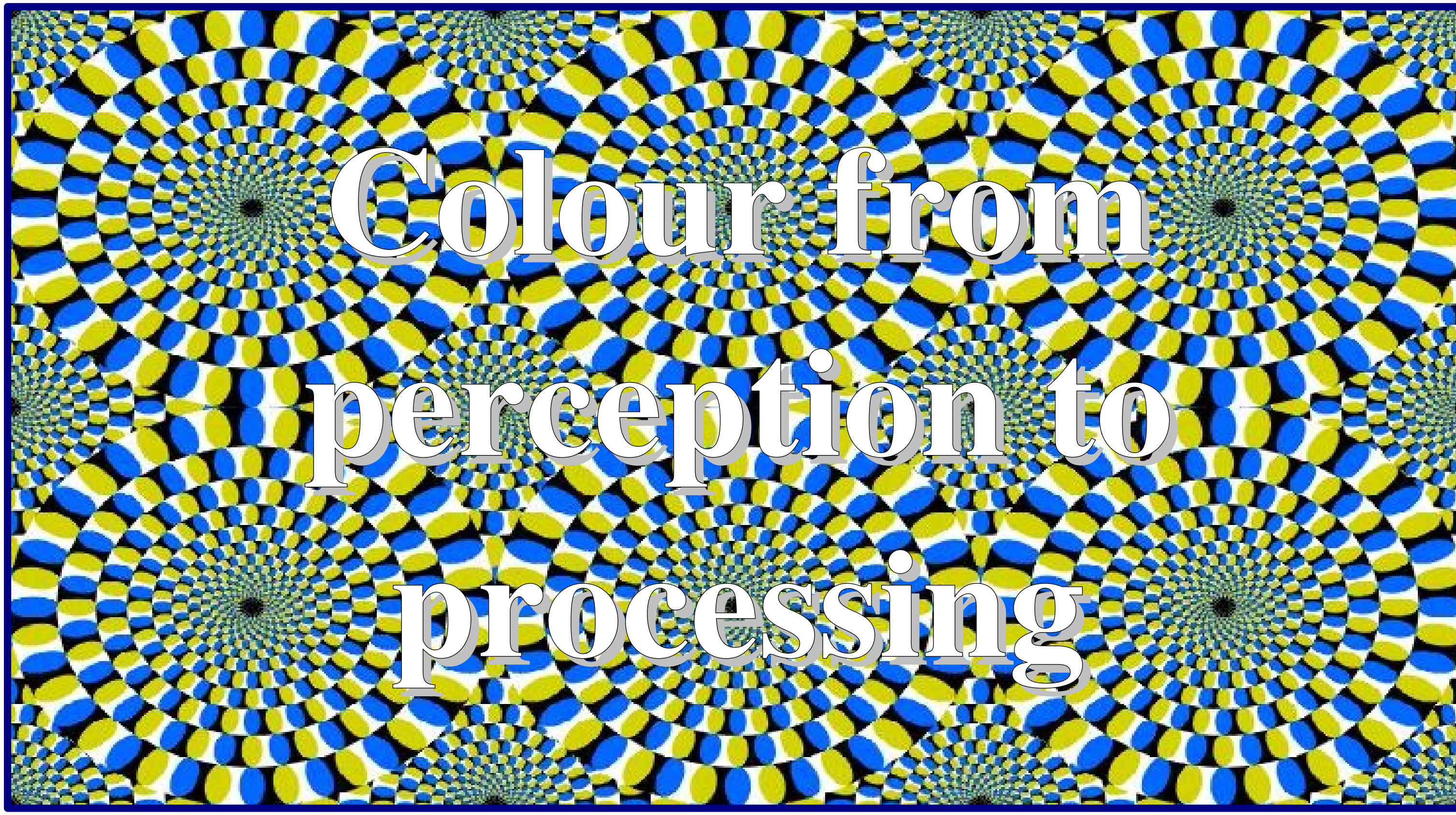
Colour from perception to processing



Title background : Rotating snakes illusion, by Akiyoshi KITAOKA

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ENSTA ParisTech

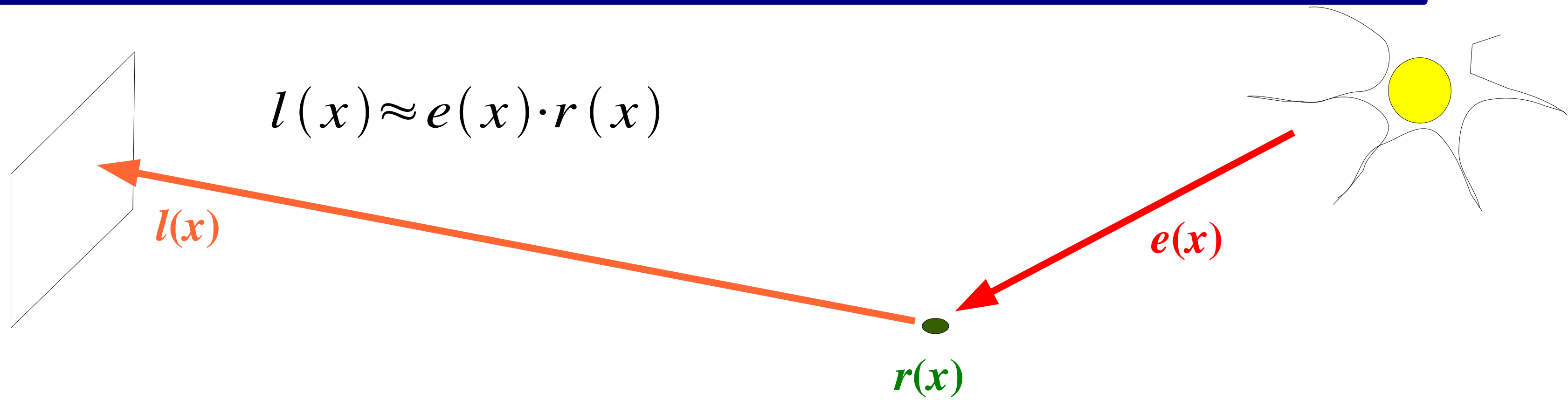
An introduction to **Colour...**

Colour: perception, modelling and processing

- *Introduction: shadows and reflectance*
- *Physical and perceptual aspects*
- *Acquisition and Rendering of Colour*
- *The colour spaces: RGB, XYZ, HSV, Yuv*
- *Colour image processing*

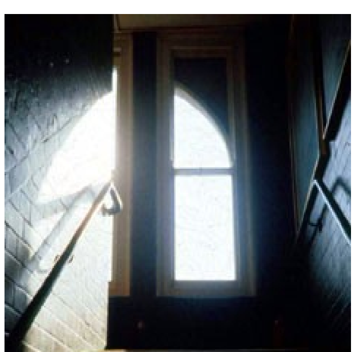
Gray level and reflectance

$$l(x) \approx e(x) \cdot r(x)$$



- **What is measured by the sensor**: ***intensity of the reflected light flow l(x) = r(x).e(x).***
- **What is actually significant of the object: *reflectance r(x).***
- **But it also essentially depends on: *intensity of the incident emitted light e(x).***

To recover $r(x)$ from $l(x)$ is an *inverse problem* usually solved by transforming $l(x)$, assuming that the emitted light intensity map represents a perturbation (a noise!) which is both *multiplicative* and *low frequency*.



Visible image presenting a wide variation of the lighting function e: the purpose is to recover the reflectance r from the gray level l :

$$l(x) = r(x)e(x)$$

Homomorphic filtering

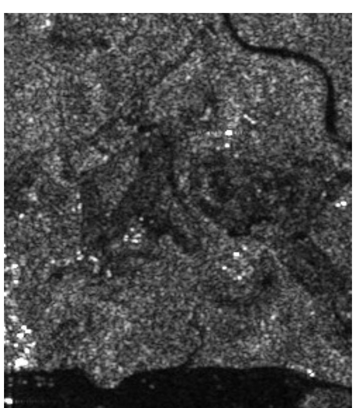
For an additive noise: $g(x) = f(x) + b(x)$, and then in Fourier domain: G(u) = F(u) + B(u).

It is then possible to eliminate B(u) from the spectrum (e.g. Low pass filter), or equivalently, by convolution.

For a multiplicative noise : $g(x) = f(x).b(x)$, there is no longer addition of the spectra, so the direct convolution does not work.

