Color Design & Technology

A Multidisciplinary Approach to Colour

PART 1

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Preface

Color is a fascinating theme that involves many disciplines like physics, chemistry, optics, psychology, anthropology and sociology, together with colorimetry, computer science, design and many others. Color is related with the visual sensation and perception and has an impact on the cognitive and emotional nature of every human being. We are surrounded by colors, at home, in the cities, at the supermarkets. Despite this, the education of professionals in this field, remains very complex but necessary task.
Since 2014, Associazione Italiana Colore - Gruppo del Colore, the Italian Color Association with Poli.DESIGN (Politecnico di Milano) and Università degli Studi di Milano, have cooperated to held (in English) the initial four editions of the Master in *Color Design and Technology*.
As far as we know, nowadays, this Master is the only international, multidisciplinary, theoretical and practical course aiming at training color specialists and technicians, providing them skills for acquisition, measurement, and management of color in many application areas. Main strength of the Master is its strong correlation between theoretical lectures and practical lessons, which allow a rapid learning and the development of professional skills.
So far, the Master has been attended by many students from all over the world like e.g., Australia, Austria, Brazil, Colombia, Finland, India, Italy, Japan, Lebanon, Spain, Portugal, Russia and many others. The multicultural environment in which the students are involved enriches them and allowed the development of a positive discussion about color culture, naming and uses across different nations.
The main purpose of this book is to present the major part of teachers and subjects of the Master, as well as to foster the discussion about the many different possible ways of teaching and educating on the complex topic of color.
This book is divided in three Volumes, each one of them focused on specific issues about color theories, management, applications and design. In this book, as in the Master, color will not be described as simple attribute of an object, but as technical means of expression, at the base of perception and interaction with reality.

Alice Plutino, Gabriele Simone and Alessandro Rizzi, Editor

Chapter 1 Introduction to Standard Colorimetry

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Abstract
Colorimetry is the branch of color science concerned with the numerical specification of color. The main focus of colorimetry has been the development of methods for predicting perceptual color matches on the basis of radiometric (physical) measurements.
In this chapter, starting from the Grassman laws and the first color-matching experiments, we will introduce the LMS fundamental reference, the RGB instrumental reference and the XYZ CIE 1931 standard system.
After discussing the non-uniformity of the well-known CIE chromaticity diagram, we will present the two CIE psychometric color systems, termed CIELAB and CIELUV, respectively.
Finally, we will explore the development of the most recent color difference formulae.
For the scientists keen in programming, we will also present some of the basic colorimetric numerical calculations.

Keywords:
Psychophysical Colorimetry, Psychometric colorimetry, CIE Systems, Color difference formulae, C++ algorithms.

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1. Introduction

Colorimetry is constituted by two main parts, psychophysical and psychometric colorimetry, and both parts have their origin in visual physiology. A general knowledge of the human visual system is needed.
In colorimetry, the eye can be considered as a spherical optical chamber.
Light is measured outside the eye and the visible range of wavelength is $360 \div 780$ nm. The light entering the eye is named color stimulus and is physically represented by a spectral radiance $L_e(\lambda)[\mathrm{W/(sr\ m^2 nm)}]$ (Wyszecki, G. and Stiles, W. S. (2000).
Light enters the eye, crosses some different media and is focused on the back of the eye, that is covered by a membrane sensitive to light, named retina. The spectral power distribution of the light is altered by the lens of the eye, that is strongly absorbent in the short wavelength region below 450 nm.
The retina is a non-uniform tissue of many layers of different kinds of cells with proper roles in the visual process. The external layer of cells is composed of photoreceptors, thus the light can be absorbed by the photoreceptors only after travelling across almost all the retina. In particular, the central part of the retina, named macula lutea, contains an inert pigment that modifies the spectral power distribution of the light. Thus, the light that crosses the photoreceptors is altered differently in the macular region with respect to the non-macular region. Such a difference leads to define two different colorimetric systems, one for the macular region, and the other for the region external to the macula. The visual field related to macular vision has an angular section lower than 4°, generally 2°, while extra macula vision an angular section of 10°. Generally, this angle is called visual angle.
The photoreceptors are subdivided into rods and cones, as their shapes suggest. The rods are dedicated to crepuscular vision, named scotopic vision, while the cones are dedicated to color vision, named photopic vision.
We are interested only in color vision, thus we consider the cones, that are of three different kinds characterized by different photopigments. The absorption of light by the cones is the first step in visual processing and is named cone activation. The cones with maximum absorption of light in the short, medium and long wavelength region are named cones S, cones M and cones L, respectively.

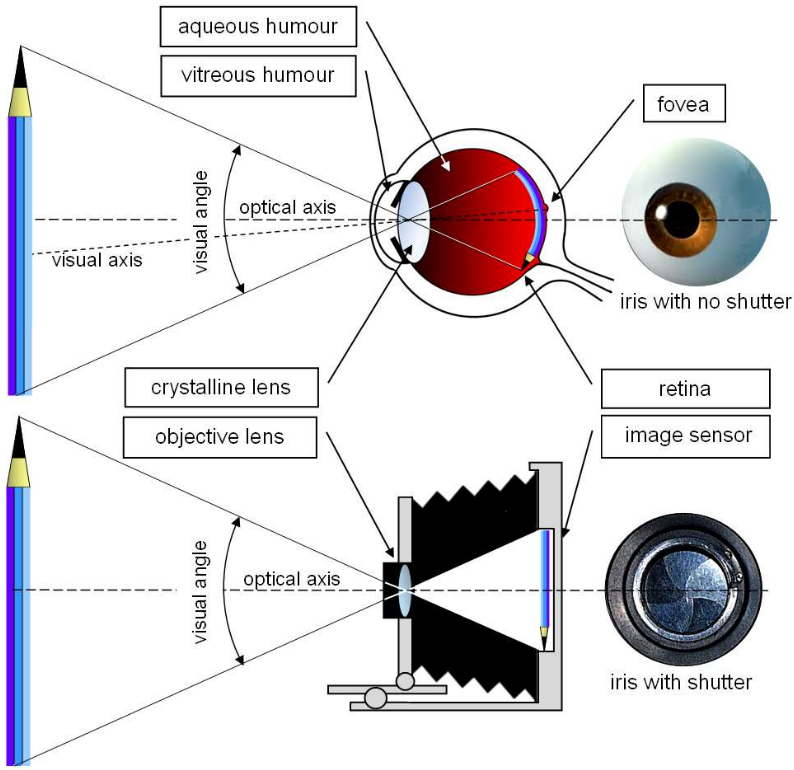

Figure 1. Comparison of the eye with a camera. Figure reproduced with permission from Oleari C. (2016).

The light absorbed by cones produces cone activation. Cone activation is based on Rushton's univariance principle, that says that the visual effect of radiation depends only on the number of absorbed photons and is independent of the photon energy, i.e., a photon, once absorbed by the pigment of a cone, triggers a photochemical process, that is independent of the photon energy. Photons with different energy have their own probability to be absorbed and consequently produce different visual effects. Cone activation is the first step in the color vision phenomenon and is represented by the numbers of photons absorbed by the three kinds of cones in the unit of time. In any defined visual situation, the correspondence between cone activations and color sensations is one to one. Thus, cone activation can be used to specify color.

First, the other layers of cells of the retina make a comparison between the signals of the cones generated locally in the retina. The result of this comparison depends on the signals generated in the proximal field and the color sensation of a point depends on the global visual situation. This signal processing, that constitutes the second step in the color vision phenomenon, is not yet completely understood and is in part linear and in part non-linear. These stages of the color-vision phenomenon correspond to the zones of Mueller's zone theory.
The picture here given of the retina is sufficient to define different colorimetric systems as functions of the retinal region and as functions of the stage of visual processing.
This simple system of three photoreceptors is very powerful and gives a wavelength discrimination between 1 and 3 nm in a wide part of the visible range.

2. Psychophysical colorimetry

Let us consider the cone activations, the first stage of the visual phenomenon in the macular region.
The cone activations are represented by a set of three numbers that satisfy linear addition (Grassmann's laws) and are well represented by points (vectors) in a three-dimensional linear space, known as tristimulus space. In this case the reference frame of the tristimulus space is named fundamental reference frame (Wyszecki, G. and Stiles, W. S. (2000), Grassmann H. (1853), Grassmann H. (1853), Wyszecky G. and Judd D.B. (1975)).
Many reference frames are possible in the tristimulus space, of which let us recall:

- The LMS fundamental reference.
- The RGB instrumental reference.
- The XYZ CIE 1931 standard system.

For didactic reasons, we introduce, first, the tristimulus space with the fundamental reference frame and then, departing from this, the RGB and the more used XYZ CIE 1931 system.

2.1 Tristimulus space and the fundamental reference frame

The cone activations produced by a color stimulus with spectral radiance $L_e(\lambda)$ are proportional to three numbers *(L, M, S)*, named tristimulus values, and representing the activations of the cones *L, M* and *S*, respectively:

$$L = \int_{380}^{780} L_e(\lambda) \cdot \bar{l}(\lambda) d\lambda, M = \int_{380}^{780} L_e(\lambda) \cdot \bar{m}(\lambda) d\lambda, S = \int_{380}^{780} L_e(\lambda) \cdot \bar{s}(\lambda) d\lambda,$$

where the functions $\bar{l}(\lambda), \bar{m}(\lambda), \bar{s}(\lambda)$ (Figure 2), named color-matching functions (CMF), are the spectral sensitivities of the cones L, M and S, respectively, and take into account also the light absorption of the lens of the eye and of the macula lutea. The color-matching functions are normalized to give $L = M = S = 1$ for the equal-energy radiance $L_e(\lambda) = 1$, thus represent the monochromatic components with unitary radiance of the equal-energy stimulus $(\bar{l}(\lambda),\ \bar{m}(\lambda), \bar{s}(\lambda))$ in the tristimulus space.

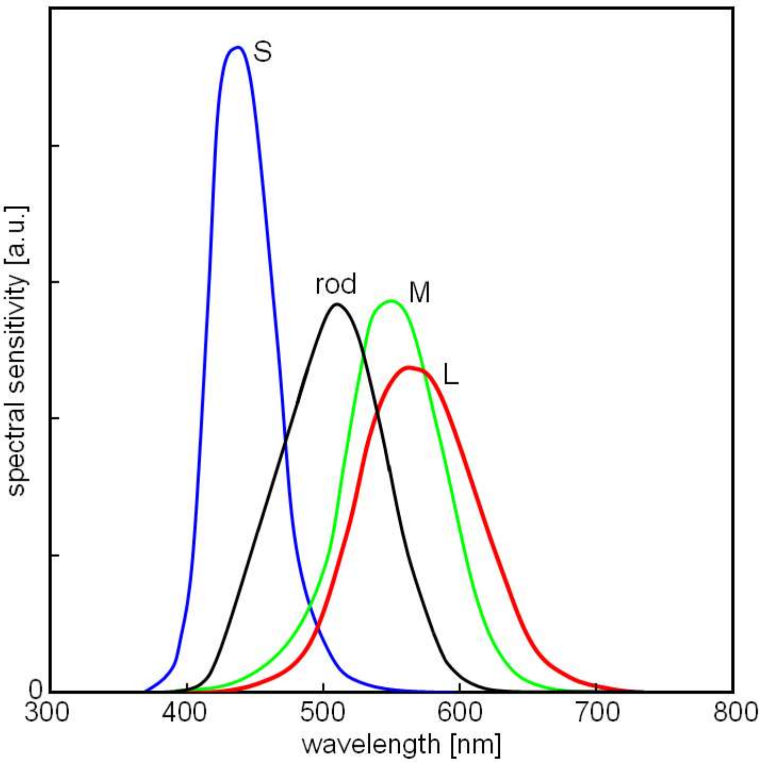

Figure 2. Color-matching functions in the fundamental reference frame.

The mathematical properties of the tristimulus space are defined for the first time by Grassmann's laws, although the original idea is Newton's centre of gravity rule.
The sum of color stimuli is represented in the tristimulus space by the sum of the corresponding vectors (Figure 3). The definition of the (L, M, S) vectors claims that the correspondence between color stimuli and tristimulus vectors is many to one, i.e., different radiances can produce equal cone activations and equal color sensation. This phenomenon is named metamerism and the color stimuli producing the same color sensation are named metamers. The CIE definition of metamerism regards the "metameric colour stimuli: spectrally different color stimuli that have the same tristimulus values in a specified colorimetric system" (Publication CIE S 017/E:2011 (2011)).
The length of the vectors is related to the intensity of the color stimuli and the direction is related to chromatic sensation. Since the vector directions are in a one-to-one correspondence with the intersection points between the tristimulus vectors and a plane, these points constitute a diagram, termed chromaticity diagram because it represents the chromaticity (Figure 3). The chromaticities of the monochromatic lights are points of a line named spectrum locus and the segment between short wavelength and long wavelength regions regards the purple hues. The practical role of the chromaticity diagram is very important.
The coordinates system on the plane of the chromaticity diagram in order to define the chromaticity of the color stimuli is as follows:

$$l = \frac{L}{L + M + S},$$
$$m = \frac{M}{L + M + S},$$
$$s = \frac{S}{L + M + S} = 1 - l - m.$$

These coordinates are called chromaticity coordinates.

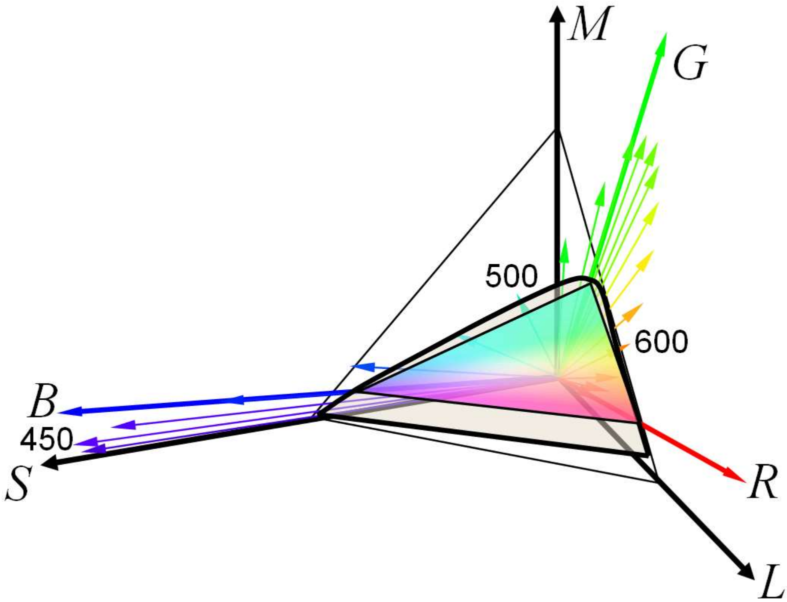

Figure 3. Fundamental reference frame in the tristimulus space. On the plane $L + M + S = 1$ is defined the chromaticity diagram (grey area). Figure reproduced with permission from Oleari C. (2016).

2.2 Tristimulus space and instrumental RGB reference frame

The color-matching functions are not measured by probes introduced in the cones, but are measured indirectly by a technique known as color-matching. This technique needs the choice of three lights (generally monochromatic) as reference lights (often called primary lights, although contradicting CIE [21]), generally one red, one green and one blue, whose corresponding tristimulus vectors constitute the reference frame in the tristimulus space.
In color matching, in correspondence to any monochromatic light of wavelength λ and of unit radiance, two lights are shown to the observer: the first light is obtained by mixing the two reference lights, for which the monochromatic light is in between, and the second light is obtained by mixing the monochromatic light with the third reference light. The observer modifies the radiances L_R, L_G and L_B of the three reference lights until a match is obtained. The values of the radiances $\overline{r}(\lambda) = L_R$, $\overline{g}(\lambda) = L_G$ and $\overline{b}(\lambda) = L_B$ represent the CMFs at the wavelength λ. Generally, after measuring these

CMFs, they are normalized in order to obtain equal tristimulus values for the equal-energy stimulus, i.e., the stimulus of a spectral radiance constant in wavelength. The tristimulus values in the RGB reference frame are defined by the integrals:

$$R = \int_{380}^{780} L_e(\lambda) \cdot \overline{r}(\lambda) d\lambda,$$

$$G = \int_{380}^{780} L_e(\lambda) \cdot \overline{g}(\lambda) d\lambda,$$

$$B = \int_{380}^{780} L_e(\lambda) \cdot \overline{b}(\lambda) d\lambda,$$

and the chromaticity coordinates are represented by barycentric coordinates (r, g, b):

$$r = \frac{R}{R+G+B},$$

$$g = \frac{G}{R+G+B},$$

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

A linear transformation exists between the tristimulus values (L, M, S) and *(R, G, B)*, as well as between the color-matching functions $(\overline{l}(\lambda),\ \overline{m}(\lambda), \overline{s}(\lambda))$ and $(\overline{r}(\lambda),\ \overline{g}(\lambda), \overline{b}(\lambda))$. This linear transformation can be realized by the knowledge of the LMS reference axes in the RGB reference frame, which is obtained from the dichromat color matching. The dichromats are observers with only two kinds of cones.

The RGB reference frame here considered regards the CIE 1931 standard observer. A standard observer is the hypothetical individual whose color-matching behavior is represented by the set of standard CMFs.

Any trichromatic device (monitor, scanner, video camera, ..., TV system like NTSC, PAL, SECAM, HDTV, ...) has its own RGB reference frame and the passage between different RGB reference frames is made by linear transformations. Confusing different RGB reference frames is a mistake. Moreover, an RGB system exists, whose (R, G, B) components are obtained as powers of tristimulus values, destroying the original linearity of the space (e.g., sRGB used for images on computers and the web).

2.3 Tristimulus space and XYZ reference frame of the CIE 1931 system

The CIE 1931 colorimetric system was realized by embedding photometry in colorimetry. The photometry relates the sensation of luminosity of a light defining the luminance, the quantity that would represent the brightness associated the radiance $L_{e,\lambda}$:

$$L_v = K_m \int_{380}^{780} L_e(\lambda) \cdot V(\lambda) d\lambda,$$

with $V(\lambda)$ = relative photopic luminous efficiency function that defines the standard photometric observer CIE 1924 and $K_m = 683$ lumen / watt.
Abney's law states that the luminance of a color stimulus obtained as a sum of many stimuli is equal to the sum of the corresponding luminances. This law, although a weak law, induced scientists to represent luminance as a linear weighted sum of the tristimulus values:

$$L_v = L_L + L_M M + L_S S = L_R R + L_G G + L_B B.$$

The coefficients L_L, L_M, L_S, L_R, L_G and L_B are called Exner coefficients and equation Schrödinger's "Helligkeit" equation.
As a consequence, to search for a reference frame XYZ such that the Y component of the stimulus is proportional to the luminance L_v, i.e., $L_v = K_m = Y$ cd/m^2 and $\overline{y}(\lambda) = V(\lambda)$, where $(\overline{x}(\lambda),\ \overline{y}(\lambda),\ \overline{z}(\lambda))$ are the color-matching functions in the XYZ system, the following constraints are imposed:

- The *X*, *Y* and *Z* axes are mutually orthogonal.
- The *X* and *Z* axes belong to the zero luminance plane *Y* = *0*.
- The tristimulus vectors with physical meaning have all positive components.
- The planes *X* = *0* and *Z* = *0* are tangent to the spectrum locus in the short and in the long wavelength region, respectively.

This reference frame is possible and is obtained from the RGB one by a linear transformation. This reference frame is the XYZ of the CIE 1931 standard colorimetric observer (Figure 4). The tristimulus values are:

$$X = \int_{380}^{780} L_e(\lambda) \cdot \bar{x}(\lambda) d\lambda,$$

$$Y = \int_{380}^{780} L_e(\lambda) \cdot \bar{y}(\lambda) d\lambda = \int_{380}^{780} L_e(\lambda) \cdot V(\lambda) d\lambda = \frac{L_v}{K_m},$$

$$Z = \int_{380}^{780} L_e(\lambda) \cdot \bar{z}(\lambda) d\lambda,$$

and the chromaticity:

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

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

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

The usual chromaticity diagram is obtained from the diagram on the plane $X = Y = Z = 1$ by a projection from infinity on the plane $Z = 0$ (Figure 5).

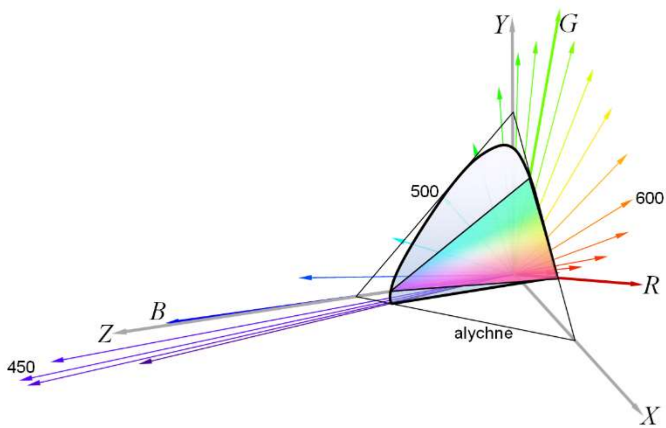

Figure 4. XYZ reference frame in the tristimulus space in which the vectors X, Y and Z constitute a set of three orthogonal vectors. The chromaticity diagram is on the plane $X + Y + Z = 1$. Figure reproduced with permission from Oleari C. (2016).

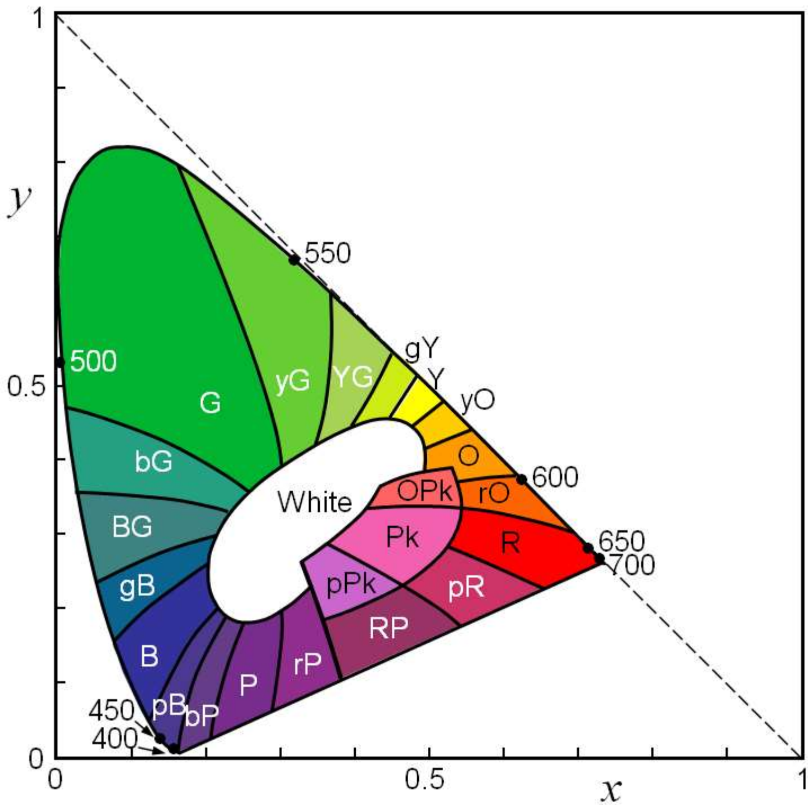

Figure 5. Chromaticity diagram CIE 1931 (x, y). Figure reproduced with permission from Oleari C. (2016).

Many other chromaticity diagrams have been proposed over the time, mainly with the intent to obtain uniform perceived scales. CIE proposed as a standard the chromaticity diagram (u', v'), which is at the basis of the psychometric system CIELUV, proposed in 1976 (see Chapter 3.x).

The CIE 1931 standard colorimetric observer is affected by a systematic error in the short wavelength region, revealed by D. B. Judd in 1951. This error has been corrected by Judd and refined by Vos (Vos J. J. (1978)) and today the corrected observer is used by physiologists. Anyway, since the correction is small, the original CIE 1931 observer is still used in industrial colorimetry today.

2.4 Supplementary Standard Observer CIE 1964

Analogous treatment can be made for extra-macula vision (visual field of 10°) and this gives the CIE 1964 system. In this case the tristimulus values are denoted by the foot-index "10", that regards the size of the visual field, i.e., by (X_{10}, Y_{10}, Z_{10}), and the color-matching functions by $(\bar{x}_{10}(\lambda), \bar{y}_{10}(\lambda), \bar{z}_{10}(\lambda))$ (Figure 6).

The shift of the chromaticities of the monochromatic radiations is remarkable, despite the apparent equality of the two diagrams (Figure 7). The luminance for the CIE 1964 observer is computed by assuming the luminous efficiency function defined by:

$$V_{10}(\lambda) = \bar{y}_{10}\,(\lambda).$$

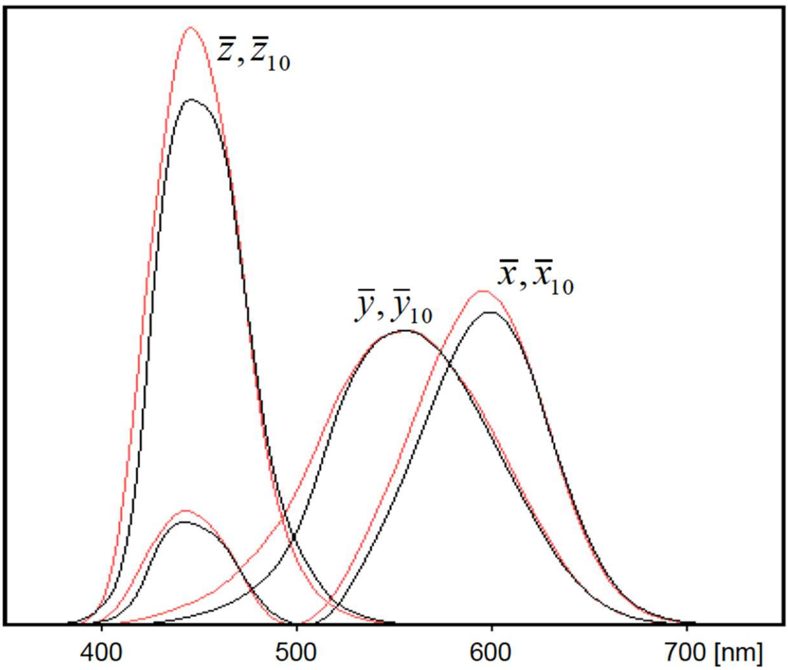

Figure 6. CIE 1931 (black line) and CIE 1964 (red line) color-matching functions.

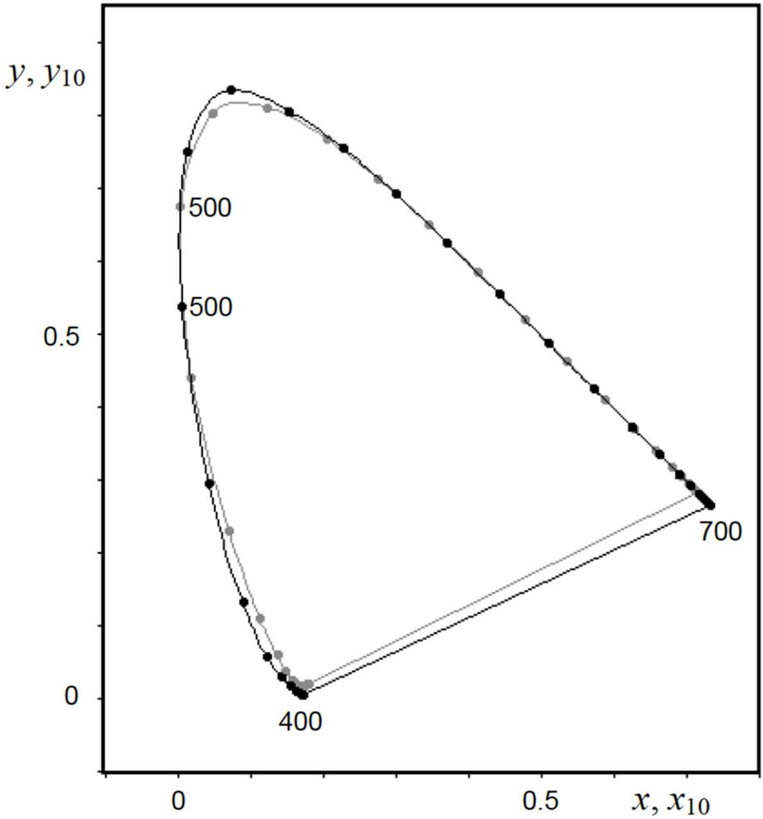

Figure 7. CIE 1931(•) and CIE 1964(•) chromaticity diagrams.

2.5 Vos Observer and MacLeod-Boynton diagram

VOS's observer has been obtained from the standard colorimetric observer CIE 1931 by correcting a systematic error present in the short wavelength region, shown by D. B. Judd in 1951 (P. K. Kaiser and R. M. Boynton (1996)). The coordinates and color-matching functions (Figure 8) are denoted as follows:

$$(X', Y', Z'), (Y', x', y'), (\overline{x}'(\lambda), \overline{y}'(\lambda), \overline{z}'(\lambda)).$$

This observer is mainly used by physiologists and is generally represented in the fundamental reference frame *(L, M, S)*.

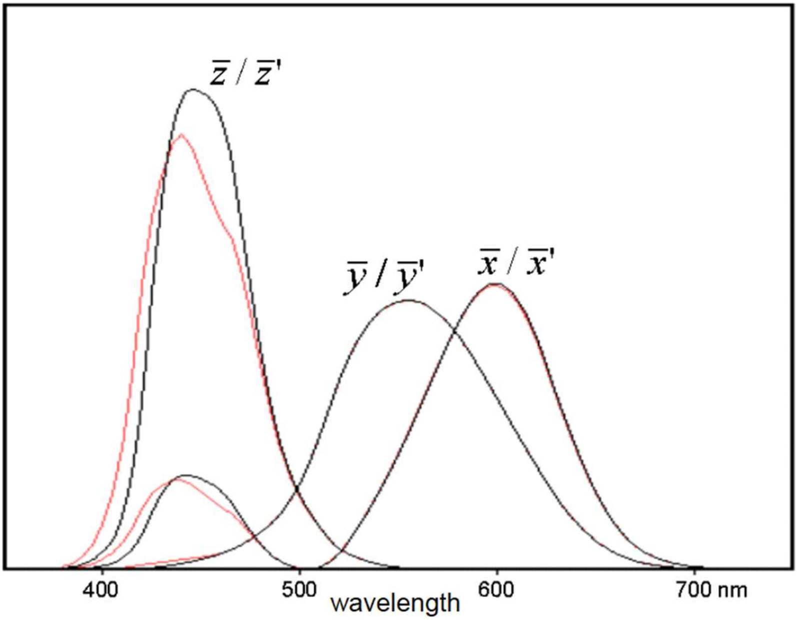

Figure 8. Comparison between VOS's (red line) and CIE 1931 (black line) color-matching functions. The discrepancy between these two sets of color-matching functions is in the short wavelength region.

The chromaticity coordinates (*l, m, s)*, introduced by MacLeod-Boynton, are defined by:

$$l = \frac{L}{L+M},$$
$$m = \frac{M}{L+M},$$
$$s = \frac{S}{L+M},$$

and satisfy the equation $l + m = 1$. The plane of this chromaticity diagram $L + M = 1$ has constant luminance, according to the hypothesis that the cone S has no contribution to the luminance, while L and M cones have equal contributions. This diagram is named the equiluminant chromaticity diagram of the cone excitations.

[N.B. these tristimulus values must not be confused with the homonymous ones defined in the previous fundamental reference frame (Section 2.1)].

2.6 Stockman and Sharpe fundamentals

In 2006 CIE accepted the CMFs proposed by Stockman and Sharpe (Stockman A. and Sharpe L. T. (2000)) as fundamentals and physiologists are now using these new observers. The XYZ reference frame is defined also for these observers (the index "F" means "fundamental", and "10" denotes the visual field of 10°):

$$\begin{pmatrix} \bar{x}_F(\lambda) \\ \bar{y}_F(\lambda) \\ \bar{z}_F(\lambda) \end{pmatrix} = \begin{pmatrix} 1.94735469 & -1.41445123 & 0.36476327 \\ 0.68990272 & 0.34832189 & 0 \\ 0 & 0 & 1.93485343 \end{pmatrix} \begin{pmatrix} \bar{l}(\lambda) \\ \bar{m}(\lambda) \\ \bar{s}(\lambda) \end{pmatrix}$$

for 2° visual field, and:

$$\begin{pmatrix} \bar{x}_{F10}(\lambda) \\ \bar{y}_{F10}(\lambda) \\ \bar{z}_{F1}\ (\lambda) \end{pmatrix} = \begin{pmatrix} 1.93986443 & -1.34664359 & 0.36476327 \\ 0.69283932 & 0.34967567 & 0 \\ 0 & 0 & 2.14687945 \end{pmatrix} \begin{pmatrix} \bar{l}_{10}(\lambda) \\ \bar{m}_{10}(\lambda) \\ \bar{s}_{10}(\lambda) \end{pmatrix}$$

for 10° visual field.

3. Color specification

Generally, an object's color is due to optical dishomogeneities of the bodies that produce absorption, diffusion, refraction and diffraction of light. The color specification of non-self-luminous objects depends on the spectral reflection or transmission of light. In the vast majority of cases, we are dealing with nearly diffuse reflection or nearly regular transmission. That is the reason that reflected flux is generally compared to the flux reflected by a perfect reflecting diffuser and that transmitted flux is generally compared to open aperture.

The physical quantity representing the phenomenon of reflection useful for the color specification is the spectral reflectance factor, as recommended by CIE Reflectance factor is the ratio of the flux reflected by a specimen to the flux reflected by a perfect reflecting diffuser under the same geometric and spectral conditions of irradiation.

The perfect reflecting diffuser is an ideal reflecting surface that is non-absorbing and non-transmitting, but it is an isotropic diffuser such that the radiance is the same in all directions and is independent of the irradiation geometry and of the wavelength. The perfect diffuser is termed Lambertian. In practice, since the perfect reflecting diffuser does not exist, a real white diffuser in used (reference standard, or a copy named working standard),

whose reflectance factor is certified by a metrological reference laboratory under equal geometries.
In this case the reflectance factor is the ratio of the flux reflected by a specimen to the flux reflected by the reference standard under the same geometric and spectral conditions, multiplied by the certified spectral reflectance factor (Publication CIE 15:2004 (2004)).

3.1 Light sources and illuminants

The color depends also on the illuminating light. An important distinction has to be made between light source and illuminant. CIE defines precise terms.

- Source: an object that produces light or other radiant flux.
- Illuminant: radiation with a relative spectral power distribution defined over the wavelength range that influences object color perception.

CIE has standardized illuminants, i.e., files representing the relative spectral power distributions $S(\lambda)$ of light sources (Figure 9). There are several important CIE standard illuminants.

- Illuminant A: associated with the tungsten lamp with the radiant exitance of the black body at the temperature of approx. 2856 K.
- Daylight type illuminants: associated with conventional daylights denoted by D50, D55, D65, D75 … at a temperature of 5000 K, 5500 K, 6500 K, 7500 K …, respectively.
- Fluorescent lamp illuminants: e.g., F2 coolwhite, F7 daylight fluorescent and F11 white fluorescent.

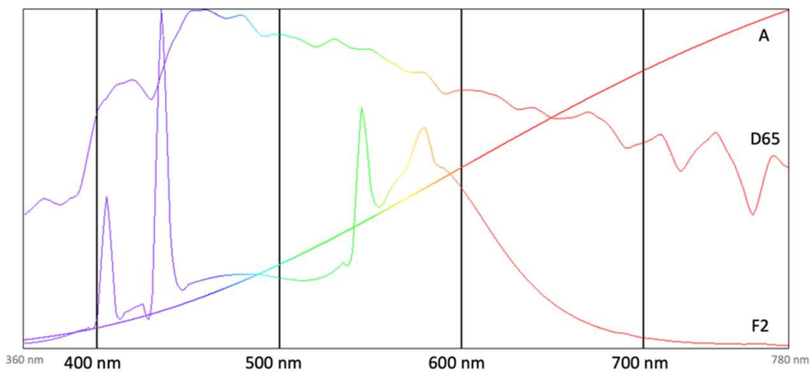

Figure 9. Spectral power distribution of illuminants A, D65 and F2 respectively. Figure created with "Colorimetric eXercise" from Oleari C. (2016).

Equi-energy spectrum or equal-energy spectrum is the spectrum of the radiation whose spectral power distribution is a constant function of the wavelength throughout the visible region. In colorimetry and photometry, the radiation with equi-energy spectrum is the equi-energy or equal-energy illuminant denoted by the symbol E.
Primary light sources and illuminants are represented by their relative spectral power distribution $S(\lambda)$, that is proportional to radiance entering the eye. The colorimetric specification is given by:

$$X = K \sum_{\lambda=360,\Delta\lambda=1}^{830} S(\lambda)\bar{x}(\lambda)\Delta\lambda\,,$$
$$Y = K \sum_{\lambda=380,\Delta\lambda=1}^{780} S(\lambda)\bar{y}(\lambda)\Delta\lambda\,,$$
$$Z = K \sum_{\lambda=360,\Delta\lambda=1}^{830} S(\lambda)\bar{z}(\lambda)\Delta\lambda\,,$$

with:

$$K = \frac{100}{\sum_{\lambda=380,\Delta\lambda=1}^{780} S(\lambda)\bar{y}(\lambda)\Delta\lambda}\,,$$

and Y is the percentage luminance factor.
Equations regard the CIE 1931 observer, but the generalization to any observer is made by changing the color-matching functions. The summations obtained by steps of $\Delta\lambda = 5$ nm are considered practical approximations.

3.2 Non-self-luminous objects

Illuminated surfaces are represented by the spectral reflectance factor $R(\lambda)$ and the radiance entering the eye is proportional to $S(\lambda)\,R(\lambda)$. The colorimetric specification is given by:

$$X = K \sum_{\lambda=360,\Delta\lambda=1}^{830} S(\lambda)R(\lambda)\bar{x}(\lambda)\Delta\lambda\,,$$
$$Y = K \sum_{\lambda=380,\Delta\lambda=1}^{780} S(\lambda)R(\lambda)\bar{y}(\lambda)\Delta\lambda\,,$$
$$Z = K \sum_{\lambda=360,\Delta\lambda=1}^{830} S(\lambda)R(\lambda)\bar{z}(\lambda)\Delta\lambda\,,$$

with:

$$K = \frac{100}{\sum_{\lambda=380,\Delta\lambda=1}^{780} S(\lambda)\bar{y}(\lambda)\Delta\lambda}\,,$$

and Y is the percentage luminance factor.
Equations regard the CIE 1931 observer, but the generalization to any observer is made by changing the color-matching functions. The summations obtained by steps of $\Delta\lambda = 5$ nm are considered practical approximations.

4. CIE psychometric colorimetry

In 1976, CIE proposed two psychometric color systems, termed CIELAB and CIELUV (MacAdam D. L. (1985), Publication CIE 15:2004 (2004)), respectively, with two main intents:

1. To give a practical and intuitive color specification.
2. To give a color specification with uniform perceived scales.

CIELAB and CIELUV can be considered as multi-stage color-vision models, obtained from the psychophysical color specification (X, Y, Z) by linear and non-linear transformations and introducing the dependence to an illuminant (X_n, Y_n, Z_n), to which the observer is supposed adapted. In most cases, the specified white object color stimulus should be light reflected from a perfect reflecting diffuser illuminated by the same light source as the test object. In this case, X_n, Y_n, Z_n are the tristimulus values of the light source with Y_n equal to 100.
Here are given the specifications related to the standard colorimetric observer CIE 1931. Equal specifications are given for the standard colorimetric observer CIE 1964 and are distinguished by the foot-index 10.

4.1 CIE 1976 L*a*b*color space or CIELAB color space

CIELAB color space is a three-dimensional color space with approximately uniform scales, spanned by the rectangular coordinates (L^*, a^*, b^*), where:

- L^* is the CIE 1976 psychometric lightness.
- a^* represents approximately the red-green opponency.
- b^* represents approximately the yellow-blue opponency.

These quantities are defined by the equations:

$$L^* = 116\left[f\left(\frac{Y}{Y_n}\right)\right] - 16,$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right)^{\frac{1}{3}} - f\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right],$$

$$b^* = 200\left[f\left(\frac{X}{X_n}\right)^{\frac{1}{3}} - f\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right],$$

with:

$$f\left(\frac{X}{X_n}\right) = \begin{cases} \left(\frac{X}{X_n}\right)^{\frac{1}{3}} \text{ for } \left(\frac{X}{X_n}\right) > \left(\frac{24}{116}\right)^3 \\ \frac{841}{108}\left(\frac{X}{X_n}\right)^{\frac{1}{3}} + \frac{16}{116} \text{ otherwise} \end{cases},$$

$$f\left(\frac{Y}{Y_n}\right) = \begin{cases} \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} \text{ for } \left(\frac{Y}{Y_n}\right) > \left(\frac{24}{116}\right)^3 \\ \frac{841}{108}\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} + \frac{16}{116} \text{ otherwise} \end{cases},$$

$$f\left(\frac{Z}{Z_n}\right) = \begin{cases} \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}} \text{ for } \left(\frac{Z}{Z_n}\right) > \left(\frac{24}{116}\right)^3 \\ \frac{841}{108}\left(\frac{Z}{Z_n}\right)^{\frac{1}{3}} + \frac{16}{116} \text{ otherwise} \end{cases},$$

where:

- (X, Y, Z) is the psychophysical specifications of the color stimulus considered.
- (X_n, Y_n, Z_n) is the psychophysical specifications of the achromatic stimulus of the chosen illuminant.

In a cylindrical coordinate system in the same space, the coordinates are (Figure 10):

- Psychometric lightness L^*.
- Psychometric chroma $C_{ab}^* = \sqrt{a^{*2} + b^{*2}}$.
- Psychometric hue angle $h_{ab} = \arctan\left(\frac{b^*}{a^*}\right)$.

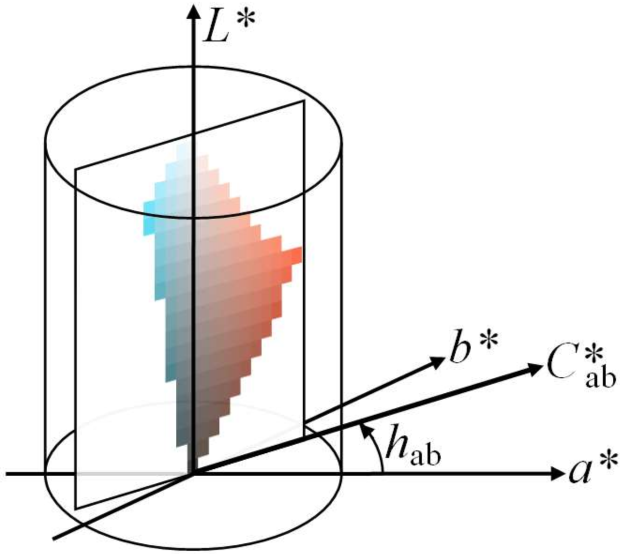

Figure 10. Perspective view of cylindrical coordinates in CIELAB space. Figure reproduced with permission from Oleari C. (2016).

