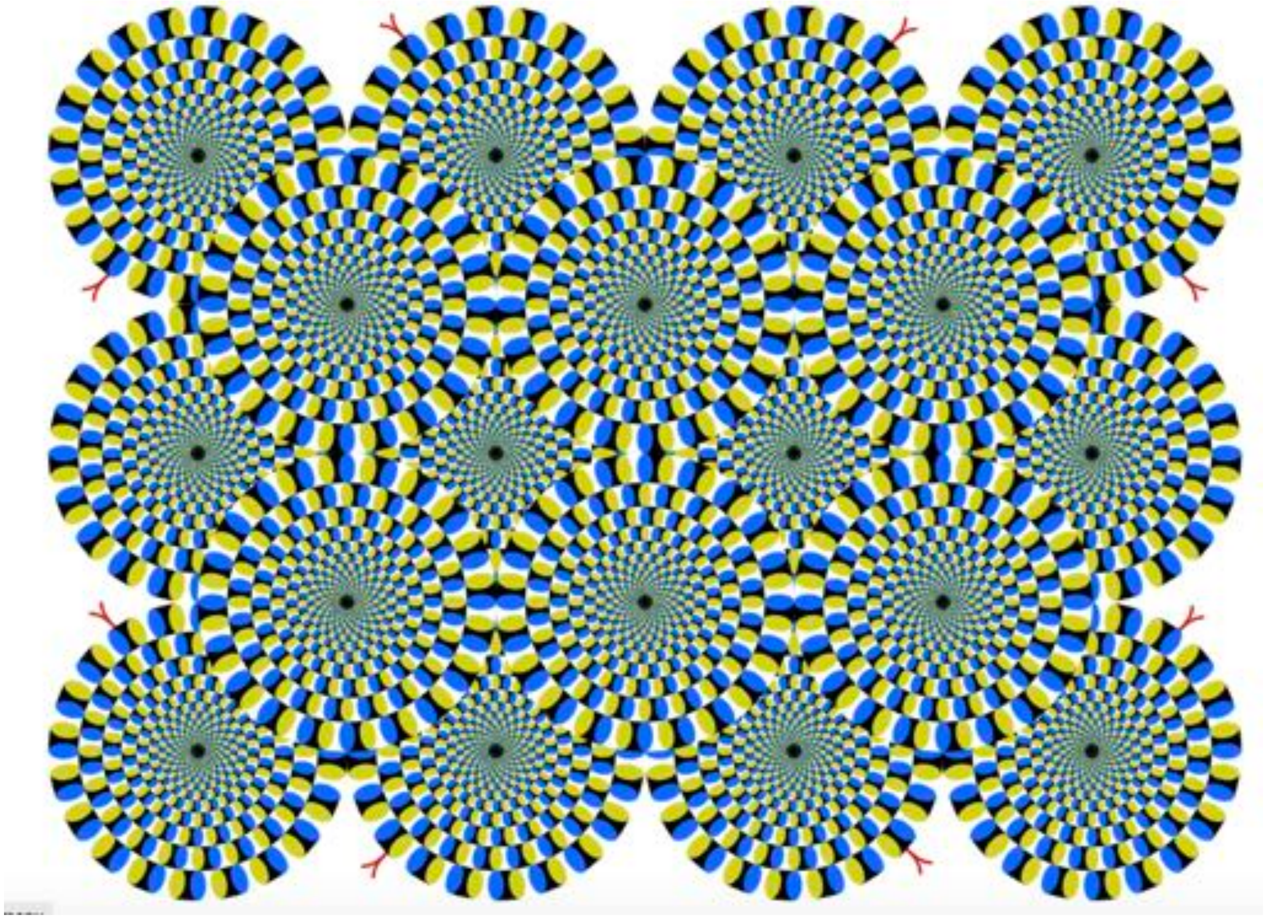
Optical illusions

Face illusion http://www.michaelbach.de/ot/fcs-ghostlyGaze/index.html



Optical illusions

Moving objects http://www.ritsumei.ac.jp/~akitaoka/index-e.html



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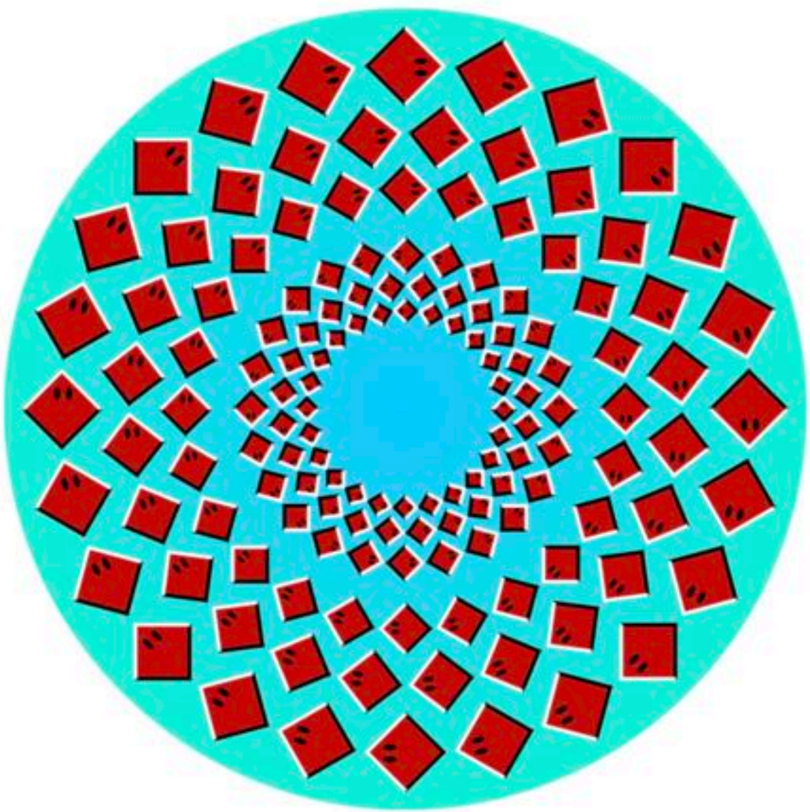

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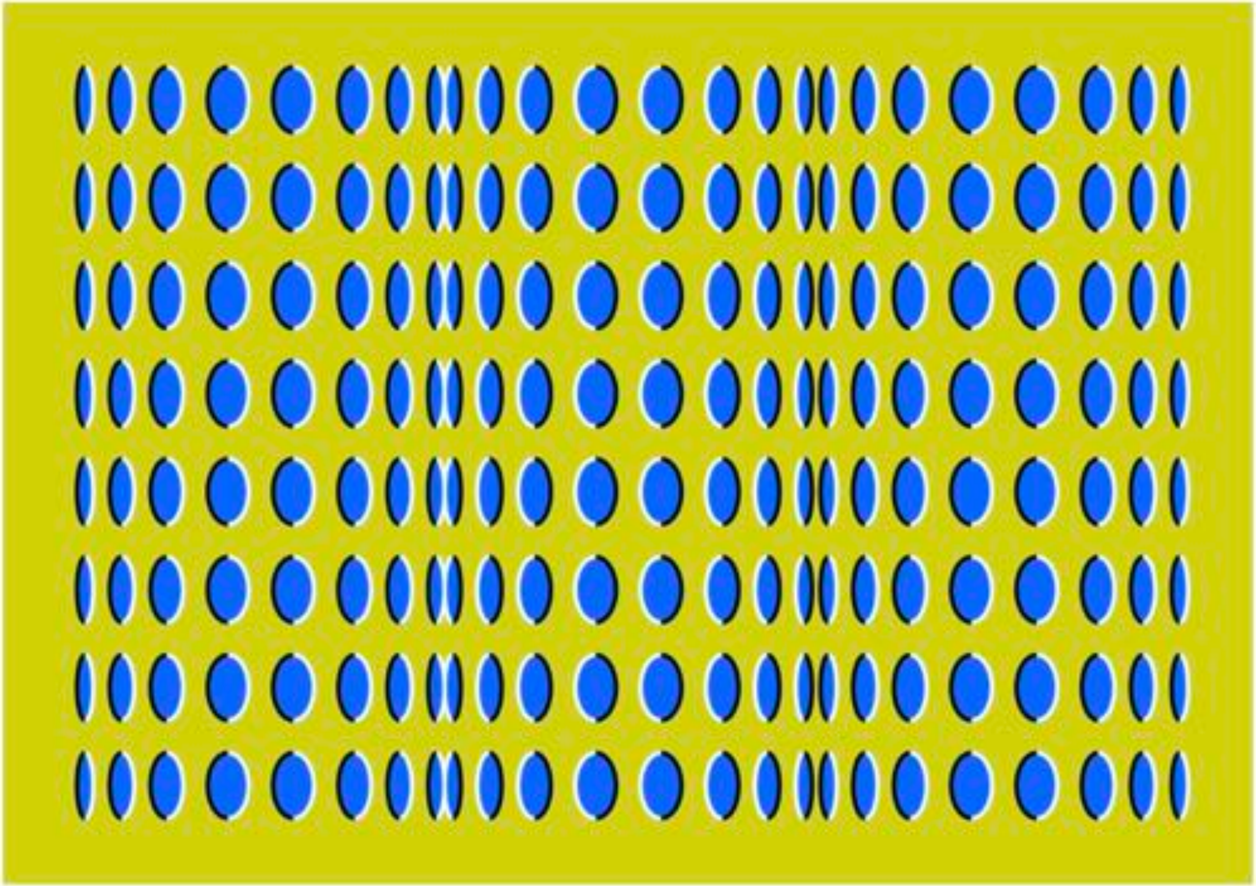


Overall conclusion

Many effects in the HVS are still not well explained:

- Like moving stuff
- Like imaginary parts observed in different ways by different people

- Interesting for: the image compression when a lot of infromation can be removed or compressed without any significant impact on image quality
- Like very small sampling rate of cones providing nevertheless enough information for the unique recognition of objects and interpretation of scenes
- Think about the completely opposite trends in the modern technology development trying to increase the sampling density of sensors, etc. that has many side effects (sensitivity of cells (photon noise), size of data, etc.)
- Link it to the recent results in machine learning where it is known that the recognition or recovery can be done even from partial information, if enough training was available.

Color vision

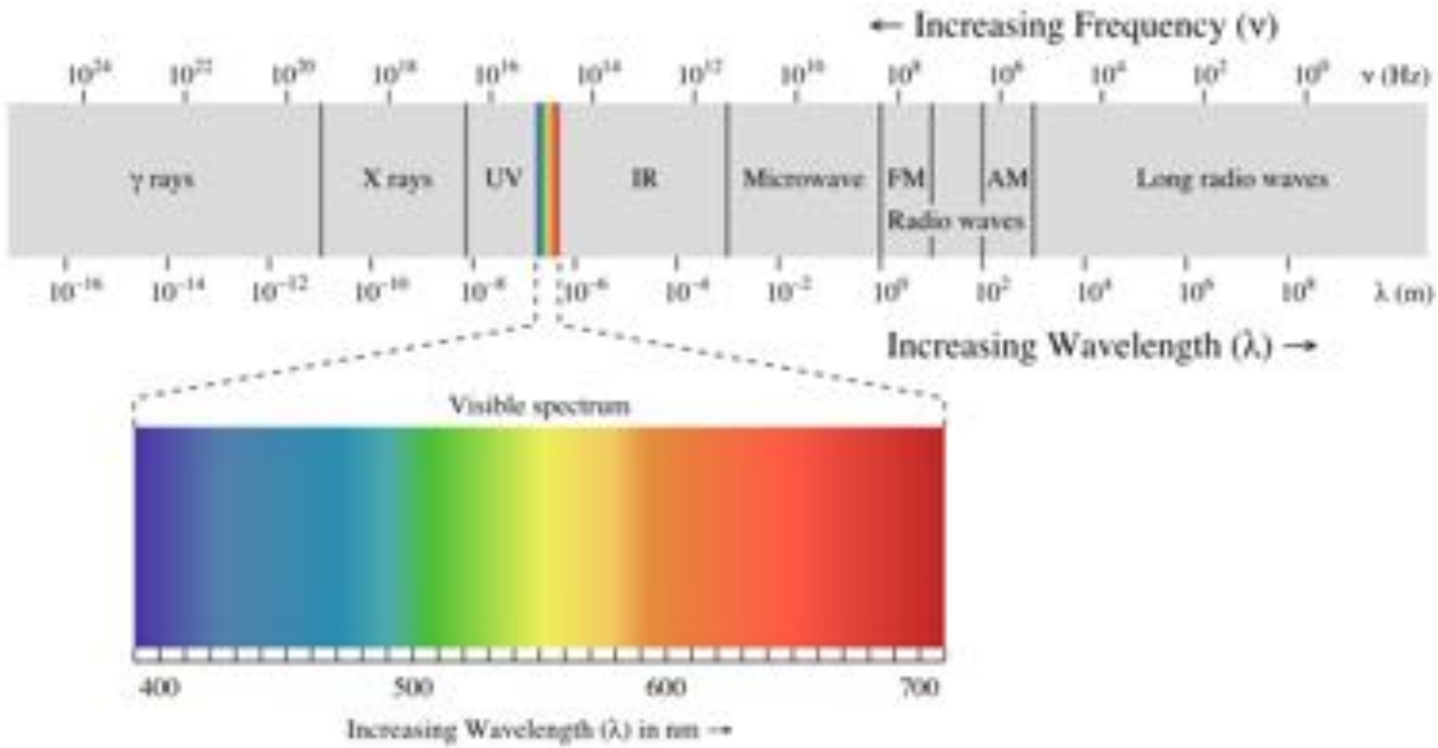
There are two ways to consider the color vision:

Way 1: To consider it as a part of a electromagnetic spectrum and from the perspectives of the perception by the human eye and interpretation by the human brain

Way 2: To consider it as a part of richness that can be provided by the color to help perceive the world and how the color as such is created by the prime colors (spectrum) or by mixing colors

Color vision: way one

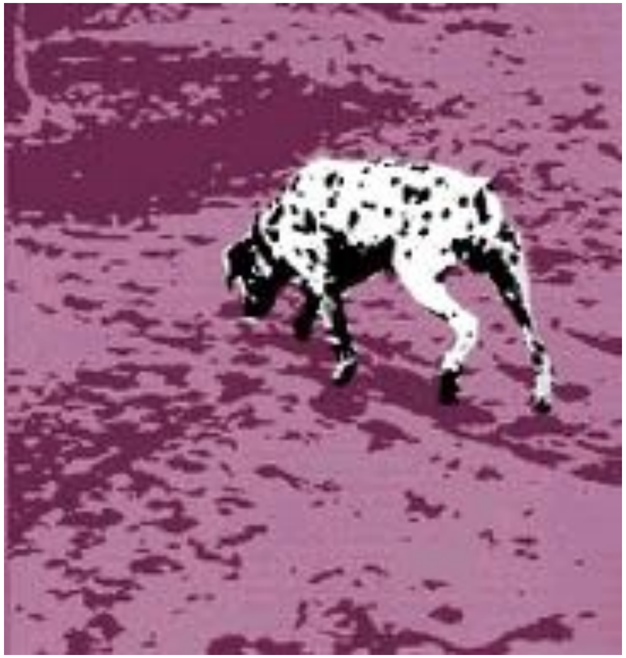
The visible light is a small band where the HVS works.



https://en.wikipedia.org/wiki/Light

Color vision: way two

1. A very basic “help” of color



Addition of the background color emphasizes the presence of objects, i.e., it makes it easier detectable, and help interpret their shapes

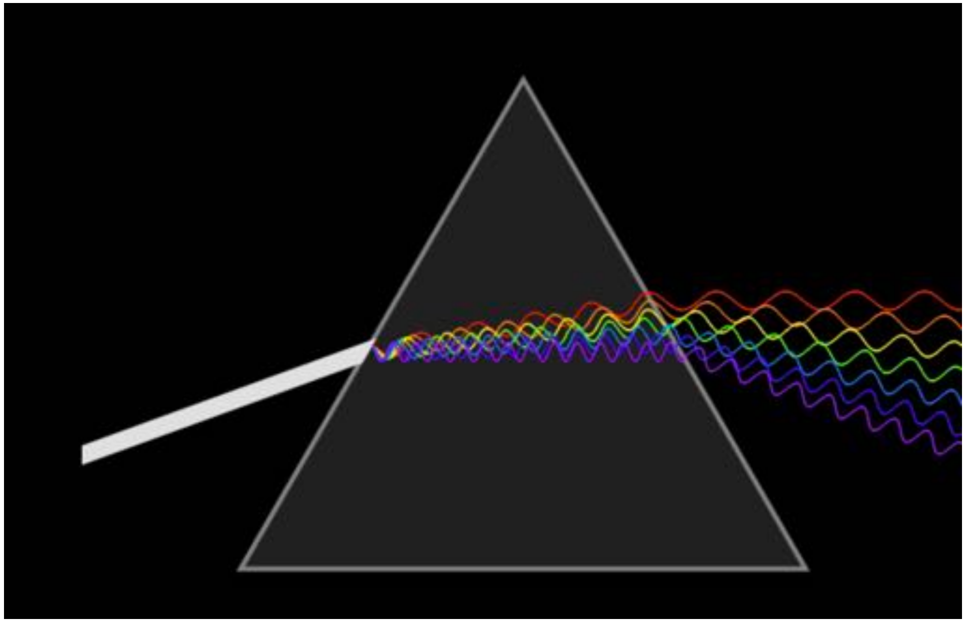
2. How to create color:

- Directly via the colors we have in a rainbow (colors given by nature)
- By mixing different colors (“artificial” colors) −yet not distinguishable by humans!
    - Addition or subtraction

Color vision: interpretation of white light

Q: do you think "white" is a color?

Dispersing light



Newton's prism experiment (1666)

Dispersive prism is used to break up light into its constituent spectral colors because the refractive index depends on frequency.

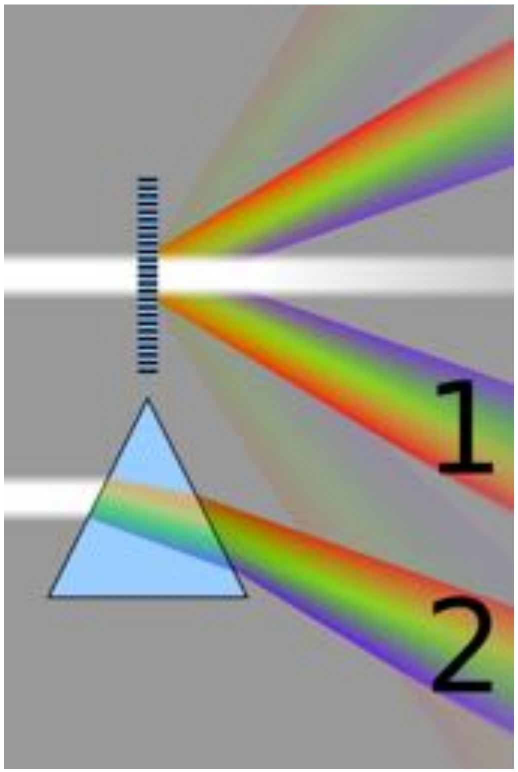
The white light entering the prism is a mixture of different frequencies (wavelength).

The prism treats each frequency differently.

https://en.wikipedia.org/wiki/Prism

Color vision

https://en.wikipedia.org/wiki/Prism



Comparison of the spectra obtained from a diffraction grating by *diffraction* (1), and a prism by *refraction* (2).

Longer wavelengths (red) are diffracted more, but refracted less than shorter wavelengths (violet).

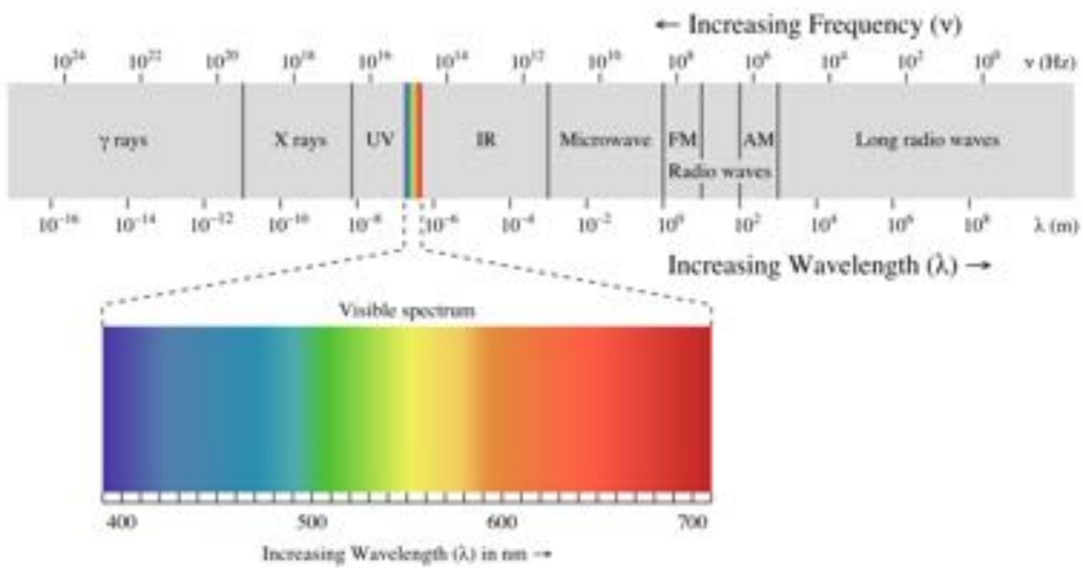
"raw" or prime rainbow colors

Conclusions:

1 white (as a color) contains all rainbow colors

2 **what matters for us is a perception of all these colors together!**

Color vision



Technically speaking, the range of human perception is very narrow compared to the complete electromagnetic spectrum

Color vision

It is difficult to characterize what is perceived by each human.

Objectively, we can distinguish:

Acromatic light (no color):

is characterized by the ***intensity*** (or amount) of light. It varies from black (no light) to white (very bright light). The intermediate level is gray.

