Couleur - Perception - Transfert

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(Cours basé sur les ressources transmises par Julie Delon)

MVA Introduction à l'Imagerie Numérique
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Introduction

Today, we will tackle the following subject:

- How the Human visual system perceives colors.
- How we can build models for the space of perceived colors.
- How we can correct an image with non white illuminant (white balance).
- How color is acquired through a camera sensor.
- How optimal transport can be used to transfer colors between two images.

Plan

Introduction

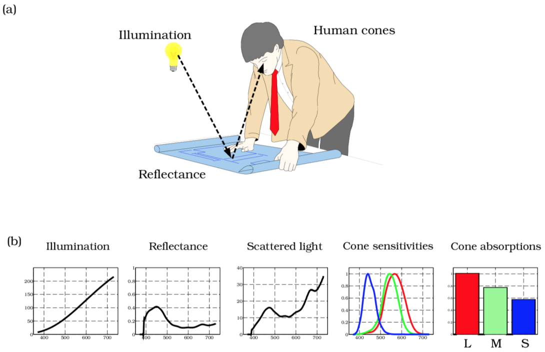


Figure 3.1: Illustration of main components in color image formation. a) Example of light interacting with reflective surface and reaching human retina. b) The plots show scattered light as a product of illumination and reflectance, and the amount of cone absorptions. Image courtesy of [Wandell 1995].

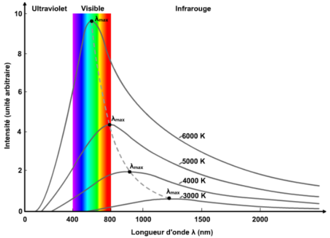
Lights and Illuminants

Visible spectrum : wavelengths between $\lambda_{min} = 380\text{nm}$ and $\lambda_{max} = 700\text{nm}$.

Monochromatic illuminant : illuminant whose spectral distribution is a Dirac mass on a single wavelength.

Black body at temperature T: Ideal object whose radiation depends only on its temperature:

$$I(\lambda) = \frac{2hc_\lambda^2}{\lambda^5}\frac{1}{e^{\frac{hc_\lambda}{k\lambda T}} - 1}.$$



[Source: F. Bouquet, Univ. Paris Sud]

Illuminated objects

Assume that we illuminate an object with an illuminant with spectral distribution
The spectral response $R(\lambda, x)$ of the object at point x is a linear combination of

- a Lambert part
- a specular part which depends of the angle of observation of the point x

To know more, see
[S.A. Shafer, Using color to separate reflection components, Color. Res. Appl. 10 (1985), no. 4, 210–218.]

Observer

Classical hypothesis : 3 types of photorecepters with spectral sensitivities ρ_r, ρ_g et ρ_b

Practical realization:

- Eyes of primates: 3 types of cones
  (Remark: only 2 for other mammals and up to 5 for certain birds)
- Standard camera sensor : 3 types of cells (red, green, blue)

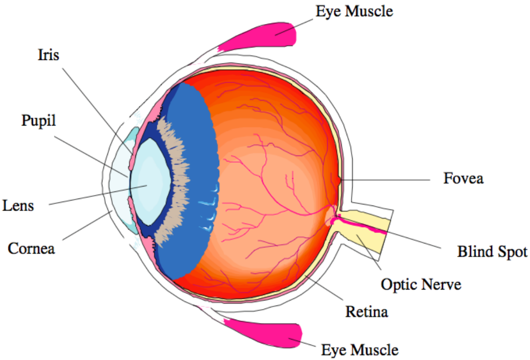
The energy measured at point x for receptor of type $c \in \{r, g, b\}$ is

$$q_c(x) = \int I(\lambda) R(\lambda, x) \rho_c(\lambda) d\lambda$$

where

- $I(\lambda)$ is the spectral distribution of the illuminant
- $R(\lambda, x)$ is the spectral response of the object at point x
- $\rho_c(\lambda)$ is the sensitivity of the photoreceptor at wavelength λ.