4.2 CIE 1976 L*u*v*color space or CIELUV color space

CIELUV color space is a three-dimensional color space with approximately uniform scales, spanned by the rectangular coordinates (L^*, u^*, v^*), quantities defined by the equations:

$$L^* = 116\left[f\left(\frac{Y}{Y_n}\right)\right] - 16,$$
$$u^* = 13\, L^*(u' - u_n'),$$
$$v^* = 13\, L^*(u' - u_n'),$$

with:

$$u^{'} = u,$$
$$v^{'} = 1.5\, v,$$

where:

$$u = \frac{4x}{x + 15y + 3z},$$
$$v = \frac{6y}{x + 15y + 3z}.$$

5. Color-difference formulae

Over the time many color difference formulae have been proposed and here the most important, today still in use, are recalled.

5.1 Euclidean color-difference formulae defined on CIE 1976 uniform color spaces

In factories, the measurement of the color difference between a color reference and a color imitation is a daily task, that regards psychometric colorimetry. One of the aims of the CIELAB and CIELUV systems was to give an algorithm for the color difference computation. The CIE formulae given in 1976 are Euclidean, supposing that these spaces have uniform color scales. Furthermore, these Euclidean formulae are the same for CIE 1931 and CIE 1964 observers. The visual situation for these formulae is defined by CIE as follows (Supplement 2 to CIE Publication 15 (1978)):
"Euclidean distances in CIELAB (or CIELUV) color space can be used to represent approximately the perceived magnitude of color differences between object color stimuli of the same size and shape, viewed in identical white to middle-grey surroundings, by an observer photopically adapted to a field of chromaticity not too different from that of average daylight. In cases of deviating conditions, the correlation between calculated and perceived color differences may be impaired."
The CIE 1976 L*u*v* color difference, denoted by ΔE^*_{uv}, is defined as the Euclidean distance between the points representing them in the L*u*v* space and calculated as equation:

$$\Delta E^*_{uv} = \sqrt[2]{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2},$$

with:

$$\Delta L^* = L^*_s - L^*_b$$
$$\Delta u^* = u^*_s - u^*_b$$
$$\Delta v^* = u^*_s - u^*_b$$

where the suffix "s" denotes the standard sample (reference) and "b" the test (batch).

The CIE 1976 L*a*b* color difference, denoted by ΔE^*_{ab}, is defined as the Euclidean distance between the points representing them in the L*a*b* space and calculated as equation:

$$\Delta E^*_{uv} = \sqrt[2]{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2},$$

with:

$$\Delta L^* = L^*_s - L^*_b,$$
$$\Delta a^* = a^*_s - a^*_b,$$

$$\Delta b^* = b_s^* - b_b^*,$$

In cylindrical coordinates the differences $\Delta L^*, \Delta C_{ab}^*$ and ΔH^*_{ab} are defined, and the color difference formula becomes:

$$\Delta E_{\mathrm{ab}}^* = \sqrt{(\Delta L^*)^2 + (\Delta C_{\mathrm{ab}}^*)^2 + (\Delta H_{\mathrm{ab}}^*)^2},$$

where the chroma difference is:

$$\Delta C_{\mathrm{ab}}^* = C_{\mathrm{ab,s}}^* - C_{\mathrm{ab,b}}^*,$$

and the absolute hue-difference is:

$$|\Delta H_{\mathrm{ab}}^*| = \sqrt{(\Delta E_{\mathrm{ab}}^*)^2 - (\Delta L^*)^2 - (\Delta C_{\mathrm{ab}}^*)^2},$$

with ΔE_{ab}^*defined by equation above. For small color differences the difference of hue $|\Delta H_{ab}^*|$can be expressed by the difference in the hue angles:

$$|\Delta H_{\mathrm{ab}}^*| = \sqrt{C_{\mathrm{ab,s}}^* C_{\mathrm{ab,b}}^*} |\Delta h_{\mathrm{ab}}| \left(\frac{\pi}{180}\right) \text{ with } |\Delta h_{\mathrm{ab}}| = \left|h_{\mathrm{ab,s}} - h_{\mathrm{ab,b}}\right| \text{ [deg].}$$

5.2 Non-Euclidean color difference formulae defined on CIELAB

The Euclidean color difference formulae defined in CIELAB and CIELUV did not satisfy the necessities of the factories, thus over time many other formulae have been proposed for small color differences. These formulae are defined on the CIELAB space and are the same for CIE 1931 and CIE 1964 observers. All these formulae are dependent on some parametric factors, that have to be defined on the experimental condition. For the CIEDE2000 formula, the reference conditions for these parametric factors to be set equal to 1 are the following (Luo et al. (2001)):

- Illumination: source simulating the spectral relative irradiance of CIE standard illuminant D65.
- Illuminance: 1000 lx.
- Observer: normal color vision.
- Background field: uniform, neutral grey with L* = 50.
- Viewing mode: object.
- Sample size: greater than 4 degrees subtended visual angle.
- Sample separation: minimum sample separation achieved by placing the sample pair in direct edge contact.
- Sample color-difference magnitude: 0 to 5 CIELAB units.

- Sample structure: homogeneous color without visually apparent pattern or non-uniformity.

We can consider these conditions good for all the following non-Euclidean formulae.

The Colour Measurement Committee (CMC) of the Society of Dyers and Colourists (UK) recommended a color difference formula that has been integrated into some ISO standards (Clarke et al. (1984)). The CMC formula is conceived for the CIELAB system and is mainly based on color difference data known as BFD [Bradford] (ISO 105-J03:1995 (1995). This formula is obtained by introducing different weightings for $\Delta L^*, \Delta C^*_{ab}$ and ΔH^*_{ab} (defined above), that destroy the original Euclidean nature. They are defined as follows:

$$\Delta E_{cmc}(l : c) = \sqrt{\left(\frac{\Delta L^*}{lS_L}\right)^2 + \left(\frac{\Delta C^*{}_{ab}}{cS_C}\right)^2 + \left(\frac{\Delta H^*{}_{ab}}{S_H}\right)^2},$$

where:

$$S_L = \begin{cases} 0.040975 \dfrac{L_1^*}{1 + 0.01765 L_1^*} \text{ for } L_1^* \geq 16 \\ 0.511 \text{ for } L_1^* < 16 \end{cases},$$

$$S_C = \frac{0.0638\, C^*_{\mathrm{ab},1}}{1 + 0.0131 C^*_{\mathrm{ab},1}} + 0.638,$$

$$S_H = S_C(Tf + 1 - f),$$

with:

$$f = \sqrt{\frac{\left(C^*_{\mathrm{ab},1}\right)^4}{\left(C^*_{\mathrm{ab},1}\right)^4 + 1900}},$$

$$T = \begin{cases} 0.36 + \left|0.4 \cos(h_{\mathrm{ab},1} + 35)\right| \text{for } h_{\mathrm{ab},1} \geq 345^\circ \text{ or } h_{\mathrm{ab},1} \leq 164^\circ \\ 0.56 + \left|0.2 \cos(h_{\mathrm{ab},1} + 168)\right| \text{ for } 164 < h_{\mathrm{ab},1} < 345^\circ \end{cases}.$$

The parametric factors are mostly chosen $c = 1$ and l varied between 1 and 2. The choice of l and c must be indicated by setting the right numbers in the name of the formula, e.g., for textiles a choice of CMC(2:1) is in common use. This formula is now an ISO standard. The CMC formula was a forerunner for the successive ones.

The development of the CIE94 color difference formula was made considering the CMC one as a model (Luo and Rigg (1986)). The CIE 94 formula introduced weighting factors to the lightness, chroma and hue differences, $\Delta L^*, \Delta C^*_{ab}$ and ΔH^*_{ab} of the CIELAB Euclidean formula. The main deviations of the CIE94 formula from the CMC one are in the weighting factors that are much more simple mathematically and do not contain hue-dependent correction terms. The resulting recommendation is as follows:

$$\Delta E *_{94} (k_L : k_C : k_H) = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*_{\mathrm{ab}}}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*_{\mathrm{ab}}}{k_H S_H}\right)^2},$$

where the weighting functions, S_L, S_C, S_H adjust the internal non-uniform structure of the CIELAB formula using:

$$S_L = 1,$$
$$S_C = 1 + 0.045\, C^*_{ab,s},$$
$$S_H = 1 + 0.015\, C^*_{ab,s}.$$

If the standard and the batch of a sample pair is not clearly defined, C^*ab may be replaced by the geometric mean $\left(C^*_{ab,s}\, C^*_{ab,b}\right)^{1/2}$.
The parametric factors, k_L, k_C, k_H are correction terms for variation in experimental conditions. Under reference conditions they are all set to 1.
Today, CIE considers the CIE 1994 color difference formula obsolete because it has been superseded by the CIEDE2000 formula.

The CIEDE2000 total color difference formula corrects for the non-uniformity of the CIELAB color space for small color differences under the above defined reference conditions (Luo et al. (2001)). The CIELAB space was considered inadequate to represent small color differences and a new space is derived from CIELAB, spanned by new coordinates $L'a'b', C', h'$:

$$L' = L^*,$$

$$a' = (1+G)a^* \text{with } G = 0.5\left(1 - \sqrt{\frac{\bar{C}_{\mathrm{ab}}^{*\ 7}}{\bar{C}_{\mathrm{ab}}^{*\ 7} + 25^7}}\right),$$

$$b' = b^*,$$

$$C' = \sqrt{a'^2 + b'^2},$$

$$h' = tan^{-1}\left(\frac{b'}{a'}\right) \text{ [deg].}$$

Improvements to the calculation of total color difference for industrial color difference evaluation are made through corrections on perceived color difference for the effects of lightness dependence, chroma dependence, hue dependence and hue-chroma interaction, weighted by a factor R_T. The CIEDE2000 color difference formula is defined as follows:

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\right) \rightleftarrows \left(\frac{\Delta H'}{k_H S_H}\right)}$$

where the weighting functions, S_L, S_C and S_H adjust the total color-difference for variation in perceived magnitude with variation in the location of the color-difference pair in L', a', b' coordinates:

$$S_L = 1 + \frac{0.015 \rightleftarrows (\rightleftarrows \bar{L}' - 50)^2}{\sqrt{20 + (\rightleftarrows \bar{L}' - 50)^2}},$$

$$S_C = 1 + 0.045 \rightleftarrows \bar{C}^{'},$$

$$S_H = 1 + 0.015 \rightleftarrows \bar{C}'T$$

with:

$$T = 1 - 0.17\,cos(\bar{h}' - 30°) + 0.24\,cos(2\bar{h}') + 0.32\,cos(3\bar{h}' + 6°) - 0.20\,cos(4\bar{h}' - 63°),$$

and:

$$R_C = 2\sqrt{\frac{\bar{C}'^7}{\bar{C}'^7 + 25^7}},$$

$$R_T = -R_C \, sin(\, 2\Delta\theta) \text{ with } \Delta\theta = 30 \, exp\left[-\left(\frac{\bar{h}' - 275°}{25}\right)^2\right],$$
$$\Delta L^{'} = L'_b - L'_s,$$
$$\Delta C^{'} = C'_b - C'_s,$$
$$\Delta H^{'} = 2\sqrt{C'_b C'_s}\, sin\left(\frac{\Delta h^{'}}{2}\right) \text{with } \Delta h^{'} = h'_b - h'_s.$$

As is written in the above reference conditions, the parametric factors k_L, k_C and k_H are correction terms for variation in experimental conditions and under reference conditions they are all set to 1.
CIE recommends the use the CIEDE2000 formula whenever in the past the CIE 94 or CMC formula were used and such a recommendation is in agreement with the persons who developed the CMC formula.

6. Numerical calculations in C++

For scientists keen in programming, we have developed and tested the following programs in C++ providing the numerical calculations for:

1. TestTristimulusfromIlluminantSpectra: Tristimulus values of illuminant A and D65 starting from Spectral Power Distribution as described in Section 3.1.
2. TestXYZtoFundamental: Conversion of a tristimulus value into fundamental systems as described in Chapter 2.
3. TestXYZtoCIE: Conversion of a tristimulus value into CIE ’76 color systems as described in Chapter 4.
4. TestColorDifferenceFormulae: CIE ’76, CMC, CIE ’94 and CIEDE2000 color-difference formulae described in Chapter 5.

Source codes available at: http://mips.di.unimi.it/download.html.

7. Conflict of interest declaration

The authors declare no conflict of interest.

8. Funding source declaration

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10. Short biography of the authors

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His main research interests are HDR Imaging, Image Quality, Image Enhancement, Color Perception and Colorimetry.
He is adjunct Professor at Master in Digital Humanities and collaborator with the Multimedia Interaction Perception and Social Lab at University of Milano. Today he is working as Software Engineer at Elica-ASM.
Mauro Fiorentini. Mauro Fiorentini graduated in Physical Sciences at the University of Milan in 1979. Since then he worked on software development, mainly in basic software tools, like compilers and interpreters, mathematical software and embedded systems. In 1986 he wrote a book on the C programming language and in the '90s he worked on some Esprit project, being also the director of OMI/CORE. His interests include mathematics, chess and bridge. Today he is working as R&D director at STE industries.

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Chapter 2 Introduction to Digital Colour

Celeste Eugenia Lombardi, photographer

Abstract

This chapter explains the logic of digitising analogue colour information.

Keywords:

Digital Colour, Sampling, Quantization, Bit

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1. Introduction

The Introduction section should include the background and aims of the chapter in a comprehensive manner.
Once you have focused on the specific topic of your study, you should investigate the latest and most relevant literature related to your study. Your literature review should be complete, but not overly long.

1.1 Introduction to digital colour

Human beings have developed language as a form of communication: every state and regional subdivision brings more or less substantial differences to language. A native Italian speaker can easily understand other native Italian speakers; he may have some difficulty in understanding dialectal nuances; he will not be able to understand a native German speaker (unless he has studied the language).
Machines communicate with each other in this way:

01000011 01100101 01101100 01100101 01110011 01110100 01100101

Incomprehensible to humans, but clear and immediate for all machines, whether they are programmed in Japan or America.
It is called binary language and, as the name suggests, it is a positional numeral system in base 2. We can see that only two numbers are used:

0 1

If we pay attention to the multi sockets we have in our house, we can see that the same symbols are present on the red switch. The binary system works like a switch: it's either on, or off. There is no middle ground.

#B2FFFF

This, on the other hand, is the hexadecimal alphabet and, as the name suggests, is a positional number system in base 16. The symbols used are:

0 1 2 3 4 5 6 7 8 9 A B C D E F

This language is used by machines but can be understood by some humans.
On a program like Photoshop, the hexadecimal language (also called Hexa or hex) is used to define a colour.
#B2FFFF corresponds to the colour Celeste.

Three different languages carry the same message. So how can we convert a set of analogue information into a **digital image**[1]?
The output of most of the image sensors is an analogue signal, and we cannot apply digital processing on it because we cannot store it. We cannot store it because it requires infinite memory to store a signal that can have infinite values.
So we have to convert an analogue signal into a digital signal.
To create a digital image, we need to convert continuous data into digital form. There are two steps in which it is done.

- Sampling
- Quantization

Both operations correspond to a discretization of a quantity but in different domains.

2. Sampling

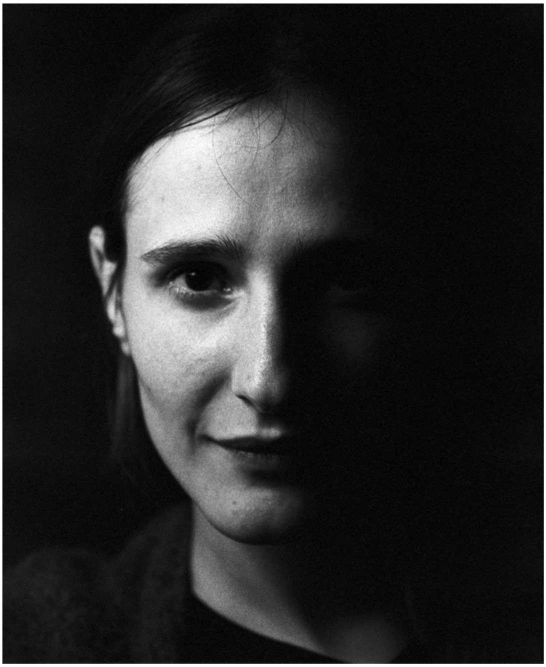
Sampling corresponds to a discretization of the space (spatial resolution)
Images having higher spatial resolution are composed with a greater number of pixels[2] than those of lower spatial resolution.
The term resolution refers to the total number of counts of pixels in a digital image. For example: If an image has M rows and N columns, then its resolution can be defined as M X N.
If we define resolution as the total number of pixels, then pixel resolution can be defined with a set of two numbers: one for height and the other for width.

---

[1] It is a numerical representation of a two-dimensional image. Usually the image I is represented by a Matrix with dimension MxN

[2] A pixel, by definition, is the smallest element resulting from the discretization of the space. It hasn't physical dimensions and it is composed of 3 sub-pixels (one for each RGB channel): every sub-pixel has 1 value, plus the position's value.
If you open a photo with photoshop and zoom in, you will see a lot of tiny, cute, little, coloured blocks: those are the pixels!

Let's look at this image:



Taken with a Nikon f5 on Ilford HP5 Plus 400 film and digitized with a special scanner.
The spatial resolution of this image is:

3374x4121 pixel

This means that there are 3374 pixels on the short side, which we will call N from now on, and 4121 pixels on the long side, which we will call M from now on.
The total number of pixels is 13,904,254 and the weight of the JPEG file is 864 KB.

Now, let's change the spatial resolution by decreasing the number of pixels in the image:

The spatial resolution of this image is:

200x243 pixel

The total number of pixels is 48.600 and the weight of this JPEG file is 24,3 KB.

We continue in this process, further decreasing the number of pixels in the image:

The spatial resolution of this image is:

50x61 pixel

The total number of pixels is 3.050, for a weight of 13,4 KB.

Again:

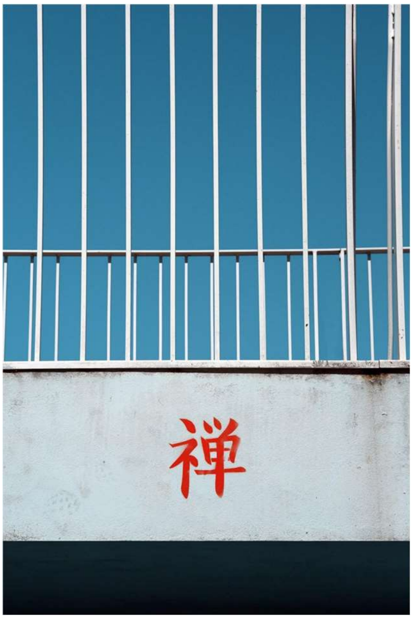
The spatial resolution of this image is:

10x12 pixel

For a total of 120 pixels and a weight of 11,5 KB.
The operation we performed is called decreasing the sampling rate: we went from an image with 13 million pixels to one with only 120 pixels.
What has changed? In the last image, it is impossible to understand what is represented in the picture.
In digital images, increasing the sampling rate is equivalent to increasing the image resolution: with a higher resolution, we have more pixels (which we can also call sampling points) representing the same scene.
The weight of the image will be greater and we will have more detail.

Higher sampling rate
=
Higher image resolution
=
Higher quality of the image
=
More memory used

A natural image is coloured in continuous tones, and thus it theoretically has an infinite number of colours. The discrete and finite language of the computer restricts the reproduction of an infinite number of colours and shades. During Quantization, the infinite colour shades are synthesized into a finite list of values. This means that each colour is mapped and inserted into a single pixel.
How many colours do we want to use in an image?



This image, taken with a Nikon D750, has been quantized with 256 colours.

What happens if I lower the number of colours from 256 to 4?

Quantization reduces the number of colours used in an image: this leads to a loss of definition and fidelity because different colours are remapped into the same colour. In the example above we have two shades of blue: one darker and one lighter.
Are two colours enough to represent the infinite number of nuances that a spring sky can have? Of course not.

Low quantization rate
=
Loss of details

The quantization process is closely related to the concept of **bit depth:**

- 2-bit image will display 2^2 (4) colours
- 8-bit image will display 2^8 (256) colours.

Higher bit depth

=

More bits to represent a colour

=

More memory to use

Ok but, what is a bit?

Binary dig**IT** is a basic unit of information used in computing and digital communications. It can have only one of two values (0 / 1). Remember the binary language? Here we are.

How many numbers can we represent with 3 digits in a base-2 system?

000 - 0
001 - 1
010 - 2
011 - 3
100 - 4
101 - 5
110 - 6
111 – 7

8 numbers.

The memory of a computer usually uses an elementary unit of 8 bits: a byte

1 byte = 8 bits

The number of used bits defines the quantity of information (and the colour quality of the digital image)

8 bits = 2^8 (256) possible values.

3. Exercise time – How many bits?

Camera's megapixel: 6

Pixel resolution: 3000x2000 px

Colour depth: 24-bit

3.1 Step 1

Multiply the detectors number of horizontal pixels by the number of vertical pixels to get the total number of pixels of the detector

Horizontal: 3000 px

Vertical: 2000 px

3000 px x 2000 px = 6.000.000 px

3.2 Step 2

Multiply total number of pixels by the bit depth of the detector to get the total number of bits of data

Total number of pixels: 6.000.000 px

Bit depth: 24 bit

6.000.000 px x 24 bits/px = 144.000.000 bits

3.3 Step 3

Dividing the total number of bits by 8 equals the file size in bytes.

Total number of bits: 144.000.000 bits

144.000.000 bits / 8 bits = 18.000.000 bytes

3.4 Step 4

Divide the number of bytes by 1024 to get the file size in kilobytes. Divide by 1024 again and get the file size in megabytes.

18.000.000 bytes / 1024 = 17.578,125 Kilobyte

17.578, 125 KB / 1024 = 17,166 Megabyte

4. In summary

of pixels x Bit Depth / 8 / 1024 / 1024 = File Size in Megabytes (MB)

5. Conflict of interest declaration

The authors declare no conflict of interest.

6. Funding source declaration

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7. Short biography of the author(s)

Celeste Eugenia Lombardi, tutor at Polidesign in Milan in the Master in Colour Design and Technology, is a photographer and videographer specialised in colour as a storytelling element in audiovisual products. Since 2019, she has been collaborating with Prof. Rizzi, giving lectures for the Multimedia Project course at Università Statale di Milano, Computer Science Department.

Chapter 3 Measuring colour in the artistic heritage field

Sergio Omarini, National Institute of Optics- CNR - Italy

Abstract

The various aims of measuring colour in the artistic heritage field are described here. The first is "helping knowledge", i.e. increasing our knowledge of the materials contained in artefacts, like, for example XRF (X ray fluorescence) support measurements to identify the pigments used by a painter in a painting. The second aim is to record at a certain moment the colours in a work of art to memorise and document them for the future and this takes on particular importance with contemporary works of art. The third is how colour measurement can be of valuable assistance in checks made during restoration and cleaning operations. The final aim is the important one of conservation monitoring, that is being aware that a colour is changing before this is distinguishable by the usual methods, which send signals when it is by now too late. We also stop to look at measurement procedures and new potential ways of interpreting data. All this is illustrated with examples from real life experimental campaigns.

Keywords:

Artistic heritage, pigments, restoration, monitoring.

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1. Introduction

Colour is a question of perception and as such is not measurable. By "colour measurement" here we mean the measurement, in line with CIE standards, of the stimulus inducing perception. It is a question therefore of the absolute measurement of the radiation inducing the stimulus, a measurement normally obtained with a contact spectrophotocolorimeter with specular included and/or excluded in line with CIE procedures and expressing the sizes measured in space L*a*b*. The measuring is carried out in a point or "spot" with a diameter between 2 and 10 mm. depending on each case and within which the colour is considered homogeneous.
In the artistic heritage field measuring colour can have various aims and, of course, these can overlap. The first is "helping knowledge", i.e. increasing our knowledge of the materials contained in artefacts, like, for example XRF (X ray fluorescence) support measurements to identify the pigments used by a painter in a painting. The second aim could be to record at a certain moment the colours in a work of art to memorise them for the future and this takes on particular importance with contemporary works of art. The third is the fact that colour measurement can be of valuable assistance in checks made during restoration and cleaning operations. The final aim is the important one of conservation monitoring, that is being aware that a colour is changing before this is distinguishable by the usual methods, which send signals when it is by now too late. For any one of these aims it is in any case important to identify the measurement point and data filing procedures with a view in particular to the data being readable even in the distant future without there being any interpretational uncertainties

2. Helping knowledge

Many different types of technology have been used to research into the materials and implementation techniques in works of art with particular reference to paintings: from radiography and reflectography, to see what is below the surface, to XRF (X rays fluorescence) and Raman spectroscopy, for the identification of the pigments employed and multispectral analyses for identifying materials and painting techniques.

Figure 1. Radiography of the Caravaggio canvas “La buona ventura”. The underlayer is an other painting. (measurements carried out by ENEA – National Agency for the Energy and the Environment)

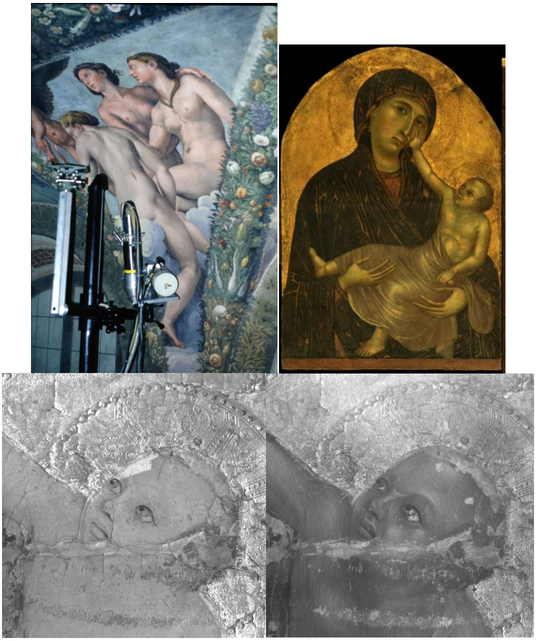

Figure 2. XRF measurements by ENEA – Loggia di Psiche, Raffaello fresco (up on the left) Multi NIR scanner. “Madonna with child” Cimabue, wood. (up on the right). Particular at λ = 850 nm (on the right) and at λ = 2265 (on the left) The differences found when reflecting different wavelengths are evident.(measurements carried out by INO – CRN*)*.

But even the simple measuring of colour can be very important for understanding what went on. Let us consider a well-known case. Red ochre is a natural pigment but rarely a nice dark red. However, as Vitruvius wrote, it can be easily obtained from the more common yellow ochre.

"*… usta vero quae satis habet utilitatis in operi bus tectoriis sic temperatur. Glaeba silis boni coquitur ut sit in igni candens. Es autem aceto extinguitur et efficitur purpureo colour."*
".... about the burned ochre, very useful in wall painting, this is the preparation method: burn a piece of high quality "sil" until it is red hot and then make it cold with vinegar and it will be a dark red." (Vitruvius)

The presence, in the area around Vesuvius, of areas of plastered walls with yellow frescos transformed into red as a result of the temperature caused by the volcano is well-known and can be seen by any attentive visitor. These are of course walls frescoed with yellow ochre that got transformed to red because of the heat of the eruption. Herculaneum in particular was hit by a high temperature gas cloud.
There has recently been much research, and it is still continuing, into this transformation by parametrically studying the materials (the different types of ochre), temperatures, heating speeds, temperature residence times and so on. Measurements have also been made involving pieces of original plaster in order to compare the correctness of extrapolations with "real" measurements, that is with materials used in Roman plaster and even with fragments of original plaster.
Pompeian red is one colour or, rather, a range of colours. There is no precise definition from a colorimetric point of view neither as regards a reference table or as regards its coordinates. Some encyclopaedias or dictionaries define it as the "typical red used for the majority of the backgrounds in the wall paintings of Pompeii". Others engage in imprecise definitions like pigment defining it generically as a red obtained from compounds of mercury or iron (which is true if we are dealing with a certain type of ochre). Everyone knows that what is meant is that rather sombre red seen, as in fact several encyclopaedias say, in the majority of the backgrounds in the wall paintings in Pompeii.
Even if more systematic research is needed, based on, for example, measurements conducted on the walls of the Villa dei Papiri in Herculaneum (Fig. 3), from a colorimetric point of view it has been assumed that the areas definable as "Pompeian red" are in the following range of values L*a*b*:

35<L*<37, 21<a*<23, 15<b*<17, while for the walls definable as yellow the range is 53<L*<60, 14 <a*<16 and 32<b*<36.
The phenomenon of the transformation of yellow ochre into red ochre due to the heating up caused by the volcanic gases was measured in a quantitative sense. In this regard it should be remembered that, particularly in Herculaneum, the eruptions started with a gas cloud mixed with high temperature water vapour that took over the town before this was sealed by lapilli or lava and that this was the cause of the majority of the inhabitants' deaths. It has been assumed that a wall, originally yellow but now seen as red, underwent a transformation into red if this cover at least 70% of its surface.

Figure 3. Villa dei Papiri – Ercolano. The effect of the high temperature gas transforming yellow ochre to red ochre is evident. The crack in the wall also points to what happened. (by INO – CRN

The phenomenon is very significant and a large number of walls interpreted and seen as red were in reality yellow. Some interpretations of the Romans' architectural tastes, at least in Pompeii and Herculaneum, perhaps need to be revised or modified. The red part that was originally in reality yellow represents a considerable percentage of the total red that a visitor can see and this fact probably modifies the chromatic perception of the whole. There however need to be some objective assessments and therefore measurements conducted with colorimeters. Numerically, taking account of the L*a*b* values chosen for defining “yellow” and “red” as indicated above, it turns out that 246 walls are currently assessed as being red versus 57 yellow ones, but originally there were 165 red ones versus 138 yellow.

3. Memorising the original colour

Spectrophotocolorimetry is a technique for indisputably identifying a colour in a particular point and indicating it with an internationally codified alphanumerical system.
Analyses of paintings are frequently requested, especially to verify the before and after where there has been restoration work, but what one would often like to know is the colour used by the painter originally before any restorations or deterioration, if this is the case. On most occasions it is possible, with a minimum impact on the painting, to identify the pigments used but an exact determination of the original colour, in terms of reflectance, chroma and saturation, has by now become impossible and the same applies to other parameters such as sheen.
If this is understandable for ancient paintings, it seems very strange that in the majority of cases there are no colorimetric analyses - with a memorisation of the data to avoid this very same problem reoccurring in the future - of modern paintings, which could instead be examined in a condition that is practically original and when at times one asks oneself whether such and such a white has not, perhaps after only a few years, become a little ”yellowish”.
Techniques such as photography, even if colorimetric and digital, are not suitable for memorising in files, in that they involve an initial acquisition that is complex and with a calibrated lighting system. The complete acquisition of an image could also lead on occasions to problems with the ownership of it as it is possible to reproduce it.
Numerical data indicating, in the final analysis, a physical property that can change over time, i.e. the ability of a material to reflect the electromagnetic waves of light in a particular point, are conceivably memorisable for ever.
We should point out that the technique we are talking about is cheap, has practically no impact and is extremely quick; about twenty different measuring points, which constitute a reasonable average for a painting of about 1 m^2, can be surveyed and memorised in about one hour. Moreover, once some valid operating instructions have been drawn up, the tests can also be performed by non-specialised personnel.
For this kind of file there does not need to be a good image quality but even a poor resolution in black and white is acceptable, provided that it is enough to give a precise indication of the points where the measurements have been carried out. Naturally these measurements should not be considered a

catalogue card but rather a sub-card or, better still, one of the various measurements necessary for compiling a complete catalogue card. The data acquired can, of course, also be used for a calibration of the colours should reproductions be needed.
As happens often in very many different fields, there is a problem of lack of contact, typical of two different cultures, between those putting together some research and/or a technique and those needing to use it in the sense that they are going to be the final user. In this case, between those involved in technological research applied to artistic heritage for the purpose of both enhancing our knowledge thereof and of conserving it and those given the task of studying a work for the purpose of conserving and enjoying it.
For the definition of the methodology and/or drawing up of a list of instructions, curators and art historians need of necessity to be involved for two reasons. The first is, as already said, that they are the final consignee. The second because without their experience it would be impossible to correctly put together the methodology. The procedure, in the sense of technical norms is, and will be ever more, put together and defined by technical personnel but what is perhaps lacking is guidelines about what to in fact measure, or rather, looking at a painting in the usual way, which points or areas need to be taken into account for its memorisation for the future. Put simply, what and in what way it would be useful to record. Clearly the question, when looked at in its entirety, is extremely complex, given that, for example, it should not neglect the aspect of the materials used in the point measured - with one pigment deteriorating differently from another and so on – but nevertheless, even if the artist conceived the work in question in terms of "non-immobility of materials", the memorisation of the starting point is important, at the very least as documentation.

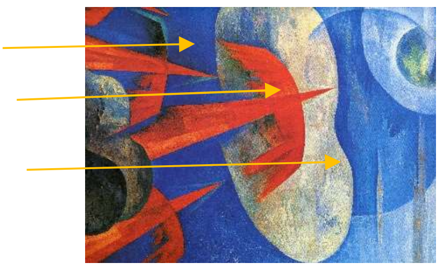

Figure 4. Measurement points. Each point is an area and the measure is the media of ten spots – Baldessarri, aeropittura, 1934

4. Restoration and cleaning

Colorimetry can have only an auxiliary role in restorations or cleaning. In such cases it is important to keep to the spectral reference factor (SRF) which is more related to the material used in the point measured. For every visible wavelength an SRF graph represents how much of it gets reflected in the point measured. During cleaning one can, comparing before and after but this is rather random, even try to extract "the colour of the dirt".

The following example is a significant one. Figure 5 shows colour measurements during the Pala di Pesaro (Savoldo 1524) restoration. It is possible to observe differences between before and after cleaning (blue points) and to do a comparison between the trends in reflectance factor in three different areas in a painting. Assuming that the "dirt" is uniform, the result is a yellowish colour as expected. This is the reason why graphs of before and after show limited differences as regards flesh tones and show the appearance of the curve of the blue of the sky and even more the violet of the robe, which has become brown.

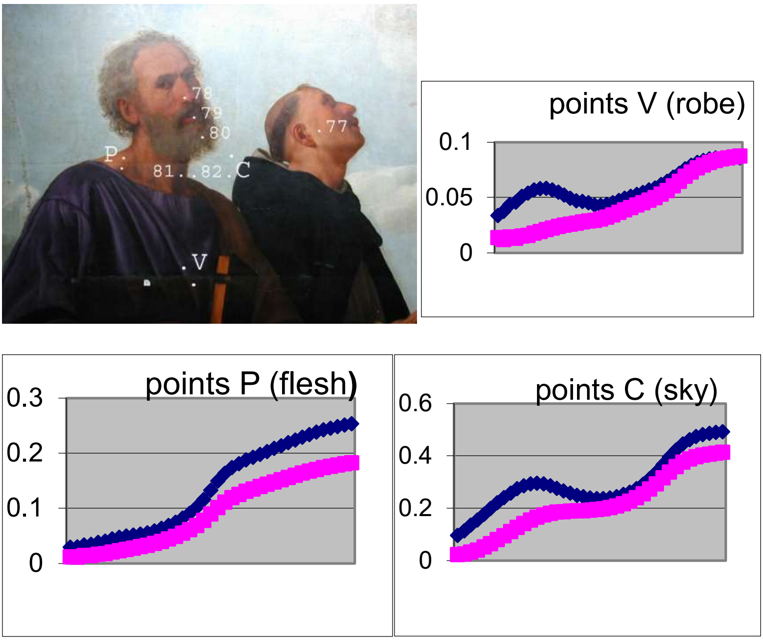

Figure 5. Pala di Pesaro (part.). Savoldo 1524. Color measurements before and after the cleaning. Spectral reflectance factor (SRF) versus λ (wavelength). blue = cleaned

In any case during cleaning, especially if conducted by several persons, it can be useful to have objective measurements of a layer of paint that is being cleaned in areas that are of reasonably the same colour (Fig 6.) or classify and link parts of a painting that needs to be put back together again especially in the case of decontextualized fragments (Fig 7).

Figure 6. Guido Reni – Trinity - 1625
Particular during the cleaning

Figure 7. Rebuilding after the earthquake. Colorimetric photographs were made of fragments of the frescos in Assisi while they put back together.

5. Monitoring for conservation purposes

A very important principle results in the analysis of colour formation physical processes:

A material, reflecting visible electromagnetic waves, can vary while its colour stays the same and this is through metameric effects, but if its colour varies, there has certainly been a variation in the material, given that light gets reflected differently.

The statement "The material may change and the colour remain the same but if the colour changes the material has changed" is applicable here.
This gets translated into a simple checking concept if a work of art is getting altered. As an aim of conservation monitoring we therefore mean the periodical measurement of colour in the very same places. Clearly, this is a so-called first level analysis, that is a simple alarm signal that a material is changing but without indications as to the causes of such a change. It is then the task of whoever is in charge of safeguarding a work to evaluate the need for other analyses to identify the causes of this variation.
Obviously, as we already said when talking about measurements with the aim of communicating information about the original colour of a work to the future, the choice of the points involved and their precise identification are important, but here another aspect arises, that is the choice of an appropriate interval in time between one monitoring campaign and another, given that "natural" degradation is different between a Roman fresco and a watercolour. Of course such a choice will be up to the operators and can be modified in line with the trends in the variations found during the monitoring campaigns. All this, of course, in order to get an alarm call before a variation can be seen by the human eye and its memory, and thus when already too late.
One of the first example of this kind of monitoring was the roman Villa di Arianna. (Fig. 8 and 9)

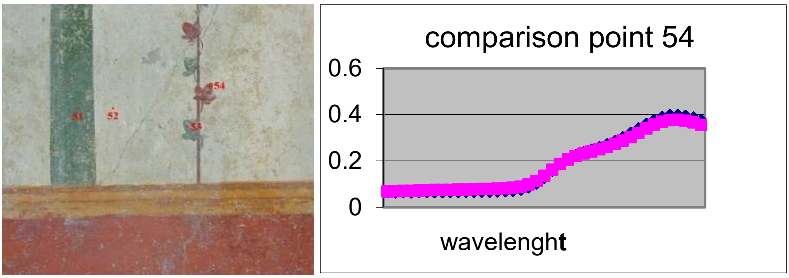

Figure 8. Spectral reflectance factor versus the wavelength in the visible region (380 – 780 nm.) Comparison of two points in a fresco of the Villa di Arianna. The blue line represents the measure after 6 years. No difference. On the contrary there is a big difference in the following figure 9.

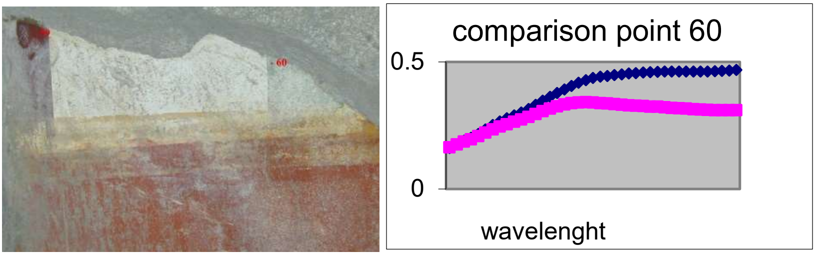

Figure 9. Comparison of measurement points of a Villa di Arianna fresco.

6. Procedures and new possible avenues

Procedures:
A defined protocol does not exist but only some recommendations regarding: **data memorization, identification of the point measured**, **experimental conditions** and **instrument parameters**.
The most significant problems are those regarding the choice of the diameter of the measurement spot, the uniformity of the colour in the area being measured and if it possible to conduct contact measurements (even if very light ones).
There are normally three types: an area with a uniform colour, a point-like area and a variegated area like, for example, some wood with slight veining. In the first case one only needs to collate some reliable data and, of course, it is easier with a spectrophotocolorimeter with a large diameter spot. Point-like measurements need a small diameter spot and the recommended procedure is to repeat the measurements several times but always by moving the instrument away and repositioning it. A variegated or non-uniform area requires a statistical approach, that is defining within an area an even relatively large section, like a square with sides of several cm., taking a large number of measurements within the square and using the average of them.
The relative protocols have not been finalised yet but what is important is that every measurement be clearly memorised in all its aspects and not clearly only to the measurer. Consequently not only the specification of the measurement spot and of the result, but also the auxiliary data like instrument used, number of measurements used to obtain the average, spot diameter, etc. Only in this way will operators, carrying out subsequent measurements or at least needing to interpret the data, be able to take the right actions to get a correct comparison.
As regards monitoring for conservation purposes certain criteria and recommendations should be considered:

10 % of the measurements should be repeated during the same campaign by another operator in order to verify the data's repeatability and the **ΔE** should be calculated. The **ΔE** is the colour difference between two points in the same colorimetric reference space (CIE Lab) and is none other than the geometric distance between two points in this space, the axes of which are L*, a*, b*. This value implicitly involves the reliability of the data.
In the case of conservation monitoring **2ΔE** is the alarm value.

New possible avenues:
The graph of the SRF as a function of the incident radiation (λ) wavelength is the most significant piece of data for interpreting a material. A comparison between the graphs of two points can only suggest if the colours are the same but comparisons are now being made that seem more significant when observing the derivatives of these graphs. There is no correct and comprehensive physical interpretation but in the majority of cases things seem to add up.
Let's now observe some results of the Etruscan Tomb of the Reliefs in Cerveteri.
The painted plasters were subdivided into 6 red zones and in 3 yellow zones in order to carry out the usual measurements. The red zones data were compared with the data of a red plot of red ochre musealized and found during an excavation.

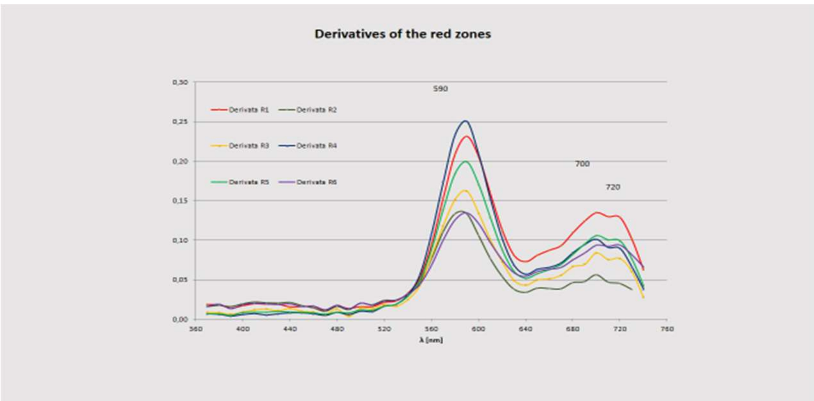

Figure 10.

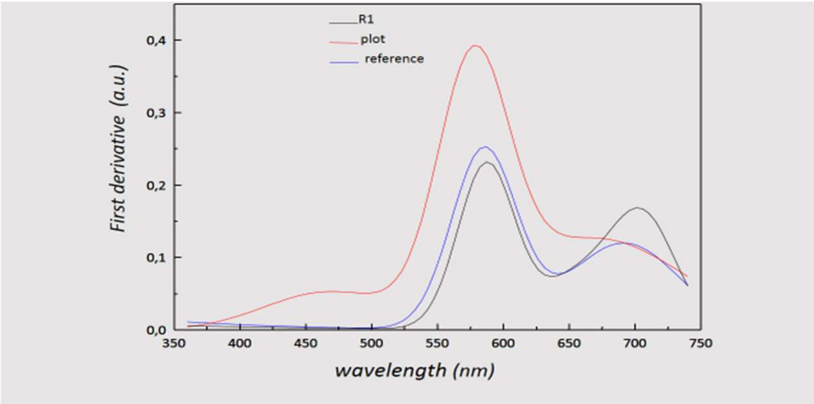

Figure 11.