The principle of homomorphic filtering is to get back to the linear case using the logarithm:

$$g \xrightarrow[\text{logarithm}]{} h = \log(g) \xrightarrow[\text{FT}]{} \boldsymbol{H} \xrightarrow[\text{Filter}]{} \boldsymbol{H} \times \boldsymbol{T} \xrightarrow[\text{Inverse FT}]{} k \xrightarrow[\text{exponential}]{} \hat{f} = e^{k}$$



Radar image (SAR): high frequency multiplicative noise (speckle)

Visible image: low frequency multiplicative noise (lighting)

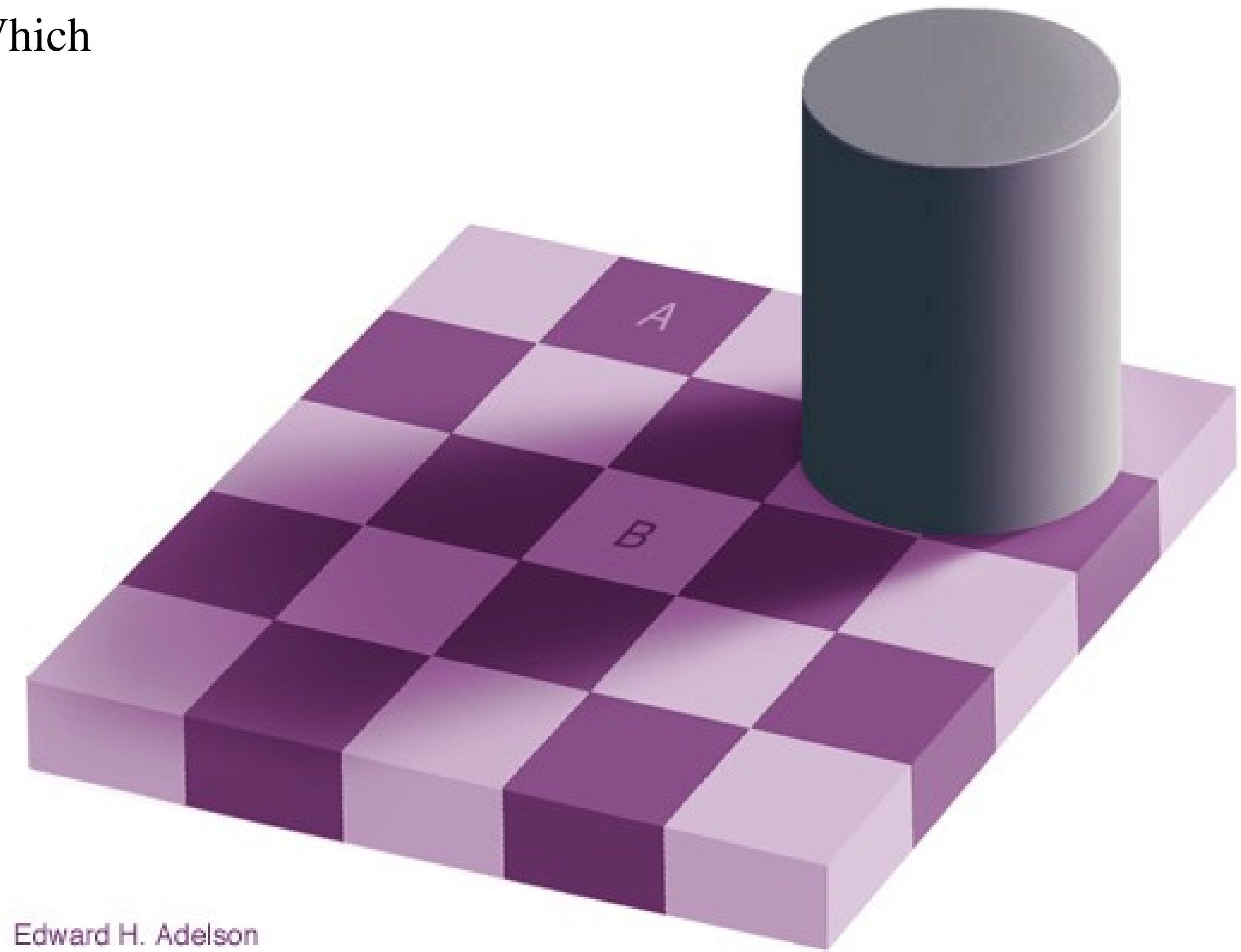
Homomorphic filtering

Gaussian Homomorphic filtering (reduction of frequency band 0,5--1,1) – Agarwal-Gupta.