The Eye Optical System



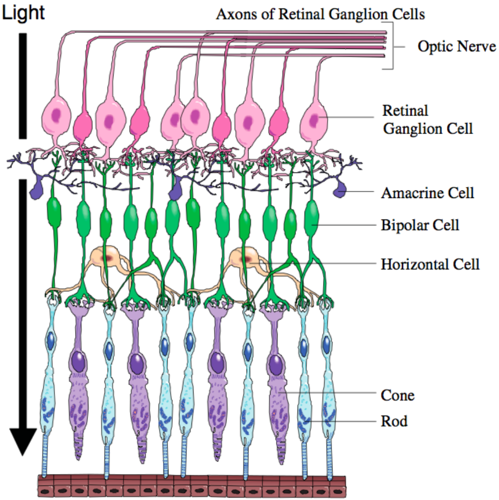
Fovea : part of the retina where the vision is the most precise (high density of photoreceptors).

Blind spot near the optical nerve.

Cellules de la rétine

Optical nerve $\simeq 10^6$ fibers which convey information from 10^8 photorecepters...

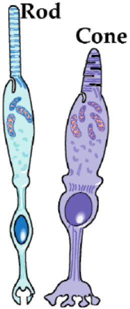
$\rightarrow$ **high compression** in the retina cells

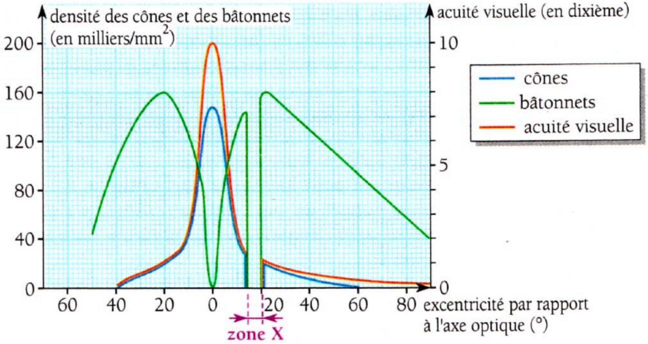


Cones and Rods

Photorecepters on the retina :

- **rods** (*bâtonnets* in French), very sensitive but not precise (night vision)
- **cones** (*cônes* in French :-)), much more precise but less sensitive (day vision, color perception)

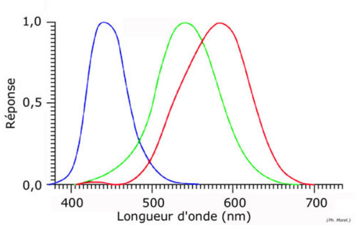




Cones

There are three types of cones:

- 4% of cones of type S (“short”, 440 nm) for **blue-violet**,
- 32% of cones of type M (“medium”, 545nm) for **green**,
- 64% of cones of type L (“long”, 580nm) for **yellow-red**.



Cones M,L have **higher sensitivy** than cones S,
meaning that the eye responds more to some wavelengths at equal light intensity.

Cones S are scattered at the periphery of the fovea.

Normalized eye sensitivity $V(\lambda)$ is maximal for $\lambda \simeq$ 555nm at day and 500nm at night.

Metamerism

If ρ_s, ρ_m, ρ_l are the sensitivities of cones S, M, L, a light $I(\lambda)$ is perceived as

$$(\langle I, \rho_s\rangle, \langle I, \rho_m\rangle, \langle I, \rho_l\rangle)\,, \quad \text{where} \quad \langle I, \rho_c\rangle := \int_{\lambda_{min}}^{\lambda_{max}} \rho_c(\lambda) I(\lambda) d\lambda.$$

Therefore, the space of perceived colors is at most 3-dimensional.

NB: Because the sensitivities overlap, it is impossible to stimulate one type of cones separately. (Even the elementary triplet $(1, 0, 0)$ stimulate two cones!)

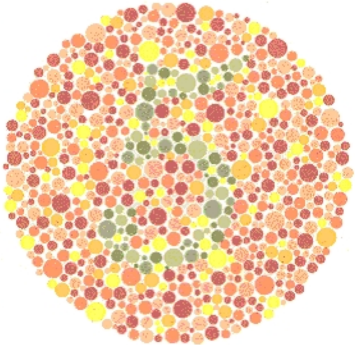
Two objects with spectra R_1, R_2 seems identical under an illuminant I if :

$$\langle I.R_1, \rho_c\rangle = \langle I.R_2, \rho_c\rangle, \ \ \forall c \in \{s, m, l\}.$$

Warning: this property depends strongly on the illuminant!

