Colorimetry

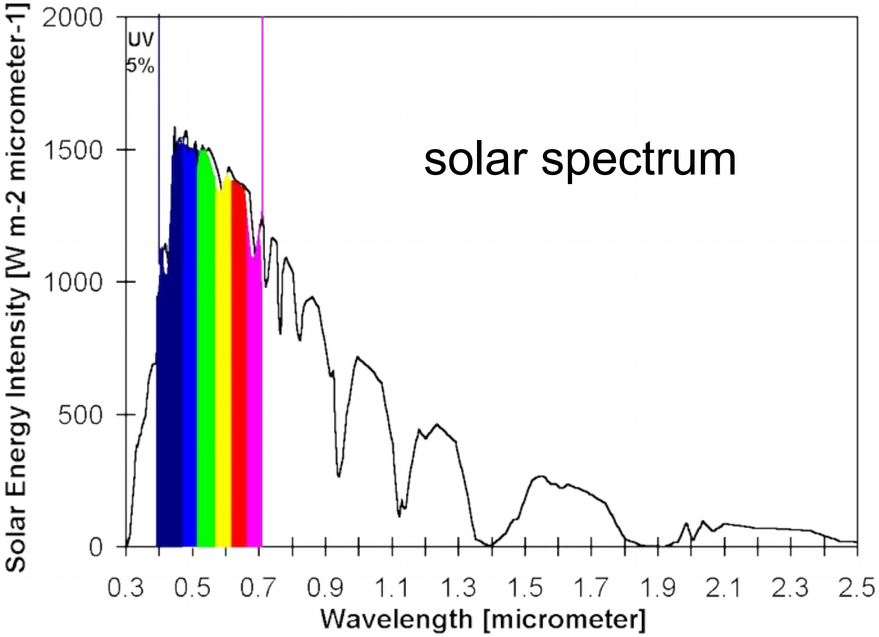
Colorimetry

Colorimetry

- Science related to the perception of colors
- Perceptive « Measure » of color
  - Never an objective measure : the perceived color depends on the capturing device. Here, it is the human eye. Other species see differently (Bees do see ultraviolet for instance)
  - Goal here : accurate reproduction of colors from our point of view.
- What is color ?
  - Light = mix of radiations having different wavelengths
  - different wavelengths = different colors
  - Light may be decomposed into a spectrum = separation of photons (light quanta) with respect to the different wavelengths

Colorimetry

- Spectrum measure: Watt per square meter per nanometer (of wavelength) (/steradian)



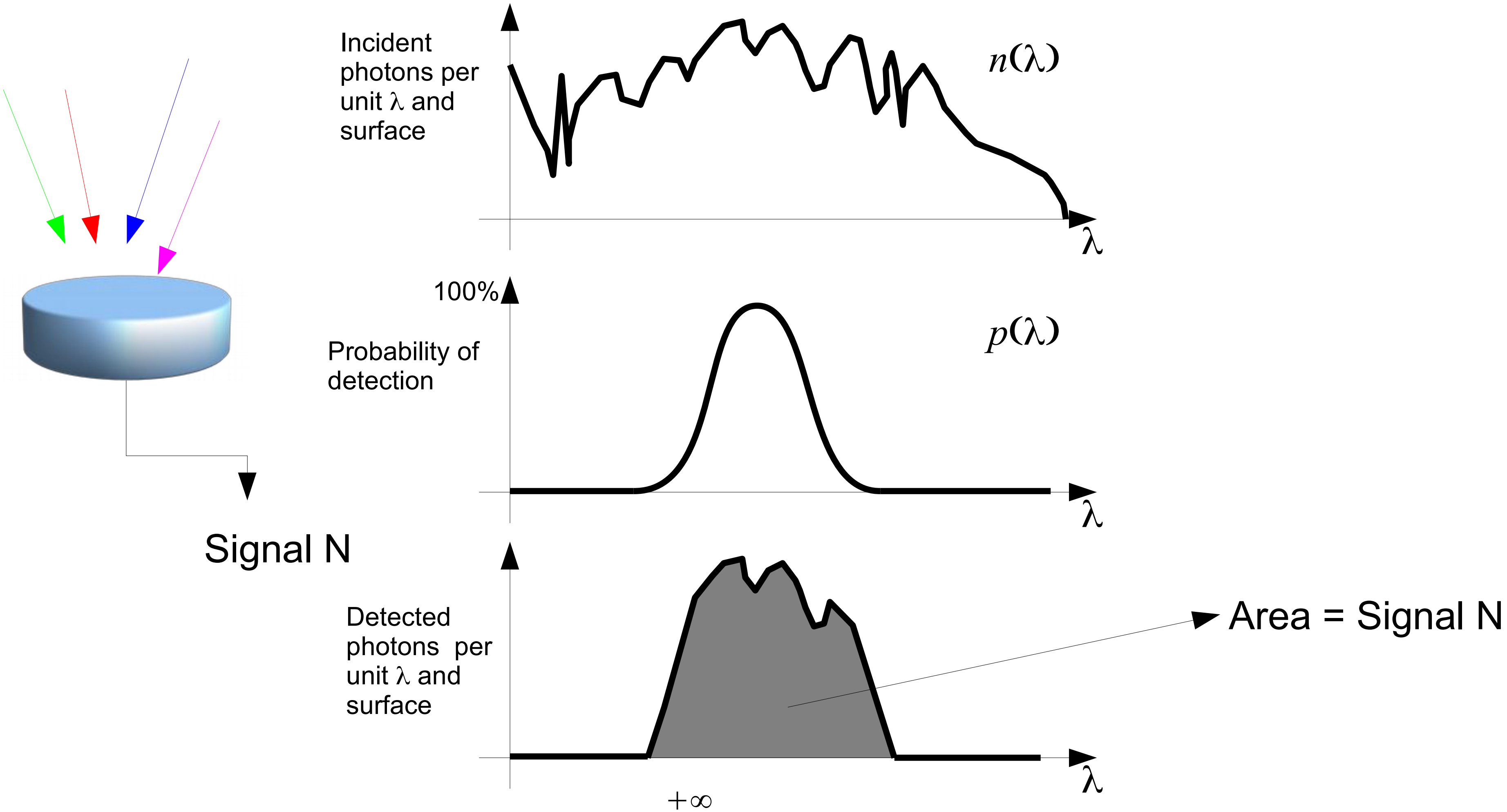
- The spectrum is continuous. There are an infinite number of independent elementary colors for who is able to see them all (… spectrometers)

Colorimetry

- Measure of light
  - A detector gives a scalar value (a number) when it by photons
  - That scalar is roughly proportional to the number of photons, for a given wavelength
  - Each photon has a chance to be detected that depends on its wavelength
  - One never directly measures the wavelength of a radiation !
  - This model is true for semiconductors as well as for the eye’s photosensitive cells

Colorimetry

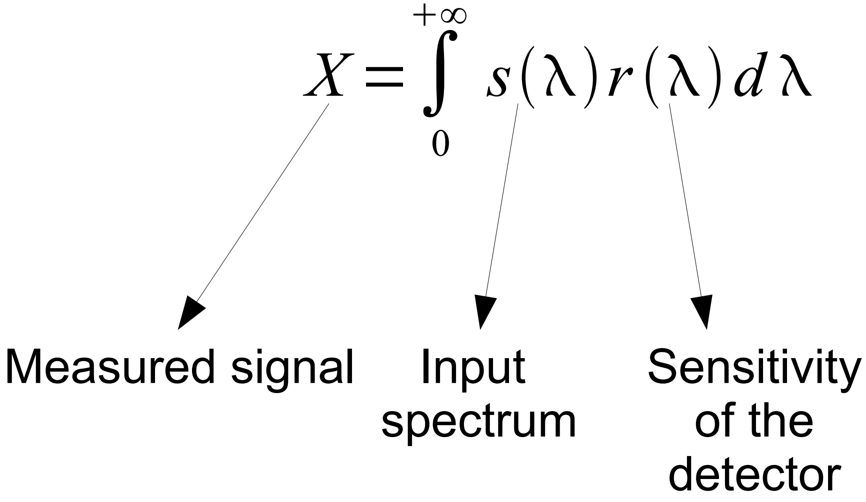
- Detector



$$N=\int_{0}^{+\infty} n(\lambda)\,p(\lambda)\,d\lambda$$

Colorimetry

- The formula is true for the received luminous power
  - Power is proportional to the nb of photons / sec
  - The input spectrum has a spectral power distribution
  - The detector has a spectral sensitivity (spectral response)



$$X = \int_{0}^{+\infty} s(\lambda)\, r(\lambda)\, d\lambda$$

Measured signal

Input spectrum

Sensitivity of the detector

Colorimetry

- Scalar product
  - If s and r are vectors (with an infinite number of dimensions) therefore :
    $$X=\int_{0}^{+\infty} r(\lambda)\,s(\lambda)\,d\lambda$$
    is a scalar product : $X=s\cdot r$
  - In fact, the computation is made exactly like that, if one considers a sampled version of s et r (every 5 nm for instance)

$$\bar{s}[i]=\frac{1}{\Delta\lambda}\int_{\lambda_i-\frac{\Delta\lambda}{2}}^{\lambda_i+\frac{\Delta\lambda}{2}} s(\lambda)\,d\lambda \quad \bar{r}[i]=\frac{1}{\Delta\lambda}\int_{\lambda_i-\frac{\Delta\lambda}{2}}^{\lambda_i+\frac{\Delta\lambda}{2}} r(\lambda)\,d\lambda \quad , \quad \lambda_{i+1}-\lambda_i=\Delta\lambda$$

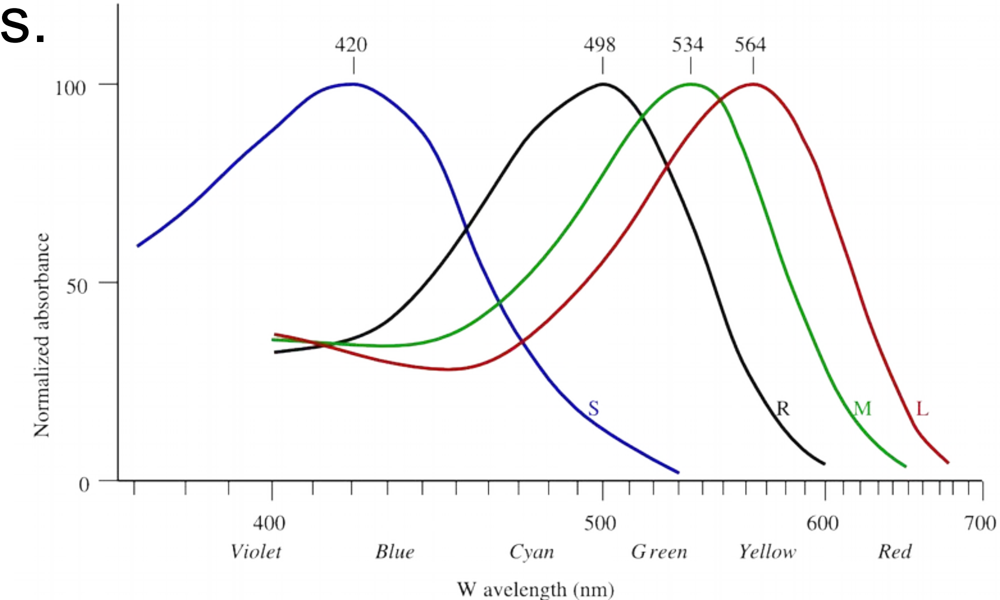
$$X\approx\sum_{i} s[i]\,r[i]\,\Delta\lambda$$

Colorimetry

Sensitivity of the human eye

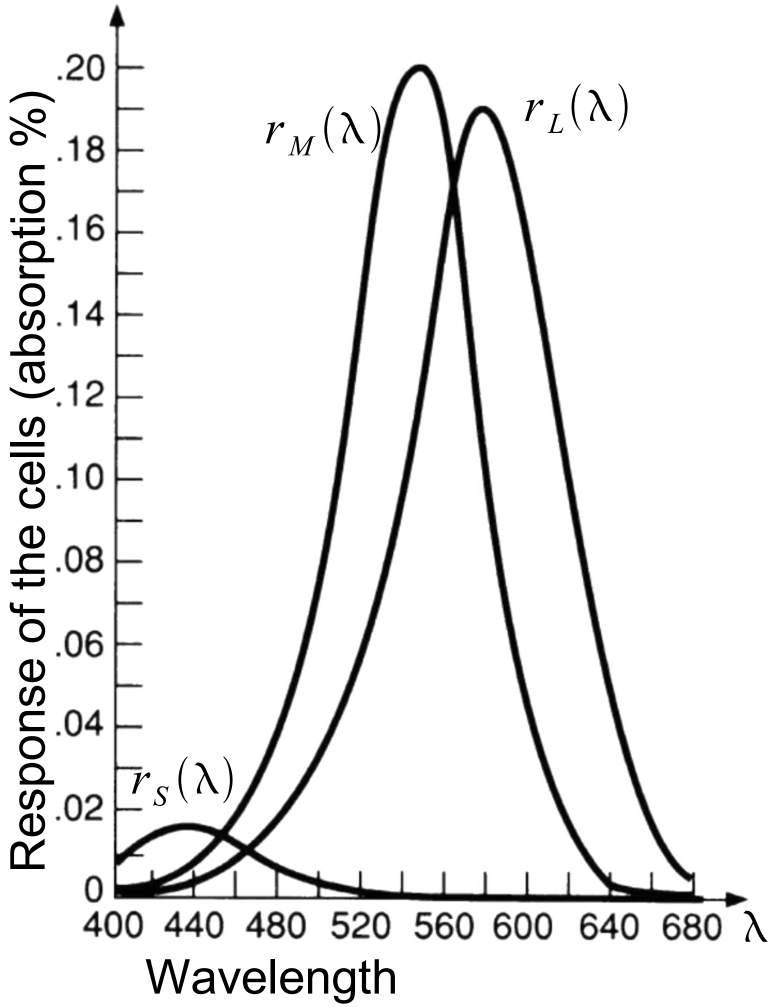
Colorimetry

- The retina contains four types of light-sensitive cells
  - Cones (S), (M) and (L) are sensitive to short, medium and long wavelengths respectively
    - S sensitive to blue
    - M and L sensitive to green and red
  - Rods (R) are sensitive only to low luminance, and cannot discriminate colors.



Colorimetry

- Response of the cells to light
  - Those are broadband detectors
    - Compromise between sensitivity and ability to discriminate colors
    - S cells (blue)
      are less sensitive that M and L cells
  - One may integrate over the wavelength
  - One obtains the individual response for each cell type
    S,M or L.



Colorimetry

- Response of cones to a spectrum $s(\lambda)$

$$S = \int_0^{+\infty} r_S(\lambda)\, s(\lambda)\, d\lambda$$

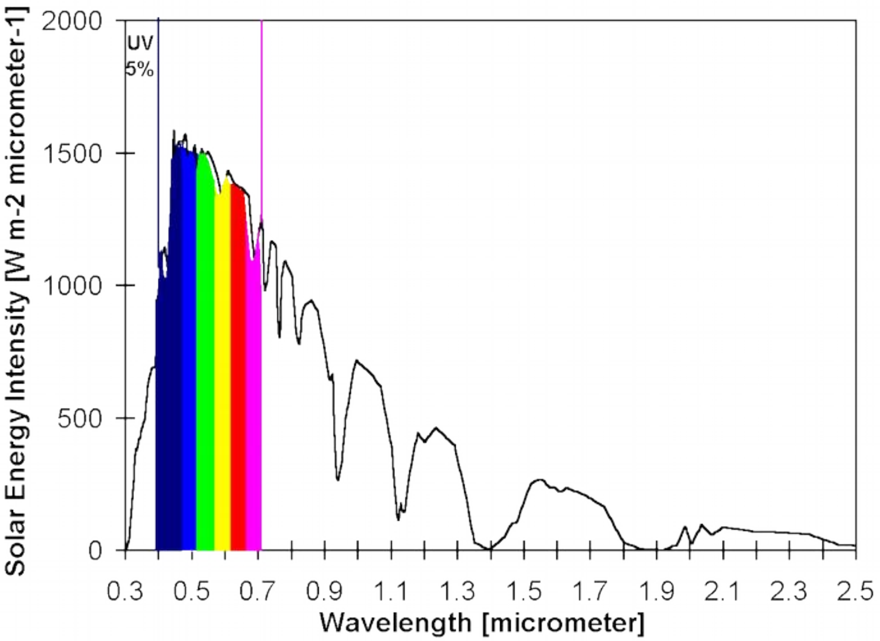
$$M = \int_0^{+\infty} r_M(\lambda)\, s(\lambda)\, d\lambda$$

$$L = \int_0^{+\infty} r_L(\lambda)\, s(\lambda)\, d\lambda$$

Colorimetry

- Colorimetry is the answer to the following problem:

  « From a physical description of light, explain the perception of colors »
- The answer to this question is known and standardized since the 30’s



Physical description

$$S = r_s \cdot s$$

$$\longrightarrow \quad M = r_m \cdot s$$

$$L = r_l \cdot s$$

Perception

Colorimetry

- From a continuous spectrum, one gets only three scalars.
- Lots of information is lost !
- It is possible to find distinct spectra that give the same “tristimuli” scalars S, M and L .
  - These spectra are **metamers** for the human vision
  - We’ll take advantage of this in the sequel.