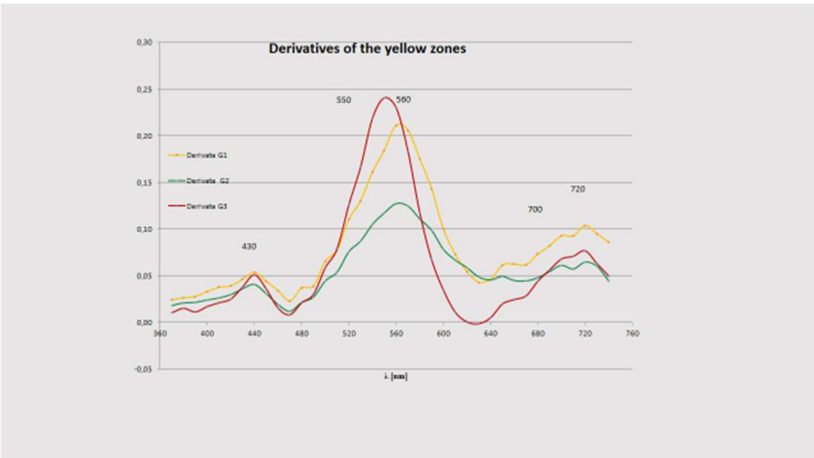

Figure 12.

The graphs of the derivative of the red zones (Fig.10) may confirm that the material is the some especially if we look the Fig.11 that represents a comparison with the red plot and with reference material. On the contrary the derivative of the yellow zones (Fig.12) shows high probability of quite different material.

7. Conflict of interest declaration

The author declare no conflict of interest.

8. Funding source declaration

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10. Short biography of the author

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Chapter 4 Methods and techniques for Color film restoration

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Abstract
Color restoration, digitization and management requires skills in physics, chemistry, optics, computer science as well as art, psychology, design and visual language. In this heterogeneous context, film restoration is a fascinating field of application which provides to students examples and records of successful (or unsuccessful) multidisciplinary methods and techniques to restore and manage colors through different media.
A film can be considered as a content in which color is used to raise emotions or support the storytelling, or can be seen as a container, made of colorants which age and decay through the years.
In the Master course of Color, Design and Technology, we introduce the students to the field of color film restoration, and we guide them through the different techniques and methods to perform the main actions of digitization, retrieval and conservation. Through this approach, we focus on the main actions to keep under control in order to perform a correct color reproduction and management.

Keywords:
Film Restoration, Color Films, Cinematography, Color

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1. Introduction

The FIAF (Fédération Internationale des Archives du Film), in his Status, defines a film as:

[…] a recording of moving images, with or without accompanying sounds, registered on motion picture film, or on any other medium now known or to be invented (FIAF, 2016).

The name *film* originates from the fact that, historically, the medium used to record and display motion pictures has been a thin sheet of cellulose acetate or nitrocellulose coated with a radiation-sensitive emulsion for taking photographs (also called film stock) (Merriam-Webster, 2020). But film – with the meaning of movie or motion picture – also identifies a story, told in different ways and using different technologies, always with the goal of raising emotions and amuse the audience watching it on a screen in a theatre, on a television or, more recently, on a smartphone.
Therefore, a film has a dual nature, content, and container and film restoration practice aims at preserving both the materials which compose the film and the intangible experience produced on the audience.
In this chapter, we will explore the two aspects of a film related to colors: the content, where color is used to raise emotions or support the storytelling and the container, where colorants and filters are used to recreate the illusion of reality but are subjected to aging and decaying.
In the first Section we will present a brief historical *excursus* of film technology evolution since its ancestors to the currently DCP.
In Section 2, we will present the technologies and the phases more relevant for the film history evolution, thus the film both as container and as content, showing some of the pivotal moments and technologies fundamental to understand the evolution of cinema, from the first moving images to the modern DCP, mainly focusing on the technologies that allowed the use of colors in films.
In Section 3, we will analyse the film base composition, his structure, and the principles of the cinematographic technique.
In the last two sections, we will make an *excursus* of the best practices for storing (Section 4) and restoring (Section 5) film materials.
For practical reasons, we will mainly refer to the 35 mm standard film support, skipping the reduced film supports history (for example the 16 mm, 8mm or Super 8 for amatorial usages), that should require another extend analysis.

Aim of this work is the presentation of film restoration techniques, from the beginning practices to the new digital restoration tools, in order to underline which are the best practices to correctly perform the color management in film restoration workflow. To do this, we will use and analyse some examples and records of successful and unsuccessful multidisciplinary methods and techniques used during the years to restore and manage colors through different media.

2. History of cinematography: an overview

In this Section we will present the more relevant technological steps that have influenced the film history evolution, thus the film both as container and as content. We do not claim to be exhaustive of all the aspects, the technologies and the phases which characterize the history of cinema. In fact, in this Section we will explain the pivotal moments and technologies, which are fundamental to understand the evolution of cinema, from the first moving images to the modern DCP.

The date of birth of cinema is commonly considered the December 28, 1895. That day, at the Salon Indien of the Grand Café at the Boulevard des Capucins in Paris, took place the first commercial cinematographic demonstration. The audience had the possibility to watch 10 short films, which have been shot, printed and projected (at 16 frames per second) using the *Cinématographe*, patented February 13, 1895 by the Lumière brothers. This history-making presentation included their first film, *Sortie des Usines Lumière à Lyon* (Louis Lumière, 1895) (Britannica, 2021). In this period, the Cinématographe Lumière started one of the most flourishing industries, but cinematography was born from the accumulated efforts of lots of craftsmen and forerunners. Among them we remind the magic lantern, the zoetrope, the praxinoscope and the optical theatre as the main precursors of cinematography.

To obtain true motion pictures, two developments were necessary: (1) a mechanism to enable the acquisition of sequences of photographs with a single camera at regular and rapid intervals, and (2) a medium capable of recording those images. In fact, a motion-picture camera must be able not only to advance the medium rapidly enough to permit the acquisition of at least 16 separate exposures per second (i.e., the minimum number of images to have the illusion of movement), but also to record a correctly exposed image.

The first transparent and flexible film base material was *celluloid*, manufactured commercially in 1872 and perfectioned in 1889 at the George Eastman company, in Rochester. This first film base was sturdy, flexible and perfect to record motion pictures, but it is extremely flammable (Britannica,

History of film, 2021). The first to use the celluloid as film base were William K.L. Dickson and Thomas Edison, at the Thomas Edison's Company. They worked on a recording system called *Kinetograph* which was coupled with a second instrument, the *Kinetoscope*, used for film projections**.** The Kinetoscope was a viewing device, where a continuous 14-metre film loop ran on spools between an incandescent lamp and a shutter. The main difference between the use of the Cinématographe and the Kinetoscope was that this second device was made for individual viewers, instead of the Cinématographe which was like a modern projector andallowed a large group of people to watch the same film at the same moment. Furthermore, the international patents of the Kinetograph and Kinetoscope were not registered, so these machines were widely and legally copied, modified and improved throughout Europe. This situation allowed the Cinématographe of the French brothers to become the European standard during the early cinema era and the celluloid film base became the standard material used to record and project films (Britannica, History of film, 2021). The big success of the Cinématographe was also linked to the fact that, compared with other attempts at producing a movie camera, it was remarkably compact, and it did not rely on electrical power. The Cinématographe could be placed anywhere, both to shoot film and to project – all that was required was a magic lantern lamphouse with a gas or limelight illuminant. Thus, the Lumières quickly started to tour the Continent to exhibit their films privately and publicly, acquiring, in every country, new and local short films for their catalogue.
For what concerns the film as content, the shift in consciousness from films as animated photographs to films as stories, began to take place around the turn of the XX Century and it is clearly evident in the work of the French filmmaker Georges Méliès. He was interested in the illusionist possibilities of the Cinématographe and his first films are characterized by the use of stop-motion photography to make one-shot tricks in which objects disappeared, reappeared or were transformed in other objects. After this first phase, George Méliès began to make experiments with brief multi-scene films, following the logic of linear temporality to establish causal sequences and tell simple stories, anyway his main purpose remained the public amusement by showing prestige games, assembling independent episodes, or making theatrical shows as purely visual art. By 1902 Georges Méliès produced his most famous film *Le Voyage dans la Lune*, a film adaptation of a novel by Jules Verne, characterized by a length of one reel (i.e., about 25 meters, or 14 minutes) (Britannica, Motion-picture technology, 2021).
Together with Georges Méliès many other filmmakers started producing innovative visions of the world, trying to establish the temporal continuity

from one shot to the next. Among them, *The Great Train Robbery* (Edwin S. Porter, 1903) is widely acknowledged to be the first narrative film example of parallel editing comprising 14 separate shots of noncontinuous, nonoverlapping action.

After this experimental period, the cinematographic technique started developing: more modern motion-picture cameras and techniques were invented allowing the sound recording, the picture and sound editing, the creation of special effects and the animation production. In this heterogeneous context we are mainly interested in the technologies allowing the integration of colors in films.

2.1 Color films

Contrary to what we were used to think about film of the origins, the silent cinema was full of colors: silent films were colored using nonphotographic methods such as hand-coloring, *tinting* (i.e., process of soaking the film into dyes) and *toning* (i.e., replacing the silver in the emulsion with colored, silver salts, by means of chemicals.).

Hand coloring: The workers applied aniline colors by hand-coloring the film with thin camel hairbrushes, under a magnifier, frame by frame, to enhance particularly significant scenes or elements. With this technique colors can appear unnatural, too vivid and limited in range, furthermore, the process was very long and expensive. One of the more famous studios that made this type of colorization was the *Elisabeth Thuillier's coloring lab* in Paris, where two hundred people were involved in film hand coloring.

In order to improve the hand coloring technique, in 1903, the Pathe Company experimented the stencil color prints. This technique (*à poichoir,* in French) required the manual cutting, frame by frame, of the area to be colored from another identical print. The necessary prints were one for each color, usually from 3 to 6, and were characterized by soft pastels hues. After the production of a stencil for each color, it was placed in contact with the print to be colored (Montanaro, 2019).

With the advent of the feature and the conversion of the industry to mass production during the 1910s, frame-by-frame stenciling was replaced by mechanized tinting and toning. Occasionally, the two processes were combined to produce elaborate two-color effects (Cherchi Usai, 1991).

Tinting: It is a monochromatic technique that provided a uniform color of all the light areas of a picture. It was achieved by immersing a black-and-white print in a dye or using a colored film base for printing. In this way, the dye was absorbed by the gelatin, uniformly coloring the film, and it is distributed evenly across the film support. In this case, color extends also into the nonimage area, directly affecting the emulsion layer. With this technique, a wide range of color options were available, and color was used to emphasize specific emotional states: yellow for daytime sequences and blue for the night, green for the country scenes or red for passion and danger (Pritchard, 2021). Thus, positive release prints could be made from different color sections joined together. In 1921, Kodak introduced nine different colors for film tinting (i.e., red, pink, orange, amber, light amber, yellow, green, blue, and lavender) and in 1929, when sound-on-film became common, Kodak introduced a pre-tinted film stocks in seventeen different hues that could accommodate soundtracks (i.e., Sonochrome) (RTI I. P., Motion Picture Film Processes, 2021).

Toning: It is a chemical process that consists of treating film emulsion to color the dark areas of the print. Tinting only affects the developed parts of the image, without dyeing the gelatin in the parts that have been impressed (it does not affect the film base). One method to obtain film toning is the metallic toning, obtained through a chemical process that involves a reaction of the emulsion with appropriate substances, which cause the replacement of the silver in the emulsion with colored metallic salt like copper or iron. Here, the most popular obtainable colors were sepia (using the silver sulfide), Prussian blue (adding iron ferrocyanide) and red brown (using ferrocyanide). The second method to obtain film toning is the dye toning, also known as mordant toning. This technique requires the conversion of the silver image to a colorless salt which acts as a mordant. The mordanted image is treated in a basic dye solution, where dye molecules bind to the mordant and produce a colored image. The metallic-toned images tend to be more stable than organic dye-toned images and with these techniques, dyes penetrate only the upper surface of the gelatin layer and the dyes applied might be very imprecise (Pritchard, 2021).

While the advent of sound films quickly made silent films and theater musicians obsolete, color replaced black-and-white much more gradually. With the sound introduction, tinting and toning were temporarily abandoned, leaving the market open to new systems of color photography. Different experimental methods to reproduce the "natural colors" were introduced during the film history evolution both for amateur and professional use and using additive and subtractive processes, but only a few of them were successful (Flückiger, Eva, & Nadine, 2020).

Kinemacolor: It was the first successful color motion picture process, invented in England by George Albert Smith in 1906 and used commercially from 1908 to 1914. It was a two-color additive color process, used for photograph and project a sensitized black-and-white film exposed through an alternating red and green-blue filter. The colors resulted from the blending of the two separate red and green alternating images. The main limit of this system, as all the additive systems, is that it was very wasteful of light due to the absorption by the color filters that allowed only a little percentage of light to really reach the screen, resulting in an image that was dimmer than the typical black-and-white film. For this reason and partly due to the expense of installing special Kinemacolor projectors in cinemas, the use of additive processes for theatrical motion pictures had been almost completely abandoned by the early 1940s.

Technicolor: After some experiment with additive systems, Dr. Herbert Kalmus, Dr. Daniel Comstock, and mechanic W. Burton Wescott developed a subtractive color system for Technicolor. This system used a modified camera in which the entering light was split in red and cyan light, subsequently sent to adjacent frames of one strip of black-and-white film. From this negative, two different positive prints were created. The obtained positives were, subsequently, chemically toned in cyan (from the red negative) and magenta (from the cyan negative), then cemented together into a single strip of film. This innovative process was later refined through the incorporation of dye imbibition, which allowed the transferring of the two matrices color dyes into a single print (George Eastman, 2021).

The pivotal innovation that made Technicolor a successful company was the introduction of the three-strip transfer process (produced by Kodak), also known as Technicolor Process 4. The process was very expensive but the public really appreciated the films vibrant colors and the dyes were extremely stable. With this techniques, different films were made: *The Wizard of Oz* (Victor Fleming, 1939)*, Gone with the Wind* (Victor Fleming, 1951)*, Snow White and the Seven Dwarfs* (David Hand et al., 1931)*, Fantasia* (Wilfred Jackson et al., 1940).

Kodachrome: The introduction of this monopack multilayer film in 1935 produced an immediate changeover from black-and-white production to color film. This film produced by Eastman Kodak incorporated three separate layers of differently color sensitive emulsion into one strip of film. It is based on the subtractive color system, which filters colors from light by using superimposed cyan, magenta, and yellow dye images, created from the record of the amounts of red, green, and blue light in each point of the scene.

Eastmancolor: In 1950, Kodak introduced the first economical, single-strip 35 mm negative-positive process incorporated into one strip of film. For the first few years, Technicolor continued to offer his three-strip system combined with dye-transfer printing, but by 1953, and especially with the introduction of the anamorphic wide screen CinemaScope, Eastmancolor

became the marketing imperator. More and more films were made in color, which soon became the rule. From the 1960s, chromogenic films predominate, and Technicolor prints became more and more scarce.
Today, the main problem of film color is that many of the dyes used in color films are unstable organic colorants affected by natural aging and fading. Dye fading reduces the overall density of the image, which results in loss of contrast and in shifts in color balance. This phenomenon is inevitable and it is accelerated by uncontrolled conditions of temperature and relative humidity.
The stability of chromogenic films varies considerably among film emulsions and the time of the film stock's manufacture. For instance, Kodacolor films from the period 1942- 1953 are known to have remarkably poor dye stability in the dark and exhibit intense yellow/orange staining. Kodak Ektachrome films introduced in the early 1950s are dramatically less stable than the Kodachrome films they replaced. For 35mm motion picture films, Kodak Eastmancolor negatives and prints from 1950 onwards exhibit poor dark stability, especially in comparison with the Technicolor films that employed a proprietary dye transfer printing process with very stable dark fading characteristics. From the mid-1980s onwards, chromogenic films achieved the best dark stability possible for the process (Enticknap, 2013).
Dye fading is irreversible and once the dye images have faded, it cannot be recovered but cold or frozen storage environments and moderate relative humidity will slow the process. However, digital color restoration techniques may approximate the original color balance and simulate the original color information.

2.2 Digital cinema

Digital cinema, also known as D-Cinema, indicates the distribution and the projection of digital films. The transition from analog to digital in filmmaking was already announced in the late 1970s and led to an increasingly hybrid film production practice throughout the following three decades, improving and rapidly progressing in digitization of mainstream film production. Just in 2012, digital distribution and exhibition outmatched the traditional analog workflow (Fossati, 2018). Digital 3D is considered one of the factors that contributed to the accelerated shift to digital, thanks to several successful film releases relying heavily on this technology. However, despite a drastic change in balance between analog and digital, analog film tradition is still very much alive. Indeed, it still serves as the basis of film practice and is essential for understanding, restoring, and preserving film history (Fossati, 2018).

The last decade has seen a few other developments related to the new possibilities of digital means in film production workflows. Image and sound aesthetics, and film preservation practices such as using cameras with digital image sensors to shoot, non-linear system for editing (NLE), and the new digital intermediate process (DI) led to the full digitization of films during post-production, digitizing film rushes or a film to be restored, or ingesting born-digital rushes, before post-production is carried out (from editing to final grading). DI can also be used to refer to the final result of such a process, which is the digital master used to create distribution copies (on film or digital) (Fossati, 2018). Then, it could be stored in a Linear Tape-Open (LTO) magnetic tape data storage, or digitally distributed to theaters tanks to the Digital Cinema Package (DCP), a compressed and encrypted digital file package, defined in the digital cinema initiatives specifications, that is sent to cinemas by way of media carriers, virtual private networks or satellite communications, and finally showed through a digital motion pictures projector instead of the historical 35 mm film stocks.
In the last few years, more and more filmmakers are turning to digital for shooting their films, and it is expected that in a few years digital distribution and projection will become the norm making the whole film production chain celluloid-free (Fossati, 2018).

3. Film as container

A motion picture film is a set of contiguous *scenes*, edited together following a plot. Every scene is a *segment* of a film – composed by only a sequence or by different sequences edited together – that depicts a single situation or incident. Every individual image on a strip of a motion picture film is a *frame* or photogram and every frame is separated by others through a frame line. A *cut* is the instantaneous change from one scene to another: successive frames over a cut contain a short overlap between the last frame of one scene and the first frame of the following.
If we analyze the stratigraphic structure of a film, it is composed by a protective layer, an emulsion layer, a base and an antihalation layer. The emulsion layer is where the film image is registered and it can be composed by one single silver layer (in black and white films) of by different colored layers (color film); it is very fragile, that is why the protective layer is essential to preserve the film emulsion from dust and external factors which could damage the film image. The film base composes the main thickness of the film and must provide transparency, flexibility and resistance to it. In conclusion, the antihalation layer absorb the light which passes through the emulsion, thus preventing any light from being scattered through the

emulsion from the rear surface of the base, which could cause halo effects on the surface.

3.1 Film base

To obtain the characteristic of transparency, flexibility and resistance, film bases have been produced in different ways and materials along the film history.

Nitrate films: As presented in Section 1, George Eastman introduced the first commercial roll film on transparent cellulose nitrate in 1889. In resolving the cellulose lack of chemical stability, great difficulty was experienced, and its high flammability caused significant explosions both during the manufacturing process and during the projection of films. In fact, passing through the projector's film gate, the films were exposed to high temperatures increasing the likelihood of auto-ignition and several incidents of this type resulted in audience deaths by flames and smoke.

Cellulose was used as photographic film base for a period of almost 60 years and then retired but the photographic industry and film archives is still having troubles with these two serious shortcomings with films that have been retained (Shanebrook, 2016) .

Nitrate decay is a daily struggle for the archivists, that are familiar to the increasingly pungent, noxious odor that accompany the decay. Once begun, it proceeds at an ever-increasing pace and results in the decomposition of the nitrate plastic itself. Over time, as nitrate film is exposed to moisture, heat, and acids, the nitro side groups break away, producing nitrogen oxides in the film’s environment that react with moisture and produce nitric acid. Nitrogen oxides and nitric acid readily promote silver corrosion, decompose gelatin emulsions, and catalyze the chemical reactions that cause further nitrate decay. Decomposing gelatin may present as sticky bubbles on the surface of the film and cause negatives or wraps of film to adhere together (i.e., blocking), that eventually becomes irreversible, so that the film roll becomes a solid mass. The last phase of nitrate decay involves the decomposition of the nitrate plastic into red/brown dust comprised of cellulose and colloidal silver.

In this 35mm reel of film with a yellow tint, most of the image has already faded, discolored, and the gelatin binder is bubbling and sticky to the touch. The yellow tint is now only visible on the edges of the film, where no silver image is present. This reel contains very few salvageable images.

Acetate films: Since 1910s, the cellulose diacetate film was introduced but the nitrate film base was discontinued only in 1951 thanks to the gradual introduction of the cellulose triacetate base. The diacetate had the tendency to become brittle and shows a high degree of distortion due to its high moisture absorption while the triacetate had the required strength and dimensional stability properties required for professional motion pictures, but rather is subject to other degradation problems such as the so-called *vinegar syndrome*. First, when acetate is not appropriately stored, and it is exposed to heat, moisture or acids of the acetyl groups could release free acetic acid staring a strong degradation process that causes the film base to become brittle and shrink.

Like the nitrate film base, acetate is subjected to distortion, embrittlement and shrinkage, and also to other specific problems such as delamination, antihalation layer color retrieval and plasticizer exudation (RTI, Visual Decay Guide, 2021) (Horak, 2005).

Polyester films: Since the acetate film base still presents many problems and issues of conservation, there was the need for a more moisture-resistant support, possibly hydrophobic and with very low affinity for water: a synthetic polymer. Many experiments have been tried along the 1940s and 1950s. The Polyethylene terephthalate (PET) was discovered in 1941 but the commercial production of this polymer occurred after World War II. Kodak's first salable Estar Film Base was made in late 1959, sensitized, and released for sale in 1960 but films continued to be made on cellulose triacetate films until the 1990's. Polyester films, are highly preferable for post-production, exhibition, and archival purposes because of their flexibility, strength, tear resistance, wet stiffness and thermal and humidity dimensional stability.

Various techniques have been used, to improve this film performances. To the film base have been added primers, antistatic layers, conductive layers, physical protection layers, and gelatin to counteract curl created by opposite side coatings. For instance, the antistatic greatly reduces static charging of the film, "shocks", and static discharge, even at high transport speeds; it also helps reduce static attraction of dirt to the processed film during projection, resulting in longer print runs with less build-up of black dirt and cinch marks. Furthermore, the antihalation layer has been added to the film base (as a dark layer coated on or in the film base) to absorb and minimize the reflection of light that penetrates the emulsion from the base-emulsion interface and that could cause a sort of secondary exposure and an undesirable reduction in the sharpness of the image and some light halation around images of bright objects.

3.2 Film light-sensitive emulsion

Black and white films: The emulsion layer in black-and-white film is made by silver halide (*AgX*) crystals suspended in gelatin and spread on a plastic substrate. Generally, the gelatin is a colorless glue, with a strong adhesive power that serves several purposes, e.g, it controls chemical diffusion and protects the silver halide crystals (Shanebrook, Making Kodak Film , 2016). The silver crystals are the light sensitive compound in the emulsion layer, and their sizes determine the sensitivity, contrast, and resolution of the film. When the silver halides are hit by light entering in the acquisition system, each crystal reacts to the electromagnetic radiation creating a latent image in the emulsion which can be chemically developed into a visible photograph. During the film development, the grains in the latent image are converted to metallic silver, resulting as the black part of the film negative.

The first film emulsions were *Orthochromatic*, thus they had high sensitivity to blue, green and bright yellow wavelengths, low sensitivity to orange and quite blindness to red (see Figure 1) (Montanaro, 2019).

This problem was solved with the introduction of the *Panchromatic* emulsions, which extended the films color sensitivity through the whole visible spectrum (see Figure 1), reproducing all colors in shades of gray approximately matching their subjective brightness (Britannica E. , 2021). The Panchromatic emulsions were introduced in 1904 for motion picture and completely replaced orthochromatic stocks by 1930.

Color films: In color films, the light-sensitive emulsion presents several layers (general one sensitive to the blue, one sensitive to the green and one sensitive to the red light) which contain thin grains in a variety of similar shapes and sizes, gelatin and other materials coated on film base.

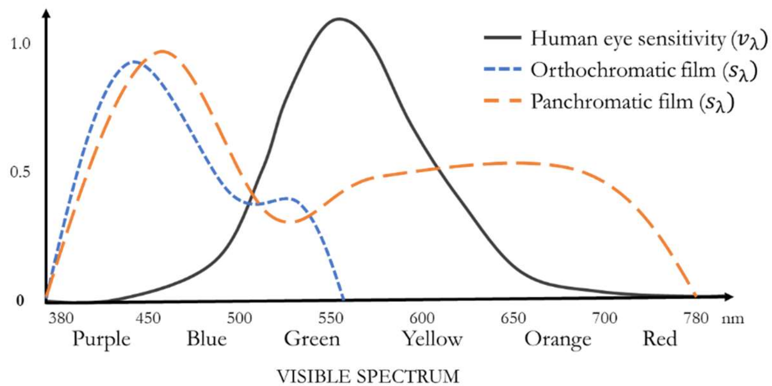

Figure SEQ Figure * ARABIC 1 Spectral sensitivities of the human eye compared with Orthochromatic and Panchromatic emulsions.

Considering a cross-section of a color negative camera film, its composition can be summarized as reported in Table 1. On top, there is an *overcoat matte* that lowers the surface coefficient of friction, reduces static electricity, and carries the materials (1). This layer is followed by the UV Filter Dye, that absorbs ultraviolet radiation (2) and then there are the three sensitive emulsions that creates three different latent images when exposed to color. While the Blue Sensitive Emulsion is divided in a Fast (3) and a Slow (4) emulsions, the Green and the Red Sensitive Emulsions are divided in a Fast (7), Mid (8) and Slow (9) emulsions. After the Blue layer, a yellow filter (5) prevents UV and blue light from exposing green and red layers. Between the color sensitive emulsions, an interlayer made of gelatin works as chemical barrier (6 and 10) and, an antihalation layer (14) composed of dye and particles absorbs the scattered light, filters light for printing and reduces static electricity.
Over the Cellulose Triacetate base, that provides physical strength to support the coatings, are applied on one side a subbing layer (16) that improves coating adhesion, and on the other side a backing layer (17) that protects the emulsion layer and reduces the static electricity.

Layer	Materials	
1. Overcoat Matte	Plastic beads, Lubricant, Antistat, Polymer and gelatin	
2. UV Filter Dye	Dye	
3. Fast Blue Emulsion	Gelatin, silver halide and dye	
	Yellow Image Dye Coupler	
4. Slow Blue Emulsion	Cyan Dye Coupler	
5. Yellow Filter	Dye	
6. Interlayer	Gelatin	
7. Fast Green Emulsion	Gelatin, silver halide and dye	Magenta Image Dye Coupler
		Cyan Dye Coupler
		Yellow Dye Coupler
8. Mid Green Emulsion		Magenta Dye Image Coupler Magenta Masking Coupler
		Cyan Dye Coupler
		Yellow Dye Coupler
9. Slow Green Emulsion		Magenta Dye Image Coupler Magenta Masking Coupler
10. Interlayer	Gelatin	
11. Fast Red Emulsion	Gelatin, silver halide and dye	Cyan Image Dye Coupler
12. Mid Red Emulsion		Cyan Image Dye Coupler Cyan Masking Coupler
		Yellow Dye Coupler
13. Slow Red Emulsion		Cyan Image Dye Coupler Cyan Masking Coupler
14. Anti-halation	Dye and Particles	
	Cyan Dye	
	Magenta Dye	
	UV Dye	
	Yellow Dye	
	Antistatic	
16. Subbing	Polymer	
15. CTA Base	Cellulose Triacetate	
17. Backing	Plastic beads, lubricant, polymer, anti-stat	

Table 1. Cross-section of a camera negative film. Figure reproduced from *Making Kodak Film.* Robert L. Shanebrook.

4. Film conservation

As a medium, historic films have problems in terms of preservation and storage, and the motion picture industry is exploring many alternatives to save those records of past life. If properly stored, a film can theoretically last forever, but during the years, relatively few films have been correctly preserved, and many of these are still in poor conditions.

Every time a film runs through a projector, it is eventually worn, scratched, or damaged and it is impossible to avoid its deterioration. The only possible action is the film stock preservation in the best possible conditions, anyway this requires a careful and constant control of storage environments.

The earliest film archive is the Swedish Film History Collection, which has been followed by the film archives in Paris, London, and New York City. In 1938, the *Fédération Internationale des Archives du Film* (FIAF) was founded and still today this is an international federation which brings together institutions dedicated to rescuing of films both as art and as historical documents (FIAF, 2021).

The biggest problem of film preservation is that, even with a limited selection, acquisition and storage are expensive and difficult, and nitrate film requires regular tests to determine whether it has deteriorated enough to require copying. In this context, the preservation of color films presents the most serious difficulties, in fact all color films made since 1953 are subject to fading that can be arrested only by storing prints at very low temperatures (Nishimura, 1993).

The best way to preserve a film stock is to store it depending on the support. Furthermore, it is fundamental to remember that the effect of temperature on the decay rate is a continuum: the higher the temperature, the faster the decay, and vice versa.

To simplify the evaluation and planning of storage conditions for mixed media collections, the range of possible temperatures has been divided into four categories at a relative humidity between 30% and 50% (RTI I. P., 2021), where *room* is a temperature around 20°C, *cool* is around 12°C *cold* is around 4°C and *frozen* around 0°C. (see Table 2) There, *Unacceptable* means that the temperature may cause significant damage, *Acceptable* means that the temperature meets ISO recommendations and *Best Practice* means that the temperature will provide an extended lifetime.

	NITRATE	ACETATE (B&W; COLOR)	POLYESTER	
			B&W	COLOR
ROOM	Unacceptabl e	Unacceptable	Acceptable	Unacceptable
COOL	Unacceptabl e	Unacceptable	Acceptable	Unacceptable
COLD	Acceptable	Acceptable	Best practice	Acceptable
FROZE N	Best practice	Best practice	Best practice	Best practice

Table 2. Storage conditions defined by the Image Permanence Institute for every support. Figure reproduced from (RTI I. P., 2021)

5. Film restoration

Although institutional practices of film preservation date back to the 1930s, the field received an official status only in 1980, when UNESCO recognized *moving images* as an integral part of the world's cultural heritage. For many years *restoration* and *preservation* have been used as synonymous. They meant a series of ongoing efforts among film historians, archivists, museums, cinematheques, and non-profit organizations to rescue decaying film stock, to preserve the images contained and to create a durable copy without any significant loss of quality.

The National Film and Sound Archive of Australia and Michele Canosa give useful definitions of preservation activities:

> *Preservation are all the practices and procedures necessary to ensure permanent accessibility (with a minimum loss of quality) of the visual or sonic content of the materials. Preservation may be considered as having both active and passive dimensions.*
>
> *Passive preservation is synonymous with 'storage' meaning keeping the material in an ideal environment and not subjecting it to any mechanical risk through use.*
>
> *Active preservation includes such practices and procedures as technical examination, technical selection, conservation, methods of storage in correct environments, housekeeping and collection control procedures (such as maintenance of technical records, surveillance, labelling etc.), technical restoration, rejuvenation, duplication and quality control.*

In Boarini and Opela the operations of *conservation* and *restoration* are defined as:

> *Conservation is a part of preservation and are all the processes necessary to ensure the physical survival of the film with minimum degradation.*
>
> *Restoration is the process of compensating for degradation of an artefact in order to return its visual and sonic content to its original character and condition.*

These definitions give some guidelines about the terminology that concerns the restoration workflow of a film, but they remain general and do not specify the technical operations involved in the single actions. This weakness most always leads to every restoration laboratory and every restorer to follow its own guidelines according to their formation and experience. Thus, the lack of shared definitions and technical references for film restoration is leading to the creation of students and experts specialized in the use of specific instruments and software, strictly dependent by the school and laboratory of origin.

5.1 Film restoration workflow

Through the mid-'90s, film restoration work was done photochemically but since late 1990s, films were restored with digital techniques. Damaged frames could be scanned, repaired and a picture that would previously have been presented in fragments or severely truncated could now be seen in a version close to its original. Today, the whole restoration work is almost all done digitally, allowing films to have whole new live, anyway the technology sometimes drives the restoration choices, when it should be the opposite (Plutino, Tecniche di Restauro Cinematografico – Metodi e Pratiche tra Analogico e Digitale, 2020).
The restoration process is not limited to establishing the technical procedures necessary for the interventions to be carried out, but instead allows a better understanding of the film being restored. Whatever workflow will be undertaken, there are preliminary phases in common (see Figure 3). In this work, we are not considering the sound restoration but if the film object of the restoration has sound, the images and the soundtrack are treated and restored separately until the final combined positive copy is printed.

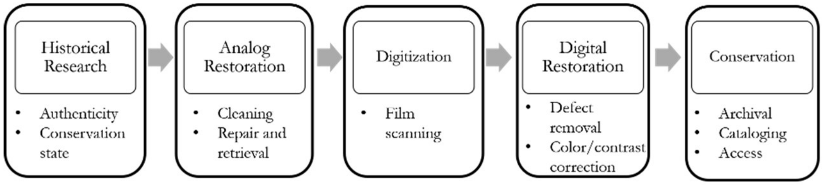

Figure SEQ Figure * ARABIC 3. General film restoration workflow.

5.1.1 Historical research

The first step of the restoration workflow is the *historical research*. In fact, when an archive or a lab decide to restore a certain film, it is necessary to look for the *availability* of other copies of the same movie around the world in order to identify where they are located and in what conditions they are.

In the field of the figurative arts, the same work can have various types of qualifications: the original, a copy of an author or a collector or of another artist, an author's *replica* or a *replica* with variations. Historical investigation includes the studies on authenticity of those materials and studies on the historical-artistic importance of the work.

In parallel, the research also focuses on extra-film materials like production documents, brochures and advertising, photos, censorship visas, correspondence and so on.

Once found the copies, it is necessary to define a restoration project considering the economic possibilities and the results of the availability research, but also evaluating the film elements, their general conditions and the problems of decay.

At this point, a careful comparison of the copies will help to create the reference document in which is indicated from which source has been took each shot, which changes have been made and which parts have been rebuilt. In this step, the restorer may produce an element as close as possible to the original and several factors must be evaluated to make decision valuating the cost and risk of repair.

5.1.2 Analog restoration

This phase consists in making all the copies selected in the best physical condition to be duplicated, to avoid film breakings during the digitization or the analog printing process. The first steps in film analog restoration are the repairs or substitution of damaged splices and perforations using adhesives, cement and tape splicers. In fact, the splices between film lengths degrade over time and eventually fail, even under optimum storage conditions and must be repaired by manually scraping away the adhesive residue and remaking the splice (Enticknap, 2013).

The analog restoration can take several weeks because this phase includes also chemical operations that can take long time: e.g., sticky films require incubation periods with silica gel to reduce humidity and consequent slow and controlled reintroduction into the atmosphere.

Once the copies are repaired, it is possible to proceed in different ways, according to the state of the material and the output required for the project (Enticknap, 2013).

Part of the analog restoration are also the operations of film cleaning, which could include both the simple use of an organic solvent to remove contaminants from the film surface using a pad of cotton wool and the automated application of chemical substances, to leave the permanent, protective residue on the film. Anyway, this second procedure could affect the film irreversibly, so today there is the tendence to avoid the application of chemical treatments.

An alternative commonly used non-invasive cleaning technique is the ultrasonic film cleaning, which allows the cleaning through the ultrasonic-induced agitation of the solvent separating contaminants from the film surface and dissolving them. In addition, the particle transfer roller (PTR), can be another commonly used technology to clean films that consists of several cylindrical rollers coated with a mildly adhesive, polyurethane-based substance placed in a film path, usually between the feed reel and the point at which an image is read in a projector, printer, or scanner. The surface of the roller is formulated to be adhesive enough to transfer contaminants from the film surface to the roller, but not sticky enough to impede the film motion.

In a photochemical workflow, the master element consists of physically assembling sections of different film elements together, from which the restoration master element will be created by printing. In a photochemical workflow, it is necessary to ensure that all the footage components within the assembled master element are of common polarity either a positive or a negative image.

Image enhancement by photochemical process usually includes the mitigation of scratches and the removal of dirt and artefacts. In a wholly or primarily photochemical restoration project, the main duplication stage begins when technical selection, cleaning and scratch diminution treatments and master element assembly have been completed, and the assembled reels exist with the order of shots as they are to appear in the restored film. The

duplication is carried out using a printer, which re-photographs the image on an existing processed film element onto unexposed, new film stock to create a copy of the assembled master element, in some circumstances changing its visual characteristics in the process.
In film restoration, the printing process can incorporate a number of techniques intended to change the aesthetic properties of the image on the destination film stock to solve the perceived effects of physical damage or chemical decomposition to the source element which cannot be removed or mitigated by working directly on the film itself such as the shrinkage of the film base, severe scratching, grading, sensitometry and densitometry, or color dye fading (see Section 6). In the case of an analogue restoration workflow for the image, the result will be either a new negative or fine-grain positive element, depending on the polarity of the assembled source element being printed (Enticknap, 2013).

5.1.3 Digitization

In the film scanning phase, each frame of the analog film is converted in a digital image through a gate, equipped with a LED source that digitize each frame using defined parameters. At the end of the process, the digitized film is returned as uncompressed file usually in DPX (Digital Picture Exchange) format, designed specifically for restoration. This format, in fact, encodes information about the gamma of acquisition and incorporates a *lookup table* (i.e., calibration data that is used to ensure that the color space in the scanned film looks consistent in all the display devices used in the workflow). The DPX format also enables the creation and storage of metadata information about the file.
A remarkable advantage of the digital restoration is that the shots do not have to be scanned in the order they appear in the finished restoration, and non-linear editing can be done on a software timeline after scanning and post-processing, and the source elements from which the restored film will be constructed can be scanned separately.
The scanning resolution is a trade-off between the detail of image information captured (resolution and color depth at which the individual frames will be scanned) and the volume of data that will need to be processed (for grading and color correction) and stored, and thus the overall cost of the project. Today, the scanners used for film restoration uses standard resolution of 2K up to 4K. As a general rule, 2K (with a width of 2,048 pixels) is generally considered sufficient for scanning film frame sizes up to 16 mm and for digital cinema projection on smaller screens (Fossati, 2018). Whereas 4K

(with a width of 4,096.80 pixels) is regarded as the norm for 35 mm film and projection on larger screens (Dagna, 2014).
In parallel with the development of innovative and new systems of acquisition, at both national and international level, many guidelines and regulations have been developed and adopted by archives, libraries, and laboratories (FADGI., 2015), (Van Dormolen, 2012).
Nevertheless, in the digitization pipeline, an evaluation of the instrument performance is rarely considered, as well as an objective evaluation of the results. In fact, digitization guidelines rarely contain information on instrument calibration, and in many practical cases film scanning is performed in uncontrolled conditions or using automatic color correction and adjustments introduced by the scanner software. In this context, the lack of proper systems of performance evaluation makes impossible to measure and assess the influence of the system processing in the final acquisition, and an excess of automatism can be dangerous, when the digitization purpose is a faithful digital reproduction of an analog film (Plutino & Rizzi, 2020).
Digital restoration: After the film digitization, the following step is the digital restoration. Today, this phase is done through specific software, which allow for a manual, semiautomatic, or automatic workflow, supported by a thorough control and a frame-by-frame correction carried out by specialists in this sector. In this way, the digital restoration phase can take several months, and specialized professionals are required.
These software exploit dedicated algorithms able to identify and remove all the undesired elements in the film that are impossible to be removed through analog restoration (e.g., strains, flickering, graininess, dust and scratches). However, despite the great potential of digital restoration, these algorithms are not foolproof and user supervision is always needed. In fact, the instruments for defects identification are significantly less efficient than the human eye. Consequently, one of the biggest requirements of digital restoration systems is the capacity to work automatically, but the archives or restorer's ethical stance demand also a transparent restoration process. In fact, the restorer must be able to check the results of the software intervention, ideally by comparing frames before and after every step of the process. The restorer has the choice to let the software automatically search and remove damage according to the chosen parameters, restrict the application of the tool to certain areas, such as to the single-frame damage only and, carry out manual retouching (Wallmüller, 2007).
The use of automated restoration tools is, therefore, an economically attractive possibility. These tools will look for similar defects in multiple frames of scanned film frames and apply a fix automatically when they find

them, but the software defect identification is not infallible and is less accurate than the human eye (Bellotti, Bottaro, Plutino, & Valsesia, 2020).
Generally, software-based image restoration tools fall into seven broad functions: polarity correction, mitigation of dirt, adjustment for consistency of stability and illumination, brightness, contrast and color correction, recreation of original post-production effects and achieving consistency in the overall aesthetic.
The digital restoration step in the film restoration workflow involves not only the restoration *per se*, as described above, but also the color correction.
Although the general workflow and the available software are still very similar, the specific tools for resolving color issues have clearly improved in the last decade. In line with the general development in the field, restoration software packages have included some basic color correction applications which can be used for tackling smaller problems. Furthermore, with a faster processing and rendering time, color restorers can work efficiently with high resolution (typically 4k) material. In general, for all color restorations, the same tools are used as those used for color grading in post-production (Fossati, 2018).
As well as for all the other steps in the restoration workflow, also for digital restoration the used instruments and hardware are fundamental, in fact is mandatory the use of a high-quality calibrated monitor to edit and show the results of the restoration process. In some cases, in large laboratories the results are also projected in a standard calibrated cinema.
Nevertheless, the dependency of digital film restoration on consumer software often can lead to the tool-dependency of the restorers. This means that the restorer in his carrier become an expert in the use and application of a single editing software, and this led to the tendency of accepting passively all the solutions provided by the software producer without knowing important details about how them have been produced or demanding for new solutions. This situation led to the lack of research in alternative solutions for film restoration and thus, film restoration technologies are left in the hands of industries and companies which produces general image and video editing solutions, without a proper focus on restoration (Plutino & Rizzi, 2020).
Furthermore, since in film restoration a proper reference is missing or has been subject to decay, is even more important to find new solutions and tools to study, analyze and restore film colors. In fact, even today, a technical colorimetric characterization of films, is quite always impossible (Plutino & Rizzi, 2020) (Mazzanti, 2019).

5.1.4 Conservation

The result of the entire photochemical or digital process will be a new master film element or digital asset, one that is intended to serve the purposes of maintain its integrity in long-term storage and of serving as the source element from which all subsequent access copies are made. For what concerns the long-term durability, an analogue final output is considered preferable. In fact, if stored in appropriate atmospheric conditions (i.e., cool and dry), a new polyester base film element has a useful lifetime measured in centuries (Enticknap, 2013), (RTI I. P., 2021). Despite this shared knowledge, many archives and restoration laboratories cannot afford the expenses of an analog film printing and decide to preserve the digital format.
On the other hand, for what concerns the film accessibility, the possible solutions depend on the most diverse needs. If the image restoration was photochemical, the final negative or fine grain positive will itself be scanned, and the resulting digital version will be used as the source from which to transcode the versions required for distribution. If the image restoration was digital, software available today enables to reduce the resolution or other quality characteristics while copying a digital file so it makes sense to plan a digital restoration project such that the final output file will have the highest quality needed for access, or higher.
The most diffuse technologies to preserve digital files are the RAID (Redundant Array of Independent Disks) and the LTO (Linear Tape-Open). Anyway, the obsolescence of the digital format is a key factor that contributes to the common state of conservation practices for which the preservation on analog film is often cheaper than its digital equivalent. In fact, all the digital technologies require an active approach, continuous maintenance and renewal of the software and hardware, and this led to a strong need of constant data migration.
The archival issues of the long-term conservation masters are an open problem in film restoration and archiving domain and, today, the archives are still looking for a trade-off between analog and digital conservation.
In this last step of film restoration workflow, together with the conservation, the cataloging of the restored film is included. Nowadays, the cataloging boards and guidelines give particular attention to the documentation of the analog process and just a few of them also consider the digital restoration process. In fact, many cataloging sheets, databases and guidelines, report just marginally the intervention made during the digital restoration, it is not satisfying (Dagna, 2014).
Among the few points generally accepted in the restoration workflow, there is the ethical practice of reporting in details all the interventions and decisions

made on the film during the restoration, to create a complete record. That aims at giving the future end-users the reversibility of all the operations: it is commonly done for all the analog intervention, but not for the digital step, where the lack of documentation is one of the most important issues in the restoration workflow, because often it is not only impossible to reverse a digital intervention, but it is also impossible to know which enhancement or modification has been made on the film.