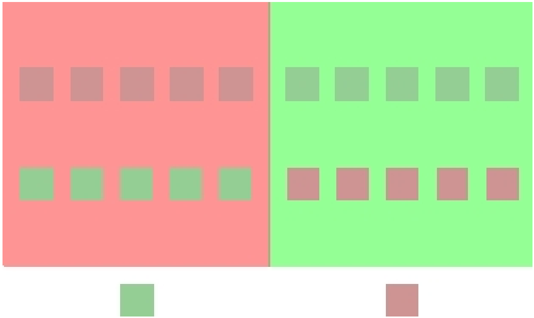
Daltonisme

Il existe différents types d'anomalies visuelles liées à la vision des couleurs. Selon les pigments atteints, on parlera d'achromatisme, de dichromatisme, ou de trichromatisme anormal.



Quelques principes élémentaires de la perception couleur

Sensibilité au contraste local.



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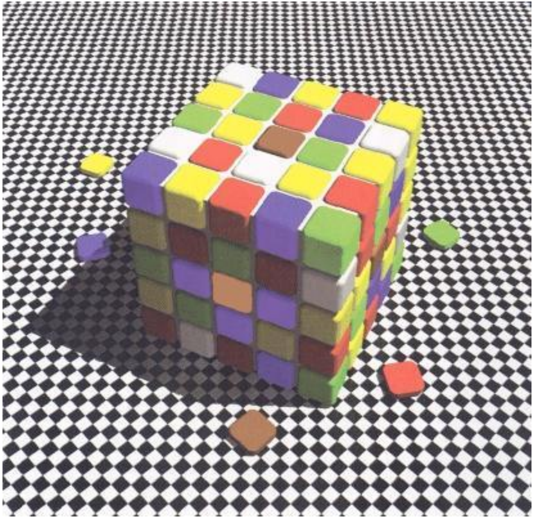


Opposition de couleur

Oppositions rouge / vert et bleu / jaune.
Découvertes par Ewald Hering (1834–1918). Confirmées dans les années 50/60 par la découverte de cellules sensibles aux opposition de couleur dans la rétine et dans le cortex.

Plan

Additive Synthesis

- Visual trivariance expressed by Grassman after his experiment in 1853:
  “Tout stimulus coloré peut être reproduit par un mélange additif de trois primaires convenablement choisies".
- Description of Grassman’s experiment:
  - show on a screen one unknown color from the visible spectrum (from 400nm to 750nm)
  - show a combination of three fixed primary lights (each with a single wavelength)
  - the observer adjusts attenuations of the three primaries in order to match the unknown color
- This experiment was later refined by Wright and Guild (mid-1920’s).
  They showed that, for some of the colors, one of the primary should be negatively weighted.

The CIE Experiments

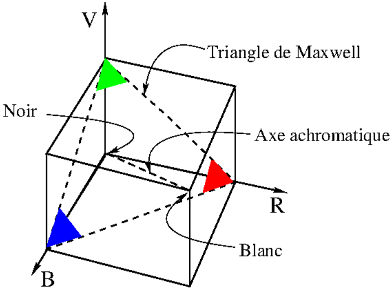
- The “Commission Internationale de l’Éclairage” (CIE) reproduced the experiments of Grassman and Wright-Guild in a normalized and more reproducible way.
- Experiment: an observer tries to reproduce a monochromatic stimulus $L(\lambda)$ by mixing three monochromatic light sources of wavelengths $(\lambda_B, \lambda_G, \lambda_R) = (436, 546, 700)$ nm.
- The observer can attenuate each primary to reach the equilibrium “one monochromatic stimulus = one mixing of the three primaries”
- If this equilibrium cannot be reach, then one tries to reach another equilibrium “one monochromatic stimulus + one primary = one mixing of the two other primaries”