Colorimetry

Parameters of the human eye and definition of absolute colorimetric variables

Colorimetry

- Grassmann’s laws - 1853 (Hermann Grassmann 1809-1877)
  - Human vision is trichromatic
  - Every color may be represented by a combination of three primaries (independent colors)
  - Principle of superposition

Colorimetry

- Grassman’s laws
  - Principle of superposition

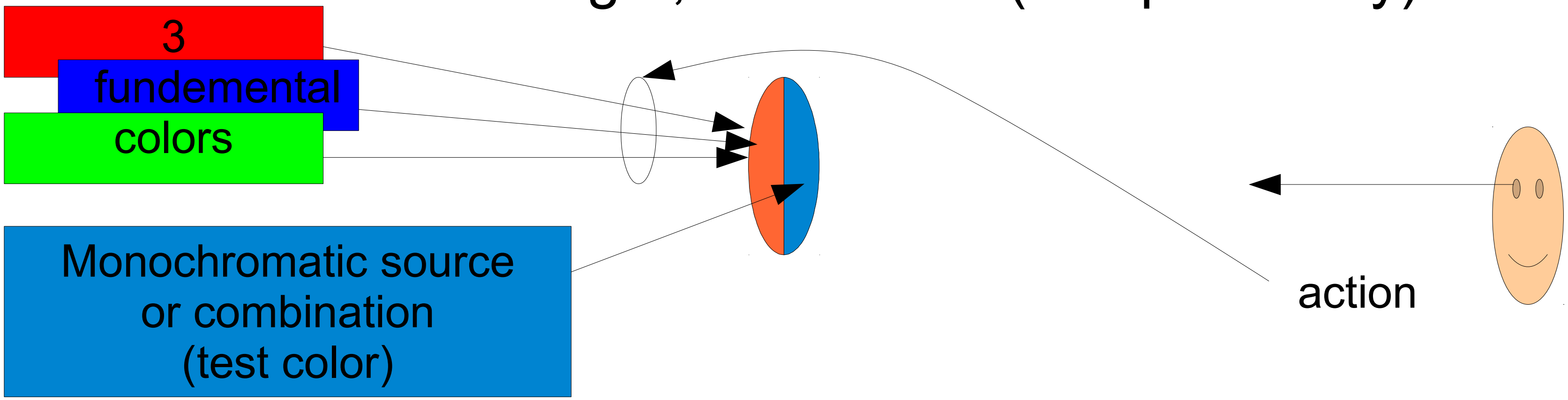
    Color perception is approximately linear – this is validated experimentally
    - Let M_1 and M_2 be two monochromatic light beams
    - It is asked to an observer to recompose the light of M_1 from the primaries by choosing the right proportions R_1,G_1 and B_1. Same for M_2.
    - When the same procedure is asked for a composition of the two beams M_1+M_2, he will choose the following : $(R_1+R_2,G_1+G_2,B_1+B_2)$
      - Consequence : One may choose any RGB triplet to build the entire visible color set by linear combination, if the three primaries are (linearly) independent.

    The RGB triplet is, to a certain extent, *conventional*.

Colorimetry

- Two experiences in the 30s on the sensitivity of the human eye to colors

William Wright, John Guild (independently)



3 fundemental colors

Monochromatic source or combination (test color)

action

What proportion of the three colors give a similar appearance of the two semi-discs for the subject on the right ?

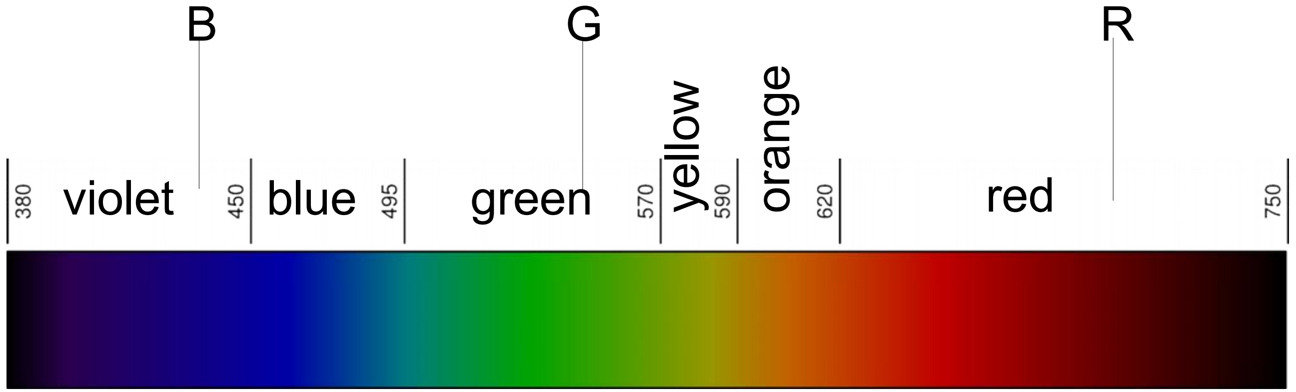
  - Experiences done on numerous « normal » subjects (« normal » means they do not have known visual deficiencies)

Wright, William David (1928). "A re-determination of the trichromatic coefficients of the spectral colours". Transactions of the Optical Society 30: 141–164

Guild, John (1931). "The colorimetric properties of the spectrum". Philosophical Transactions of the Royal Society of London A230: 149–187.

Colorimetry

- Here, experiences are done with the following color triplet :
  - R = monochromatic source with λ = 700 nm
  - G = monochromatic source with λ = 546.1 nm
  - B = monochromatic source with λ = 435.8 nm



  - The intensities of the three primaries are such that if combined, they blend into a “standard” white.
    - Standard white: e.g. lambertian material, reflecting all the incident visible wavelengths, that is lit by the sun, at noon, on a clear day.

Colorimetry

- One wishes to reconstruct the following functions : $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$

Given / imposed (test color)

Given by the subject

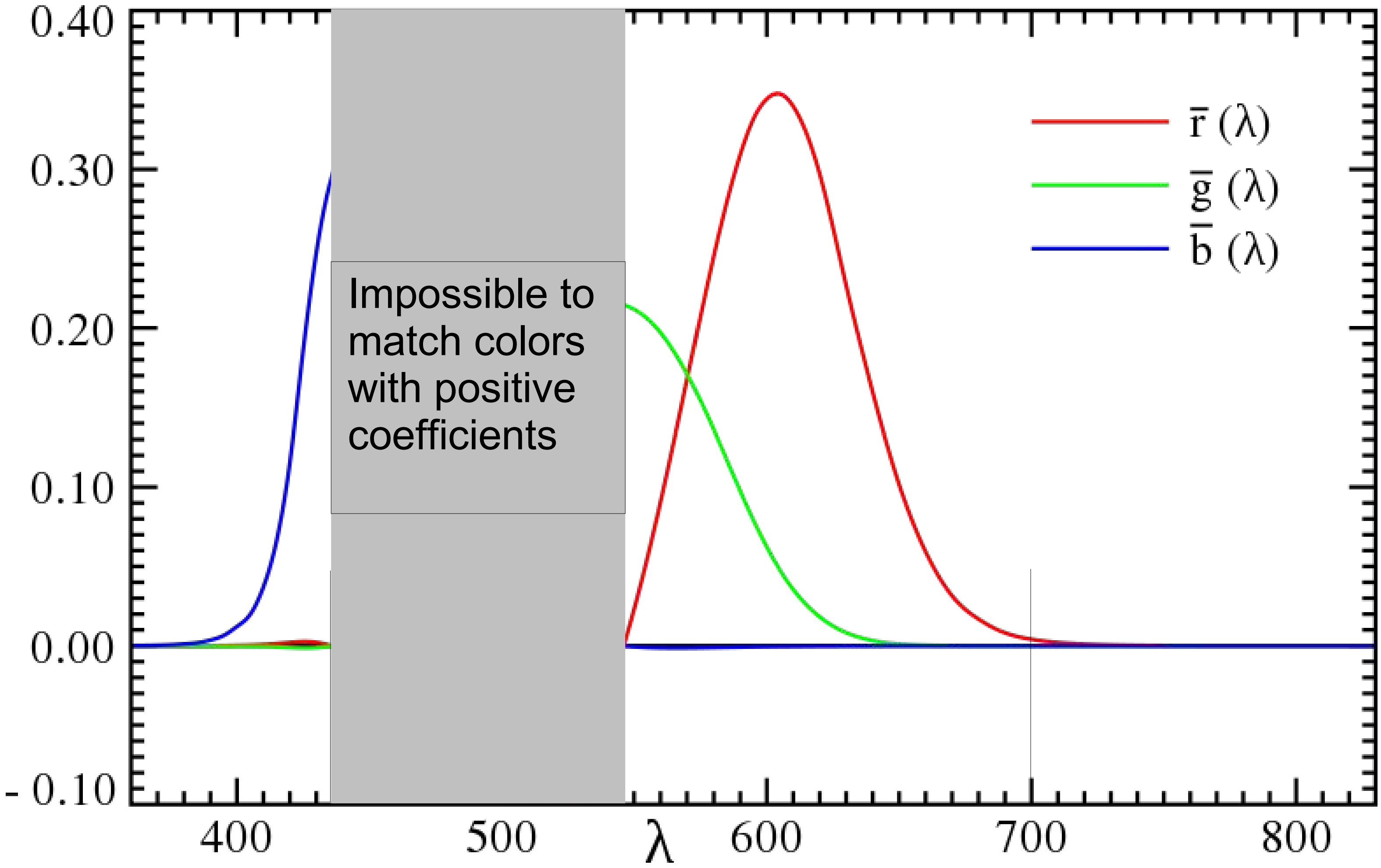
$$R = \int_0^{+\infty} \bar{r}(\lambda) s(\lambda) d\lambda$$

$$G = \int_0^{+\infty} \bar{g}(\lambda) s(\lambda) d\lambda$$

$$B = \int_0^{+\infty} \bar{b}(\lambda) s(\lambda) d\lambda$$

Colorimetry

- Results with a monochromatic test color with a variable wavelength λ ...



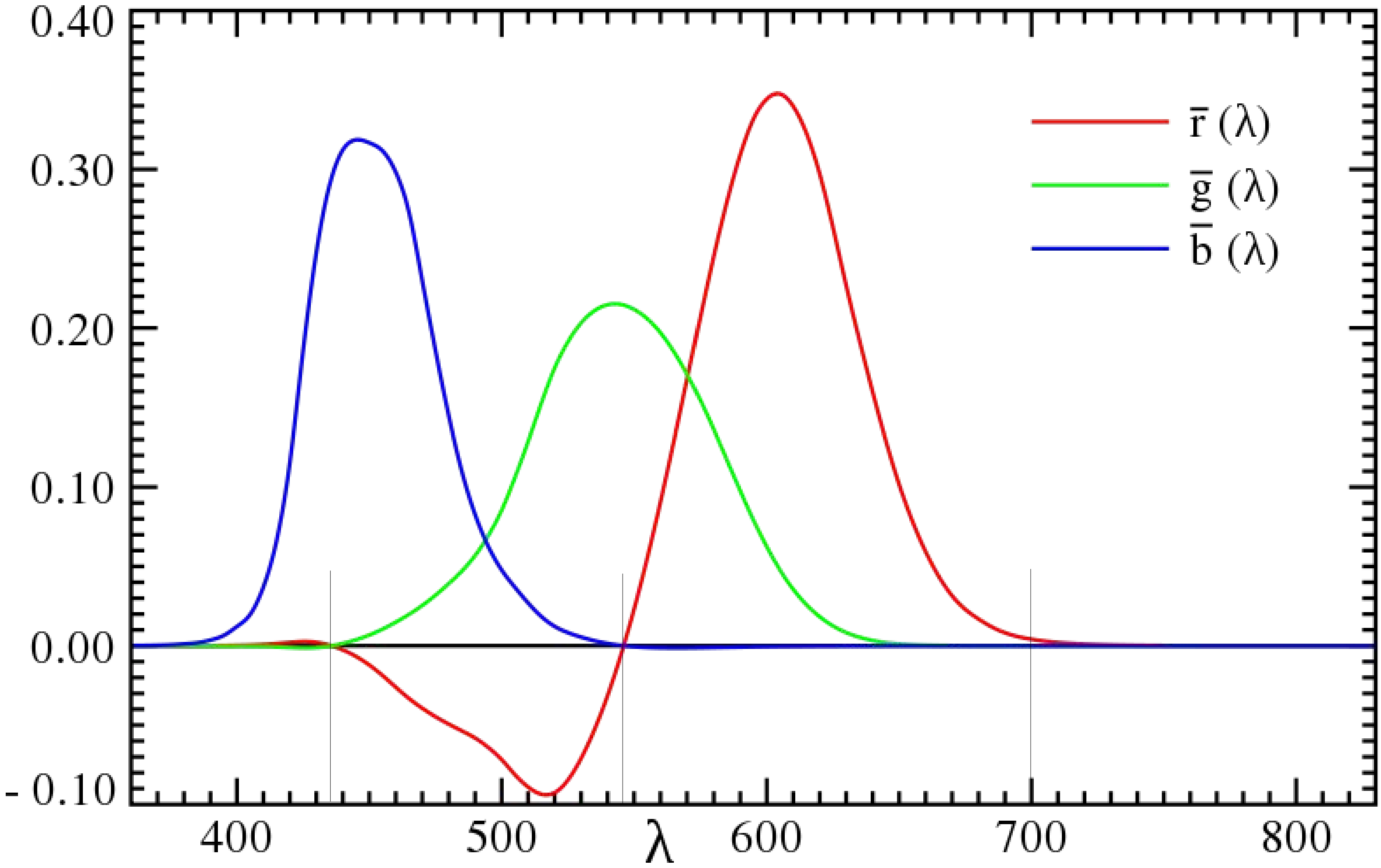
Impossible to match colors with positive coefficients

Colorimetry

- It is sometimes impossible to match the test color with positive intensities (the only ones making sense physically and experimentally)
    - This is due to the fact that the eye's sensitivity is not related to the primaries that have been chosen (monochromatic)
    - When the matching is impossible, the subject is allowed to add some of the RGB triplet colors to the test color.
        - In that case, we consider that this color has been withdrawn from the other side (thus giving a negative value)

Colorimetry

- Results with a monochromatic test color with a variable wavelength λ ...



Colorimetry

- The curves called $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$ are normalized so that the area is unitary:

$$\int_0^{+\infty} \bar{g}(\lambda)\,d\lambda = 1$$

$$\int_0^{+\infty} \bar{r}(\lambda)\,d\lambda = 1$$

$$\int_0^{+\infty} \bar{b}(\lambda)\,d\lambda = 1$$

Colorimetry

- The spectrum is continuous...

    The test must therefore be done for any combination of spectra.

    - Grassmann’s laws (additivity) allows us to use only monochromatic lights, since any spectrum is a linear combination of monochromatic lights.
    - The **response** for any spectrum is then also a mere linear combination of the responses to individual monochromatic lights. That is exactly what we did.