5.2 Simulating early film colors

The color dye fading in the photochemical restoration is usually resolved by the Desmet color method that allows to replicate the tinted and toned effect used in a film. The technique was developed by Nöel Desmet from the Royal Film Archive of Belgium and involves printing a black-and-white negative on a color print stock and the colored tints and tones are replicated by exposing the print stock using a combination of red, green, and blue filters on a continuous contact printer. In some cases, the color is replicated by *pre-flashing* the raw stock with no negative between the light source and the color print stock. Other colors are replicated by varying the light filtration with the black-and-white negative in contact with the color print stock (NFSA, 2021).
To reproduce a print only colored by tinting, the developed black and white inter-negative is first printed onto a modern color print stock, then the same film stock is flashed with the appropriate colored light (complementary to the desired one) or with a neutral light filtered through specific filters.
To reproduce toned prints, the developed black and white inter-negative film is exposed onto a color print film using a colored light source rather than a neutral one. As the light passes more easily through the light parts of the negative image, the result will present color only on the dark parts of the positive image, simulating the original toning.
Combined tinting and toning effects can be reproduced using the same process used to simulate the tone but adding a second printing pass to color the light parts of the image, simulating the original tint.
Also in digital restoration, the Desmet method can be used to simulate early cinema colors such as tinting and toning. The Digital Desmet method has become widely used and its results have improved significantly in recent years. The digital version of the Desmet method is in many ways similar to the photochemical one. To simulate the tinting, the method is carried out on the black-and-white image and, only at the end, a color layer is added to the image; to simulate the toning the blacks in the image are replaced by a color.
It should be mentioned that analog techniques for recreating tinting and toning effects are still quite practical and can also give very good results.

Similarly, in the case of hand-colored and stenciled films, digital restoration has proven to be quite satisfactory in simulating the original tints: does not only allow for great flexibility in determining each separate color that was originally applied with an aniline tint on a black-and-white image, but it also provides a neutral reproduction of the underlying black-and-white image. The restoration of later chromogenic color films has become common practice in the field as digital, unlike analog methods, allows restoring faded films more easily and efficiently. For all color restorations, the same tools are used as those used for color grading in post-production (Fossati, 2018).

6. Supplementary materials

In this chapter we briefly we introduced the story of cinematographic technique, we presented the main features of film as a container and as content and explained the general workflow of film restoration. Since many images and photos of different film coloration processes are covered by copyright, we have not the possibility to report them. Nevertheless, here we report different websites where it is possible to find many descriptive images of the topics discussed in this chapter:

Timeline of historical film colors by Barbara Flueckiger: https://filmcolors.org/

Motion picture film processes by RTI-Image Permanence Institute: https://www.filmcare.org/identification

Technicolor online research archive by George Eastman Museum: https://www.eastman.org/technicolor-online-research-archive-0

Online open access Resources by FIAF: https://www.fiafnet.org/pages/E-Resources/FIAF-Summer-School-Resources.html#_Toc517876626

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9. Short biography of the authors

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Assessment: from point-wise colorimetry to film restoration". Her research interests are: Colorimetry, Image Processing, Image Enhancement and Image Quality. She wrote a book about film restoration and published several works of national and international relevance.

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Chapter 5 A very brief history of colour photography

Giovanni Vanoglio, photographer

Abstract

In 1816 Joseph Nicephore Niepce had yet to invented photography, although he had already shared with his brother Claude his concern to "find a way to fix colours" (Niepce, 1973). Other curious and practitioners of the new technique shared the same feeling, and their endeavours led to a first accessible solution: hand-applied colour. From the dawn of photography come splendid examples of skillfully painted daguerreotypes and the wonderful albumen prints of the Beato brothers painted by Japanese artists in Yokohama studio in 1860.

The search for a photochemical process capable of fixing light, shadows and colours at the same time has engaged scholars and scientists in a continuous chase of techniques. Similar to other human events, such a race would see losers and winners. From Levi Hill's first "false" discovery to John Joly's intuition, upon which the digital photography is still based today. From Thomas Sutton's photography, which put into practice physicist J. C. Maxwell's theories, to the first digital camera by Steven Sasson and Kodak. We should not forget the marvellous photographs taken by Sergei Mikhailovich Prokudin-Gorskii, the first to bring colour photography out of laboratories and studios into the real world.

Colour photography as an expressive medium developed along with the evolution of the photochemical process. Before becoming a consolidated reality it had to wait for the stability of the results achieved by the Lumiere brothers' Autochrome films. Most important photographers in the history of photography have challenged themselves with colour photography, thus showing its expressive potential. However, colour photography has never freed itself from the halo effect of a means intended for commercial or vernacular purposes. Only when William Eggleston opened the first exhibition of colour photographs at the MoMA in New York in 1976, a real change of pace and consideration took place.

Keywords:

Colour photography, photography, history.

Chapter 5 A very brief history of colour photography

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1. Introduction

We are all used to colour photographs to the point that we take them for granted. Family photographs, travel photographs and photographs of our memories are in colour, maybe a little faded and timeworn, but they are in colour. When we take a photograph using our smartphone, the photograph is in colour.

In the world of photography, colours might be considered natural because of the very fact that photography exists. However, it has not always been so. Photography originated in black and white, almost despite general expectations and only after many mistakes, some early enthusiasm and much study did it turn into colours.

The history of photography is a dense mesh of paths and stories that are difficult to separate from one another. It is impossible to talk about cameras without talking about the evolution of the chemical-physical - and now also electronic - aspects of its processes. It is also impossible to talk about the personalities who have studied its history without mentioning genres and artistic movements.

Here we will try to pay particular attention to the aspect of colour in photography, exploring how it was considered a fundamental requirement from the very beginning and therefore a much sought after element. We will outline how it became an integral part of each photographer's expressive language, to all intents and purposes. The names and events covered in this paper are by no means exhaustive as the history of photography is made of many more fascinating stories and equally mesmerising characters that, for the sake of space, we are not able to include here.

2. At the beginnings

2.1 The Camera Obscura

On a bright sunny day, a ray of light finds a small hole in the curtain closing a door, creeps in and is projected onto the opposite wall, bringing with it the image of the outside world.

The step from the moment of awe to the study and repetition of the physical phenomenon was a "short" one: in his 'Problems' (in ancient greek: Προβλήματα, Problémata) Aristotle had been one of the first to study it (Ferrini, 2002), but it was the Arab scientist Alhazen Ibn Al-Haitham (Basra, c. 965 – Cairo, c. 1039), just before the end of the first millennium, to dive into the study of light reflection and give a name to the 'box' that allowed this phenomenon: the *camera obscura,* the darkroom.

In the 16th century, the Italians Gerolamo Càrdano (Pavia, 24 September

1501 – Rome, 21 September 1576) and Daniele Matteo Alvise Barbaro (Venice, 8 February 1514 – Venice, 13 April 1570), in close succession, improved the optical performance of the *camera obscura,* first by adding a biconvex lens to the pinhole and then a diaphragm with a diameter smaller than the one of the lens.
Thanks to the German Jesuit Athanasius Kircher (Geisa, 2 May 1602 – Rome, 28 November 1680), in 1646, the *camera obscura* transitioned from being a simple entertainment spectacle to a real tool in the hands of illustrators and painters. A drawing darkroom was built in Amsterdam in which the artist and his assistants could comfortably work inside to produce engravings or paintings.
Among the many users of the *camera obscura* worth mentioning here is Giovanni Antonio Canale (Venice, 18 October 1697 – Venice, 19 April 1768), commonly known as Canaletto. The 18th-century Venetian Vedutista, renowned for the incredible precision of his perspectives and geometries, used a portable *camera obscura* now housed in the Museo Correr in Venice (Canaletto's Camera obscura - Google Arts & Culture, 2021). The contemporary use of the *camera obscura* by Cuban-American photographer Abelardo Morell (Havana, 17 September 1948) (Abelardo Morell, 2021) in his projects 'Camera Obscura' and 'Tent-Camera', is also of great artistic interest.

2.2 The Magic Lantern

The origin of the Magic Lantern is still confused, but it is commonly accepted that its discoverer was by the same German Jesuit mentioned above, Athanasius Kircher: in 1646, Kircher published 'Ars Magna Lucis et Umbrae' (Kircher, 1671) in which he included the use of a convex lens to enhance the projection of images with the aid of candles or sunlight.
The Magic Lantern is technically the reverse of the *camera obscura*: a light source enclosed inside a box emits a light that, passing through a hole and through a drawn glass, projects what is drawn on the glass onto a surface outside the box.
All the magic is in the decorated and coloured glass that is projected from a miniature onto an external surface. The bigger the distance, the larger the projected image.
"The most colourful images appear on your white wall!" wrote Goethe (Frankfurt, 28 August 1749 – Weimar, 22 March 1832), "[And even if they were only faint ghosts], they still delight us when we admire them with the naivety of children, thrilling to the marvellous apparitions" (Goethe, 1774).
The enthusiasm could only be boosted further with the discovery that a quick

transition from one glass to another could give the impression of movement. Adding to that, the superimposition of two or more glasses could make the projected scene look even more complex. The apex of fervour was reached when a simple mechanism could make superimposition and movement coexist.
With the Magic Lantern we find ourselves in a field closer to cinema than to photography (although the magic lantern principle will return powerfully in the slide projector). To some extent, we could say that the public 'knew' that colour images 'existed', they saw them and therefore somehow it was deemed possible to obtain them, although they were still the outcome of a 'manual' procedure.
Meanwhile, the c*amera obscura* was becoming an increasingly common technological aid for creating images, engravings or paintings. However, it was still an evanescent image, which would disappear as soon as the light that projected it vanished. Further studies and experiments were needed, especially with those materials and chemical compounds that blackened under the action of the air or, preferably, of the light.

3. The birth of photography

On 22 June 1802, the Journal of the Royal Institution of Great Britain published a contribution by Thomas Wedgwood (Etruria, 14 May 1771 – 10 July 1805) and Humphrey Davy (Penzance, 17 December 1778 – Geneva, 29 May 1829), the former the heir to a dynasty of potters and the latter one of the most influential chemists of the time. The title of the article was "An account of a method of copying paintings upon glass and of making profiles by the agency of light upon nitrate of silver." In fact, the publication gave way to the invention of photography. It combined, for the first time in a resourced way, the scientific knowledge of optics and chemistry available at that time.
Wedgwood and Davy successfully created 'outlines' (or 'silhouettes') but could not prevent these images from fading when viewed in a light brighter than candlelight.
Nevertheless, the groundwork had now been laid, and it was up to Niepce (Chalon-sur-Saône, 7 March 1765 – Saint-Loup-de-Varennes, 5 July 1833), William Henry Fox Talbot (Melbury, 11 February 1800 – Lacock, 17 September 1877) and Louis-Jacques-Mandé Daguerre (Cormeilles-en-Parisis, 18 November 1787 – Bry-sur-Marne, 10 July 1851) to complete the journey of discovery. This culminated on 7 January 1839 when Daguerre presented a process that would later take his name at the Academy of Sciences in Paris. As it happens, despite the strive for conquering colour -an endeavour

that Niepce had already shared with his brother in 1816- photography was first born in black and white.
The newly discovered photograph was greeted with great surprise: at last, a face or a landscape could be recorded in great detail and with great ease. However, a great disappointment immediately followed the surprise: the colours were missing!

3.1 Hand-applied colour

The first clients of such a newly discovered photograph and their photographers immediately advanced the request for colour photography. In a short while, they found the easiest way to solve the problem: applying colour manually.
"When the photographer has succeeded in obtaining a good likeness, it passes into the artist's hands, who, with skill and colour, give to it a life-like and natural appearance" (Rintoul, 1851).
To be precise, the colouring procedure is not as simple because of the characteristics of the daguerreotype, which consists of silver or silver-plated copper plate, polished to a mirror finish, which is then exposed to iodine vapour. The surface of the daguerreotype is extremely delicate and the colouring process was not accessible to everyone. In 1842, London-based daguerreotypist Richard Beard (Plymouth, 22 December 1801 – Hampstead, 7 June 1885) filed a series of patents illustrating several methods for colouring, the simplest of which involved "stippling dry colours onto different parts of the picture and then settling the colours by breathing on them2 (Coote, 1993).
While in Europe, the hand-application of colour on photographs was almost a necessary expedient to satisfy the expectations of customers and practitioners, in Japan, this technique became very popular and gained fame as a refined and respected art form from 1860 onwards. Much of the credit for this success can be attributed to Felice Beato (Venice, 1832 – Florence, 29 January 1909), who certainly had the foresight to entrust the colouring of his albumen prints, obtained from wet collodion glass plates, to Japanese water-colourists. The beauty of the result of this collaboration can be admired in the prints and albums that Felice Beato sold at his studio in Yokohama (Views of Japan, Getty Museum, 2021).
However, there was still a problem. No matter how good the artist was at colouring the photograph, the selection of colours was still arbitrary. The colours selected could be different from those of the recorded scene. Photography was increasingly required to be able to faithfully record the colours as well as the lighting of the scene. Hand-colouring of photographs

remained widespread until the middle of the 20th century, especially in portrait and wedding photography (see, for instance, the Polish *monidło*). However, its use eventually declined, a process that was accompanied by the equally rapid advent of the colour film.

4. The colour revolution

At the time of the birth of photography, the nature of colour had been known for around 200 years: Isaac Newton (Woolsthorpe-by-Colsterworth, 25 December 1642 – Kensington, 20 March 1726) used a prism in 1666 to divide a beam of light into the seven colours of the spectrum. Moreover, Magic Lantern shows were quite common among people. However, more knowledge was needed.

The breakthrough came in 1861 when Scottish physicist James Clerck Maxwell (Edinburgh, 13 June 1831 – Cambridge, 5 November 1879) presented a brilliant demonstration of his three-colour additive method at the Royal Institution in London (Evans, 1961). The presentation combined physics and physiology. To best explain the experiment, Maxwell asked photographer Thomas Sutton (Kensington, London, 1819 – Kensington, London , 19 March 1875), who would also be the inventor of the Single-Lens Reflex Camera, to expose a ribbon of tartan on three wet collodion glass plates, each exposed through a coloured filter: red, green and blue.

Then the three sheets of glass were projected on a wall, one on top of the other in register, each filtered through the original coloured glass. To everyone's amazement, the colours of the tartan ribbon were displayed on the wall. However, above all, the world's first colour photograph was brought to view.

While Europe was racing to find a process capable of fixing colours, the United States of America proved to be fertile ground for two events that, above all, by crossing their paths, would mark the evolution of photography. In 1885, while searching for a strong, transparent material to use in his lectures, the Reverend Hannibal Goodwin (Ulysses, 21 April 1822 – Ulysses, 31 December 1900) came across celluloid. After months of experiments, he mixed nitrocellulose with nitrobenzol and diluted it with alcohol and water. The mixture was then spread on a glass plate, and once the volatile components had evaporated, celluloid remained, as transparent as glass and as flexible as paper.

That was a blessing in disguise for photographers, who finally had a flexible material that could be coated with a photosensitive emulsion.

Goodwin decided to apply for a patent on 2 May 1887 for "a photographic pellicle and process of producing the same [...] especially in connection with

roller cameras", but did not obtain it until 13 September 1898 after several corrections and numerous legal actions (Moran, 2021).
A few kilometers away from Goodwin, another inventor, George Eastman (Waterville, 12 July 1854 – Rochester, 14 March 1932), had already started to produce and market cameras. In 1889, he replaced the roll of photosensitive paper with a roll of film he had invented with a process very similar to the one of Reverend Goodwin.
George Eastman and his new company, Kodak, applied for a patent on 9 April 1889 and received it on 10 December 1889, just 11 months later.
While there seem to be all the ingredients for a spy novel, the apparent unequal treatment had been caused by the Reverend Goodwin's consistent inaccuracies in his replies to the multiple requests for clarification sent by the patent office. Clearly, the Kodak's patent application drafted by the chemist Reichenbach must have been much more precise.
Goodwin nevertheless took legal action against Kodak in order to have his patent recognized as preceding George Eastman's film. In the meantime, the ANSCO company which had acquired the Goodwin Film and Camera Co. of New Jersey, succeeded in winning the case against Kodak in 1914 and was paid $5 million (New York Times, 1914), about $130 million today.

4.1 Synthesis and Interference of Colour

The first steps into direct colour in photography bring us to meet four characters of different fortunes.
The first one is the American Reverend Levi Hill (26 February 1816 − 9 February 1865), who announced as early as 1850 that he had discovered a process for fixing colours based on the daguerreotype. When, after much reluctance, the process called Hillotype was disclosed to the public, it proved so complex that it was deemed almost fraudulent, and Hill was accused of painting his daguerreotypes. In 2007, after six months of research, the curators at the Smithsonian's National Museum of American History confirmed both the process and the fraud: Hill had succeeded in fixing some of the colours, but external pressures led him to add the missing ones by hand. "Hill was indeed a genius, but he was a flawed genius" (The J. Paul Getty Trust, 2007). At the age of 48 in 1865, he died by the continuous inhalation of chemicals vapours he had used in his experiments.
The second character, Gabriel Lippmann (Bouneweg, 16 August 1845 – SS France, Atlantic Ocean, 13 July 1921), professor of physics at the Sorbonne in Paris, announced in 1891 to the Academy of Sciences that he had discovered a direct method for obtaining and maintaining colours in photographs. The procedure consisted of recording the interference of the

electromagnetic waves of direct light with its reflection. That was an original method, different from all others in that it used the fundamental components of light itself and did not require inks and pigments. To achieve this, Lippmann used a panchromatic plate behind which was placed a mercury mirror. The incident light waves interfering with their reflections create a kind of texture within the thickness of the emulsion (where each colour corresponds to a specific spatial value), achieving a correct separation of colours. As a result, when the plate is viewed in white light, it will show a correct colour reproduction of the photographed scene (Lippmann, 1891). It was an exact, but also very complex procedure, which prevented it from becoming a popular commercial product. Nevertheless, thanks to this research result, Lippmann won the Nobel Prize in 1908.

Luis Ducos du Hauron (Langon, 8 December 1837 – Agen, 31 August 1920), a multi-faceted scientist with a background as an amateur painter, is our third protagonist. Du Hauron was well aware that mixing red, green and blue in different proportions could result in infinite shades of colour. He decided to investigate the matter as a physicist and came up with a procedure that seemed to give good results, which he presented to the French Society of Photography in 1868. He was not aware that on the same day, just before him, another inventor, Charles Cros (Fabrezan, 1 October 1842 – Paris, 9 August 1888), was at the French Society of Photography to describe exactly the same process. The two became friends and began a maintained collaboration until Cros decided to move onto something else. The procedure devised by Ducos du Hauron involved taking three negatives filtered with green, orange and violet, respectively. These would then be printed on dichromated gelatine film coloured with pigments complementary to the shot's filters (red, blue and yellow). They would finally be superimposed in register until a colour image was obtained (Langlois, 2017) (Ducos du Hauron, 1897).

Our fourth character is the Soviet Sergei Mikhailovich Prokudin-Gorskii (Murom, 30 August 1863 – Paris, 27 September 1944) who used his experience as a chemist to extensively experiment with colour separation. To minimise the time between exposures, he first used and then perfected a camera with an oblong, sliding back designed by his friend and mentor Adolf Miethe (Potsdam, 25 April 1862 – Berlin, 5 May 1927), an important German chemist who was also involved in research into colours in photography. Prokudin-Gorskii had, above all, the merit of taking colour photography out of the laboratories and studios: he decided to travel and explore the vast territories of Russia to record the splendour of the pre-revolutionary Russian Empire. For the purpose, the Tsar Nicholas II gave him a pass and presented him with a darkroom carriage where he could work during long journeys

(Prokudin-Gorskii, 2012). The wondering took Prokudin-Gorskii to Paris, where he opened a photographic studio, still in operation today, and died in 1944. Sergei Mikhailovich Prokudin-Gorskii's great work is preserved in the Library of Congress of the United States of America (Prokudin-Gorskii, 2021).

5. Additive colour synthesis

5.1 The Krōmskōp

"The Krōmskōp is an optical instrument which accomplishes for light and colour what the Phonograph accomplishes for sound and the Kinetoscope for motion" (Ivers, 1898).

Thus begins the preface to the volume that Frederic Eugene Ivers (Litchfield, 17 February 1856 – Philadelphia, May 27, 1937) dedicated to the Krōmskōp, a device he had invented that allowed the vision of negatives created by applying the theory of colour separation demonstrated a few years earlier by J. C. Maxwell.

The transparent positives, also known as kromograms, were made according to the dictates of colour separation and were then placed on Ivers' device and displayed through special red, green and blue filters. The correct orientation of a mirror provided the necessary backlighting to appreciate the chromatic precision achieved fully.

With the viewer, Ivers also developed and marketed equipment that could create kromograms, but the future was just around the corner. After a few years, the initial enthusiasm for the incredible beauty of the colours that could be achieved left behind the complexity of the process to pave the way to the simplicity of the newcomer: the Autochrome process.

5.2 The Joly's Process

Colour photography was, in fact, a reality. It required complex processes, extreme precision and bulky cameras. The three-shot process for colour separation was an insurmountable obstacle for many, not only from a financial perspective.

At Trinity College, Dublin, in 1895, John Joly (1 November 1857 – 8 December 1933) took a considerable and consistent step forward in the evolution of colour photography technology: the theoretical foundation still rested on Maxwell's colour separation, but he managed to relieve it of the complexity of three consecutive shots. The brilliant intuition was to compress and miniaturize the three coloured filters on a single glass plate. Very thin coloured lines (aniline dyes mixed with rubber) were drawn and juxtaposed

to the photographic plate. Once the negative, which was in black and white, had been developed, it was superimposed on the coloured screen used for filming (or a similar one), and the colours could be seen through the transparency (Hirsch, 2004).
For the production of glass plates with coloured lines, Joly designed a machine capable of drawing very thin (<0.1mm) juxtaposed and non-overlapping lines.
Joly's additive process was the first to be introduced on the market and remained available for a few years; however, the poor colour fidelity due to the partial colour sensitivity of the emulsions of the time limited its success and diffusion (Coe, Brian, 1978).

5.3 The Autochrome

The Auguste (Besançon, 19 October 1862 – Lyon, 10 April 1954) and Louis (Besançon, 5 October 1864 – Bandol, 6 June 1948) Lumière brothers had been working on colour photography since the last decade of the 19th century. They had published their first article on the subject in 1895, almost at the same time they made their most famous discovery: the Cinematograph.
In 1903 they applied for a patent for their process, the Autochrome, and a year later, they finally made a presentation at the French Academy of Sciences.
Compared to Joly's work, the Lumière brothers realised that combining photographic emulsion and coloured filters into a single body was possible. In so doing, they further simplified the process and materials needed to take photographs, which was designed to be viewed "by hand" or by using a "diascope" (Diascope - RIHS Graphics Collection Survey Project, 2021) or magic lanterns.
The production of Autochrome plates was complex but fascinating. The key ingredient that managed to revolutionise the world of photography after 100 years of applied chemistry was potato starch. Using a very fine sieve, the Lumières selected grains with a diameter of 10-15 microns that were then coloured red, green and blue-violet. They then spread them on a glass plate, the empty spaces filled by sprinkling charcoal powder. The plate was then pressed to thin the grains and improve the passage of light, and finally varnished to protect the starch from moisture. Finally, the photographic emulsion was applied. It is estimated that more than 600,000 grains of starch fit into one square centimeter.
The Autochrome commercial success was immediate, and Alfred Stieglitz (Hoboken, 1 January 1864 – Manhattan, New York, 13 July 1946) was an enthusiastic ambassador for it: "Colour photography is an accomplished fact!

The seemingly everlasting question of whether colour would ever be within the reach of the photographers has been definitely answered. […] The possibilities of the process seem to be limitless […] In short, soon the world will be made with colour, and Lumière will be responsible […]" (Stieglitz, 1907).
Autochrome production continued until 1932, at a rate of around 6,000 units per day when the advent of new technology sparked a new revolution.

6. The subtractive synthesis of colour

Luis Ducos du Hauron can also be considered the forerunner of the subtractive theory of colours. As early as 1860 he proposed using the same filters used in additive synthesis to make three positives dyed with the respective complementary colours: cyan, magenta, and yellow (which subtract - hence the name - the corresponding primary colour). By superimposing these colours, it is possible to reproduce all the other colours (Ducos du Hauron, 1860).
If the additive method requires a large amount of light to display the colour white, the subtractive method needs a simple sheet of paper or very clear glass.
The need to obtain three different exposures was the driving force behind creativity. Many solutions were found, from the simplest one, such as sliding back with three positions with different filtering, to the most complex ones such as single-shot cameras that, thanks to complex games of prisms and mirrors, were able to record three exposures at the same time.

6.1 The rise of Tripack

Frederic Ivers, the inventor of the Krōmskōp, made the first attempt to combine the three plates used in colour separation into a single element. Ivers' "Hiblock" system, presented in 1916, was a sandwich in which a green-sensitive film was inserted between two sheets of glass that reacted to blue and red. After exposure, the sheets were developed separately.
In 1928, Colorsnap made its first appearance in England, promising natural colours with any camera, affordable costs and effortless reproduction of any size. The promises were soon broken to their disappointment, forcing the company to hand-colour the black-and-white prints they could make from the first tripack element. In less than a year, the company was forced to close.
The congenital problem of the tripack, which had not been adequately investigated, lay in the behaviour of the light as it passed through the numerous layers of transparent material. The continuous deviations of the

light rays blur the images of the second and third layers, making a ‘geometric’ correspondence between the layers and any magnification impossible.
The only possible solution was to apply the three emulsions rather than physically separate them. They adhere to each other directly on the support, be it glass or plastic film.
Rudolph Fischer (Berlin, 1881 - Berlin, 1957) patented the using of what would later be called colour couplers in 1912 and 1914 and coined the term chromogenic (Hirsch, 2004). Fischer suggested that these colour couplers necessary for the creation of cyan, magenta and yellow should be embedded in specific layers of tripack so that the coloured images would be obtained after development. Unfortunately, during the development, the colour couplers mixed in the emulsion and compromised the result. However, Fischer’s insight paved the way for the commercial success of tripack.

6.2 The Kodachrome

“[…]Kodachrome
They give us those nice bright colors
They give us the greens of summers
Makes you think all the world’s
a sunny day
I got a Nikon camera
I love to take a photograph
So mama don’t take my Kodachrome away […]” (Simon, 1973)

The Kodak Kodachrome was the first tripack to achieve real technical and commercial success. It was the undisputed queen of colour photography from 1935 to 2009, marking the imagination of entire generations of photographers. It even earned a song by Paul Simon, which is a perfect fit given that two professional musicians, Leopold Mannes (New York, 26 December 1899 – Tisbury, 11 August 1964) and Leopold Godowsky Jr. (Chicago, 27 May 1900 – New York, 18 February 1983), worked on its invention. Their good initial work impressed Kodak’s director of research laboratories Kenneth Mees (Wellingborough, 26 May 1882 – Honolulu, 15 August 1960), so much that he decided to support their research, which eventually resulted into the definitive Kodachrome.
Like Fischer, Mannes and Godowsky struggled with colour couplers leaking into the emulsion during development. However, they managed to circumvent the problem: Kodachrome was a colour positive (or so-called ‘slide’) film produced by a subtractive colour photography process, in which colour pigments were added during the complex stages of developing, dyeing

and bleaching. That was a very complicated 28-station process that forced Kodak to centralize the development of Kodachrome in its Rochester, NY facilities.

6.3 The Agfacolor-Neu

In 1936, Agfa also announced its own tripack: the Agfacolor-Neu, which started from and improved on Rudolph Fischer's insights into colour couplers. Agfa's laboratories figured out how to embed the colour couplers in the individual layers of the emulsion. This made its development process less complex than that of Kodachrome, so that individual photographers could even carry it out in their private darkrooms.
One hundred years had passed since the official birth of photography. With the commercialization of Kodachrome and Agfacolor-Neu, colour photography was finally a concrete reality available to all.

6.4 Colour Photography inspire new languages

The name Kodachrome is also inextricably linked to some great photographers who were the first to explore colour in photography as a new language or, trivially, as a new opportunity to record reality.
The American photographer Eliot Porter (Winnetka, 6 December 1901 – Santa Fe, 2 November 1990) devoted almost his entire career from 1935 to shooting birdlife and landscapes, recording the wonderful colours of nature; in 1941, he won a Guggenheim Fellowship to devote himself entirely to birdlife. Inspired by Ansel Adams (San Francisco, 20 February 1902 – Monterey, 22 April 1984), who called him "the master of the colour of nature" (Porter, 1979), and by the writer Henry David Thoreau (Concord, 12 July 1817 – Concord, 6 May 1862), Porter is considered one of the noble fathers of nature photography.
In the years immediately following World War II, colour photography on film reached a point of no return: emulsions were sufficiently stable and accurate in colour reproduction, films were available for a wide variety of cameras, and a network of developing labs began to thicken. While this progress supported the image professionals, it also helped to create a new category: the occasional photographer who recorded the family parties and holidays.
In 1953, LIFE magazine published a 24-page full-colour report on New York for the first time. In a world of photojournalism, where black and white photography ruled, also for technical reasons, a breakthrough had been made. The author of the report was a young Austrian photographer, Ernst Haas (Vienna, 2 March 1921 – New York, September 12, 1986). Already a member of the exclusive Magnum Agency, as soon as he arrived in the United States,

he began experimenting with the Kodachrome colour, arousing considerable criticism within the agency itself. At the time, colour was reserved for commercial and advertising photography and was not considered to have any journalistic or artistic value.

It was only in 1976 that colour photography became an established means: John Szarkowski (Ashland, 18 December 1925 – Pittsfield, 7 July 2007), the curator of photography at the Museum of Modern Art in New York, decided that William Eggleston's (Memphis, 27 July 1939) colour photography deserved a solo exhibition. It was a rupturing event that gave rise to numerous criticisms and deep rifts in the world of photography and art.

However, by then, the road was marked, and colour photography could shed its vernacular mantle and move towards new horizons: Luigi Ghirri (Scandiano, 5 January 1943 – Roncocenesi, 14 February 1992), Franco Fontana (Modena, 9 December 1933), Stephen Shore (New York, October 8, 1947), Candida Höfer (Eberswalde, 4 February 1944) are just a few of those great photographers who have used colour as an extraordinary tool of artistic expression.

7. Polaroid's instant colour

The story goes that the spark of creativity was ignited by his daughter Jennifer. After posing for a photograph, she insisted with her father that she wanted to see it immediately, which was impossible in 1943. Edwin H. Land (Bridgeport, 7 May 1909 – Cambridge, Massachusetts, 1 March 1991), a physicist of prolific intelligence, worked secretly for three years on how to please his daughter. In 1947 he succeeded in making the first public demonstration of his instant-development film. After pressing the shutter release button, the camera mechanism ejects the film by passing it through two rollers. This compression breaks the containers hidden in the white frame characteristic of the Polaroid. After about 60 seconds, depending on the ambient temperature, the negative could be peeled off so that the image could be appreciated firmly imprinted on the positive.

In 1963 Land released the colour version of his film, the Polacolor, and in 1972 he debuted a new 'integrated' film design, which no longer needed to be 'torn'.

The Polaroid system was a commercial success, loved by amateurs and artists, who often made it their primary tool.

Land died in 1991, ten years before his Polaroid Corporation was declared bankrupt.

Edwin H. Land also had the intuition to invite some of the great photographers of the time to collaborate with Polaroid: free material in

exchange for feedback and a few works as gifts. The specificity of Polaroid fascinated some of them who made it their tool, if not their icon. David Hockney (Bradford, 9 July 1937) started with his collages in the early 1980s when he realised "he had never seen a similar result with photography" (The David Hockney Foundation: 1982, 2021).
It is almost hard to imagine Andy Warhol (Pittsburgh, 6 August 1928 – New York, 22 February 1987) without a Polaroid camera in his hand, as his personal image is so closely linked to the camera that accompanied him for almost twenty years without interruption.

7.1 Demosaicing and Digital Photography

In order to complete the history of colour photography, we cannot fail to mention the birth and definitive advent of digital photography.
Digital photography was born in Kodak's laboratories in 1975 thanks to Steven Sasson's (New York July 4, 1950) work, who was asked by his director what could be done with the new CCD sensors. Sasson then built a camera that could record a 100x100pixel (equivalent to a resolution of 0.01Megapixel) black and white image on a cassette, which needed a television set and 23 seconds to display it. The technology and the idea were right, but the courage was probably lacking, and Kodak decided not to fund the project further, believing that "no one would want to look at their pictures on a screen" (Kodak, 2021). A year later, Steve Jobs (San Francisco, 24 February 1955 – Palo Alto, 5 October 2011) would present the first Apple computer.
A milestone in digital colour photography was the invention and patent filing by Bryce E. Bayer (Portland, 15 August 1929 – Bath, Maine, 13 November 2012) of Kodak of the eponymous filter which simulates the physiological characteristics of human vision, and allows digital sensors to create colour images through demosaicing algorithms (Kodak, 1976). The demosaicing algorithm is a digital process able to build a digital image from the incomplete sampling of colours due to the Bayer filter, it is also known as colour reconstruction or CFA interpolation. Demosaicing is a fundamental part of image elaboration necessary to render these images in a viewable format.
In 1981, the Sony Mavica FD5 was the first digital camera available on the mass market, using a floppy disc to store images of size 570x490 pixels. Sasson created the first digital SLR camera in 1989, but again Kodak's commercial department decided to hold off on the idea: they thought it was more convenient to profit from patent sales than to invest in and ride what was now clear to be the future.
In 1990 thanks to Thomas (Ann Arbor, 14 April 1960) and John (Ann Arbor,

6 October 1962) Knoll the first version of Photoshop were released. Photoshop is a raster graphics editor that is so closely linked to digital photography that it has become a standard.
In 2004 Kodak, and then in 2006 Canon and Nikon announced they no longer produced film camera.
Now, digital has brought colour photography into every pocket through smartphones. Unlike at the beginning of this story, black and white photography has become an option as if, ideally, to complete the circle.

8. Conflict of interest declaration

The authors declare no conflict of interest.

9. Funding source declaration

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10. Short biography of the author

Giovanni Vanoglio is a professional photographer, active in social, music and theatre photography. After graduating in Urban Planning at IUAV from the University of Venice, he has been collaborating with companies and national magazines. He specialises in contemporary landscape, a field of photography he has been developing in ongoing personal projects.

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Chapter 6 Lighting design - color applied

Osvaldo Perrenoud, light designer

Abstract

This chapter discusses the ways to illuminate and apply colors in lighting projects.

Keywords:
Design, Color, Lighting, Stage, Architecture, Perception

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1.Introduction

The creative process and creation.

The creative process can be described and theorized as a chain of decisions that guide the construction of a final product and creation must be understood as the formal result itself.
In the case of Lighting Designers, we can generate specific works empirically or from a clearly established creative process. An empirical creative process is just gestation, like a flowering seed.
Some professionals make their creations without thinking about organizing their way of thinking and developing a new product, but this way it can, at any time, be understood, conceptualized and transformed into a theory about this creative process.
Above all, creating is using the way we see and understand the world within a given context.
I usually work with a lot of freedom, without strings attached, but I make decisions based on a creative process that I developed over the years and that guides me with clear ideas.
LDs often need to share and commit their ideas with others; whether professionals or clients involved in the construction of a work.
It is this expertise and knowledge accumulated throughout my professional life and as a teacher that I want to talk about from now on!

When you find an indication in the center of the page with the word "Internet" it is an invitation for the reader to search for that image. Sometimes there will be a link accompanying it to make your job easier

2.Light Art

Lighting is not just making visible, putting an end to darkness, but creating out of light. In view of this bias, some LDs say they do LIGHT.
We must think of light not as a way of giving visibility to the world, but as part of an interpretive artistic procedure that involves sensation and perception.
These are the main ingredients of Light Art.
From the moment we come into contact with an illuminated environment, we start to have emotions, feelings and to attribute meaning to what we see.
The more direct the message, the greater the chance of reaching its final destination, the observer, with clarity.

Internet
Dan Flavin - Untitled, 1973. Pinakothek der Moderne, Munich, Germany.
James Turrel - Alpha (East) Tunnel. Roden Crater, Flagstaff, United States.
Dan Flavin - Untitled to Bob and Pat Rohm, 1970. Weltraum Gallery, Munich, Germany.
James Turrel - Inner Way, 1999. Munich RE, Munich, Germany.

The ideas of the artworks above are congruent, modifying the space through the inclusion of the observer in a reality that is different from everyday life.
Internet
Dan Flavin - Chiesa Rossa, 1996. Milan, Italy.
James Turrel - Memorial Chappel at Dorotheenstädtischer Cemetery. Berlin, Germany, 2015.
The technology of fluorescent lamps allowed only one color per light source, currently, with LED technology we can have several colors using the same devices.

2.1 Sensation, perception and interpretation

About 15.000.000 years ago. Very hot, very dense and disorganized. No life, no stars, no galaxies, no molecules, no atoms, no atomic nuclei. A soup of elementary particles: electrons, photons and also quarks and neutrinos, the future constituents of atoms.
And then, the Big Bang.
Carbon, Hydrogen and Oxigen… But we get a Sulfur…

Figure 2. CHO and S.

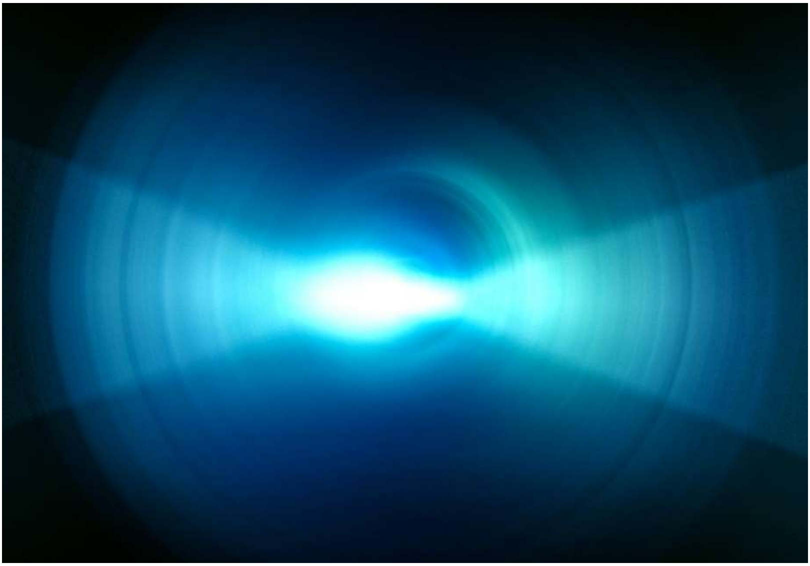
Figure 3. My Big Bang.

After that, our solar system exists.

Sensation is our body and brain's first reaction when we come into contact with something in the world. Imagine human beings from the remote past watching the next scenes. Certainly because they did not have scientific explanations (and there was no science yet, only knowledge through life experience) they attributed these phenomena to primordial gods, naturally, to the gods of nature.

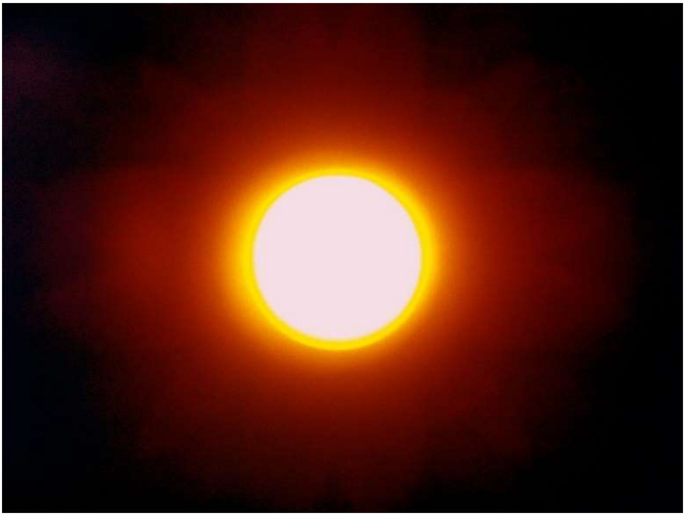

Figure 4. The Sun.

Figure 5. Maranguape, Brasil.

Figure 6. The Moon.

After the sensations, we make connections between what we are experiencing and the repertoire of knowledge from past experiences, consciously or unconsciously fixed in us. We form, then, a concept and a value judgment, the Perception.
A painter goes through this process when observing an everyday scene. When we see a painting, we follow the same path, but usually without the real scene in front of us and this is the magic!
The same can happen when we are faced with the vision of a scenography or a scenic lighting.

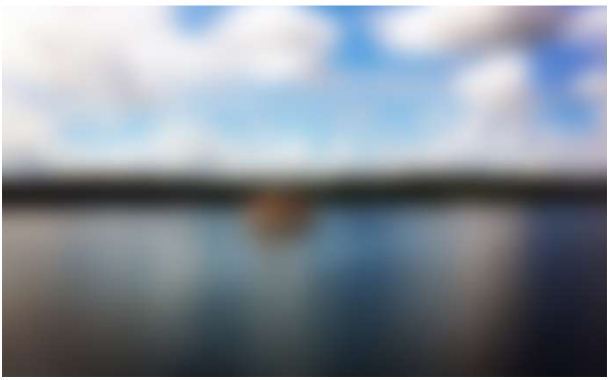

Figure 7. Piranhas, Brasil.

Figure 8. Concert, Canoas, Brasil, 2009.

And the images seemingly confused but that have definite meaning?

Figure 9. Grafitti Wall, Street Art.[3]

The perception will be much more requested to decoup and resignify the image and, for some, it is impossible to be understood.

Interpretation is an accomplished perception but it can also be a new form of expression based on what was previously registered by any form of communication and perceived by one or more senses of the observer.

[3] Image by ShonEjai from Pixabay.

Figure 10. Interpretation of Rembrandt's paint Philosopher in Meditation, 1632.[4]

Light has no smell, sound or taste, but bright environments can encourage the use of these elements. Touch is rarer to be used, but the feeling of heat or the material of some luminaires can sometimes be part of the work itself.

How to make a big bang with light? We have to ask ourselves some questions. At where? When? Who are the observers? How much investment can be made in this work… of money… of time? How long will this be available for observation? Is a Big Bang a short timed effect or do we want to show the whole process? Hmmmmmmmm...

The previous Big Bang was made by me, with light and phone camera.
We can divide the basics of lighting with reference to some aesthetic and technical aspects and appropriate a type or a set of them to conceive lighting in the broad sense of the word, to make LIGHT.

[4] Rembrandt: Study in realtime lighting techniques, work by Alexandros Demetriades.

Figure 11. Technical.[5]

Figure 12. Conceptual.[6]

[5] Exposition Casa Cor, Belo Horizonte, Brasil.