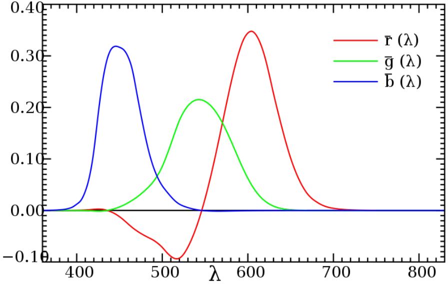
The Color Space CIE-RVB 1931

- For each wavelength λ of the monochromatic stimulus S, by averaging over $\approx$ 10 observers, they obtained average coefficients $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$ so that

$$S \quad \text{looks like} \quad \bar{r}(\lambda)\delta_{\lambda_R} + \bar{g}(\lambda)\delta_{\lambda_G} + \bar{b}(\lambda)\delta_{\lambda_B}.$$

- This color representation is called CIE-RVB (and often refered to as the “RGB cube”).
- This confirmed that for a large part of the spectrum, some negative weights appear.

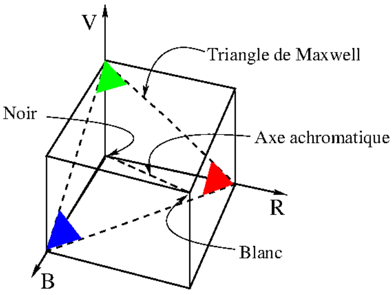


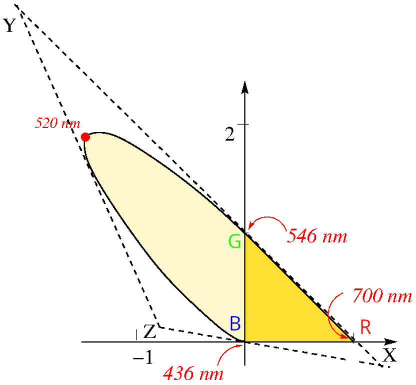


RGB Space vs Perceptible Colors

- We often display "normalized" colors.
- For example, divide RGB by $R + G + B$, or equivalently, consider the plane

$$R + G + B = 1.$$





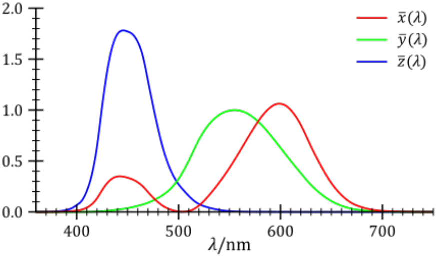
Due to negative weights $\bar{r}, \bar{g}, \bar{b}$, perceptible colors are not all in the triangle (R, G, B).

Color Additive Systems

- In 1931, the CIE proposed a new color system denoted by CIE-XYZ.
- It amounts to fix three new primitives with explicit RGB coordinates

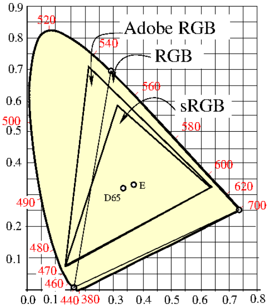
$$
\begin{aligned}
P_X &= (2.37067, -0.9, -0.47063) \\
P_Y &= (-0.51388, 1.42530, 0.08858) \\
P_Z &= (0.055298, -0.14695, 1.00939)
\end{aligned}
$$

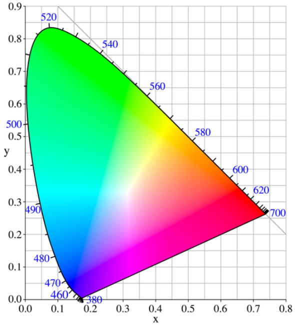
- In the XYZ system, any monochromatic stimulus with wavelength λ can be decomposed with non-negative weights $(\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda))$.



Chromaticity Diagram

- We can also look at colors in the plane $X + Y + Z = 1$.
- All "perceptible colors" can then be represented in a two-dimensional "chromaticity diagram". This diagram is often called the "CIE xy diagram" (see below on the right).
- The RGB triangle can be represented as a region of this diagram.
- The upper border of the diagram corresponds to pure wavelengths.



