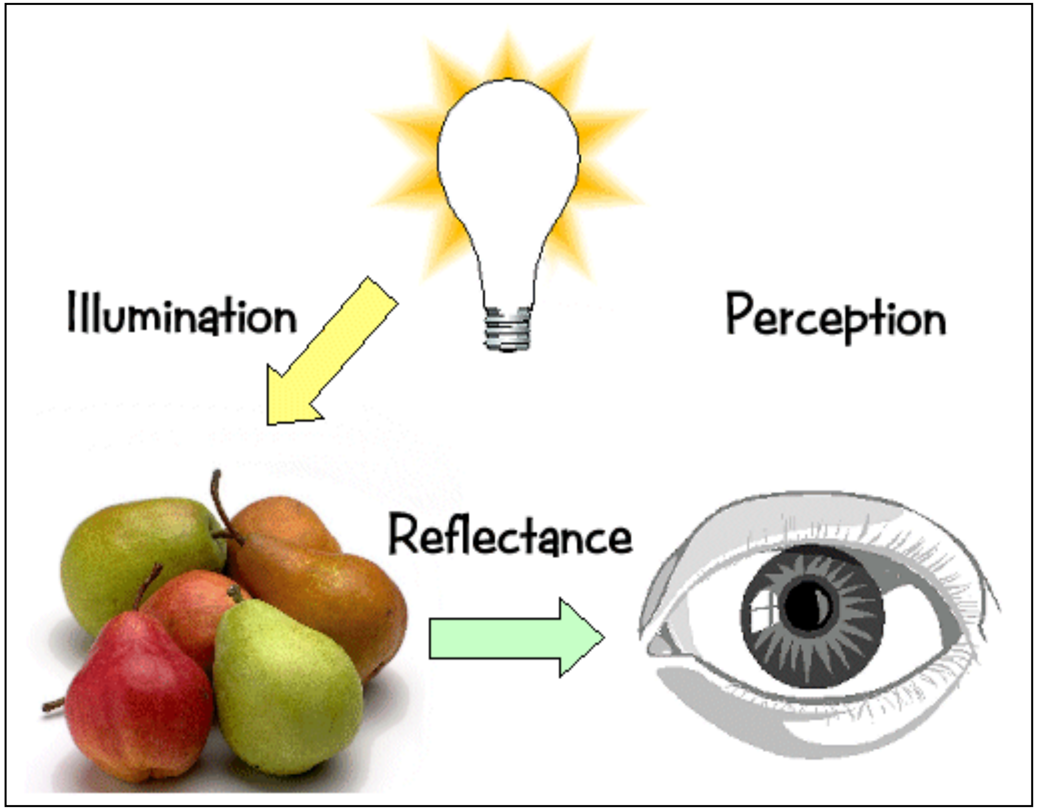
Color science

The Elements of Colour



Perceived light of different wavelengths is in approximately equal weights – *achromatic.*

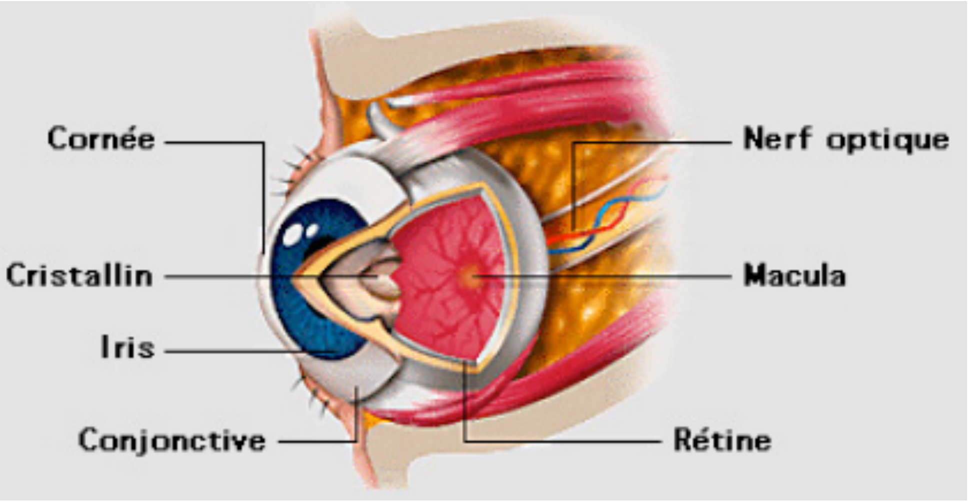
<3% from black object.

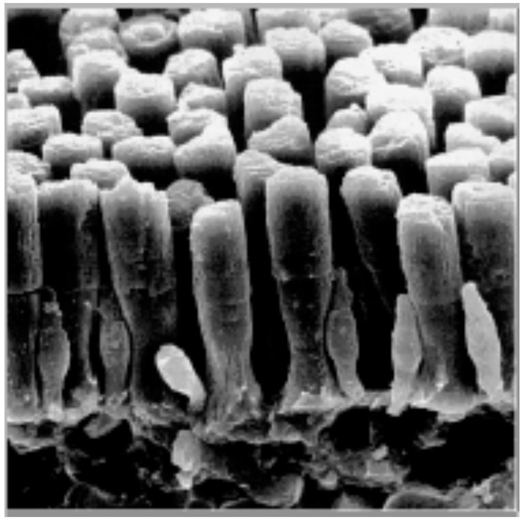
Reflected light

– perceived as colour

Colorimétrie et perception

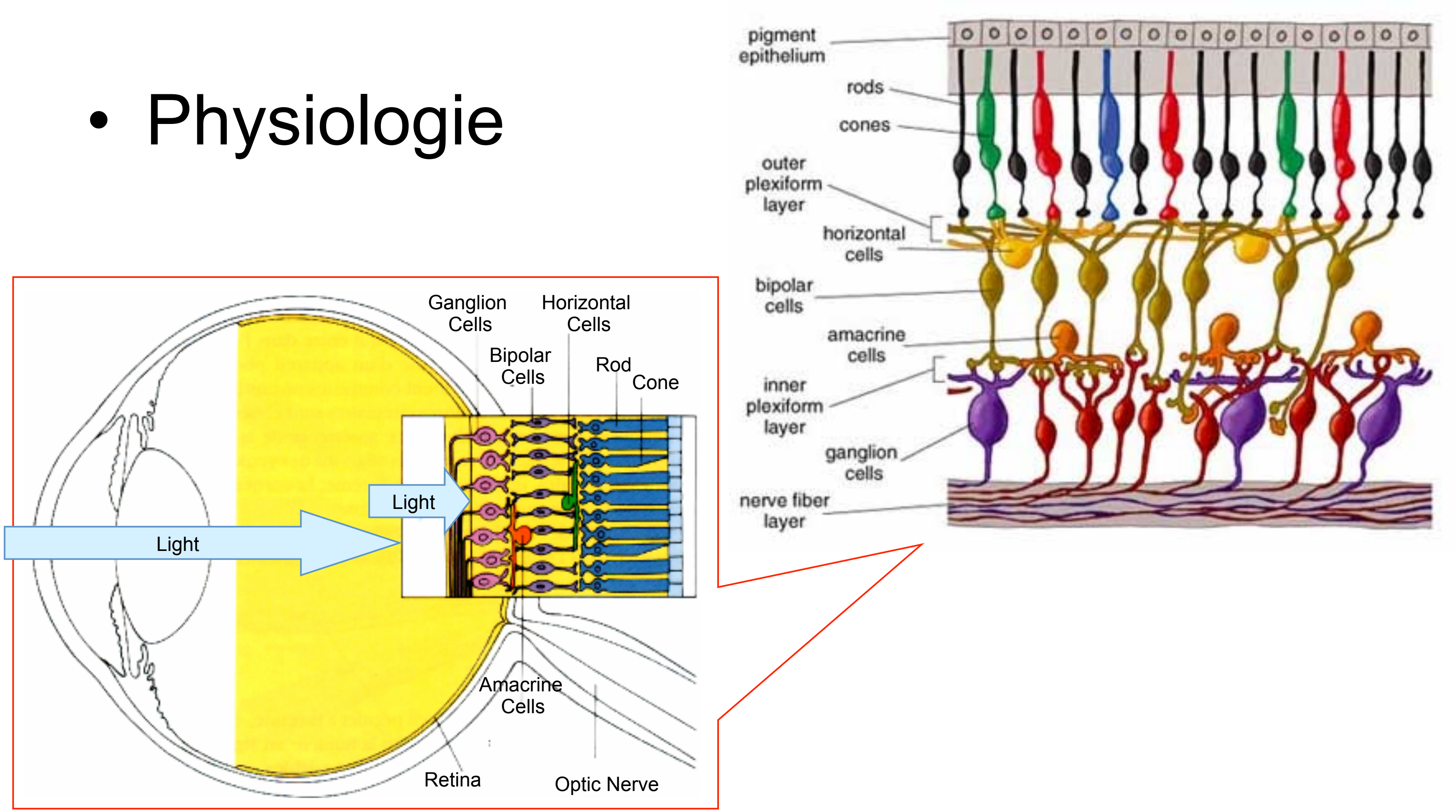
- Œil humain
  - « Optique »
  - Cônes et bâtonnets