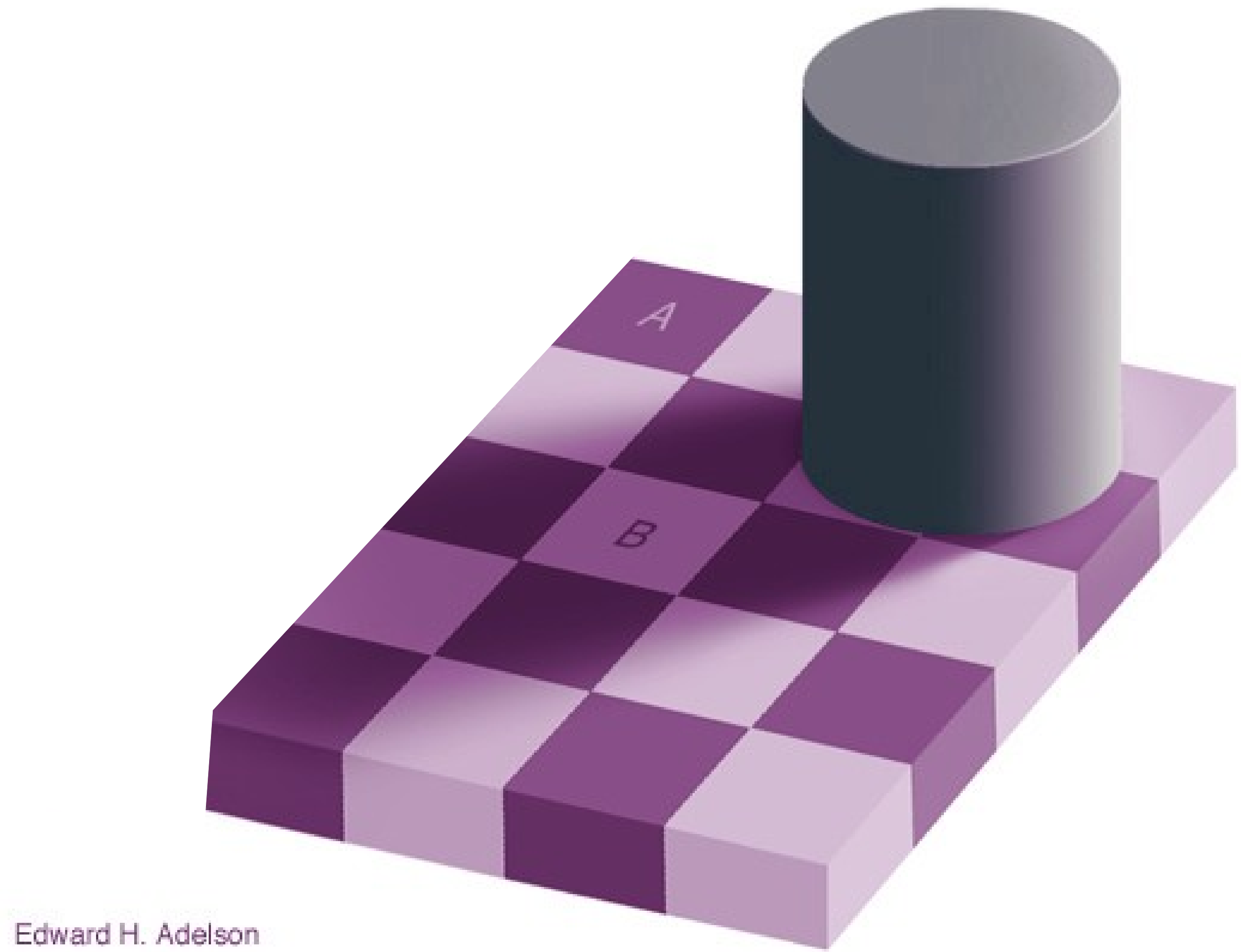
Self shadow / Cast shadow

Colour constancy: an illusion

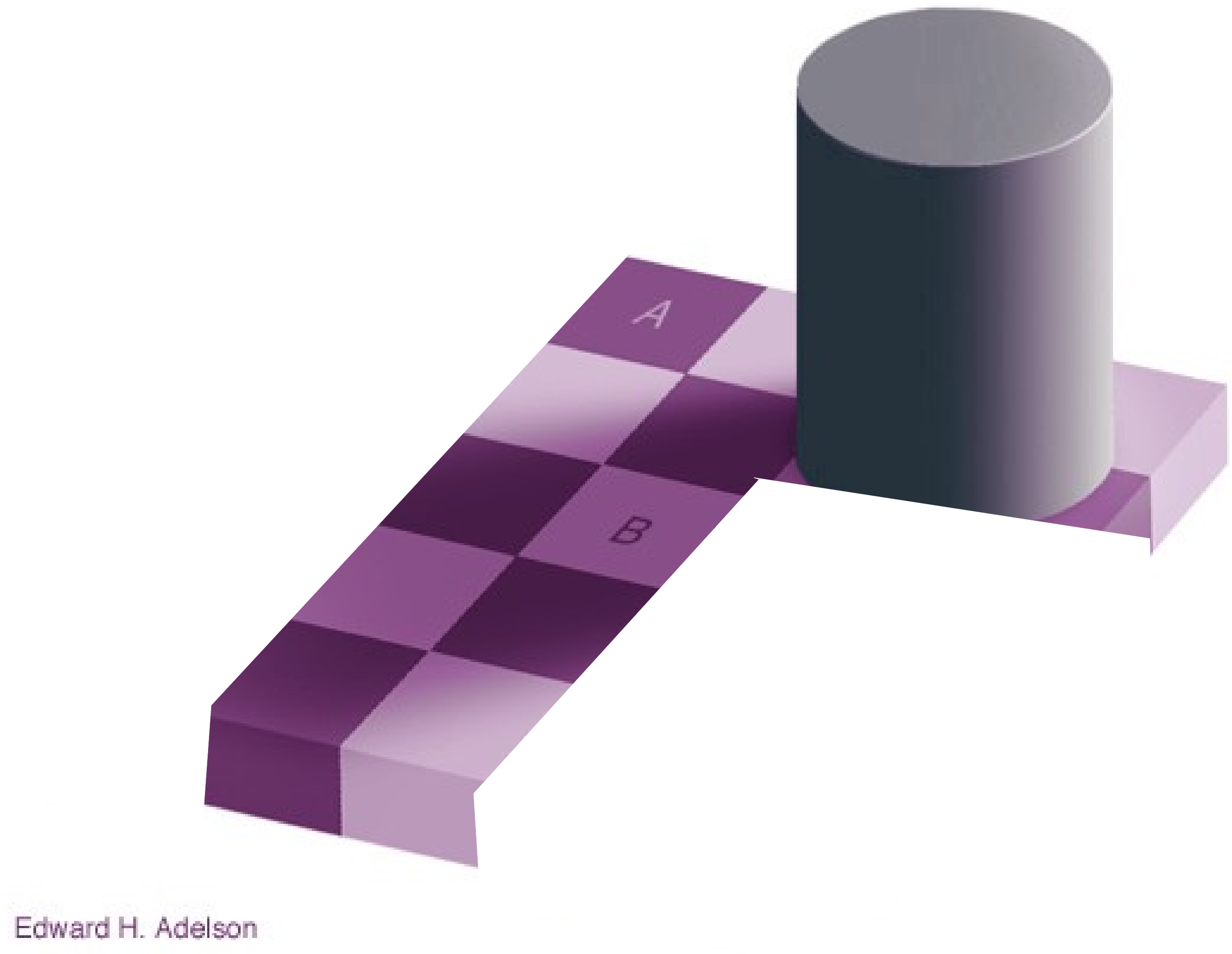
Checker shadow illusion: look at the two areas marked A and B. Which one is the darker?



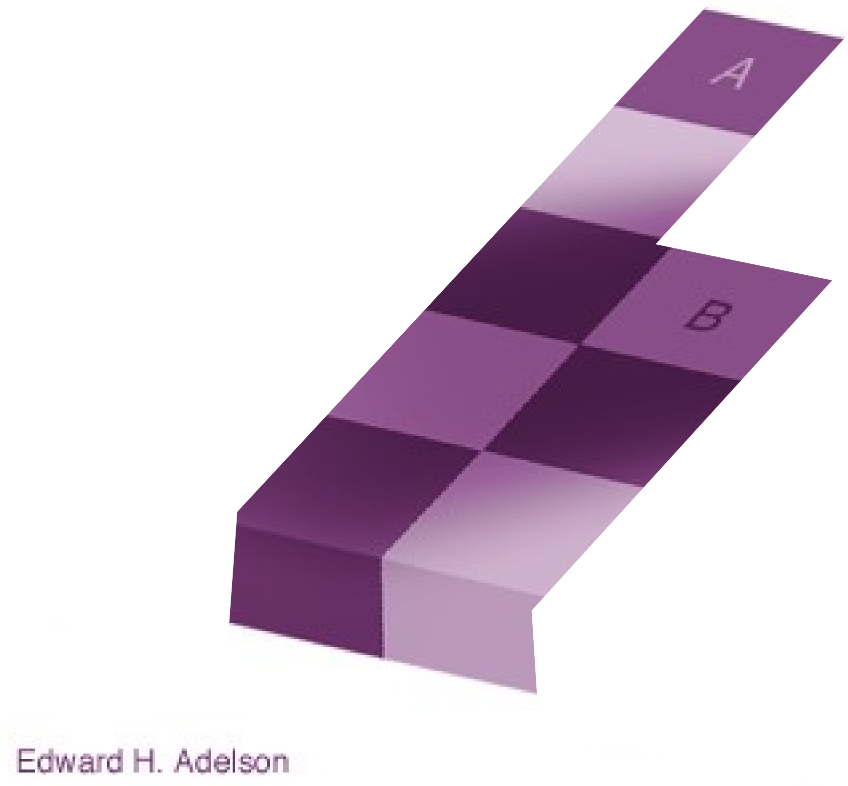
Colour constancy: an illusion



Colour constancy: an illusion



Colour constancy: an illusion

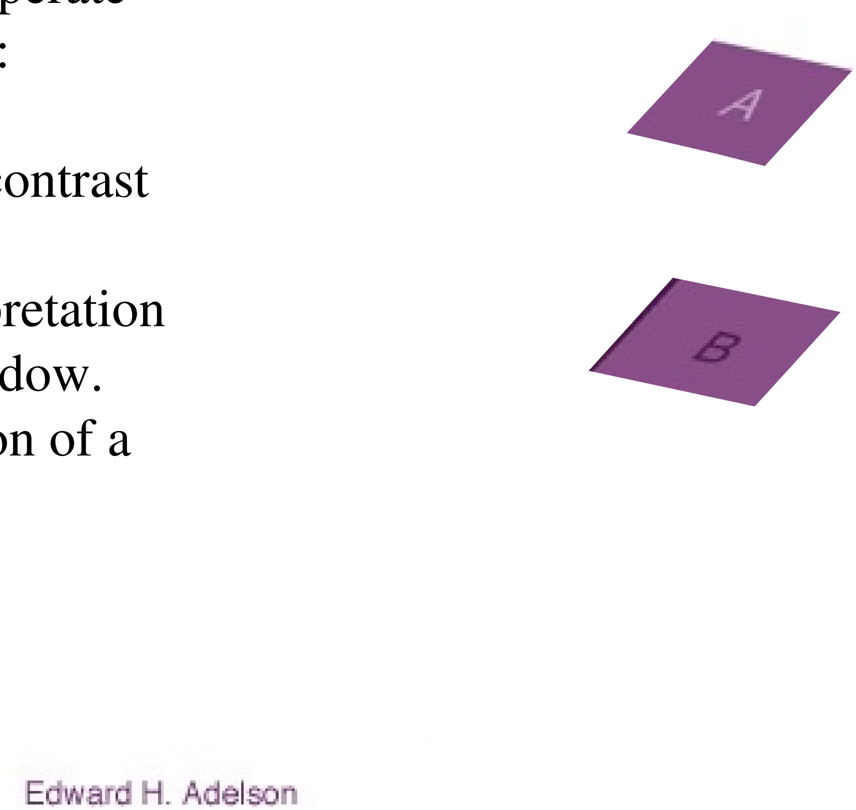


Colour constancy: an illusion

Checker shadow illusion: the areas marked A and B are the same shade of colour.

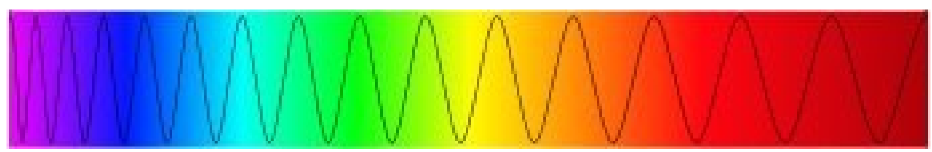
3 levels of perception cooperate towards this illusion:

1) Low level (Retina): local contrast enhancement.
2) High level (Cortex): interpretation and correction of the cast shadow.
3) Very high level: recognition of a checkerboard.

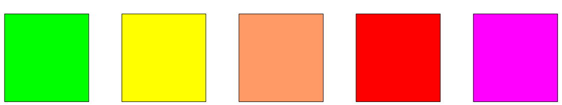


Colour: Introduction

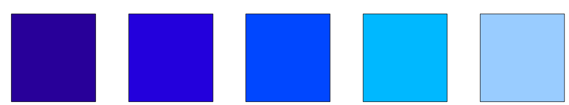
The colours originate in the *separation of natural white light* into *absorbed* and *reflected* components. Every visible light source is made of a *mixture of coherent electromagnetic waves* (i.e. pure colours), whose wavelength is between 0.4 µm (purple) and 0.7 µm (red):



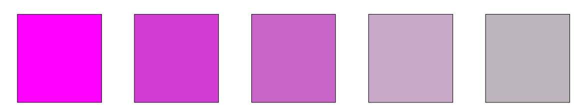
Any mixture of these pure colours generate another colour that can be qualified according to different criteria whose appreciation is more or less subjective:



"hue"



"dark / light"



"bright / faded"

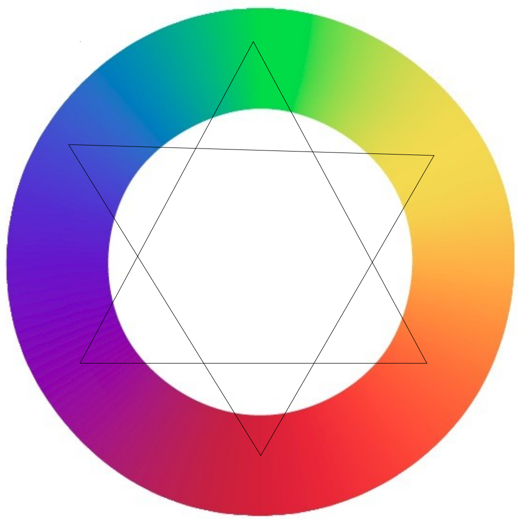
The main question addressed in the following is:

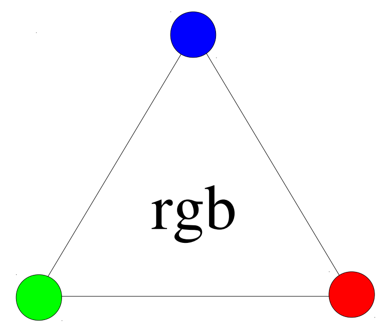
"How to represent those colours within a space that is both easy to manipulate and relevant in terms of image processing ?"