Chromatic light (color) (in the visible spectrum 380-700nm)

that is characterized by ***3 quantities***:

1. **Radiance** is a total amount of energy emmited by a source of light (measured in watts (W)).
2. **Liminace** is a measure of the amount of energy that an observer perceives from the light source. We can consider it as filtered by the HVS (lumens) (see previous slides)
3. **Brigtness** is a subjective evaluation what is the source of radiation we talk about **(see all issues discussed above).**

Color vision: rods vs cones

Rods	Cones
Very sensitive to light intensity (night vision) “scotopic” vision	Only sensitive to relatively high intensity light “photopic” vision
Achromatic (one “color”)	Chromatic (3 “colors”)
Distributed over retina	Concentrated in fovea
Outputs of many rods are aggregated to a common nerve	Each cones has its own nerve
Peripheral vision	High visual acuity and spatial resolution
Slow response	Fast response
100 Mio	6-7 Mio

Color vision: cones

3 types of cones responsible for color vision:

	Not exact but	Amount
L-cones – sensitive to **high**-wavelength	"Red"	65%
M-cones – sensitive to **medium**-wavelength	"Green"	33%
S-cones – sensitive to **short**-wavelength	"Blue"	2% *Very sensitive*

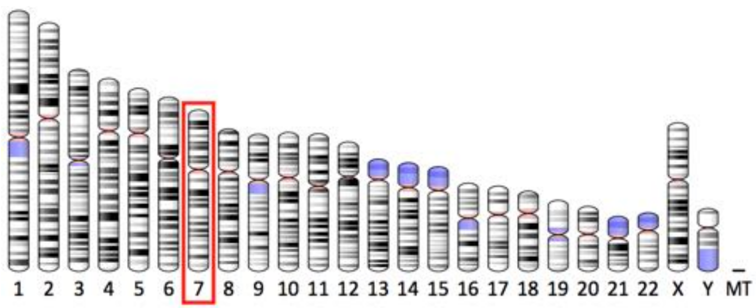
M-cones are quite sensitive and are present in a relatively high proportion. This indicates that the HVS is very sensitive to green.

L- and M-cones are coded in X-chromosome (the cause of color-blondeness).

Color vision: cones

These cones have different photopsins (photoreceptor proteins)

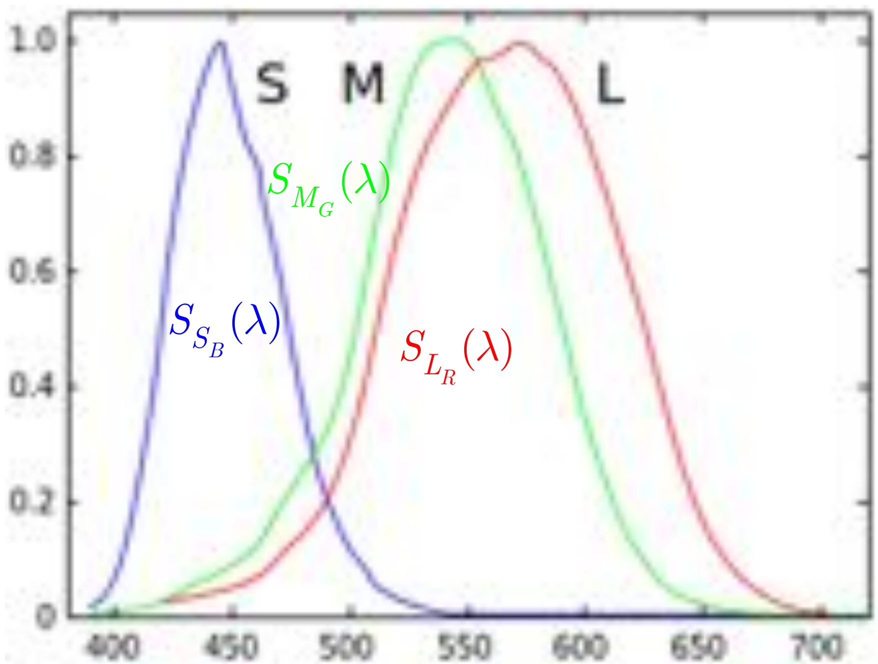
Cone type	Name	Range	Peak wavelength[1][2]
S (OPN1SW) - "tritan", "cyanolabe"	β	400–500 nm	420–440 nm
M (OPN1MW) - "deutan", "chlorolabe"	γ	450–630 nm	534–545 nm
L (OPN1LW) - "protan", "erythrolabe"	ρ	500–700 nm	564–580 nm



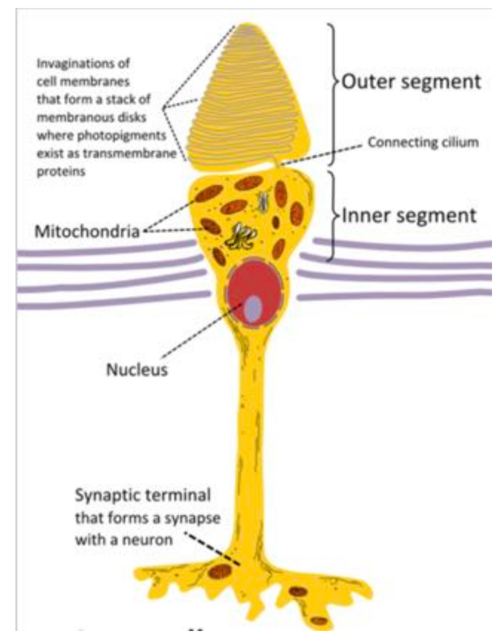
https://en.wikipedia.org/wiki/Photopsin

Because humans usually have three kinds of cones with different photopsins it is called trichromatic vision.

Color vision: cones



Normalized responsivity spectra of human cone cells: S, M and L types



Cone cell structure

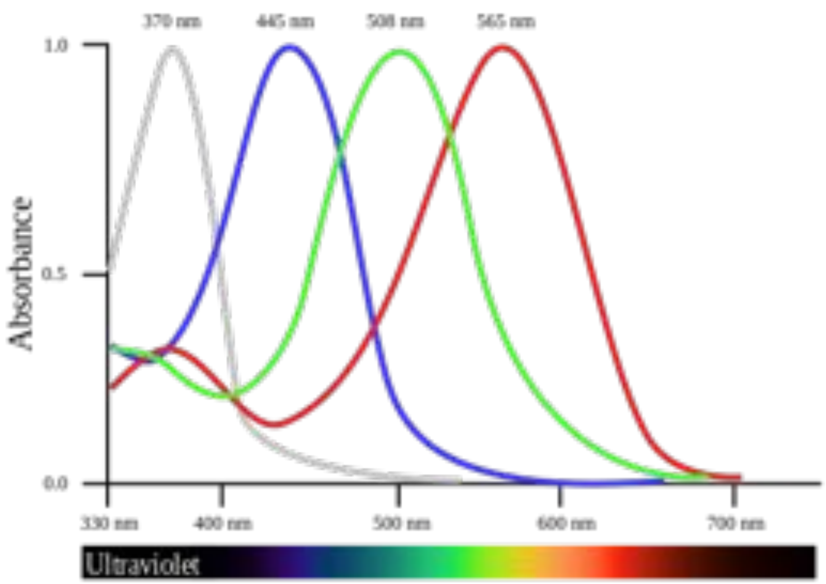
Note: different sources indicate different wavelengths for the maximum sensitivity.

https://en.wikipedia.org/wiki/Cone_cell

Color vision: cones

Remarks:

- **Colorblind** people might not have all types of cones or have some issues with them
- There are reports that some people have **four or more types of cones** that leads to the tetrachromatic vision



https://en.wikipedia.org/wiki/Cone_cell

The four pigments in a bird's cone cells extend the range of color vision into the ultraviolet!

Also different animals have different types of cones:

dauphines – for 1color

Cats and docs – for 2 colors

Some birds - for 4 or even 5 colors….

Color vision: examples of color blindness

https://en.wikipedia.org/wiki/Color_blindness

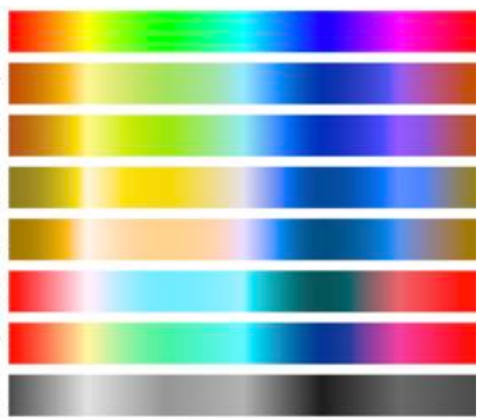
Normal sight

Deuteranopia sight

Tritanopia sight

Monochromacy sight

92%	Normal Vision
2.7%	Deuteranomaly
0.66%	Protanomaly
0.59%	Protanopia
0.56%	Deuteranopia
0.016%	Tritanopia
0.01%	Tritanomaly
<0.0001%	Achromatopsia



Woman XX chromosome

Man XY chromosome

Issues with X chromosome

Color vision: examples of color blindness

https://en.wikipedia.org/wiki/Color_blindness#/media/File:ConeMosaics.jpg

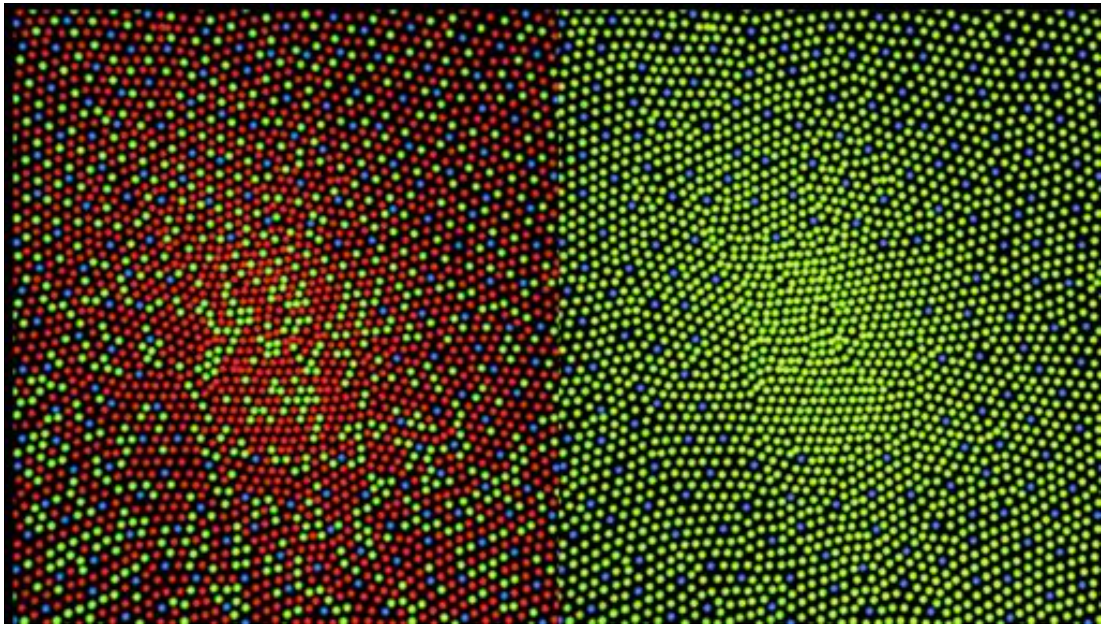
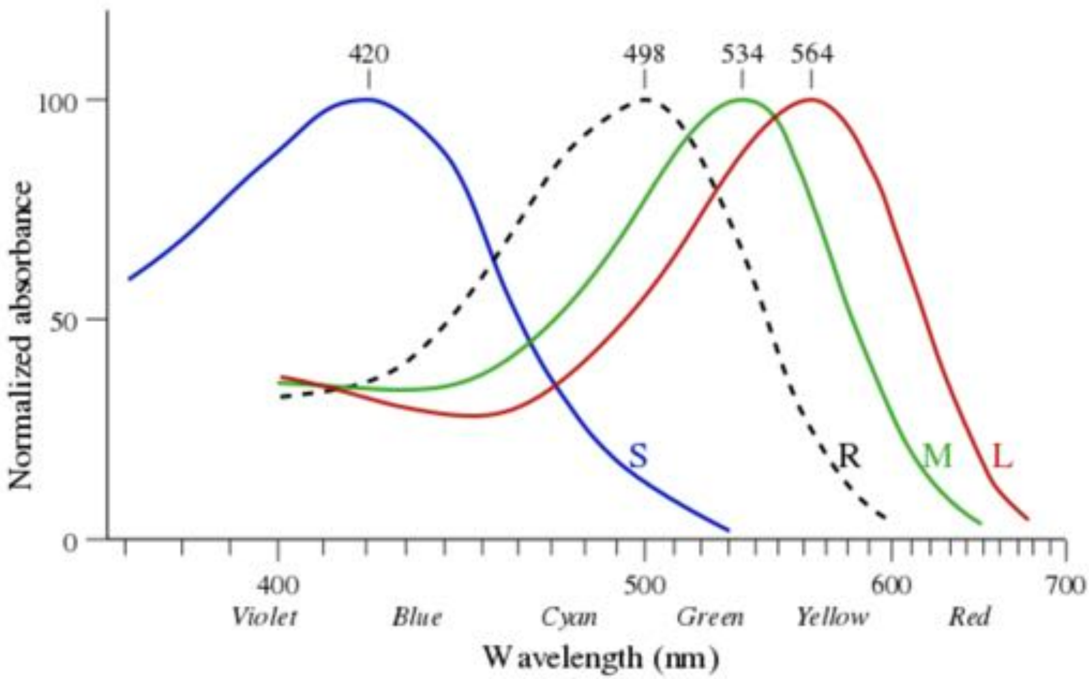


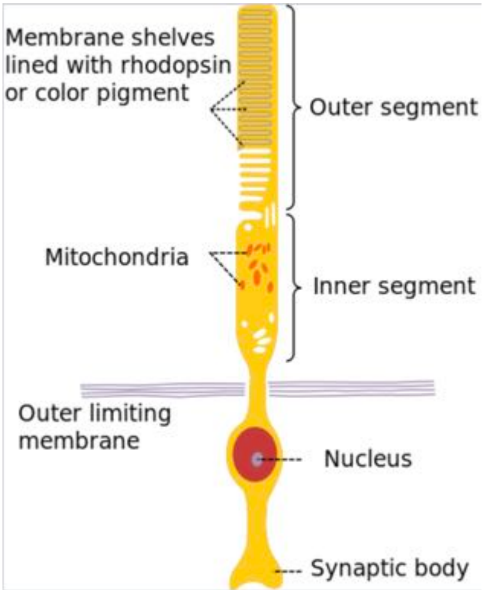
Illustration of the distribution of cone cells in the fovea of a person with normal color vision (left) and a colorblind (protanopic) retina.

Color vision

https://en.wikipedia.org/wiki/Rod_cell



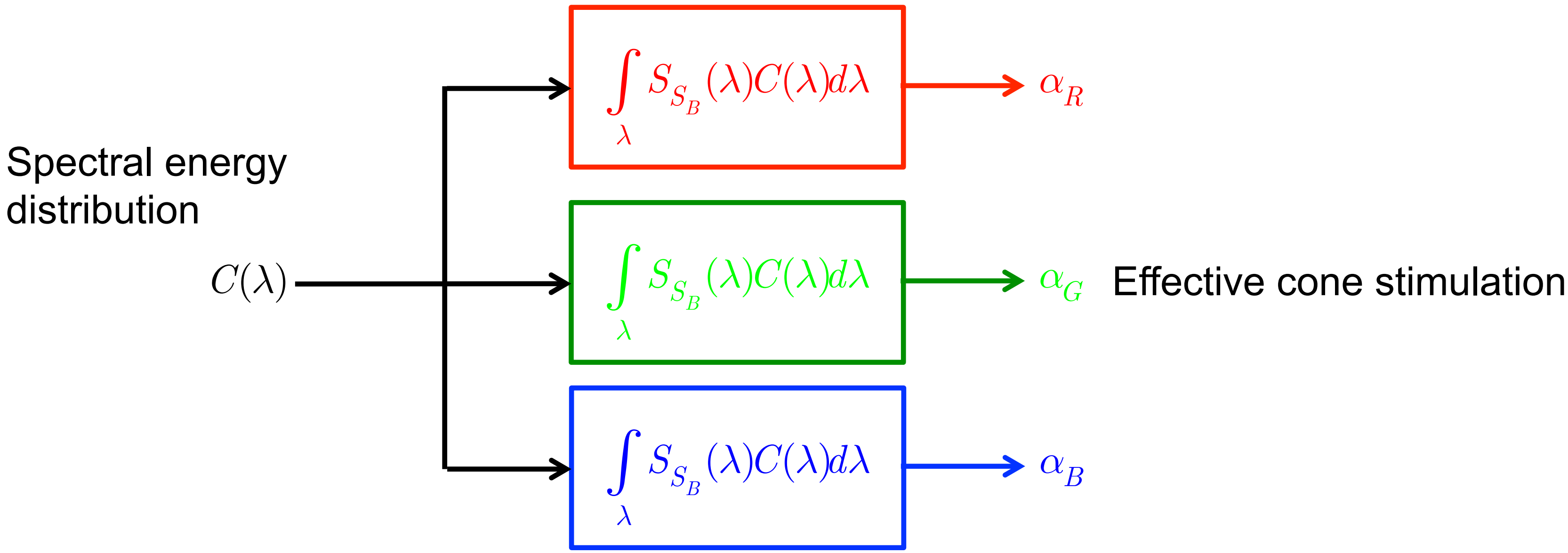
Wavelength responsiveness of short (S), medium (M) and long (L) wavelength cones compared to that of rods (R)



Anatomy of a rod cell

Color vision: 3 color perceptive model

Direct model

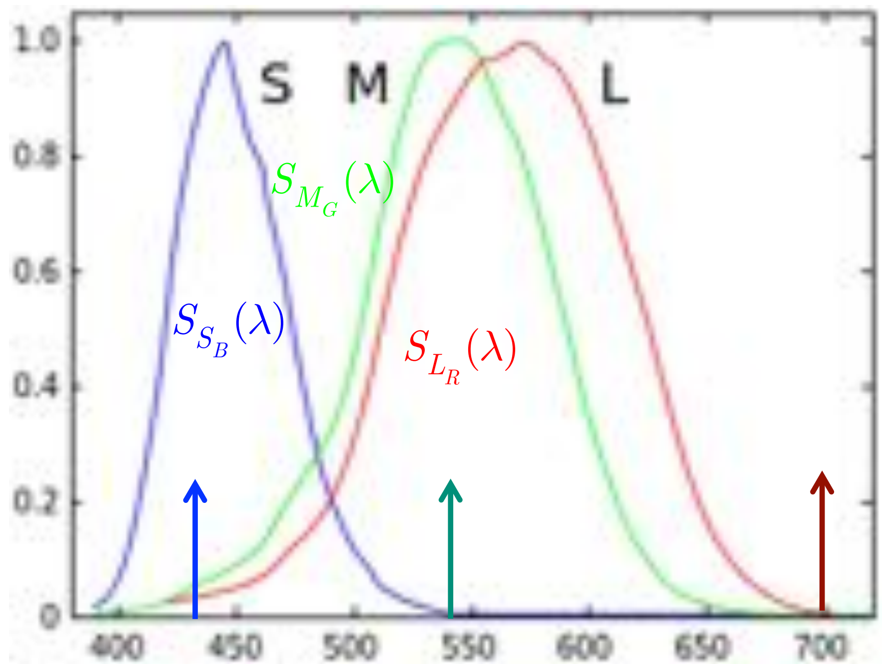


Note:

- Different spectra can map into the same tristimulus values and therefore look identical
- Such a 3 color basis can represent a color

T. Young, 1802, J. Maxwell, 1890

Color vision: color matching in LMS space



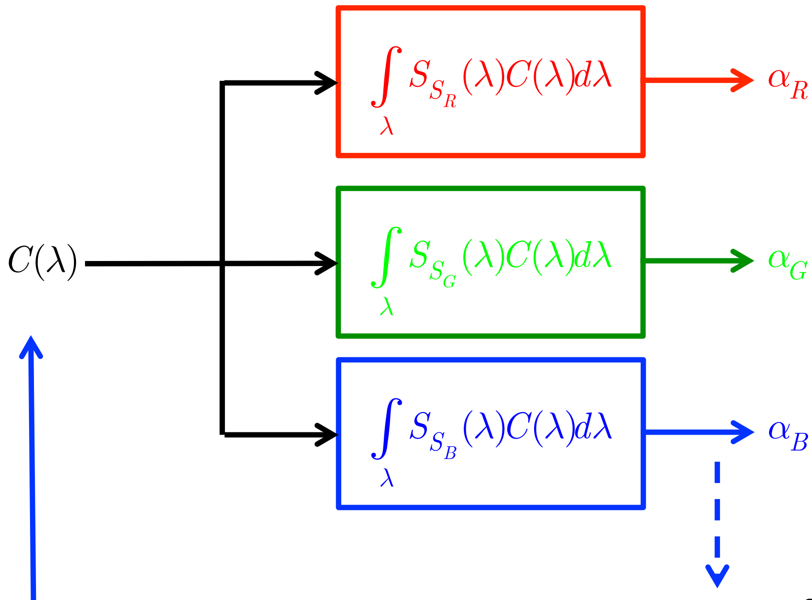
https://en.wikipedia.org/wiki/Cone_cell

- Suppose 3 primary light sources with power spectra $P_k(\lambda), k = 1,2,3$
- Intensity of each color source can be adjusted by factors β_k
- One is interested to choose such that the expected color stimulus $\alpha_R, \alpha_B, \alpha_G$ are obtained

Note:

- one source might be perceived by several color receptors with different sensitivity
- The results are superimposed (fused)
- The power spectra are chosen to be primary colors BUT they might be any!