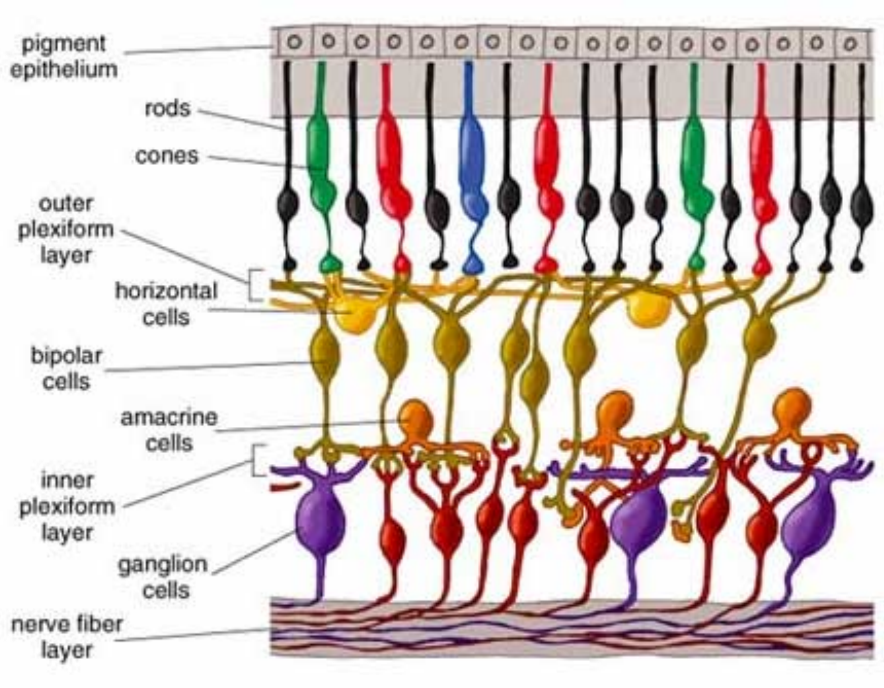
Colorimétrie

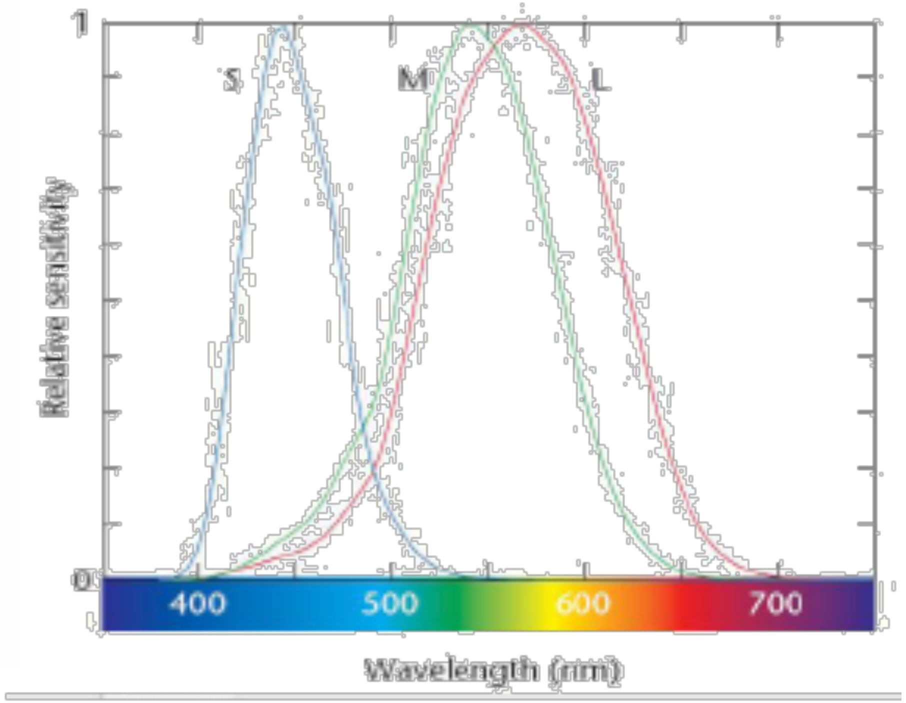
- Physiologie



Colorimétrie

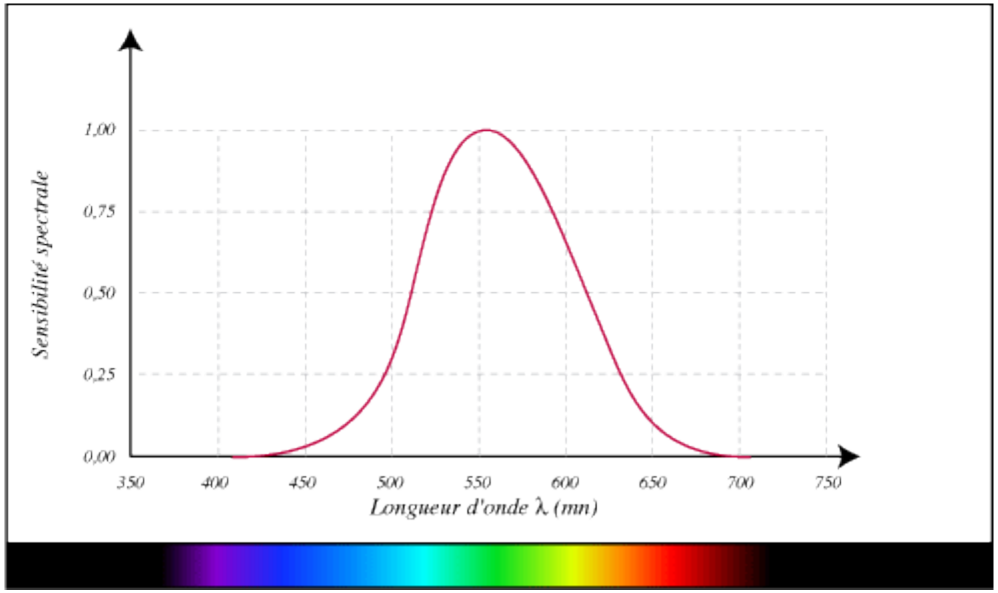
- De la physiologie à la physique





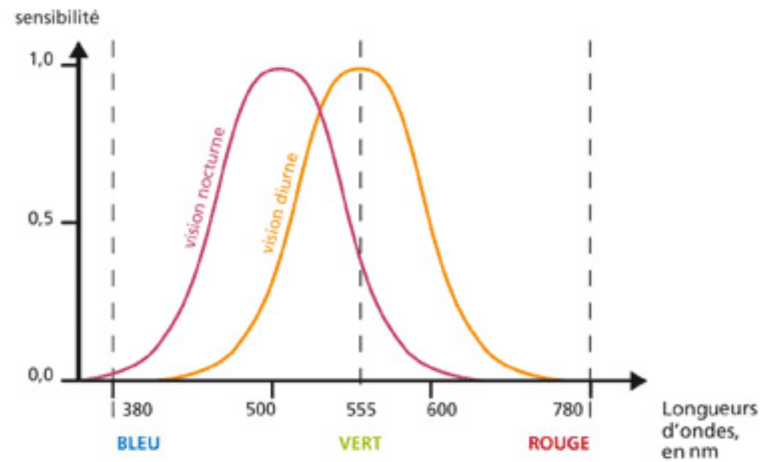
Colorimétrie

- Physique et physiologie
  - **L'œil sensible à la Luminance**
    - Du fait de l'optique de l'œil
  - Sensibilité dépend de la longueur d'onde $L(\lambda)$

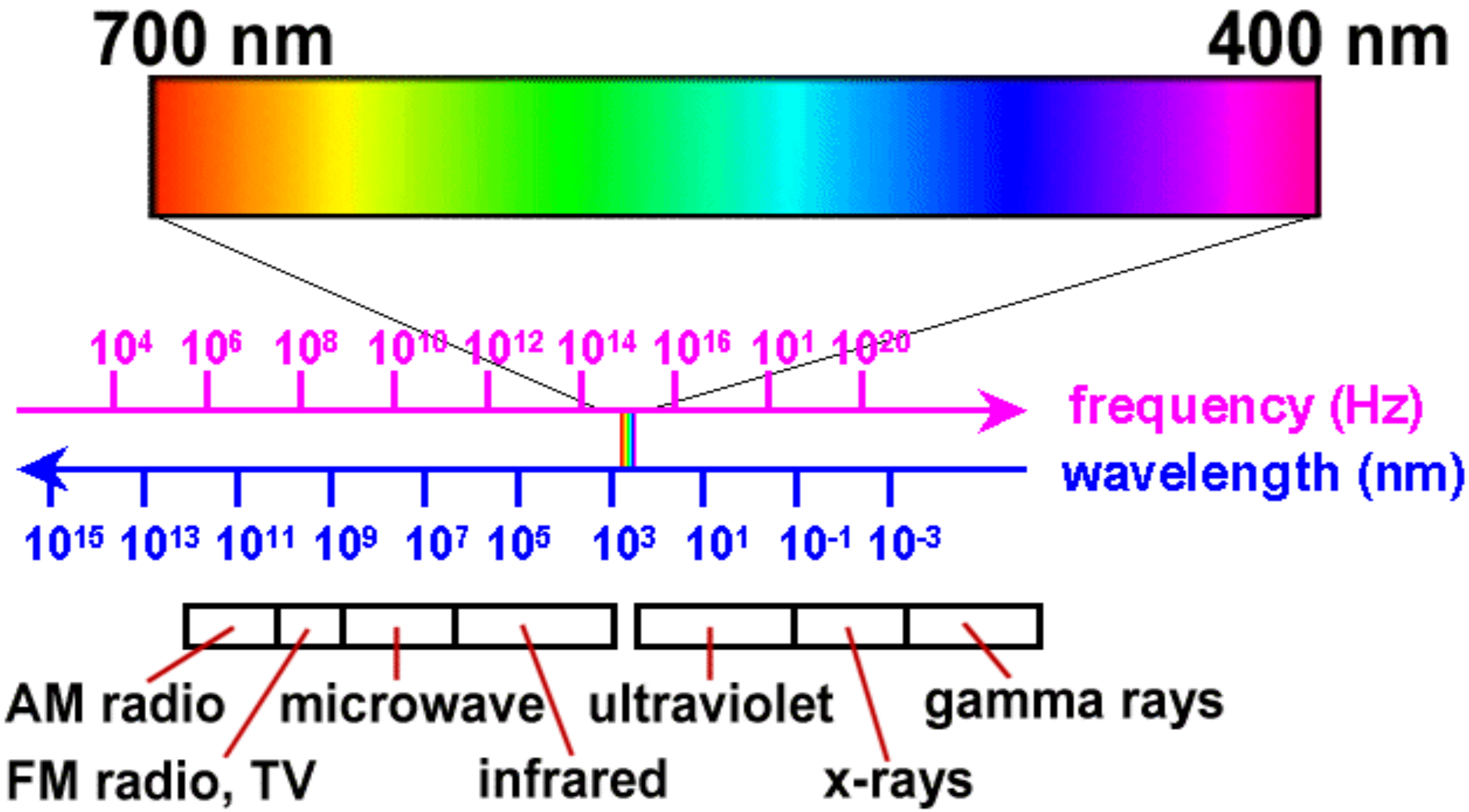


Colorimétrie

- Deux types de vison
  - Scotopique
    - Nocturne
    - Dénuée d'impression colorée
  - Photopique
    - Diurne
    - Impression colorée



The Visible Spectrum



Photons

- The basic quantity in lighting is the photon

- The energy (in Joule) of a photon with wavelength λ is: $\mathbf{q_\lambda = hc / \lambda}$
  - c is the speed of light
    - In vacuum, c = 299.792.458m/s
  - h ≈ $6.63*10^{-34}$Js is Planck's constant

Radiometry and Photometry

Radiant Energy and Power

- **Power**: Watts vs. Lumens
  - Energy per unit time
  - Spectral

Φ

- **Energy**: Joules vs. Talbot
  - Exposure
    - Film response
    - Skin - sunburn

(Spectral) Radiant Energy

- The *spectral radiant energy,* Q_λ, in n_λ photons with wavelength λ is

$$Q_\lambda = n_\lambda q_\lambda$$

- The *radiant energy,* Q, is the energy of a collection of photons, and is given as the integral of Q_λ over all possible wavelengths:

$$Q = \int_0^\infty Q_\lambda d\lambda$$

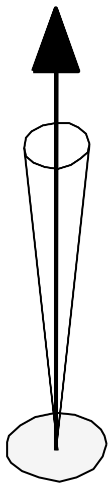
Radiometry vs. Photometry

- **Radiometry** [Units = Watts]
  - Physical measurement of electromagnetic energy
- **Photometry and Colorimetry** [Lumen]
  - Sensation as a function of wavelength
  - Relative perceptual measurement
- **Brightness, Lightness** [Brils] $B = Y^{1/3}$
  - Sensation at different brightness levels
  - Absolute perceptual measurement
  - Obeys Steven's Power Law

Radiance

- **Definition**: The surface *radiance* (*luminance*) is the intensity per unit area leaving a surface

$$L(x,\omega)$$



$$L(x,\omega) = \frac{d^2\Phi(x,\omega)}{d\omega dA}$$

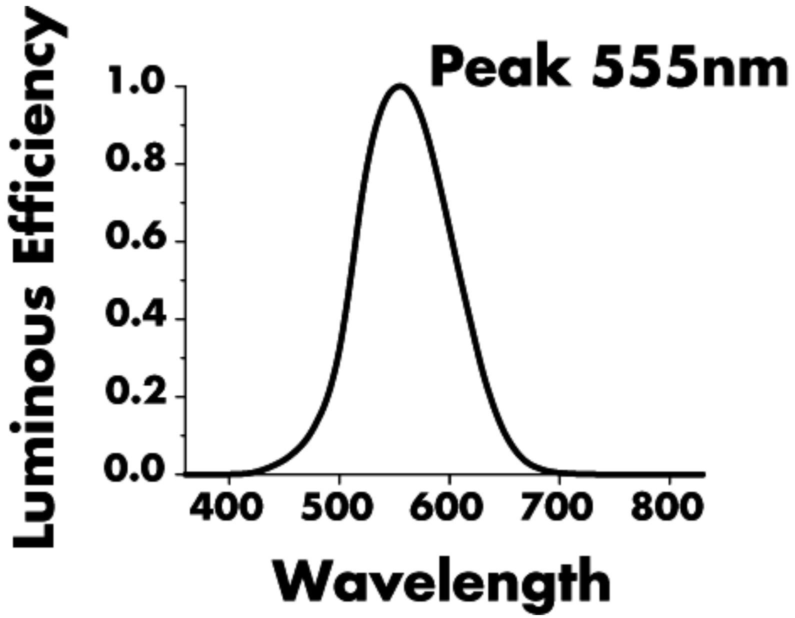
$$\left[\frac{W}{sr\, m^2}\right]\left[\frac{cd}{m^2} = \frac{lm}{sr\, m^2} = nit\right]$$