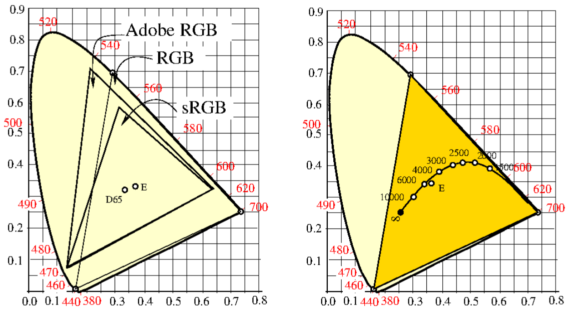


The Gamut of a Device

- Let us consider a device (printer, screen, etc) that can reproduce colors.
  Usually this device is based on three primitives (for example, red, green, blue for a screen).
- Doing all physically-possible combination of the primitives, we get the set of reproducible colors.
- This set of colors that can be reproduced faithfully is called the **gamut** of this device.
  (It can be represented in the same manner as the chromaticity diagram.)
- Some choice has to be made (projection?) in order to display one color outside the gamut.
- **Tone mapping** consists in making a correspondence from a color set to the gamut of a device.

Fifty Shades of White

- There exist several possible definition of “white”.
  In some languages (inuit), there are even many words that correspond to variants of white.
- Equienergetic white (w.r.t. wavelength) is denoted by E.
- Other white references Dxx are located on the Planckian locus (“lieu des corps noirs”)
  Dxx corresponds to the color of a black body of temperature xx00 Kelvin.



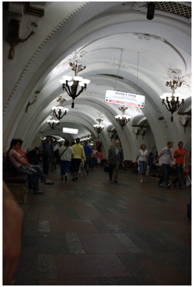
White Balance

Performing the white balance of an image consists in

- estimating the illuminant of the scene,
- transforming the colors to simulate a standard illuminant (a white reference).

This is usually implemented very simply: find a RGB value (x_w, y_w, z_w) that should correspond to white (for example by deciding that one pixel should be white), and then apply to all pixels

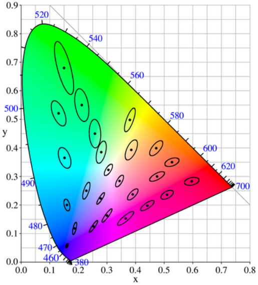
$$(x, y, z) \mapsto \left(\frac{x}{x_w}, \frac{y}{y_w}, \frac{z}{z_w}\right).$$



RGB Limitations

The RGB space has several drawbacks

- R,G,B components are strongly correlated (less green ⇔ more red)
- difficult to separate intensity and chroma
- distance in RGB space is far from percetual distance



MacAdam ellipses

In each ellipse, any color cannot be distinguished from the central color by a Human observer.

Lab Space (CIE 1976)

In 1976, the CIE introduced the Lab space to better account for perceptual color distances. It is defined from the XYZ space in the following way.

- A white reference (X_n, Y_n, Z_n) is chosen depending on the current illuminant.
- The **luminance** L is inspired by a law of logarithmic sensitivity (Weber-Fechner):

$$L = 116(\tfrac{Y}{Y_n})^{1/3} - 16.$$

- **Chrominance** coordinates a, b are defined between opponent colors

$$a = 500\left[(\tfrac{X}{X_n})^{1/3} - (\tfrac{Y}{Y_n})^{1/3}\right] \quad , \quad b = 200\left[(\tfrac{Y}{Y_n})^{1/3} - (\tfrac{Z}{Z_n})^{1/3}\right].$$

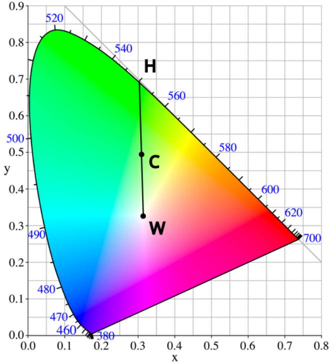
This Lab space allows to compute more relevant **color differences** :