[6] Exposition Storia e Leggenda dei Cavalieri del Tempio, Milan, Italy.

Figure 13. Historical.[7]

Figure 14. Contextual.[8]

Light has many facets and forms of interpretation.
A lighting project must consider many aspects before it is conceived.
We may create from the dark but is more important make sense, and make sense mean permits sensations, the perception belong to observers.

[7] The Painted Hall, King William Walk, Greenwich, London, UK.

[8] Night Club, Boston, USA.

Figure 15. Artistical.[9]

Figure 16. Symbolical.[10]

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[9] U.nico Produções Artísticas - The Great Attraction. Artists: Luciano Albo and Fernando Pezão. Photo: Gerson de Oliveira.

[10] Galleria Vittorio Emanuele II, Milan, Italy.

Figure 17. Material.

Figure 18. Inventive.

Figure 19. Poetical.[11]

[11] Model: Felipe Lopes Perrenoud.

3.Light and color, color and light

Probably light and color are the same thing?
Different perceptions of the same effect?

3.1 Corpuscular, undulatory and quantum theories

17th century.
Newton - corpuscular theory. All matter is made up of tiny particles called corpuscles.
Huygens - undulatory theory. Light is transmitted as waves.

Early 18th century.
Thomas Young - light IS a wave.

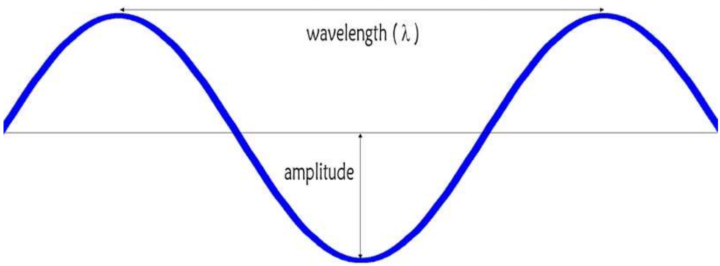


Figure 20. Wavelength.

Wavelength - distance between two successive peaks.
Amplitude - difference in level between a peak and a valley.
Frequency - a single occurrence per second in Hertz (Hz = 1 / sec).
Speed - movement referred to a timeline.

19th and early 20th century.
Kirchoff, Rayleigh, Wien, Planck and Eisntein.
Light just as an electromagnetic wave does not explain some phenomena that are understood if light also has a corpuscular characteristic.
Planck sought to discover the reason why an object's radiation changes color from red to orange and, finally, to blue as its temperature increases.

20th century.
Heisenberg and Schrödinger - quantum theory. Light is emitted in packets instead of a steady stream, the packet of light is the quantum.

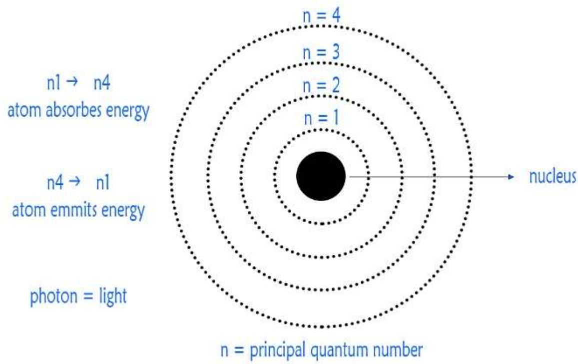


Figure 21. Quantum Theory.

This theory becomes practical with its various uses and studies in the present and we hope that some will always be in the past.
Subatomic particles - studies about the evolution of the Universe.
Atom and molecules - materials and technology.
Quantum optics - communications, lasers, quantum computing, quantum cryptography.
Nuclear physics - bombs, medical uses, power.

Physics: light is an energy. 300.000 kilometres per second. Radiated in a straight direction. Straight Direction? Certain kinds of laser beam can follow curved trajectories in free space.
It is to think small that only we human beings know what the world is like, we do not know it completely or what is on Earth and we continue to learn, when we do not stop in time accepting previous studies as absolute truths. Thus walks humanity. One day medical scalpels will only exist in museums.
Studies done by the American Physical Society show numerical simulations and experimental demonstrations for the side view propagation of a non-paraxial Weber acceleration beam and a paraxial Airy beam along parabolic trajectories. This means that light bends even in the air, because in the water we already knew. Or not?

Figure 22. Remember?

3.2 Incident light on object: reflection, absorption and transmission/refraction

It is the effect generated by the action of light on material substances and captured by an optical system; in the case of man, captured through our eyes and perceived by our brain.
Each lens or set of lenses captures light and color differently.

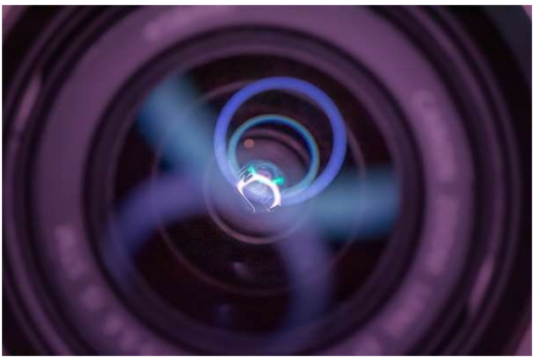


Figure 23. Artificial eye.[12]

[12] Photo: Camila Perrenoud.

Drone cameras, 35mm film, rangefinder, SLR/DSRL, medium format, compact, mirrorless, action, Polaroid, video, phone and 360 degree.

Photo means light in greek…

The photographer must master and know the possibilities of each camera and, in particular, the appropriate lenses for each situation because they capture the light and the professional can define the result through appropriate adjustments.
Just as our eyes have limits, so do lenses.

When we talk about animals, there is a much greater diversity of ways to see the world around us.
Some see better, some worse, but surely all eyes are suited to the specific needs of each being.

Figure 24. Animals.[13]

[13] Model: Photo: Camila Perrenoud.

Figure 25. Our apparatus.[14]

Necessary elements for the perception of colors by human being: the stimulus effected by the light and reception of light through our vision.
Each substratum or object has characteristics that are linked to its power to reflect, transmit or absorb portions of light and, depending on these characteristics our senses are stimulated and we see colors.

Figure 26. Incident light.

[14] Model: Débora Sales. Photo: Camila Perrenoud.

The absorbed part is transformed into another type of energy, usually heat. Dark objects tend to be hotter than bright objects when subjected to sunlight or even an artificial light that emits heat.
Reflection and refraction can occur specularly and / or in a diffuse way and this depends not only on the object, but also on the qualities of the light. Elements, molecules and even cellular structures have unique reflectance signatures. A graph of the reflectance of an object in a spectrum is called a Spectral Signature, this is very important in star studies, for example:

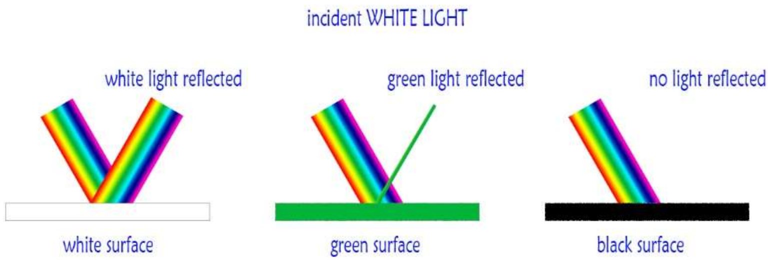


Figure 27. Reflexion and absorption.

What mean white light? What mean no light reflected?
Does this happen in reality?
The answer is no, some portion of the light is reflected, sometimes a lot of light is reflected by everything that looks black and we end up seeing a brownish fabric for example.
Some experiments and research are being done in order to obtain a perfect black, not reflective at all.

The Vantablack developed by Surrey NanoSystems using carbon nanotubes reaches 99.965% of absorption of incident light rays.
Engineers at MIT (Massachusetts Institute of Technology) developed Blackest Black with the vertical alignment technique of carbon nanotubes and managed to achieve 99.995% of absorption.
The Redemption of Vanity: that artwork was conceived by Diemut Strebe in collaboration with Brian Wardle, covering a real diamond estimated to be worth $2 million with blackest black.

Internet
Vantablack.
MIT - The Redemption of Vanity.

About refraction:

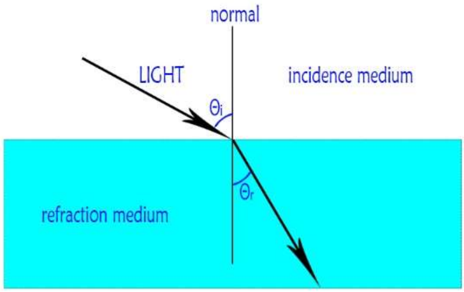


Figure 28. Law of Refraction, Snell-Descarte's Law.

n_i - index of refraction of incidence medium
n_r - index of refraction of refraction medium
Θ_i - angle of incidence of light
Θ_r - refraction angle of light

$$n_i * \sin\theta_i = n_r * \sin\theta_r$$

Figure 29. White-backed stilt at Capão da Canoa, Brasil.[15]

The fish is always at a different point from the one the bird sees, this calculation is done automatically by daily experience, applied optics!

[15] Photo: Sérgio Ordobás.

4. Perceived light

Electromagnetic radiation can be considered as a stream of massless particles, called photons, which each have a certain amount of energy, moving in a wave pattern at the speed of light.

Electromagnetic spectrum is the range of all types of EM radiation. The amount of energy contained in the photons defines each type of radiation. The waves have variable energy as can be seen in the figure below.

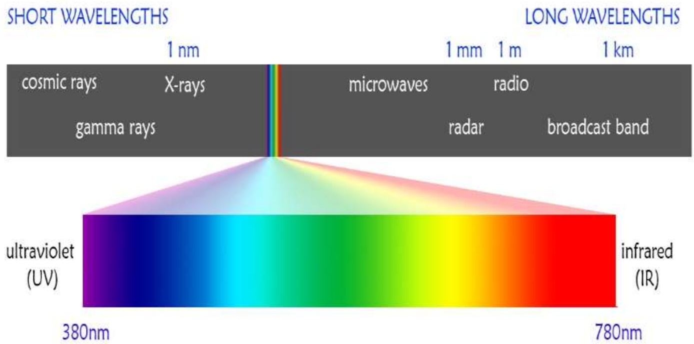


Figure 30. Electromagnetic Spectrum.

If we consider the electromagnetic radiation that reaches Earth from the Sun, light is the part that allows us to see things in the world.

Otherwise, when we call all this energy light, then the portion that the human being can see will be called visible light.

There is a misunderstanding here because "visible light" only exists when it reaches our eyes directly and we see the color of the light source or when there is a substratum that allows this visibility.

Light is radiation that allows us to see!

For this reason I prefer the first option, electromagnetic radiation is all the energy emanating from the sun that reaches us and the portion between 380nm and 780nm is called light. If we use the frequency to measure each portion of the light, we have the range between 430THz (terahertz) and 750THz, this makes it easier to understand the terms Infrared and Ultraviolet.

A radiation composed of a single wave of fixed amplitude and frequency is called monochromatic; the spectrum is composed of several monochromatic radiations with their relative frequencies.

COLOR	λ(nm)	ν(THz)
Infrared	>1000	<300
Red	~ 700–635	~ 430–480
Orange	~ 635–590	~ 480–510
Yellow	~ 590–560	~ 510–540
Green	~ 560–520	~ 540–580
Cyan	~ 520–490	~ 580–610
Blue	~ 490–450	~ 610–670
Violet (visible)	~ 450–400	~ 670–750
Near ultraviolet	300	1000
Far ultraviolet	<200	>1500

Figure 31. Colors - amplitude and frequencies.

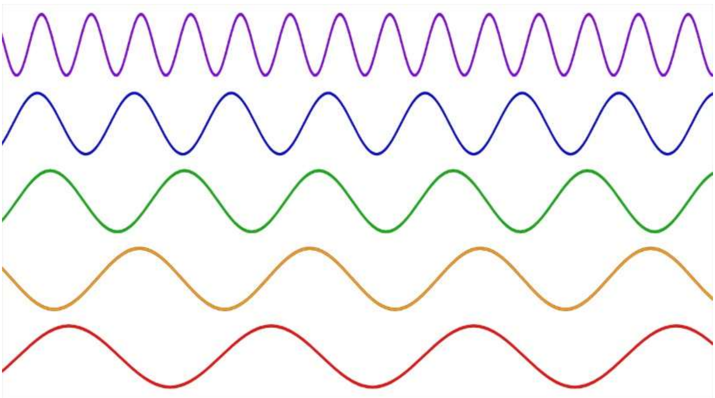


Figure 32. Colors - short and long wavelengths.

4.1 The visual process of human eye

Visible radiations (color stimuli) are directed by the eye to the reticular membrane that transforms them into physiological excitation.

The reticular message receptors send this excitation, through nerve fibers, to the optic nerve and through it to the brain.

This excitement becomes a sensation in the sulcus calcarine that is connected with the cerebral cortex and then into conscious vision (perception).

For the formation of the image two systems come into action:

the optical system and the neurological system.
Optical system: eyeballs, consisting of 3 concentric membranes (sclera, choroid and retina) and a set of dioptric means.
Neurological system: nerves and brain.

4.2 Cones and rods

The traditional explanation is that cones and rods define our initial ability to see; through our eyes, colors and light levels as well as differences in movement.

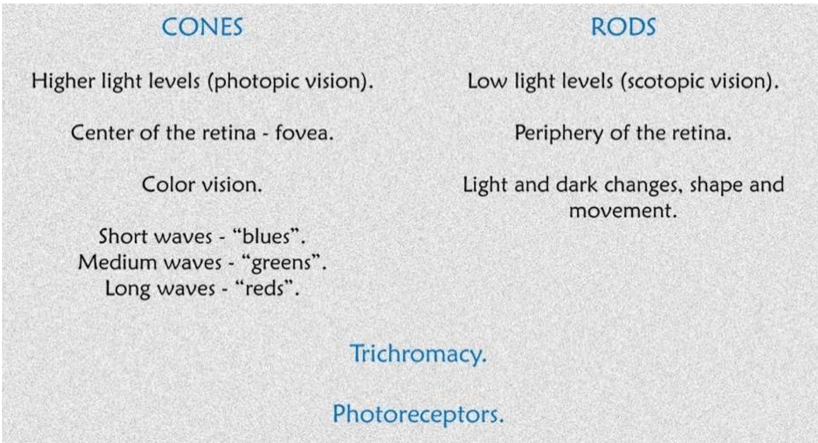


Figure 33. Cones and rods.

The fovea is the point where the greatest number of cones are concentrated and there is a very defined blind spot.

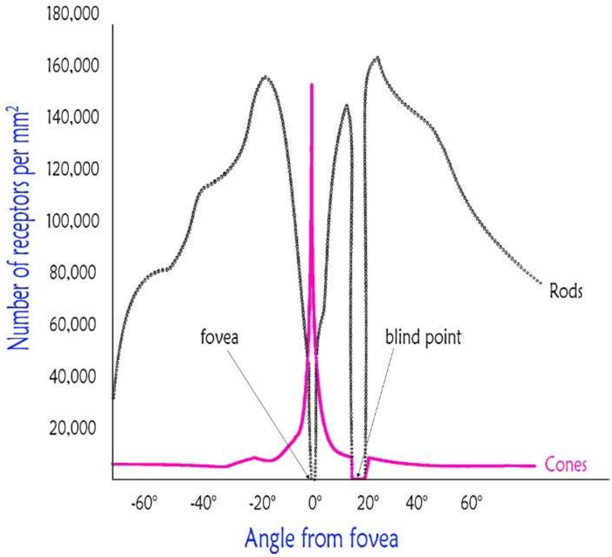


Figure 34. Receptors.

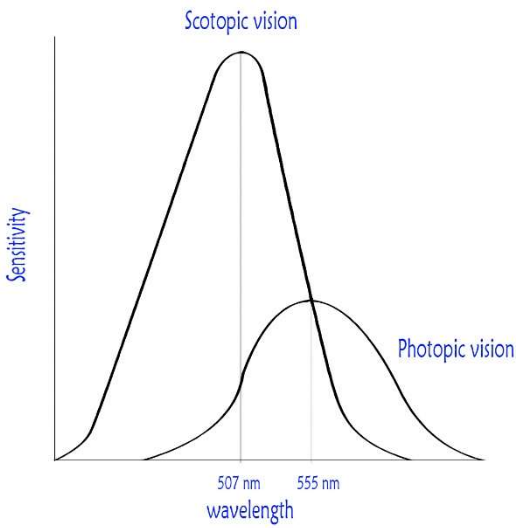


Figure 35. Photopic and scotopic vision.

4.3 Trichromacy

Traditionally, we've accepted the idea that humans are trichromats because we have three types of rods, each working more in a certain region of the spectrum, with greater sensitivity to certain wavelengths.

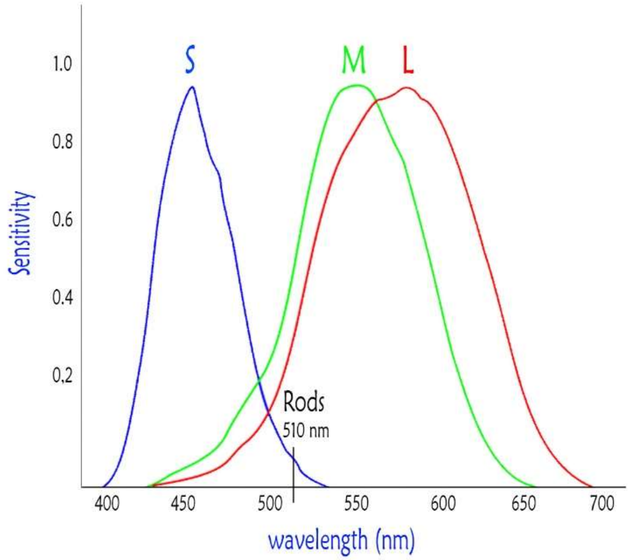


Figure 36. Eye sensitivity.

Today, the Opponent's Color Theory states that the visual system interprets colors in an antagonistic way: Red x Green, Blue x Yellow, Black x White. But note that this does not make the colors green and red complementary. The issue of complementarity concerns the mixture of colored lights that our eyes receive directly (in the case of monitors, for example) or through the reflection coming from a substratum.

4.4 4th cone?

The cones responsible for the vision of reds and greens are encoded by genes located on the X chromosome.

The cones that see most in the blue area are encoded by a gene on chromosome 7 and are rarely subject to genetic errors.

Women, having two X chromosomes, can carry the normal red and green genes on one of their X chromosomes and an anomalous gene on the other.
Due to this genetic pattern it allows it to express four types of cones.
Do not believe in simple tests done on the internet, the analysis is much more complex than you might believe.
A serious study in this regard is being done by the Tetrachromacy Project at Newcastle University, UK.

4.5 CIE observer

We perceive color and appearance subjectively and differently, which is why the CIE (Commission Internationale de l'Eclaraige) standardizes the human observer as a numerical representation of what the average person sees by establishing two basic viewing angles we may see in the next table.

view angle	distance	diameter observed
2º	50cm	1,7cm
10º	50cm	8,8cm

Table 1- CIE observer.

4.6 Tristimulus

Through calculations that consider the spectral distribution of the illuminant, the spectral reflectance of the object and the color matching functions of the observer (2º) we obtain the values of Tristimulus.(X/Y/Z).

4.7 CIE 1931 chromaticity diagram

Using the values X, Y and Z for the Tristimulus two values are reached and we can distribute them in a diagram.

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

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

The main characteristics that we can found when looking at the chart and graph bellow (the CIE 1931 Chromaticity Diagram) are: linearity, purity, dominant wavelength, complementary wavelength and, as a result, complementary colors.
We consider (x,y,z) = (0.33,0.33,0.33) as a white point, the flat spectrum.
At the edge purity is 100% and and decreases towards the white point.

We obtain the dominant wavelength of a color (x,y,z), by extending a line from the white point through (x,y,z) until we reach the edge of the curve.
Drawing a line connecting two points on the edge passing through the white point indicates complementary wavelengths and can give that white.
Mixing two wavelengths in different amounts (light again not subtractive mixture) can produce all the colors on the line joining the two points (x_1,y_1,z_1) and (x_2,y_2,z_2) on the graph.

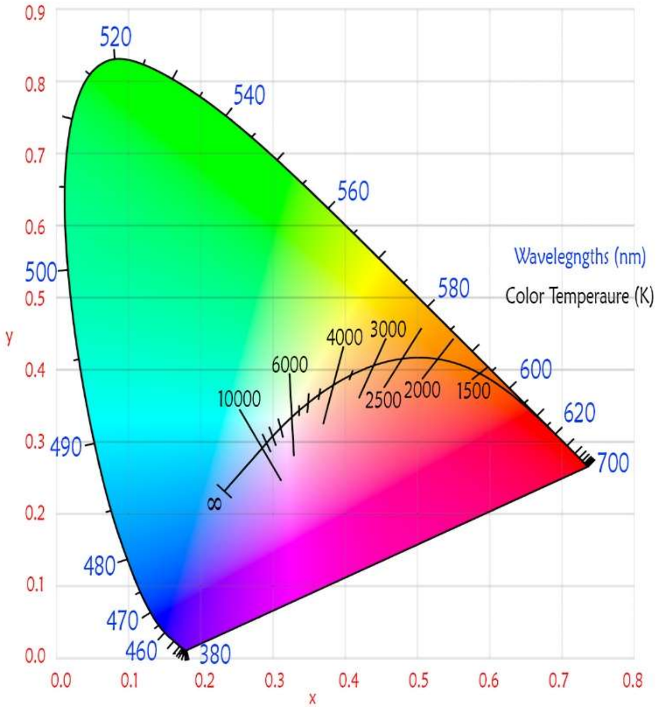


Figure 37. CIE 1931 Chromaticity Diagram.

5. Perceived color

Imagine the qualitative leap from black and white films, “noir”, to Edward Raymond Turner's color film in 1902!
How many different colors are there?
What means different?

If we consider one-nanometer intervals in the spectrum, we would only have 401 pure tones (from 380nm to 780nm), but is it even possible to see more colors than that?
Why is magenta not present in the visible spectrum, but in the CIE 1931 chromaticity diagram? This hue is a perception made by our brain, it is a non-spectral color.
But after all, how many different colors are there around us, which are visible and which are invisible to us?
Does anyone with 4 cones or animals see more colors than we normally see?
How do pigeons distinguish crumbs from stones? This little crustacean Peacock Mantis Shrimp *(Odontodactylus Scyllarus)* has 12 distinct types of photoreceptors, does it really see more colors than we do, more nuances? Does it see outside what we call the visible range of electromagnetic waves?
If we consider the possibility that R, G and B are between 0 and 255 (to suit the computational world), we can have 16,777,216 colors; one of which is total black, darkness, no light.

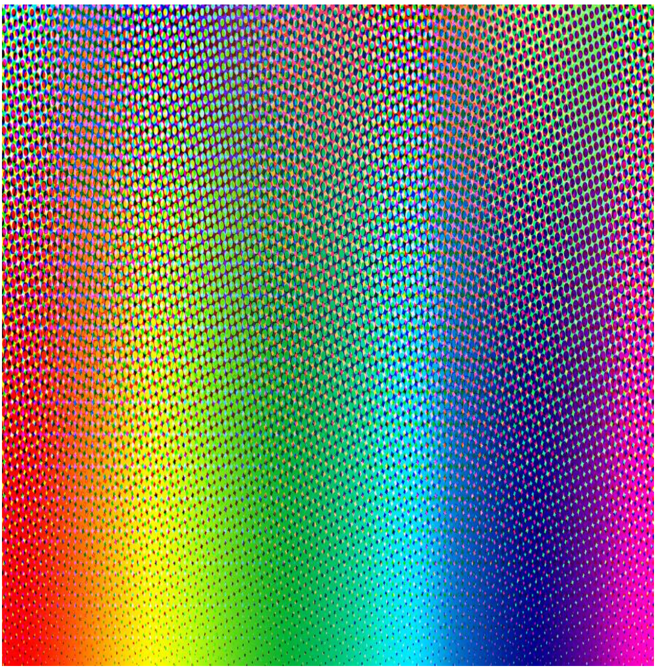


Figure 38. Colors.

5.1 Daltonism

John Dalton first describes dyschromatopsia in 1794.
Anomaly trichromacy - the person has all the cones but some of them have mutations: Protanomaly (L-cone), Deuteranomaly (M-cone) or Tritanomaly (S-cone).
Dichromacy - absence of a type of cone: Protanopia (L-cone), Deuteranopia (M-cone) or Tritanopia (S-cone).
Rod Monochromacy (achromatopsia) - cone photoreceptor disorder.
Cone Monochromacy - Atypical (there is only one type of cone) or Typical (inability to see colors).

The Shinobu Ishihara test for adults was created for the forces of Japan during the First World War, based on Jakob Stilling's (1877) pseudo-isochromatic images composed of similar dots and brightness, but different hues arranged to form visible numbers for test subjects. with normal vision and uses 38 dishes divided into 4 types:
Transformation: colorblinds perceive symbols different from those who do not have anomalies.
Disappearing drawing: only people with color blindness can notice the differences.
Hidden digits: only colorblind people see these symbols.
Classification: the board has two sides to detect red or green blindness.

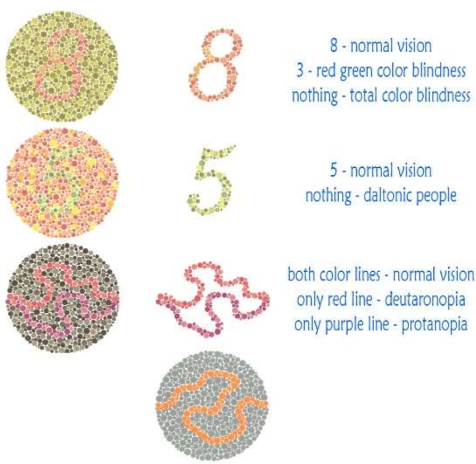


Figure 39. Some Ishihara plates for detect Daltonism.

With a little thought I came to the conclusion that a very simple test can be done for an initial detection.
Please note, I am neither a doctor nor an ophthalmologist, but I understand a little about the mystery of colors.

On the next page, look at the circle on the left, the one a little bigger, and compare it to the circles on the right. If the circle on the left looks **a lot** like one of the circles on the right, you should see an ophthalmologist.

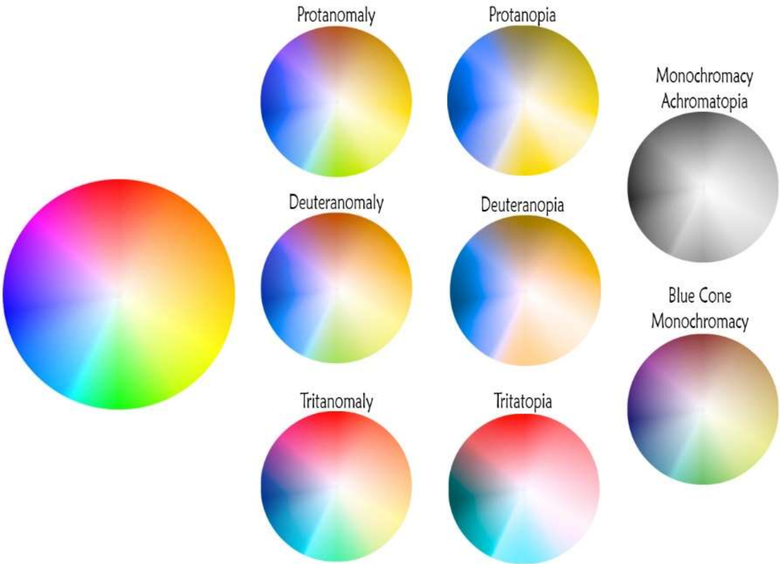


Figure 40. Practical verification.

5.2 Light, observer and material substances

What influences the perception of color?
If we think about the spectral qualities of the light, we must consider the lighting conditions, the color of the chosen light, as well as taking into account the surrounding lights, colored or not.
When we talk about the observer's visual mechanism, it is influenced by the distance and angle of vision, as well as the conditions and characteristics of that vision. Are the observer and the illuminated object still or are any of them moving? Does something hinder or confuse your vision?

Look at the next image.
As mentioned earlier, we need a substrate for light to be visible and for us to perceive colors. What color is a supposed artificial light that enters through the window, from the outside, at 30º? We don't see her in the photo, but we know she doesn't touch anything and leaves the room directly through a hole in the floor. No, it's not sunlight, it's artificial.

Figure 41. Color and light perception.

Well, without substrate, something solid, even in very fine particles, there is no perception of color. There is no vision of light. There is no perception of light. But we can perceive light without substrate is if it comes directly to our eyes because we will see the light source and its color. Screens and monitors are the best example.
The characteristics of material substances; its size, material, shape, textures and inherent color also influence our perception.
But what about that blue sky and white clouds we see behind the window?
Sunlight, which we assume to be white, is actually invisible as we've seen before; but as it passes through our atmosphere, it causes the electrons and protons inside the molecules to oscillate, producing electromagnetic radiation at the same frequency as the incident rays and being redirected in various directions, which we call scattering. Due to their shorter wavelength and higher frequencies, "blues" cause the oscillation of charged particles to be greater, producing greater scattering. At sunset, we see more wavelengths closer to red because the dispersion is smaller due to the greater distance from

the sun. In space outside our atmosphere, light is black and our planet appears blue.
Clouds are composed of water droplets much larger than air particles and the difference in dispersion is much greater; internally the light is refracted, reflected and diffracted. Clouds are not white, look at them...they are shades of white and they have subtle colors, mainly yellow and blue, which provide the vision of white. Great Van Gogh!!!

5.3 Contrast

Contrast is the difference in luminance and / or color that makes an object distinguishable.
Visual acuity is the ability to distinguish details depending on the object: dimensions, shape and texture. The speed at which they move, the quantity and quality of incident light and the contrast in relation to the background also has an influence.
Michelson - measure of luminance contrast (C)

$$C = \frac{Lmax - Lmin}{Lmax + Lmin}$$

Luminance is measured in cd / area. L_{max} is the luminance of the lighter area and L_{min} is the luminance of the darker area.

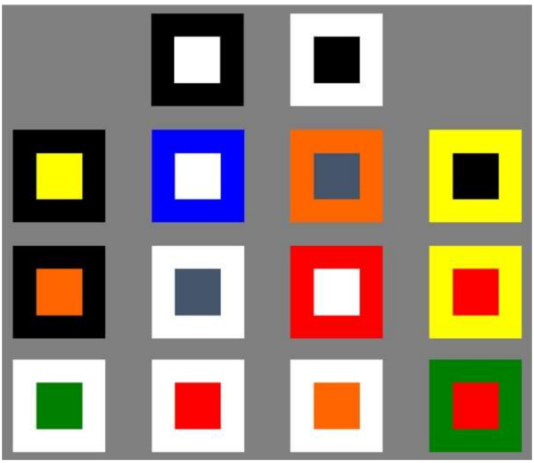


Figure 42. Color contrasts.

From left to right and top to bottom the color pairs are ordered from highest to lowest contrast.

Sometimes I ask myself: if making white paper is expensive and maybe pollutes our environment and white ink without added dyes is cheaper, why not make notebooks with dark recycled sheets, almost black, and pens with white ink?

Figure 43. Contrasts in lighting.[16]

The different levels of lighting allow contrasts and varied views of the same environment. In this specific case the store has two sales calls depending on the ambient lighting, in the image above the high contrast takes us to a fashion store and the similar luminances below are more characteristic of a commercial store.

Note that in the first image we have focal points that direct our gaze, create our interest, the lighting in the image below is more general, almost a "bath of light", wash light.

[16] Image by LEDiL - LED Optics for Light that is Right.

It is also worth noting the color of the ceiling, walls and floor that help in the beautiful final effect. If you want use the term dramatic for describe the first image, feel free, but better say more contrasted.

You would ask me:
- But after all, what is the correct light?
Both I would answer, each has its specific goal.
Return to the images and look at the mannequin's shoes.

5.4 Simultaneous contrast

Simultaneous contrast is the way in which two or more colors are affected when they are present in the same context.

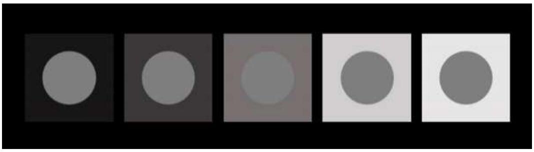


Figure 44. Simultaneous contrast.

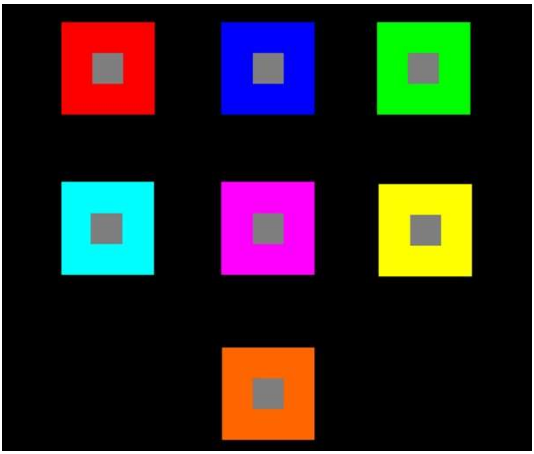


Figure 45. Simultaneous contrast.

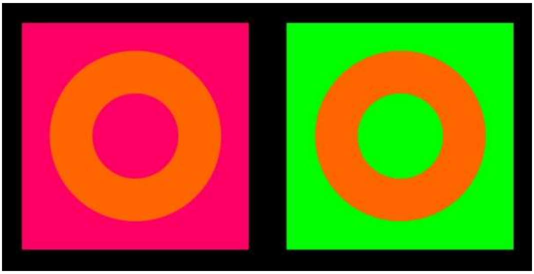


Figure 46. Simultaneous contrast.

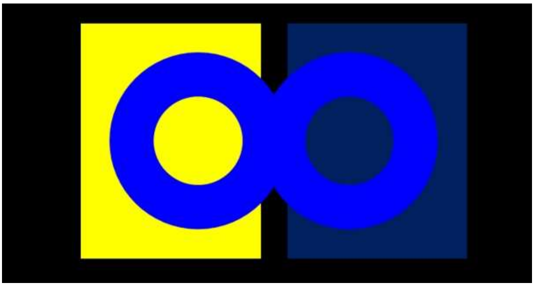


Figure 47. Simultaneous contrast.

Colors are not absolute, colors change according to the environment and according to incident lighting, the perception of colors depends on the context in which they are inserted.
The wavelengths of nearby colors are interrelated, causing the color assimilation effect (or propagation effect) to occur, one color influences the appearance of another color and vice versa.
The size of the areas in question is extremely important in the perception of this interactivity and interdependence.

Figure 48. Digital pointillism - Atlântida, Brasil.

The pointillism technique and printing in the graphic industry are based on this principle and knowledge.

6. Natural and artificial light

Normally, when we refer to natural light, we are talking about sunlight, although starlight and moonlight are also natural light sources.
Lightning is natural in the same way; we can't master it yet, but let's go. Light from fireflies, for example? It's natural.
Artificial means what is produced not by nature but by a technique.
But what if we reflect sunlight through a corrugated metal surface, creating an effect inside a home? Is this light natural or artificial? It is produced.

A carrot generated without contaminants is called organic, but again I ask, should a carrot produced with the aid of fertilizers and using pesticides be called inorganic?

The full moon said to the firefly: - Look at the light that I emanate, white and I can illuminate the sea and the land, and you already have this little green and weak light that, by the way, keeps blinking...
The firefly replied: - Yes, you are right, but this light is mine.

Okay, let's get back to the lighting.

6.1 History of produced light

From prehistory: bonfires, torches, candles, oil lamps, chandeliers, bulbs, luminaires, lanterns, etc.
But in Greek theatre there were ways to reflect sunlight or full moon light to create different effects and moods on the stage.
From 1800 to 1900: gas lighting in England, UK; carbon arc lamp used on street lighting in Paris, France; Thomas Edison and Joseph Swan patented incandescent carbon wire lamps (1879) and in a few years reaching massive use; Nikola Tesla demonstrated the first wireless lighting; Walter Nernst developed the first incandescent lamp based on solid state electrolytes.
From 1900 to 1950: Mercury vapor lighting; metal halide sources; sodium vapor followed; fluorescent; incandescent lamp with new gases and filament advances.
While this the academy and the scholars began to organize themselves creating the Illuminating Engineering Society (IES) in 1906 and the Commission Internationale de Eclairage (CIE) in 1921.
In 1927 Oleg Losev created a green LED in Russia proposed the first theory that is still valid today about how LEDs worked and used them to generate electroluminescence.
From 1950 to 2000: halogen lamp; laser; Nick Holonyak Jr. invented an LED that emitted visible red; high pressure sodium; yellow and violet LEDs were invented; compact fluorescent; OLED was created in 1987; sulfur and induction lamps; bright blue LED and white LED.
At this point we started solid-state lighting era.
Improvements continued in miniaturization, effectiveness, longevity and, finally, color.
There is also something important that is what differentiates the Sun from the LED, it has explosions which means that the light that reaches us does not have a fixed and constant emission. The "dead light" impression that we have with the LED, with a light source that only illuminates, is exactly why. We would need small explosions to change our sensations.
The improvements continued in effectiveness, longevity and, finally, color, but have declined in recent times.
I can say here that there is still much to be discovered and invented not only about LEDs, because we humans are in the habit of thinking that what we do is as evolved as possible. Perhaps in the moment we live this is true, but one day scalpels will only exist in museums.

Internet
Keraunoskopeion (Ioúlios Polydeúkēs).
Sebastiano Serlio.
Leone di Somi.
Nicola Sabbatini.
The Globe.
Blackfriars Playhouse
Giuseppe Furtenbach.
William Murdoch.
Philipe Le Bon.
David Garrich.
Chestnut Street Theatre.
Henry Drummond.
Adolphe Appia.
Edward Gordon Craig.
Jean Rosenthal.
Richard Pilbrow.

6.2 SPD

SPD (Spectral Power Distribution) describes graphically the power per unit area per unit wavelength of an illumination.

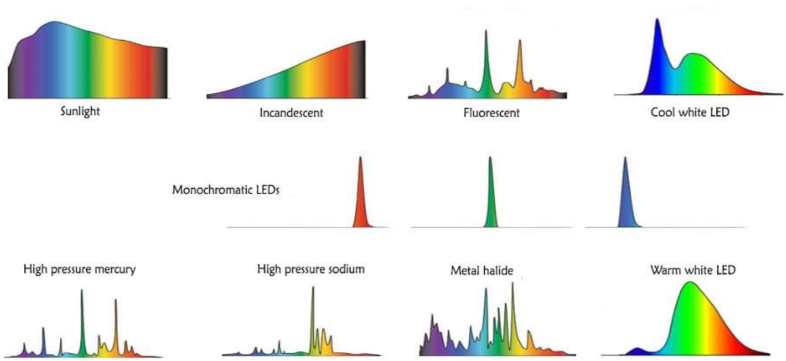


Figure 49. Several typical SPDs.

Does sunlight have a single, immutable SPD?
The answer again is: no, it varies with the seasons, according to the location of the globe, the conditions of the sky and, mainly, it varies throughout the day.
Anyway, taking into account the differences is a good start!

6.3 SPD x tristimulus

Spectral distribution refers to physical reality while the tristimulus values are related to our mind.
Between these two ways of literally seeing light, some differences can be observed and often these differences are maximized or diminished in our eyes, we should be asked for a more careful observation, when this is possible. Some observable effects are described below.

6.4 Metamerism

The metamerism describes a pair of objects that match under a certain light source or set of viewing conditions, but not under another.

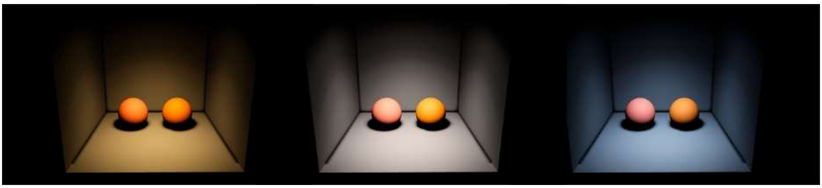


Figure 50. Metamerism.

6.5 Visual constancy

Visual constancy is the ability to recognize objects even as their size, shape, color or orientation change.

6.6 Color constancy

Color constancy is the ability to perceive colors of objects, invariant to the color of the incident light.

Figure 51. Color constancy.

6.6 Color consistency

Color consistency is of utmost importance so that there is no difference between the color or the white emitted by light sources of the same type used in a project.
It is also essential that this color remains as constant as possible throughout the life of the lamp or LED.

7. Correlated color temperature

7.1 CCT

Color emitted by a black body correlated with its temperature.
A black body is a theoretic object that absorbs radiation in all frequencies.
If we consider an iron bar being heated, at each temperature in degrees Kelvin, we will perceive a different color that corresponds to a specific color temperature.
Color appearance of the light emitted by a light source.
The reddish light resembles fire and seems hot to us. The “warm” light gives us a sensation of cosiness; on the opposite side is the bluish light that resembles a cold glacier. The “cool” light demands more attention.

Figure 52. CCT - psychology.

The CCT starts to be described numerically from 1000K (red) passing through what we can call neutral white, going up to approximately 10000K (blue) and from there tending to infinity.

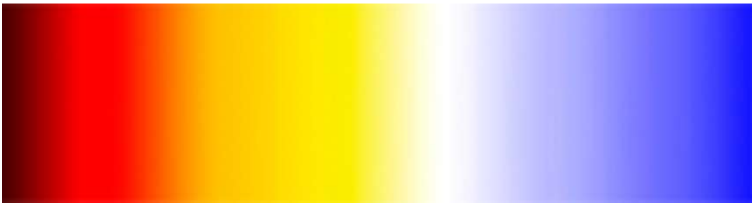


Figure 53. CCT - range.

Calculation of a CCT for LEDs from the (x, y) coordinates in the CIE 1931 chromaticity diagram using the McCamy formula:
Determine the parameter n with the values of the x and y coordinates.

$$n = \frac{x - 0.3320}{0.1858 - y}$$

Insert the n value into McCamy's formula:

$$CCT = 449 * n^3 + 3525 * n^2 + 6823{,}3 * n + 5520{,}33$$

According to this formula, the white point that is defined in the chromaticity diagram as x = 0.3127 and y = 0.3290 corresponds to the CCT of 6508K.

We can have the same CCT but different apparent colors, take a look at 5000K in the next figure.

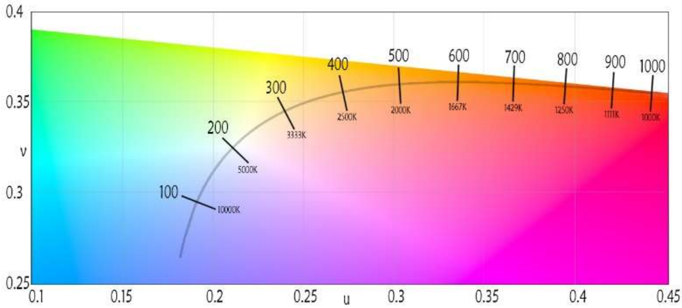


Figure 54. Planck Locus at CIE 1960 (u,v) Chromaticity Space - Mired and CCT.

Then we'll understand what Mired means and what is its use in lighting, but here's the tip: the color temperature of a light source and its relationship with heat and cold sensations are inverted, correct?
The idea is to fix this.
What was the temperature in degrees Kelvin at the sites when the next four photos were taken?

Figure 55. Rio Grande do Sul, Brasil, under the sky.[17]

[17] Photo: Simone Lopes

Figure 56. Angera from Arona, Italy.

Figure 57. Genova, Italy.