Color vision: color matching in LMS space



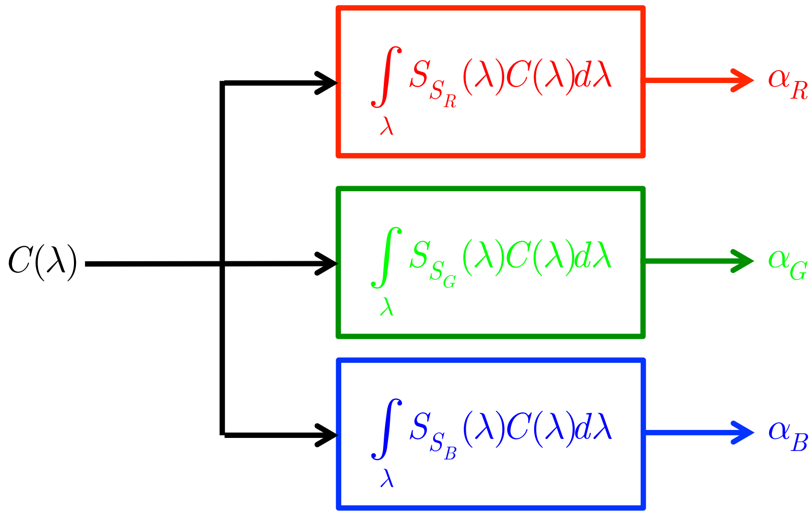
- Suppose 3 primary light sources with power spectra $P_k(\lambda), k = 1,2,3$
- Intensity of each color source can be adjusted by factors β_k
- One is interested to choose such that the expected color stimulus $\alpha_R, \alpha_B, \alpha_G$ are obtained

$$C(\lambda) = \beta_1 P_1(\lambda) + \beta_2 P_2(\lambda) + \beta_3 P_3(\lambda)$$

$$\begin{aligned}\alpha_k &= \int_\lambda S_k(\lambda)C(\lambda)d\lambda \\ &= \int_\lambda S_k(\lambda)\left[\beta_1 P_1(\lambda) + \beta_2 P_2(\lambda) + \beta_3 P_3(\lambda)\right]d\lambda \\ &= \underbrace{\beta_1 \int_\lambda S_k(\lambda)P_1(\lambda)d\lambda + \beta_2 \int_\lambda S_k(\lambda)P_2(\lambda)d\lambda + \beta_3 \int_\lambda S_k(\lambda)P_3(\lambda)d\lambda}_{Linear}\end{aligned}$$

Color matching is linear! $\leftarrow$

Color vision: color matching in LMS space



LMS space is defined by a vector of

$$\begin{bmatrix} \alpha_R \\ \alpha_B \\ \alpha_G \end{bmatrix} \quad \text{values}$$

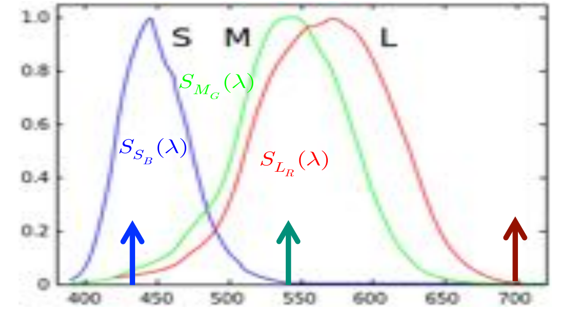
- It is possible to associate a color with the LMS color space.
- **Practical issue**: it is very difficult to measure the response of the cones in the HVS to particular light spectrum $C(\lambda)$ (we shown for a simple one)
- Therefore, **in practice** we proceed with not measuring the objective output of cones but by asking:
    - How close shown true monochromatic color corresponds to a color obtained from mixing some reference colors in some proportion?
    - The reference or primary colors are chosen from technical point of view

Color vision: towards standardization

- By definition, there is nothing fixed in the “color world”.
- That is why there have been many standardization efforts to use a common basis for the technical systems.
- However, it is decided to choose 3 basic colors due to the LMS absorption of cones the human eye sees colors as variable combinations of the so called **primary colors** R, G and B.

- **Standardization**: the International Commission on Illumination (CIE) designed in **1931** the following wavelength values to the 3 primary colors:

$$\lambda_B = 435.8\ nm, \lambda_G = 546.1\ nm, \lambda_R = 700\ nm$$



- Remark: it was set before the results about the sensitivity of cones were obtained in 1965.

Color vision: towards standardization

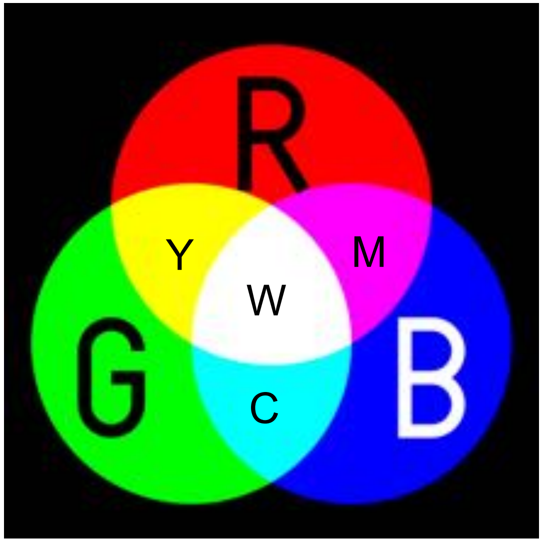
Remarks:

- *The CIE is only approximate and it does not mean that one can generate all colors from 3 primary colors.*
    - “Primary colors” is a misleading term.
    - The CIE assumes the fixed 3 colors (fixed wavelength values). In reality to produce all colors, the wavelengths of these “primary” colors should be varying.

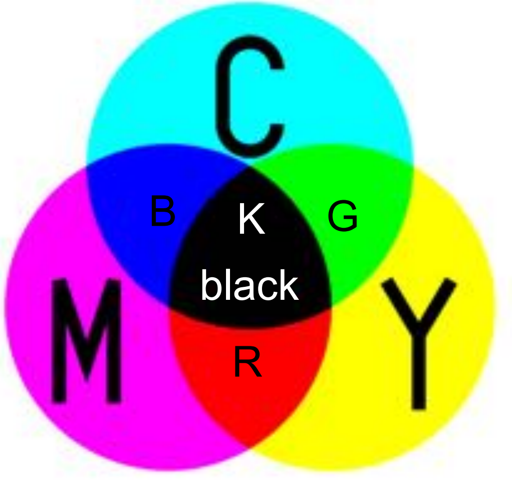
CIE 1931 is a Color Matching System. Color matching *does not attempt to describe how colors appear to humans*, color matching tells us how to numerically specify a measured color, and then later accurately reproduce that measured color (e.g. in print or digital displays).

Color vision: color mixing

Additive color mixing



Subtractive color mixing



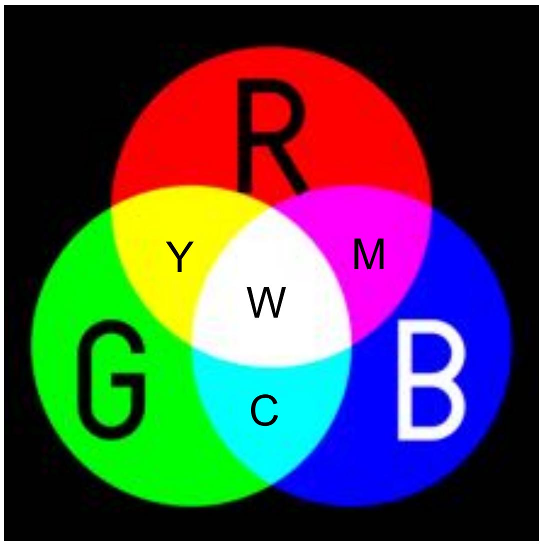
R+G+B=W

RGB are primary colors (light)

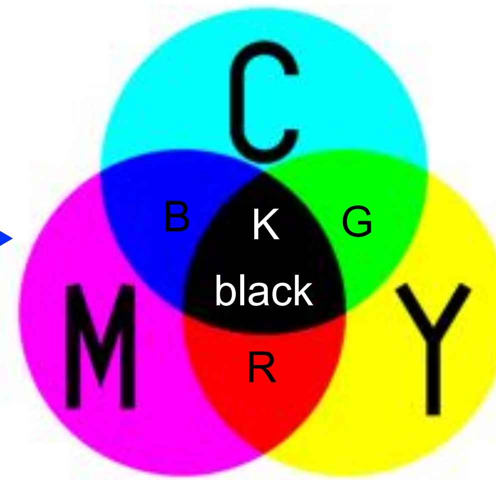
CMY(K) are primary colors (inks)

Color vision: color mixing

Additive color mixing



Subtractive color mixing

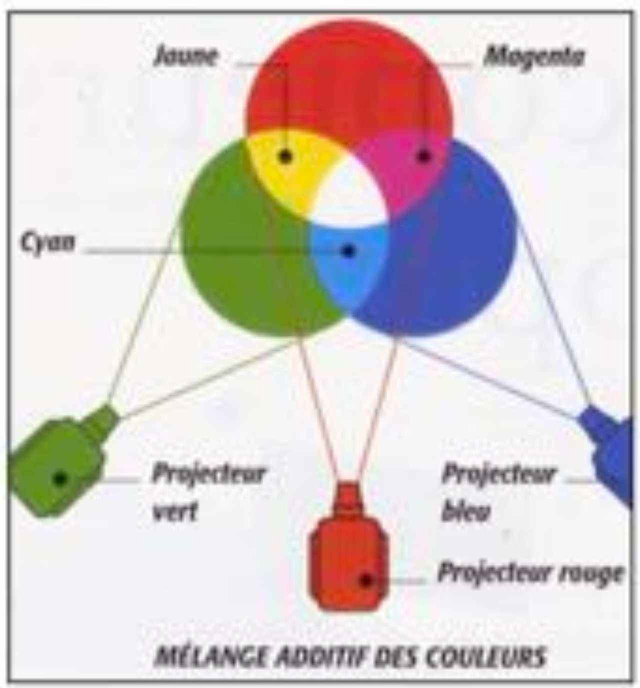


- RGB are **primary light colors** (light, laser)
- Cyan (C), Magenta (M) and Yellow (Y) are **secondary colors** are obtained by adding primary colors

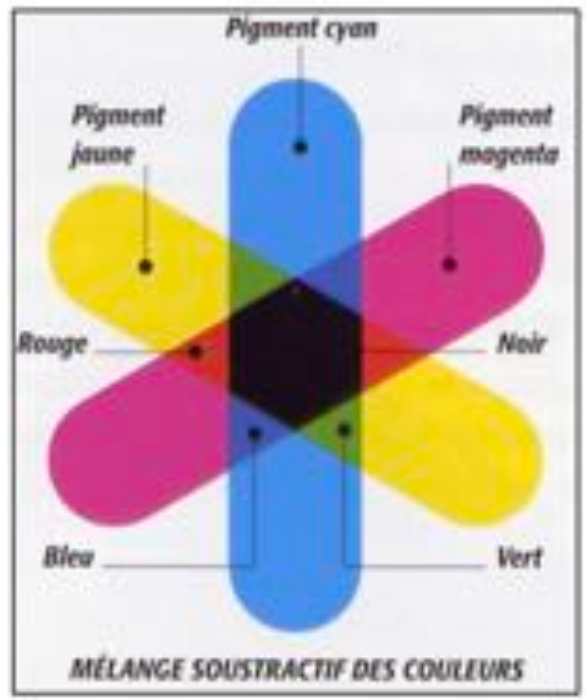
- CMY are **primary pigment colors** (inks/pigments)
- Primary color of ink subtracts or absorbs a primary "opposite" color of light and reflects or transfers the other two colors.

Color vision: color mixing

Additive color mixing



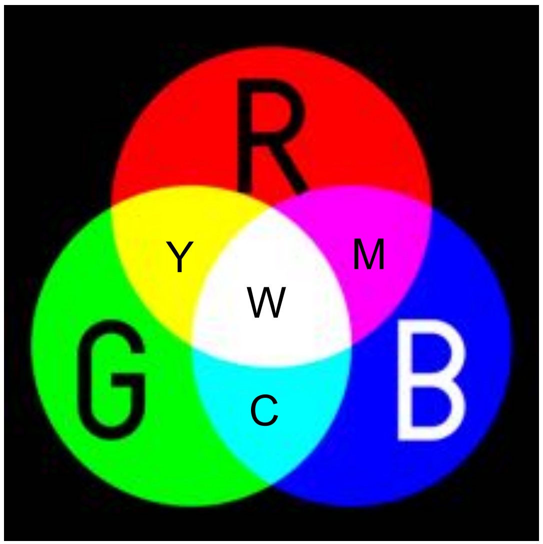
Subtractive color mixing



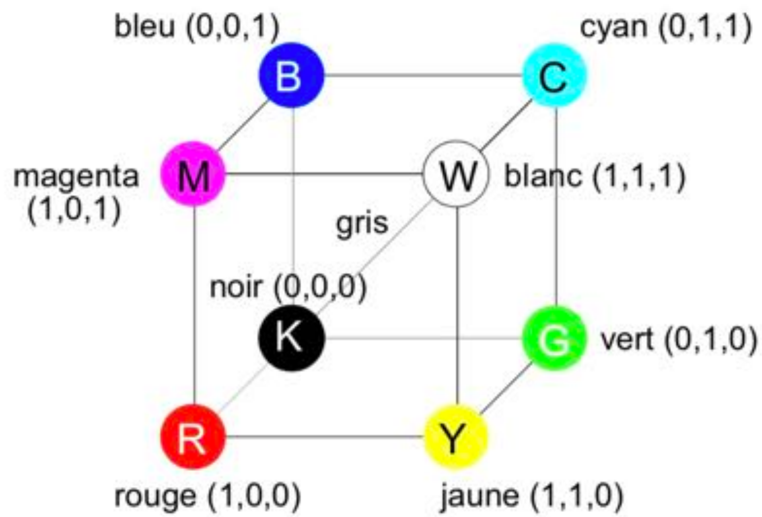
M. Wright, Comment tout march, Edition Mondo, CH, 2001

Color vision: color mixing

Additive color mixing



Encoding

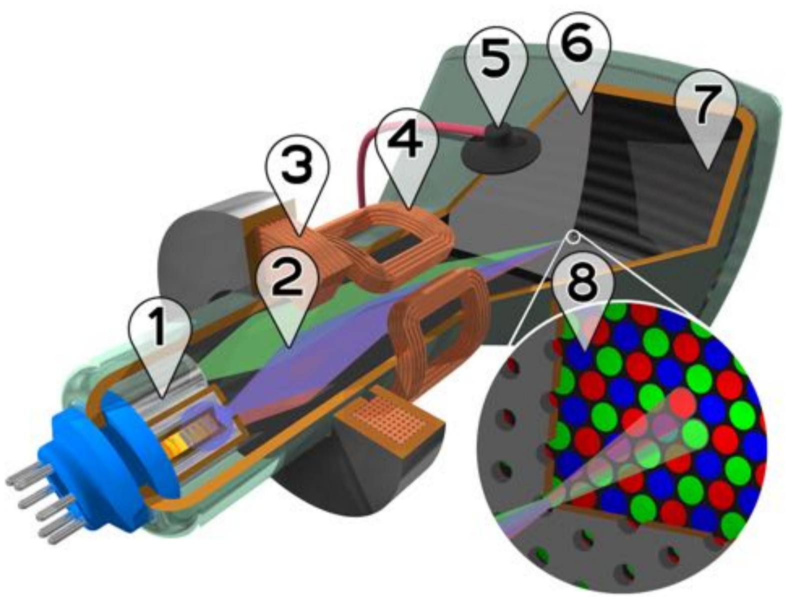


T. Pun

Color vision: color mixing –fundamentals of TV

All TV systems represent examples of additive color mixing

CRT (cathode ray tube)



https://en.wikipedia.org/wiki/Cathode_ray_tube

Cutaway rendering of a color CRT:

1. Three electron emitters (for red, green, and blue phosphor dots)

2. Electron beams

3. Focusing coils

4. Deflection coils

5. Connection for final anodes (referred to as the "ultor" in some receiving tube manuals)

6. Mask for separating beams for red, green, and blue part of displayed image

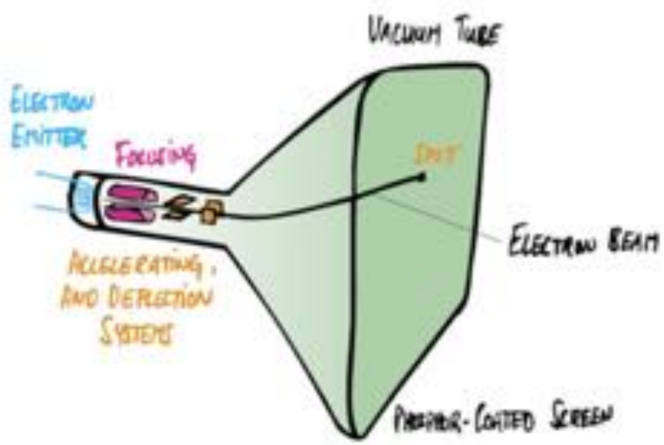
7. Phosphor layer (screen)with red, green, and blue zones

8. Close-up of the phosphor-coated inner side of the screen

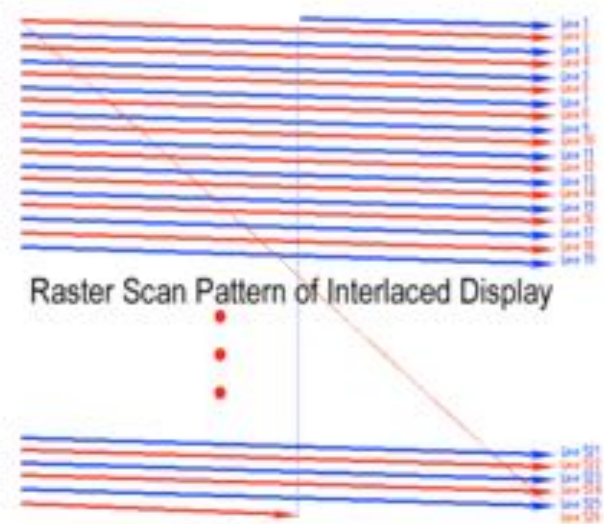
Color vision: color mixing –fundamentals of TV

All TV systems represent examples of additive color mixing

CRT (cathode ray tube)



Cathode Ray Tube



Raster Scan
(modulate intensity)

https://cs184.eecs.berkeley.edu/uploads/lectures/02_sampling/02_sampling_slides.pdf

Color vision: color mixing –vfundamentals of TV

More recent systems:

- **LCD** – the same 3 color components; the properties of polarized light to block or pass light through the LCD screen
- **OLED** – organic light-emitting diode (can be printed)
- **TFT** – thin-film transistor; active matrix display technology
- **Plasma** – pixels are tiny gas cells coated with phosphor to produce 3 primary colors
- **Quantum dots** – small semiconductor particles (nanometers) smaller that those of LED. Similar to all previous one, they omit the light of specific frequency, if the electricity or light is applied to them.

Color vision: “characteristics“ of color

Three characteristics are used to distinguish one color from another:

- Brightness
- Hue
- Saturation

Brightness corresponds to the achromatic notion of *intensity*

Hue is associated with the *dominant wavelength in a mixture* of light waves as perceived by an observer (Red, orange, yellow object = Hue)

Saturation refers to the *relative purity* or the amount of white light mixed with a hue:

- the pure spectrum colors are fully saturated
- colors like pink (red and white) are less saturated = “how much white light is added to the pure color”

Color vision: “characteristics“ of color

- **Hue** and **saturation** taken together are called **chromaticity**
- Therefore, a color might be characterized by its brightness and chromaticity

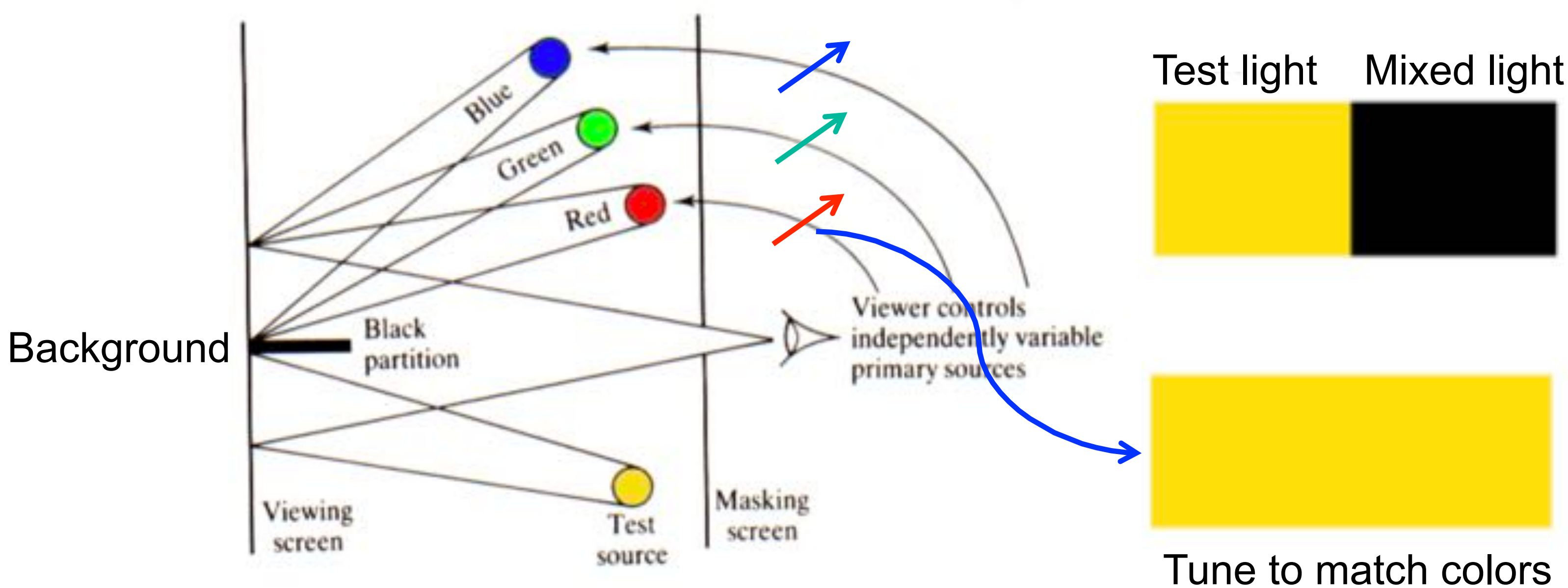
The amounts of red, green and blue needed to form any particular value are called **tristimulus values** and are denoted as X, Y and Z

“tri”=three “chroma”=color

Color vision: color matching experiment

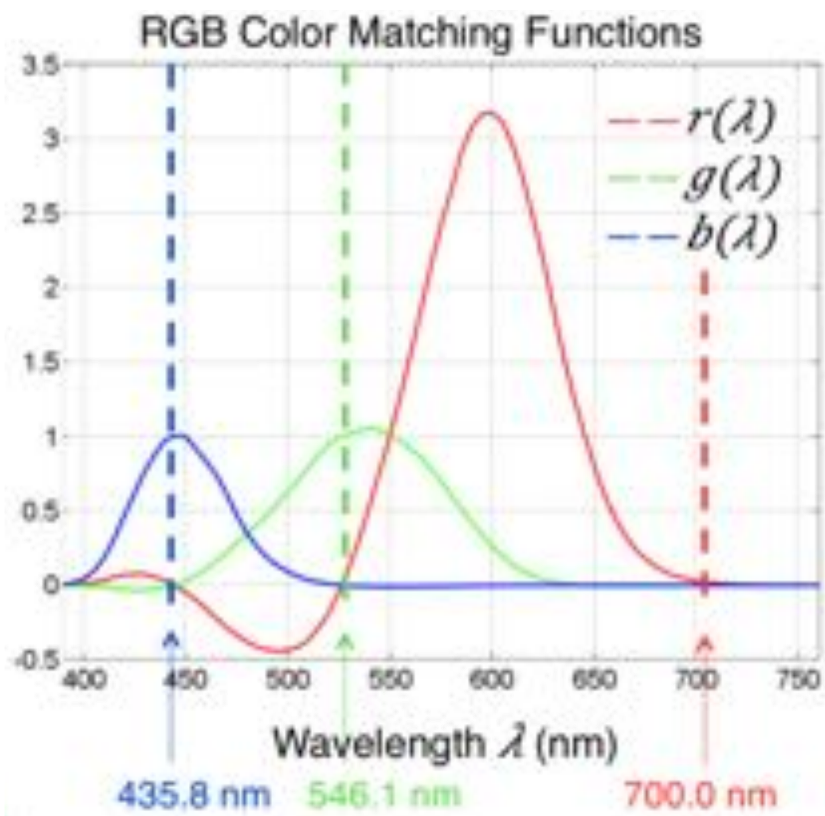
- Wright and Guild in 20-30th performed experiments how to produce various colors by mixing 3 basic colors to answer the question:

  How close shown true monochromatic color corresponds to a color obtained from mixing some reference colors in some proportion?