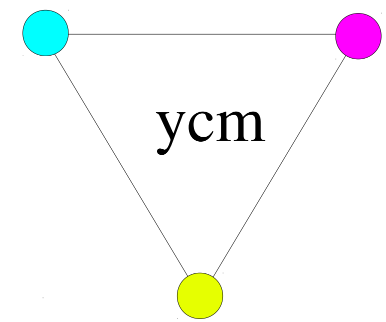
Three colour principle

It is based on the following discovery: a *triplet of pure colours* suffices to render – by mixture of those three components thus called *primary* – all the existing colours.

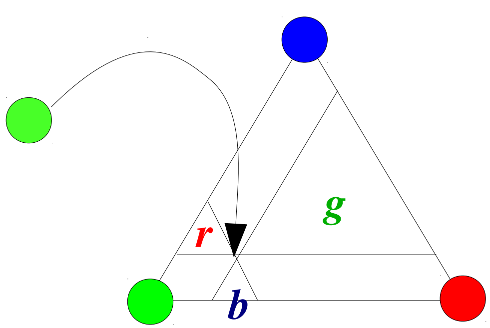
The **Newton's circle** can then be represented by a triangle of primary colours.

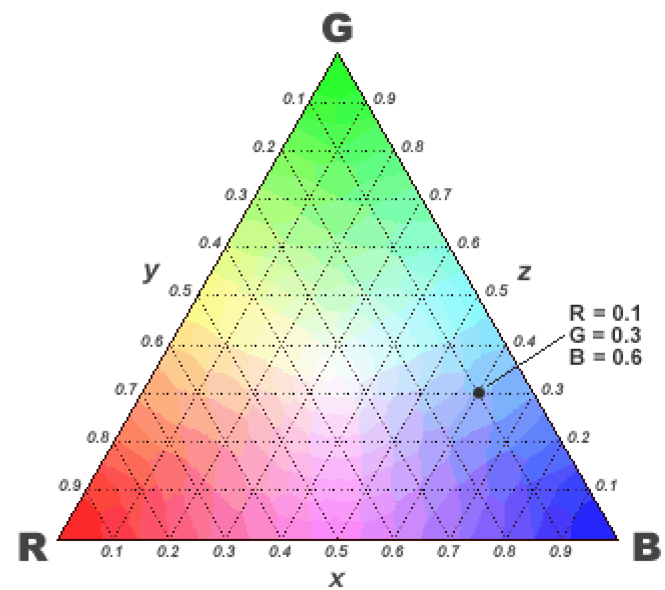






By filling the triangle of primary colours according to the law of areas, we get the **Maxwell's triangle**:

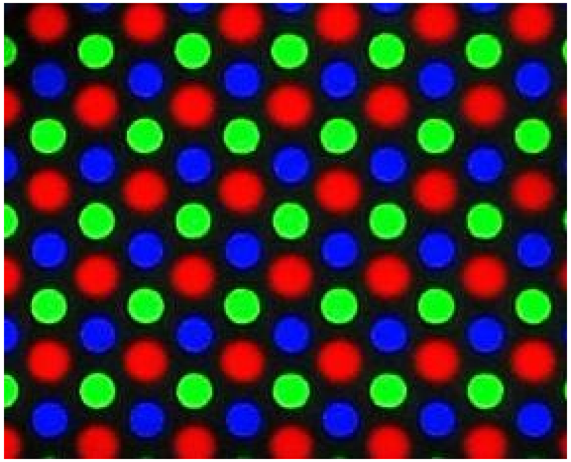




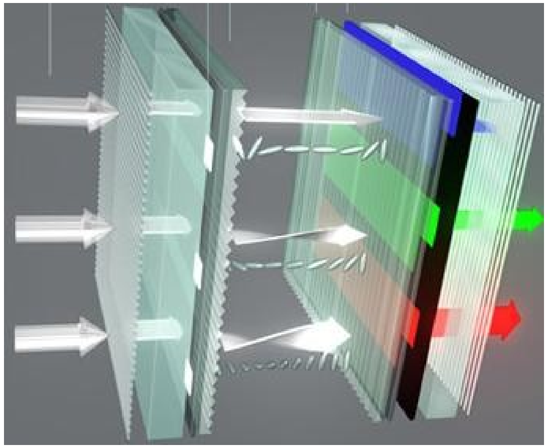
Colour rendering

According to the three colour principle, the set of colours can be considered as **a vector space of dimension 3**, with 3 primary light sources (r,g,b) varying in intensity between 0 and 100%.

This principle of additive synthesis holds on most light devices capable of colour rendering: CRT, LCD, Plasma.



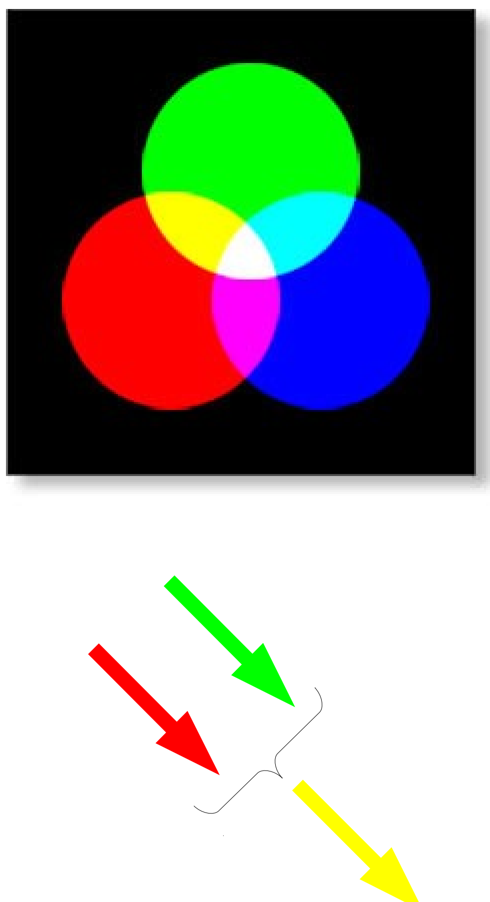
In cathodic screens (CRT), 3 electron beams are scanning an array of red, green and blue phosphore elements, with variable intensity.

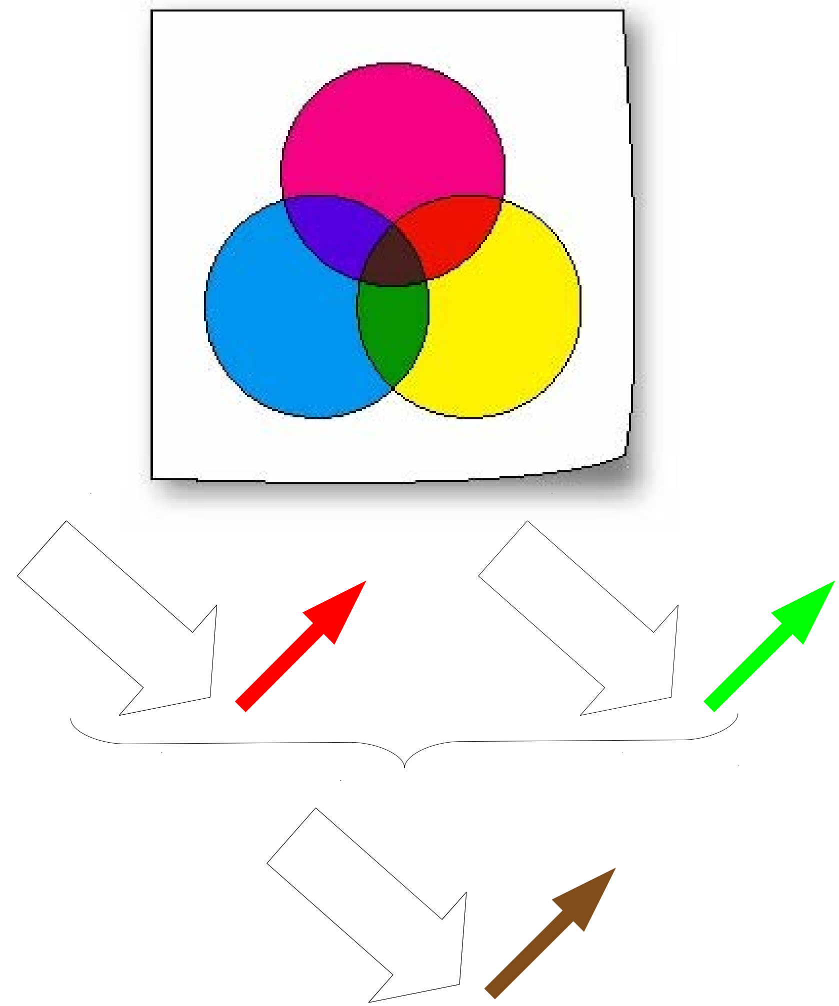


In liquid crystal displays (LCD), 3 matrices of liquid crystals are controlled by a couple of polarizers that change the orientation of crystals, thus modifying the transparency of every pixel, these matrices are backlit through red, green and blue filters.