Colorimetry

- Some colorimetry concepts
  - Luminance
    - Magnitude of the response of the eye to the spectrum, independently of color
    - Given by the product of the spectrum (spectral power distribution) and the sensitivity of the eye for each wavelength V_λ
    - Artificial light sources are nowadays optimized to radiate exclusively where the sensitivity is maximal.
    - Luminance is noted Y
    - It has a response curve (like S, M and L) , given by r_Y

$$Y = \int_0^{+\infty} r_Y(\lambda) s(\lambda) d\lambda = r_Y \cdot s$$

      - r_Y « is » V_λ

    - r_Y is a linear combination between r_S, r_M, r_L

Colorimetry

- Chromaticity
  - What remains when the luminance is set to e.g. 1 (constant)
  - It is true color, independently to luminance
  - Multiply a spectrum by a constant does not change the chromaticity, only the luminance !
- Dominant wavelength
  - Every color can be decomposed into “white” plus a pure monochromatic color of the dominant wavelength
  - « Tint »
- Purity
  - Ratio of the power of the dominant wavelength to that of the “white”.
  - Also called « saturation »

Colorimetry

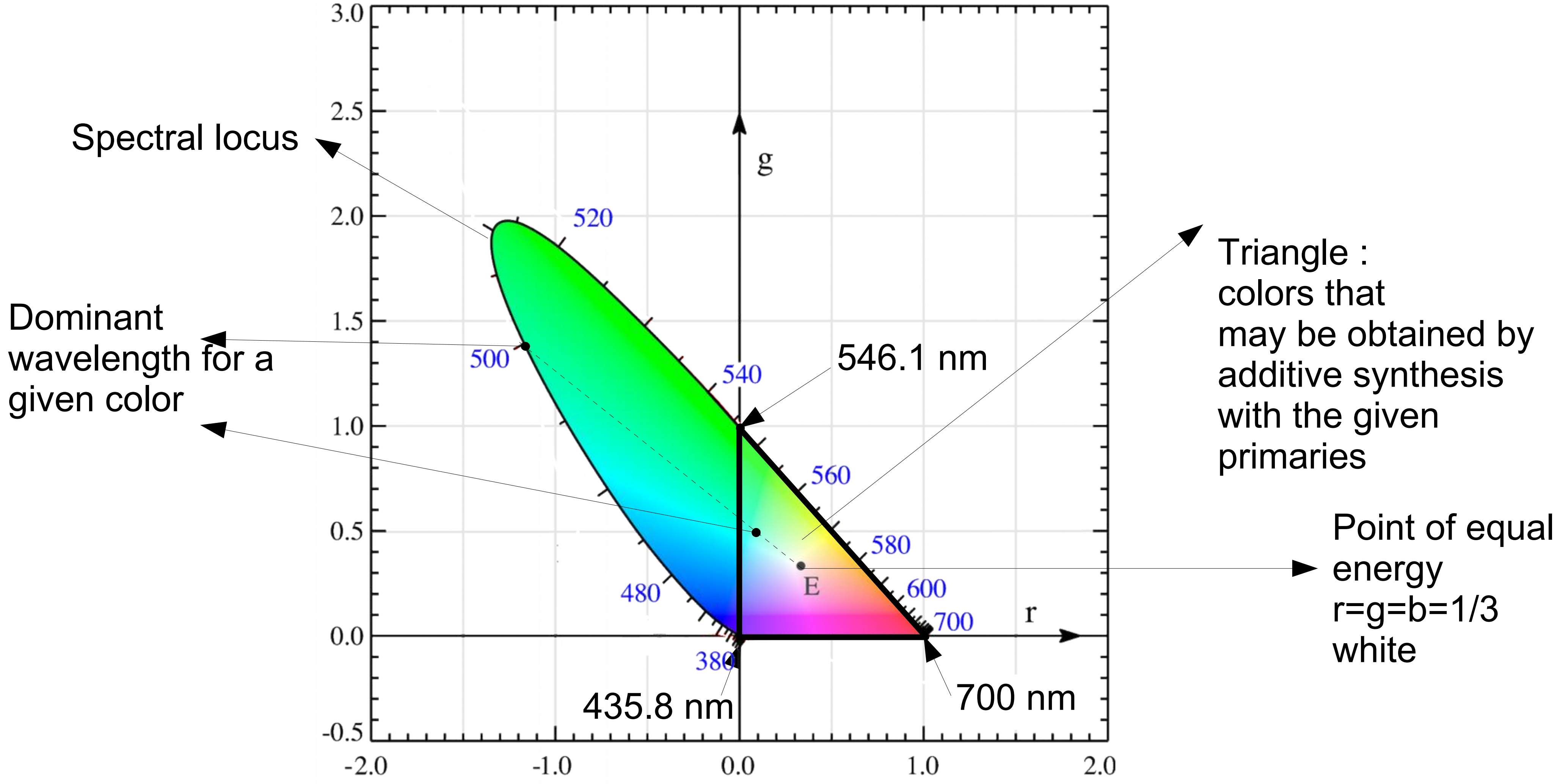
- Color space
  - 3 dimensional space
  - The color “feeling” is approximately independent with luminance (except at low light intensities → inactive cones, only rods are active)
    - There is a narrow window where all 4 cell types are active. In this window, at least theoretically, human vision is quadrichomatic !
  - We may therefore restrict to 2 dimensions by normalizing

$$r=\frac{R}{R+G+B} \quad g=\frac{G}{R+G+B} \quad b=\frac{B}{R+G+B}=1-r-g$$

  - One obtains a chromatic diagram in the e.g. in the r,g axes (these are the variables usually chosen in the litterature)

Colorimetry

- Chromatic diagram in r,g axes



Spectral locus

Dominant wavelength for a given color

546.1 nm

Triangle : colors that may be obtained by additive synthesis with the given primaries

Point of equal energy r=g=b=1/3 white

435.8 nm

700 nm

Colorimetry

- 1931 CIE Standard
  - Use of “imaginary” primaries such that the convex combination (with positive coefficients) allows to represent any color the human eye is able to perceive.
  - Those are qualified as “imaginary” because it is impossible to physically realize these light sources. They are more saturated than monochromatic radiations !
  - It is a mere change of frame in the chromatic diagram thanks to Grassman’s laws
  - The new coordinates are simply called X,Y et Z

Colorimetry

- XYZ color space
  - Y is the luminance (by definition)
  - X and Z are chromatic components
  - As in the RGB color space, one may divide by the sum to return to a 2D color space (constant luminance)

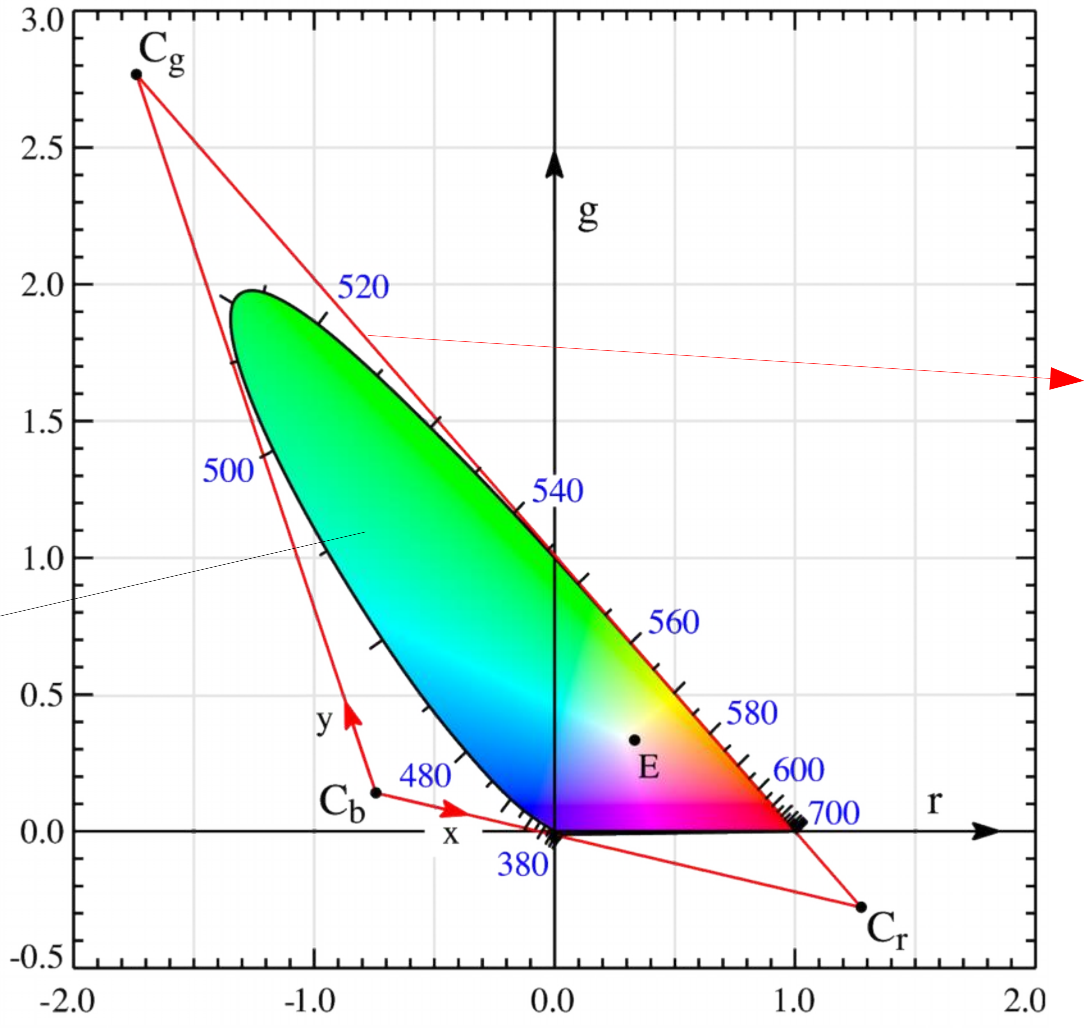
$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z}$$

$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

  - One may therefore use x,y and Y as coordinates to represent any color. This is the xyY color space, which is equivalent to the XYZ color space, but more practical for 2D representations.

Colorimetry

- Chromatic diagram in r,g axes



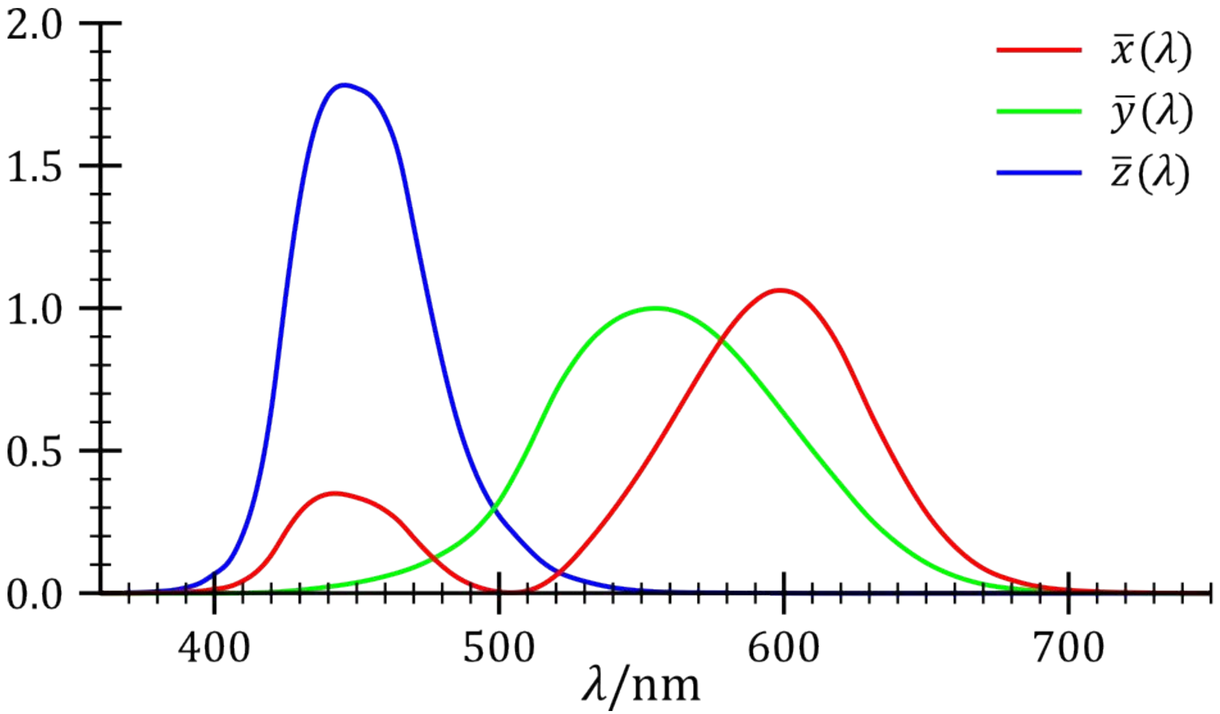
Limits of colors that may be obtained with an additive synthesis with the imaginary primaries

« Real » colors

Colorimetry

- Transfer functions

$$X=\int_0^{+\infty}\bar{x}(\lambda)s(\lambda)d\lambda \quad Y=\int_0^{+\infty}\bar{y}(\lambda)s(\lambda)d\lambda \quad Z=\int_0^{+\infty}\bar{z}(\lambda)s(\lambda)d\lambda$$



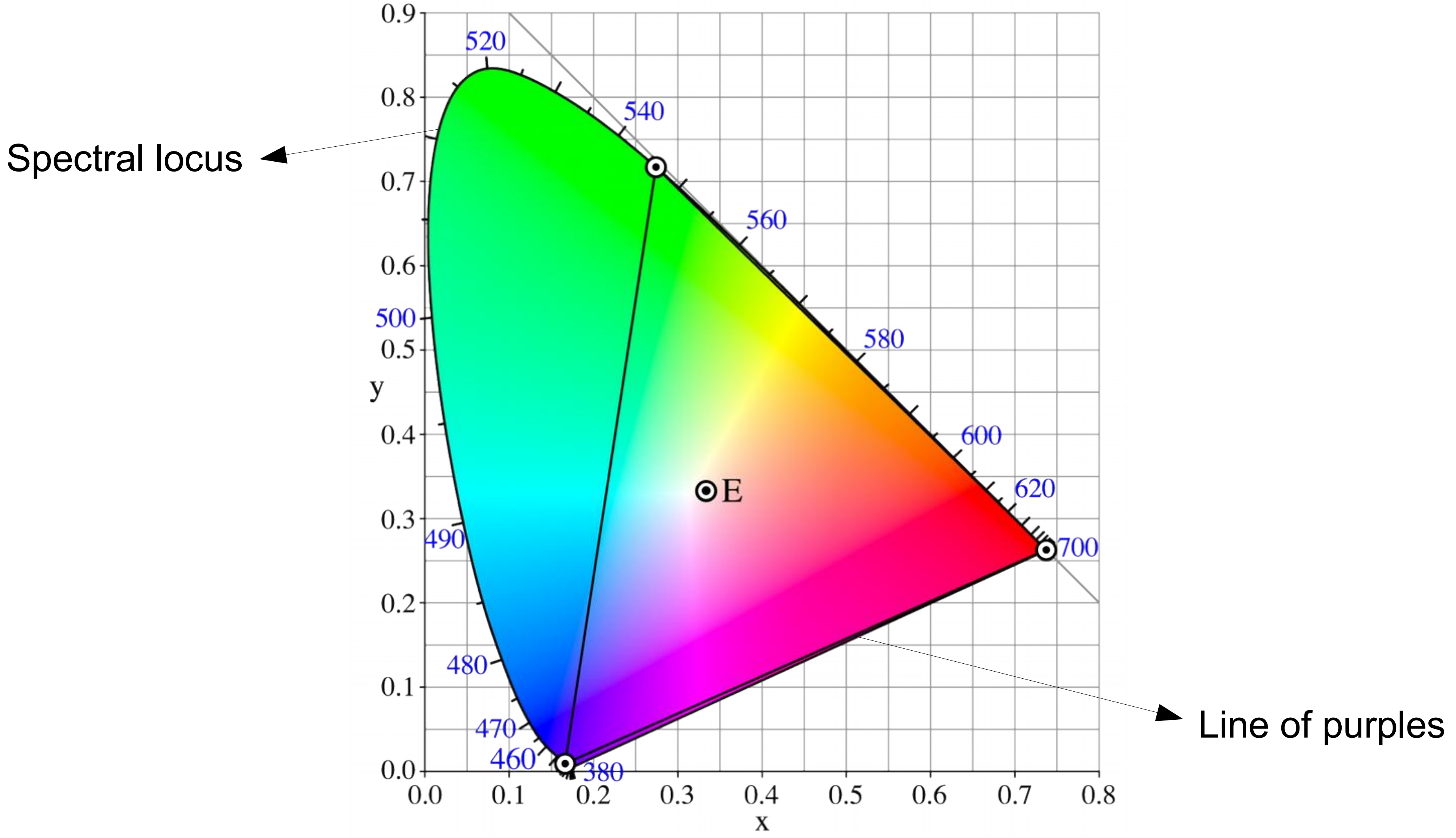
Colorimetry

- XYZ in function of RGB
    - Linear combination; (conventional, all the values are **exact**)

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

Colorimetry

- Chromatic diagram in x,y axes

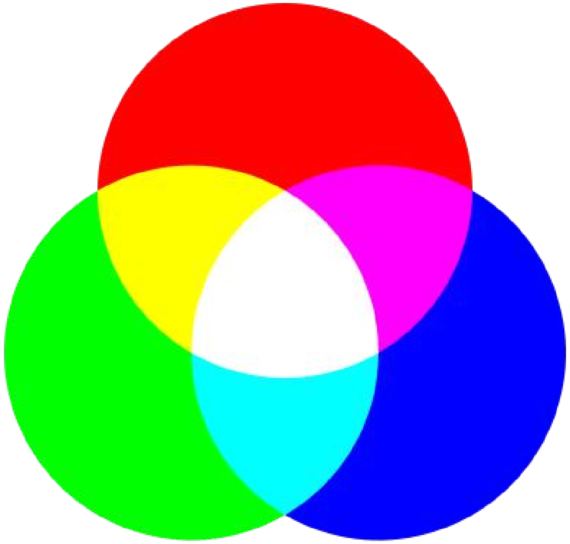


Colorimetry

- Color fidelity
  - Let $s(\lambda)$ a spectrum (real one), one wants to display it correctly on a given device (e.g. LCD screen)
  - One could of course reproduce exactly the same spectrum; but it is very difficult (and almost impossible with current technologies)… however, any spectrum that has the same projection in the color space (XYZ or RGB not matter) will do the trick, thanks to metamerism.
  - The idea is to find a spectrum that is the screen is able to reproduce AND that is a metamer (for the eye) of $s(\lambda)$.