Radiometry vs. Photometry

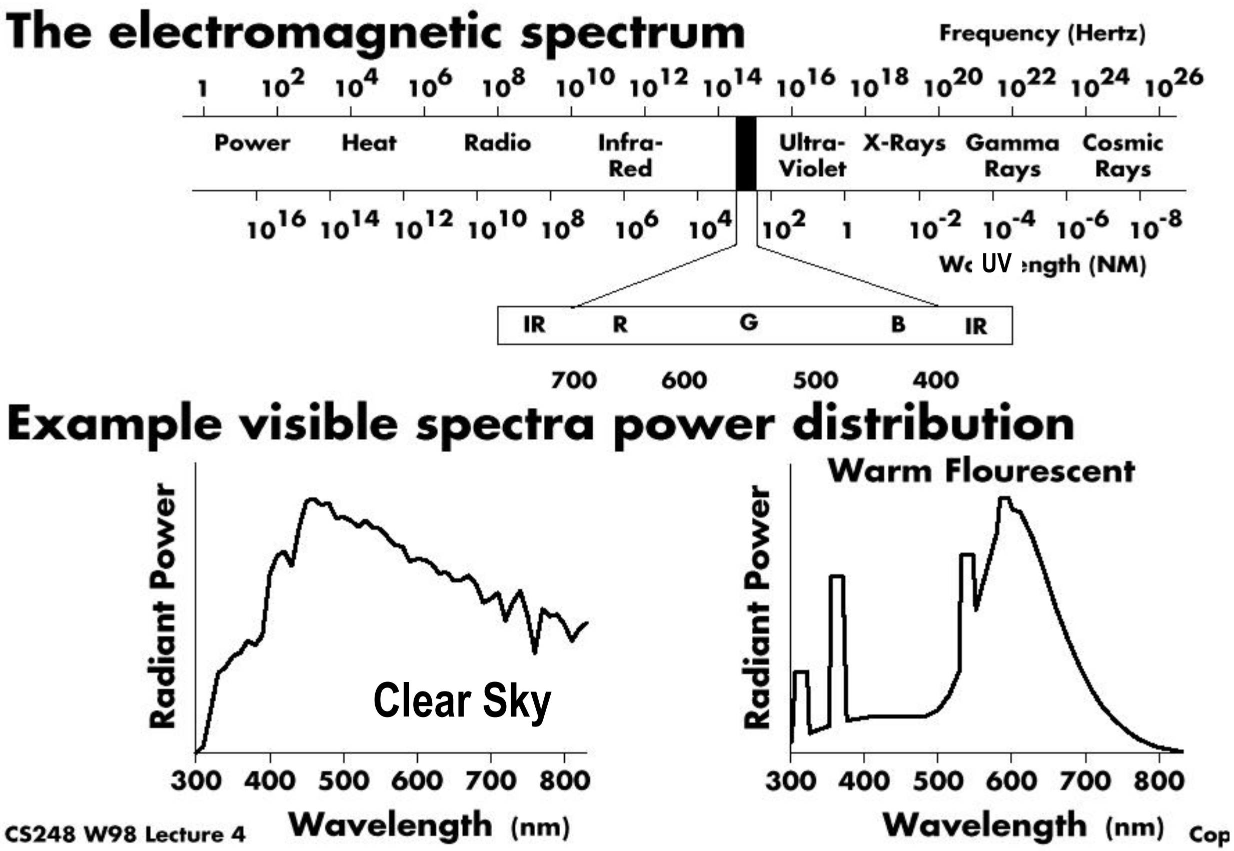
- **Radiometry and photometry**

  Photometric quantity = product of the radiometric quantity by the luminous efficiency $V(\lambda)$

$$Y = \int V(\lambda) L(\lambda) d\lambda$$



Daylight Vision



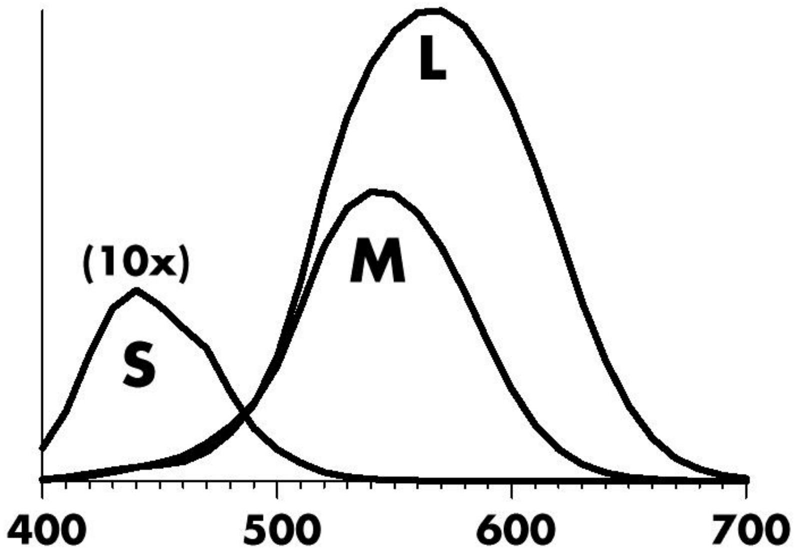
Human Colour Vision

- There are 3 light sensitive pigments in your cones (L,M,S), each with different *spectral response curve.*

$$L = \int L(\lambda) \cdot E(\lambda)$$

$$M = \int M(\lambda) \cdot E(\lambda)$$

$$S = \int S(\lambda) \cdot E(\lambda)$$



Colour Matching is Linear!

Grassman's Laws

- Scaling the colour and the primaries by the same factor preserves the match :

$$2C=2R+2G+2B$$

- To match a colour formed by adding two colours, add the primaries for each colour

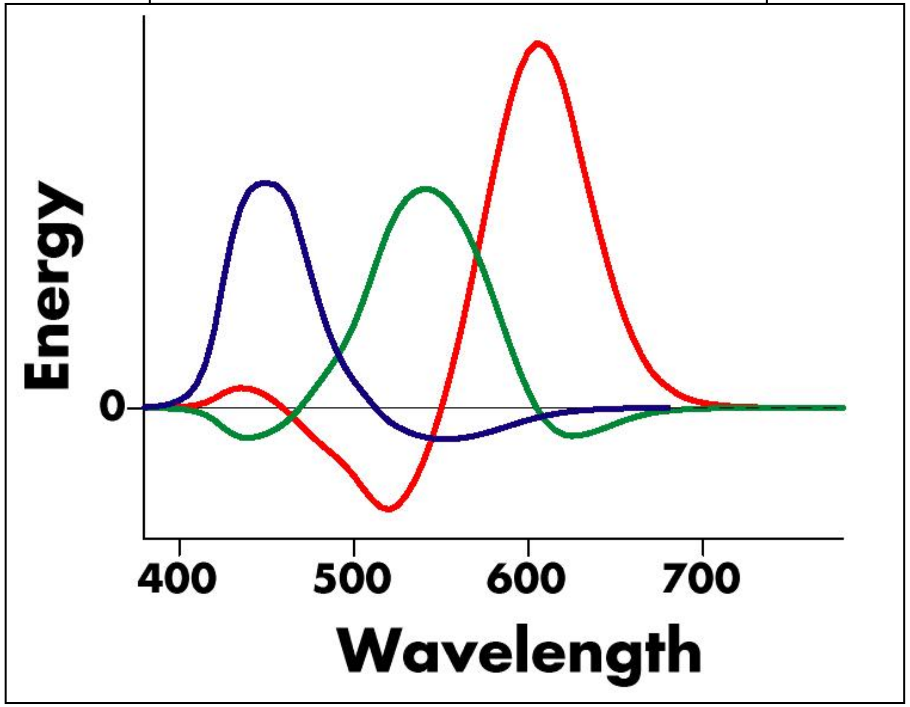
$$C_1+C_2=(R_1+R_2)+(G_1+G_2)+(B_1+B_2)$$

Spectral Matching Curves

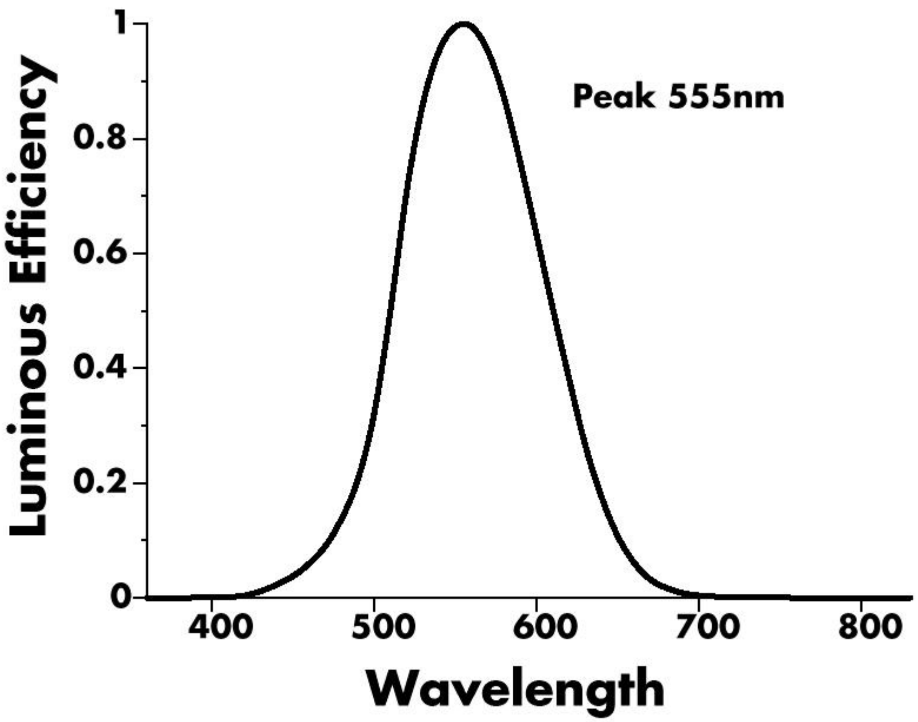
Match each pure colour in the visible spectrum with the 3 primaries, and record the values of the three as a function of wavelength.

Note : We need to specify a negative amount of one primary to represent all colours.

Red, Green & Blue primaries.



Luminance



Compare colour source
to a grey source

- Luminance

Y = .30R + .59G + .11B

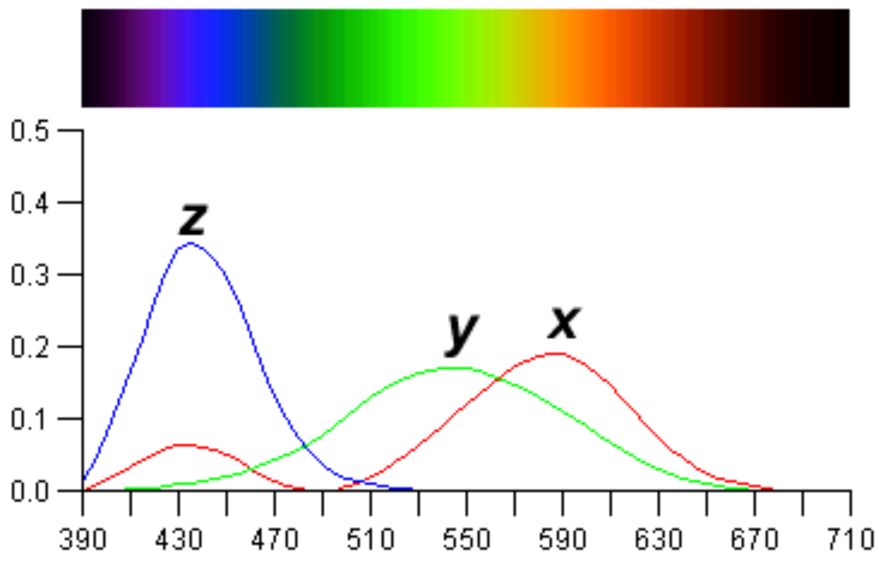
Colour signal on a B&W TV
(Except for gamma, of course)

- Perceptual measure : Lightness

$$L = Y^{1/3}$$

CIE Colour Space

For only positive mixing coefficients, the CIE (Commission Internationale d'Eclairage) defined 3 new hypothetical light sources x, y and z (as shown) to replace red, green and blue.

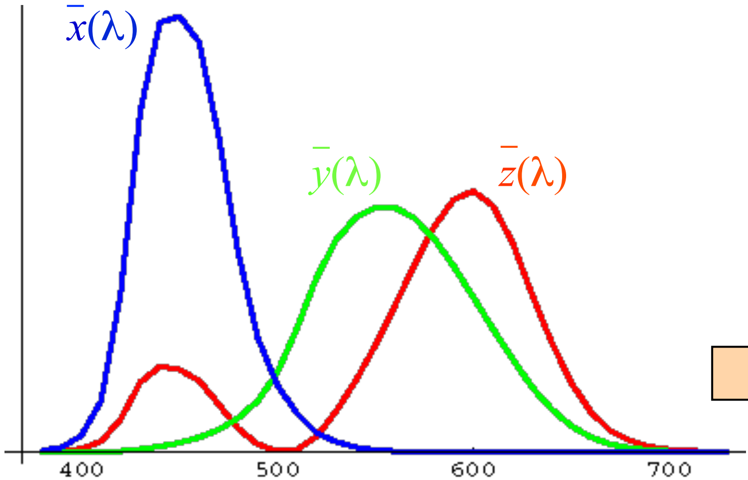


Primary Y intentionally has same response as luminance response of the eye.

The weights X, Y, Z form the 3D CIE XYZ space (see next slide).