Additive *vs* Subtractive Synthesis

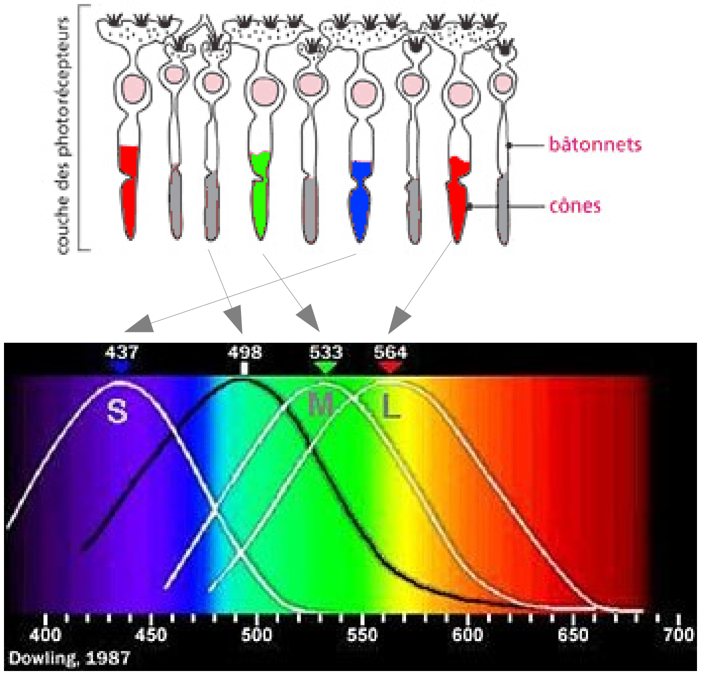
The distinction must be made between *additive synthesis* made by *coloured light sources,* and *subtractive synthesis* performed by the mixture of *coloured pigments*.





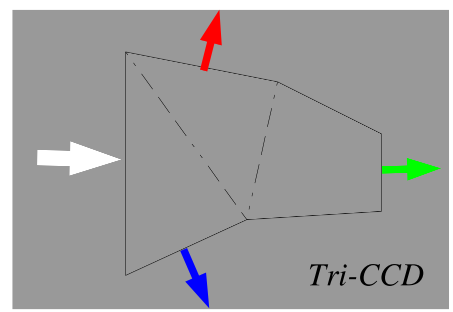
Colour acquisition

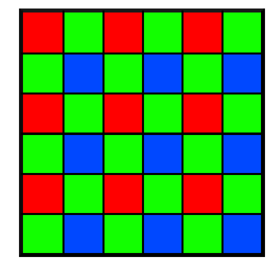
Colour acquisition systems are also usually based on a local combination of selective sensors which are only sensitive to a certain part of the light spectrum.



In the central area of the human retina (fovea) the photoreceptor cells called cones may be categorised into three types according to their sensitivity spectrum.
Note that globally, the sensitivity of our vision is not the same according to the wave length (peak in the green-yellow region).

The most sophisticated tri-CCD contain 3 sensor matrices lit through a semi reflecting prism. Main stream CCD and CMOS cameras possess a single sensor checkerboard matrix made of red, green and blue filters (Bayer matrices).





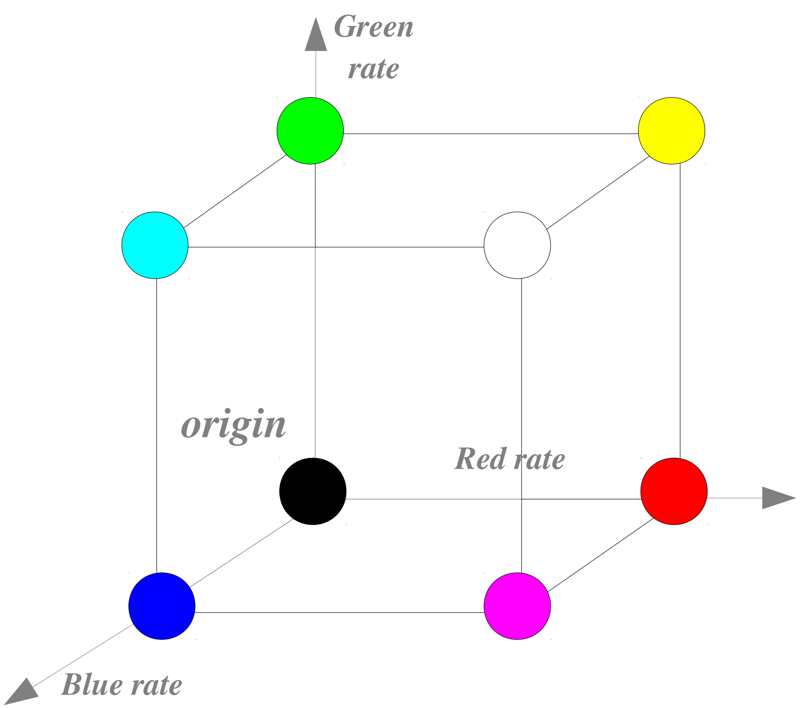
Bayer Matrix

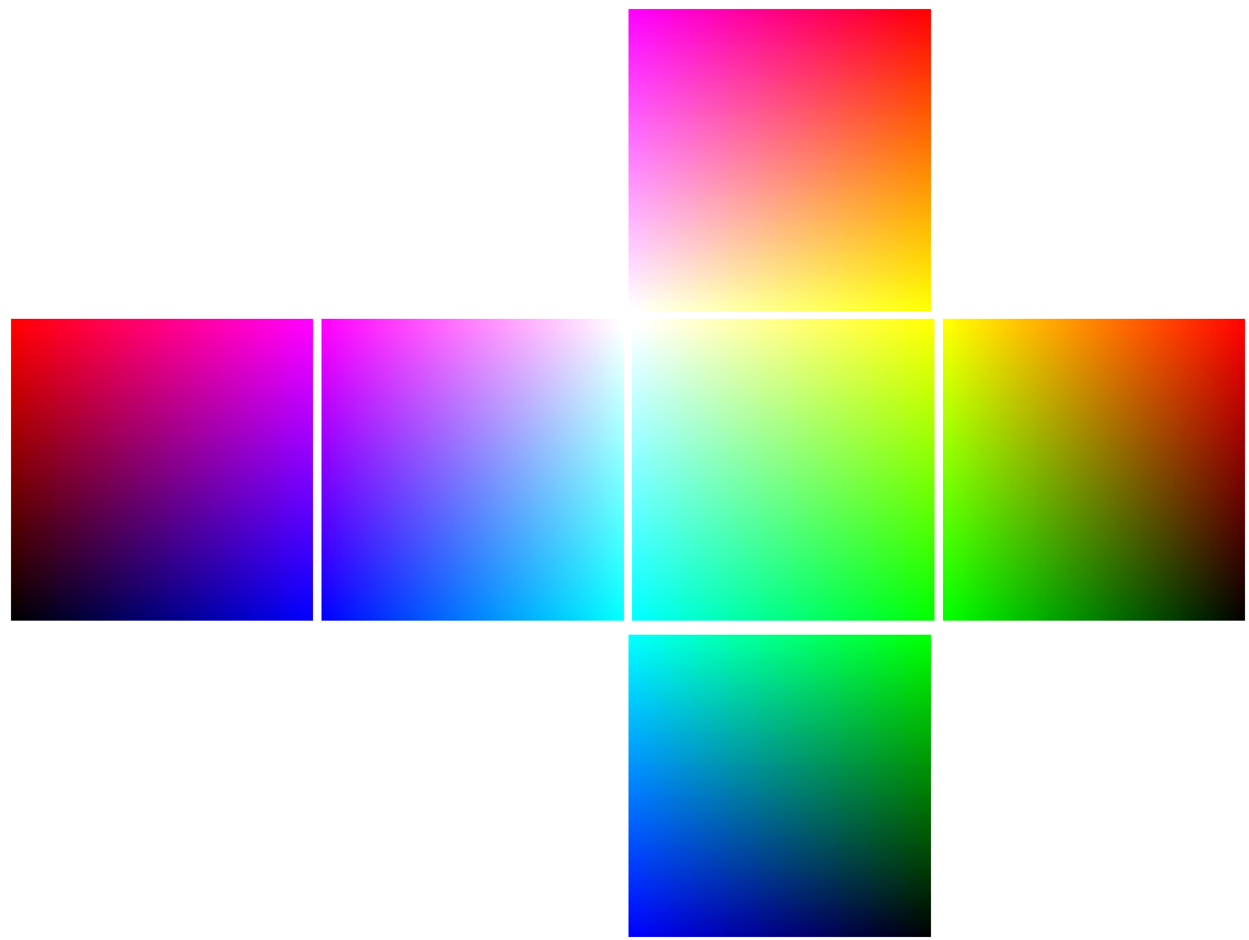
In Bayer Matrices, the spatial resolution differs from the colour resolution, which implies interpolation to limit colour aliasing phenomena:

The RGB colour space

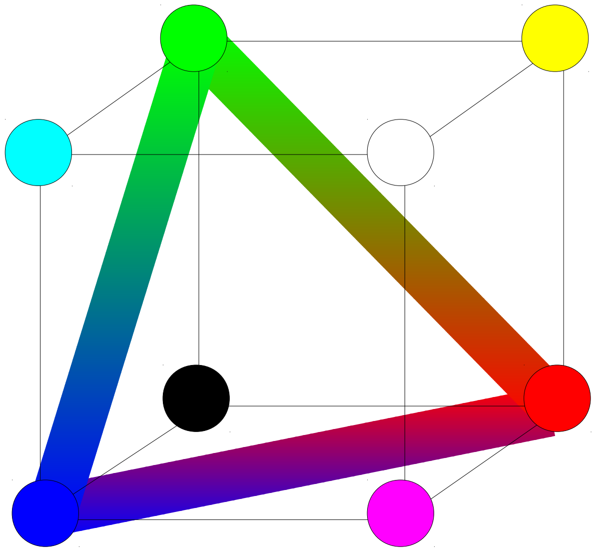
The RGB space is the vector space generated by the three primary components (Red, Green, Blue).

The resulting colours can be represented inside a cube:

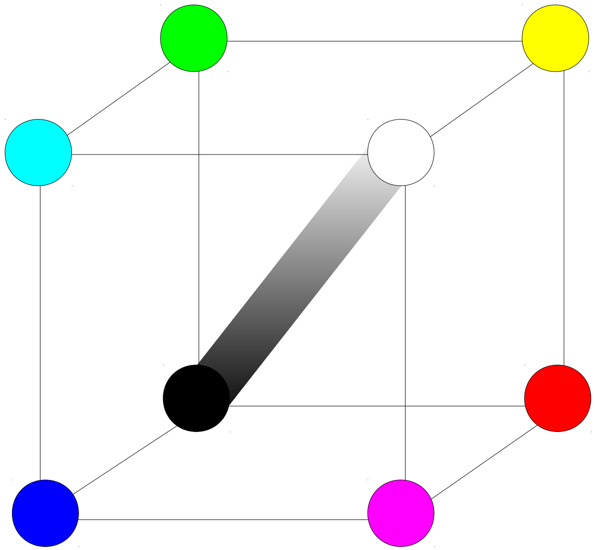




The RGB colour space



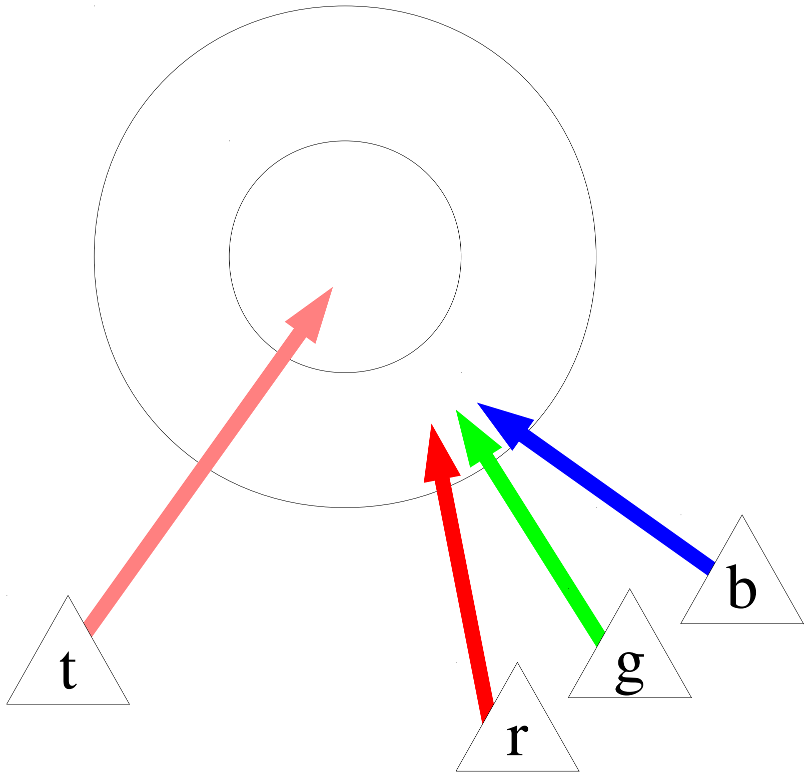
Chromatic triangle

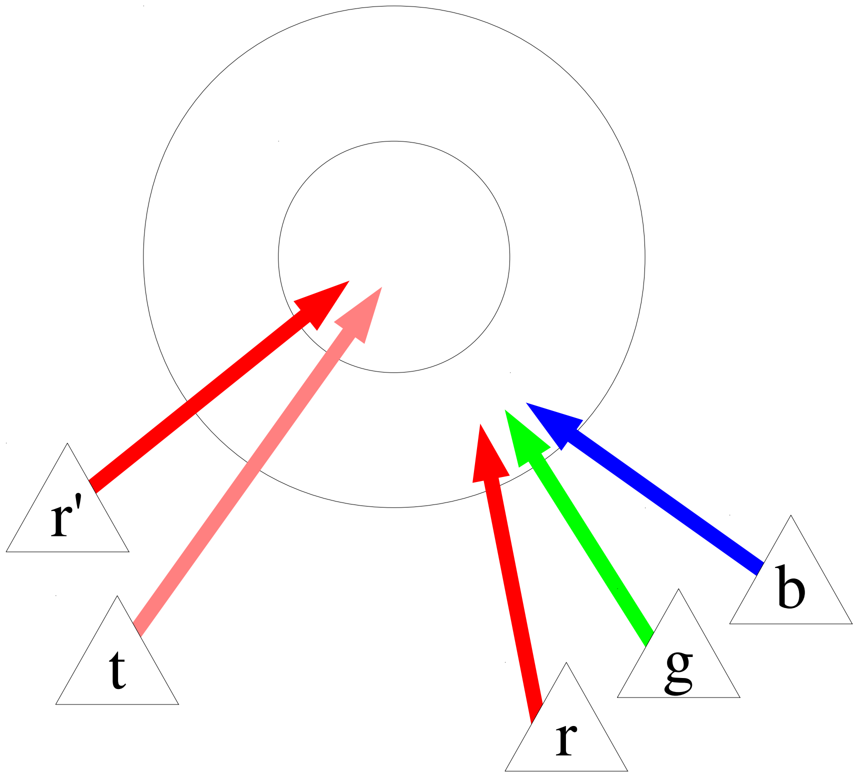


Achromatic axis

Limitations of the three-colour principles

As a matter of fact, the three components RGB do not really allow to recover all the colours that can be perceived by the human vision system:

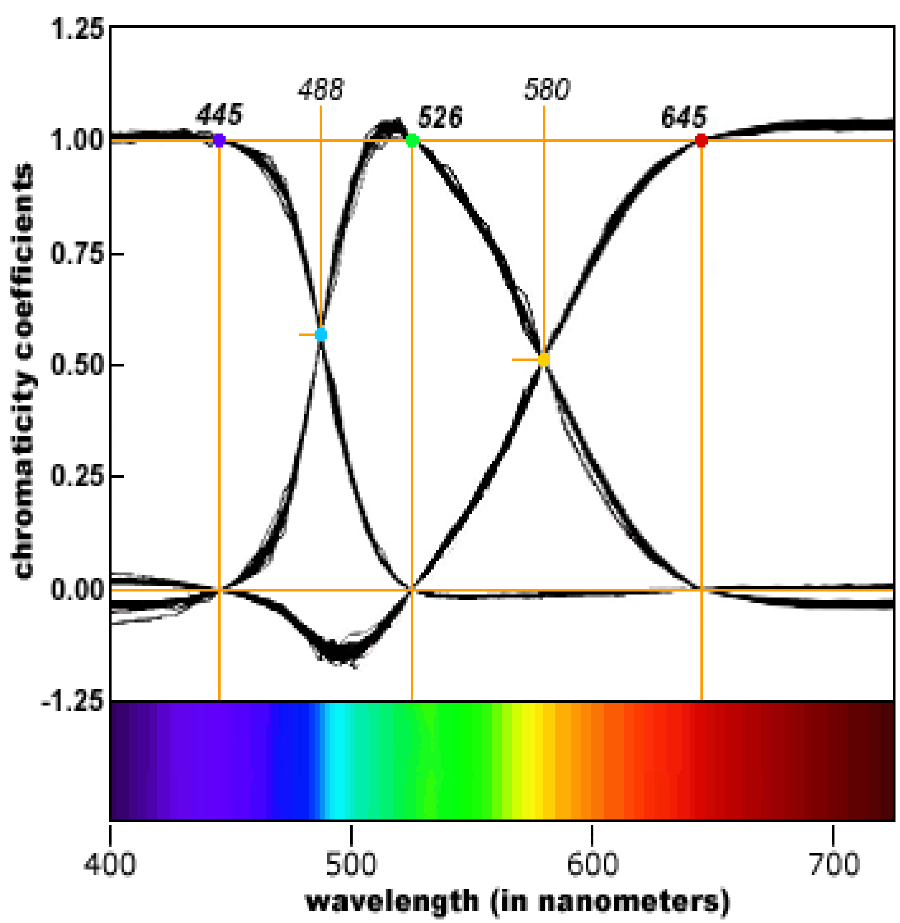




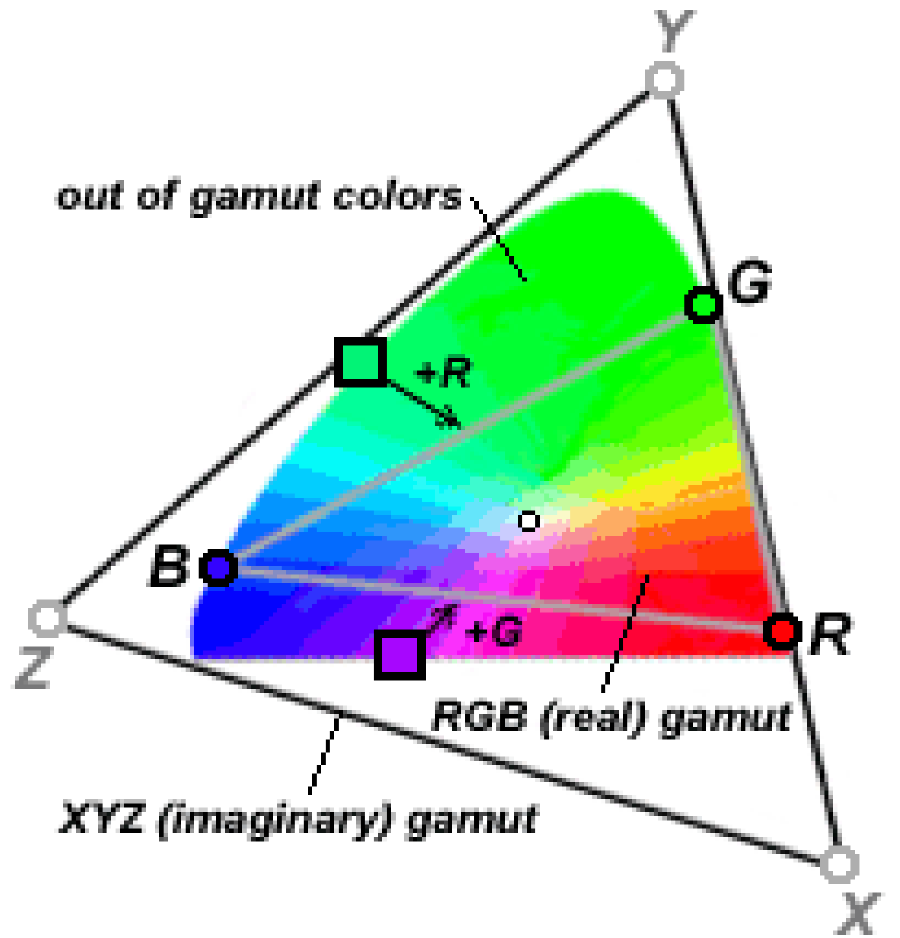
"Colour matching experience": a coherent light source t is compared to a mixture of the 3 primary colours. The (r,g,b) rates are adjusted until the 2 look perfectly identical.

It is observed that certain colour targets cannot be reproduced by any (r,g,b) triplet, and that a certain rate of one primary colour needs to be mixed with the source target t to provide colour identity. This rate r' will then be counted *negatively* in the expression of t.

Limitations of the three-colour principles



Colour matching experience results on a large number of human subjects.



Maxwell's triangle and the CIE diagram.

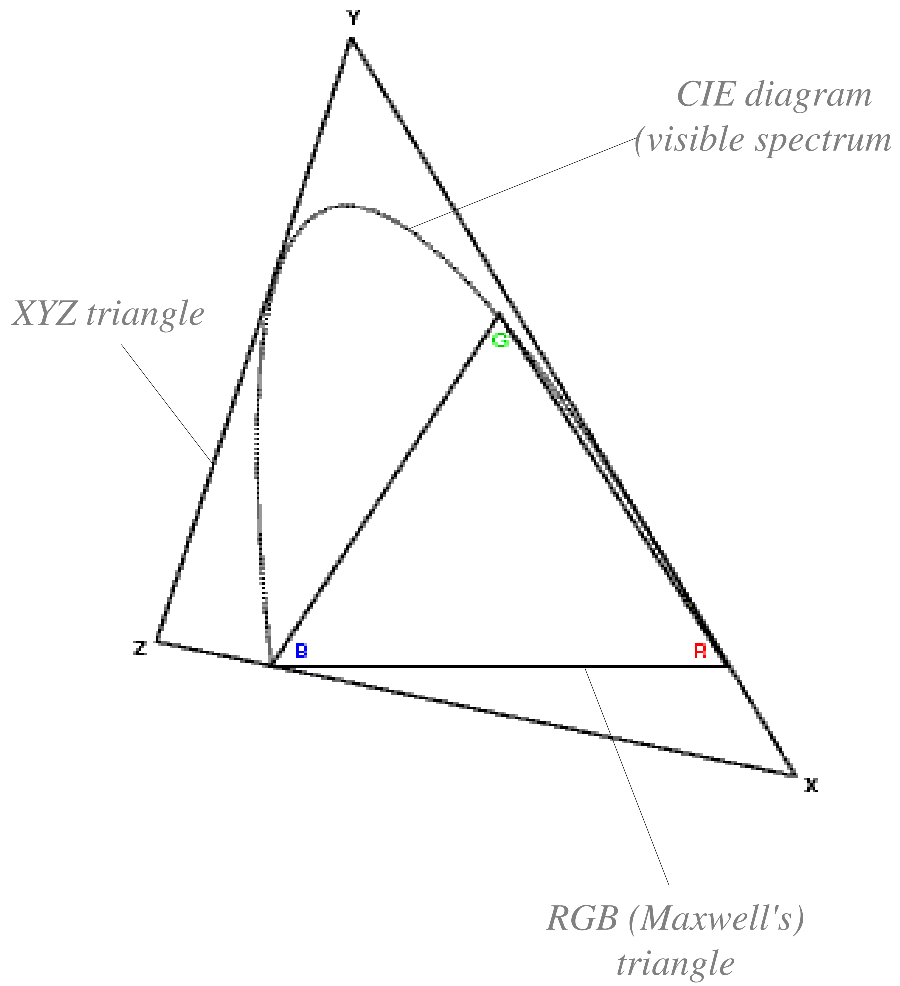
The XYZ colour space

The XYZ (CIE 1931) colour space is defined from a linear ransformation of the RGB space such that all the colours of the visible spectrum are contained in the xyz triangle.