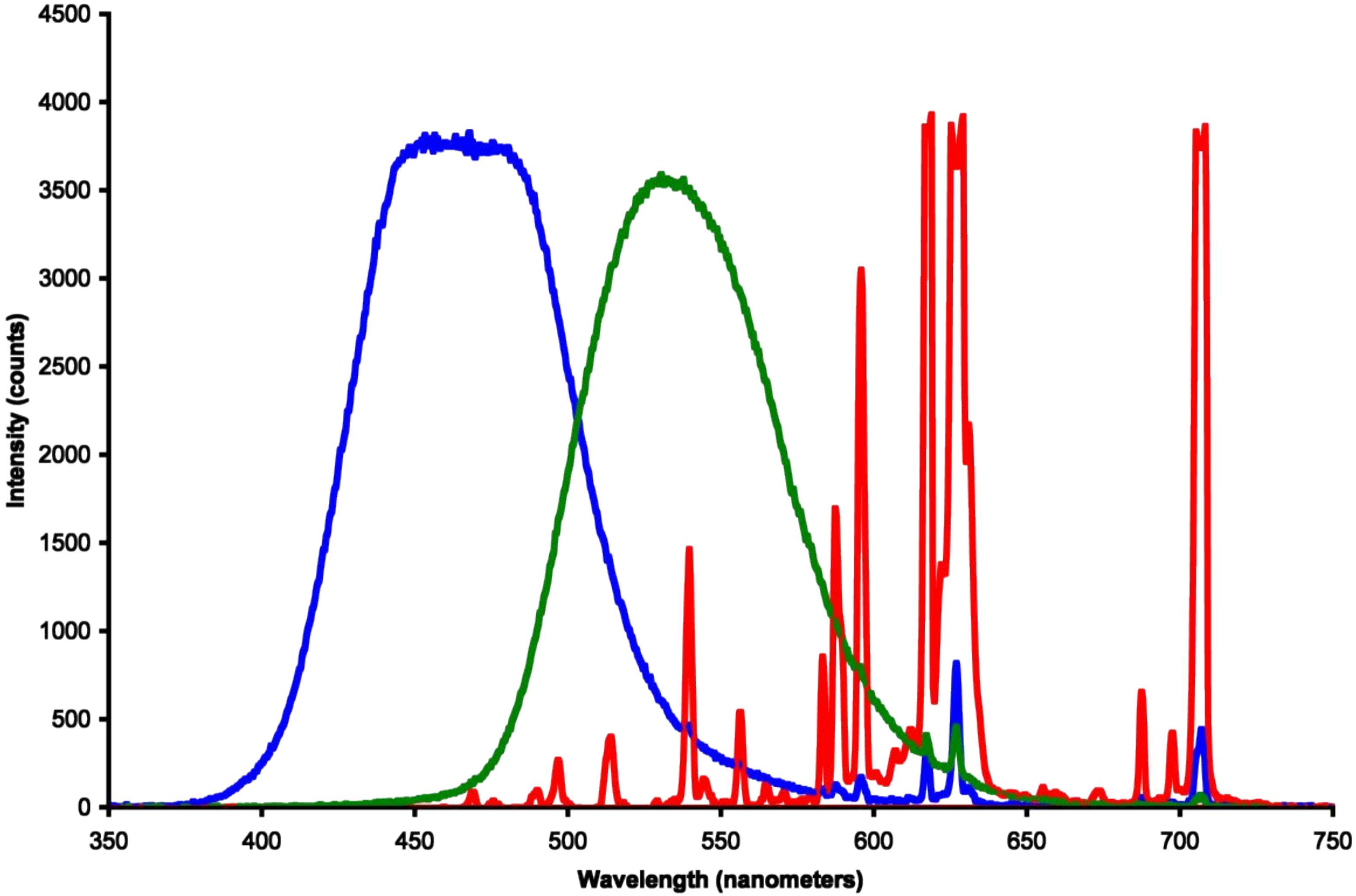
Colorimetry

- Display devices usually work by additive synthesis...



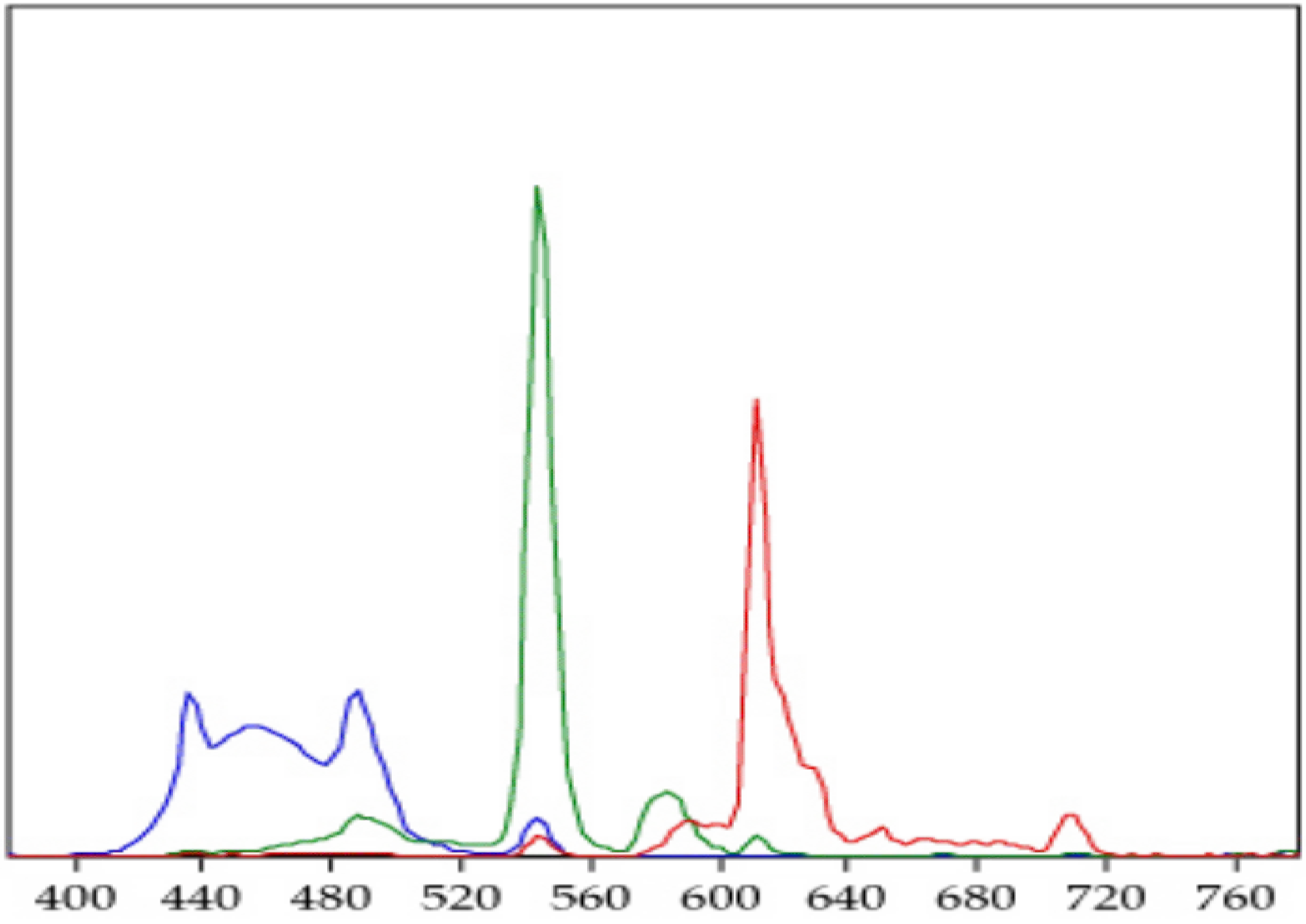
Colorimetry

- RGB emission spectra for a CRT-based display device (e.g. old TV sets)



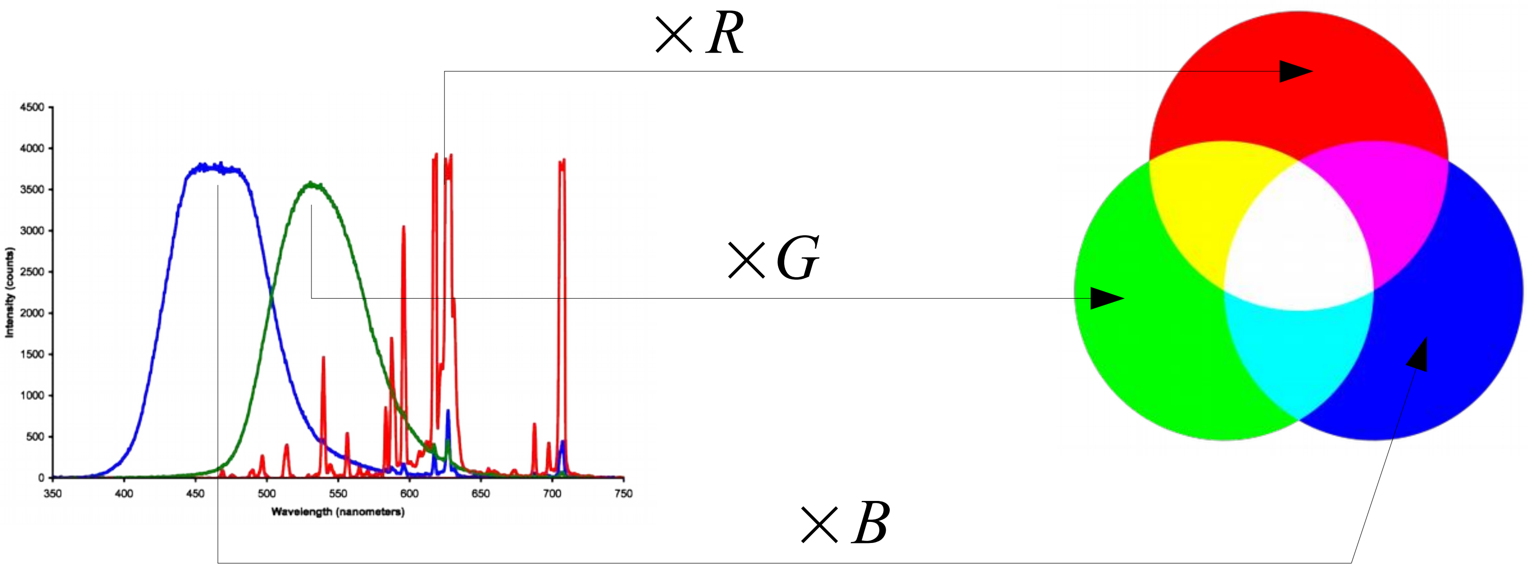
Colorimetry

- RGB emission spectra for an LCD-based display device (e.g. flat panel TV sets)



Colorimetry

- The display device may only combine the spectra of the primaries with positive coefficients, and that yield a spectrum that has only 3 “degrees of freedom”, even thought it is continuous.



Colorimetry

- How to fin the right metamer of s that may be displayed by the device ?
  - Compute the R,G et B signals such that the visual response of the eye to the spectrum created by te screen is the same as that obtained with the real spectrum
  - Response to the real spectrum :

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} - & r_L(\lambda) & - \\ - & r_M(\lambda) & - \\ - & r_S(\lambda) & - \end{pmatrix} \begin{pmatrix} | \\ s(\lambda) \\ | \end{pmatrix}$$

$$V = M_{LMS} \cdot s$$

Colorimetry

- Response to the screen’s spectrum :

$$\begin{pmatrix} L_e \\ M_e \\ S_e \end{pmatrix} = \begin{pmatrix} \text{—} & r_L(\lambda) & \text{—} \\ \text{—} & r_M(\lambda) & \text{—} \\ \text{—} & r_S(\lambda) & \text{—} \end{pmatrix} \begin{pmatrix} | \\ s_e(\lambda) \\ | \end{pmatrix}$$

$$V_e = M_{LMS} \cdot s_e$$

- One wants :

$$\begin{pmatrix} L_e \\ M_e \\ S_e \end{pmatrix} = \begin{pmatrix} L \\ M \\ S \end{pmatrix}$$

$$V_e = V$$

Colorimetry

- Computation of the screen’s spectrum :

$$s_e(\lambda)=R\cdot s_R+G\cdot s_G+B\cdot s_B$$

$$\begin{pmatrix} | \\ s_e(\lambda) \\ | \end{pmatrix}=\begin{pmatrix} | & | & | \\ s_R(\lambda) & s_G(\lambda) & s_B(\lambda) \\ | & | & | \end{pmatrix}\begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

$$s_e=M_{RGB}\cdot C$$

Colorimetry

- Computation the control parameters of the screen :

$$V_e = V$$

$$\begin{pmatrix} — & r_L(\lambda) & — \\ — & r_M(\lambda) & — \\ — & r_S(\lambda) & — \end{pmatrix} \begin{pmatrix} | & | & | \\ s_R(\lambda) & s_G(\lambda) & s_B(\lambda) \\ | & | & | \end{pmatrix} \overset{C}{\begin{pmatrix} R \\ G \\ B \end{pmatrix}} = \begin{pmatrix} — & r_L(\lambda) & — \\ — & r_M(\lambda) & — \\ — & r_S(\lambda) & — \end{pmatrix} \begin{pmatrix} | \\ s(\lambda) \\ | \end{pmatrix}$$

$$M_{LMS} \cdot M_{RGB} \cdot C = M_{LMS} \cdot s$$

$$C = (M_{LMS} \cdot M_{RGB})^{-1} \cdot M_{LMS} \cdot s$$

Colorimetry

- But one does not know the real spectrum !
- But we may know the coordinates in an adequate color space : XYZ (or RGB).
- On may construct a metamer spectrum, just by using the reference spectra of the reference light sources (monochromatic) that are defined in the standard; see experience from 1931.

$$\begin{pmatrix} \vert \\ s_m(\lambda) \\ \vert \end{pmatrix} = \begin{pmatrix} \vert & \vert & \vert \\ s_{mR}(\lambda) & s_{mG}(\lambda) & s_{mB}(\lambda) \\ \vert & \vert & \vert \end{pmatrix} \begin{pmatrix} R_m \\ G_m \\ B_m \end{pmatrix}$$

with

$$\begin{pmatrix} R_m \\ G_m \\ B_m \end{pmatrix} = \left(\frac{1}{0.17697} \begin{pmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{pmatrix} \right)^{-1} \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