Figure 58. Mechanical workshop - São Paulo, Brasil.

What was the temperature in degrees Kelvin at the sites?
We can't say, we don't know at all.
It is worth remembering that the CCT is a reference to the perception we have or want the observer (human, artificial or animal system to capture the illumination reflected by objects) to have and not the absolute temperature of the place or the source light, if that were the In this case, we would be burned when touching a fluorescent lamp with CCT 5000K.

Figure 59. Colosseo, Roma, Italy.

The mixture of CCTs can sometimes be desired and interesting precisely because it creates contrasts.

The neutral white considered for lighting is around 4000K, but our eye tends to use ambient light and "calibrate" it to neutral white with the exception of extreme “hot” or “cold” CCTs, where we perceive the lighting more reddish or more bluish.

Figure 60. Neutral white.

7.2 Mired Shift

The fact that a higher CCT corresponds to a “cold light” and a lower CCT to a “hot light” causes some confusion…

Irwin G. Priest observed that the difference in the perception of color temperature between two illuminants is based on the difference in the reciprocal of their temperatures, not in the temperatures themselves.

MIRED is an acronym for Micro Reciprocal Degrees, it is a unit of measurement used to describe the Color Temperature for a light source.

The Mired Shift refers to the result of the calculation that indicates, through information from the filter manufacturers, which one to use to change or correct the color temperature of a light source from the original to a desired CCT.

$$M = \frac{1{,}000{,}000}{CCT}$$

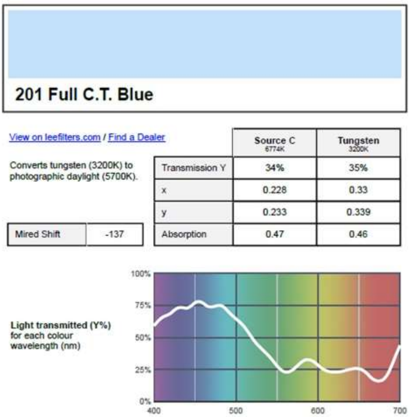
M is the mired value for a CCT in Kelvins.

$$MS = Mc - Mo$$

MS is the Mired Shift.
Mc is the Mired to the converted source.
Mo is the Mired of the original source

For example if 3200K is the original CCT and we need to convert to 5700K.
Mc for 5700K = 1,000,000/5700 = 175,4
Mo for 3200K = 1,000,000/3200 = 312,5
MS = *Mc* - *Mo* = 175,4 - 312,5 = -137,1
Then we need a filter with mired shift of -137,1.

In this example, it is evident that we must "blue up" the appearance of the light source. The most blue or green filters have negative Mired values, while those with positive values are in shades of yellow, amber or red.
The filters by default are usually indicated as CTB (correction to blue), CTS (correction to straw) and CTO (correction to orange).



	Source C 6774K	Tungsten 3200K
Transmission Y	34%	35%
x	0.228	0.33
y	0.233	0.339
Absorption	0.47	0.46

Figure 61. Full C.T. Blue.[18]

We can also use a Minus Green filter to correct fluorescents that normally have enough green in their composition or Plus Green if other light sources are being used and we want to balance them with fluorescent ones.

[18] Image by Lee Filters - Panavision.

We can selectively correct some areas of the spectrum.

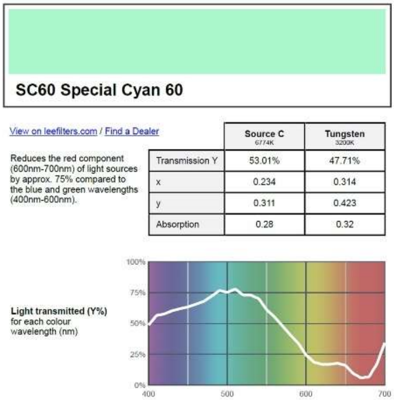


Figure 62. Special Cyan 60.[19]

8. Color rendering

How do you know if the colors the reader saw in the images in this book correspond to reality? And what would this reality be? Which light source are we comparing the observed colors to?
We hope that sunlight is the best reference, as it rules us.
As a result, quantitative metrics of a light source's ability to faithfully reveal color against a reference were created.

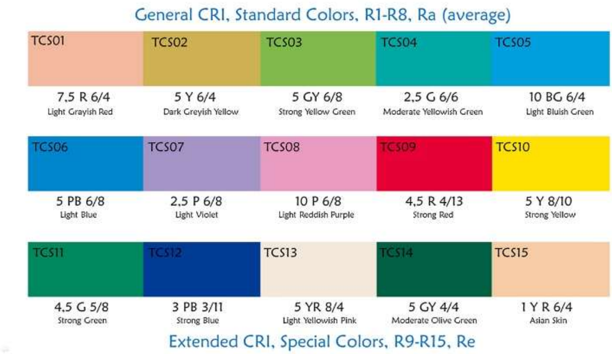


Figure 63. CRI.

[19] Image by Lee Filters - Panavision.

8.1 CRI

The color rendering index is a number that represents; on a scale of 0 to 100, how much the luminous flux emitted by a light source allows the perfect reproduction and visualization of the colors of the illuminated objects in relation to a standard illuminant.
Remember, it's not a percentage, 80%... it's a number: 80 for example.

It is based on experimentation with some samples of test colors and is represented by *Ri*, where *R* is the rendering score and *i* is the number of the TCS index.

.

The evaluation method consists of determining the CCT of the light source to be tested using a standard illuminant with the same CCT for reference, checking the chromaticity of the color samples (Ra or Re) under the test light and under the reference illuminant and then finally determining the mean difference in chromacity for the two sets, establishing the Ri.

Theoretically, if from R1 to R8 and from R10 to R15 a light source had a rating of 100 and for R9 equal to zero, what would be the Re? This data can deceive us: Re 92.9! Nice!!! But zero at R9, the red sample. This becomes worrying when it comes to LEDs.

A problem that is still very recurrent in 2021 is that some CRI declared by manufacturers have different measures, generally worse when really measured.

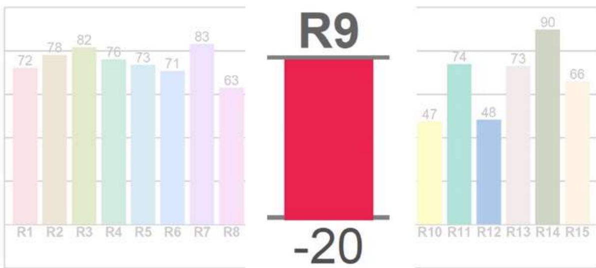


Figure 64. Very low evaluation on R9.[20]

[20] Stella | Lighting, Brasil. Reports from Stella´s Laboratory.

Figure 65. Effect caused by a lamp with low CRI on R9.

We can use the white tone of the lighting to our advantage, objects that have a warm color (bread, meat, gold, etc.) should be lit with low CCT; conversely, objects with cool colors (lettuce, silver, aluminum, etc.) will look much more attractive when illuminated with high CCT.

Anyway the higher the CRI the better.

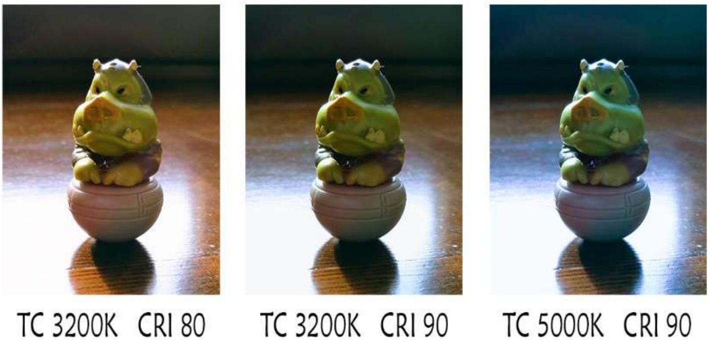


Figure 66. Lamps with different CCT and CRI.

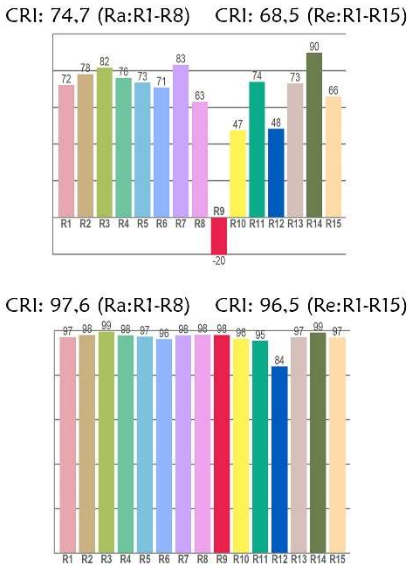


Figure 67. Comparison of CRI between LEDs of different qualities.[21]

Some problems were noticed when analyzing LED sources using the CRI method.
Certain light sources are severely penalized with low indexes when in fact they have a great yield and, on the other hand, incandescent and halogen which slightly yellow the luminous result are considered excellent color reproducers.

8.2 CQS

With the intention of trying to solve some of these divergences, the CQS (Color Quality Scale) is as an alternative developed by NIST (National Institute of Standards and Technology) using some CRI metrics but creating new ways to evaluate the color reproduction
In CQS, 15 highly saturated colors are used to compare chromatic discrimination, human preference and color reproduction.

[21] Stella | Lighting, Brasil. Reports from Stella´s Laboratory.

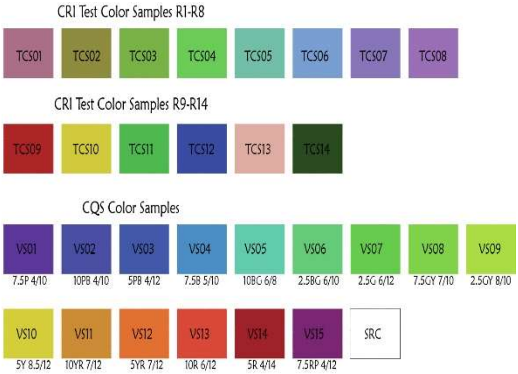


Figure 68. Comparing the samples of CRI and CQS.

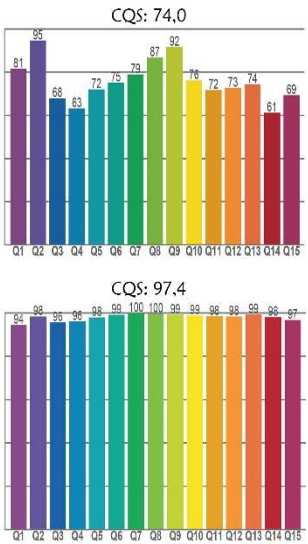


Figure 69. CQS: comparison between the same LEDs in figure 66.[22]

[22] Stella | Lighting, Brasil. Reports from Stella´s Laboratory.

8.3 IES TM-30-15 (IES TM-30-18)

Created by the Illuminating Engineering Society and communicated through Technical Memorandum 30 in 2015 (there was a review in 2018, distributed through IES TM-30-18).

Method for evaluating color reproduction, where photopic vision is dominant, is a system composed of two metrics: color fidelity index and color gamut (gamma) index and produces a Color Vector Chart.

99 Color evaluation samples (CES) of real world objects ordered by hue under the sun (5000K) and divided into groups: nature, skin color, fabrics, paints, plastics, printed material and color systems.

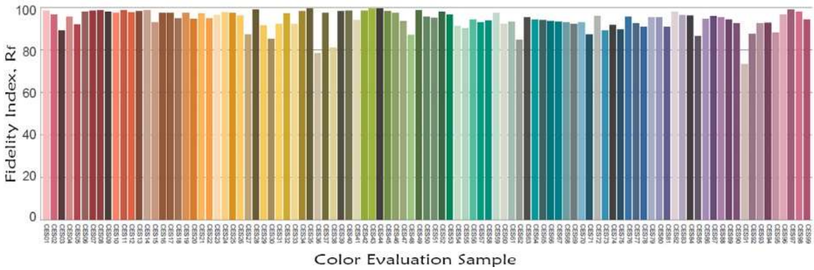


Figure 70. Fidelity index by sample.[23]

Figure 71. IES TM 30-15 - color types (W refers to white).

[23] Stella | Lighting, Brasil. Reports from Stella´s Laboratory.

A	B	C	D	E	F	G
Nature	Skin color	Textiles	Paints	Plastics	Printed material	Color systems

Table 2. IES TM 30-15 - color types.

8.3.1 Color Fidelity Index (R_f)

Used to measure the light source's closeness to a reference source, like the CRI method.

$$0 < Rf \leq 100$$

R_f equal to 100 represents the perfect combination between the samples illuminated by the reference and the tested light source.

8.3.2 Color Gamut Index (R_g)

To measure the increase or decrease of the color's purity of a light source, calculated by comparing the area of the color space of the tested light source and the reference.

$$60 < Rg \leq 140$$

R_g equal to 100 means that the saturation of the light source is equal to that of natural light.
R_g greater than 100 which means that the light source can increase color saturation, lower than 100 the color saturation is scant.

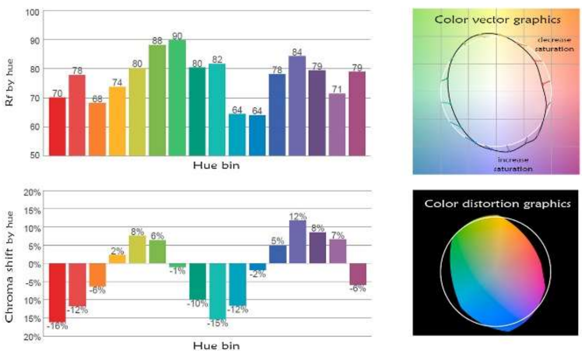


Figure 72. Color and hue analisys.[24]

[24] Stella | Lighting, Brasil. Reports from Stella´s Laboratory.

8.3.3 Color Vector Graphic

This graph, above and to the right in figure 71, shows the changes in hue and saturation in an observed light, if the colors appear more or less vivid.
The near-perfect circle represents the standard illuminant and the arrows the deviation according to wavelengths.

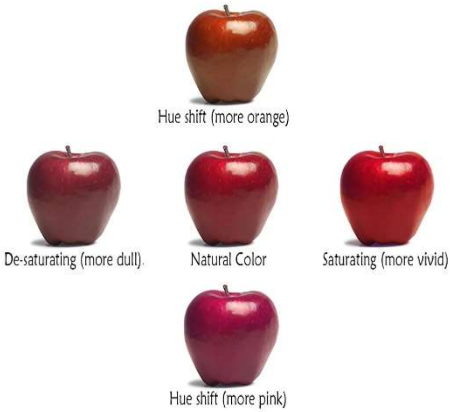


Figure 73. Changes in hue and saturation.

9. Color designation

9.1. Verbal

Verbal designation is a variable and inaccurate nomenclature.
For everything there is a word, for every word there are many things.
For every color may have a word, but for every word there are many colors.
When I say TREE, you imagine any tree, your tree.In the same way when I say RED, each one imagines its red and even when I show the color I am referring to, it is difficult to name it.

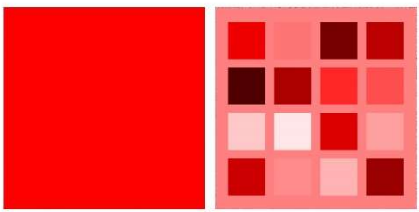


Figure 74. Red, light reds and dark reds.

The verbal nomenclature also varies according to the language, in some places there is the term light red to name the rose also the light or dark blue in some places have a specific name.

Figure 75. Yellow, which yellow?

Try naming the colors in the next image, always clockwise from the left circle to the right one.

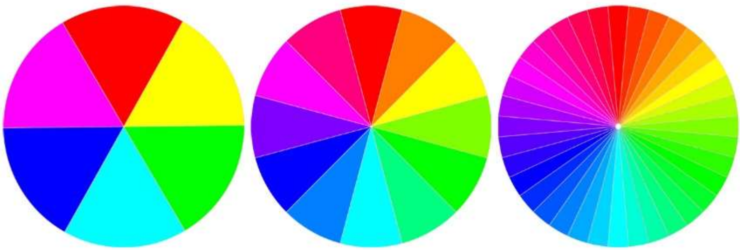


Figure 76. Chromatic Circles.

Naming colors is a completely individual act and usually just an approximation to colors of real objects that are not always standardized, usually companies usually catalog their colors in this way.
"Egg yolk". What color would it be?
Try to point out in the circle on the right what that color would be.
We've already seen so many gems with different colors, meaning we can't choose one of the four or five options.

9.2 Mathematic

In the mathematical designation a color is defined by values in coordinates within a chromaticity diagram.

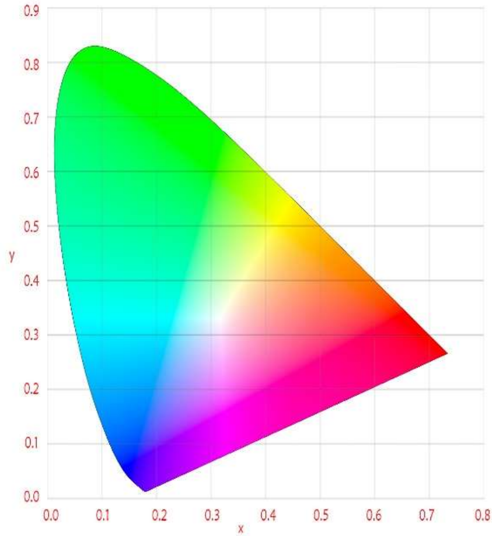


Figure 77. CIE 1931 Chromaticity Diagram, x and y coordinates

What is the color (x,y) = (0.247,0.355)? Yes, it's a dot within the diagram that defines a hue, but it's not practical for non-professionals.

9.3 Chromatic languages

These are standardized systems and notations where each color receives a value for hue, luminosity and chroma, for example.

9.3.1 Munsell and NCS notations

5R 4/10 is a typical notation for Munsell and for NCS we have, for example that one: S 2050-Y40R.

At first it seems complex, but if we understand the proposals and their codes, the notations make sense and give us the possibility to communicate with customers and other users of the systems.

Figure 78. Notations.

9.3.1.1 Munsell System

The Atlas of the Munsell Color System was first published in 1913 with colors ordered by equidistance in perception. It consisted of two sets of charts illustrating Albert H. Munsell's color measurement system.
Was revised and republished in 1929, as The Munsell Book of Color.

Internet

https://munsell.com

As a function of being organized by steps of differences, regularity of differences; note that the graphics have different sizes.

9.3.1.2 Natural Color System

The basis of the Natural Color System, a proprietary perceptual color model, is supported by Ewald Hering's thesis that six are the primary psychological colors and are opposed to pairs, as mentioned earlier. All colors can be defined in terms of similarities with their component elementary colors and with black and white.

Internet

https://ncscolour.com/ncs/

9.3.2 Other color organization and communication systems

Companies and institutions have created their own color communication system and some have become standard in different market applications.

9.3.2.1 RAL

In 1927, the German commission Reichs-Ausschuß für Lieferbedingungen (National Committee for Delivery and Quality Assurance), for short called RAL, created a collection of 40 colors for the definition of technical standards. It currently has a range of products designed to control color reproduction for industry, graphic arts and digital systems.

Internet

https://ralcolor.com

9.3.2.2 Pantone

Pantone was founded in 1963 by Lawrence Herbert, to identify, combine and communicate colors in the graphic arts environment, today operating in various types of industries.

Internet

https://www.pantone.com

Consult the websites' Pantone and RAL tables and look for the differences between them. You will also find similar colors with different denominations. Marsala in Pantone tables, for example, is Orient Red in RAL tables and evidently, the reverse path can be done.

10. Colorful world

Our world is not just colorful, it's multicolored.

Internet

Daigo-ji Temple, Kyoto, Japan. Manarola, Cinque Terre, Liguria, Italy.

Pink Sand Beach, Komodo National Park, Indonesia. Brazilian Opals.

Aurora Borealis, Finland. Caño Cristales River, Colombia.

Zhangye Danxia, China. Eucalypthus Deglupta, Maui, Hawaii.

Malabar Giant Squirel, India. Corn, Aksaray, Turkey.

Tosanoides Aphrodite, Brasil.

10.1 Light painting

Newton considered physical aspects of light and color as a starting point for his studies; Goethe, in turn, was interested in aspects involving the psyche. Renaissance painters mixed pigments to make their work material, used brushes and chisels as instruments and fabric as the main support base for their creations. However, light was extremely important in the formation of his works, even more than the paint colors themselves. Different paths were taken in this relationship between the observer and the artistic product. Much later, someone thought about using light to paint.

Internet

Janne Parviainen - Light Topography, Dhamma. 2016.

Brent Person - Spider On The Track. 2009.

Eric Staller - Lighting Drawings. 1970.

Gjon Mili photographs Pablo Picasso - 1949.

Frank and Lillian Moller Gilbreth - 1914.

11. Paradigms of light

11.1 Attribute light

Property light, the venerated light, light belonging to bodies, up to the Renaissance.

Internet

MNAC Museum's - Romanesque Art.

11.2 Effect light

Effect light, domesticated light, Renaissance and Baroque.

Internet

Beato Angelico, Fra Angelico - Virgin Annunciate.

Darkness is a starting point, the light enters the “dark room” and from there to the photograph.

Internet

Camera obscura.

Penetrates the eyes: Impressionism and Pointillism.

Figure 79. Impressionism style.[25]

11.3 Light cause

Instrumented lighting, support or material for light art.
Characterization of spaces, paths and environments for architectural surfaces, with greater visual richness.
That's what we'll cover in our next topics.

Internet

Adolphe Appia - Orpheus Hellerau. 1913.

11.4 Lighting Design for stages

The central axis of modern Lighting Design is the change from an instrument of visibility into a structural and structuring element of scenic writing, constituting itself as a language.

Internet
Bela Bartók - Bluebeard’s Castle (1911) by Ópera Perú. 2015.

http://operaperu.blogspot.com/

[25] Model: Lia Neusa Meirelles Perrenoud. Photo: Gastão Perrenoud.

12. From light to non-light

We can make a sensory path from light to dark, from light to non-light. And all these little rides are noticeable and carry a definite emotional charge.

12.1 General lighting

It is the lighting used for catwalk, for example, with uniform lighting and covering the entire area of action.
Internet

Graduate Fashion Week.

https://www.graduatefashionweek.com

12.2 Specific focuses

In this case, we use some light points that attract the audience's view.

Internet

Ford's Theatre - Fly.

https://www.fords.org/performances/past-productions/fly/

12.3 Using shapes – Gobo

Gobo is the acronym for Goes Before Objective used in a luminaire called ellipsoidal. This light source has an elliptical mirror that reflects light and its optics create a focal point for the crossing of light rays inside the device. In this location, the gobo can be placed. An iris can also be used to reduce the beam of light or shutters to cut this beam.

Internet

The Crucible @ Henderson State University Stage & Lighting.

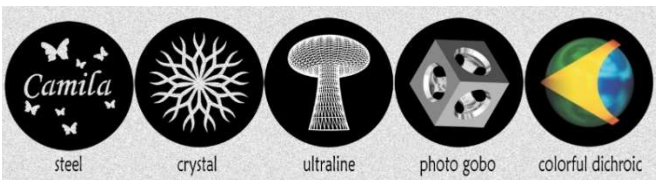


Figure 80. Gobos.[26]

[26] Images by Gobos do Brasil.

12.4 Through projection
Image projection has been increasingly used to recreate virtual scenarios that do not need to be physically, materially constructed.

Internet

Video Mapping.

12.5 Shadow design
Not lighting is also a function of Lighting Design.
Besides the light we should think about how the shadows produce sensations.
Volumes are extremely influenced by the clear and dark of an image because they give the impression of approaching and moving away from us.

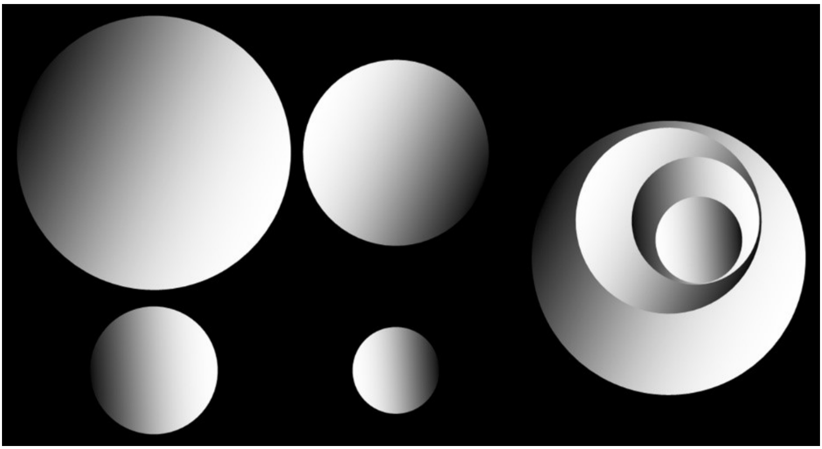


Figure 81. Shapes and volumes.

Shadows communicate and we can give a specific meaning to this communication. How about a puppet that creates its own bird with light?

Internet
Kumi Yamashita.

Figure 82. Light and shadow.[27]

13. Photometric quantities

Technical parameters of the physical and optical qualities of light, mostly used in Lighting Design for architecture.

13.1 Luminous flux

Total amount of light emitted in all directions by a light source.
symbol: Φ
unit of measure: lumen (lm).

13.2 Light intensity

Intensity of the luminous flux projected by a light source in a given direction; it's the ability to illuminate, measured per unit of a solid angle.
symbol: I
unit of measure: candela (cd).

[27] Shadow dramaturgies - Companhia Teatro Lumbra 2021, Brasil. Photo: Alexandre Fávero

13.3 Illuminance

The intensity of light reaching a surface after being emitted by a light source.
symbol: E
unit of measure: lux (lx).

13.3.1 Horizontal illuminance

$$Eh = \frac{I * cos^3 Ø}{h^2}$$

when the angle Ø is zero, the cosine is 1 and this formula may be simplified:

$$Eh = \frac{I}{h^2}$$

Each time we move a light source away from the illuminated object, we have "less light"; and, from this formula it is understood that the illuminance decays according to the square of that distance.

13.3.2 Vertical illuminance

$$Ev = \frac{I * cos^2 Ø * sin Ø}{h^2}$$

$$E = \sqrt{Eh^2 + Ev^2}$$

13.3.3 Semi-cylindrical illuminance

The measurement of semi-cylindrical lighting gives us an idea of the balance between diffused and concentrated lighting.
The recommended needs vary according to the activity carried out at the considered site.
The calculation of the average cylindrical illuminance is done at 1.2 m above ground level (in normal situations) and we need to maintain an uniformity of illuminance equal to or greater than 0.1.
For good ambient lighting, we must have at least 50 lux, but in the case of offices and educational establishments, for example, the average cylindrical illuminance cannot be less than 150 lx.

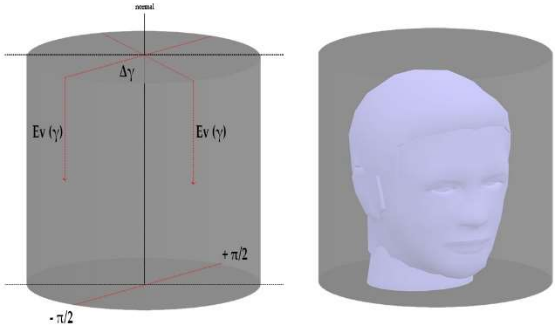


Figure 83. Semi-cylindrical illuminance.

For a good perception of the details of the faces, the minimum luminance (see on 13.4) should be 15 cd / m^2, but that already depends on the reflective surfaces of the place.

13.4 Luminance

The amount of incident light that is reflected by a surface in a given direction. It depends on the material and texture of the surface.
symbol: L
unit of measure: candela / area (cd / m^2).

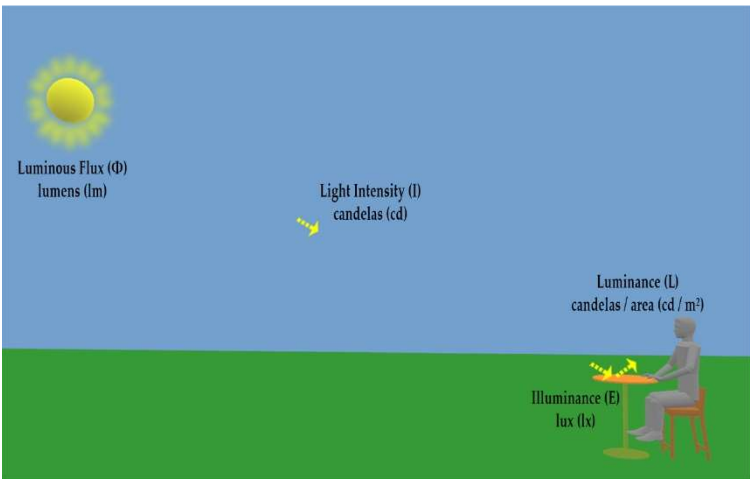


Figure 84. Photometric quantities.

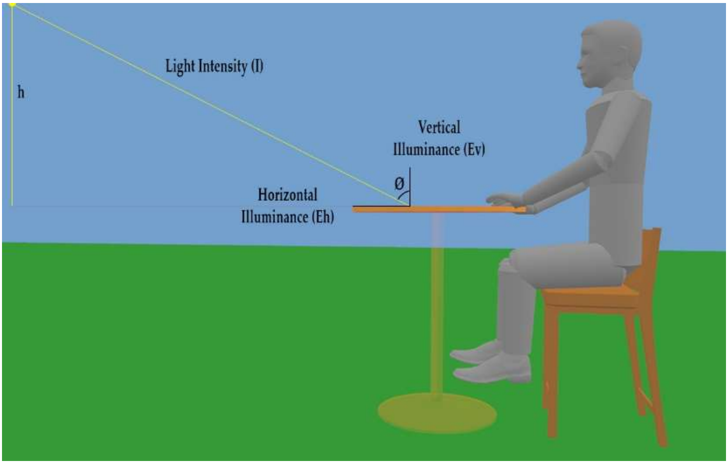


Figure 85. Photometric quantities.

13.5 Equipment and more metrics

13.5.1 Goniophotometer

A goniophotometer is a photometric device used mainly to test and measure the luminous flux generated by a directed light source, at different angles.
It is a photometer with a rotating arm containing a circular mirror. The light hits this mirror at different angles according to the rotation of the arm.
We obtain information about the luminous flux, intensity distribution**,** color uniformity and, finally; we can know the efficiency of the light source.

13.5.2 Integrating Sphere

The integrating sphere is a structure used to measure diffuse and undirected light sources.
The main element is the inner lining of the measuring sphere and we have basically two types: the Ulbricht sphere with a diffuse internal structure and the Coblentz square whose internal structure is mirrored.
The biggest advantage of this type of instrument is being able to measure the total power of a source.

13.5.3 Photometric curve, polar distribution

Also called the light distribution curve. First of all, the direction of the luminous flux can be verified in relation to the line that goes from 90º to 90º and that passes through the center of the diagram.
From the center of the diagram to one of the points on the outline of the figure we have the value of luminous intensity.

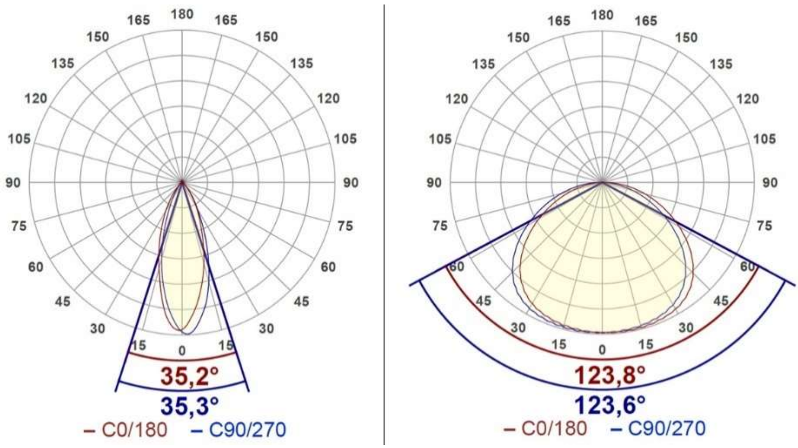


Figure 86. Beam angle and light distribution.[28]

The drawing on the right represents a light source with a wide beam, while the one on the left is a source with a narrower beam.

As in none of the drawings there is a component above line 90-90, the light comes out directly from the light source in only one direction.

All light can be, after leaving the device, direct or indirect depending on the reference object.
A beam of light comes out of a projector or reflector, illuminates a painting on a museum wall, but also bounces off the face of the viewer. Is this light direct or indirect? If we consider the painting it is direct, while the light is indirect in the viewer's face.

[28] Stella | Lighting, Brasil. Reports from Stella´s Laboratory.

13.5.4 Photometric cone

The photometric cone gives us indications of how the luminous flux varies with each distance interval. Light decays sensibly with each meter covered, remember: 1/4.

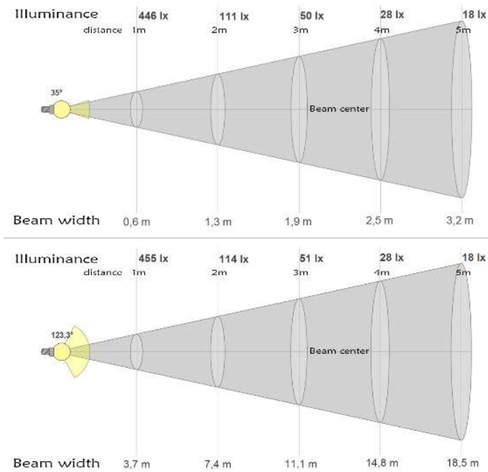


Figure 87. Photometric Cone.[29]

13.5.5 Beam and Field angles

The angular dimension of the cone of light is measured taking into account how much light is lost as we move away from the center of the beam.

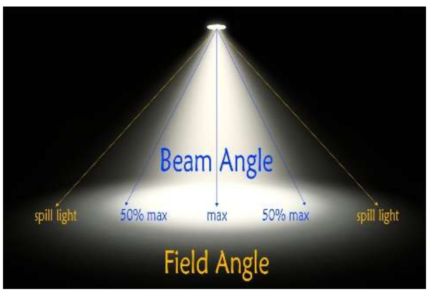


Figure 88. Beam and Field angles.

[29] Stella | Lighting, Brasil. Reports from Stella´s Laboratory.

13.5.6 Illuminated diameter

Diameter illuminated by a light source perpendicular to the considered surface. Note that when tilting this light source in relation to its illuminated surface, the calculation will be much more complex because we will have an oblique cone and no longer a right cone.

$$\text{Ø} = \frac{2 * d * tan\, \alpha/2}{2}$$

angle	-	diameter = index * distance
8°	-	diameter = 0.14 * d
12°	-	diameter = 0.21 * d
24°	-	diameter = 0.43 * d
28°	-	diameter = 0.50 * d
36°	-	diameter = 0.65 * d
41°	-	diameter = 0.75 * d
53°	-	diameter = 1.00 * d

Figure 89. Practical use.

To control the beam diameter, we may use certain accessories in the luminaire itself, internally, to decrease the beam size (iris, framing shutters) or externally, to reduce the beam size (barndoor, tophat, halfhat and donut).
We can also diffuse the light with garnitures placed outside the luminaire but connected to it; such as a soft box, for example.

Internet
Iris, framing shutters, barndoor, tophat, halfhat, donut, soft box.

13.5.7 Uniformity

The IESNA (Illuminating Engineering Society of North America) recommends that the illumination in the area immediately surrounding the task area not be five times greater than or less than one fifth the illumination in the task area itself.
Good uniformity (a ratio less than 5:1) improves visual comfort and reduces shadows.

13.5.8 Luminous efficacy

Relationship between the amount of light produced and the power consumed by a light source.
Watts do not determine the luminous intensity, only the consumption.
unit of measure: lumens / watt (lm / W).

Light source - 1800 lumens	Power (W)	Luminous Efficacy (lm/W)
Incandescent	75	24
Compact Flurescent	24	90
LED	15	120

Figure 90. An example of comparative luminous efficacy.

14. Qualities of light

14.1 Direction

An object illuminated by light coming from a certain direction can be perceived by an observer in very different ways depending on the position of the observer. Fixing the observer and changing the position of the light and/or the object will also generate new perceptions.
The fact is that we can illuminate an object of any position in 360º using one or more luminaires. Yes, the possibilities are endless.
Generally, the similar positions of the sunlight will be considered more "normal" and those that come from below will cause strangeness because we are not accustomed to seeing them in our everyday life.

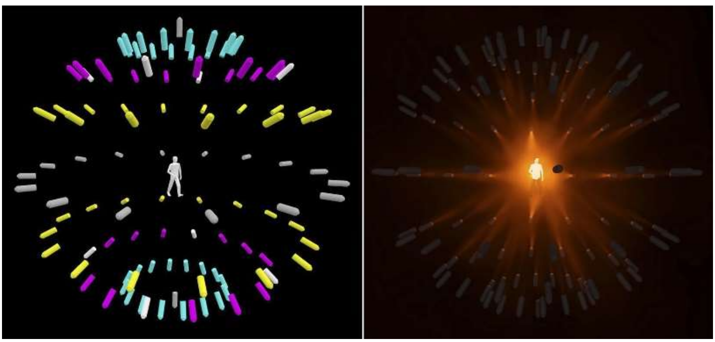


Figure 91. Lighting 360º.

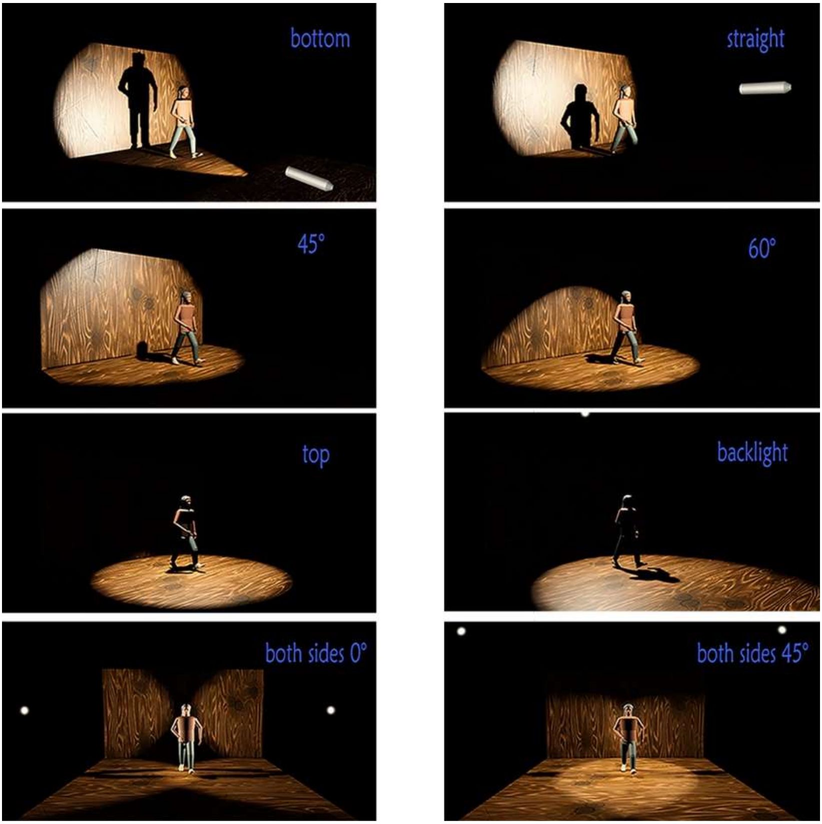


Figure 92. Some lighting positions.

14.1.1 Direct and indirect light

Regardless of what happens inside the light source, direct light comes from this source and reaches its objective without being deflected by external obstacles; indirect light, in turn, is redirected before reaching its destination, as we have already said.

In the image on the next page, sunlight is directly above the walkway and indirect at the base of it. On the walls we have both components.

Figure 93. Direct AND indirect light.

14.1.2 Sunlight system

The sunlight arrives directly from the star and reaches the earth but is a system and should be considered as such.

The quality of filtering should be taken into account, depending on the presence or absence of clouds, rain, snow, dust, smoke and other particles in the environment.

In order to illuminate objects and people with artificial lights in a pleasant and naturalistic way, we must use more than one light direction.

Figure 94. Direct sunlight.

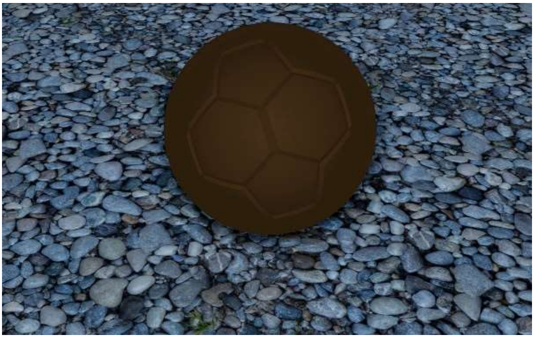


Figure 95. Diffused sky light (filtered light).

Figure 96. Reflexes (indirect light).

Figure 97. The system.

14.2 Color

We will have the opportunity to further discuss color and its physical and psychological effects on illuminated objects and on viewers in the next topics. Needless to say, color is not everything, but it is 100%!
Now a question: are black and white colors?
What are the man's hair colors in the next image?

Figure 98. Foggy afternoon, somewhere, UK.

The answer is: yes, but they are neutral or unsaturated colors. These are the extremes of the gray scale.
Perhaps the only color that can be considered colorless is total black, but this will only be true when we reach 100% absorption by the illuminated objects, that is, 0% reflection.

14.2.1 Filters

When we talk about filters, we are referring to something that changes not only the color of an observed object but also its shape appearence.
On where to place the filters, we have some possibilities:
Position them on the luminaire itself.
It can be something between the light source and the object; a fabric stretched, an acrylic plate, etc
Can be an artefact placed on the camera lens.
Worn by the observer, such as sunglasses, for example.
Basically, we have some basic types of filters:

Colorizers - change the color of the light or its reception and, therefore, the color of the illuminated object. They can be correctors or converters of the color of light.
Diffusers - alter the quality of light with respect to the dispersion of rays and light.
Polarizers - allows the passage or blocks the light waves according to their polarization.
Neutral density - changes the intensity of the light source to less.
Reflectors - silver, golden, black or white metallic plates that allow, through various surface treatments, smoother or harder reflections to redirect the light or fill the shadow areas that require more illumination.
UV - absorbs only the emission of ultraviolet avoiding the deterioration of the color of the objects.

14.2.2 Colorizer Filters

With the advent of LED and the possibility of emitting already colored light, color filters are disappearing for some applications, but they are still widely used. Filters are made mainly of polymeric materials or glass.

Figure 99. Old swatchbook.[30]

14.3 Hardness (diffusion)

When we speak of diffused or concentrated light, we are referring to the diffraction of light rays from a source and not to the size of the illuminated area, in this case we should refer to a narrow or wide beam.

[30] Image by Lee Filters - Panavision.

We can observe the type of shadow caused by the objects to assess the hardness of the light.

Figure 100. Diffuse light.

Figure 101. Concentrated light.

Sunlight can be concentrated or diffused!

14.3.1 Diffuser Filters

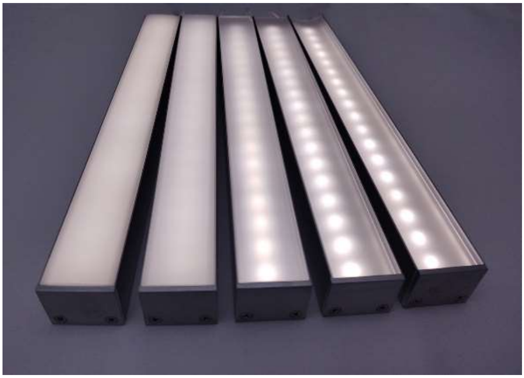


Figure 102. Difusers.[31]

We can have the same luminaire, the same lamp and a variety of diffusers to choose from.