Color vision: color matching experiment

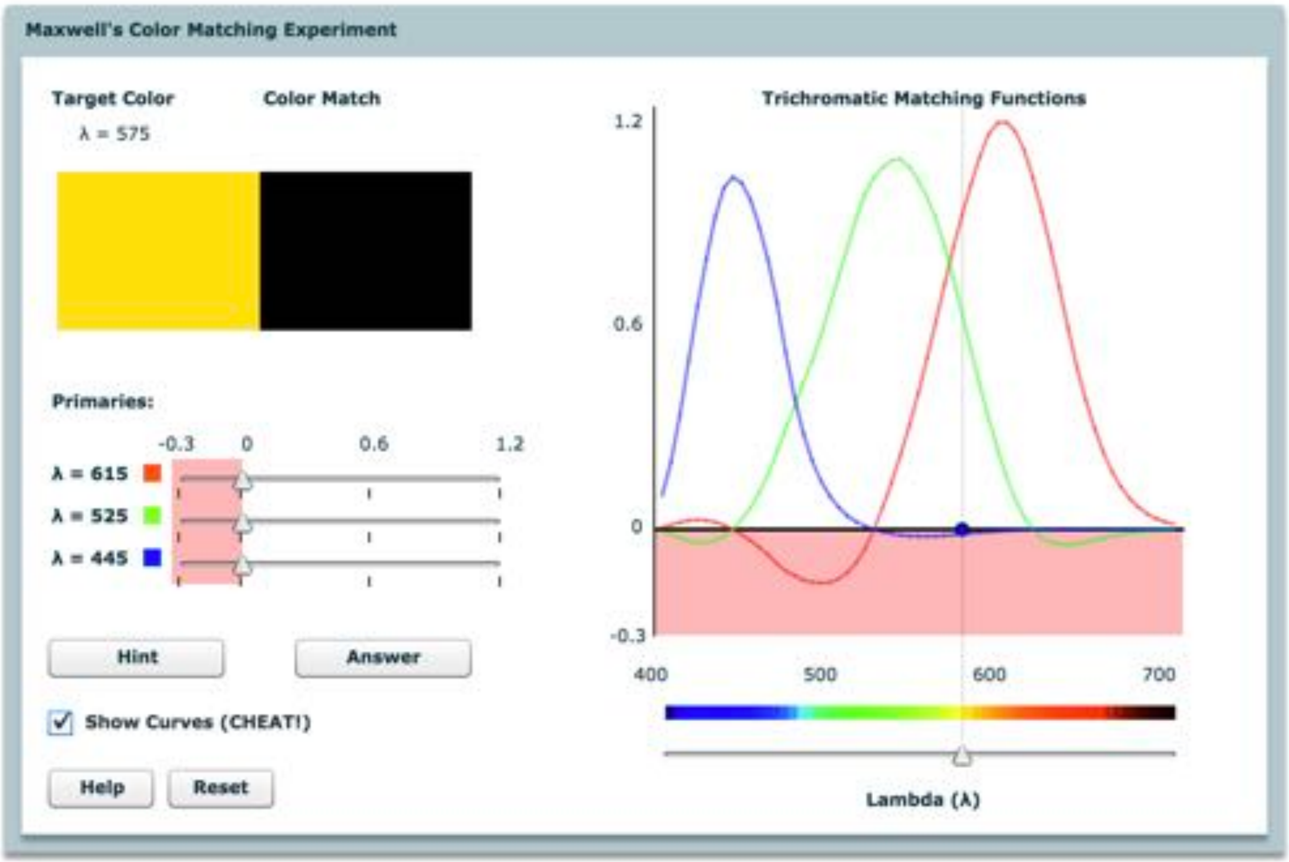
- Based on these experiments, Wright and Guild built matching curves for their 3 color system



The **CIE-RGB** primaries

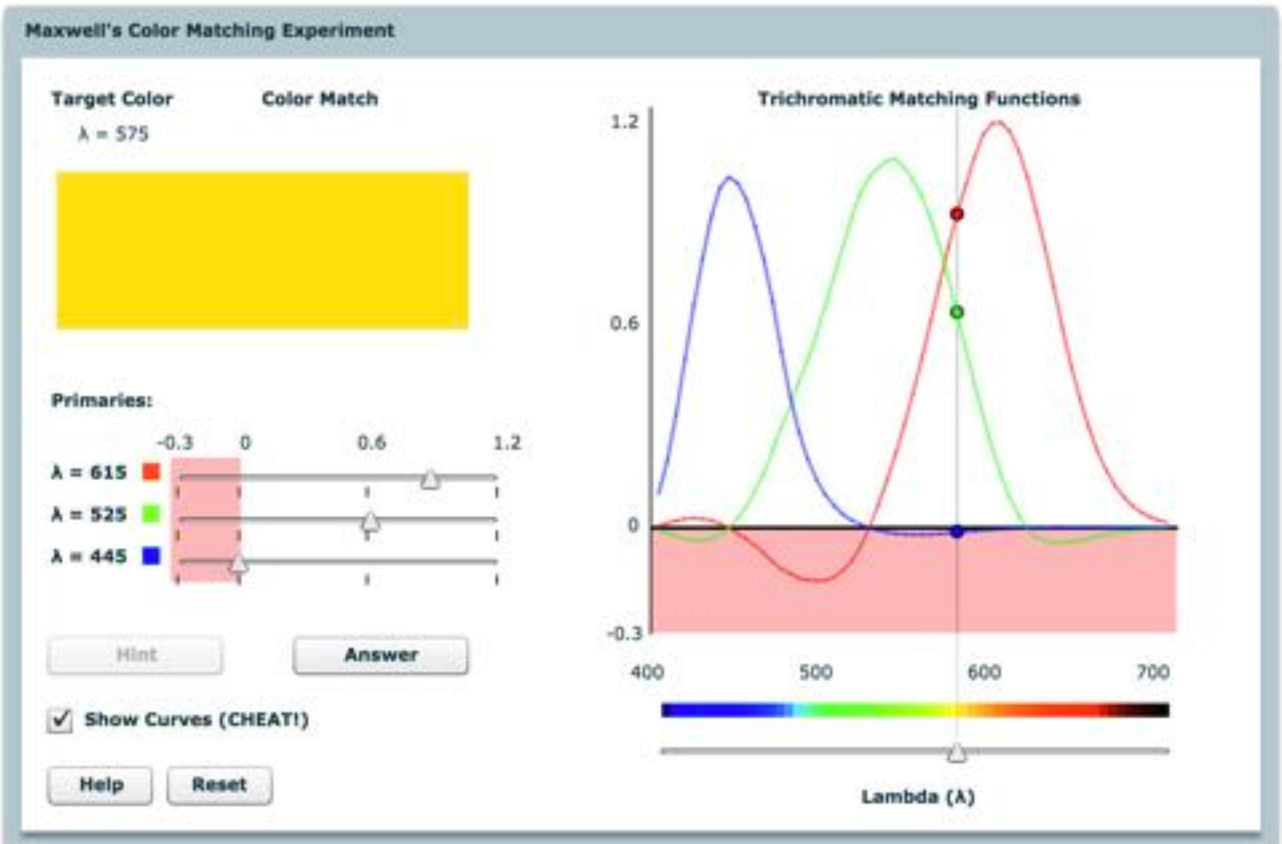
Color vision: color matching experiment

Experiment with “virtual colors” and fixed prime colors



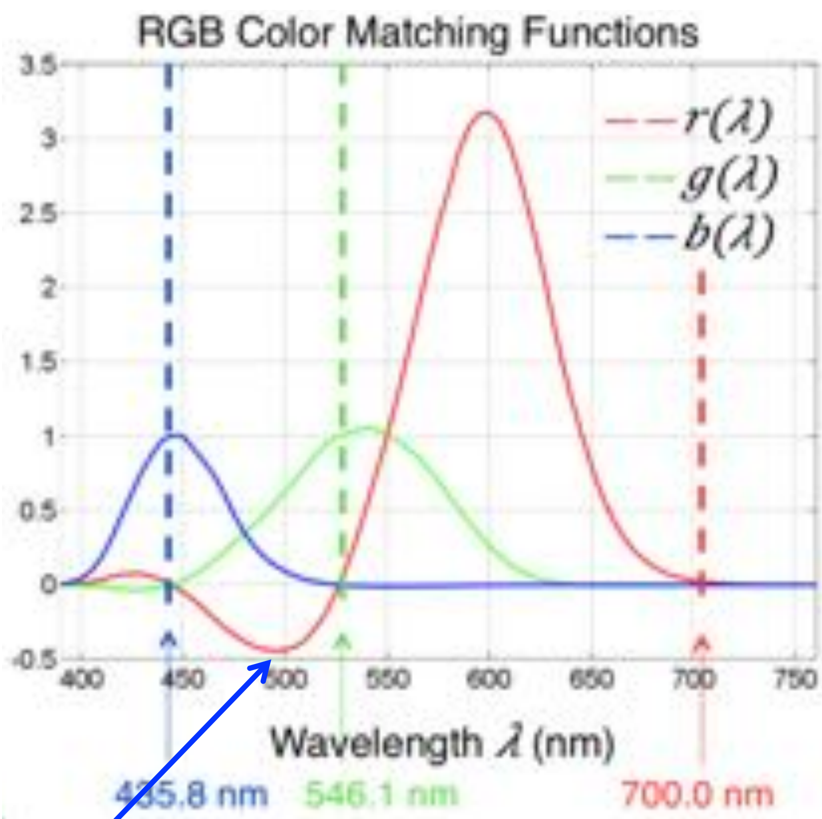
http://graphics.stanford.edu/courses/cs178-13/applets/colormatching.html

Color vision: color matching experiment



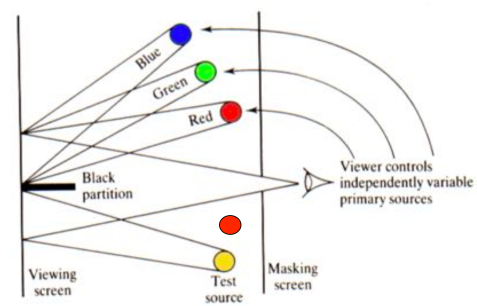
http://graphics.stanford.edu/courses/cs178-13/applets/colormatching.html

Color vision: color matching experiment



Practical issue:

- Some colors were not achievable from the 3 primary (fixed) colors.
- This means that the test subject was unable to achieve a match using positive values of the primary lights.
- To address this, some of the primary lights were mixed on the opposite side of the screen with the test light, until a color match was able to be made.

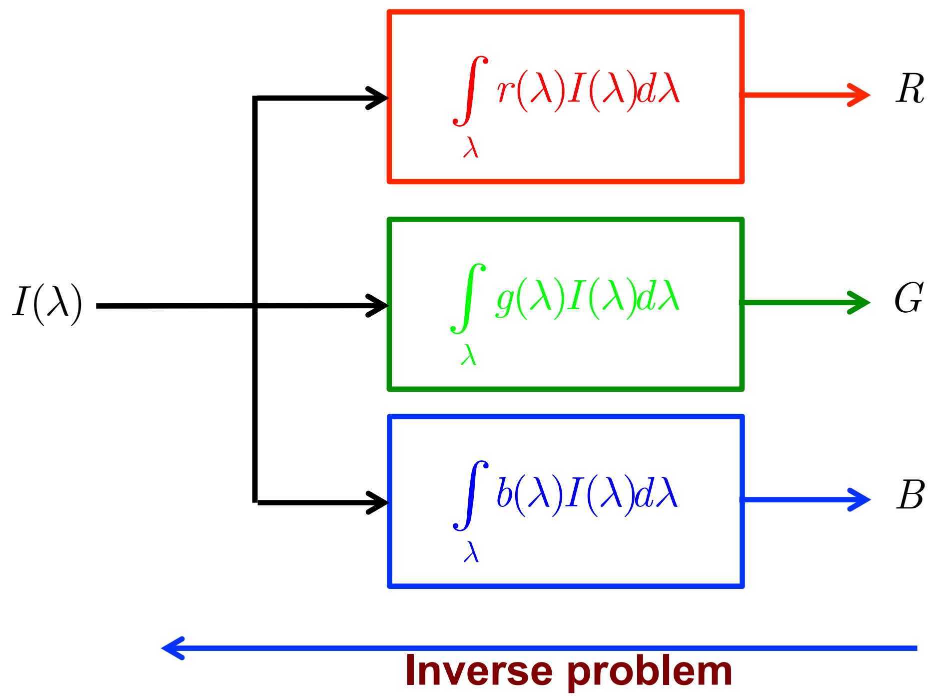


Since the system is additive, it was equivalent to "negative values"

Color vision: color matching experiment

Inverse problem:

- Given a spectral distribution for a particular target color $I(\lambda)$, these matching curves make it possible to recover the R, G and B intensities that should be used to reproduce the target color.



Color vision: towards standartization

The CIE standardization motivation:

- To have a technical system that:
  - is easy to operate :
    - device oriented (easy to generate)
    - easy to compute in terms of primary colors
    - easy to visualize (in 2D but not in 3D)
  - corresponds to the HVS (LMS)

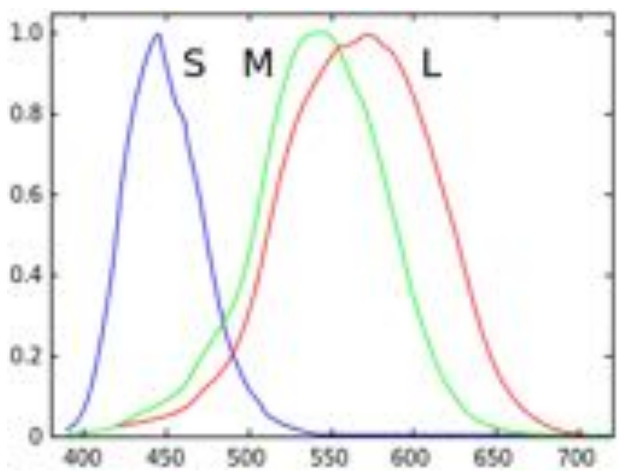
- Thus it is assumed that luminance (denoted as Y) roughly corresponds to the spectral sensitive of M cones (green curve).

Color vision: back to “characteristics“ of color

The meaning of X, Y and Z and link to the cones?

Humans tend to judge the relative luminance (brightness) of different colors to be **more brighter for green color** than for red and blue light of equal power.

Thus it is assumed that luminance roughly corresponds to the spectral sensitive of M cones (green curve).



Color vision: “characteristics“ of color

The meaning of X, Y and Z and link to the cones?

The CIE model capitalizes on this fact **by defining *Y* as luminance (“being green”)**.

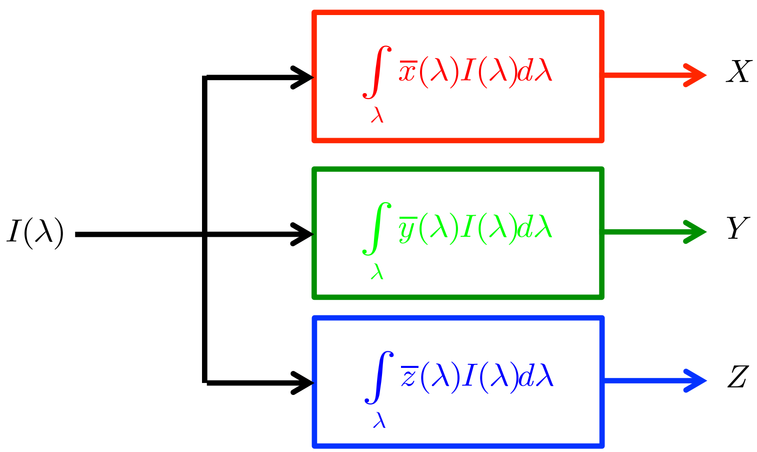
Z is quasi-equal to blue stimulation, or the S cone response, and *X* is red (nonnegative). The XYZ tristimulus values are thus analogous to, but different from, the LMS cone responses of the human eye.

Defining *Y* as luminance has the useful result that for any given *Y* value, the XZ plane will contain all possible chromaticities at that luminance.

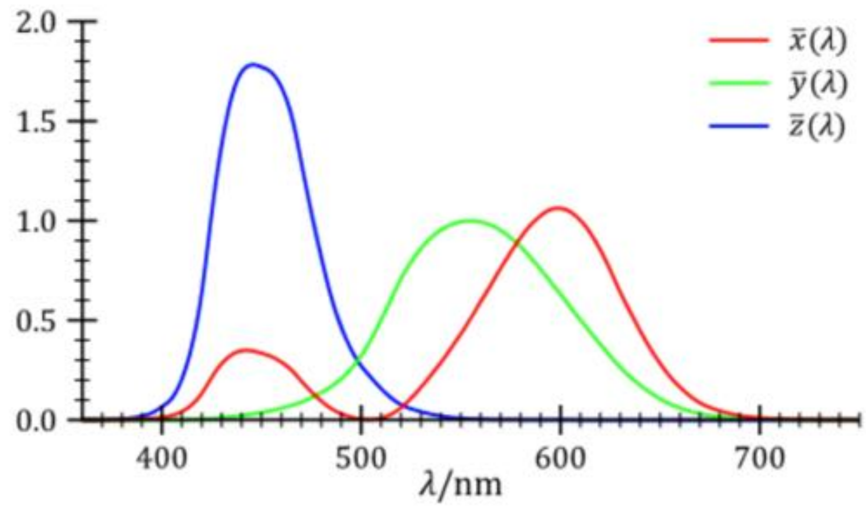
Color vision: the CIE-XYZ

Conversion from RGB to XYZ

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



XYZ Color Matching Functions



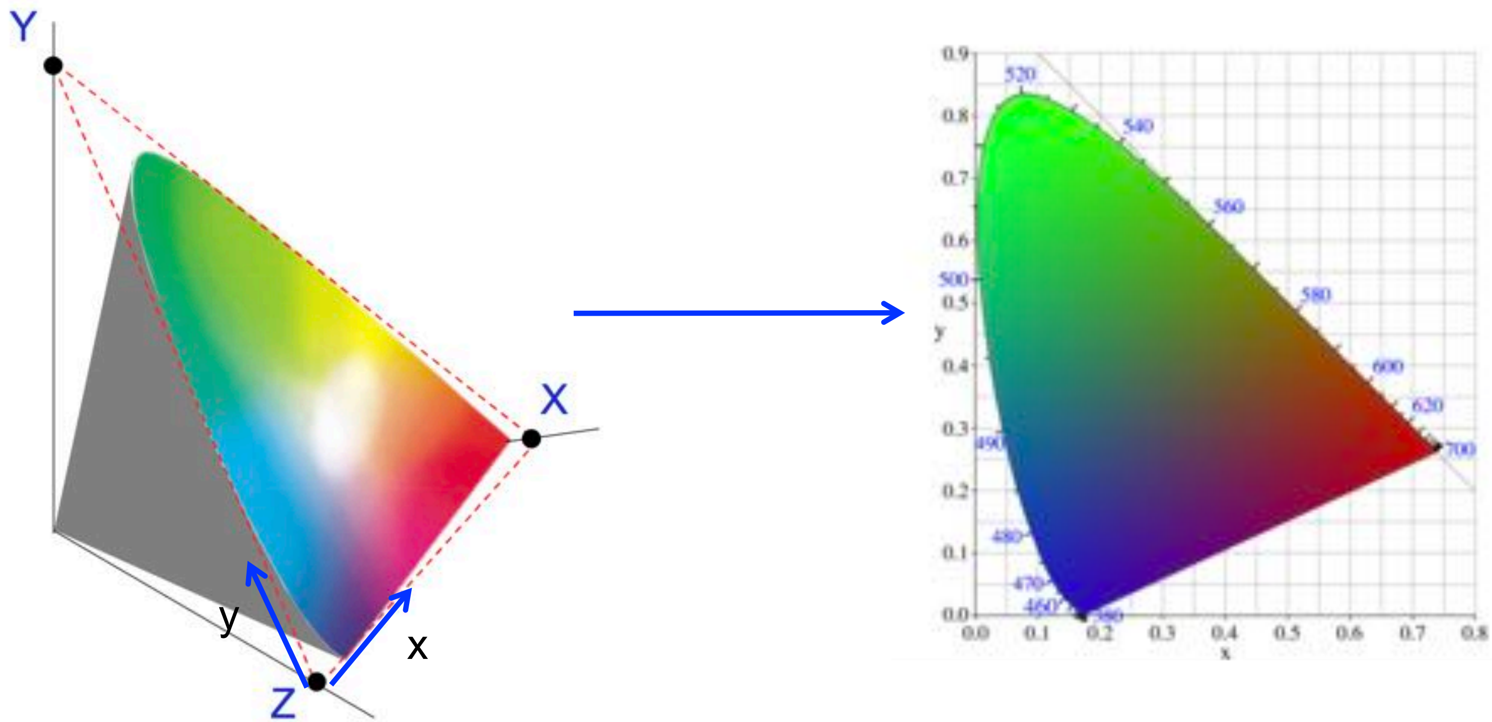
Advantages over the CIE-RGB:

- More interpretable as a link to LMS
- Matching functions are positive

Color vision: the CIE-XYZ

Practical issue:

The visualization is difficult in 3D and one prefers to have 2D



Color vision: “characteristics“ of color

Any color is defined by **its trichromatic coefficients**:

Normalized [0,1]

$$x = \frac{X}{X+Y+Z} \quad \text{- red}$$

$$y = \frac{Y}{X+Y+Z} \quad \text{- green}$$

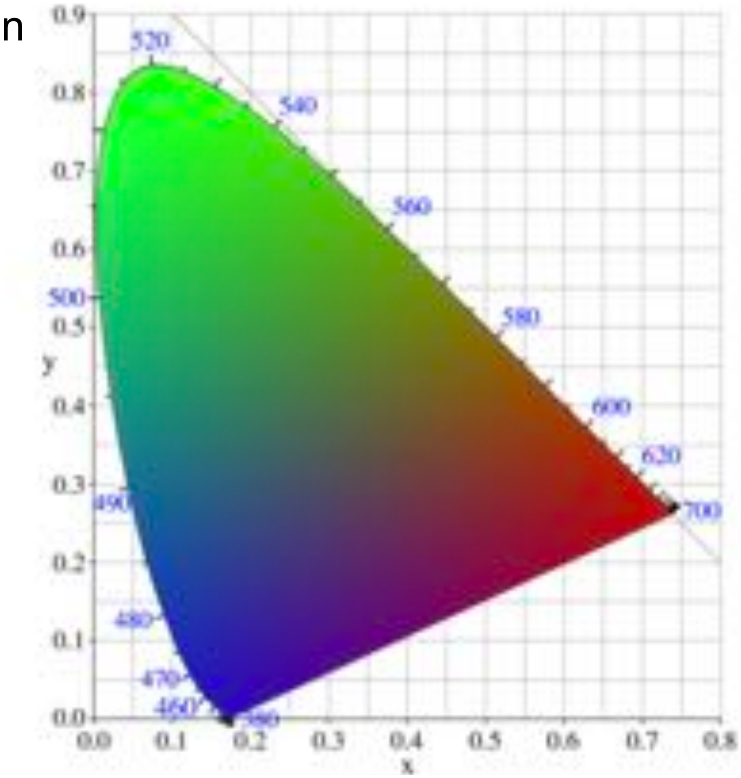
$$z = \frac{Z}{X+Y+Z} = 1-(x+y) \quad \text{- blue}$$

$$x+y+z=1$$

z can be always computed from x and y.