Colorimetry

- But one does not know the real spectrum !
- But we may know the coordinates in an adequate color space : XYZ (or RGB).

$$\begin{pmatrix} \text{---} & r_L(\lambda) & \text{---} \\ \text{---} & r_M(\lambda) & \text{---} \\ \text{---} & r_S(\lambda) & \text{---} \end{pmatrix} \begin{pmatrix} | & | & | \\ s_R(\lambda) & s_G(\lambda) & s_B(\lambda) \\ | & | & | \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} \text{---} & r_L(\lambda) & \text{---} \\ \text{---} & r_M(\lambda) & \text{---} \\ \text{---} & r_S(\lambda) & \text{---} \end{pmatrix} \begin{pmatrix} | \\ s_m(\lambda) \\ | \end{pmatrix}$$

$$\begin{pmatrix} | \\ s_m(\lambda) \\ | \end{pmatrix} = \begin{pmatrix} | & | & | \\ s_{mR}(\lambda) & s_{mG}(\lambda) & s_{mB}(\lambda) \\ | & | & | \end{pmatrix} \begin{pmatrix} R_m \\ G_m \\ B_m \end{pmatrix}$$

$$C = \left(M_{LMS} \cdot M_{RGB}\right)^{-1} \cdot M_{LMS} \cdot s_m = \underbrace{\left(M_{LMS} \cdot M_{RGB}\right)^{-1}} \cdot \underbrace{M_{LMS} \cdot M_{mRGB}} \cdot \begin{pmatrix} R_m \\ G_m \\ B_m \end{pmatrix}$$

two 3x3 matrices

Colorimetry

Response of the screen identification

$$C=\left(M_{LMS}\cdot M_{RGB}\right)^{-1}\cdot M_{LMS}\cdot M_{mRGB}\cdot\begin{pmatrix}R_m\\G_m\\B_m\end{pmatrix}$$

Constants defined once and for all

- How to obtain color coordinates in an absolute color space such as RGB or XYZ from camera data?
  - Need to know the characteristics of the camera
  - Need to perform the same type of experiences as those made with the humans eye in the 30s
  - These experiments will quantify the individual response of silicon detectors
  - The whole process is called “calibration”

Colorimetry

- Response of the camera : projection

$$\begin{pmatrix} R_c \\ G_c \\ B_c \end{pmatrix} = \begin{pmatrix} — & r_R(\lambda) & — \\ — & r_G(\lambda) & — \\ — & r_B(\lambda) & — \end{pmatrix} \begin{pmatrix} | \\ s(\lambda) \\ | \end{pmatrix}$$

- Response in the XYZ color space (human eye)

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} — & \bar{x}(\lambda) & — \\ — & \bar{y}(\lambda) & — \\ — & \bar{z}(\lambda) & — \end{pmatrix} \begin{pmatrix} | \\ s(\lambda) \\ | \end{pmatrix}$$

  - Projections on different “planes” !

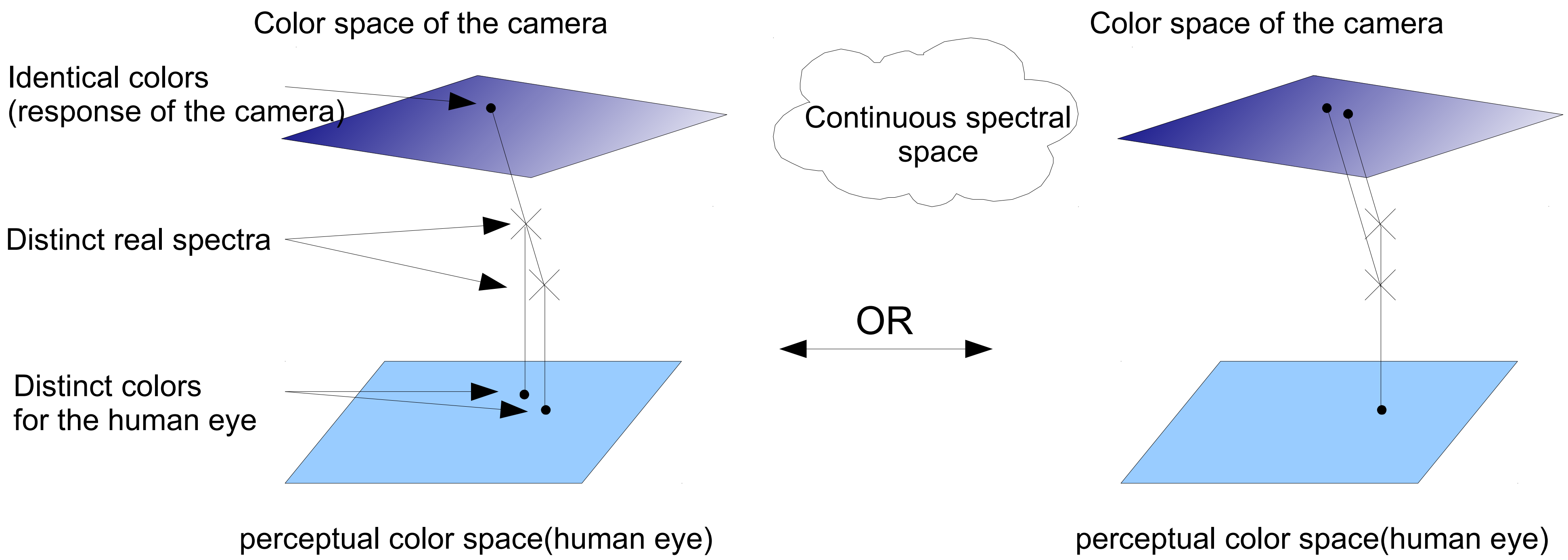
Colorimetry

- Differences between perceived colors

  Metamers of the human eye and metamers of the camera’s own photosites are different !

  - The camera may discriminate spectra the eye can’t,

    The eye may discriminate spectra the camera can’t.

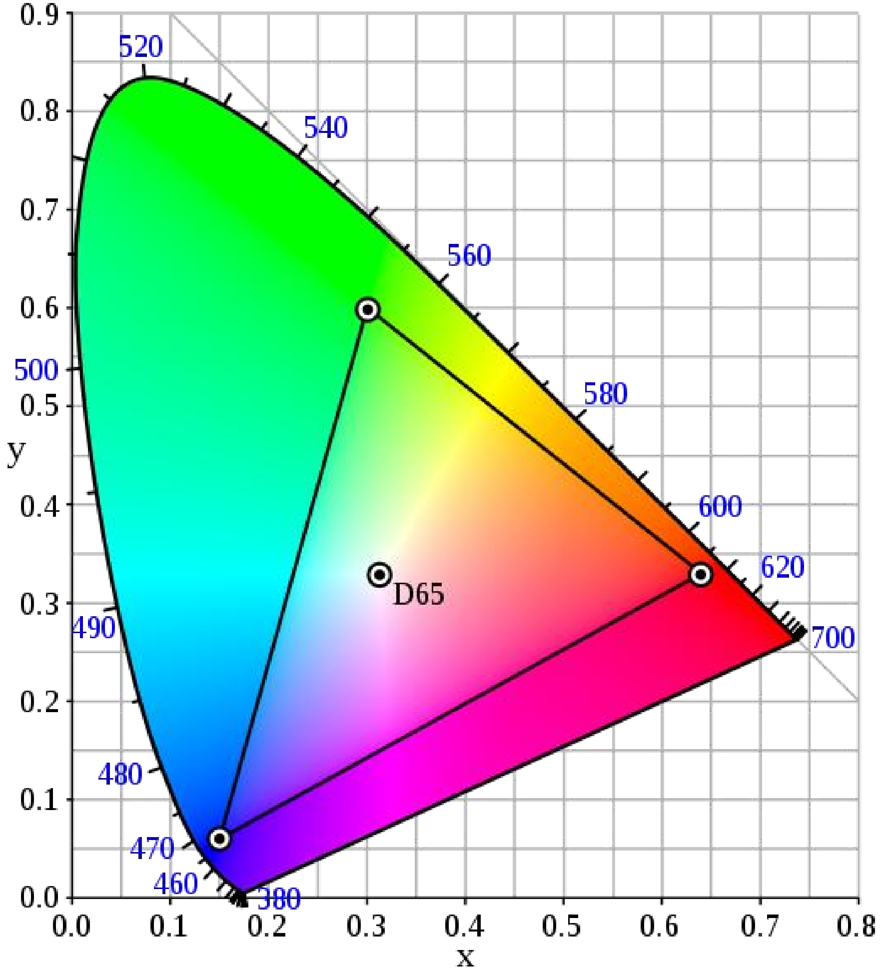


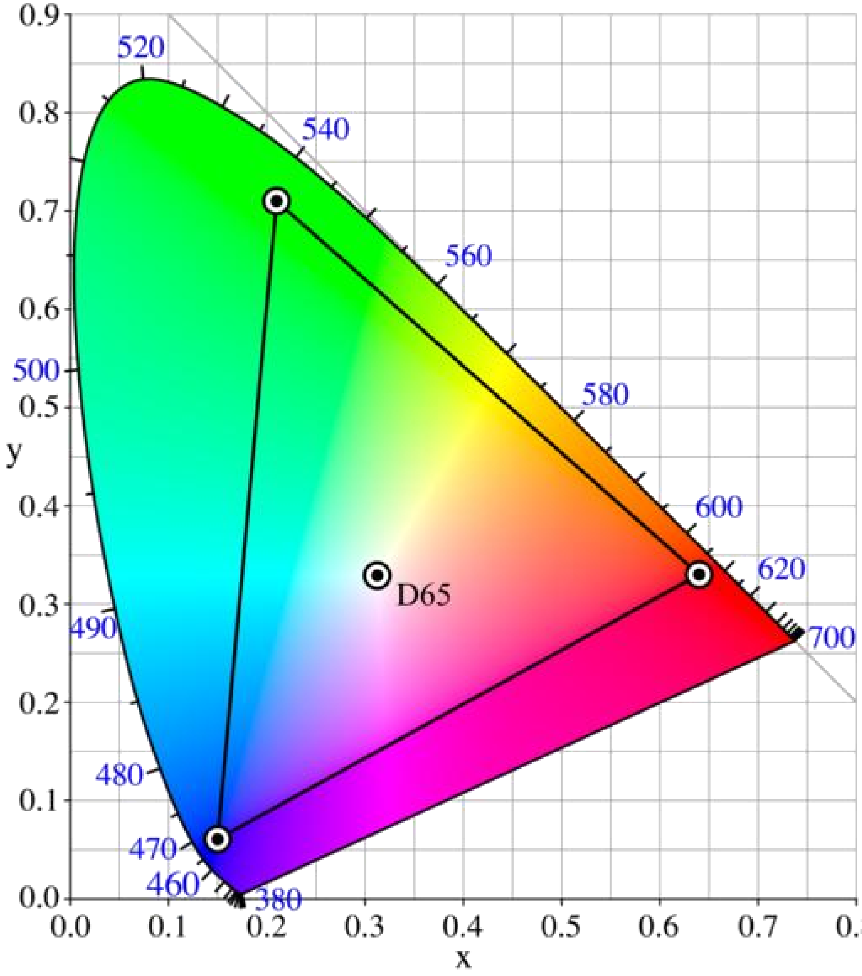
Colorimetry

- The transfer of information from a camera’s color space to the eye’s color space is not without problems
- RGB filters that set the spectral response of the photosites on the camera are crucial to the color fidelity
  - It is impossible to correct this afterwards!
- The conversion to a working color space (e.g. sRGB) is often done in-camera
- The working color space is often either sRGB or AdobeRGB (see sequel)

Colorimetry

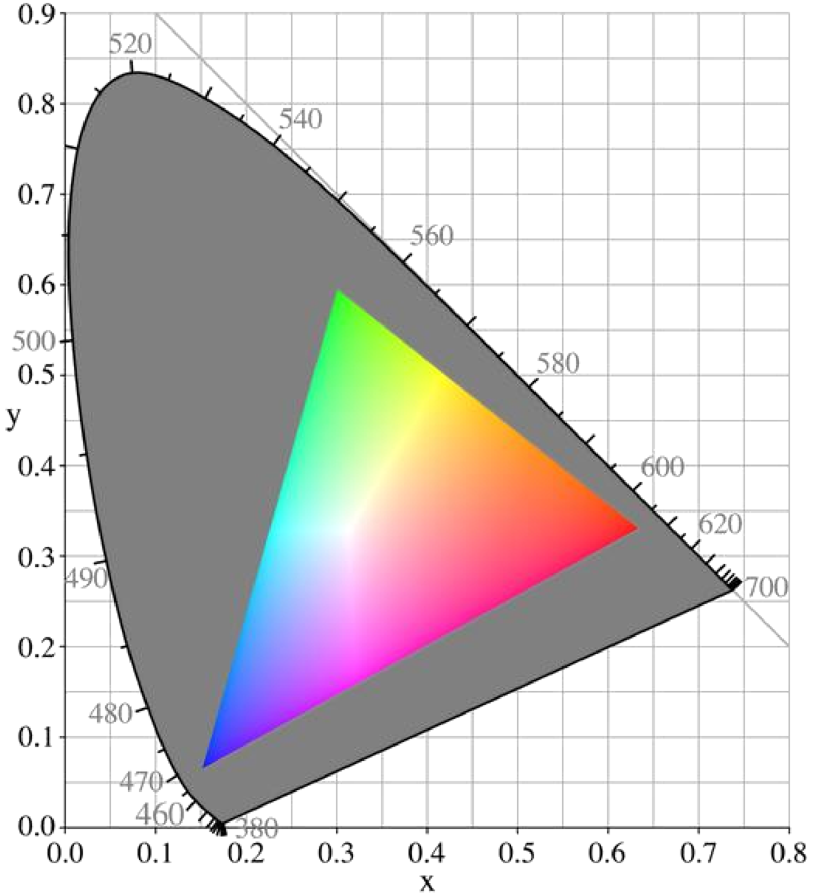
- Color space comparison


sRGB


AdobeRGB

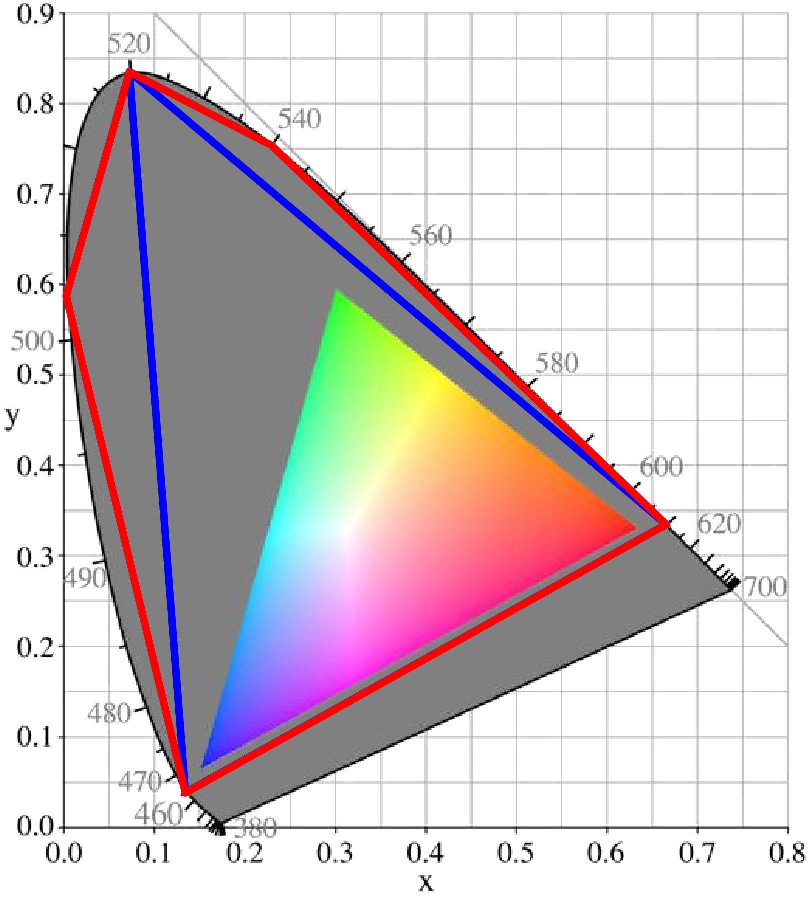
Colorimetry

- Notion of « gamut »
    - It is the set of colors a given color system may represent
    - Example : a CRT screen has three primaries and may only create colors by linear combination.
    - This linear combination has positive coefficients...
    - The locus of colors that may be produced by the system is the triangle obtained by linking the points corresponding to the three (non-monochromatic) primaries