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}.$$

Hue and Saturation

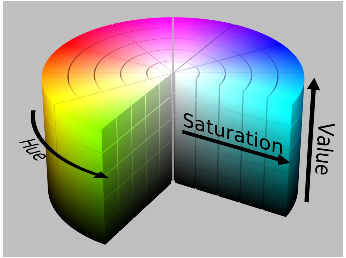
Once a white point W has been fixed in the gamut, one can define hue and saturation of a color C:

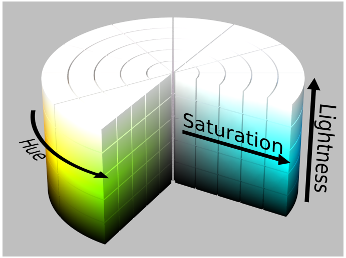
- **Hue**: intersection of the line (WC) with the upper border of the diagram.
- **Saturation**: distance WC in the gamut.



Other Colors Spaces

- Two color spaces HSV, HSL were proposed with cylindic/conic representation of the colors.
- They are based on some notions of
  Hue (Teinte) H (color sensation). **The hue is an angle!!!**
  Lightness L or **Value** V (lighter or darker)
  Saturation S (mixing degree between white and the hue pure wavelength)





Remark: There exist other simpler color spaces (e.g. YUV) that are simple linear transforms of RGB coordinates, and which were used along the development of standards of television.

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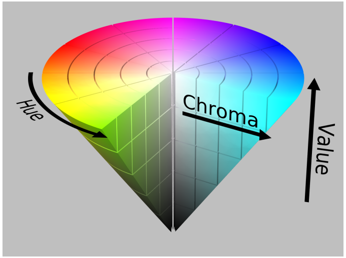

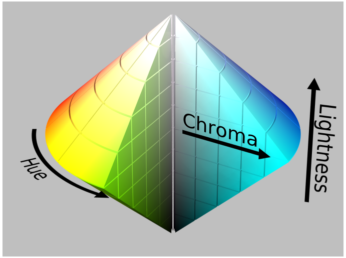

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Plan

Tone mapping [Durand-Dorsey, 2002]

How to display an high-dynamic range (HDR) image on a standard screen?

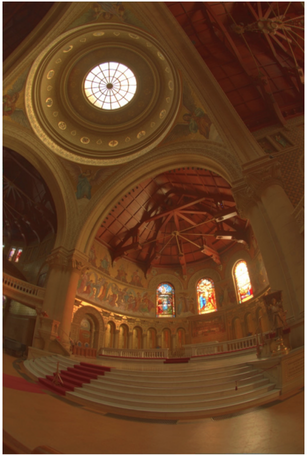
1. Decompose *u* with a multiplicative smooth base:

$$u_{HDR} = u_{smooth} \times (u_{HDR}/u_{smooth})$$

2. Reduce contrast of the base (with a contrast change *g* that shrinks the dynamics)

$$u_{LDR} = g(u_{smooth}) \times (u_{HDR}/u_{smooth}).$$

Tone Mapping Example



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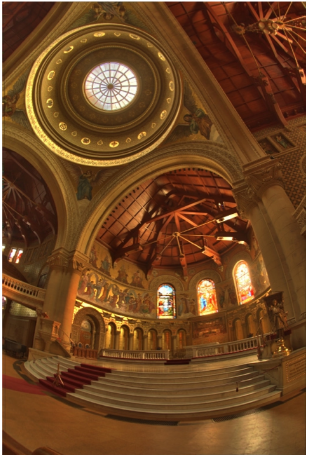
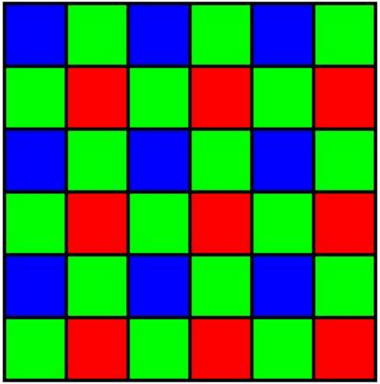
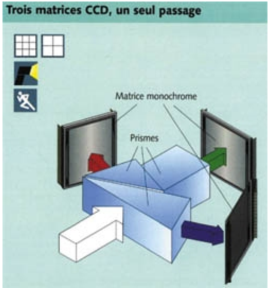