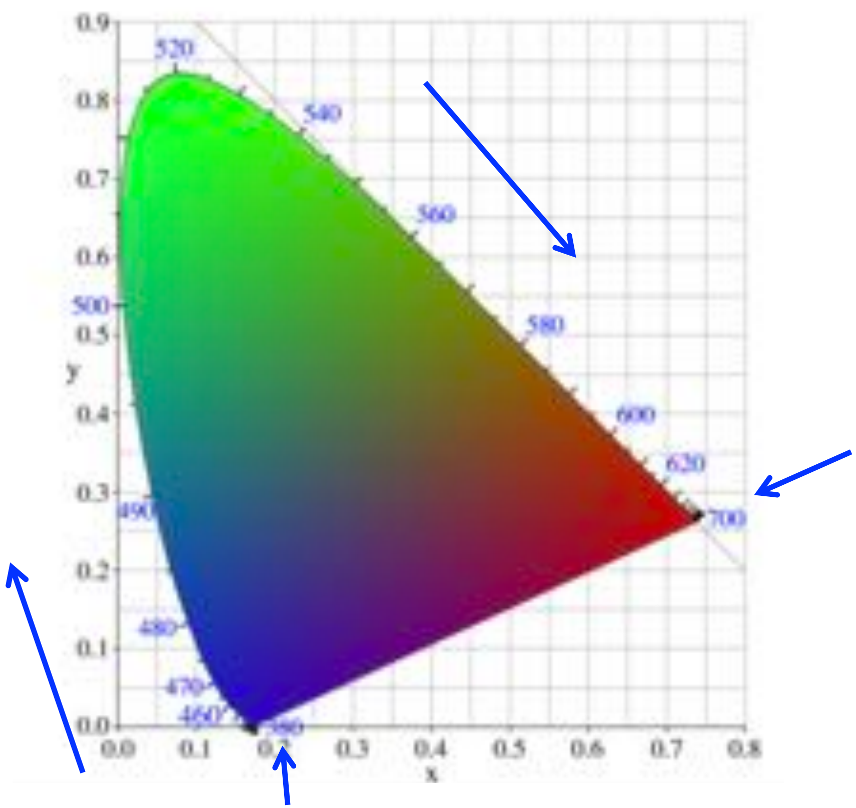
Therefore, it sufficient to use x-y 2D plane.

green



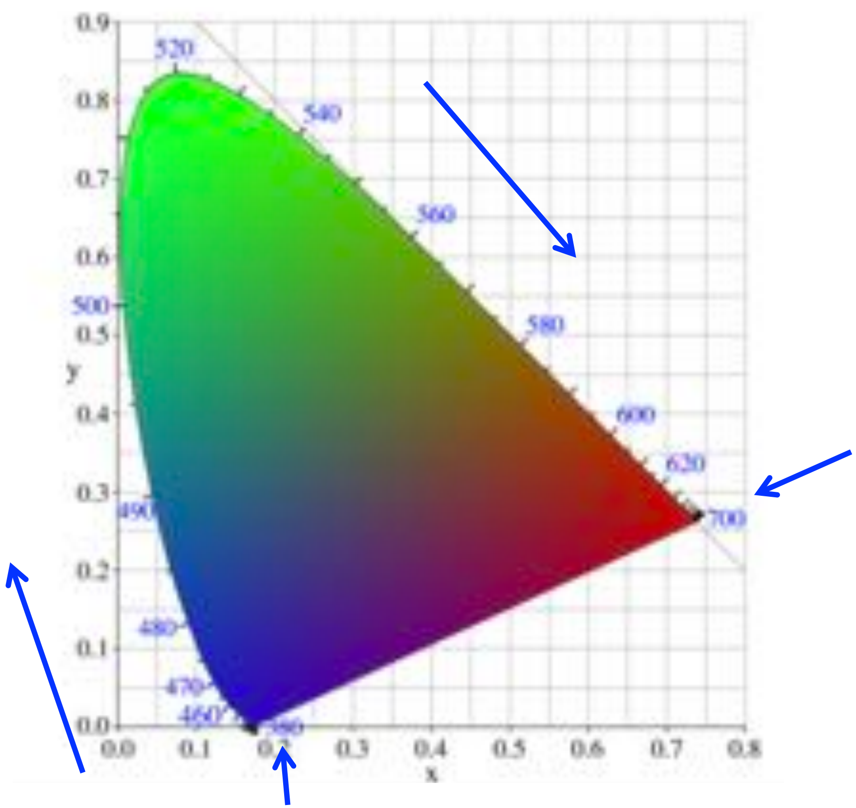
red

Color vision: the CIE chromaticity diagram



All wavelength values of pure colors (spectrum colors) are shown on the boundary line starting from 380 nm to 780 nm.

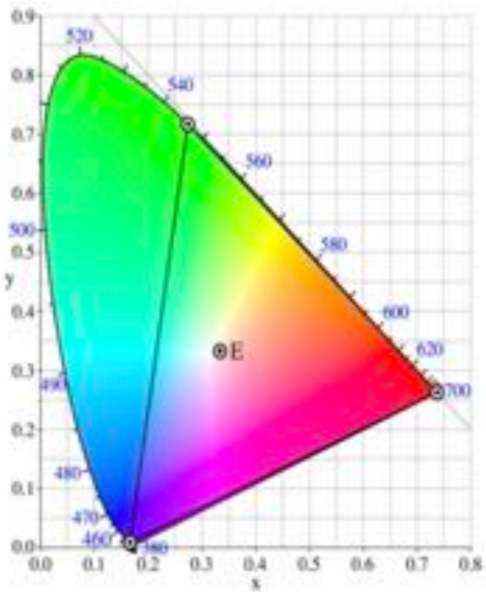
Color vision: the CIE chromaticity diagram

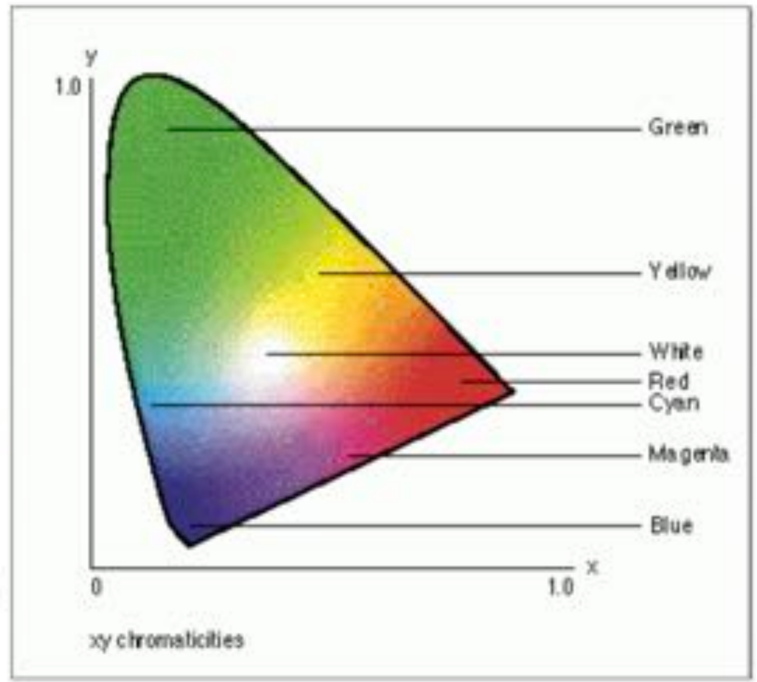


All wavelength values of pure colors (spectrum colors) are shown on the boundary line starting from 380 nm to 780 nm.

Color vision: the CIE chromaticity diagram

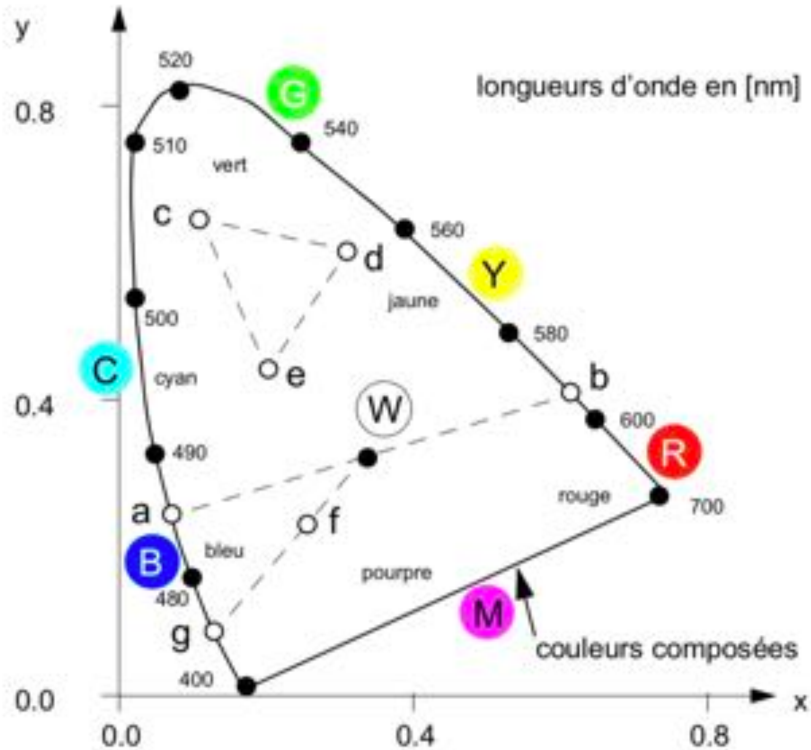
Diagramme CIE:





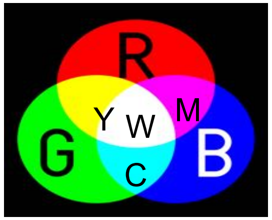
- Inside the diagram we observe a mixture of pure colors.
- The central point E corresponds to white and represents an equilibrium of 3 primary colors (W).

Color vision: the CIE chromaticity diagram

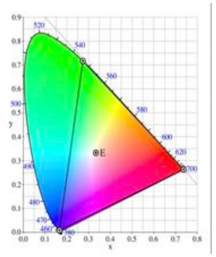


T. Pun

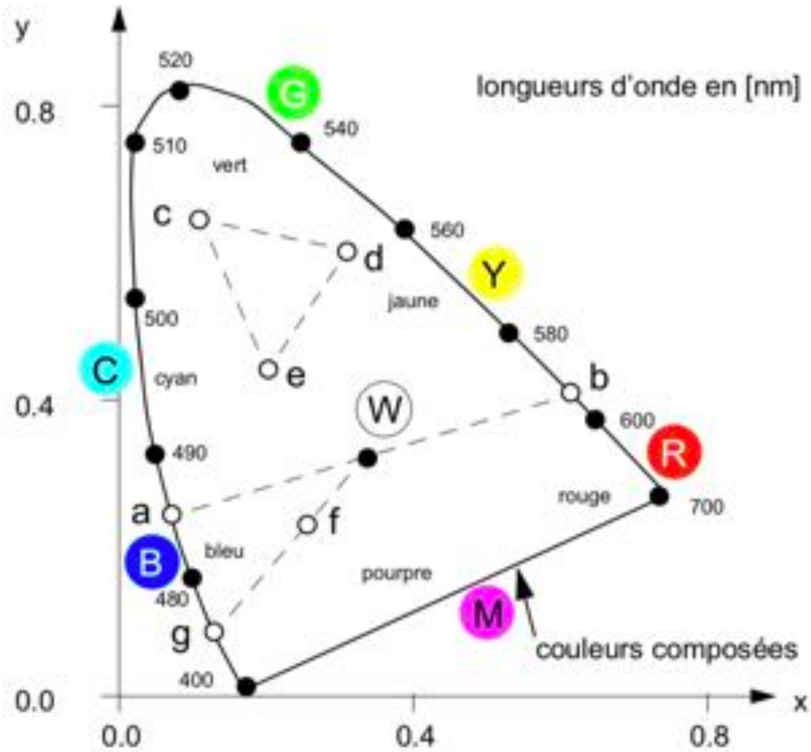
- W: x=1/3 and y=1/3
- Complementary colors – as a mixture of 2 primary colors



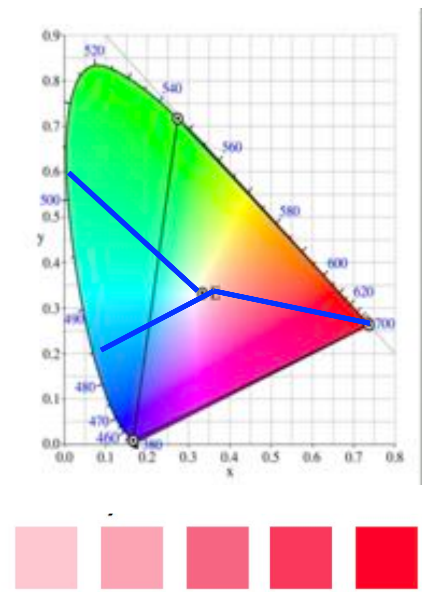
- Generally: choosing two colors and connecting them by line we can obtain all colors on this line by mixing these two colors.



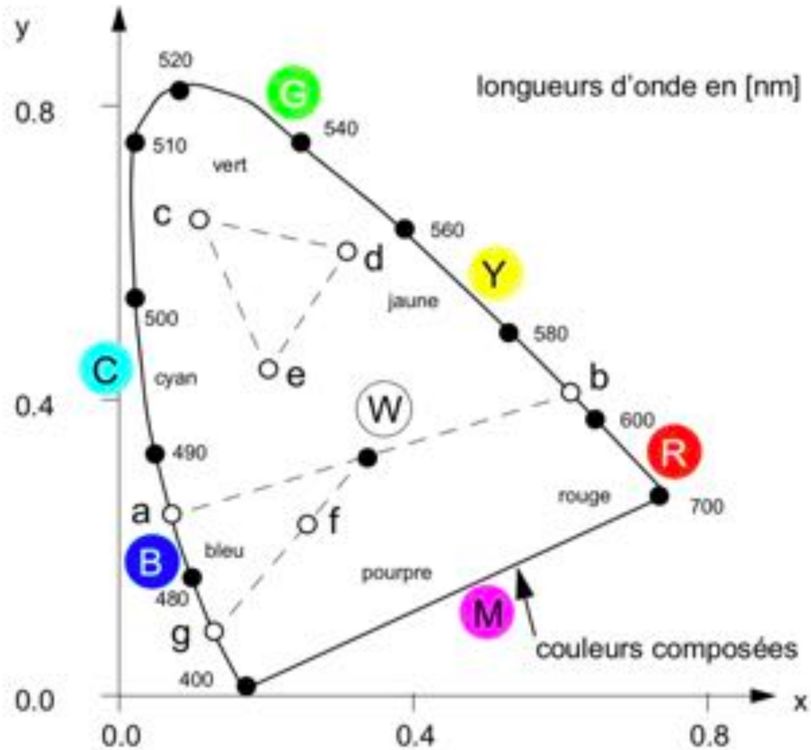
Color vision: the CIE chromaticity diagram



- Choosing any spectral color and W color and connecting them by line, one can obtain all shades of this spectral color (W-a, W-g, W-b)



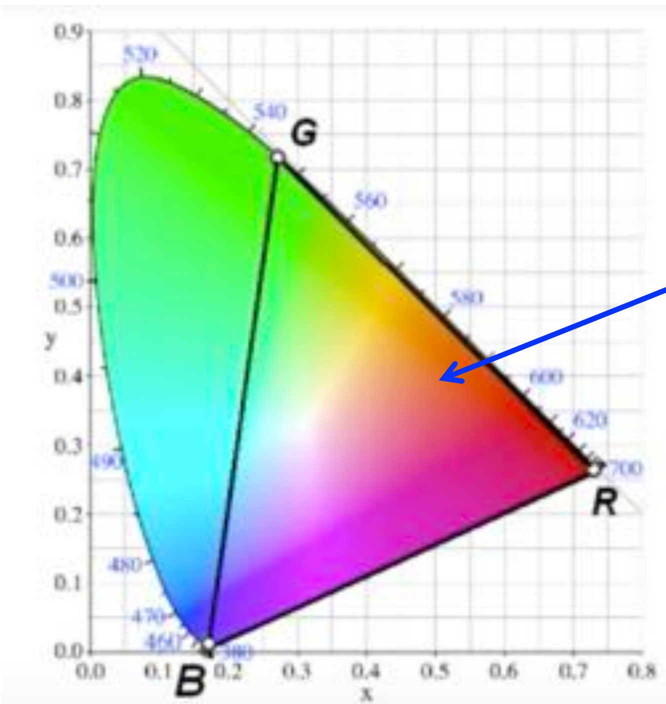
Color vision: the CIE chromaticity diagram



- Choosing 3 primary colors (c-d-e), one can obtain all color inside this triangle by composition/mixing these 3 colors.
- Note: one can not obtain all colors from the fixed primary colors (as it was shown before)
- We need to choose different primary color wavelength values, if we want doc over the entire CIE diagram.

Color vision: restriction of modern devices

Example of the CIE-RGB primary colors $\lambda_B = 435.8\ nm, \lambda_G = 546.1\ nm, \lambda_R = 700\ nm$



Achievable gamut of colors

Gamut is a reproducible range of colors inside the triangle

Color vision: restriction of modern devices

Examples of monitors and printers

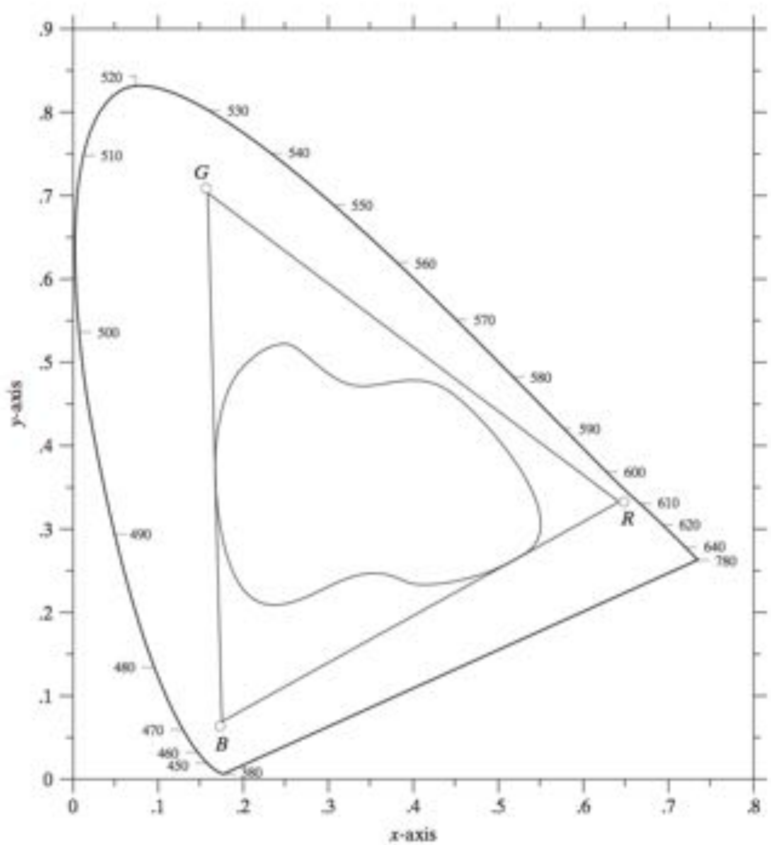


FIGURE 6.6 Typical color gamut of color monitors (triangle) and color printing devices (irregular region).