CIE-XYZ Color Space

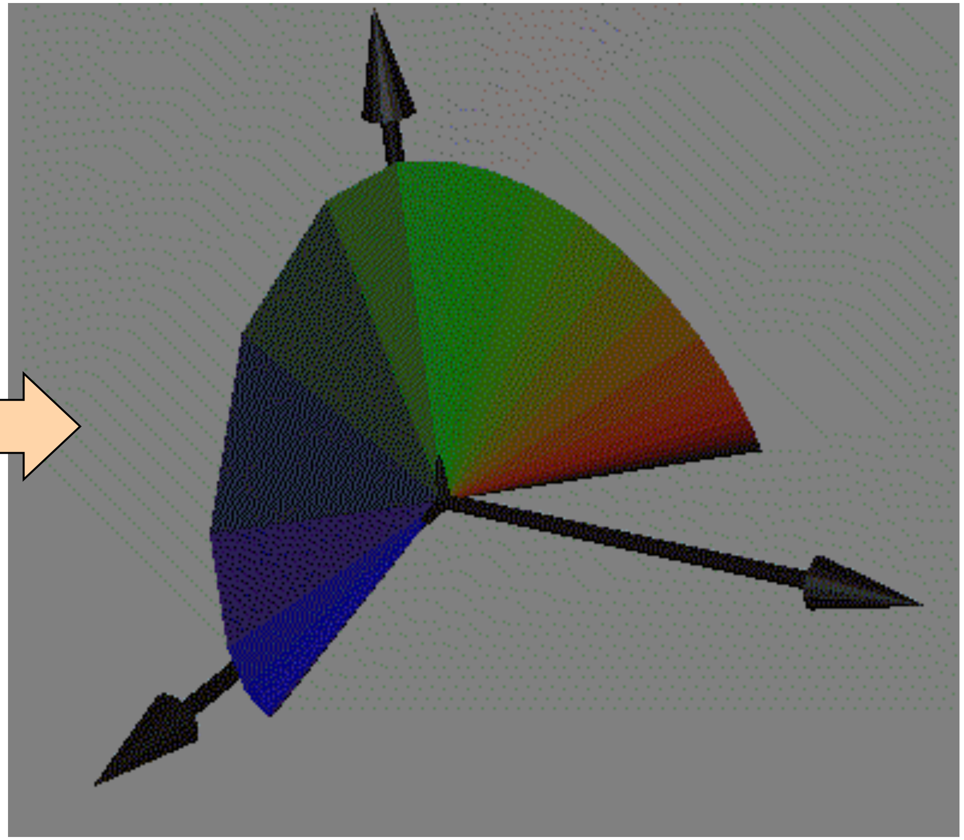
Color-matching curves



$$X = \int_{380}^{780} C(\lambda)\overline{x}(\lambda)d\lambda$$

$$Y = \int_{380}^{780} C(\lambda)\overline{y}(\lambda)d\lambda$$

$$Z = \int_{380}^{780} C(\lambda)\overline{z}(\lambda)d\lambda$$



Chromaticity Diagram

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2.77 & 1.75 & 1.13 \\ 1.00 & 4.59 & 0.06 \\ 0.00 & 0.57 & 5.59 \end{bmatrix} \begin{bmatrix} R_\lambda \\ G_\lambda \\ B_\lambda \end{bmatrix}$$

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

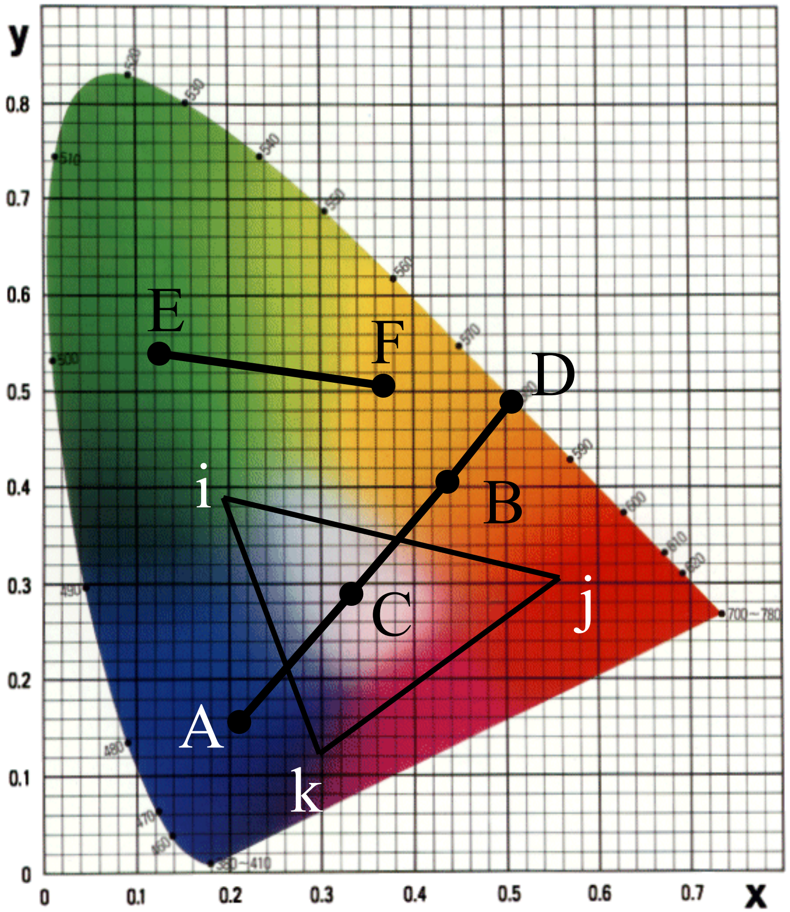
$$z = \frac{Z}{X + Y + Z}$$

Normalise by the total amount of light energy.

Often convenient to work in 2D colour space, so 3D colour space projected onto the plane X+Y+Z=1 to yield the *chromaticity diagram.*

The projection is shown opposite and the diagram appears on the next slide.

CIE Chromaticity Diagram



C is "white" and close to x=y=z=1/3

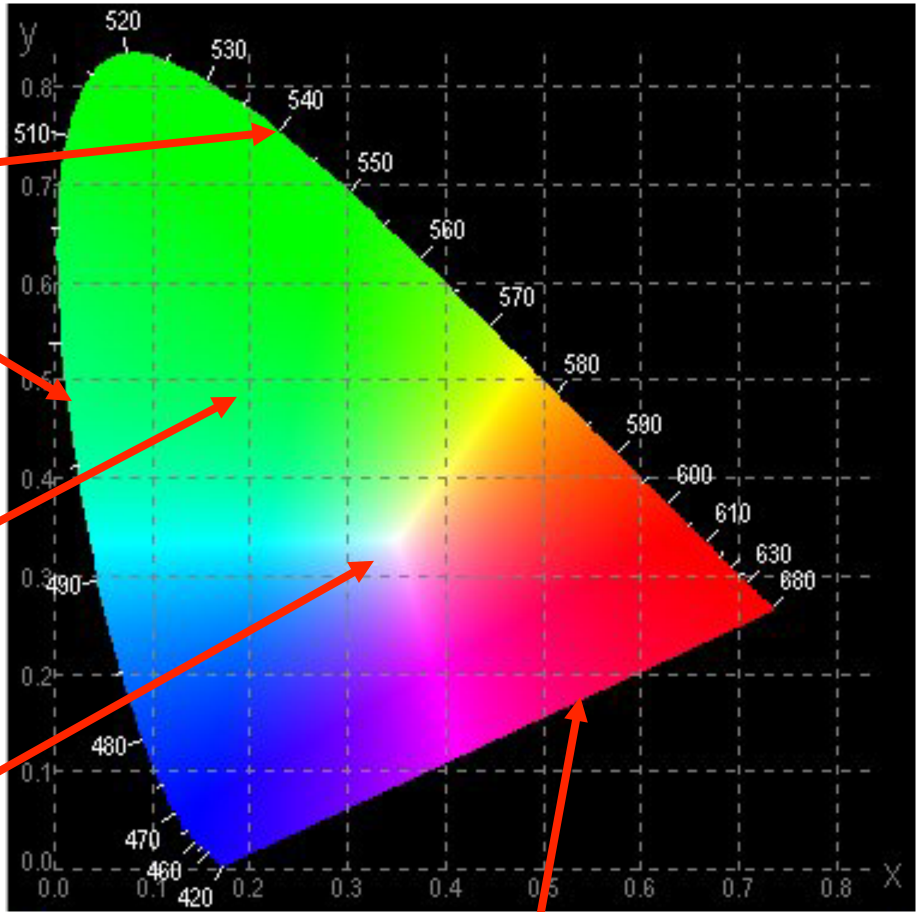
The dominant wavelength of a colour, eg. B, is where the line from C through B meets the spectrum, 580nm for B (tint).

A and B can be mixed to produce any colour along the line AB here including white. True for EF (no white this time).

True for ijk (includes white)