14.4 Intensity

The intensity of a light source can range from zero (off) to the full flux of its lighting (on), usually when the maximum current allowed for the lamp or LED to survive is reached.
This can be done with the click of a switch or by dimming.

Figure 103. 10% illuminated bike.

[31] Perfil 30, Luminescence. Photo: Andre de Bacco.

Figure 104. 50% illuminated bike.

Figure 105. 100% illuminated bike.

Figure 106. 100% illuminated bike + midday sun.

Figure 107. 100% illuminated bike + sunset.

14.4.1 ND Filters

They are filters that attenuate the light flow that enters the camera or emitted by lighting fixtures; without changing the color of this light. Sometimes metallic filters can be placed directly on luminaires that emit, in addition to light, a lot of heat.

Figure 108. ND filters.

14.5 Dimerization

Dimming allows you to vary the luminous flux (light intensity) emitted by a light source, allowing the creation of different lighting atmospheres with the same luminaires, usually taking advantage of the possibility of taking some time to turn on, off, lighten or darken the environment.

14.6 Duration

The duration concerns the chronological and dramatic times.
The way we turn a light on or off is related to both; we can turn it on with a click or take 10 seconds to do so, the results will be quite different with regard to psychological responses.
For a scene on stage that takes place in one minute, through lighting it is possible to represent the passage of the night until the morning.
In some performances by Kabuki, Japanese theatre, the exchange of light between one scene and another can take several minutes. In the past, this was done manually, today, with the advent of digital computing and control consoles, it has become much simpler and more accurate.

14.7 Movement

The movements concern both the displacement of the light beams and changes in the lighting atmosphere.
Nowadays with the aid of computerized systems the light beam can be moved manually or automatically following pre-established time rules.
In the past, torches already fulfilled the role of accompanying man on his nocturnal journeys, today a role played by lanterns.
Lighthouse lights have always been a guide and safety for navigators and continue to be a symbol of movement, direction and security.

Figure 109. Lighthouse.[32]

15. Methods of lighting the human figure

For the desired lighting, we must choose the way to reveal, as well as define the use of different light qualities (color, direction, intensity, hardness,

[32] Eduardo Becker LD – Atelier de Iluminação Logo

duration and movement), as they will cause different views in the shape, size, material and texture of the objects and surfaces as a function of different reflections, absorptions, refractions and transmissions of light. These methods below can be used to light any type of object.

15.1 Stage lighting

Probably the method most used by Lighting Designers was created by Stanley McCandeless and published in 1932 with the aim of lighting the entire stage and providing a daytime or night time atmosphere and modelling the human figure. He recommended using four fixtures 90º apart from each other in relation to an actor in the center of each of the nine areas. The light sources must be at 45º vertically and horizontally from this actor's face, taking advantage of Rembrandt's technique!

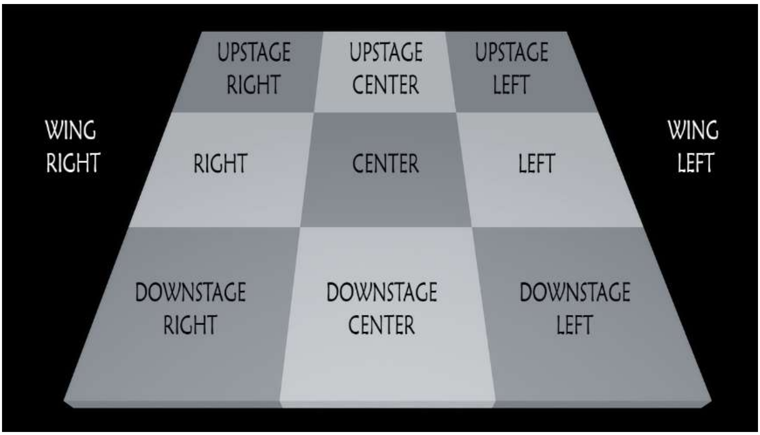


Figure 110. Positions on stage.

On one diagonal we should have the light sources corrected with amber filters and on the other diagonal with blue filters.
Let's take a look at some possibilities through an observer's frontal view.

Figure 111 Warm front from left .

Figure 112. Cold front from right .

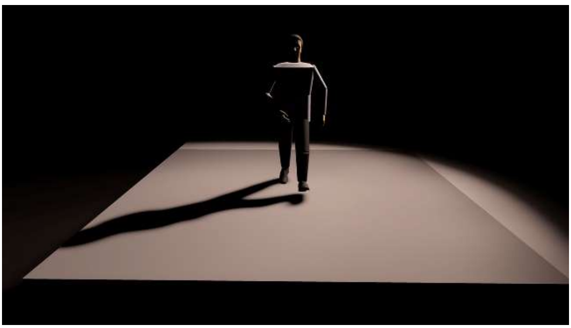


Figure 113. Warm backlight from right .

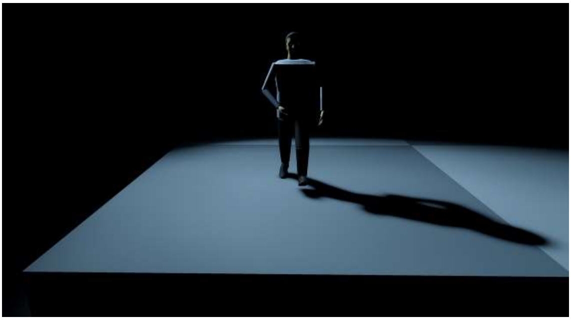


Figure 114. Cold backlight from left.

Figure 115. Warm criss-cross .

Figure 116. Cold criss-cross.

Figure 117. Front and backlight from left.

Figure 118. Front and backlight from right.

Figure 119. Front light from both sides.

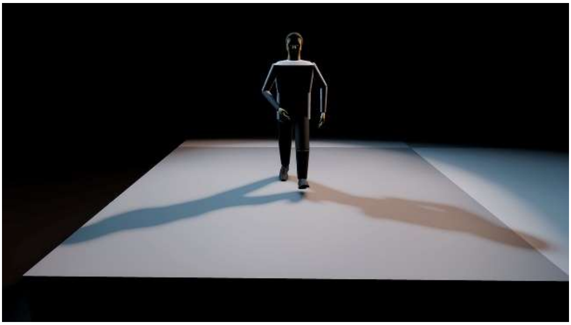


Figure 120. Backlight.from both sides

Figure 121. All at 100%.

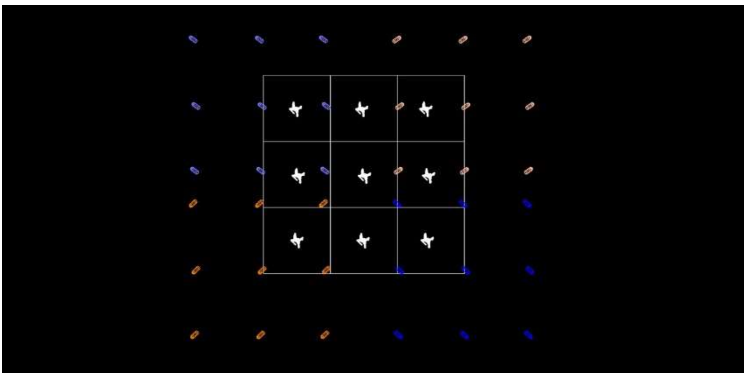


Figure 122. 9 areas.

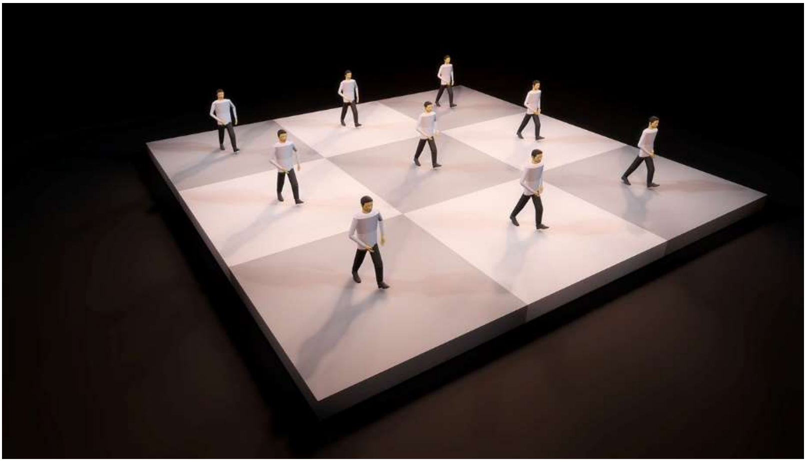


Figure 123. Illuminated areas.

Unlike the stage where we have observers at various points, for cinema the point of view is just a camera's eye. When using more than one camera in the same scene, we have to think about the necessary lighting for each one.

15.2 Cinema / video

One of the most used techniques is lighting based on three points of light directed to the objective to be illuminated and, sometimes, another light that complements the effect.

Key Light - It is the main illumination; usually it comes from the front of the object to be illuminated.

Filling Light - It is a more diffuse than the key light, a secondary light which helps to illuminate the still dark areas.

Backlight - It is the light effect to create the illusion of the third dimension and which removes the figure of the object from the background. Its light flux is harder and more intense (2 or 3 times) than that of the key light.

Light on the background or scenery - This lighting normally helps to detach the figure from the background. It is the lighting that defines the dimensions of the space, determining the width and depth where the illuminated figure is located.

Figure 124. Key, filling and scenery lights. Only sunlight, a system.[33]

16. Architectural Lighting

16.1 Concepts

The building is a living organism, multipurpose aggregator and has personality so we divide the building into layers to better understand this personality and to define the hierarchy we intend to give to the building parts using formal or functional lighting.

16.2 Light sources

There are numerous light sources and we can classify them by the type of light emitter, the type of bulb (if any), the type of socket (if any), the type of reflector (if any); but the most interesting is the type, the characteristics of lighting this device produces!!!

[33] Model: Camila Perrenoud. Photo: Rafael Azevedo da Silva.

16.3 Light fixtures

Houses and protects the light source, controls the distribution of the emitted light and contains power suppliers and wirings.
We have a lot of types: flush recessed, flush light panel, exposed canister, suspended luminary, eyeball down spot, pendant, adjustable, reel, track lighting, suspended hanging, coffered light recess, full room luminous ceiling, surface mounted luminary, surface mounted fixture, coffered light recess…
Again, what matters is knowing the luminous result to decide how to use the luminaire… think about.

16.4 Areas of architectural lighting

Industrial - Manufacturing facilities and hazardous locations (chemical plants, mines and refineries).
Commercial - Businesses that aren't manufacturing including corporate: hotels, restaurants, retail stores, warehouses, offices, hospitals, schools, condominiums. Public lighting on streets, bridges and government facilities.
Residential - Our homes, paths and landscapes.
For all these areas, we can subdivide the lighting into indoor and outdoor and will have different needs and characteristics.

And nothing, I said NOTHING prevents us from using lamps and luminaires in a different way, the rules are there to be creatively broken.

16.5 Indoor - outdoor

The main care is in relation to electricity and its conductors; in the background, we must consider that lamps and peripheral equipment must be protected from the weather.

16.6 International Protection system marking

The International Engineering Consortium (IEC) has established a coding system that aims to ensure that manufactured products are tested for the infiltration of contaminants inside the luminaires.
They are given an IP code (IP65, IP67 for example) with two numbers, the first referring to dust and the second referring to liquids more specifically, water.

1st digit	Protection against solid ingress	2nd digit	Protection against liquid ingress
0	Non-protected	0	Non-protected
1	> 50 mm gap for entry	1	Vertically dripping water
2	> 12 mm gap for entry	2	Dripping water tilted at 15°
3	> 2.5 mm gap for entry	3	Spraying water at an angle up to 60°
4	1.0 mm gap for entry	4	Splashing water at any direction
5	Dust protected	5	Jets of water fro any direction
6	Dust tight	6	Heavy seas or owerful jets of water
		6K	Powerful water jets with increased pressure
		7	Harmful ingress of water when immersed between a depth of 100 mm to 1,000 mm (5.9 to 40 in)
		8	Continuous immersion in water
		9K	Powerful high temperature water jets

Figure 125. IP.

17. Architectural Lighting Design

For a long time, it was enough to place a light source on the ceiling and in the geometric center of the room, to imitate the sun, to generally illuminate the whole place. The doubts to resolve were how much light do I have? How is the distribution and uniformity of this? And it was enough to meet the technical requirements and we used to use incandescent or halogen lamps to do the job.

This way of thinking about light has been changing both through the exchange of experiences and knowledge between professionals responsible for architectural lighting and with their peers in the performing arts area.

17.1 Methods of calculating architectural lighting

17.1.1 Point by point

This method takes into account the lighting of the luminaires that arrive directly at the work plane.

Using the intensity data for each luminaire at a given angle, the illuminance at each point is measured using calculations based on the inverse square and cosine laws.

17.1.2 Lumen (zonal cavity method)

Lumen method is a series of calculations that uses the horizontal illuminance criteria to establish a uniform luminaire layout in a space.
It is certainly a more complex method that uses a series of calculations based on horizontal illuminance and proposes a luminaire layout with the scope of the photometric curves of the sources and some technical data:
Light Loss Factors (LLF); Ballast Factor (BF); depreciation of the lumens emitted by the lamp, the Lamp Lumen Depreciation (LLD); depreciation due to accumulation of dirt in the luminaire, the Luminaire Dirt Depreciation (LDD); depreciation due to accumulation of dirt on the surface of the room, the Room Surface Dirt Depreciation (RSDD) and others.

But Lighting Design is much more than these methods... notice the layers of light in this image… and directions… and colors.

Figure 126. Layers.[34]

17.2 Human dimension

Now that more than ever we are focused on the human being when projecting lighting design, we must consider the use of the precepts of holistic and interdisciplinary neuroscience, the Human dimension.
Some aspects should be highlighted in the next topics.

[34] U.nico Produções Artísticas - The Great Attraction. Artists: Fernanda Takai and Claudio Levitan. Photo: Gerson de Oliveira.

17.2.1 Circadian rhythm
Living beings have always been governed by the movements and alternations of light during the 24 hours of the day (then called Circadian cycle), with changes in the seasons of the year according to the climatic conditions of each location. Observing and respecting the individual characteristics of beings is essential.

17.2.1.1 Lighting automation
Fixed lighting is not natural; one of the ideas is to use dynamic lighting to match natural light. According to a timeline, we can program the color temperature and intensity with dimmers for each luminaire creating lighting scenes even for special moments; analogically through manual controls or by computerized automation.
Using the dimension of time and varying the atmosphere of the environments, we stimulate ourselves visually or we can also relax because we need to refresh our eyes and brain.

17.2.2 Environmentally sustainable
Nowadays it seems obvious, but we still have to make a big effort both to make light sources less polluting and to dispose of them.
Remember that when you throw something away, there is no "outside" here.

Figure 127. Apt, France.

17.2.2.1 Liter of Light

The organization Liter of Light was inspired by the “Moser Lamp” created by the Brasilian mechanic Alfredo Moser, in 2002. One liter pet bottle with water and bleach inserted in a hole in the roof of the houses providing lighting by refraction. A simple way to rethink the use of natural resources and discard at virtually no cost.

Internet

Liter of Light.

Figure 128. Let's spread this idea.

17.2.3 Visual message

Our mood is impacted by the light and colors of the environments and by the planned or unplanned changes that occur in the spaces.

Figure 129. High spirits, not war of course.

17.2.4 Communication codes
With the evolution of theories and practical studies, Lighting Design evolves creating its own form of communication, its language.

17.2.5 According to activities
Efficient and effective lighting for users according to the activities being developed and which is directly related to visual comfort.
In lighting design connected to the world of sales, depending on the environment, we must pay more attention to some items without obviously forgetting the others. In supermarkets, for example, energy efficiency and system maintenance play an important role, but it is visual comfort that will determine the customer's stay in the store. For retail, we must guide the buyer to the products, create atmospheres and highlight the brand. In the case of shop displays, contrast is extremely important to draw attention to the products and to hide the luminaires and avoid glare is essential. In all these cases the quality of color reproduction is essential.

17.2.6 Flexible
Lighting must be flexible; if necessary and possible, according to the age and skills of the users.

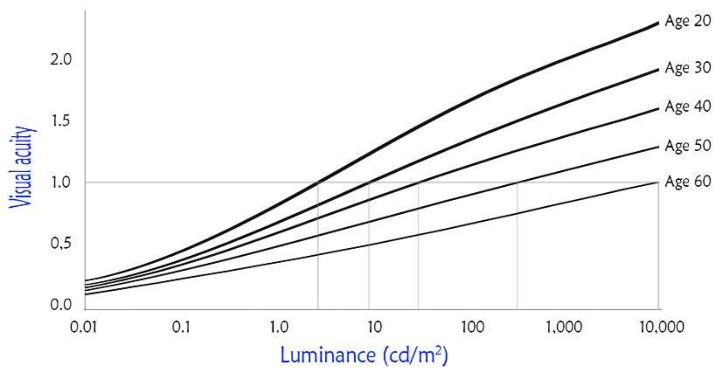


Figure 130. Visual acuity, luminance and ages.

17.3 Technical and artistic dimensions

There are two main axes of the lighting project itself, one with a technical bias focused on established ***luminotechnical*** concepts and calculations, and the other, more free and without prejudice, artistic, based on the ***luminoscenic*** studies, the dramaturgical universe.

17.3.1 Integrate natural and artificial lighting

Both at night and during the day, the more we use natural light, the better. Be it live from the light coming from the sun or storing energy to be used for illumination when we need it.

17.3.2 Space composition

It is the light that allows the visualization of spaces and their perception.

Figure 131. Milano at night.

17.3.3 Controlled lighting with excellent spatial distribution

Keep it simple. less is more. Spend time thinking ahead and not solving problems later.

Figure 132. Distribution.

17.3.4 Make selectively visible by defining interest levels

A standard concept, what you want to see is illuminated, what is not so important can be without light. This rule can often be transgressed and sometimes even, broken.

Figure 133.Interest levels? [35]

Figure 134. Be Brasil - APEX, Milano, Italy.

[35] Artist: Arthur de Faria. Photo: Eneida Serrano.

17.3.5 Modulation of shapes and volumes (3D)

That is an example of bad lighting, simply by the fact that you need to think to understand the shapes. This Lighting Design was made by me and, of course, corrected before the opening of this exhibition.

Figure 135. Be Brasil - APEX, Milano, Italy.

17.3.6 Efficient energy and technology for each location

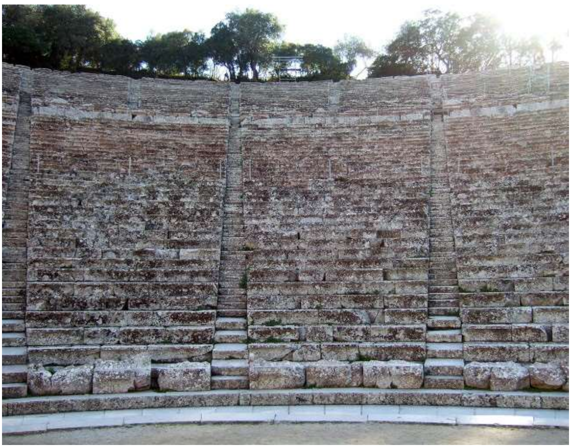


Figure 136. Ancient Theatre of Epidaurus, Greece.

17.3.7 Easy maintenance

At the time of the project, we must already foresee how the maintenance of the luminaires will be carried out.

Figure 137. Brasilia Museum, Brasília, Brasil.

17.4 Method of approach

How to commit to the work to be done? Having a clear idea of the direction we are going to take the boat in this endeavour.

17.4.1 Location and culture

The way to illuminate and perceive the lighting varies according to the location, something beautiful in one place can be horrible in another and vice versa. Designing artistically and globally is extremely complex and needs discussions and more discussions about the final product, even if it's the Lighting Designer with himself.

17.4.2 Objectives of the contractors

It may seem obvious, but if this item is not very clear and documented, we may have to take a much more hectic route than expected and things can even get complicated during the project development process.

Figure 138. What about the Lighting Design?

17.4.3 Existing lighting conditions

We must always consider the existing lighting at the location of our intervention, regardless of whether the location already has lighting or external influences that may or may not be controlled.

17.4.4 Restrictions

The standards vary according to the location of the globe where we operate and according to the type of the same, being aware of the standards is extremely important and avoids future problems.
Regionalism depends on the sun and climate and affects the Lighting and Luminaire Design. Ventilation and specific visual identity are also within the parameters of our applied science. If there is not much difference in heat stroke between places, there will be more cultural differences.
With the development of the LED sector, the control of actions goes a little out of design and gets closer to technique.
Specifically regarding the manufacture of luminaires, there is a well-established path between their creation and their manufacture.

The designers have inspirations that are reinforced at the Milan fairs resulting in design creations based on new technologies and colors. In Germany, finishes and thermal and shock protection are being developed for these luminaires. Finally, in China, manufacturing takes place according to the previous precepts.

17.4.5 Aesthetics of Lighting Design

What is Lighting Design?
What is it for?
How is done?

17.4.5.1 The way to reveal

For the desired lighting, we must choose the way to reveal, as well as define the use of different light qualities (color, direction, intensity, hardness, duration and movement), as they will cause different views in the shape, size, material and texture of the objects and surfaces as a function of different reflections, absorptions, refractions and transmissions of light.
Hey, I've read that phrase before. Yes, I am repeating it for its importance.

Figure 139. Definition of Lighting Design.

17.4.5.2 Luminous concept

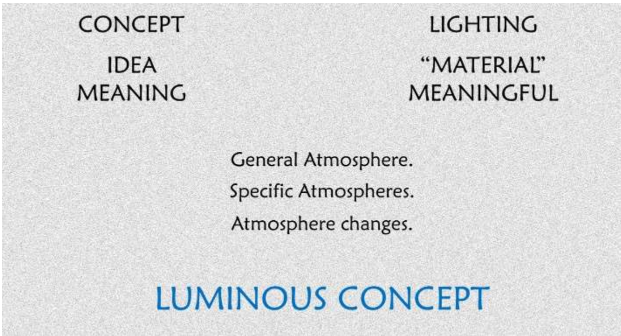


Figure 140. Luminous Concept.

17.4.5.3 Pictorial composition

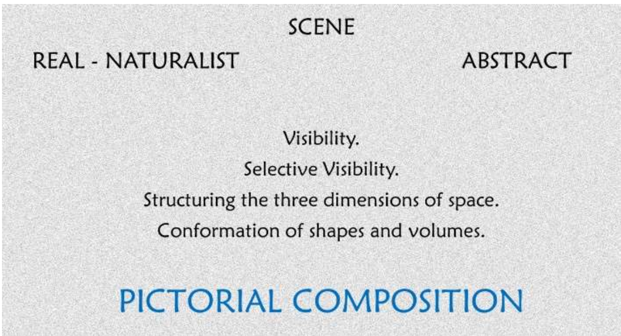


Figure 141. Pictorial Composition.

17.4.6 Technical aspects of Lighting Design
17.4.6.1 Lighting requirements - functional

Some questions we must answer:
What needs to be illuminated?
What are the illuminance levels to be used?
What balance between technical and artistic should I provide?

17.4.6.2 Lighting performance - quality

What is the quality of the light?
Can I use different CCTs?
Can I or should I use colors?
In relation to the other qualities of light, what should I formalize in lighting?

17.4.6.3 Lighting maintenance

Remember that there will be someone at the top of the stairs, twisting behind a panel or even taking apart an entire piece of furniture to change a simple light source before designing it!
Never change the lamps of a theatre chandelier one by one ... the ideal is to make a general change of luminaires or lamps with 75% of the useful life completed and to make them all at the same time. Then use the ones you remove in places with easy access and that can burn without problems of operation or for the safety of the place. In some specific cases related to health and safety, this change can be made even earlier.

17.5 Criteria

Some criteria to be used and that are more or less important and according to the use itself.

17.5.1 CCT

CCT is a slightly more artistic than technical criterion.

17.5.2 CRI

CRI, in turn, is more technical than artistic.

17.5.3 The levels of illumination

But, it's amazing, if you measure the light levels with a luxmeter after running your creative light, you'll notice that the standardized levels aren't too far from what you used. Our good taste and everyday habits lead us to make the right choices.

17.5.4 Balanced distribution of luminance

You can have a balance, but that balance can create high or low light contrasts using varying levels of lighting.
We can have little contrast with a lot of light and we can have high contrast with lower light levels.

17.5.5 Direction of the light

As I mentioned before, the direction and sense of the light makes all the difference when we see an image, a pictorial composition.
The light sends a message by itself, taking on meanings according to our previous experiences. A light coming from under the face is completely unnatural, so it scares us. Why light statues that way, then?

17.5.6 Distribution of shadows

The shadow, or the reflexes, can reveal the light, or at least denounce its presence and spectral qualities.
We can take advantage of this to improve a matte wall, for example.

Figure 142. Rhône River, Lyon, France.

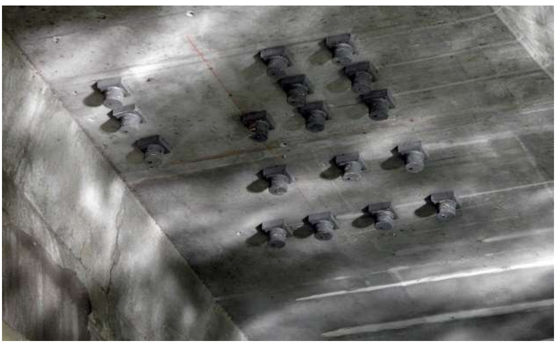


Figure 143. Rhône River, Lyon, France.

17.5.7 Color deterioration

Light fades colors over time when it contains ultraviolet rays, which causes yellowing, flaking, weakening and / or disintegration of materials.
Some paints and some printed colors can disappear in a few hours in direct sunlight or just a few years in the near darkness of a museum.
Infrared also heats the surface of objects and impairs the long-term preservation of unstable man-made materials.
Some ceramic frescoes do not fade and can last for centuries in direct sunlight; it is interesting to read more about it.

17.5.8 Glare control

Glare: direct or reflected light that make us feel uncomfortable.
The reason for the lighting is the user, if we damage his vision we will be doing disservice.
Depending on the position of the light source in relation to the observer, if the brightness is unavoidable, we can control the brightness by cutting the angle of the luminaire, using a prismatic diffuser or anti-reflective film for example.

17.6 Drafts and preliminary designs

Like everything in life we start with sketches, in general the best ones start with doodles with what we have in hand, including restaurant napkins. When we arrived at the office we started to work more seriously, condensing these ideas in an organized way.

17.7 Verifications and final project

After a preliminary project, it is normal to make revisions until we reach the final project. The more organized your method of work and creation, the faster you will reach the final result and the more time left for new napkins!

17.8 Expectations alignment

I think the most important part in a creative process that involves a client; or boss, is the Alignment of Expectations, when simple conversations define the scope of the project and what each one expects to do and receive at the end of the work.

18. Chromatic circle

Circular color distribution conveniently organized based on a determined and explicit logic. The question is how conveniently this logic was used and the conclusions of that use!

18.1 Complementary colors

"Complementary colors are two colors that are on opposite sides of the color wheel."
This statement is not correct, first because there is no THE color wheel or THE chromatic circle and two opposing colors in a color wheel are not always complementary, they may be antagonists or they may simply be opposites in that circle.
The colors on opposite sides of a circle that we use at school to paint or color paper really make beautiful compositions and seem antagonistic to us; and they are, but they are not complementary.
Yellow-purple, blue-orange and red-green are not complementary pairs.
Two complementary colors are those that, when used together on a white substratum, form white (or near white) by additive synthesis or black (or near black) by subtractive mixing.

19. Color spaces

Color space, gamma or gamma is the set of colors that a device or peripheral is capable of capturing, producing or reproducing.
The information about the colors that pass from one analogue or digital medium to another must be perfectly represented and reproduced so that there is no discrepancy between what is "spoken" and what is "heard", so that the colors are seen as in the original, as faithfully as possible.
Each device has its own way of recognizing color, which can mean limitations in its transfer. This management is complex and involves decisions such as adding a mapping through an interrelation function that often delimits the standard color space to create new spaces (range), while restricting the number of colors that can be accurated reproduced.
We currently use the CIE 1931 chromaticity diagram to define the most complete color space, the standard reference environment.

20. The dimensions of colors

We tend to establish that colors have basically 3 dimensions: hue, luminosity and chroma. These terms vary from author to author, I mention here what I consider most coherent, of course like the other authors.

20.1 Hue

The optical system distinguishes hues based on their spectral position, it's the color itself, and actually there aren't many.
When viewing a hue on a color wheel we can see differences with the nearby colors but this obviously depends on how many hues this circle contains. In the continuous spectrum, would there be as many as it is possible to name?
If I say hues are the seven colors of the rainbow, magenta is off the list.
Some authors say that the hues are perceptually not similar to others hues, in this case green and blue look different? For some African tribes; no, they are very similar.
Hues can be the basic colors that our teachers taught us to recognize and name them with a single word in school. None of these hues can have a "last name", such as dark, light, bluish, etc. But rose whose name is simple is a light red and the violet is a dark blue with something red.
Nuances: variations of a single hue towards black or white passing through shades of gray.

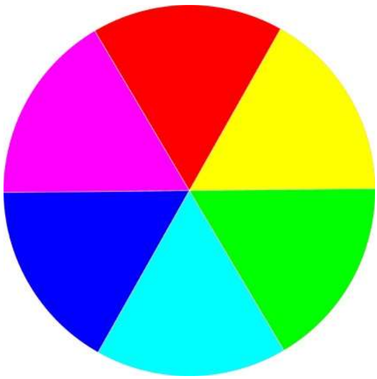


Figure 144. Red, Yellow, Green, Cyan, Blue and Magenta.

Where is amber?

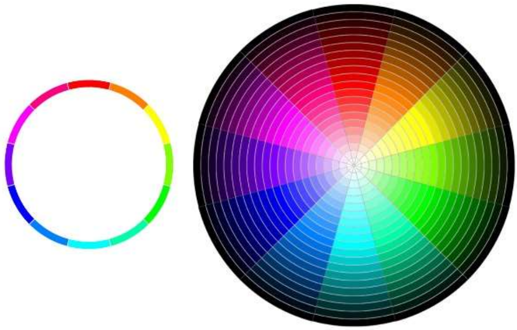


Figure 145. Red, Yellow, Green, Cyan, Blue, Magenta and other hues.

20.2 Luminosity

The blacker a hue, the lower its luminosity, and the hue saturation decreases.
Shades: variations of a hue when adding black, or taking out your own light.

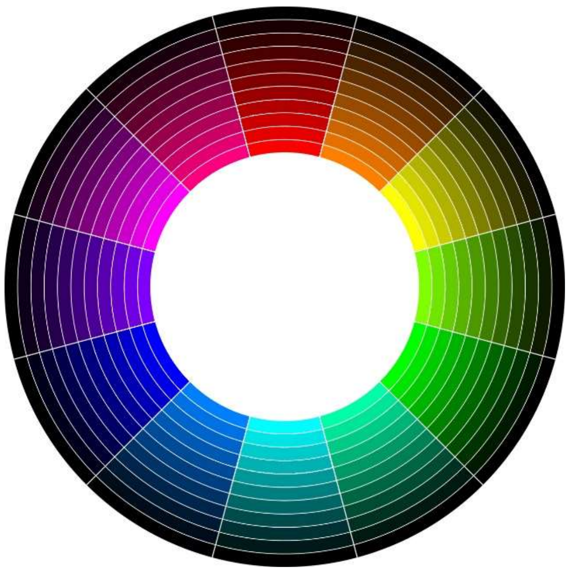


Figure 146. Luminosity.

20.2.1 Brightness and lightness

Brightness: how much white or fluorescent is a light source (luminance). Lightness: is directly related to the reflective surfaces (illuminance).

20.3 Chroma

The whiter, the lower the saturation of a pure hue, the lower the chroma of a pure hue.
The difference is that here the hue saturation is maintained as we increase the saturation of the other hues.
Shades: Variations of a hue by adding white or its complementary color.

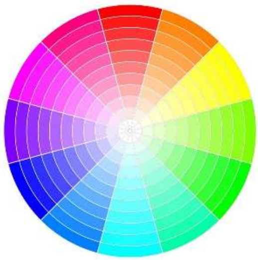


Figure 147. Chroma

21. Primary, secondary and tertiary colors

The choice of a color as a primary is related to the physiological response of the eye to light. There are usually three primary colors.
Thomas Young thinking about the constitution of our retina in 1802 assumed, very close to what we consider today the three primary colors of light, which would be red, green and violet.
Hermann von Helmholtz used the ophthalmoscope and ophthalmometer (or keratometer) made by him in 1851 concludes that the colors are a slightly purple red, a slightly yellowish green vegetation and an ultramarine blue.
James Clerk Maxwell, in a lecture at the Royal Institution of Great Britain in 1861, presented a theory of three primary colors; red, green and blue and a color photograph.
What do we consider primary colors? The generative but indecomposable colors used in a color synthesis.
The secondary colors are formed in balance by two primaries.
The tertiary are intermediate colors obtained by the balanced mixture of a primary and a secondary.

Go back to Figure 143. The opposite colors in the circle are a primary and a secondary, and they are complementary to each other.

22. Mixtures, syntheses

We mix radiations, not colors.
Opaque pigments - subtractive mixture.
Translucent pigments - subtractive mixture.
Lights - addictive synthesis.
The subtractive mixture refers to the use of opaque or translucent filters, when we talk about additive synthesis; we are referring to more than one source emitting light at the same considered point.
Yes, when using paints for example, we are subtracting light, avoiding the reflected light from the painted substratum.

22.1 Opaque pigments - subtractive mixture

Opaque pigments are mainly used in coating paints. The type of material used for the inks as well as the characteristics of the substrate influence the final result, which can vary. The mixtures depend on the covering capacity that each pigment or ink has.
Some painters have long used palettes with more than the three misnamed primary colors because of the difficulty of getting other colors simply by mixing these paints.
The notations inside the squares refer to the numeric description in hexadecimal and RGB (0-255).

Figure 148. RYB.

22.2 Translucent pigments - subtractive mixture

Mixture used in graphic arts.
The mixture of the three primary colors Cyan, Magenta and Yellow generally produces a color near the black. To use less ink and decrease the drying time of printing, we use a fourth color, Black (key black), because of this the name of CMYK color model.

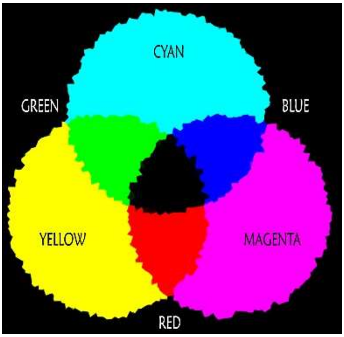


Figure 149. CMYK.

22.3 Lights - addictive synthesis

Natural and artificial lighting.
In addition to the lighting itself, this mixture is also used for TV screens, monitors, cell phones, video projectors, etc.
When we add the three primary colors white results.
The same happens when we add its complementary color to a primary color.

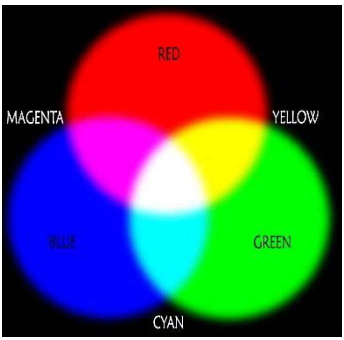


Figure 150. RGB.

23. Simplifying RGB synthesis

In practice, we can use the RGB mix for any light sources and, more modernly, for LED sources. We are very grateful to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura because the development of the blue LED allowed us to obtain the single white LED. The best devices today have RGBWAUV LEDs; in addition to red, green and blue, we have cold white, amber and ultraviolet, which is actually the last violet that allows our vision. Today we can perform color mixtures (synthesis of the luminous fluxes of each LED) and color temperature changes.
Here we are talking about approximate colors to be used in everyday practice, the white formed by the combination of light sources can vary.

R	G	B

R	G	B

R	G	B

Table 3. Magenta.

R	G	B

R	G	B

R	G	B

Table 4. Cyan.

R	G	B

R	G	B

R	G	B

Table 5. Yellow.

R	G	B

Table 6. White.

How many colors are needed to form this white? All the colors of the rainbow? The three RGB primaries? One primary and one secondary? Two colors that compliment each other?

R	G	B

R	G	B

R	G	B

Table 7. Complementary magenta and green.

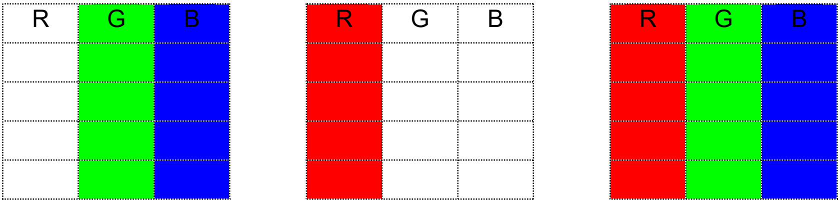


Table 8. Complementary cyan and red.

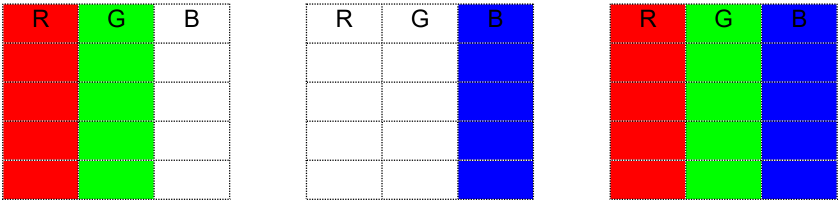


Table 9. Complementary yellow and blue.

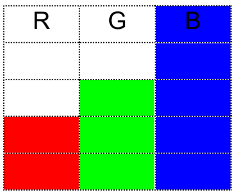


Table 10. What color is that?

W + C + B

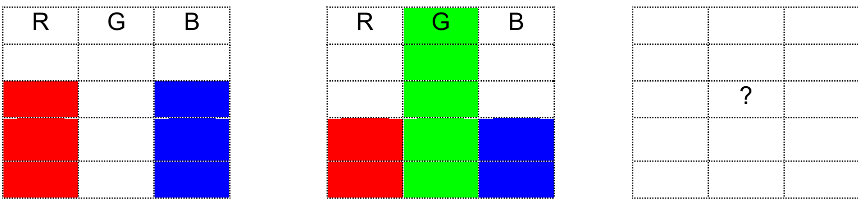


Table 11. What is the result of this synthesis?

Mixing, remember, lights from two different light sources and LEDs used in various applications like your computer or cell phone are a source of light... The first color is a dark magenta, the second is light green, we expect white as a result. Look at how one piece fits into another.

The first color is 2R+2G+2B=W, 1R+1G=Y and +1R… light amber.
The second is a light blue: 2R+2G+2B=W, 1G+1B=C and + 1B is a light blue with few green. We expect again a white as a result.

Bravo, Stanley McCandless!!! In scenic lighting we call it broken white.

24. Colored filters and SPD

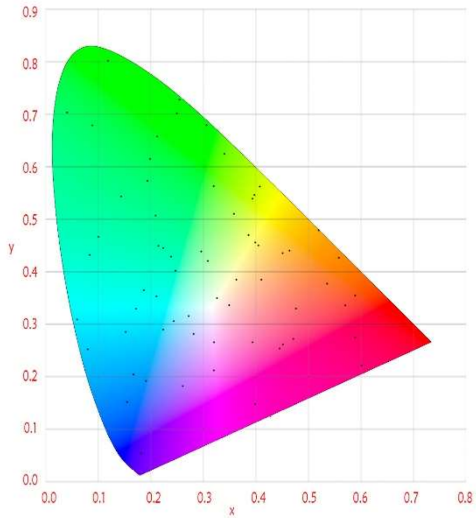


Figure 151. Distribution of some filters.

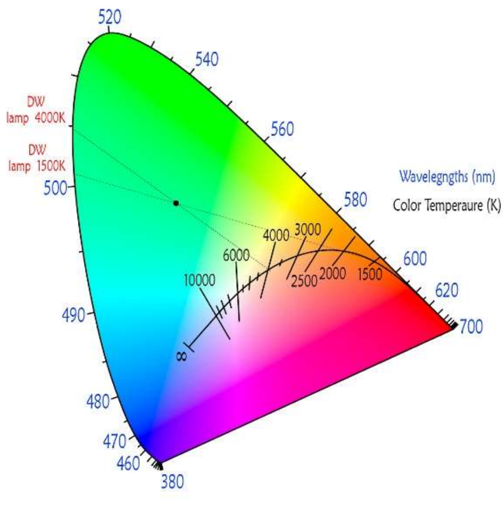


Figure 152. Dominant wavelength.

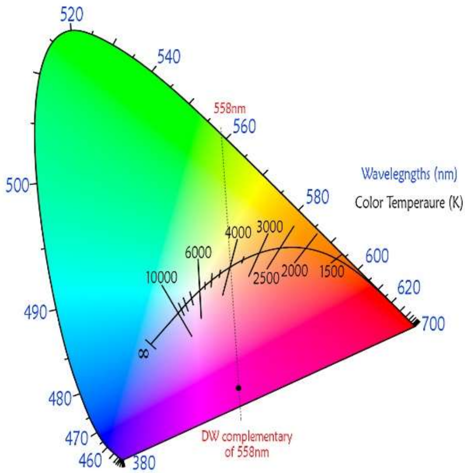


Figure 153. DW of a color that falls.

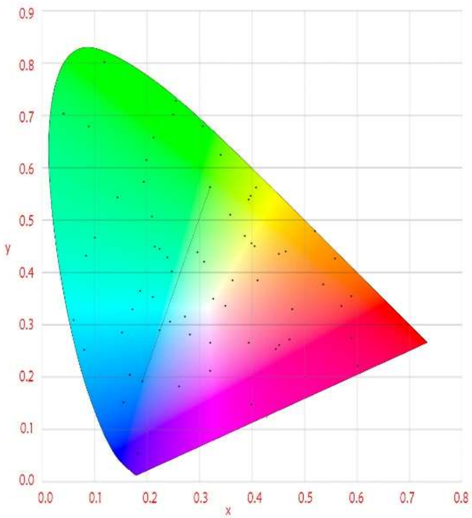


Figure 154. Mixing two lights (same characteristics) with two different filters.

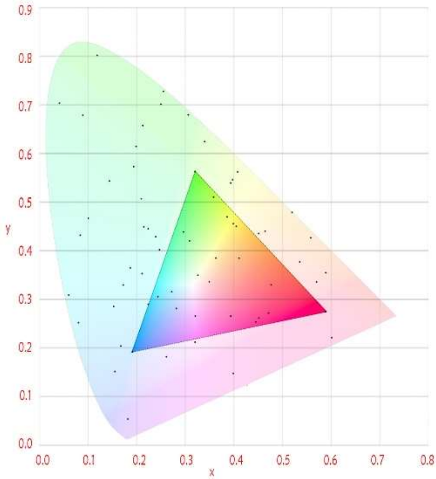


Figure 155. Three Color Mixing.

25. Light and colored objects

If you are still not convinced that red, yellow and blue are not primary colors I will try one more time.

The blue used for the painter's color mixing has a portion of green that allows the white paper to reflect beyond the blue of this green, but absorbs the red. In turn, yellow absorbs blue. If one color does not allow red reflection and the other does not allow blue reflection, we will see only green.