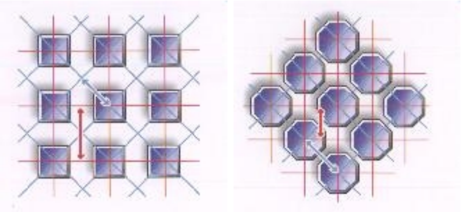
Capteurs couleur

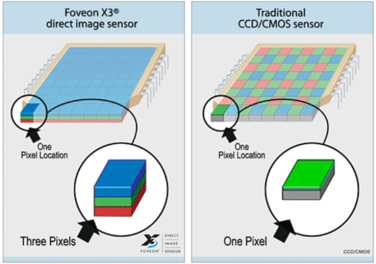
Capteur CCD : trame de Bayer ou Bayer color filter array (CFA), 1976.

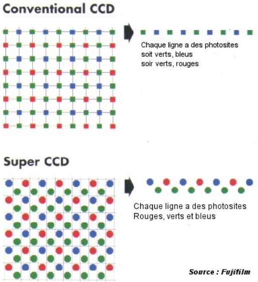


Capteurs couleur alternatifs



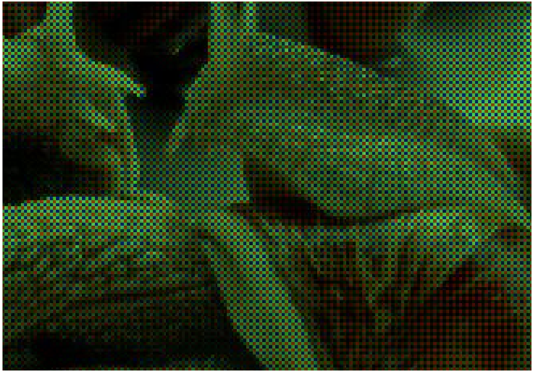






Trame de Bayer

Exemple d'image obtenue par la trame de Bayer (fichier RAW).



Fichier RAW (12 bits) compressé sans perte $\underbrace{\longrightarrow}_{\text{interpolation}}$ Fichier TIFF ou JPEG 24 bits.

Trame de Bayer

Exemple d'image obtenue par la trame de Bayer (fichier RAW). Après démosaïquage.

Fichier RAW (12 bits) compressé sans perte $\underbrace{\longrightarrow}_{\text{interpolation}}$ Fichier TIFF ou JPEG 24 bits.

Interpolation bilinéaire

→ satisfaisant dans les régions homogènes mais lissage des bords et textures et apparition de fausses couleurs, en particulier près des bords ou des zones hautes fréquences présentant des motifs complexes (interpolation naïve d'images aliasées).

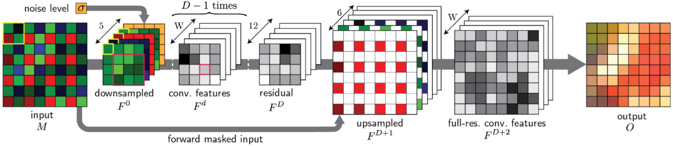
Algorithmes de détramage

Algorithmes classiques.

- interpolent d'abord la composante verte à l'aide de tous les pixels connus, en privilégiant certaines directions (estimation de dérivée par des schémas discrets)
- interpolent ensuite b/g et r/g

[Cok (1986), Hibbard (1995), Hamilton et Addams (1997), Kimmel (1999), Hirakawa et Paks (2005), Buades et al. (2007), Kiku et al. (2014), etc...]

Apprentissage profond Plus rapides et résultats nettement supérieurs aux méthodes classiques.



[Gharbi et al. TOG 2016, Tan et al. 2017...]

Exemples de résultats

Groundtruth

Bayer mosaicked

[Gharbi et al. 2016]

Essayez par vous-mêmes : **`https://www.ipol.im/pub/art/2019/274/`**

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