Gonzalez et al, p. 401

Color vision: TV standard NTSC - YIQ

YIQ is the color space used by NTSC color TV system (The North and Central America, Japan)

Y – represents luma component (intensity in the chromatic TV)

I – represents orange-blue range of colors

Q – represents purple-green range of colors

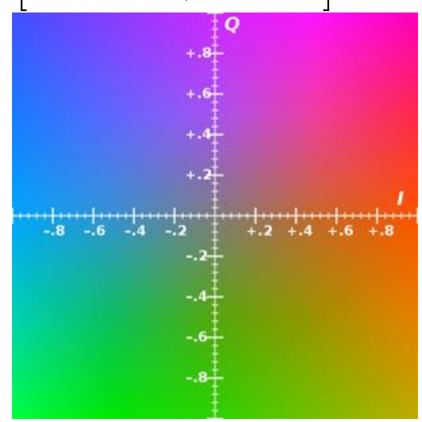
Range

$$R,G,B,Y \in \left[0,1\right],\ I \in \left[-0.5975,0.5975\right],\ Q \in \left[-0.5226,0.5226\right]$$

Conversion RGB-YIQ

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.274 & -0.322 \\ 0.211 & -0.523 & 0.312 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0.956 & 0.621 \\ 1 & -0.272 & -0.647 \\ 1 & -1.106 & 1.703 \end{bmatrix} \begin{bmatrix} Y \\ I \\ Q \end{bmatrix}$$



The YIQ color space at Y=0.5. Note that the I and Q chroma coordinates are scaled up to 1.0. See above to rescale.

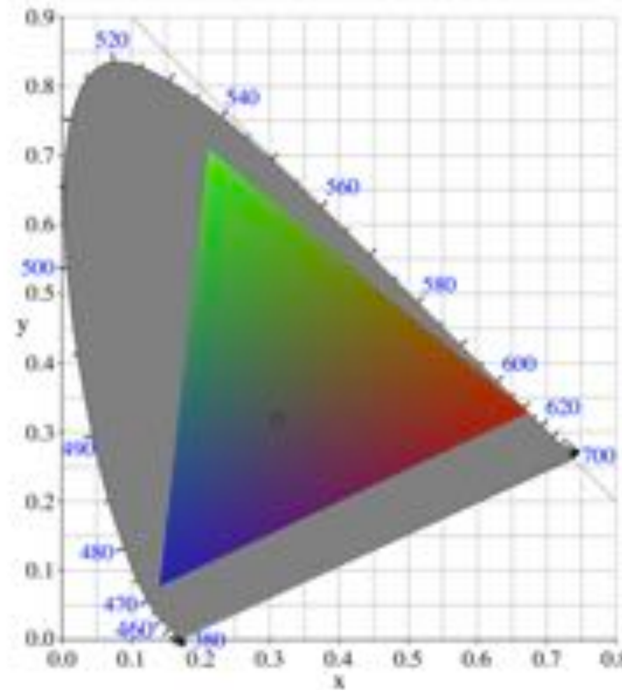
https://en.wikipedia.org/wiki/YIQ

Color vision: TV standard NTSC - YIQ

An image along with its Y, I, and Q components

https://en.wikipedia.org/wiki/YIQ

Color gamut of NTSC



Color vision: TV standards based on YUV/YCbCr

YUV (or Y'UV) is the color space used by PAL color TV system (analog TV)

YCbCr (aka YCC) is a digital "equivalent" of YUV used in digital formats JPEG and MPEG

Y' – represents luma component (different from Y in XYZ due not non-linearly corrected RGB components; not equi-proportional sum of RGB)

U/Cb – represents blue difference component

V/Cr – represents red difference component

Motivation:

- Y' carries out all luma information and can be encoded with high resolution and high rate (many bits per pixel)
- U/Cb and C/Cr represent the residual components that require less band-width in analog TV, can be downsampled or compressed with less bits in digital standards

General idea of conversion:

- Y' is a weighted sum: $Y' = 0.299R + 0.587G + 0.11B$
- U and V are scaled differences: $U \approx 0.492(B - Y')$

$$V \approx 0.877(R - Y')$$

Color vision: TV standards based on YUV/YCbCr

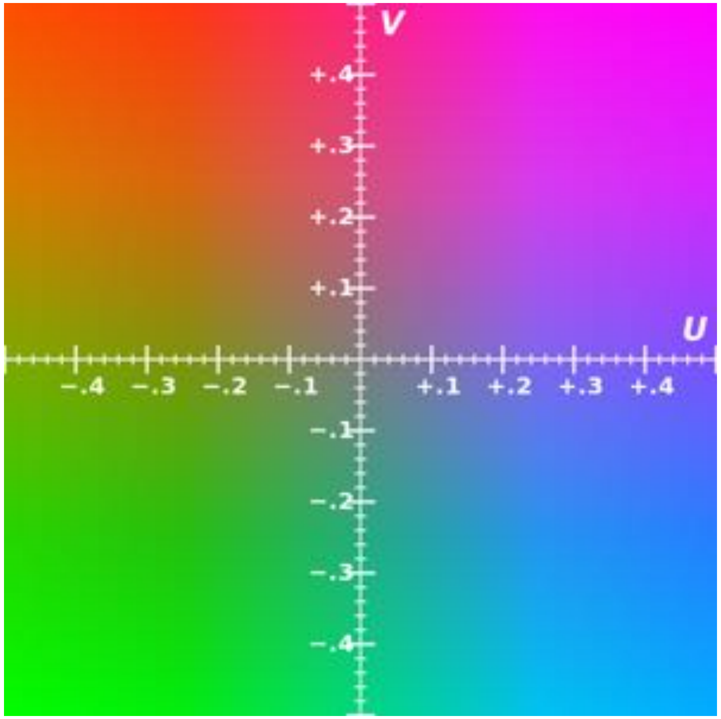
Range

$$R,G,B,Y' \in [0,1], U \in [-0.436, 0.436], V \in [-0.615, 0.615]$$

Conversion RGB-YIQ

$$\begin{bmatrix} Y' \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.14713 & -0.28886 & 0.436 \\ 0.615 & -0.51499 & -0.10001 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix},$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1.13983 \\ 1 & -0.39465 & -0.58060 \\ 1 & 2.03211 & 0 \end{bmatrix} \begin{bmatrix} Y' \\ U \\ V \end{bmatrix}.$$



https://en.wikipedia.org/wiki/YUV#Relation_with_Y′CbCr

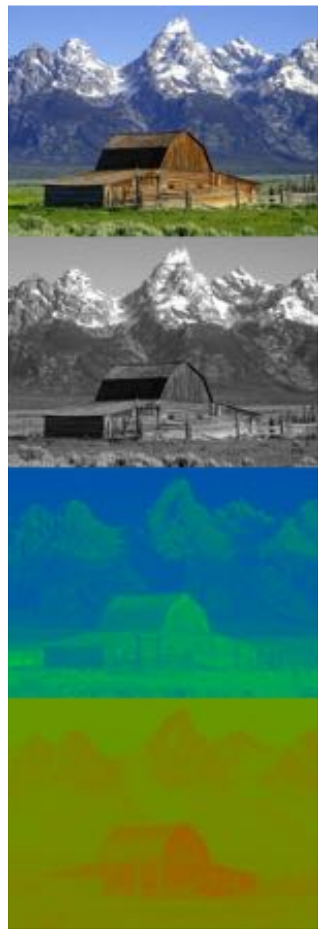
Example of U-V color plane, Y′ value = 0.5, represented within RGB color gamut

Color vision: TV standards based on YUV/YCbCr

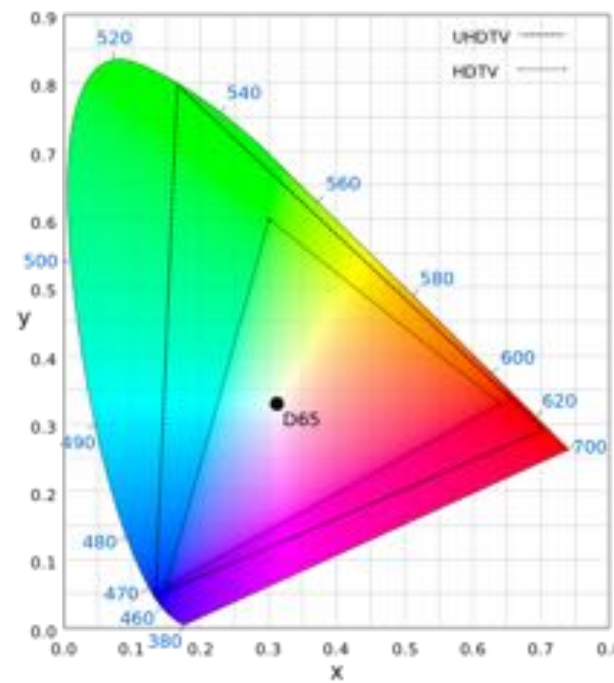
https://en.wikipedia.org/wiki/YIQ

YIQ

YUV



Color gamut of HDTV Rec. 709 and UHDTV



Color vision: TV standards based on YUV/YCbCr

Range

$$R', G', B', Y' \in [0, 255]$$

Conversion RGB-YCbCr

$$Y' = 0,299\, R' + 0,587\, G' + 0,114\, B'$$
$$Cb = -0,1687\, R' - 0,3313\, G' + 0,5\, B' + 128$$
$$Cr = 0,5\, R' - 0,4187\, G' - 0,0813\, B' + 128$$

$$R = Y' + 1,402(Cr - 128)$$
$$G = Y' - 0,344\,14(Cb - 128) - 0,714\,14(Cr - 128)$$
$$B = Y' + 1,772(Cb - 128)$$

https://fr.wikipedia.org/wiki/YCbCr

Color vision: conversion in Matlab

For example, these commands convert an RGB image to NTSC format.

```
RGB = imread('peppers.png');
YIQ = rgb2ntsc(RGB);
```

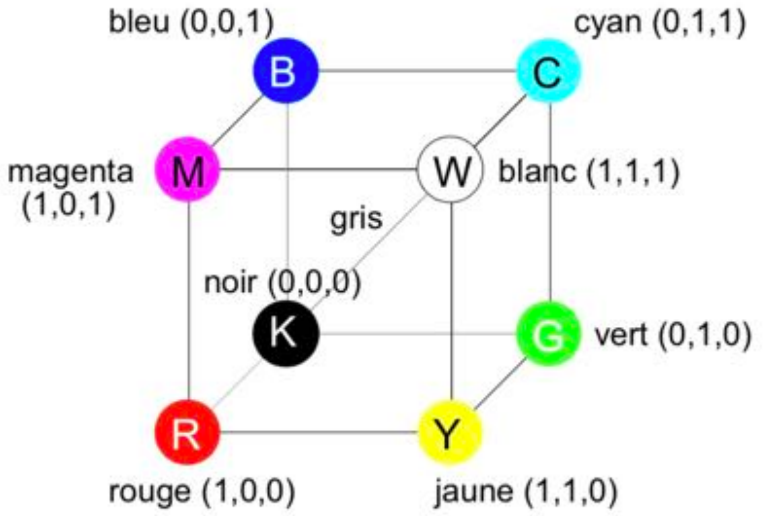
For example, these commands are equivalent to calling `rgb2gray`.

```
YIQ = rgb2ntsc(RGB);
I = YIQ(:,:,1);
```

For example, these commands convert an RGB image to YCbCr format.

```
RGB = imread('peppers.png');
YCBCR = rgb2ycbcr(RGB);
```

Color vision: RGB model



Each RGB component is represented by 8 bits.

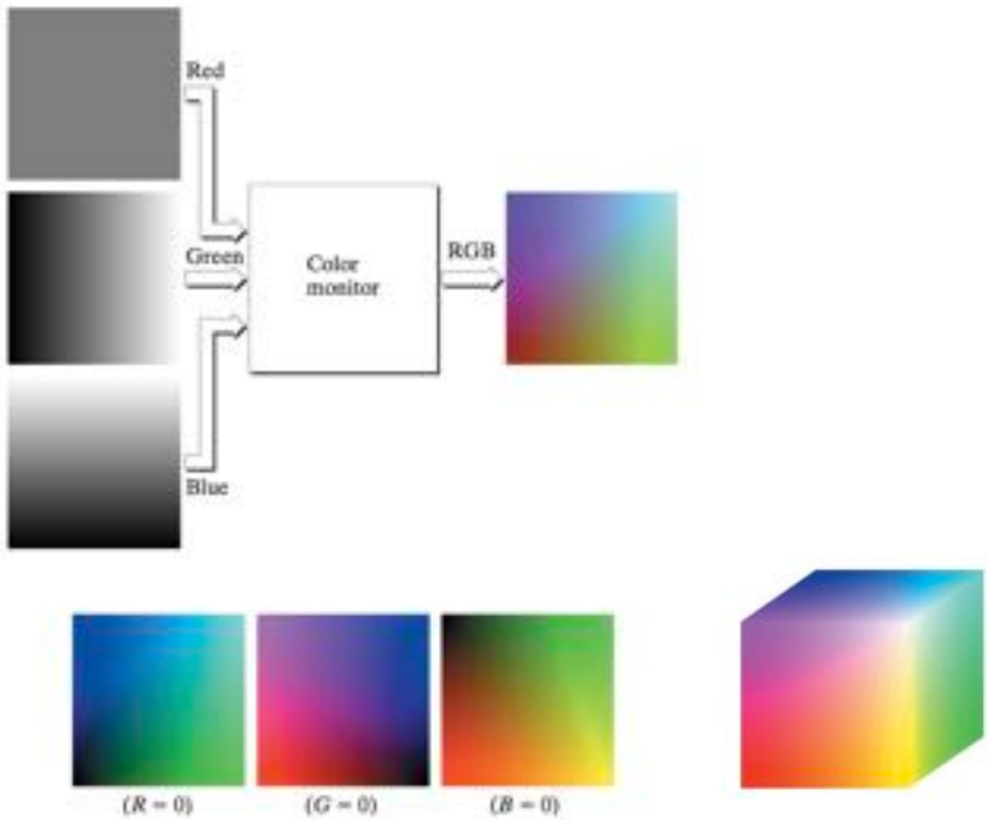
Thus in total 3x8=24 bits per color pixel.

Total number of colors in a 24-bit RGB image is $(2^8)^3 = 16'777'216$

Color vision: RGB model visualization

a
b

FIGURE 6.9
(a) Generating the RGB image of the cross-sectional color plane (127, *G*, *B*). (b) The three hidden surface planes in the color cube of Fig. 6.8.



Gonzalez et al, p 404

Color vision: RGB model encoding

- Although, the 24-bit RGB color system can encode $(2^8)^3 = 16'777'216$ many visualization systems (even today) can display only 256 colors.
- Therefore, to be sure that all devices display correctly at least these 256 colors, there is a subset of *256 safe colors or all-systems-safe colors.*
- Moreover, different applications use 40 colors in various ways and therefore only 216 colors are standardized (especially for the Internet applications).
- Each color in the RGB plane can only take 0, 51, 102, 153, 204 or 255 for the safe colors, i.e., 6 numbers in RGB: $(6)^3 = 216$

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

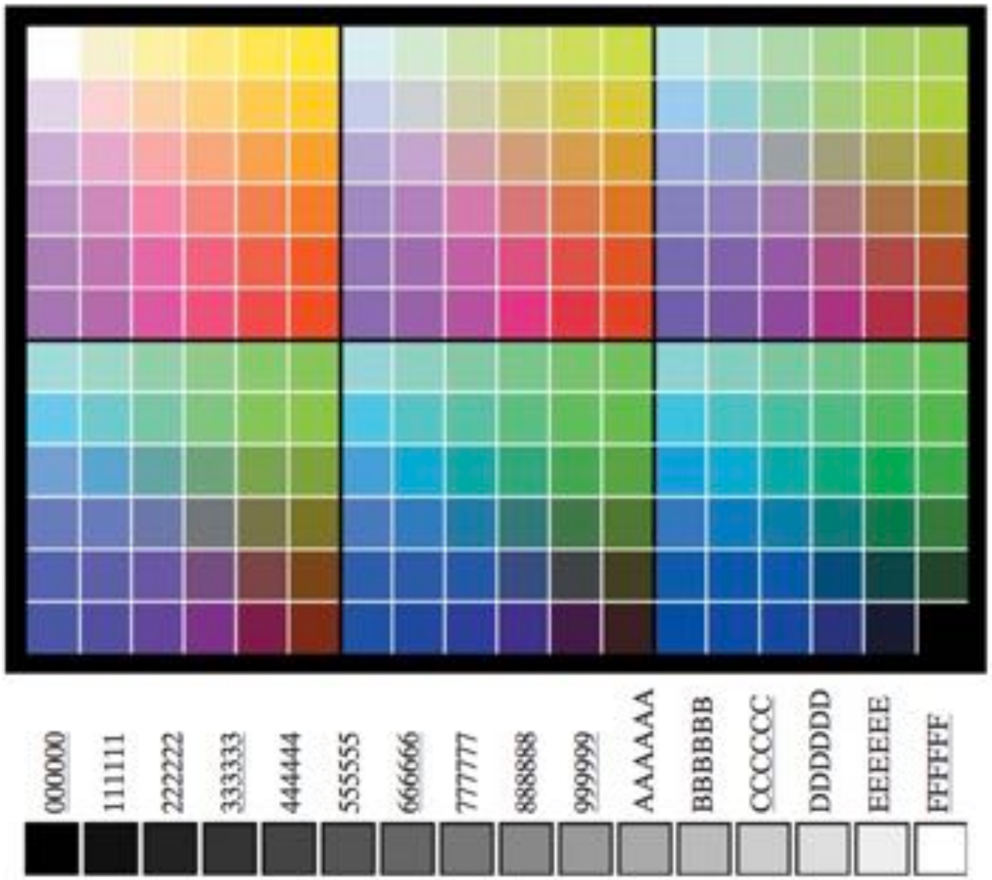
Decimal numbers: 0,1,2,…,9,10,11,1,2,13,14,15

Hex numbers: 0,1,2,…,9,A,B,C,D,E,F

$(0)_{16} = (0000)_2$ and $(F)_{16} = (1111)_2.$

$(FF)_{16} = (255)_{10} = (11111111)_2$

Color vision: RGB model encoding



a
b

FIGURE 6.10
(a) The 216 safe RGB colors.
(b) All the grays in the 256-color RGB system (grays that are part of the safe color group are shown underlined).

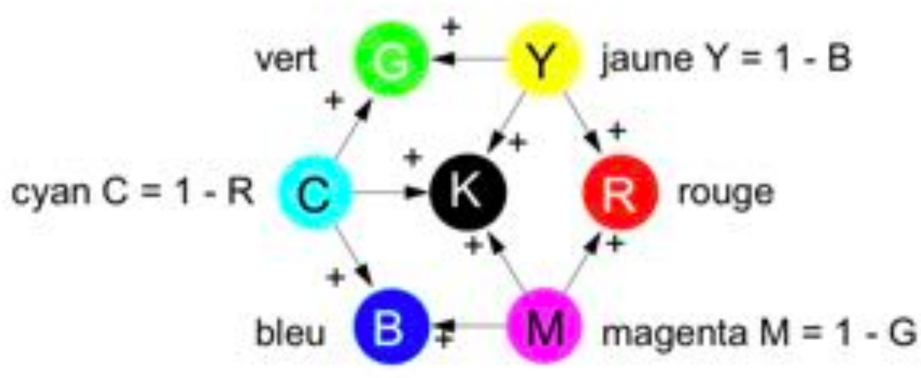
Gonzalez et al, p 405

Color vision: subtractive systems

- Suppose color ink or pigment is added to white paper
- The pigment absorbs the light of some wavelength and reflects of others
- Note: the white paper reflects all colors (W=R+G+B –> we see as a white light)
- The black paper absorbs all colors

Color vision: conversion between colors

Conversion RGB to CMY and primary color mixing of RGB and CMY



T. Pun

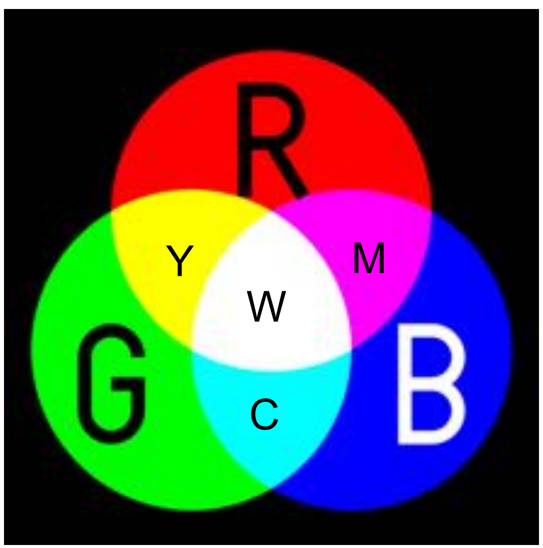
Color vision: conversion between colors

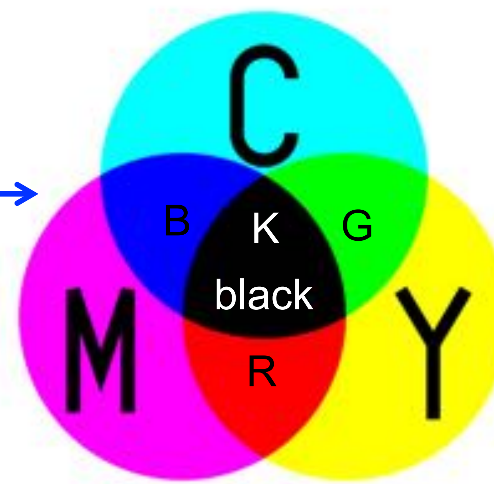
Conversion between RGB and CMY (matrix form)