Colorimetry

- With three physical primaries, it is impossible to represent every color that is seen by the human eye, only with convex combinations with positive coefficients
  - The best would be to use monochromatic radiations (e.g. laser), for which saturation is maximal
  - If one accept to use more primaries, it is possible to be close to the “gamut” of the human eye
  - But this is generally not done (expensive)



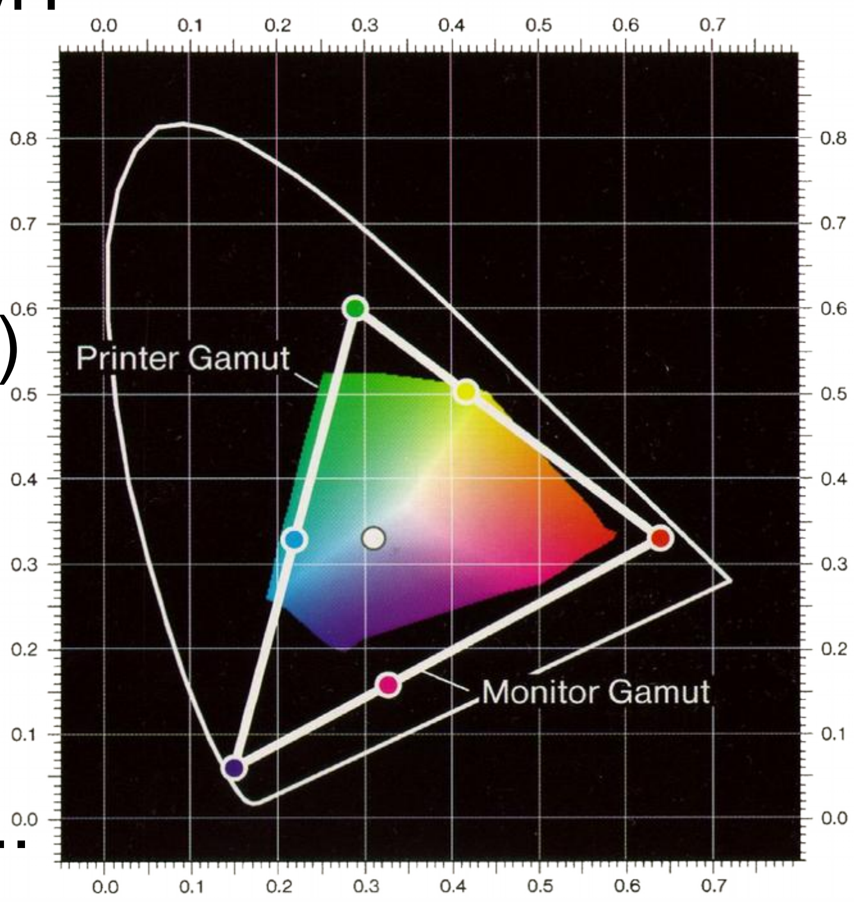
Colorimetry

- Practical managing of colorimetry
  - Digital photography : from the shoot to the display/printing
    - Knowledge of spectral characteristics of the camera and the printing/display devices
      - ICC profiles
      - Those calibration data do vary with age !
      - Difference between calibration and modeling
    - Within gamut limits, it is possible to simulate how a print will look like on a screen

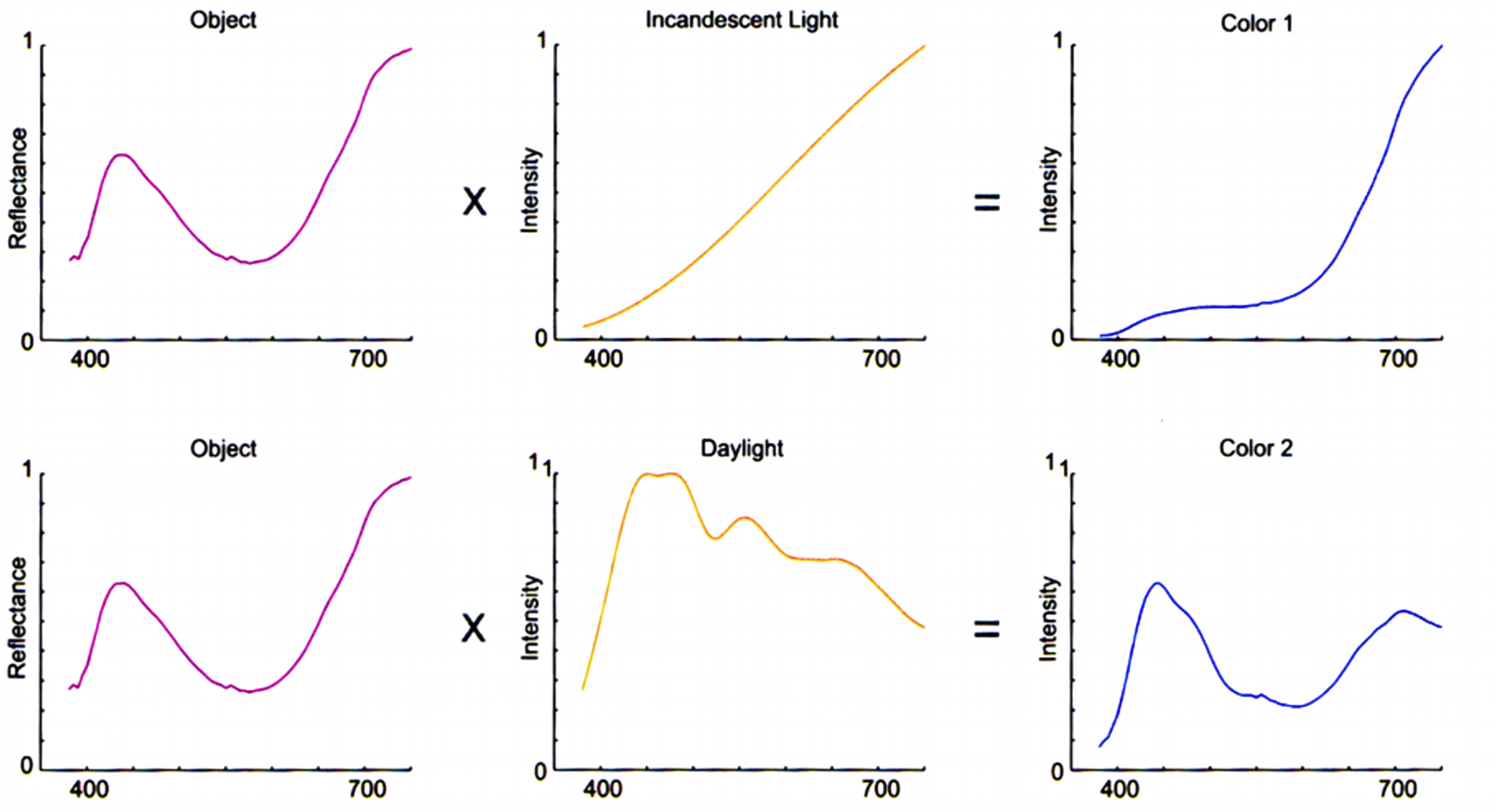
Colorimetry

- Subtractive synthesis
  - Complementary primaries CMY
  - Approximately :

    C = 1-R ; M = 1-G ; Y = 1-B
  - Photography (transparencies)
  - Films
  - Paper prints
  - Usually black added - CMYK
  - Gamut is more complex and ..
  - Depends with illumination !



Colorimetry



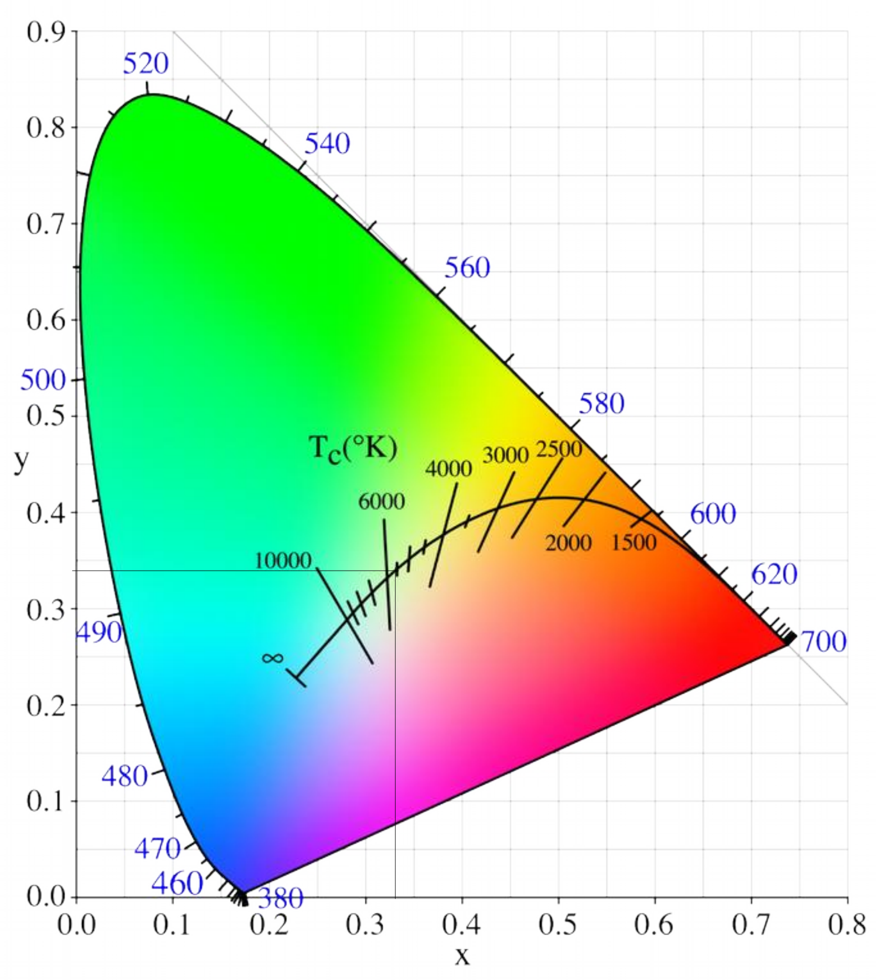
Source : Stone (2003)

Colorimetry

- How a printed proof looks like depends on the illuminant
- The illuminant is characterized by its color in any of the color spaces seen before
- That defines a so called “white point”, which in turn allows to adjust the white balance of the scene
    - The eye has a kind of automatic white balancing…

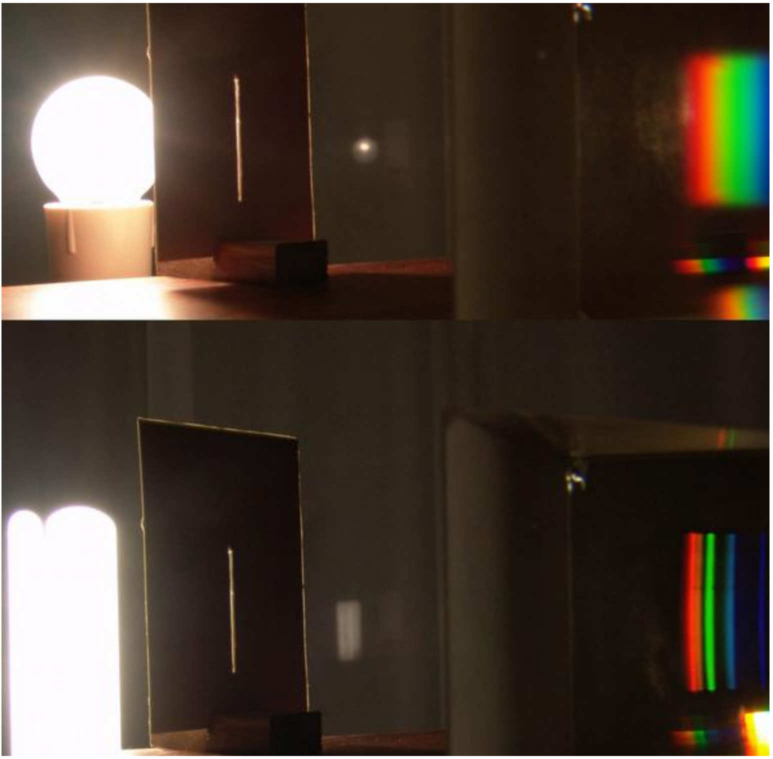
Colorimetry

- Exemple: blackbody radiation (sun, incandescent light source)
- Sunlight is approximated by light emitted by a blackbody at ~5800 K
- Determining colorimetric characteristics of a surface involves controlled light

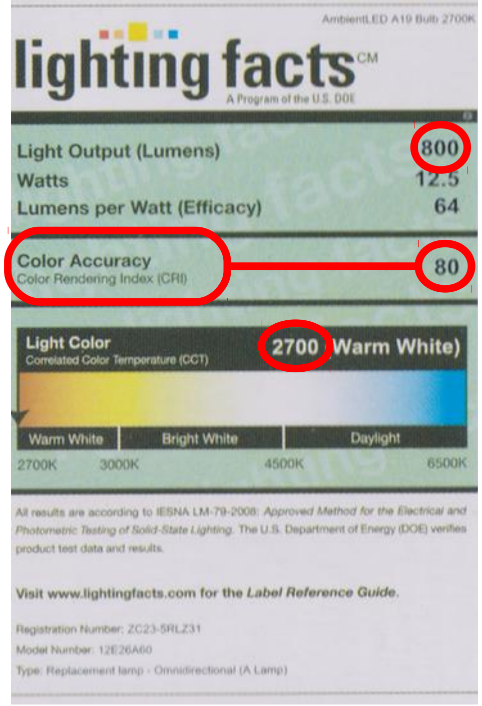


Colorimetry

- Colorimetric characteristics of surfaces
  - Done under a controlled light environment
  - Ideal case = sunlight at 5500K or incandescent lamp
  - Beware of fluorescent lights and LEDs that have a very complex spectrum (narrow bands, see picture)
  - Check the color rendering index ...



Light source	CCT (K)	CRI
Low-pressure sodium (LPS/SOX)	1800	-44
Clear mercury-vapor	6410	17
High-pressure sodium (HPS/SON)	2100	24
Coated mercury-vapor	3600	49
Halophosphate warm-white fluorescent	**2940**	**51**
Halophosphate cool-white fluorescent	4230	64
Tri-phosphor warm-white fluorescent	2940	73
Halophosphate cool-daylight fluorescent	6430	76
"White" SON discharge lamp	2700	82
Quartz metal halide	4200	85
Tri-phosphor cool-white fluorescent	4080	89
Ceramic metal halide	5400	96
Incandescent/halogen bulb	**3200**	**100**



AmbientLED A19 Bulb 2700K

lighting factsCM

A Program of the U.S. DOE

Light Output (Lumens)	800
Watts	12.5
Lumens per Watt (Efficacy)	64
Color Accuracy Color Rendering Index (CRI)	80
Light Color Correlated Color Temperature (CCT)	2700 (Warm White)

All results are according to IESNA LM-79-2008: *Approved Method for the Electrical and Photometric Testing of Solid-State Lighting*. The U.S. Department of Energy (DOE) verifies product test data and results.

Visit www.lightingfacts.com for the *Label Reference Guide*.