The Colors in the Chromaticity Diagram

Spectrally pure colors (monochromatic or prismatic) on the contour



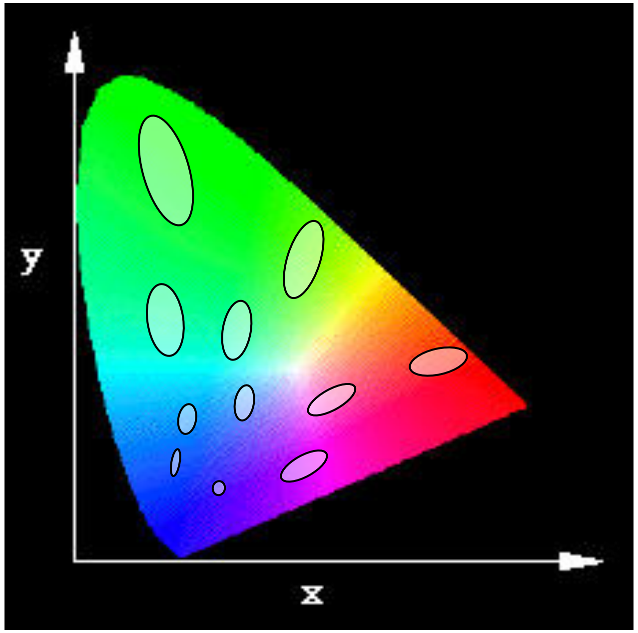
Visible spectrum

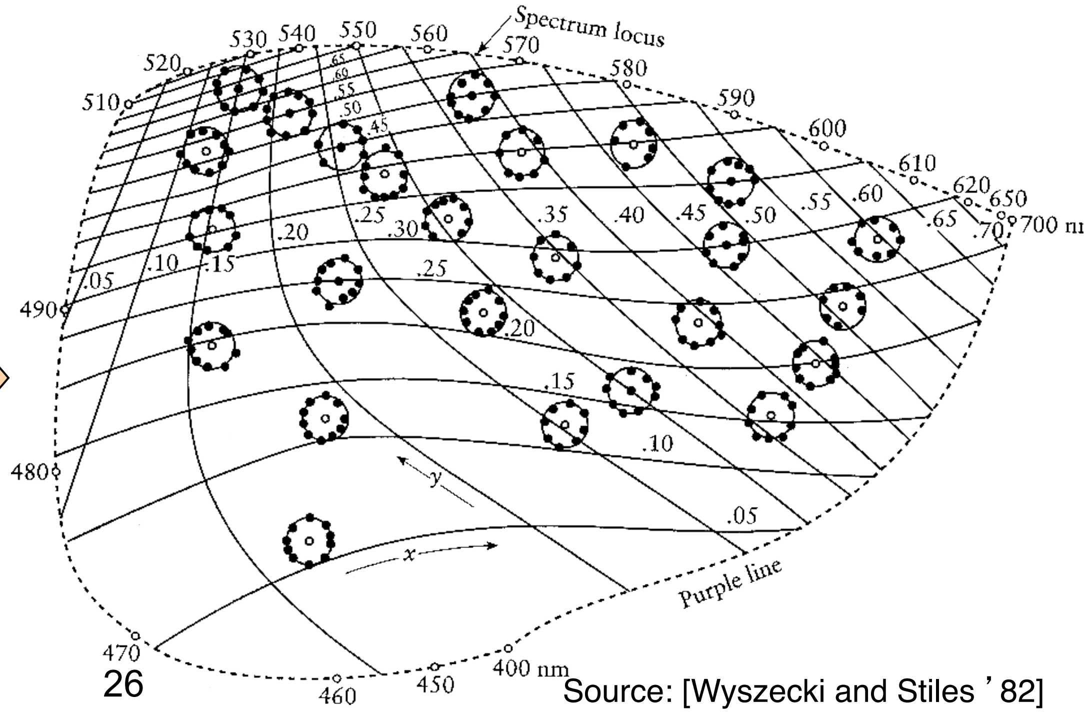
Neutral illuminant white

Non-spectral colors (purples and magentas) no dominant wavelength

Perceptually Uniform Space: MacAdam

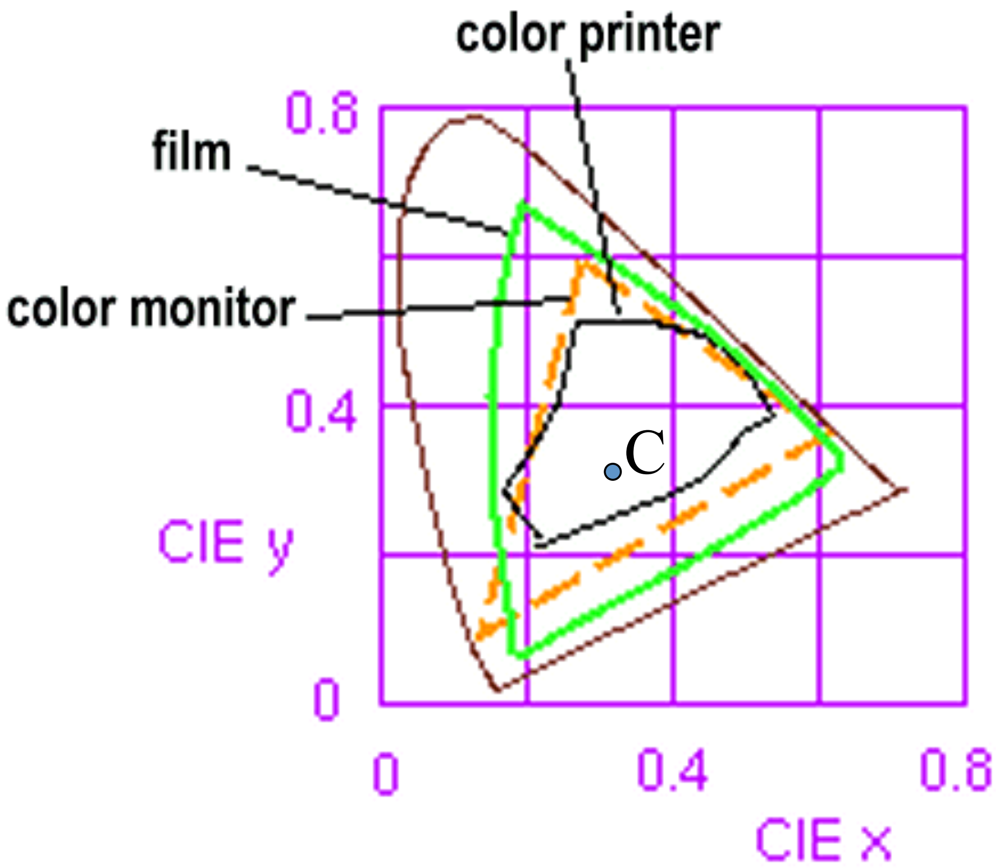
- In color space CIE-XYZ, the perceived distance between colors is not equal everywhere
- In perceptually uniform color space, Euclidean distances reflect perceived differences between colors
- MacAdam ellipses (areas of unperceivable differences) become circles





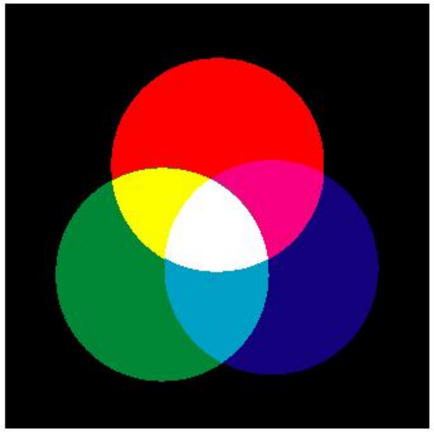
Source: [Wyszecki and Stiles ’82]

Some device colour “gamuts”

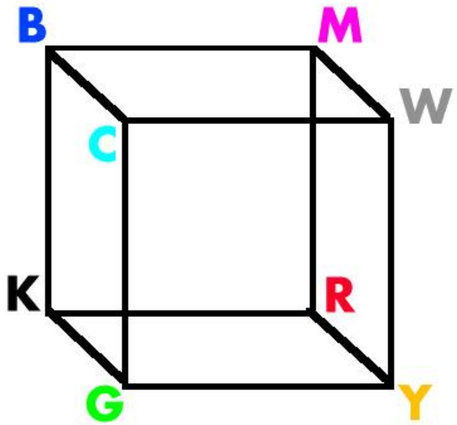


The diagram can be used to compare the gamuts of various devices. Note particularly that a colour printer can’t reproduce all the colours of a colour monitor. Note no triangle can cover all of visible space.

Colour Cube

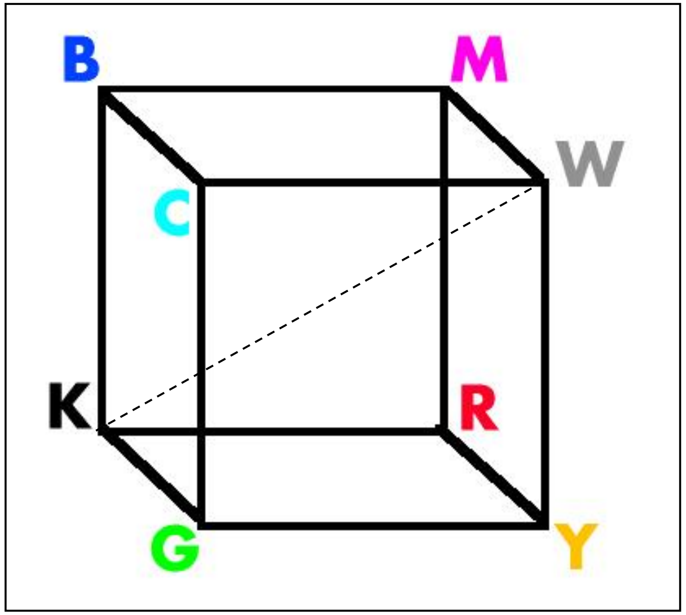


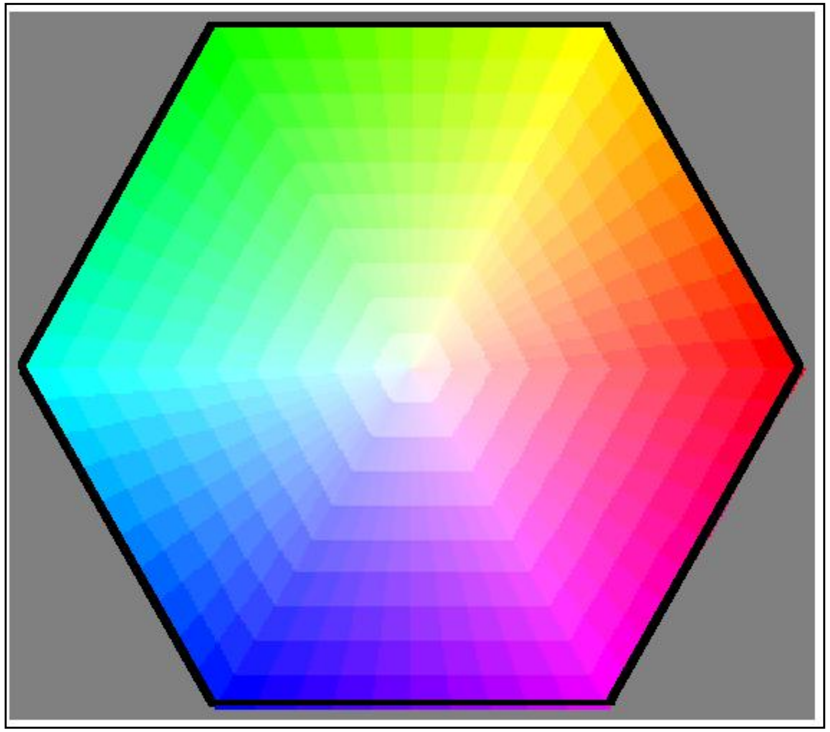
R,G,B model is *additive*, i.e we add amounts of 3 primaries to get required colour.



Can visualize RGB space as cube, grey values occur on diagonal K to W.

Intuitive Colour Spaces

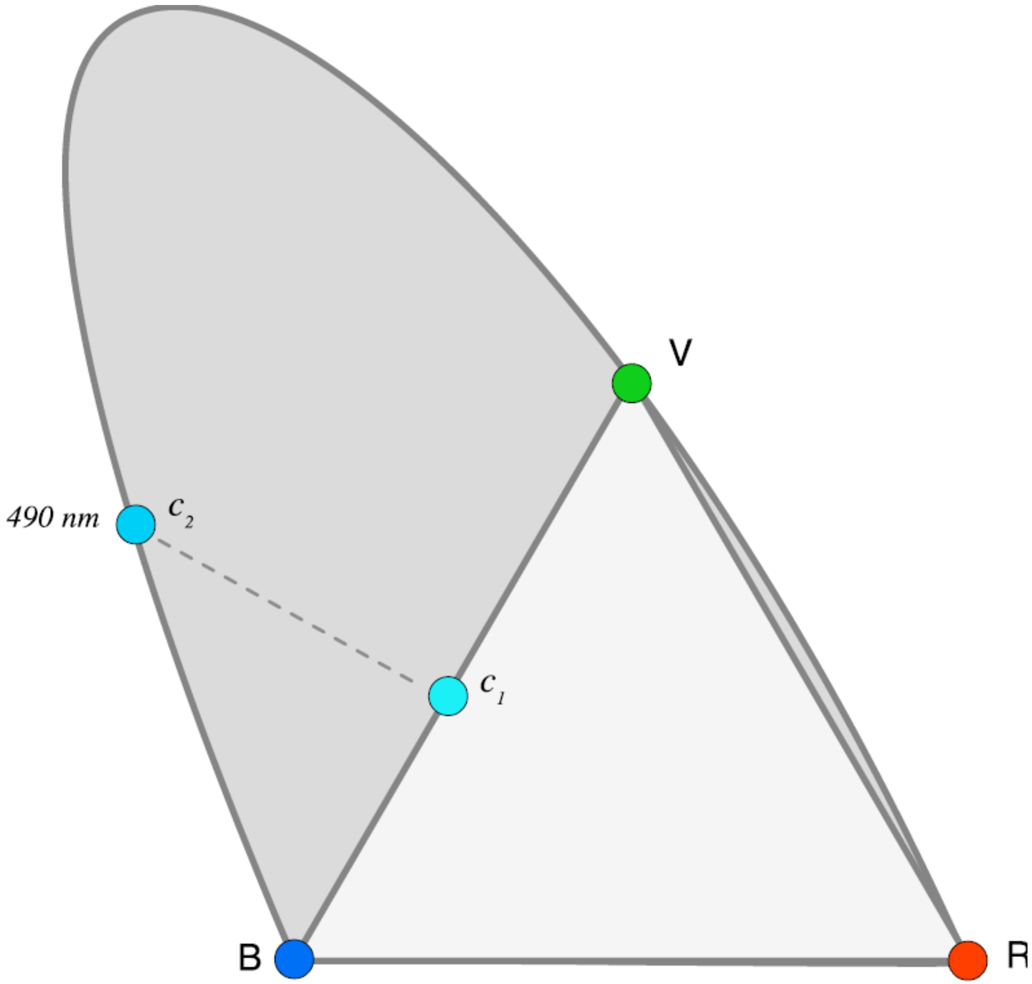




Hexagon is a diagonal Cross-Section of the 3D Colour Cube.

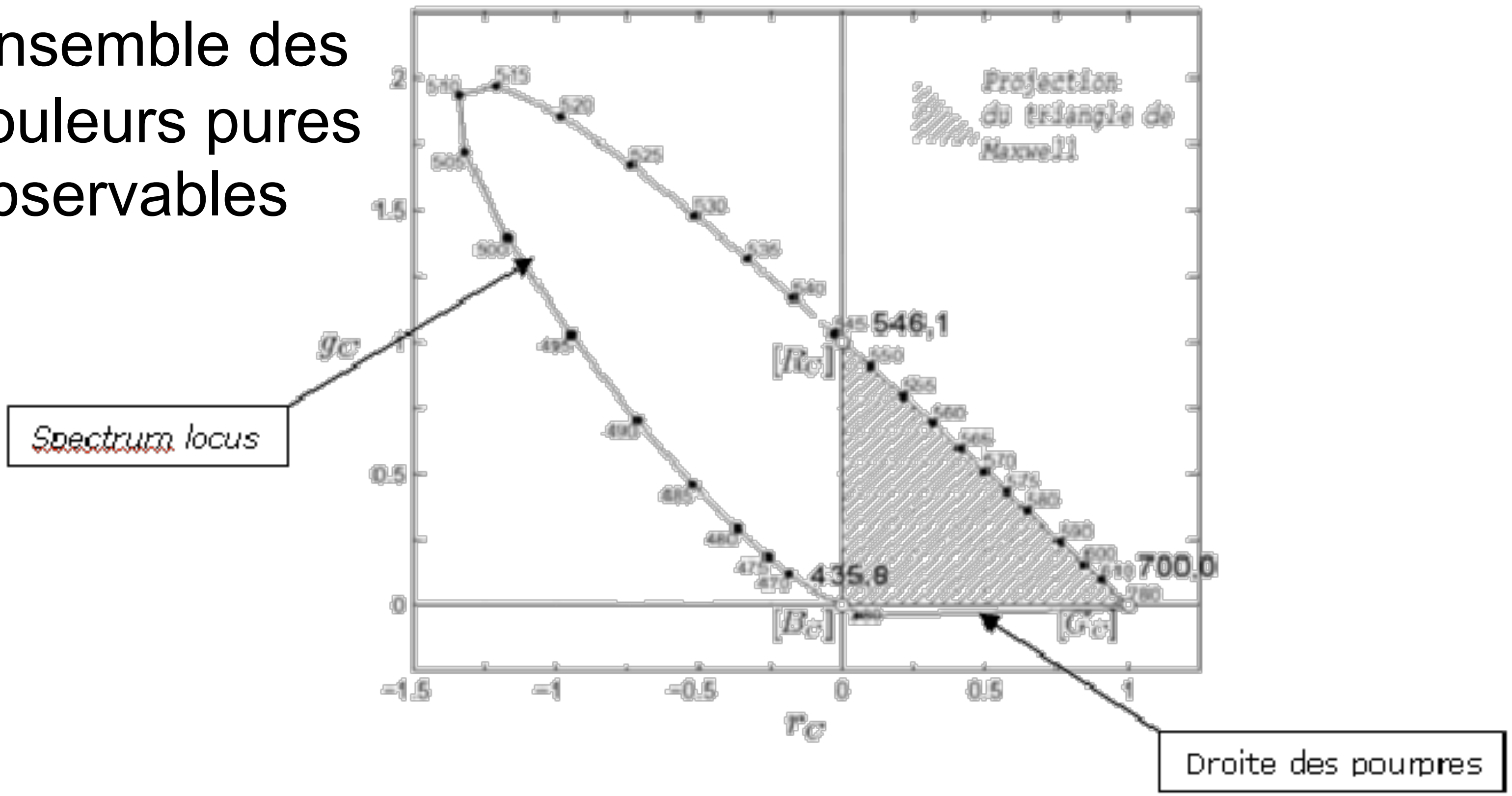
Espace de couleurs : RGB

- Gamme de couleur
  - Lieu du spectre visible
  - Diagramme de chromaticité
    - r = R /(R+G+B)
    - g = G /(R+G+B)
    - b = B/(R+G+B)