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

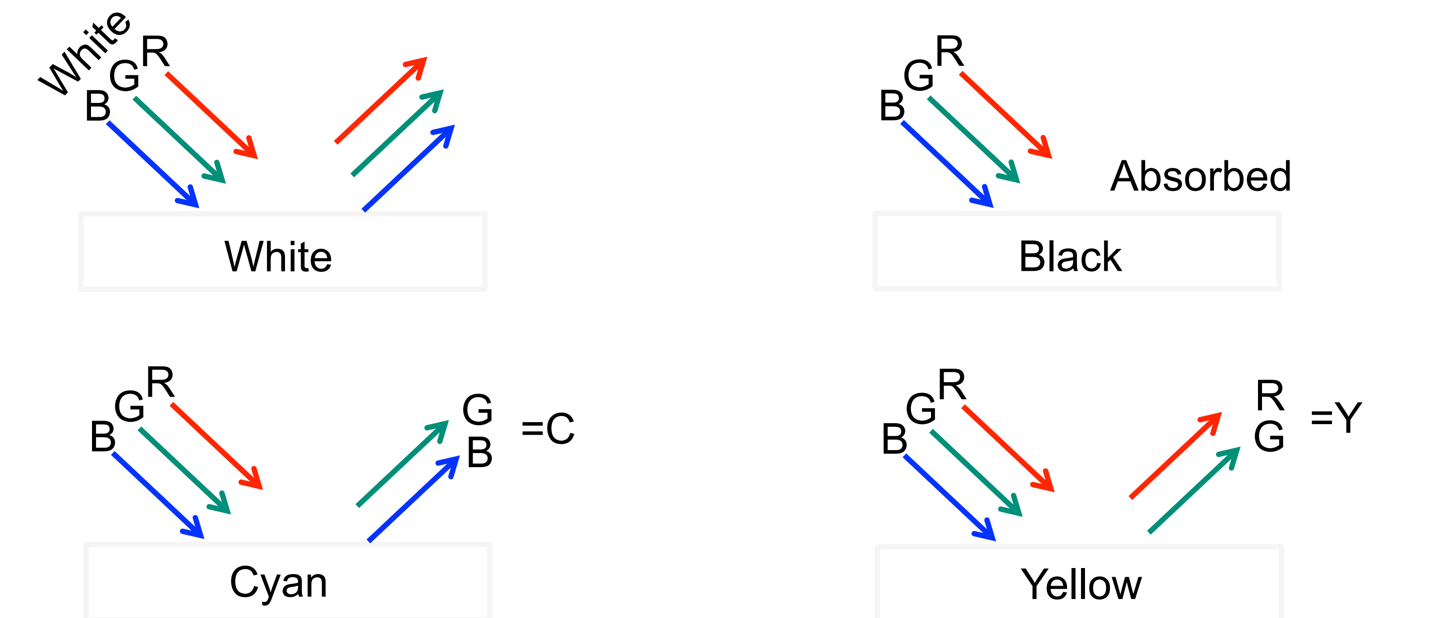
$$
\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix} \Leftrightarrow \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} C \\ M \\ Y \end{bmatrix}
$$

$$W = R + G + B = 1$$





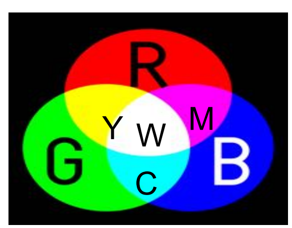
Color vision: reflection of colors



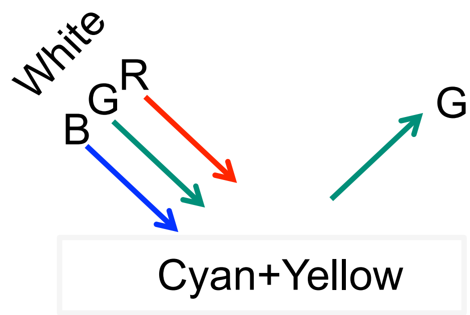
$$C = 1 - R = R + G + B - R = G + B \qquad Y = 1 - B = R + G + B - B = R + G$$

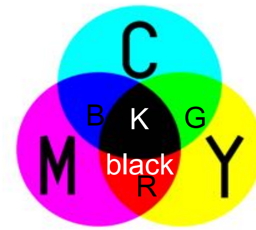
Cyan absorbs R and reflects G+B=C

Yellow absorbs B and reflects R+G



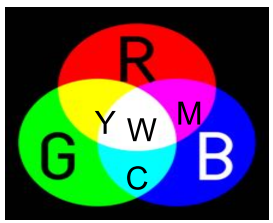
Color vision: reflection of colors





$$C: 1 - {\color{red}R} = R + G + B - R = G + B$$

$$Y: \left[G + B\right] - {\color{blue}B} = G$$



Also observe it directly via the mixture of Y+C=G

Color vision: encoding of color

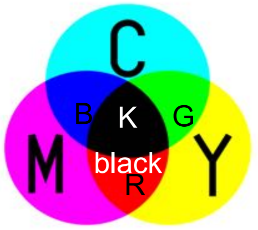
Couleur	RGB	CMY
rouge	255,0,0	0,255,255
jaune	255,255,0	0,0,255
vert	0,255,0	255,0,255
cyan	0,255,255	255,0,0
bleu	0,0,255	255,255,0
magenta	255,0,255	0,255,0
noir	0,0,0	255,255,255
niveaux de gris	63,63,63 127,127,127 191,191,191	191,191,191 127,127,127 63,63,63
blanc	255,255,255	0,0,0

T. Pun

Color vision: CMYK model

- We use 4 inks in modern printers (additionally black (K) is added): CMYK model
- K is computed as:

$$K = \min(C, M, Y) \in [0,1]$$



- Then new CMY are computed as:

$$C \leftarrow C - K, M \leftarrow M - K, Y \leftarrow Y - K$$

- This leads to the following advantages over CMY model:
  - Only the black ink is used for the B&W printing like text docs
  - The black color is more saturated (no need to mix, errors, etc)
  - It is not so wet …

Color vision

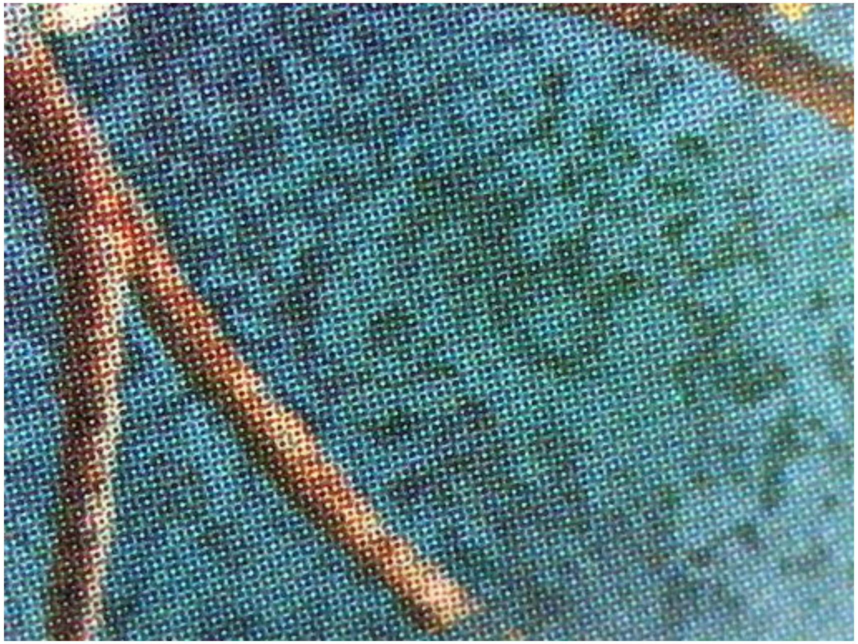
CMY printing https://en.wikipedia.org/wiki/CMYK_color_model

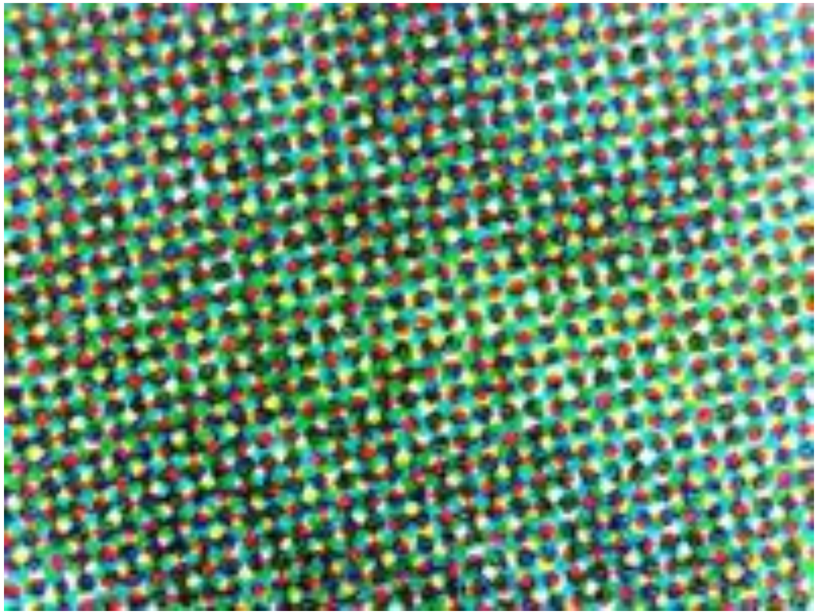
Early representation of the three-color process (1902).

Color vision: compare and conclude

Color vision: CMYK printing - halftoning

https://en.wikipedia.org/wiki/CMYK_color_model





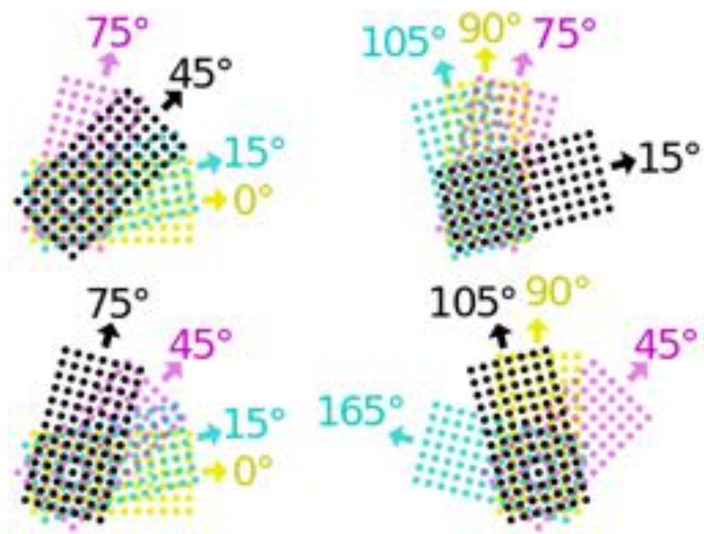
Color vision: CMYK printing

CMYK

https://en.wikipedia.org/wiki/CMYK_color_model

C	15°	15°	105°	165°
M	75°	45°	75°	45°
Y	0°	0°	90°	90°
K	45°	75°	15°	105°

To improve print quality and reduce moiré patterns, the screen for each color is set at a different angle.



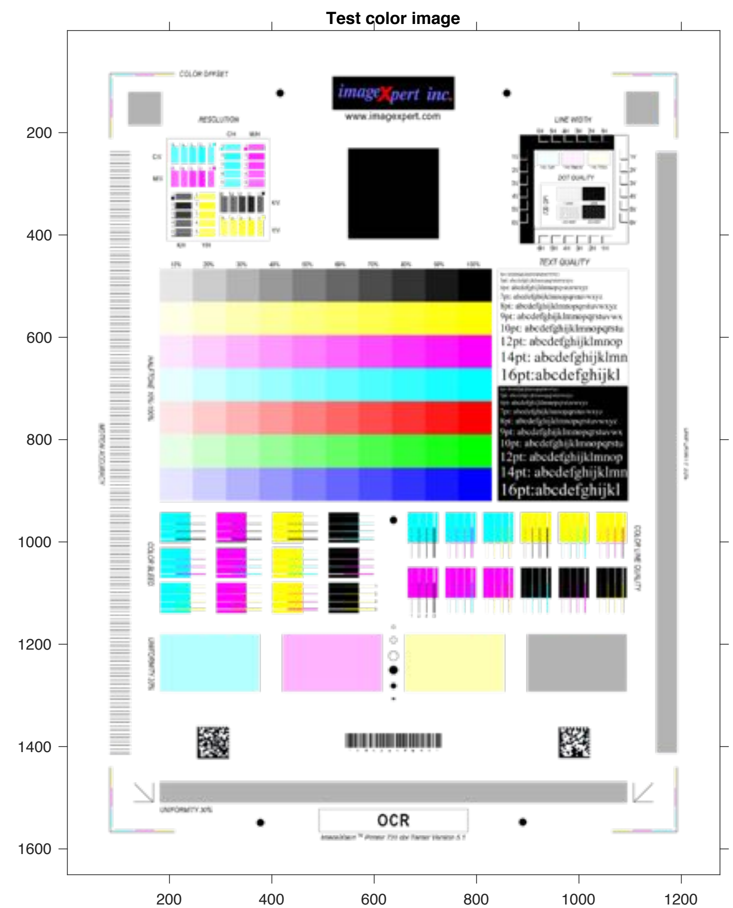
Matlab: colors

```
% Basic color coding
clear all;

% read image: pay attention to the represenation unit8
im = imread('test1.png');

% show image
figure; imshow(im); title('Test color image')
```

```
>> whos
  Name           Size                      Bytes  Class     Attributes

  im          1650x1275x3                6311250  uint8
```

Note:

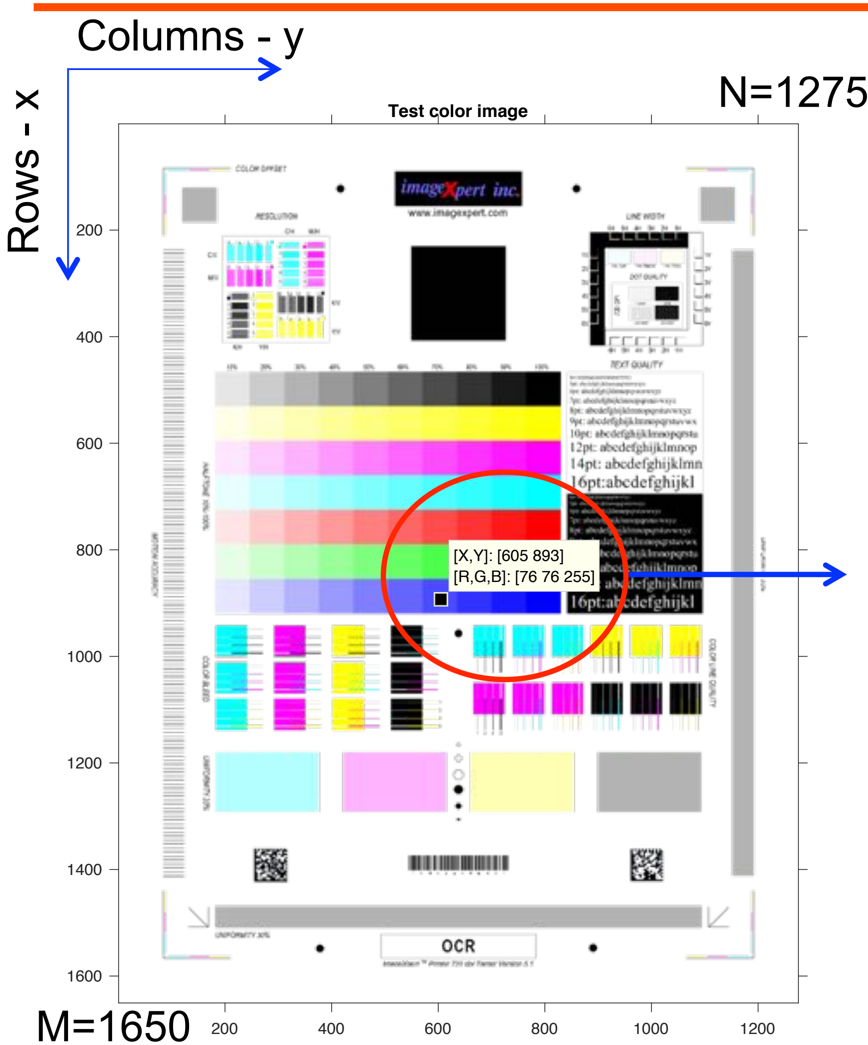
- Pay attention to 3x unit8 representation
- Pay attention to the indices on axes

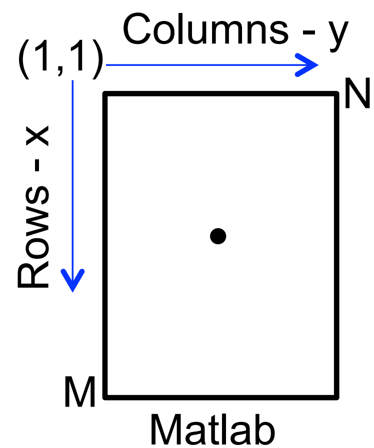


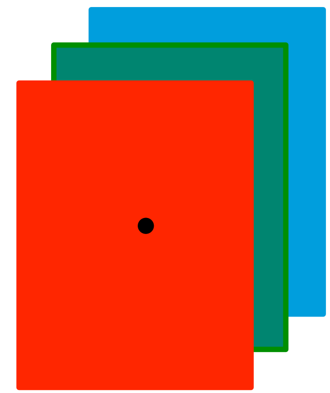
RGB encoding for different classes:

- double – [0,1]
- unit8 – [0,255]
- unit16 – [0,65535]

Matlab: colors - visualization







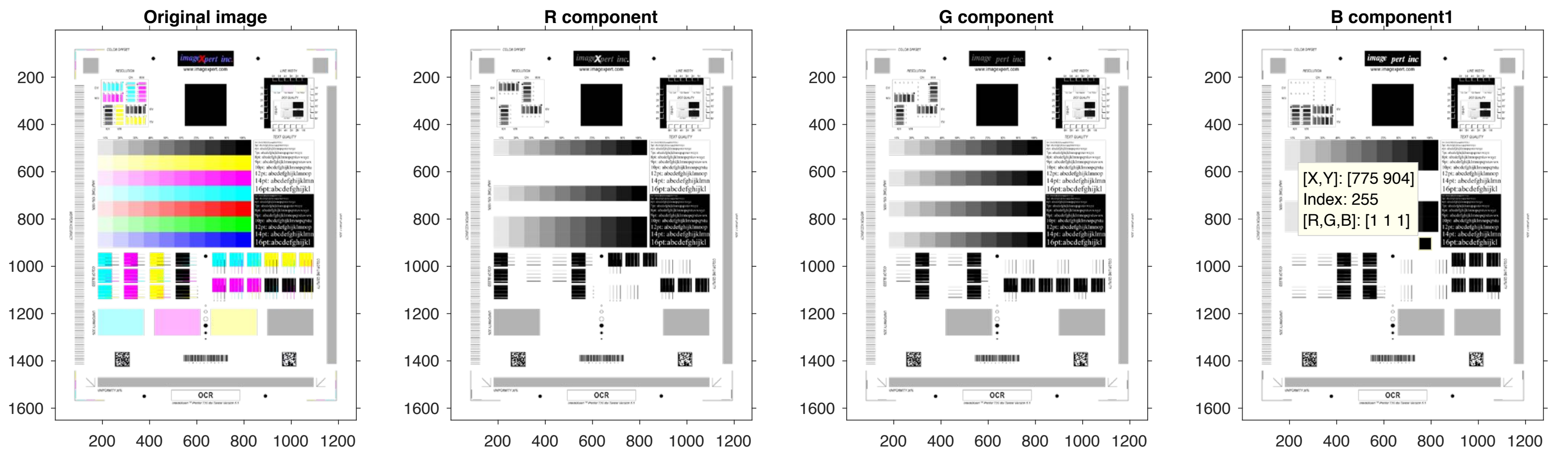
We need to reverse it

```
>> im(893,605,:)

1×1×3 uint8 array

ans(:,:,1) =

   76

ans(:,:,2) =

   76

ans(:,:,3) =

   255
```

Colors

Matlab: colors – extracting color components

```
R=im(:,:,1);
G=im(:,:,2);
B=im(:,:,3);

% Visualize the RGB color planes
figure;
subplot(1,4,1); imshow(im,[]); title('Original image')
subplot(1,4,2); imshow(R,[]); title('R component'); colormap('gray')
subplot(1,4,3); imshow(G,[]); title('G component')
subplot(1,4,4); imshow(B,[]); title('B component1')
```