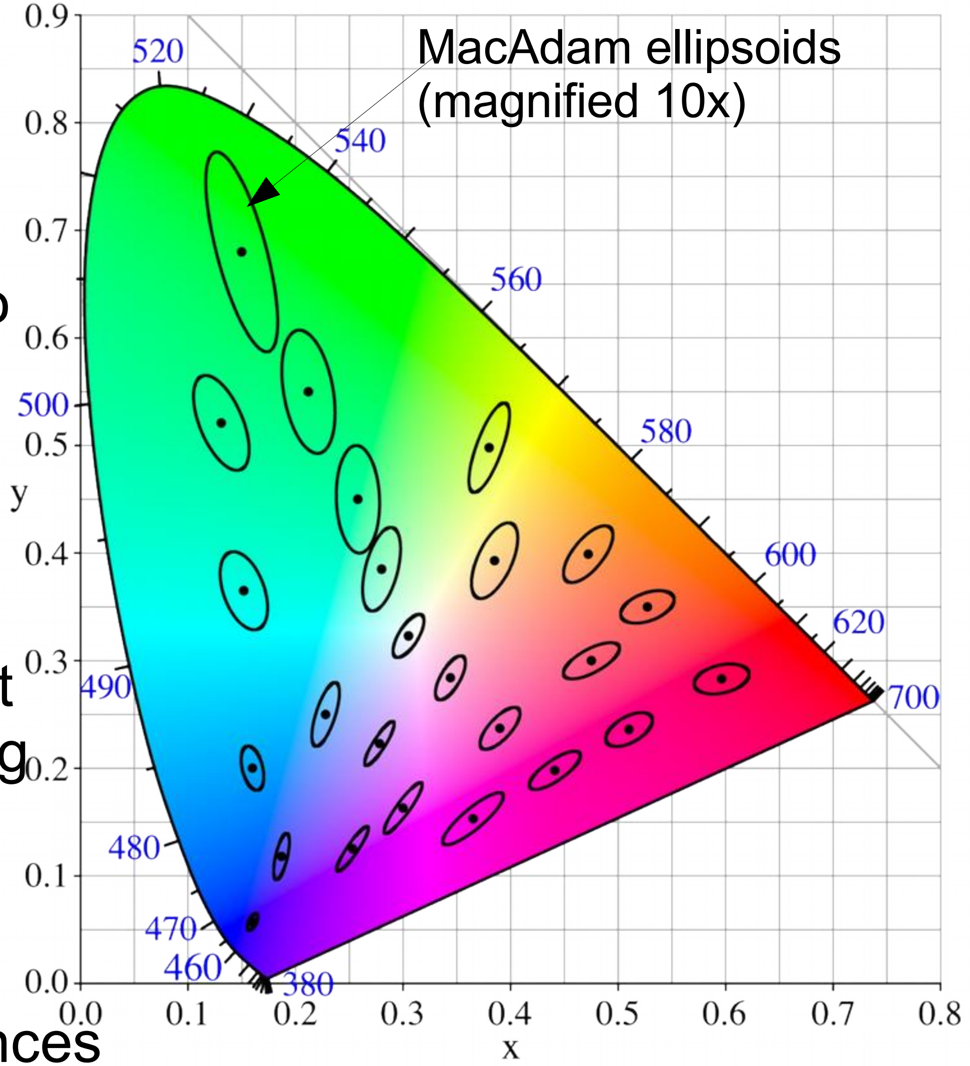
Registration Number: ZC23-5RLZ31
Model Number: 12E26A60
Type: Replacement lamp - Omnidirectional (A Lamp)

By convention

Wikipedia

Colorimetry

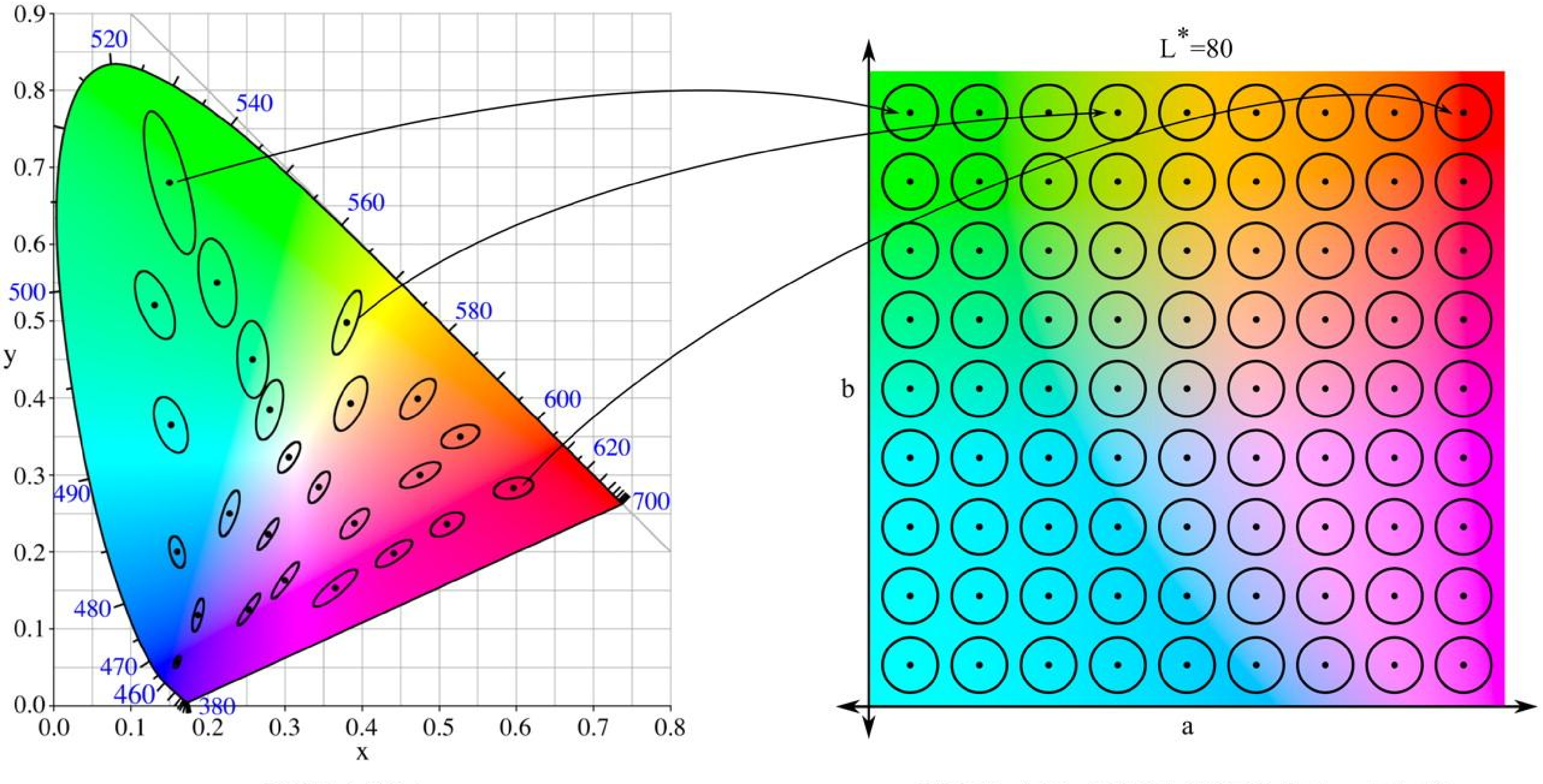
- Perceptually uniform color spaces
  - L*a*b* space
  - Gamma correction is embedded
  - Takes the illuminant into account
  - Allows to use every bit of the encoding efficiently
  - Based on an experiment of David MacAdam using 25 points in the 1931 CIE xyY color space
  - Asked observers to distinguish color differences



MacAdam, David Lewis (May 1942). "Visual sensitivities to color differences in daylight" . JOSA 32 (5): 247–274

Colorimetry

- Perceptually uniform color spaces



CIE 1931

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

Colorimetry

- L*a*b* color space definition

$$L^* = 116\, f\left(Y / Y_n\right)$$
$$a^* = 500 \cdot \left(f\left(X / X_n\right) - f\left(Y / Y_n\right)\right)$$
$$b^* = 200 \cdot \left(f\left(Y / Y_n\right) - f\left(Z / Z_n\right)\right)$$

$$f(t) = \begin{cases} t^{1/3} & \text{if} \quad t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29} & \text{otherwise} \end{cases}$$

NB. Standard in many image editing software like Photoshop

For the D65 illuminant (daylight)

$$X_n = 0.95043 \qquad x_n = 0.31271$$
$$Y_n = 1.0 \longleftarrow y_n = 0.32902$$
$$Z_n = 1.08883 \qquad z_n = 1 - x_n - y_n$$

For the D50 illuminant (crepuscular light)

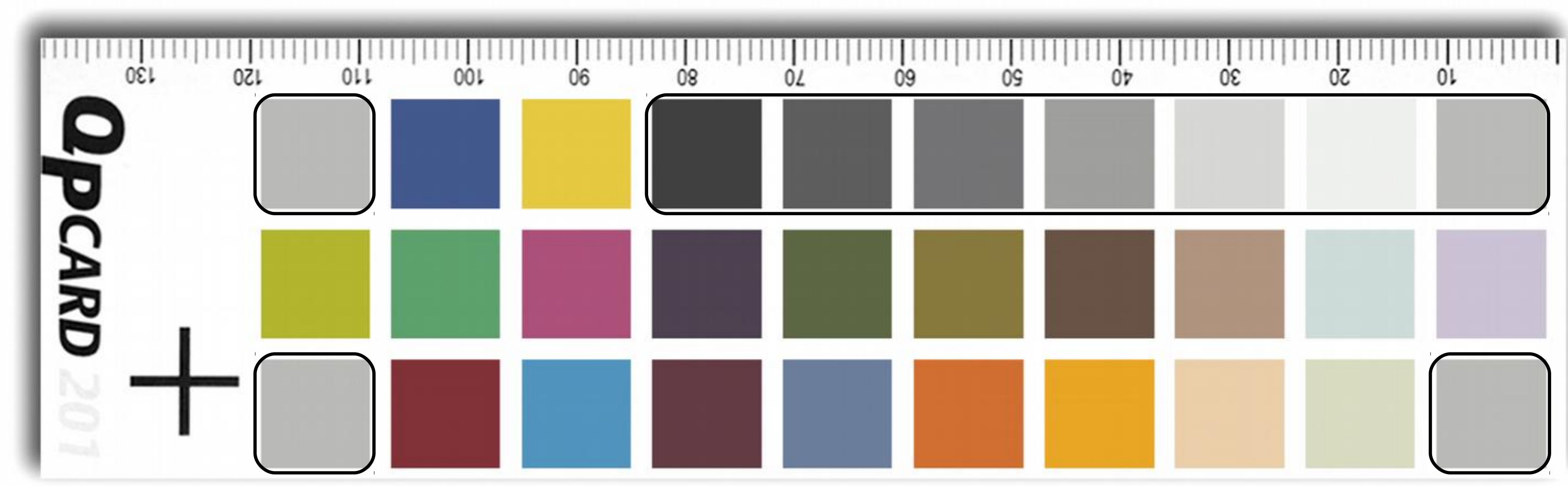
$$X_n = 0.96421 \qquad x_n = 0.34567$$
$$Y_n = 1.0 \qquad y_n = 0.35850$$
$$Z_n = 0.825188 \qquad z_n = 1 - x_n - y_n$$

Colorimetry

- How to “calibrate” a scene ?
  - Aim – accurate color rendering
  - Ideally :
    - Calibrated light sources
    - Camera whose behavior is perfectly known
  - Practically, this is never met !
    - Light sources are often not controlled (especially with current trends toward energy efficient LED or fluorescent lights)
    - Camera may age and sensor filter dyes may also evolve with time
  - Solution : use of calibrated color charts

Colorimetry

- Reference color chart
  - The exact colorimetric coordinates of every color patch is known
  - Some of the patches have a constant reflectance w/r to wavelength (grey, outlined)



Colorimetry

- Reference color chart
  - The other patches have a spectral reflectance that is close to that of usual surfaces (eg. skin, tree leaves, etc…). It is a very difficult task to find dyes with these characteristics !
  - It means that, whatever the shooting conditions, the behavior of a color patch is similar to the material it is supposed to “mimic”
  - Once the shoot done, one have, for each patch, the camera measure, and the theoretical one
    - It is then possible to calibrate the whole chain so that color rendering is correct on pictures

Colorimetry

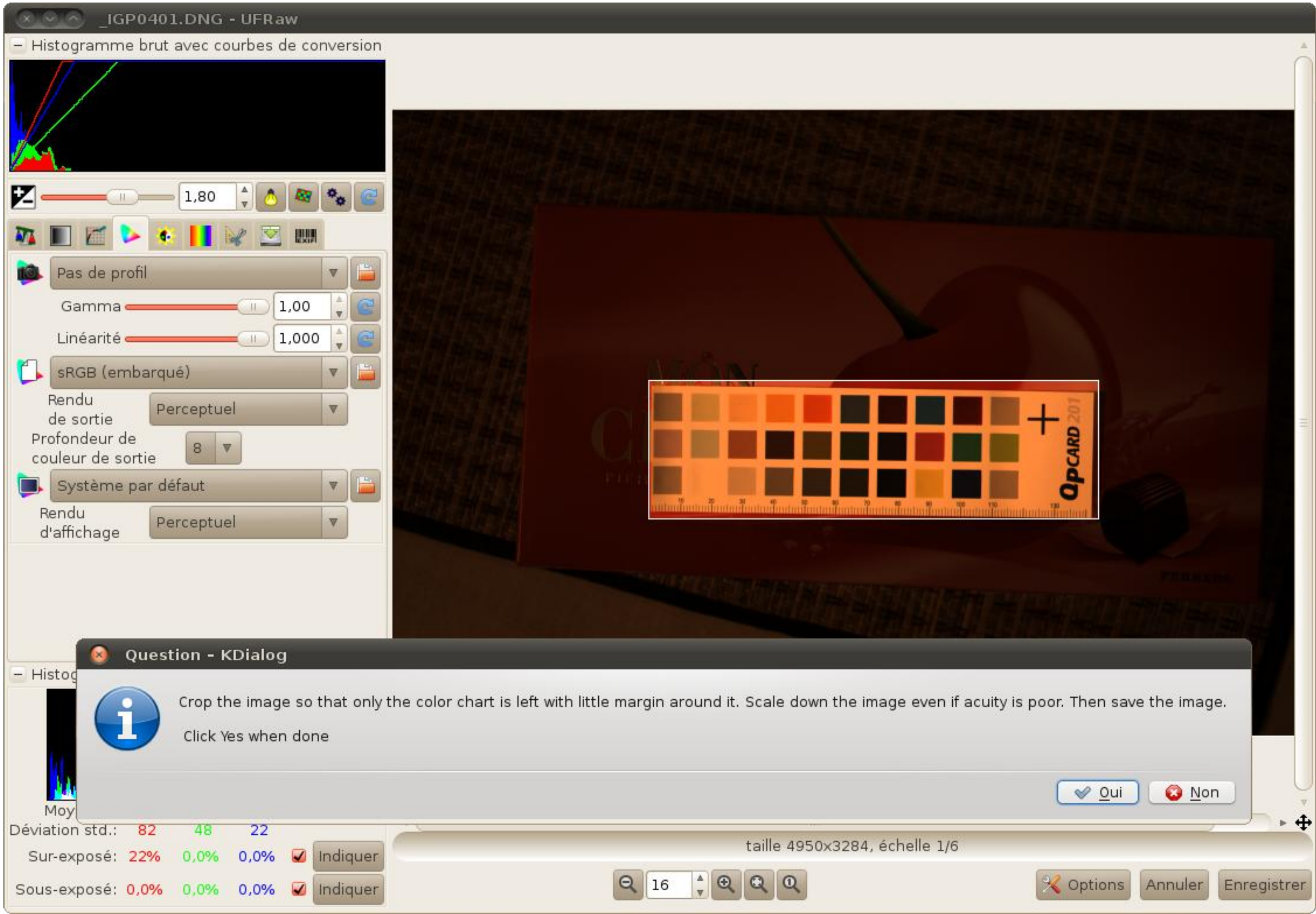
- Example : object under artificial light

Colorimetry

- Step 1: identify patches and build a colorimetric profile

On the terminal :

```
make_profile
FILE.DNG↵
```



_IGP0401.DNG - UFRaw

Histogramme brut avec courbes de conversion

1,80

Pas de profil

Gamma 1,00

Linéarité 1,000

sRGB (embarqué)

Rendu de sortie: Perceptuel

Profondeur de couleur de sortie: 8

Système par défaut

Rendu d'affichage: Perceptuel

Question - KDialog

Crop the image so that only the color chart is left with little margin around it. Scale down the image even if acuity is poor. Then save the image.