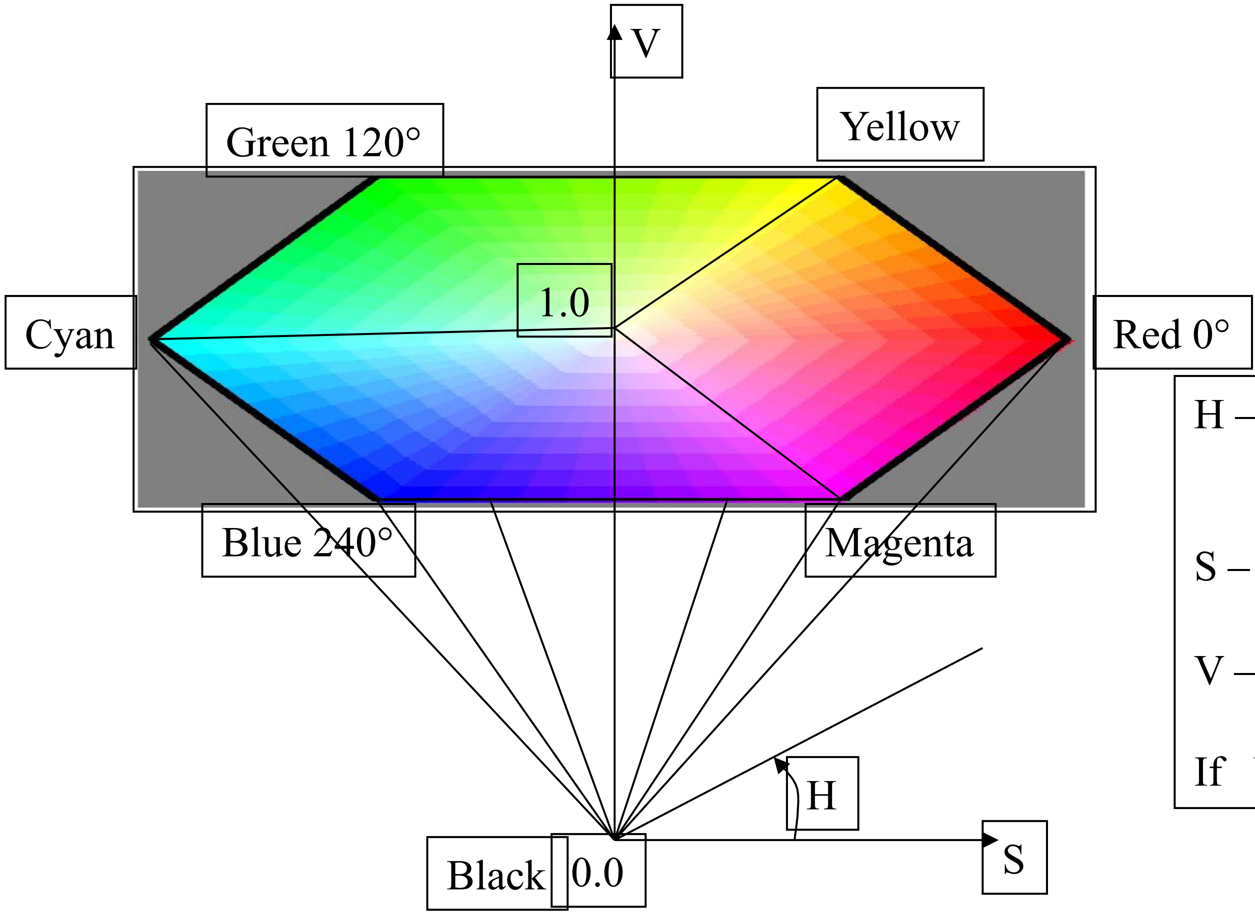


Espaces de couleurs : RGB

- RGB et spectrum locus
  - Ensemble des couleurs pures observables



The HSV Colour Space



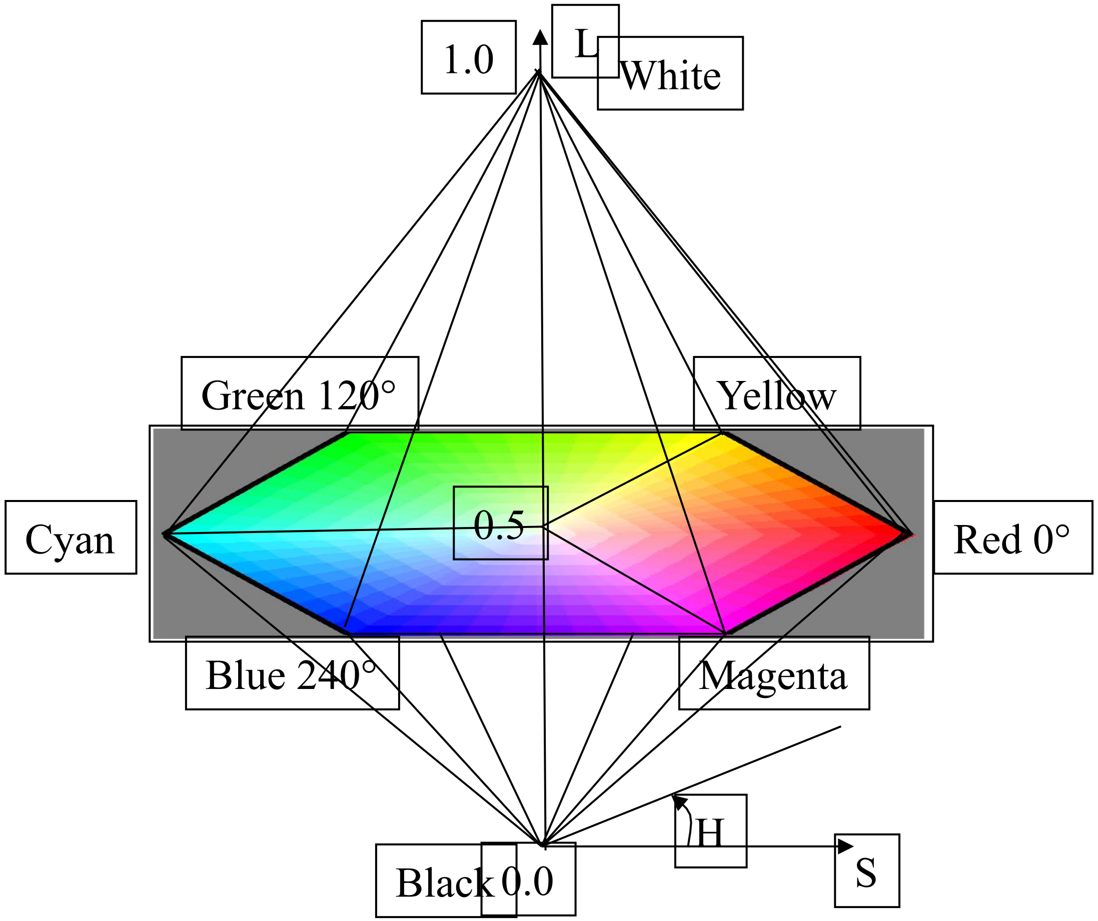
H – Hue, or the colour of the pure pigment.

S – Saturation of the colour.

V – Value, or brightness.

If V = 0, H is Undefined.

The HSL (HSB) Colour Space



H – Hue, or the colour of the pure pigment, angle around the axis.

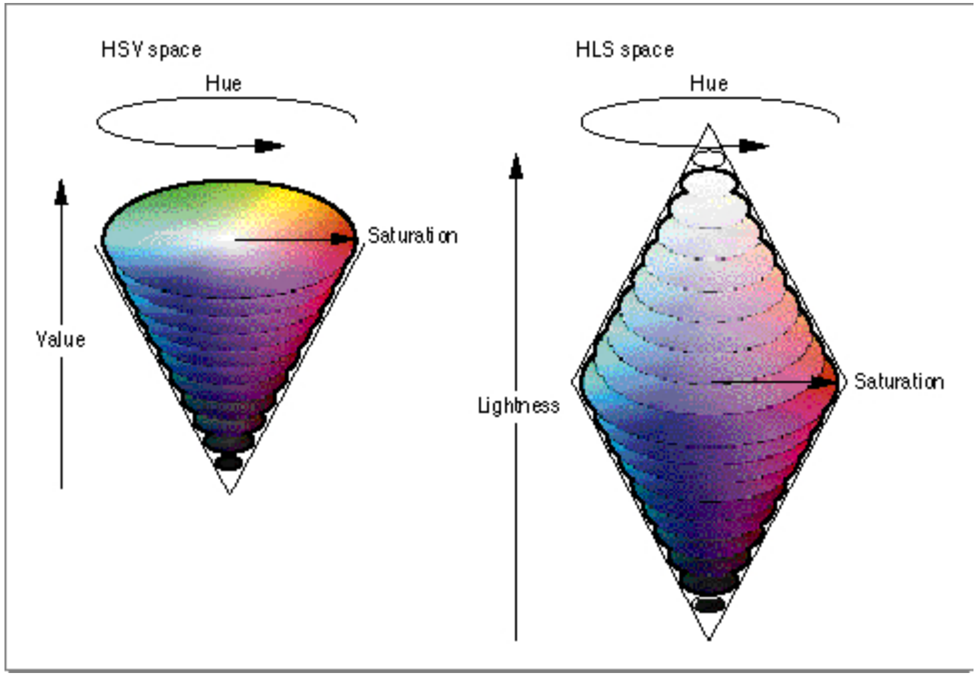
S – Saturation of the colour, distance from the axis. a measure of the "purity" of a hue. As saturation is decreased, the hue becomes more gray. A saturation value of zero results in a gray-scale value.

L – Lightness, or brightness, distance along the axis.

If L = 0,1 H is Undefined.