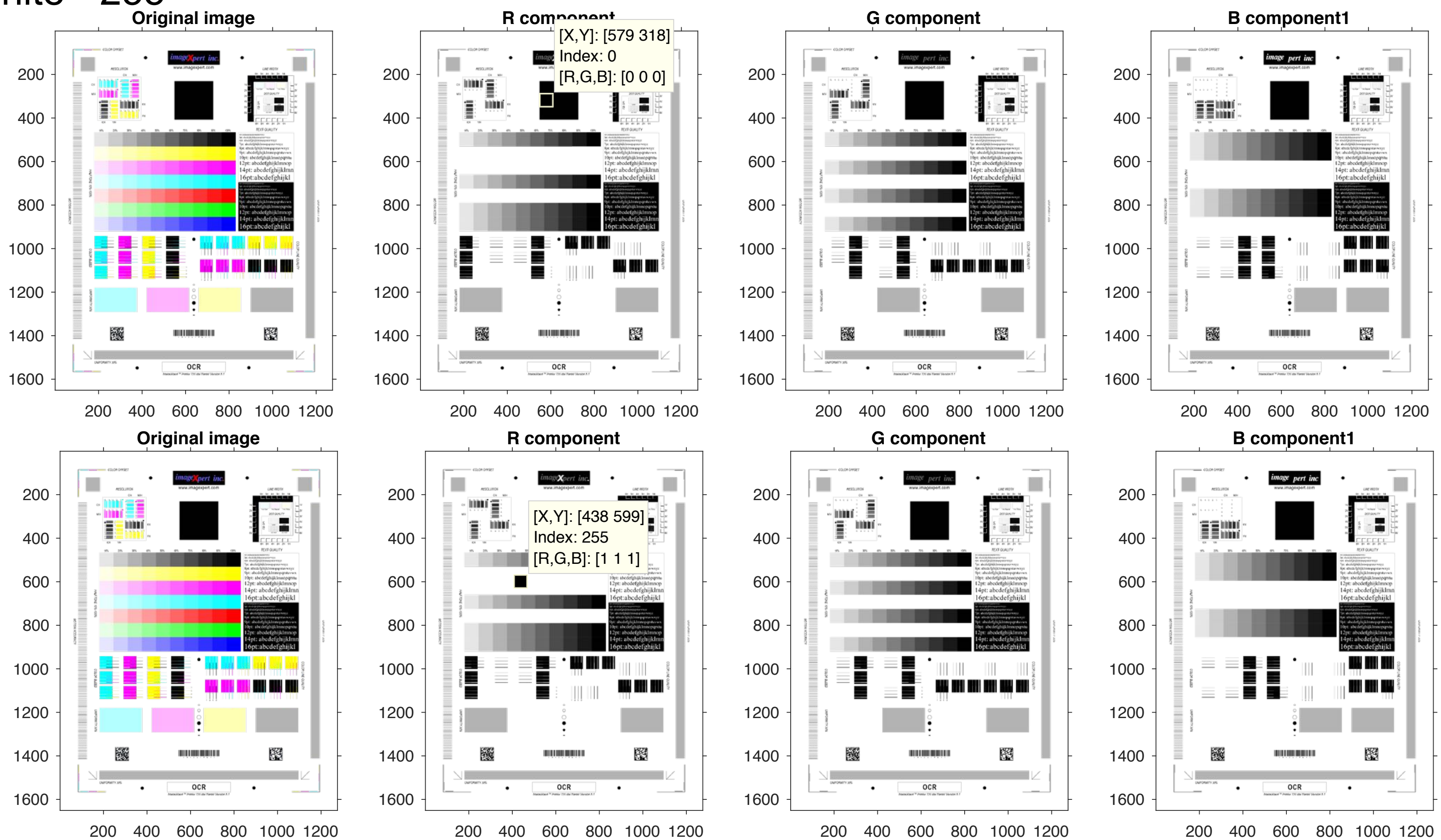


Matlab: colors – extracting color components

Black - 0

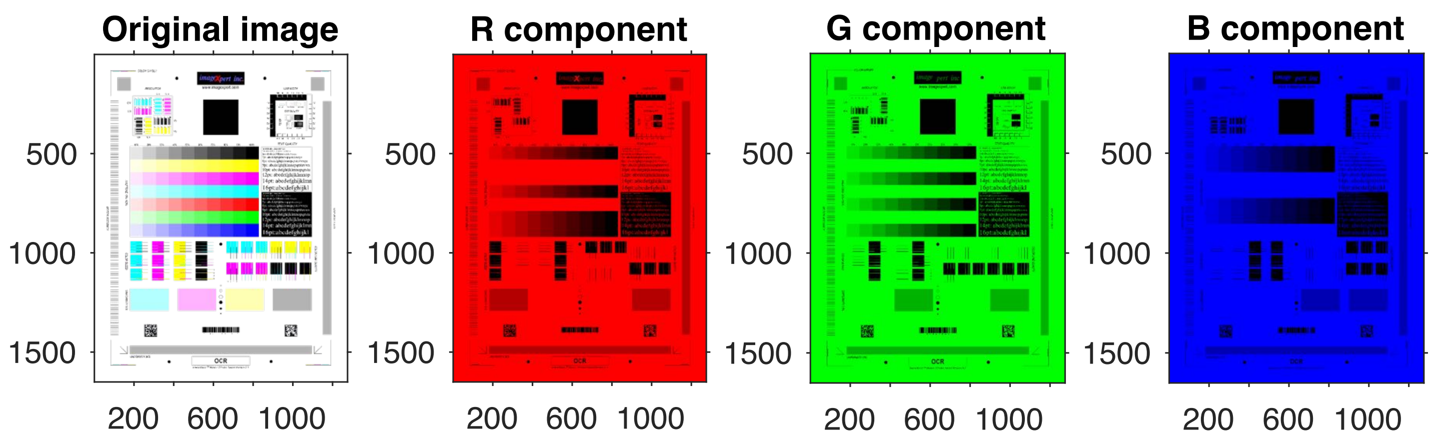
White - 255

Pay attention to intensity of RGB colors for the corresponding planes



Matlab: colors – extracting color components

Pay attention to intensity of RGB colors for the corresponding planes



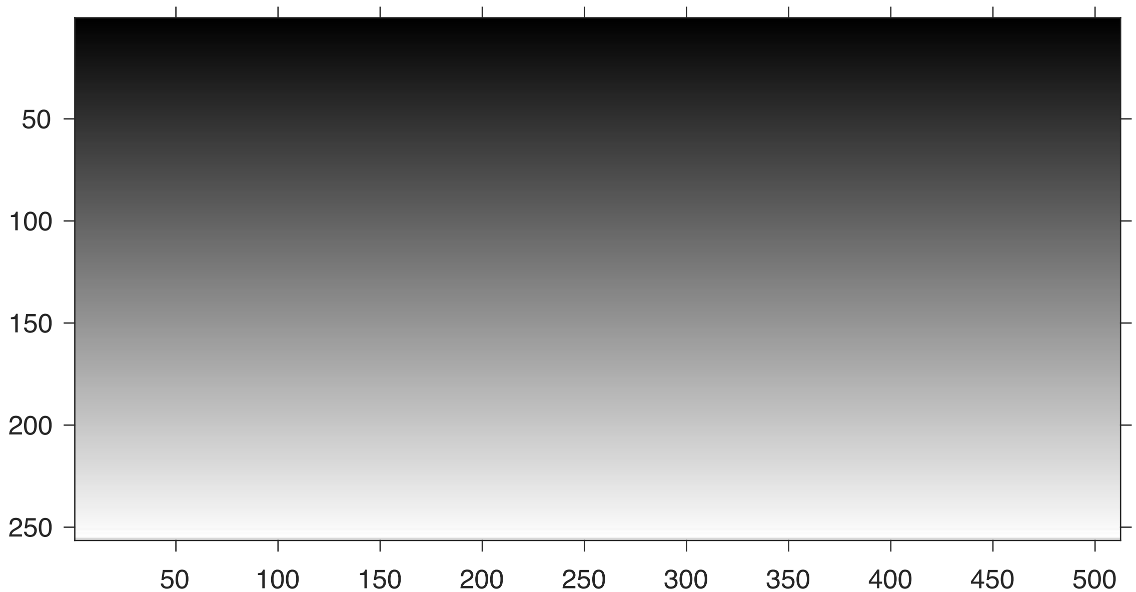

```
% Visualization in color
imR=im;imR(:,:,2:3)=0;
imG=im;imG(:,:,1)=0;imG(:,:,3)=0;
imB=im;imB(:,:,1:2)=0;

% show image
figure;
subplot(1,4,1); imshow(im,[]); title('Original image')
subplot(1,4,2); imshow(imR,[]); title('R component')
subplot(1,4,3); imshow(imG,[]); title('G component')
subplot(1,4,4); imshow(imB,[]); title('B component')
```

Note: R+G+B=W

Black - 0

White - 255

Matlab: colors – test image generation

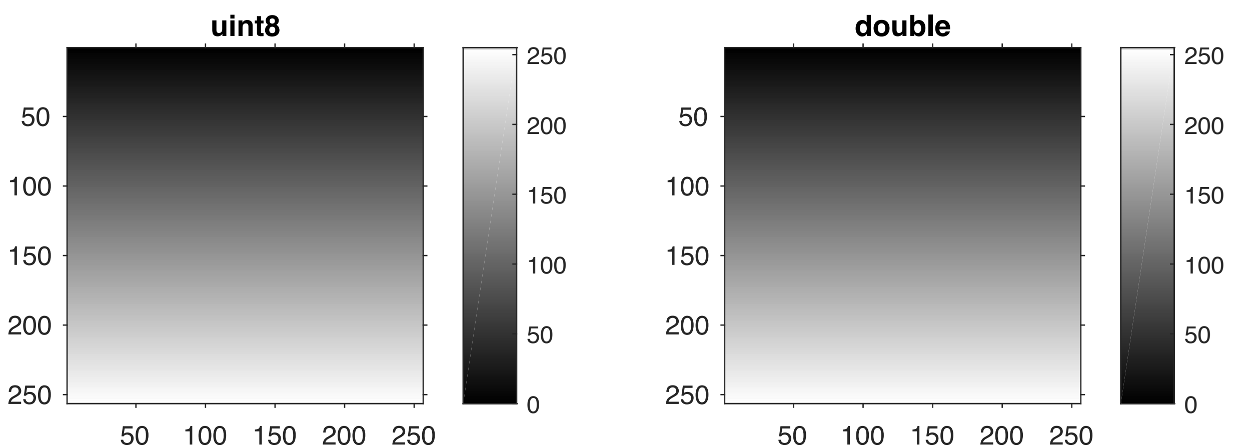


$$\begin{bmatrix} 0 \\ 1 \\ \vdots \\ 255 \end{bmatrix} \underbrace{\begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}}_{512} = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ 1 & 1 & \cdots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 256 & 256 & \cdots & 256 \end{bmatrix}$$

```
>> im=[0:255]'*ones(1,512);
```

Matlab: colors – test image generation

```
im=[0:255]'*ones(1,256);
figure;
subplot(1,2,1); imshow(uint8(im),[]); title('uint8')
subplot(1,2,2); imshow(im,[]); title('double')
```

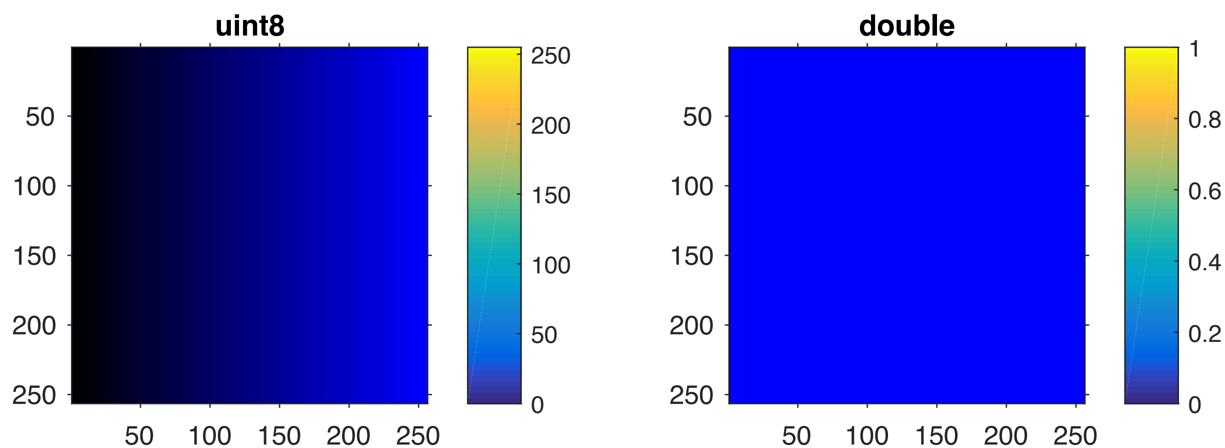


No difference

Matlab: colors – test image generation

```
imc(:,:,3) = ones(256,1)*[0:255];
figure;
subplot(1,2,1); imshow(uint8(imc),[]); title('uint8');colorbar
subplot(1,2,2); imshow(imc,[]); title('double');colorbar
```

Replace B by test image

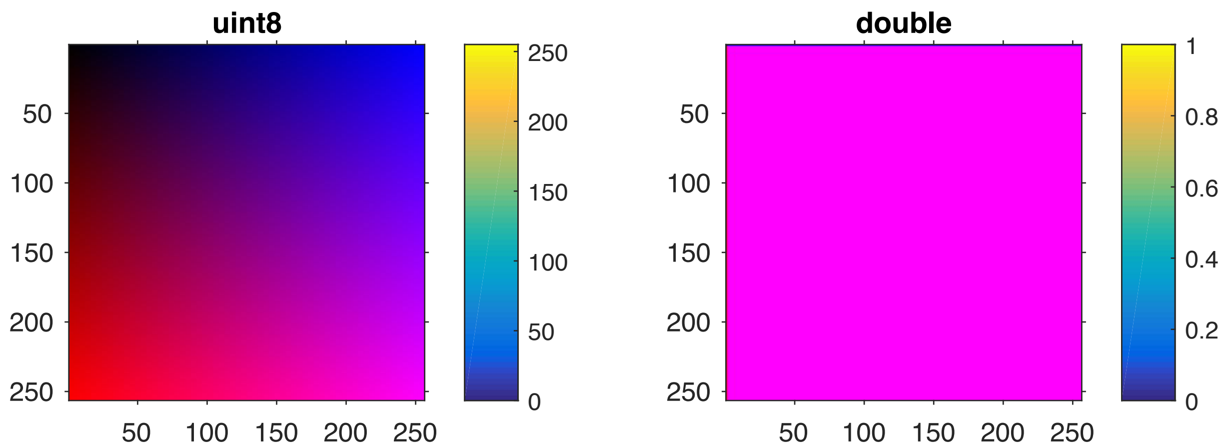


Observe the difference

Matlab: colors – test image generation

```
imc(:,:,1) = im;
figure;
subplot(1,2,1); imshow(uint8(imc),[]); title('uint8');colorbar
subplot(1,2,2); imshow(imc,[]); title('double');colorbar
```

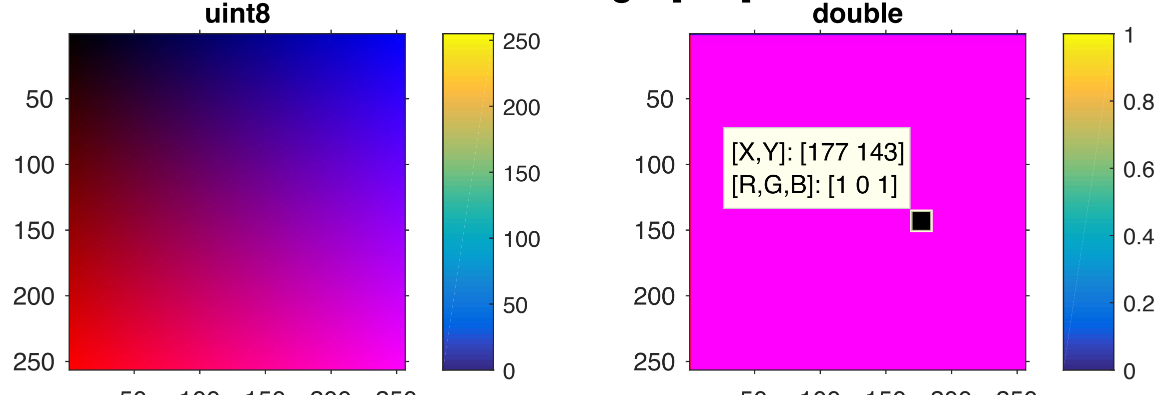
Add R by test image im



Observe the difference

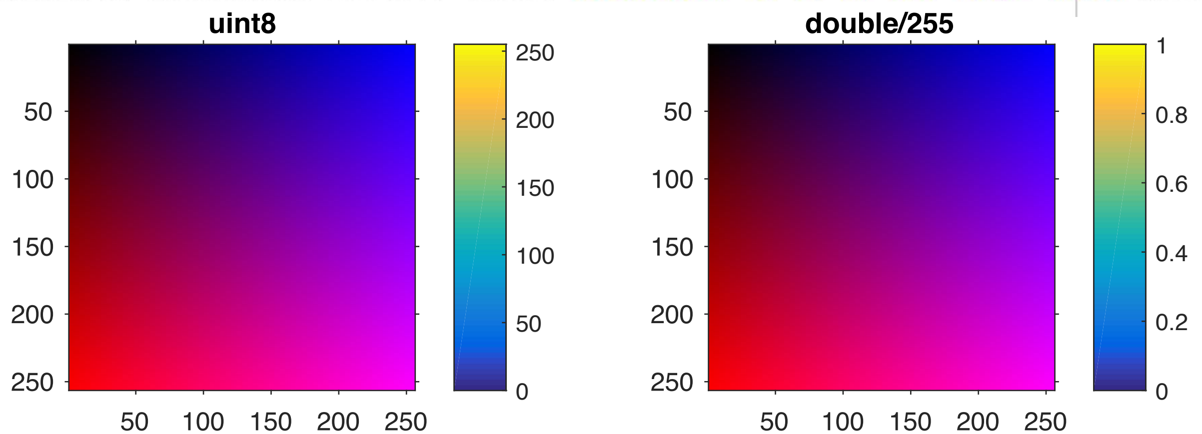
Matlab: colors – test image generation

Issue: double is assumed to be in the range [0,1] and it is saturated to 1 in R and B planes



One can correct it by the normalization of double to [0,1]

```
figure;
subplot(1,2,1); imshow(uint8(imc),[]); title('uint8');colorbar
subplot(1,2,2); imshow(imc/255,[]); title('double/255 to be in the range [0,1]');colorbar
```



Matlab: color conversion summary

Image Type Conversion

R2018a

Convert between the image types, such as RGB (truecolor), binary, grayscale, and indexed.

Functions

`gray2ind`	Convert grayscale or binary image to indexed image
`ind2gray`	Convert indexed image to grayscale image
`mat2gray`	Convert matrix to grayscale image
`rgb2gray`	Convert RGB image or colormap to grayscale
`rgb2ind`	Convert RGB image to indexed image
`ind2rgb`	Convert indexed image to RGB image
`label2rgb`	Convert label matrix into RGB image
`demosaic`	Convert Bayer pattern encoded image to truecolor image

`im2double`	Convert image to double precision
`im2int16`	Convert image to 16-bit signed integers
`im2java2d`	Convert image to Java buffered image
`im2single`	Convert image to single precision
`im2uint16`	Convert image to 16-bit unsigned integers
`im2uint8`	Convert image to 8-bit unsigned integers

Image quality criteria

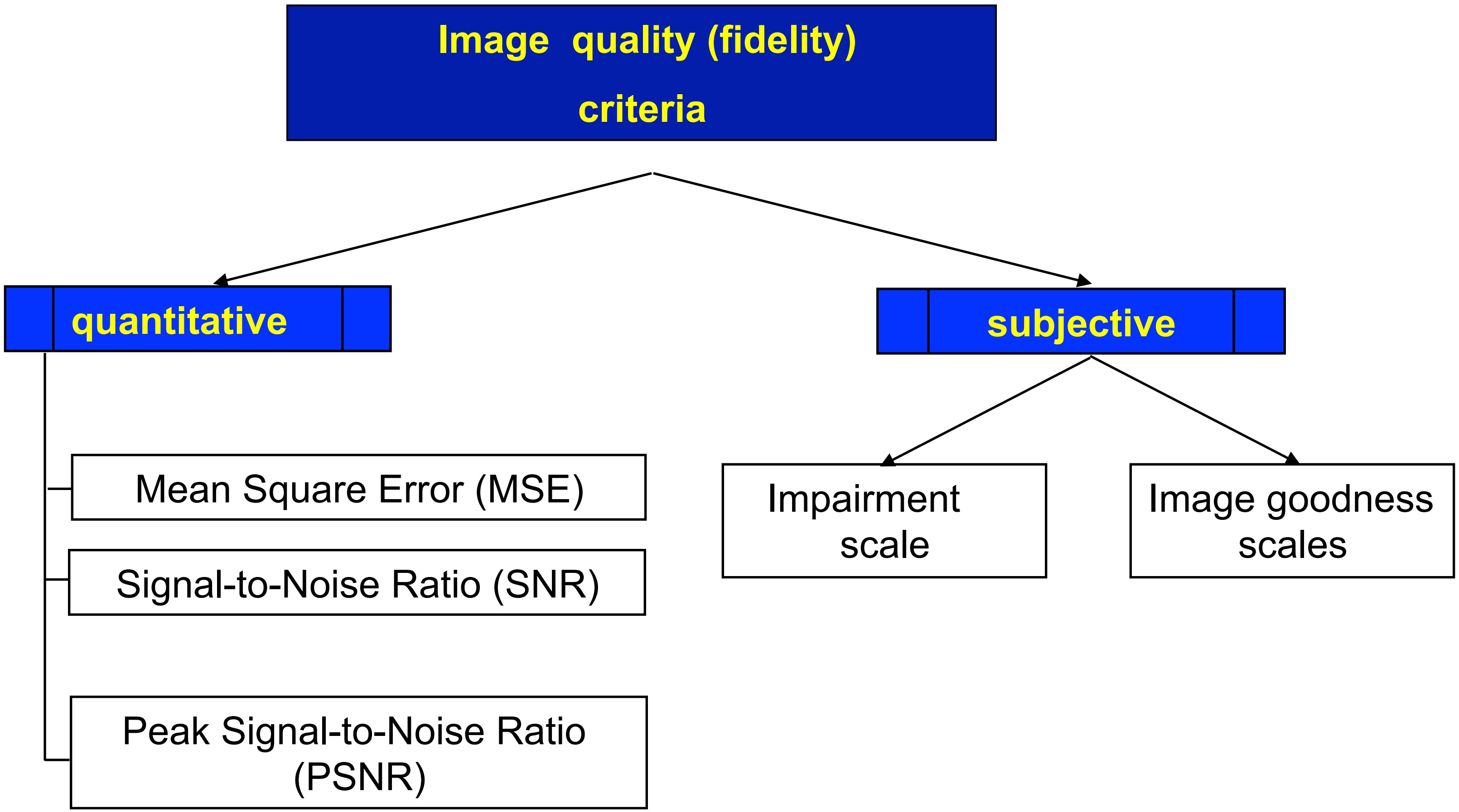


Image quality criteria

	Quantitative criteria	

- MSE (mean square error) criterion:

$$MSE = \frac{1}{MN}\sum_{x=0}^{M-1}\sum_{y=0}^{N-1}\left| f(x,y) - g(x,y)\right|^2$$

- SNR (signal-to-noise ratio) :

$$SNR, \mathrm{dB} = 10\log_{10}\frac{\sigma_x^2}{MSE}$$

- PSNR (peak signal-to-noise ratio) :

$$PSNR, \mathrm{dB} = 10\log_{10}\frac{\max(f(x,y))^2}{MSE}$$

Image quality criteria

Subjective criteria

- impairment scale :

Q Factor	Quality	Impairment
5	Excellent	Imperceptible
4	Good	Perceptible, but not annoying
3	Fair	Slightly annoying
2	Poor	Annoying
1	Bad	Very annoying

Image quality criteria

MSE:

$$MSE = \frac{1}{MN}\sum_{x=0}^{M-1}\sum_{y=0}^{N-1}\left| f(x,y) - g(x,y)\right|^2$$

Weighted MSE:

$$wMSE = \frac{1}{MN}\sum_{x=0}^{M-1}\sum_{y=0}^{N-1} w(x,y)\left| f(x,y) - g(x,y)\right|^2$$

PSNR:

$$PSNR, \mathrm{dB} = 10\log_{10}\frac{\max(f(x,y))^2}{MSE}$$

Weighted PSNR:

$$wPSNR, \mathrm{dB} = 10\log_{10}\frac{\max(f(x,y))^2}{wMSE}$$

Image quality criteria

Original image “Barbara”

Added Noise

PSNR = 24.6 dB,

wPSNR = 26.4 dB

Image with perceptually adopted noise

PSNR = 24.6 dB,

wPSNR = 29.3 dB

Image quality criteria – use in watermarking

Grayscale image

PSNR=33 dB

PSNR=37 dB

Original image

Image quality criteria – use in watermarking

Color image

PSNR=37 dB

Original image

PSNR=35 dB

What we need to know

- Understand the concept of a digital image
- Understand the definition and scope of digital image processing
- Know the fundamentals of the electromagnetic spectrum and its relationship to image generation
- Have a general understanding about the image acquisition and processing
- Know the main fields of image processing applications
- Understand the basic architectures of image processing systems and their main components