Click Yes when done

Oui | Non

Déviation std.:	82	48	22	
Sur-exposé:	22%	0,0%	0,0%	☑ Indiquer
Sous-exposé:	0,0%	0,0%	0,0%	☑ Indiquer

taille 4950x3284, échelle 1/6

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Colorimetry

- Patch description

```
BOXES 32
  F _ _ 0 0 1654 0 1654 494 0
494
  D _ _ _ _ 118 11 97 367 0 0
  D _ _ _ _ 10 117 151 314 0 0
  Y 1 10 A C 118 118 239 66
141.6 141.6

BOX_SHRINK 30
```

```
XLIST 22
  0    1.0 1.0
  239  0.6 1.0
  357  0.6 1.0
  380  0.4 1.0
  498  0.4 1.0
  522  0.6 1.0
  640  0.6 1.0
  663  0.6 1.0
  782  0.6 1.0
  805  0.6 1.0
  923  0.6 1.0
  947  0.6 1.0
  1066 0.6 1.0
  1089 0.6 1.0
  1208 0.6 1.0
  1230 0.6 1.0
  1349 0.6 1.0
  1373 0.6 1.0
  1492 0.6 1.0
  1514 0.6 1.0
  1633 0.6 1.0
  1654 1.0 1.0
```

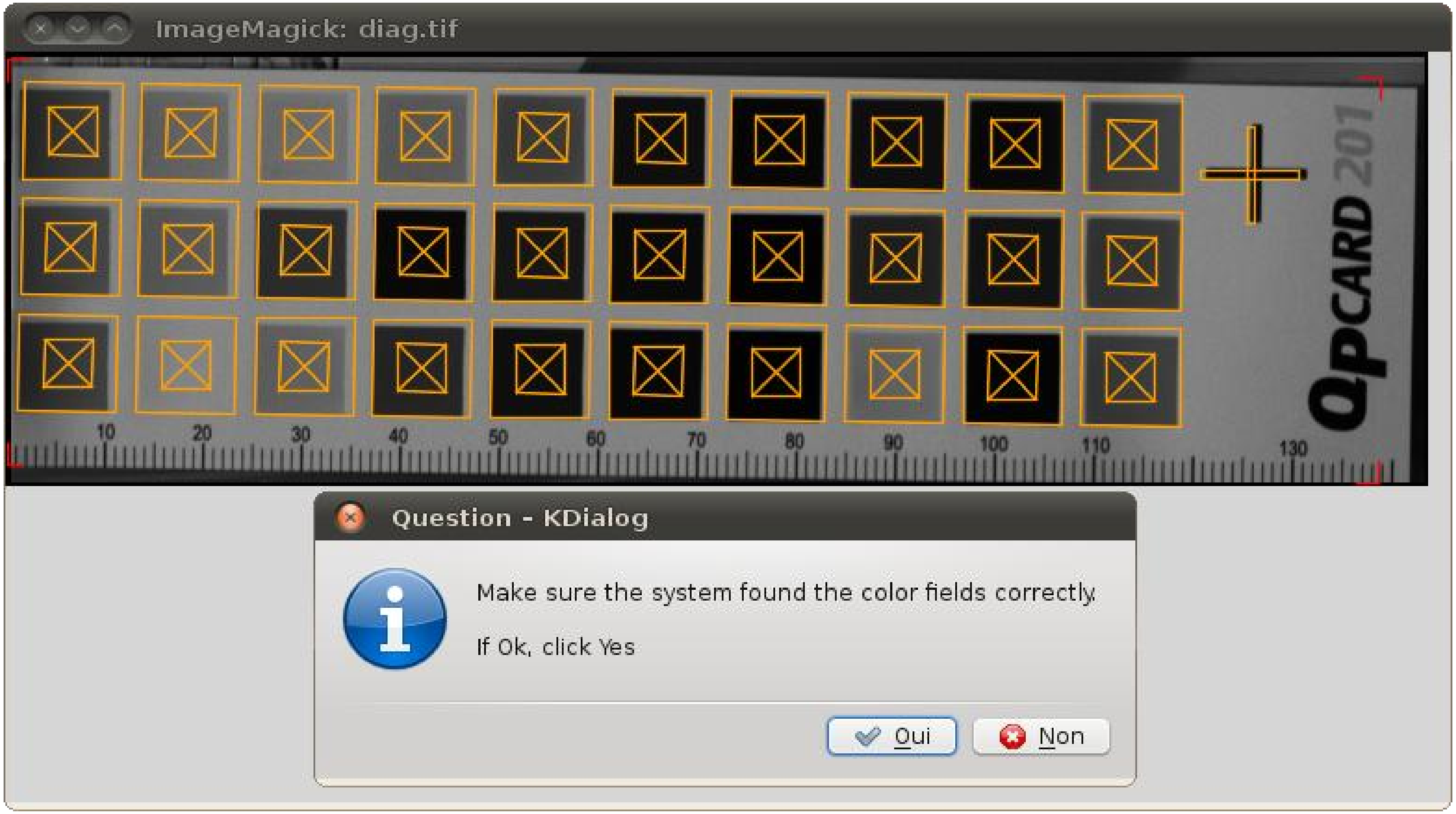
```
YLIST 8
  0   1.0 1.0
  66  0.6 1.0
  185 0.6 1.0
  208 0.6 1.0
  326 0.6 1.0
  349 0.6 1.0
  467 0.6 1.0
  494 1.0 1.0
```

- Color coordinates of each patch in the XYZ color space

```
EXPECTED XYZ 30
A1  47.8 50.5 53.2
A2  9.3  9.6  27.6
A3  60.7 62.1 11.2
A4  4.4  4.6  4.9
A5  10.5 11.1 11.9
A6  16.8 17.8 19.5
A7  32.9 34.7 36.8
A8  65.1 68.9 72.5
A9  81.8 86.6 91.0
A10 47.8 50.5 53.2
B1  36.9 43.1 7.0
B2  15.7 26.5 17.4
B3  29.8 19.5 20.8
B4  6.2  5.7  7.9
B5  10.1 12.3 6.8
B6  19.9 20.5 6.5
B7  11.0 9.9  6.8
B8  36.2 34.2 25.0
B9  60.7 67.5 73.7
B10 56.3 56.5 70.3
C1  47.8 50.5 53.2
C2  14.5 8.9  4.3
C3  18.6 24.8 52.5
C4  9.6  7.2  6.1
C5  18.0 19.8 34.8
C6  43.0 30.9 5.8
C7  57.0 49.6 6.6
C8  69.3 68.9 47.9
C9  64.5 69.9 59.9
C10 47.8 50.5 53.2
```

Colorimetry

- Software needs to find the patches (automatically)



Make sure the system found the color fields correctly

If Ok, click Yes

Colorimetry

- Data read back from the camera :

Exact (theoretical)
color coordinates
in the XYZ color space

Average over the patch
of « raw » color values
given by the sensor of the camera

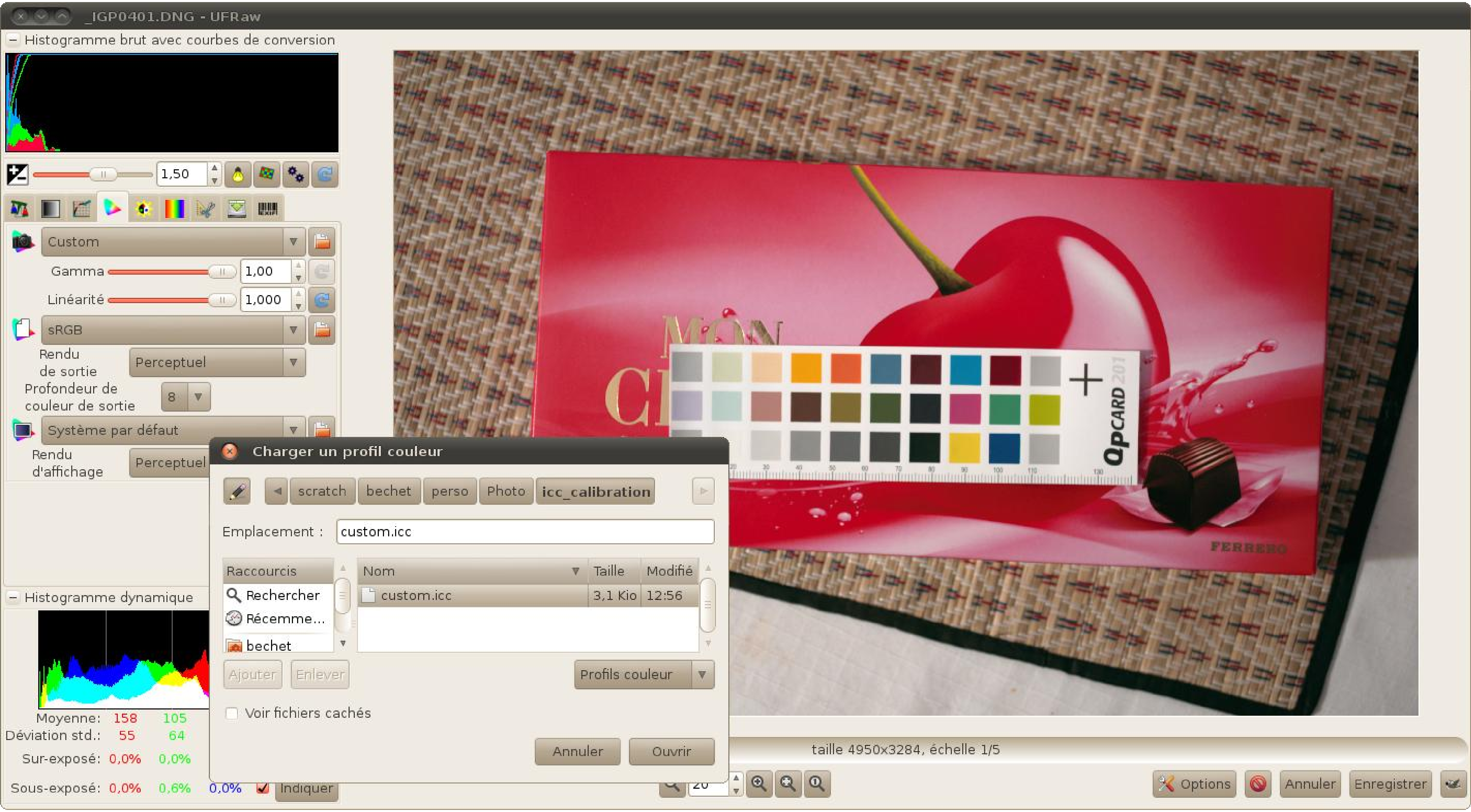
```
DESCRIPTOR "Argyll Calibration Target chart information 3"
ORIGINATOR "Argyll target"
CREATED "Wed May 11 14:56:05 2011"
KEYWORD "DEVICE_CLASS"
DEVICE_CLASS "INPUT"
KEYWORD "COLOR_REP"
COLOR_REP "XYZ_RGB"

KEYWORD "STDEV_R"
KEYWORD "STDEV_G"
NUMBER_OF_FIELDS 10
BEGIN_DATA_FORMAT
SAMPLE_ID XYZ_X XYZ_Y XYZ_Z RGB_R RGB_G RGB_B STDEV_R STDEV_G STDEV_B
END_DATA_FORMAT

NUMBER_OF_SETS 30
BEGIN_DATA
A01 47.800 50.500 53.200 54.143 28.927 12.079 1.7854 0.97768 0.58424
A02 9.3000 9.6000 27.600 5.8934 4.3038 4.6361 0.41442 0.25112 0.31921
A03 60.700 62.100 11.200 82.904 42.493 6.2955 1.8058 0.93346 0.39314
A04 4.4000 4.6000 4.9000 4.9699 2.4462 0.88128 0.40720 0.22186 0.20996
A05 10.500 11.100 11.900 12.550 6.6873 2.7487 0.57773 0.31063 0.26201
A06 16.800 17.800 19.500 19.744 10.877 4.6704 0.73688 0.39141 0.33760
A07 32.900 34.700 36.800 38.440 20.872 8.7906 1.0672 0.60164 0.42796
A08 65.100 68.900 72.500 79.212 42.634 17.886 1.7165 0.83926 0.62561
A09 81.800 86.600 91.000 99.951 53.978 22.691 1.2836 1.1414 0.73087
A10 47.800 50.500 53.200 51.524 27.821 11.848 3.8074 2.0543 0.93460
B01 36.900 43.100 7.0000 43.110 29.826 4.4348 1.2573 0.77159 0.32577
B02 15.700 26.500 17.400 11.938 16.377 5.7865 0.58789 0.46097 0.34534
B03 29.800 19.500 20.800 53.957 10.096 4.3343 1.2436 0.36050 0.31889
B04 6.2000 5.7000 7.9000 7.3258 3.1358 1.5580 0.45815 0.23025 0.21919
B05 10.100 12.300 6.8000 12.142 8.7110 2.2550 0.59272 0.34982 0.24303
B06 19.900 20.500 6.5000 28.983 14.426 2.7299 0.82059 0.40240 0.25656
B07 11.000 9.9000 6.8000 17.274 6.3054 1.9268 0.67214 0.30438 0.24077
B08 36.200 34.200 25.000 55.704 20.310 7.0637 1.2403 0.50822 0.40522
B09 60.700 67.500 73.700 67.998 42.395 18.423 1.6913 0.96299 0.66107
B10 56.300 56.500 70.300 59.680 29.310 14.531 3.4600 1.7401 0.92116
C01 47.800 50.500 53.200 55.692 29.850 12.460 1.9870 1.0206 0.58139
C02 14.500 8.9000 4.3000 21.198 3.4517 0.80590 0.83276 0.24680 0.17613
C03 18.600 24.800 52.500 10.854 12.680 10.540 0.58344 0.43548 0.48329
C04 9.6000 7.2000 6.1000 15.313 3.6935 1.2161 0.71258 0.26522 0.21045
C05 18.000 19.800 34.800 16.063 11.760 7.4468 0.71908 0.42333 0.39573
C06 43.000 30.900 5.8000 82.753 18.755 2.4951 1.6515 0.50249 0.27154
C07 57.000 49.600 6.6000 92.519 33.873 4.4067 1.5869 0.67443 0.32242
C08 69.300 68.900 47.900 95.687 44.601 13.562 2.1710 0.95884 0.54820
C09 64.500 69.900 59.900 78.202 45.299 16.095 1.8464 0.96151 0.57902
C10 47.800 50.500 53.200 51.868 28.192 12.142 3.1149 1.6931 0.85667
END_DATA
```

Colorimetry

- Step 2 : use of the colorimetry profile to adjust a photo shoot
  - The same C. profile may be used to correct every picture made with the same light sources and conditions (one has been done with the color chart)
  - But the profile is valid for only one light source, one set of shooting conditions, and one camera. It is also not valid for a long time as lights and camera characteristics usually change in time.
  - Therefore, it is NOT an exhaustive calibration procedure – which should be more comprehensive.

Terminal : `use_profile FILE.DNG↵`

Colorimetry



_IGP0401.DNG - UFRaw

Histogramme brut avec courbes de conversion

1,50

Custom

Gamma 1,00

Linéarité 1,000

sRGB

Rendu de sortie: Perceptuel

Profondeur de couleur de sortie: 8

Système par défaut

Rendu d'affichage: Perceptuel

Histogramme dynamique

Moyenne:	158	105	
Déviation std.:	55	64	
Sur-exposé:	0,0%	0,0%	
Sous-exposé:	0,0%	0,6%	0,0%

Charger un profil couleur

scratch / bechet / perso / Photo / icc_calibration

Emplacement : custom.icc

Nom	Taille	Modifié
custom.icc	3,1 Kio	12:56

taille 4950x3284, échelle 1/5

Colorimetry

- Results

Raw image under bad lighting conditions

In-camera (roughly) white-balanced image

Image corrected using the color chart

Studio image by the manufacturer (almost certainly using the same kind of procedure)

Colorimetry

- Some tools are available on the course’s website : http://cg-dev.ltas.ulg.ac.be/inf/icc_profile_qp201.tar.gz
  - Installation scripts – works with Debian-like distros.

    Terminal :
    ```
    sudo sh ./install.sh↵
    ```
  - GNU/Linux shell scripts for the creation/use of color profiles

    `make_profile`, `use_profile`
  - Data files related to the color chart used here (Qpcard 201) and configuration files
    `qpcard201.cht`, `qpcard201.cie`, `ufrawrc.use_profile`, `ufrawrc.make_profile`
  - Test image file (RAW format) `TEST.DNG`