Maximum saturation occurs when L = 0.5

The HSL (HSB) Colour Space



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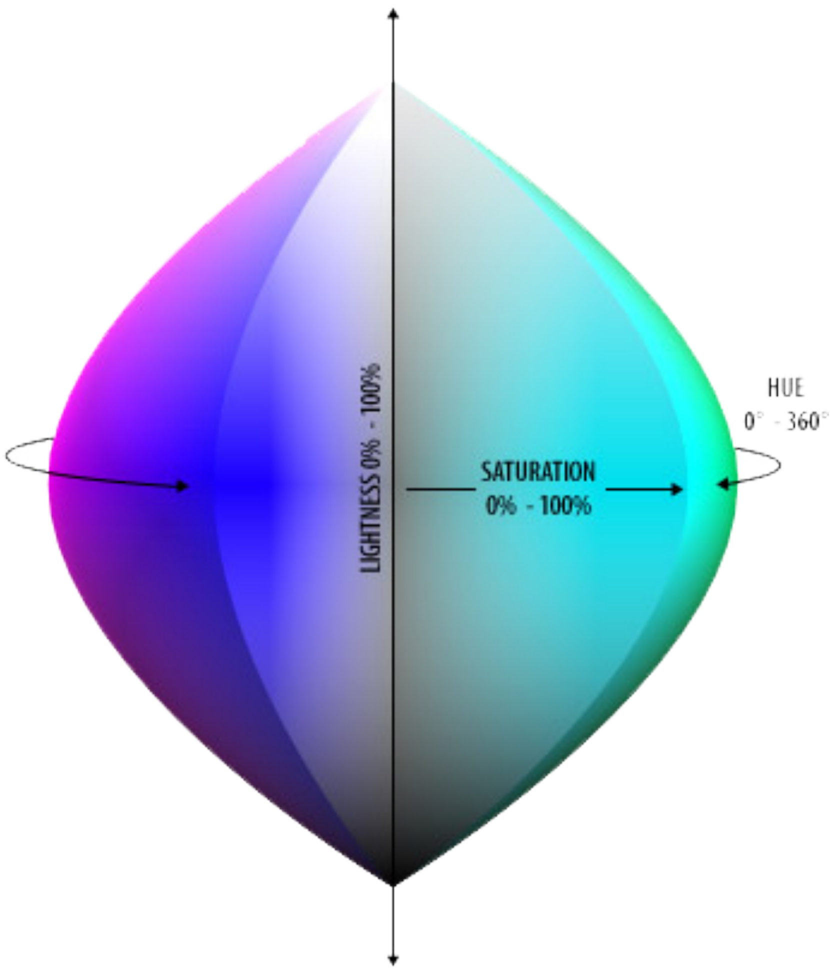
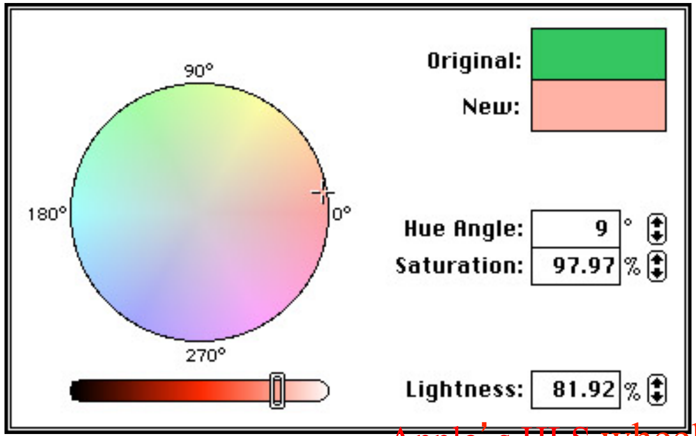
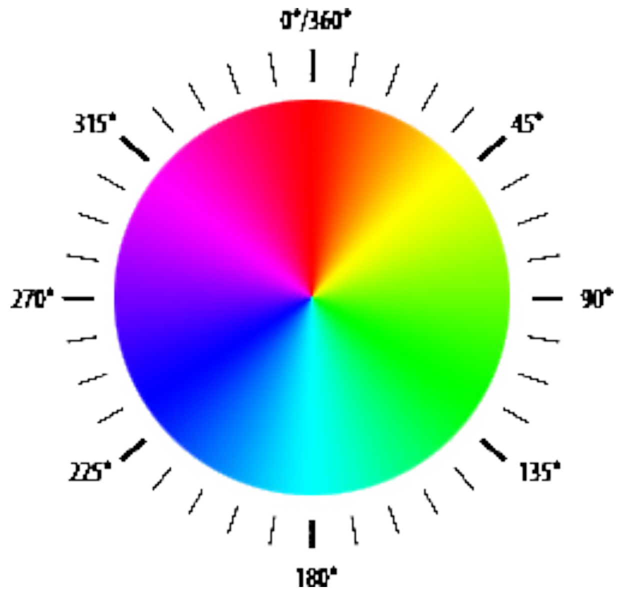
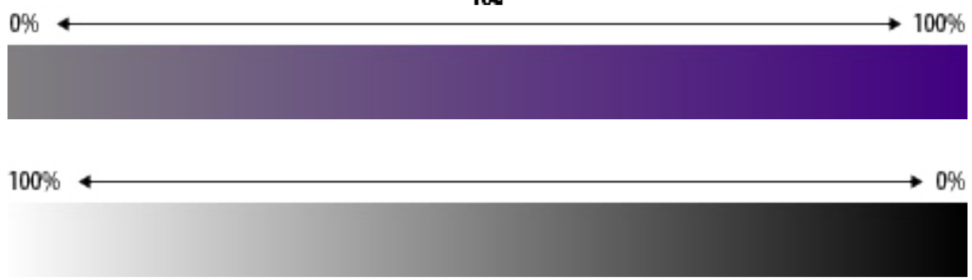
Color Pickers: HSL



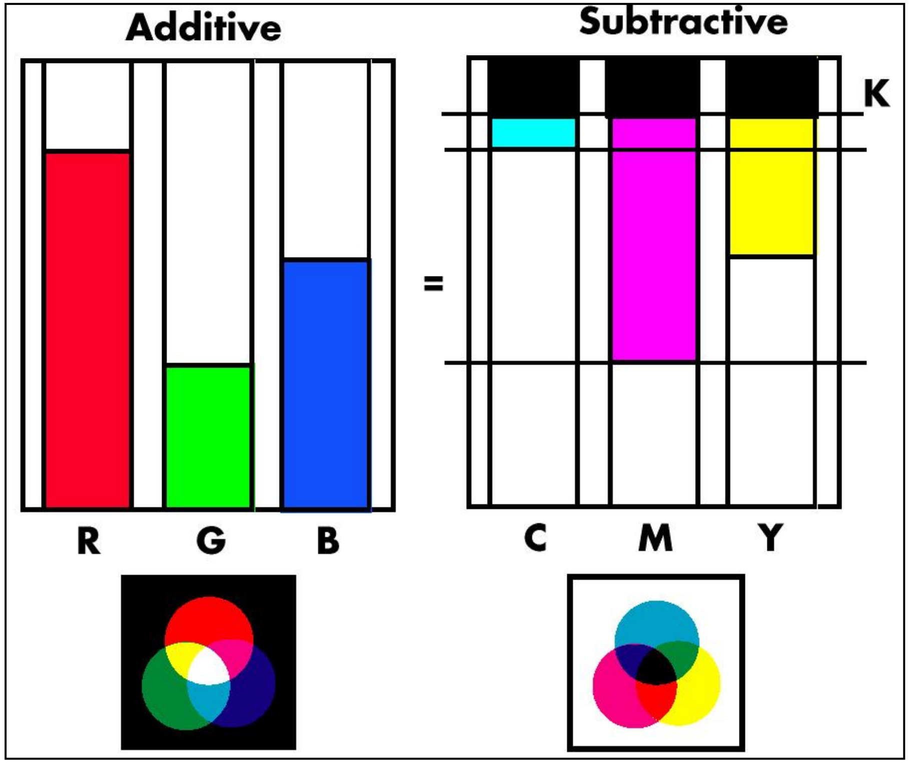


Apple's HLS wheel





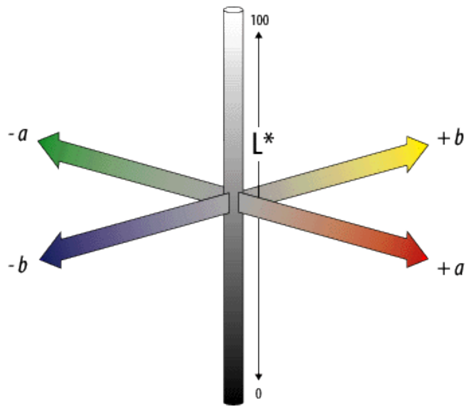
CMYK – Subtractive Colour Model

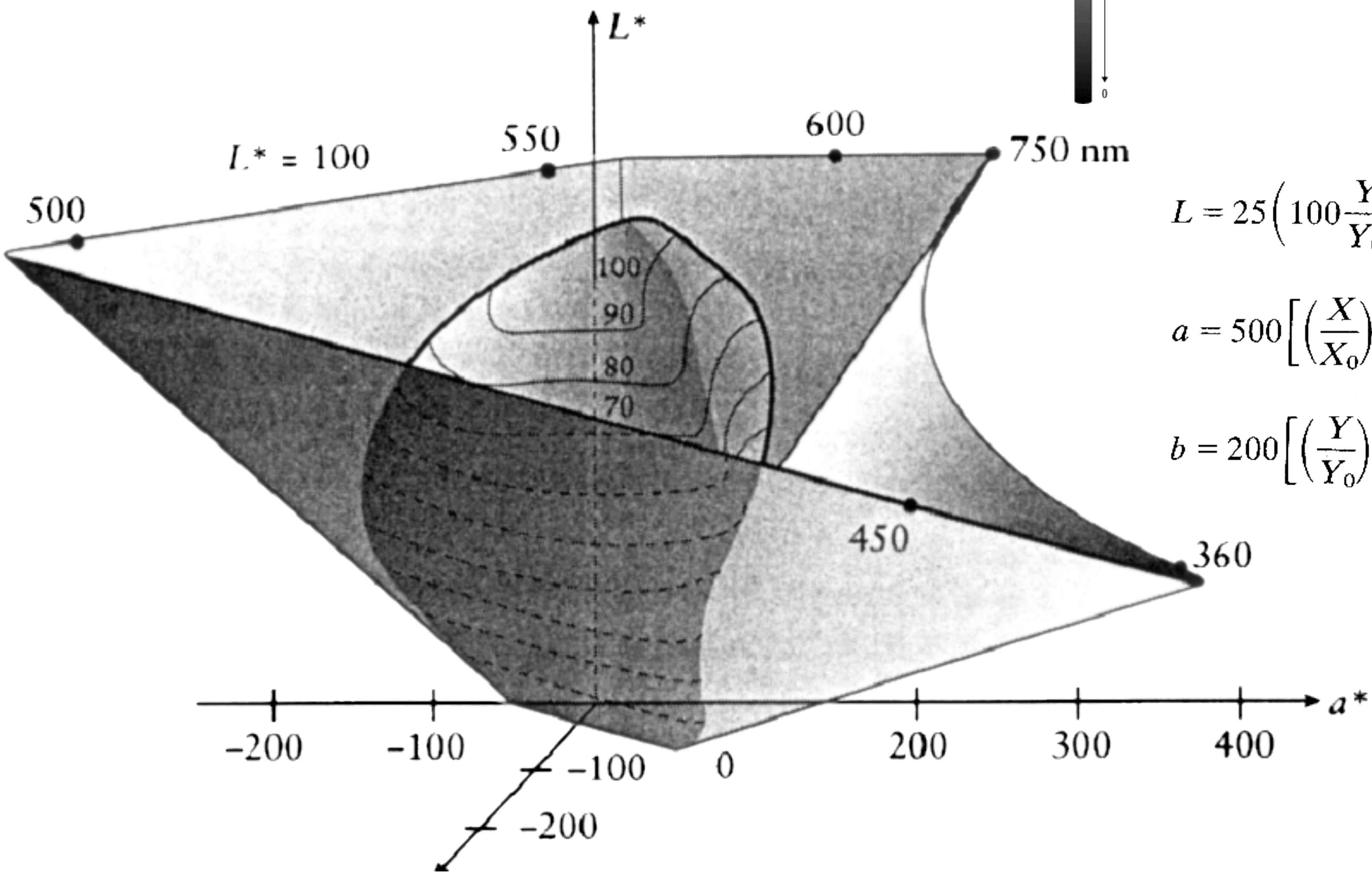


$$R = (1-C)\,(1-K)\,W$$
$$G = (1-M)\,(1-K)\,W$$
$$B = (1-Y)\,(1-K)\,W$$

$$K = G(1-\max(R,G,B))$$
$$C = 1 - R/(1-K)$$
$$M = 1 - G/(1-K)$$
$$Y = 1 - B/(1-K)$$

CIE-LAB





$$L = 25\left(100\frac{Y}{Y_0}\right)^{1/3} - 16$$

$$a = 500\left[\left(\frac{X}{X_0}\right)^{1/3} - \left(\frac{Y}{Y_0}\right)^{1/3}\right]$$

$$b = 200\left[\left(\frac{Y}{Y_0}\right)^{1/3} - \left(\frac{Z}{Z_0}\right)^{1/3}\right]$$