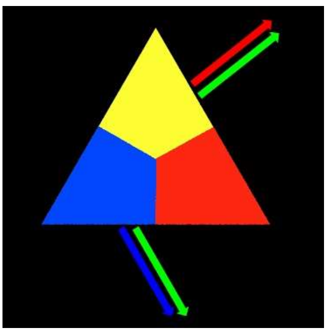


Figure 156. Why Y + B = G.

The objects do not have a defined color, they only have the possibility to reflect, absorb and transmit / refract portions of the light.
Just be in a dark place and choose any colored object. Then illuminate each of the rectangles on the following pages with a flashlight and make that light reflect off the object.
First use the first three rectangles in Figures 156, 157 and 158 as reflectors and you will see the object more or less illuminated, you are changing the intensity of the illumination because the colors of the paper are absorbing the incident light. Then use the rectangles in Figures 159, 160 and 161, with the secondary colors, in each of them you will be decreasing approximately 1/3 of the luminous intensity and avoiding the reflection of one of the three primary colors.
Finally use the rectangles in Figures 162, 163 and 164 which decrease about 2/3 of the incident light and only allow one color to reflect.

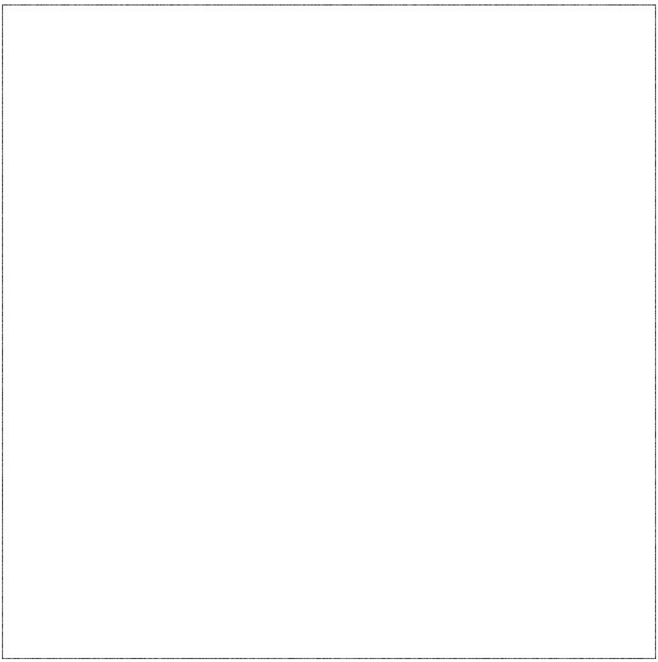


Figure 157. Color for reflexion.

Better a flashlight but you may use the light of your mobile.

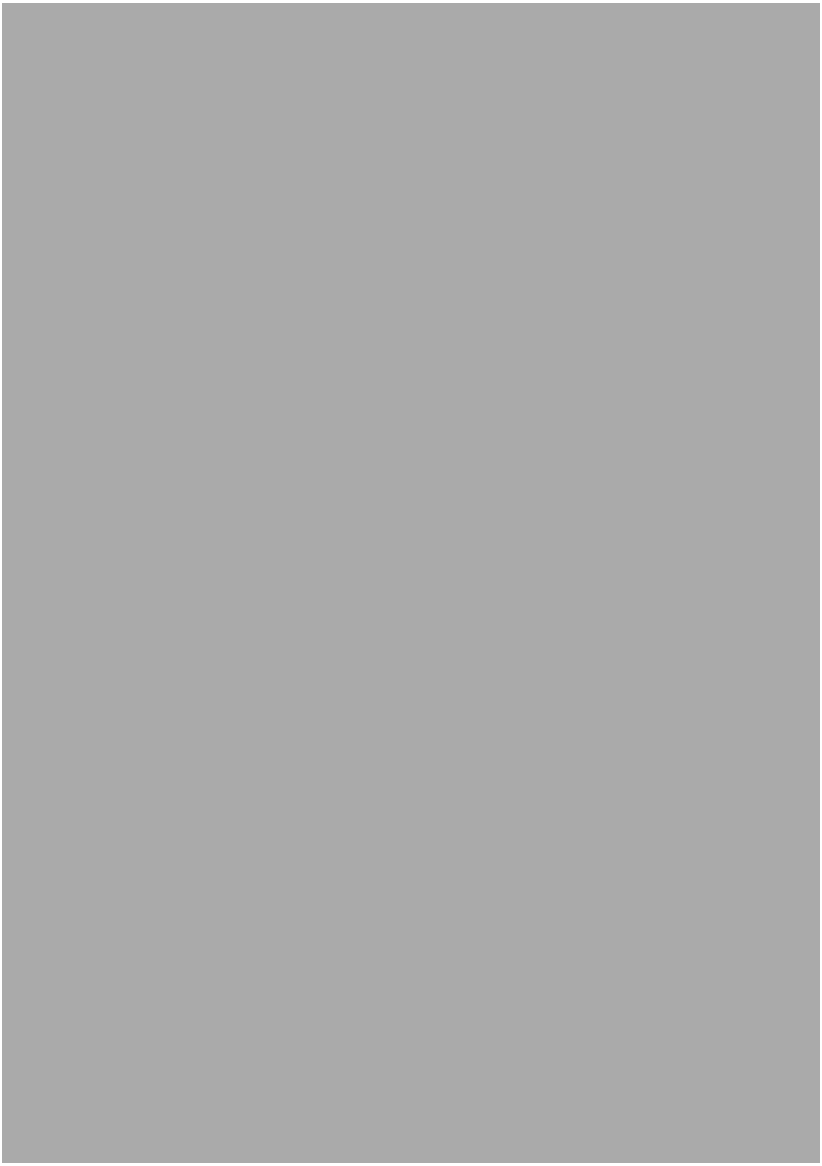


Figure 158. Color for reflexion.

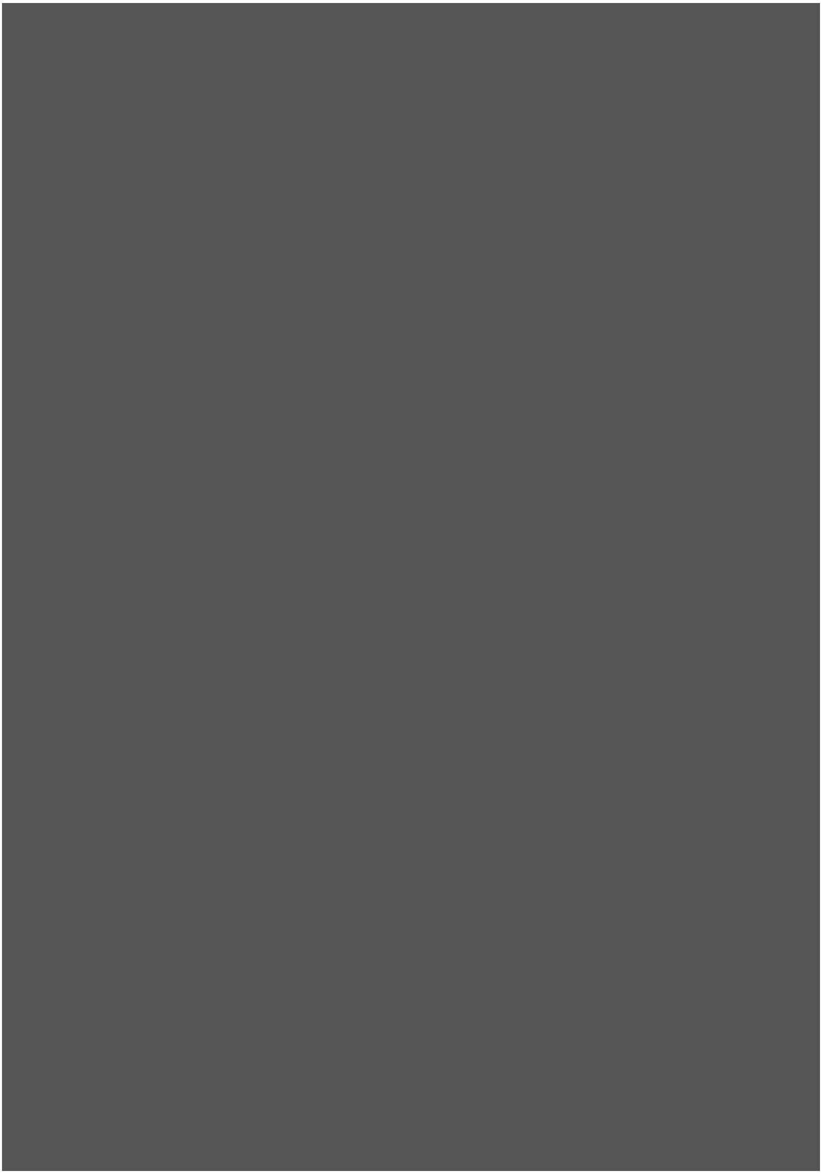


Figure 159. Color for reflexion.

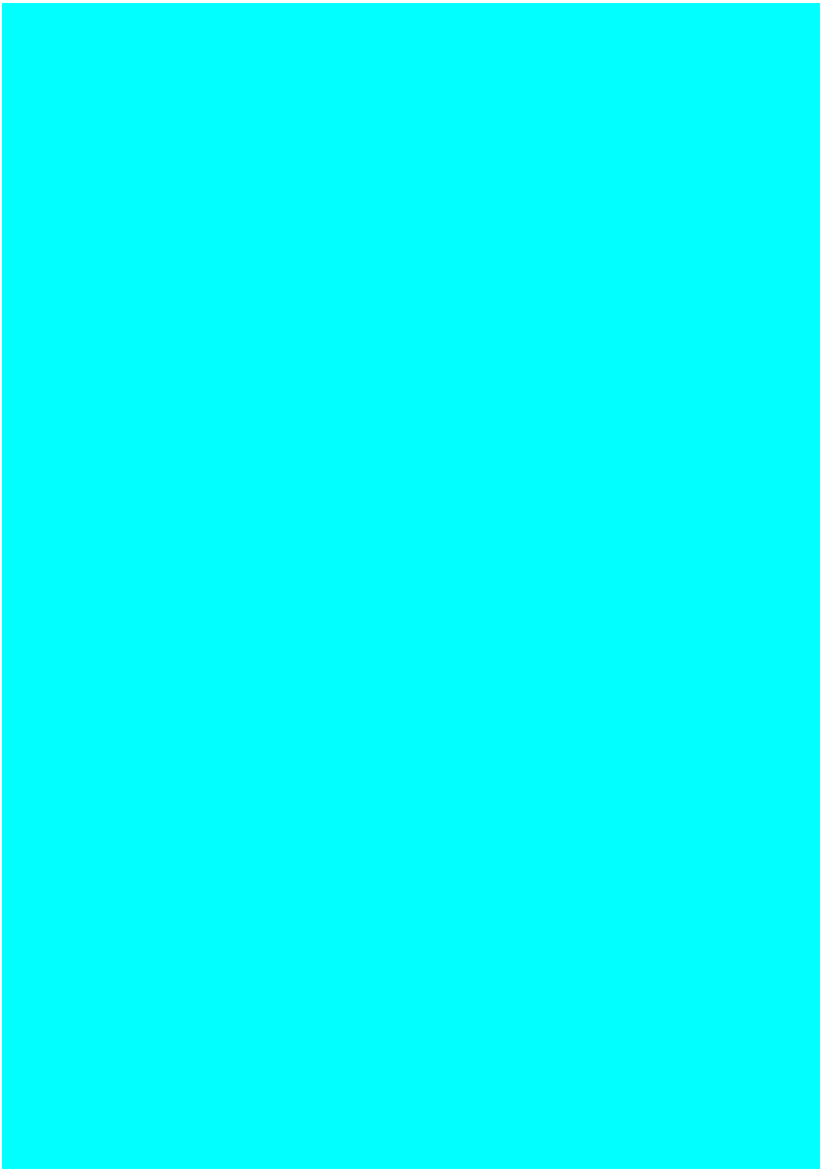


Figure 160. Color for reflexion.

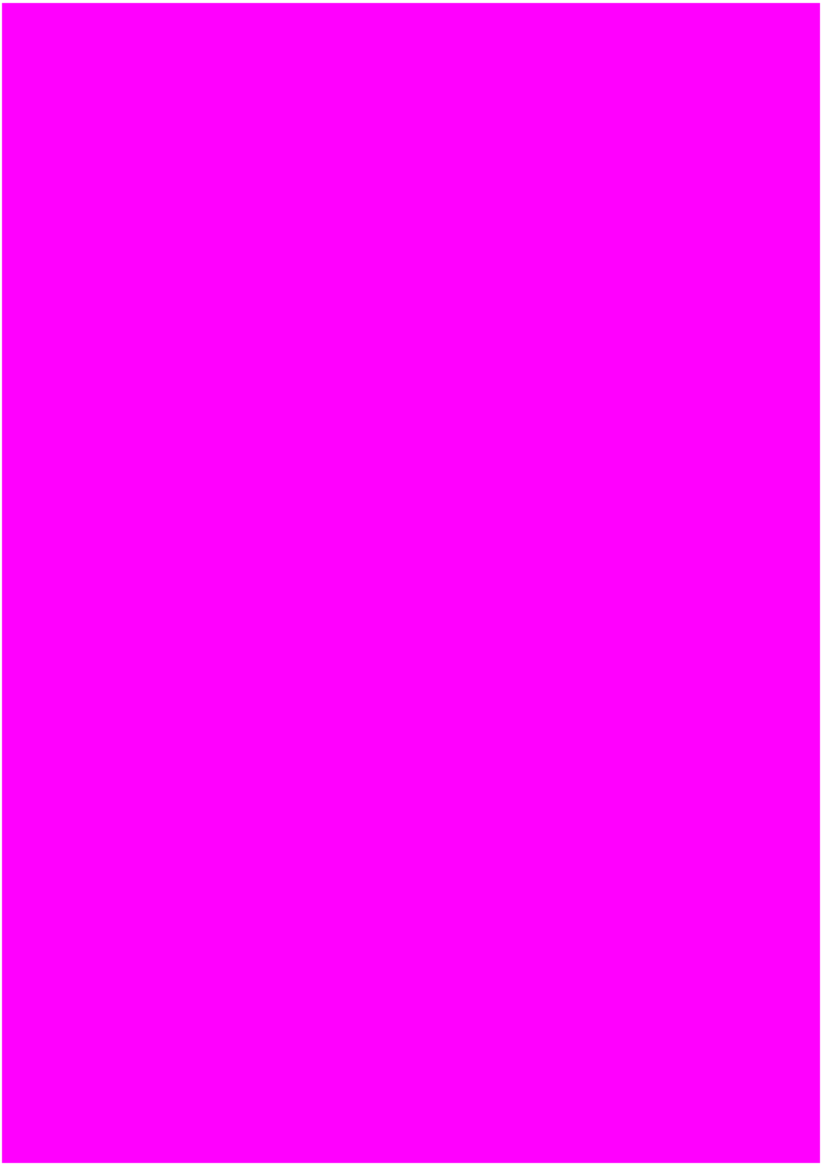


Figure 161. Color for reflexion.

Figure 162. Color for reflexion.

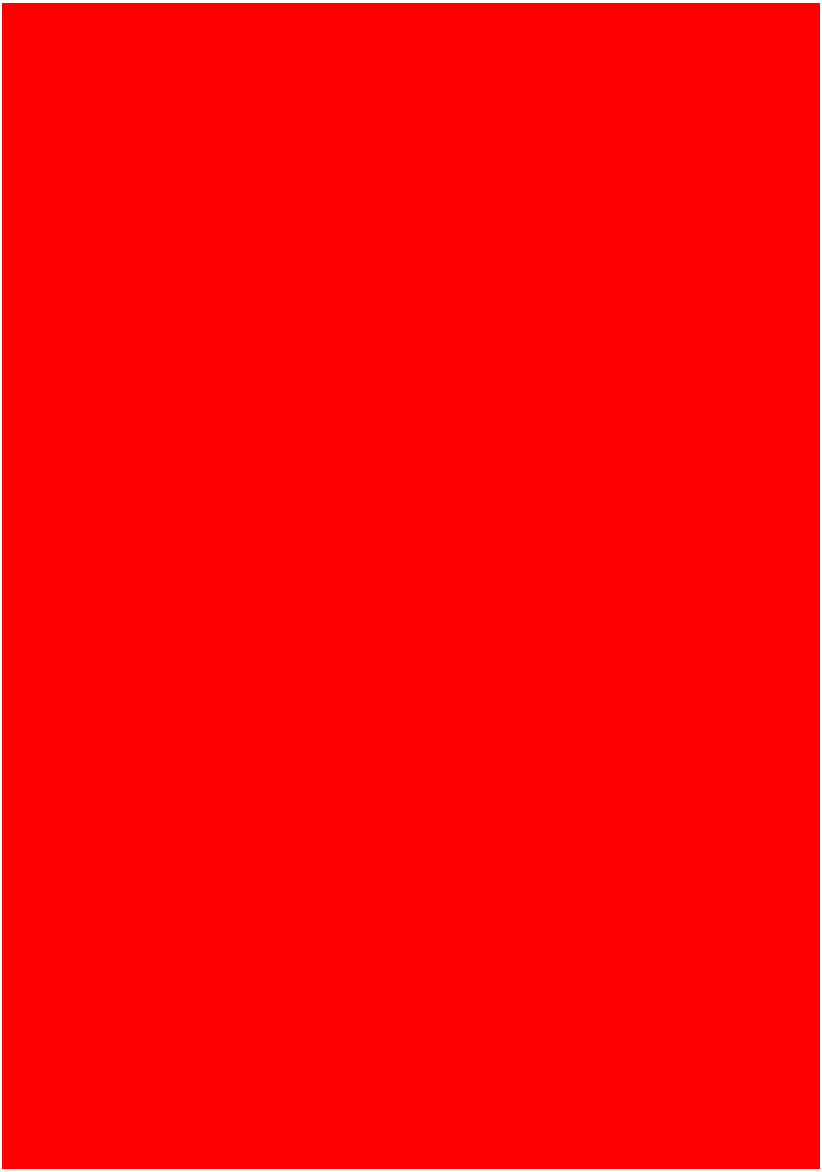


Figure 163. Color for reflexion.

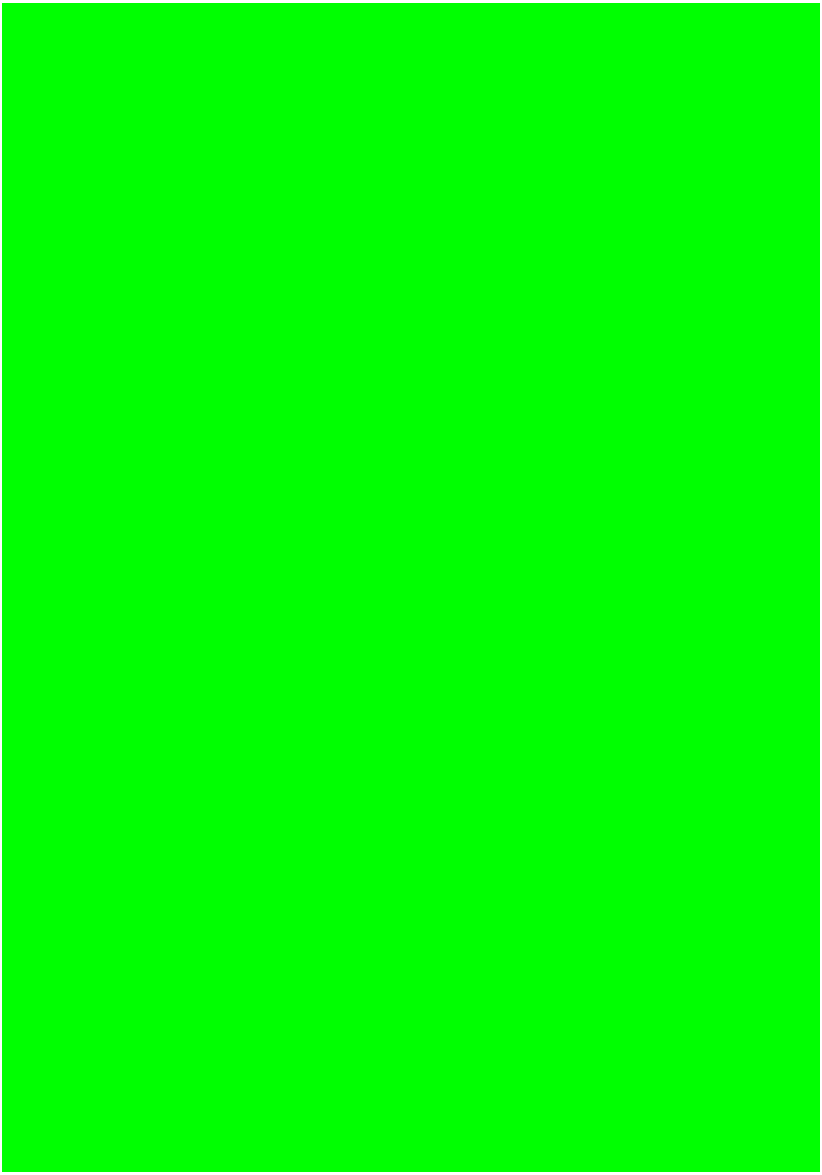


Figure 164. Color for reflexion.

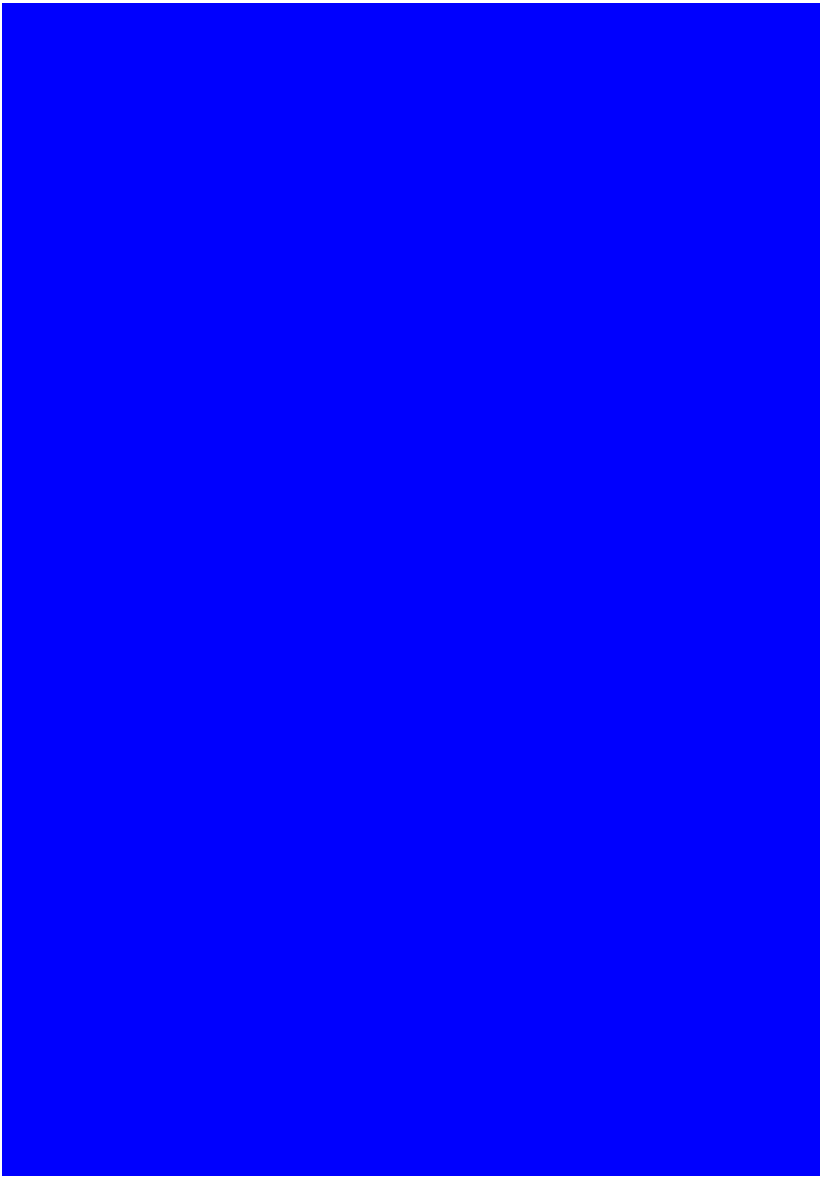


Figure 165. Color for reflexion.

26. Colored shadows

The shadow is an absence of light, it ceases to be a shadow when it is colored by the light that falls on it.
In the images below we have a simulation with three different luminaires, one with a red filter, another with a green filter and a third with a blue filter, very close to the primary colors.

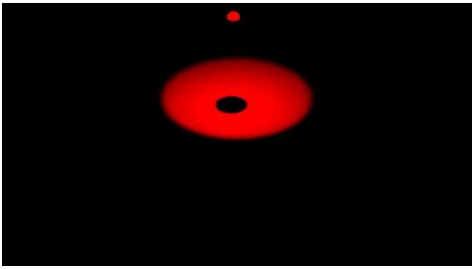


Figure 166. Only R on.

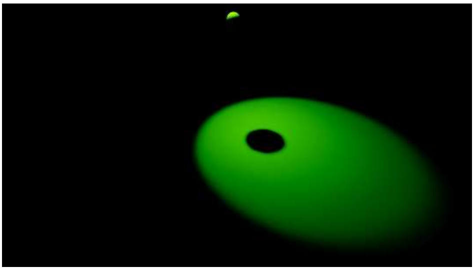


Figure 167. Only G on.

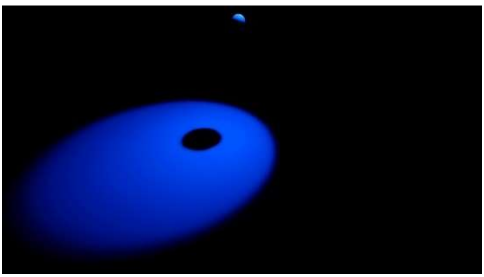


Figure 168. Only B on.

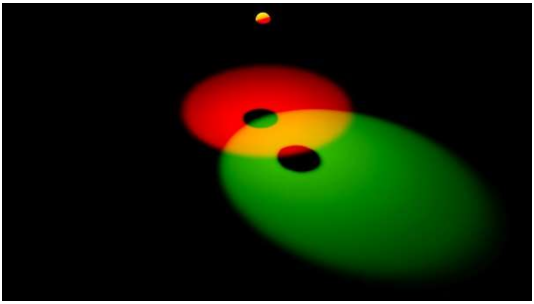


Figure 169. RG (Y) on.

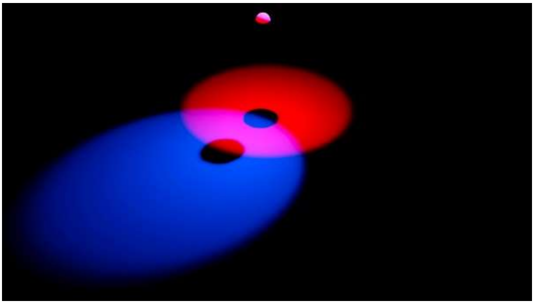


Figure 170. RB (M) on.

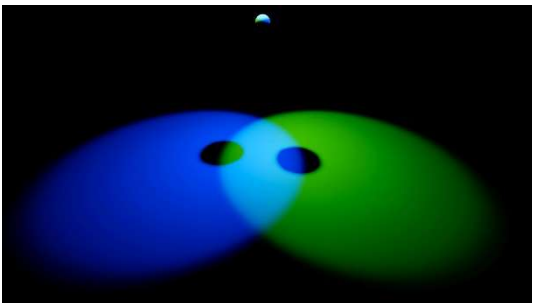


Figure 171. GB (C) on.

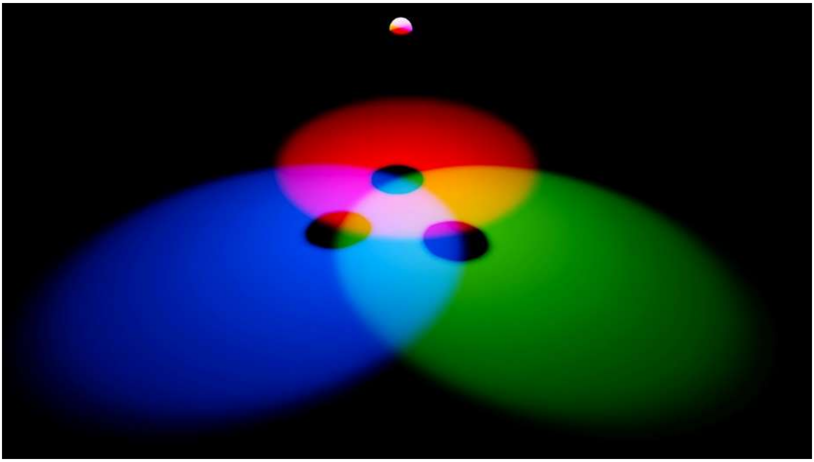


Figure 172. RGB on.

27. Negative afterimage

When we look at a color our eyes are impregnated by the complement of that color, even after the stimulus ceased, we still see this complementary for some time.
Separate a white sheet of paper for the following test and proof.
Again be in a dark environment.

Look at the Figures 172, 173, 174, 175, 176 and 177 for thirty seconds thinking about its complementary, after this look at the blank white sheet.

Give your eyes and brain thirty seconds to rest and then move on to the next color. Repeat this action for the six hues, always thinking about the color you want or expect to see.

Do the same with the Monalisa but look at the same spot on your nose for about a minute, then look at the white paper.

It will be a very beautiful experience.

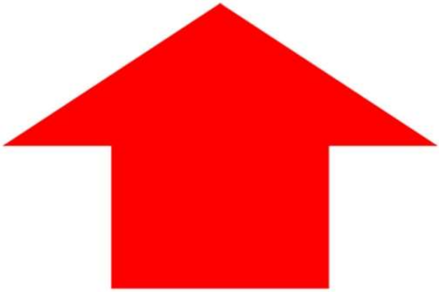


Figure 173. R/C.

Figure 174. G/M.

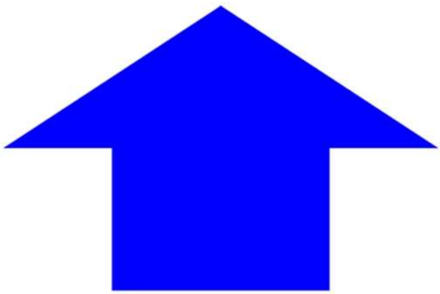


Figure 175. B/Y.

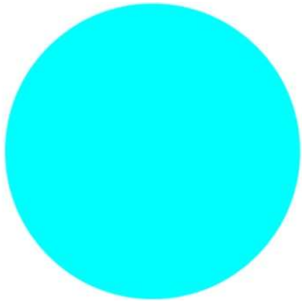


Figure 176. C/R.

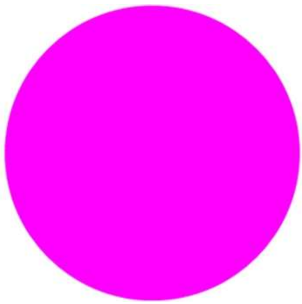


Figure 177. M/G.

Figure 178. Y/B.

Figure 179. Leonardo da Vinci – Monalisa, La Gioconda.

28. Dimension and dynamics of color and light

Differences in paint color and lighting level will cause changes in the visualization of the space.
If we apply the same painting to two walls and make light with different intensities, the wall under the effect of more light will appear lighter, the other darker.

28.1 Perception of space

Figure 180. Perception of Space.

28.2 Distance

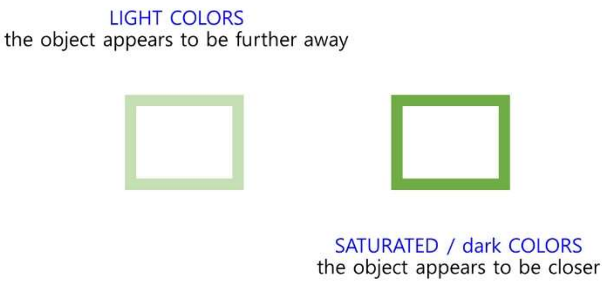


Figure 181. Distance.

28.3 Dimension

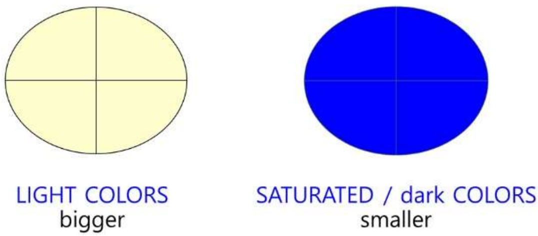


Figure 182. Dimension.

28.4 Weight

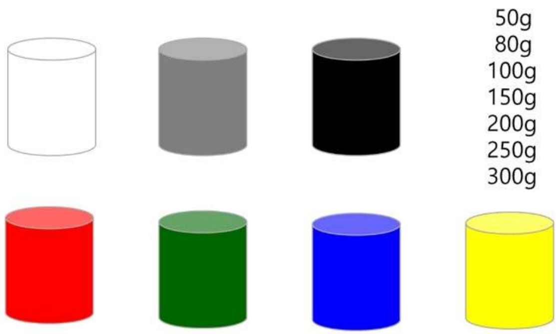


Figure 183. Weights.

Put the containers and their respective weights in order, write down the colors and weights on the blank sheet, do not look at the result on the next page.

Figure 184. Results.

28.5 Temperature

Figure 185. Temperature.

Which red star looks the hottest? And which green?
Wow, the warmest green for a cool color.

Figure 186. Results.

29. Chromatic project

You can think of the next items in order or without the obligation to follow the sequence, but they will be good guidelines.

Capture attention.

Evoke an atmosphere.

Communicate a style.

Tell stories.

Show the morphological characteristics of the space / object.

Provide rhythm.

Now is the time to define hues and use them by alternating their luminance and chroma characteristics.

You must decide on the dominant, accentuated and intermediate colors.
The dominant is the one who will be present in the largest area; the accent will be the one that will create some kind of contrast with this dominant and the intermediary, in turn, will make the connection between the previous two colors.

30. The past, nowadays and the future, no order

30.1 Optic fiber

Narinder Singh Kapany, 1952. Jean Daniel Colladon, 1841.
The light source and energy are far from the fiber.
The quality of the lighting depends on the light source.

Figure 187. End glow.[36]

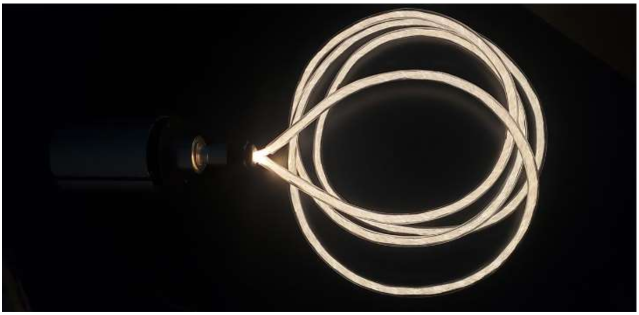


Figure 188. Side Glow.[37]

Figure 189. Crystal tip.[38]

[36] Endlight set of 36 W LED light source and different diameters of end emiting fiber optic cables, designed and manufactured by FASA Fiber Optics. Photo: FASA Fibra Ótica.

[37] Side emitting Fiber Optic – FASA Fibra Ótica. Photo: FASA Fibra Ótica.

[38] Crystal 12 mm end piece for use with FASA optical fibers .Photo: FASA Fibra Ótica.

Figure 190. Starry effect with crystals.[39]

Figure 191. Work in progress, luminous fabric.[40]

[39] Starry effect with crystals - Espaço Imperatriz 23 - FASA Fibra Ótica – Lighting Project: Scene Lighing Design. Photo: Rubens Campo.

[40] DreamLux® by Samsara S.r.l.

Figure 192. Luminous fabric.[41]

30.2 Holography

Holograms are 3D images generated by techniques for recording light interference patterns. Dennis Gabor, 1948.

Internet

Museum of Holography.

Magic Leap.

30.3 LiFi

Technology for wireless communication between devices that use LIGHT (currently the LED) to transmit data. Harald Haas lecture in 2011 at TEDGlobal (ideas worthwhile) in Edinburgh.

Internet

LiFi.

[41] DreamLux® by Samsara S.r.l.

30.4 Graphene

Massachusetts Institute of Technology (MIT) researchers realized that by illuminating graphene, on a sheet of carbon the thickness of one atom, it is possible to let electricity flow.

Internet

Graphene.

30.5 Incandescence

That was the starting point, the light emitted by an incandescent object**.**

Figure 193. Incandescence.[42]

Over time, the need for a portable light emerged, so that we could move more accurately at night, the solution was torches. Then ancient oil lamps and so on. Various materials and oxidizers were used to make light.

[42] CCO from Pixabay

The advent of electricity was extremely important for us to abandon combustion, but we were still burning tungsten.

Figure 194. Gas lamp refurbished - Newark, USA.

Figure 195. Halogen lamp with diffuser bulb.

Internet
Research each of the ways to generate light more deeply.

30.6 Luminescence

The spontaneous emission of light by a substance not deriving directly from heat.

30.6.1 Chemiluminescence

The emission of electromagnetic radiation, particularly in the visible and near infrared; which can accompany a chemical reaction.
Those glowsticks they use at parties, you know?

30.6.2 Photoluminescence

The set of processes by which certain substances absorb photons, under the effect of the incident electromagnetic radiation, and then re-emit them in all directions.

30.6.2.1 Fluorescence

An energy source, usually composed of visible light or ultraviolet radiation, excites the atoms, causing some electrons to jump to an outermost orbit, when they return to the inner orbit they emit light.

30.6.2.2 Phosphorescence

It differs from fluorescence because in the latter the effect is immediate and ceases as soon as the energy source is interrupted, while in phosphorescence the effect continues even after.
Do you remember the little stars and spaceships that we used to put on the roof of the house and, when the light was turned off, we could see shining?

30.6.3 Radioluminescence

The phenomenon whereby light is produced in a material by bombardment with ionizing radiation such as beta particles.
For example some car panels and clocks.

30.6.4 Sonoluminescence

Emitting short flashes of light from bubbles that implode in a liquid when excited by sound.
It is a physical phenomenon in which sound energy is transformed into light, it has been known since the early 1930s.

30.6.5 Thermoluminescence

It is a physical phenomenon of light emission by some crystals when heated with boiling water.

30.6.6 Cathodoluminescence

We mean the light emitted by a sample as a result of the excitation of the electron beam and observed in a scanning electron microscope.

30.6.7 Triboluminescence

A particular type of luminescence that occurs in some materials which, subjected to mechanical stress, emit part of the absorbed energy in the form of electromagnetic waves.
A famous experience with images is a shot that hits a life safer.

30.6.8 Electroluminescence

It is a particular type of luminescence that characterizes some materials capable of emitting light under the action of an electric field when crossed by an electric current.

30.7 LED - Light Emitting Diode

30.7.1 Enhancement of architecture: point, line and surface

With the advent of LED we can use this light source punctually, forming lines or participating in light plans.

Internet

Luminaire de Cagna – Ghent.

30.7.2 Integration and discretion of the source

One of the biggest aesthetic advantages of LED, in addition to miniaturization, is clean mounting.

30.7.3 Individual control of the single LED

The material used in the semiconductor element of an LED determines its color. LED voltages: R - 2.18V, G - 3.70V, B - 4.00V. If we set the voltage to red the blue will look dark, if we set the proper voltage to blue the red led will burn out first.
Average lifespan x luminous flux.
The “pure” white LED is achieved by using several layers of yellow phosphor above a blue LED.

30.7.4 Very good luminous efficacy

Longer lifespan than incandescent, halogen and fluorescent lamps.
This concerns the LED but the electronic circuit will be damaged first...

30.8 OLED and QLED

Organic Light Emitting Diode (OLED), an organic film is the electroluminescent layer that emits light in response to an electric current.
It permits curved panels.

Figure 196. OLED Panel.

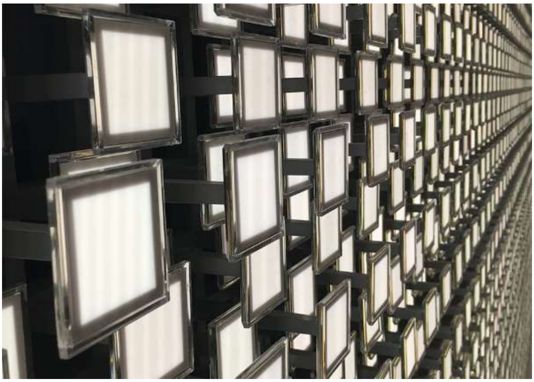


Figure 197. OLED panel seen up close.

Quantum Dots Light Emitting Diode (QLED) consisting of cadmium selenide nanocrystals that absorb light and re-emit it in a specific wave.
Cheaper than OLEDs as they do not require the complexity of organic chemistry.
Probably in the future, air transport vehicles will no longer have windows, they will have external cameras that transmit images to the interior of the aircraft, then we saw all the sky! Maybe the floor will be made by screens?
I have one more atrocious doubt. If your TV has a lower quality how can you watch the demonstration in an advertisement that the 4K picture is better if your TV is not 4K???

30.9 Bioluminescence

Study the processes used by animals to emit their own light.

Internet
Glowee.

By tinkering with the chemical composition of luciferase (a bioluminescent enzyme), the Japanese research team managed to change the emission color from its normal greenish yellow to orange and red.
Researchers from Institute of Physical and Chemical Research (RIKEN) and Kyoto University are now attempting to recreate the blue glow of the sea firefly (*Vargula hilgendorfii*) and firefly squid (*Watasenia scintillans*) so that they have all three primary colors at hand.

Figure 198. BIO RGBWAUV? [43]

There is a modernity for each era of humanity, the here and now.
Lasers are starting to be used in place of LEDs.
The future is the tomorrow of the time we witness now, but it is the yesterday of an even more distant future.

[43] Photo: Camila Perrenoud

Figure 199. Dark and light. [44]

YES, WE CAN DRESS SOMEONE WITH DARK AND LIGHT.

[44] Model: Nicole Curtinovi Martins. Photo: Camila Perrenoud.

31. Conflict of interest declaration

The authors declare no conflict of interest.

32. Funding source declaration

The authors received no specific funding for this work.

33. Acknowledgment

First of all, thank you to my family, my kids Camila and Felipe for always being so helpful. My wife Simone Lopes, for following my divergent thoughts. I dedicate this chapter to my mother, Lia, who is so dedicated to our family and to my brother Gastão, who is so dedicated to her.
I would like to express my special thanks to professors Maurizio Rossi and Alessandro Rizzi for the invitation to participate in this project so beautiful and so important for the academic world and for society as a whole, I hope I have fulfilled the task of contributing to the perpetuation of the study and the knowledge for future generations of students and those interested in Color and Lighting Design.

34. Short biography of the author

Osvaldo Perrenoud was born in Rio de Janeiro, Brasil. He received the Master Degree in Color Design & Technology from Politecnico di Milano, Italy, in 2018. Previously he did a Master in Methodology of University Education at Instituto Porto Alegre (IPA), Brasil in 1986 and a Master in Lighting and Interior Design at Instituto de Pós Graduação (IPOG), Brasil in 2010. He is a COLOR AND LIGHTING DESIGNER, working in this area since 1979; he works as a DIRECTOR OF PHOTOGRAPHY at the company Desenhos de Luz located in Brasil.
Mr. Perrenoud currently lives in Genova, Italy, is an external researcher at MIPS (Department of Computer Science) at Università Degli Studi di Milano and teaches as a guest professor at Politecnico di Milano and Fondazione Luigi Clerici, both in Milan, Italy.