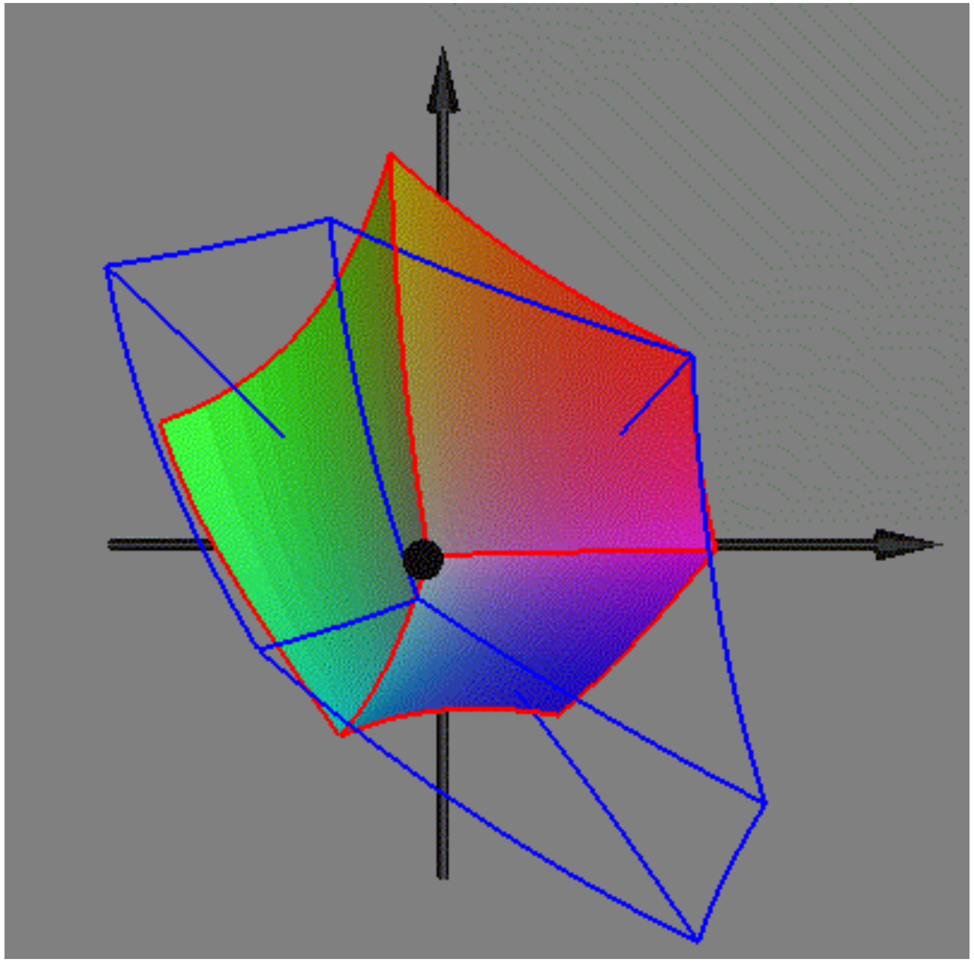
Source: [Wyszecki and Stiles ’82]

Gamut Mapping

CIE-LAB

Perceptually-uniform Color space

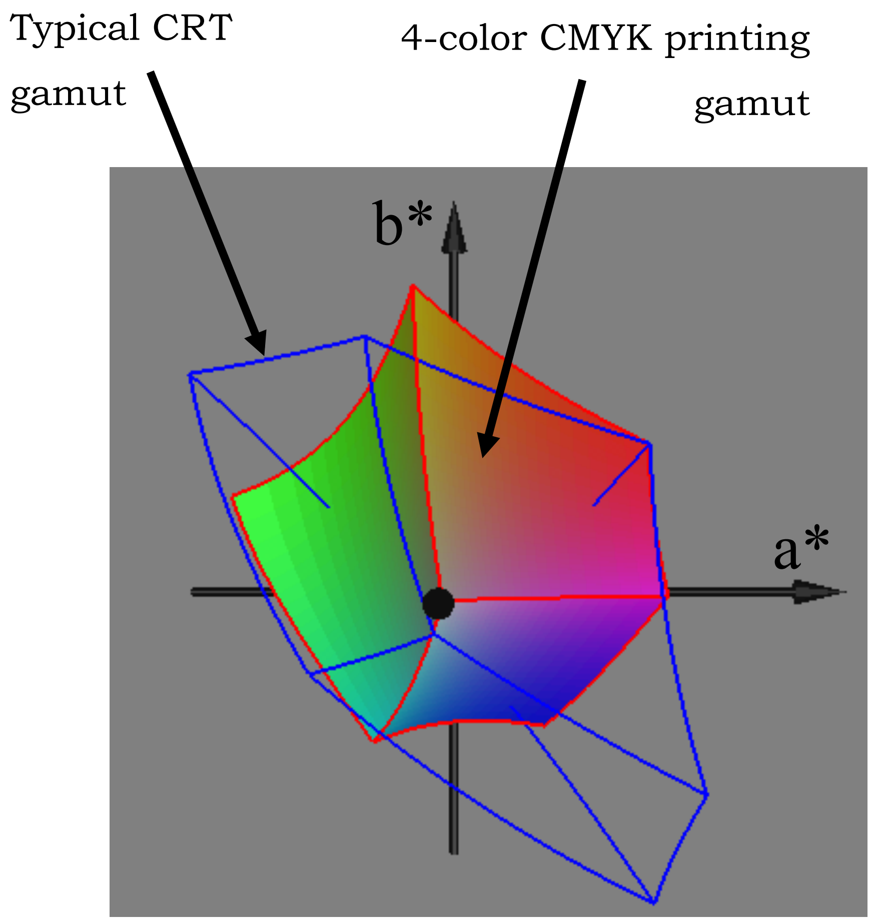
- Color gamut of different processes may be different (e.g. CRT display and 4-color printing process)
- Need to map one 3D color space into another



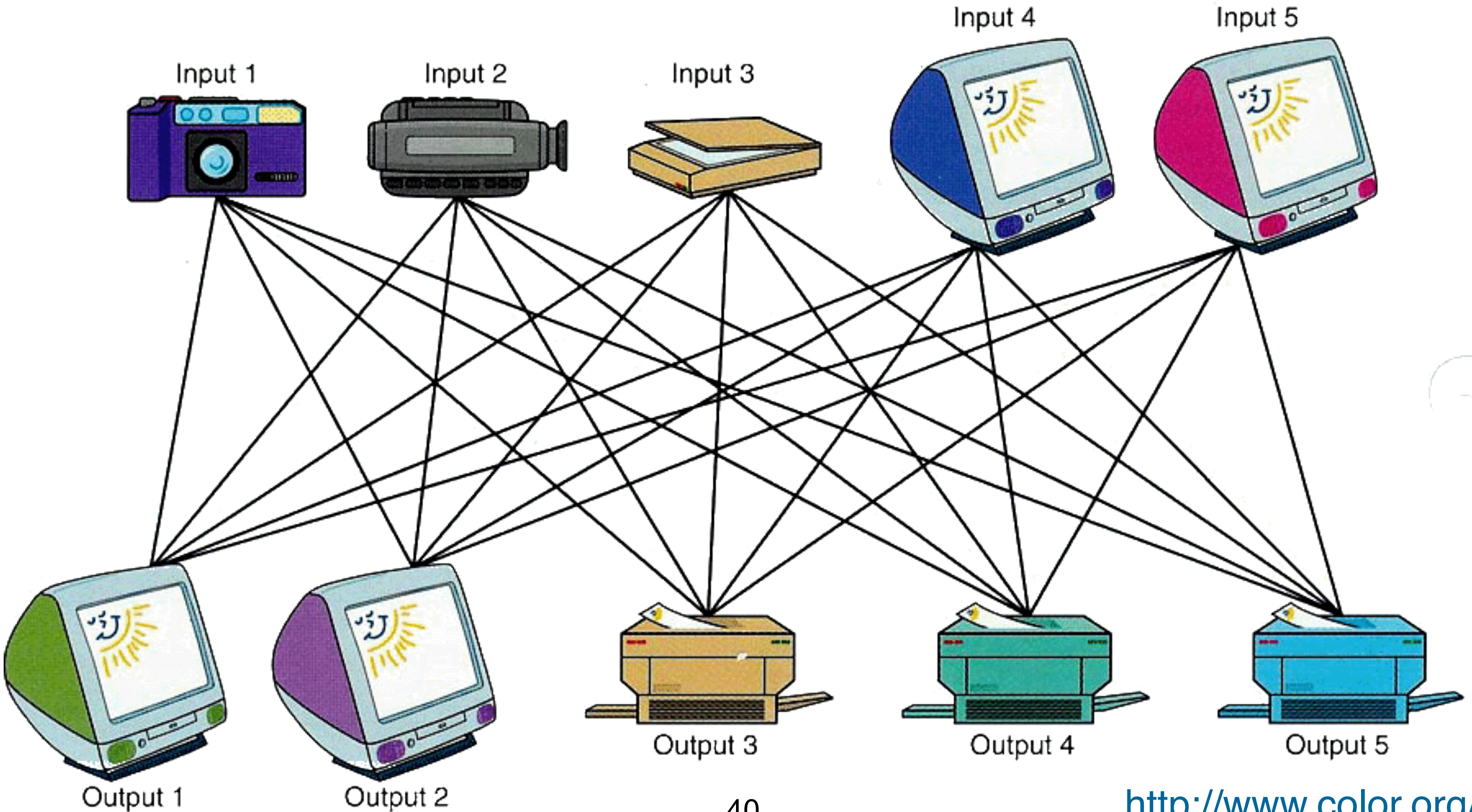
Typical CRT gamut

4-color printing gamut

Gamut Mapping



Device-Dependent Color



http://www.color.org/

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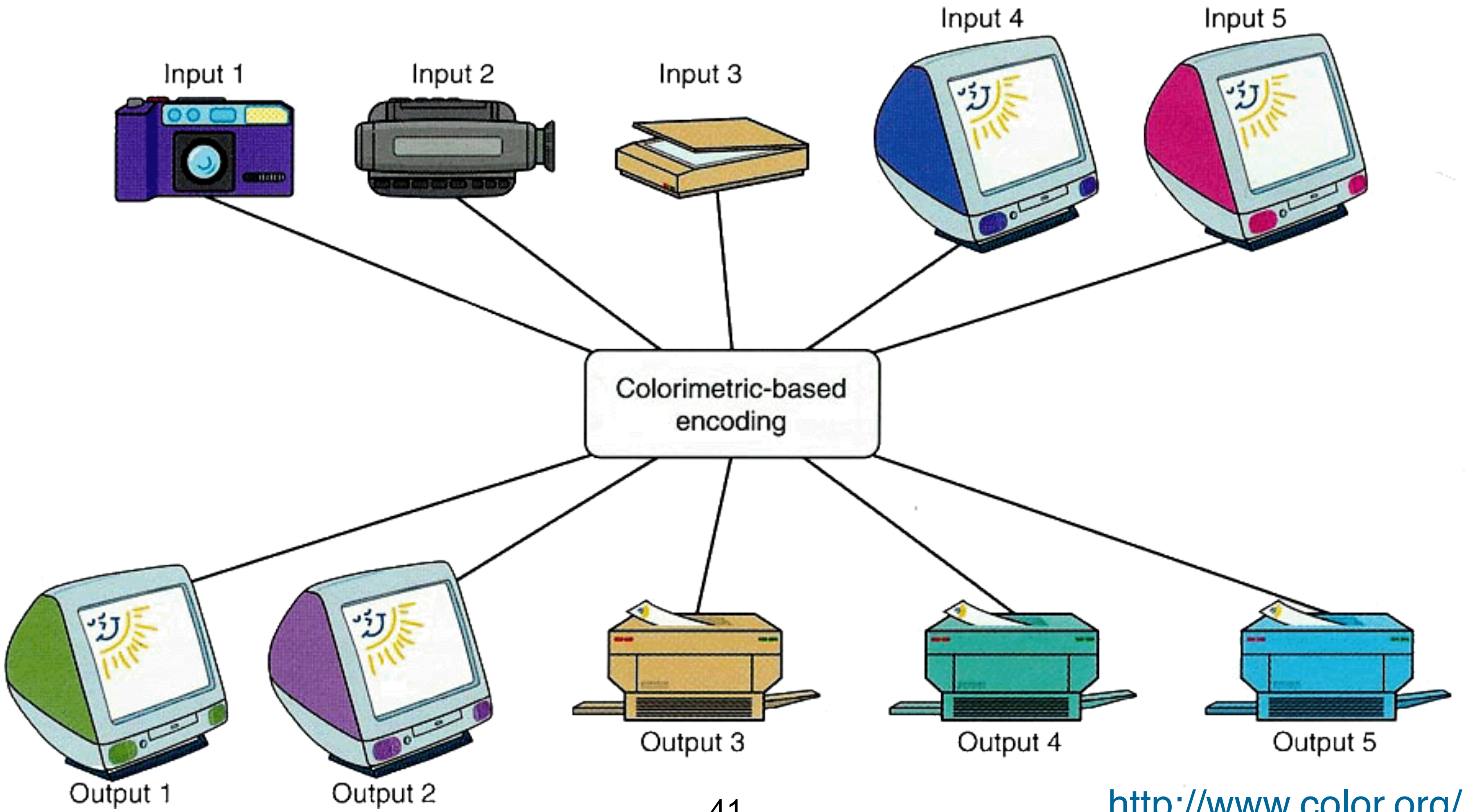

http://www.color.org/

Colour, Physics & Light - Summary

- Humans have tri-chromatic vision.
- All visible colours represented in CIE colour diagram.
- No three selected primaries in CIE colour space can generate all visible colours.
- Intuitive colour spaces.
- Subtractive colour models for hard copy.