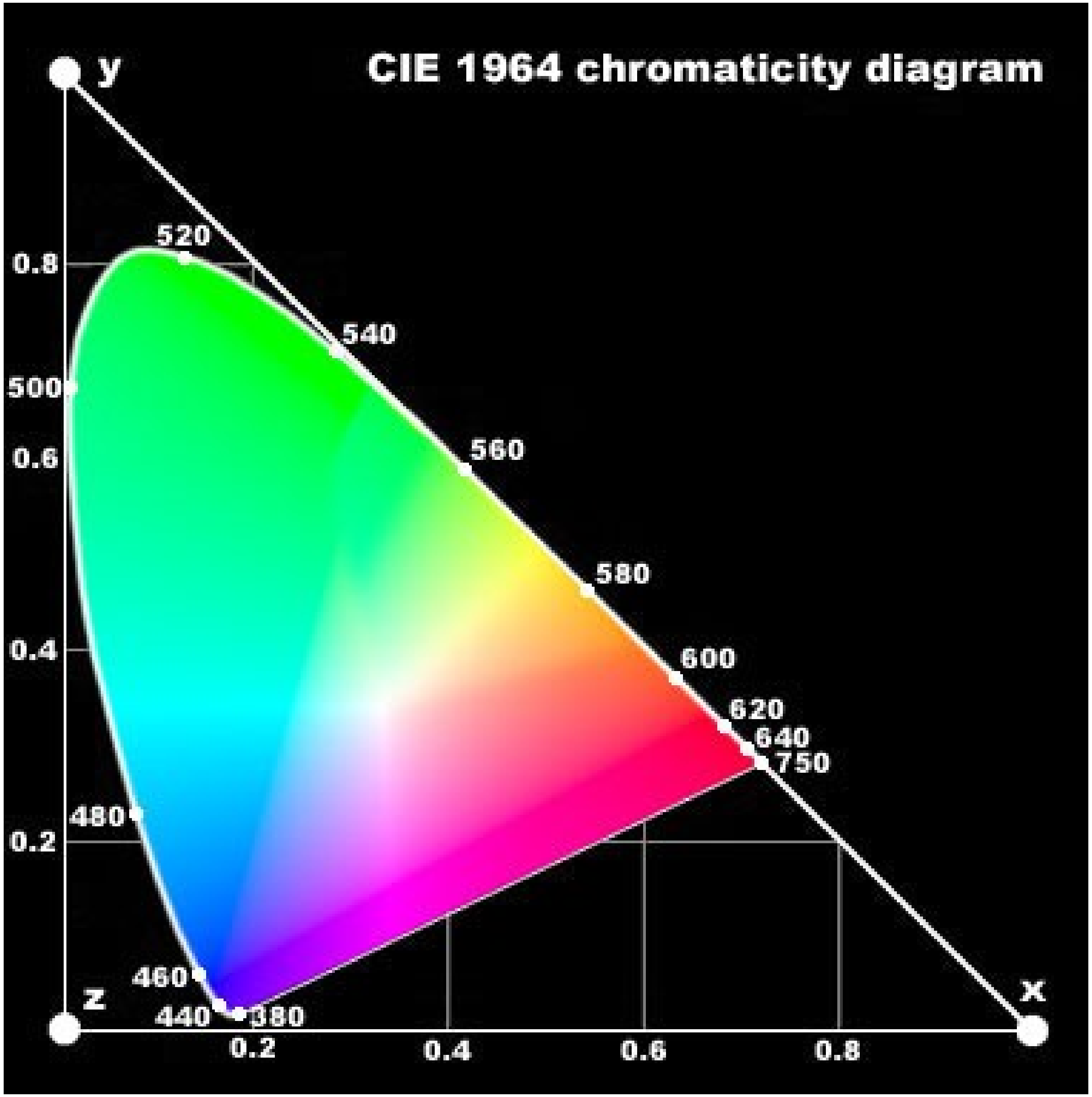
The XYZ coordinates of natural colours will then always have positive values.

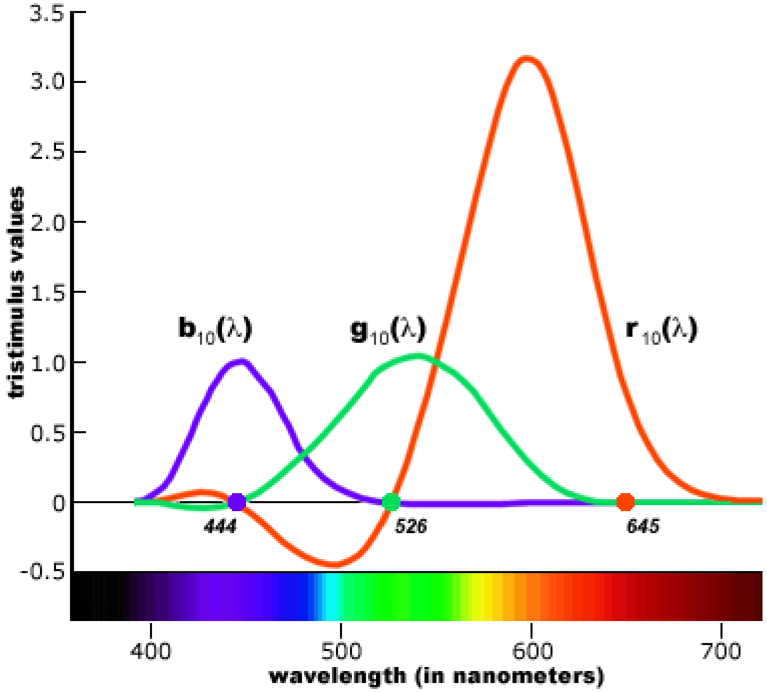
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 2{,}769 & 1{,}7518 & 1{,}1300 \\ 1{,}0000 & 4{,}5907 & 0{,}0601 \\ 0{,}0000 & 0{,}0565 & 5{,}5943 \end{pmatrix} \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

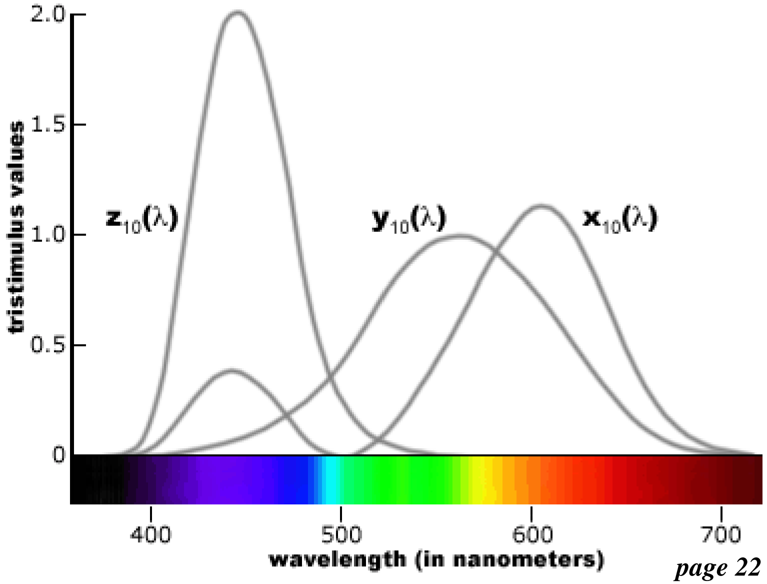
Transformation matrix from RGB to XYZ coordinates (no normalisation)



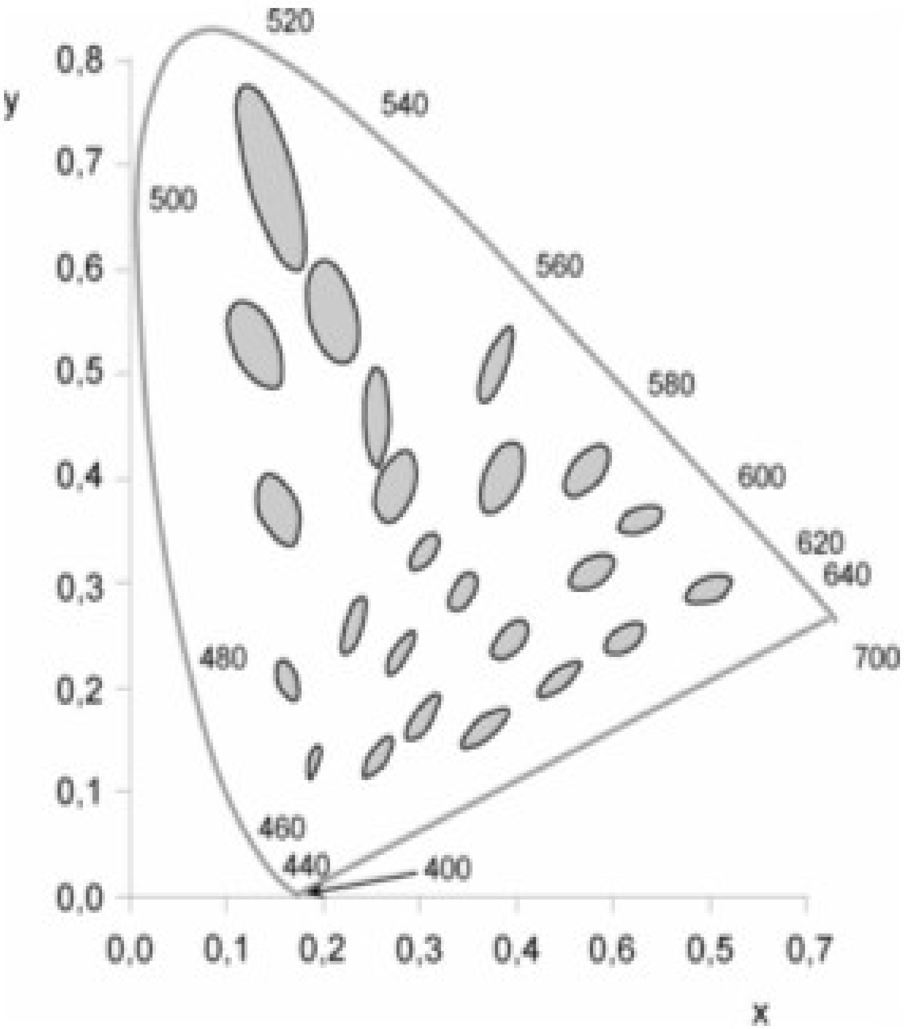
The XYZ colour space







Colour Classification



Mc Adam's ellipses

• In terms of perceptual distance, the XYZ is not uniform: more shades are perceived along x and z than along y.

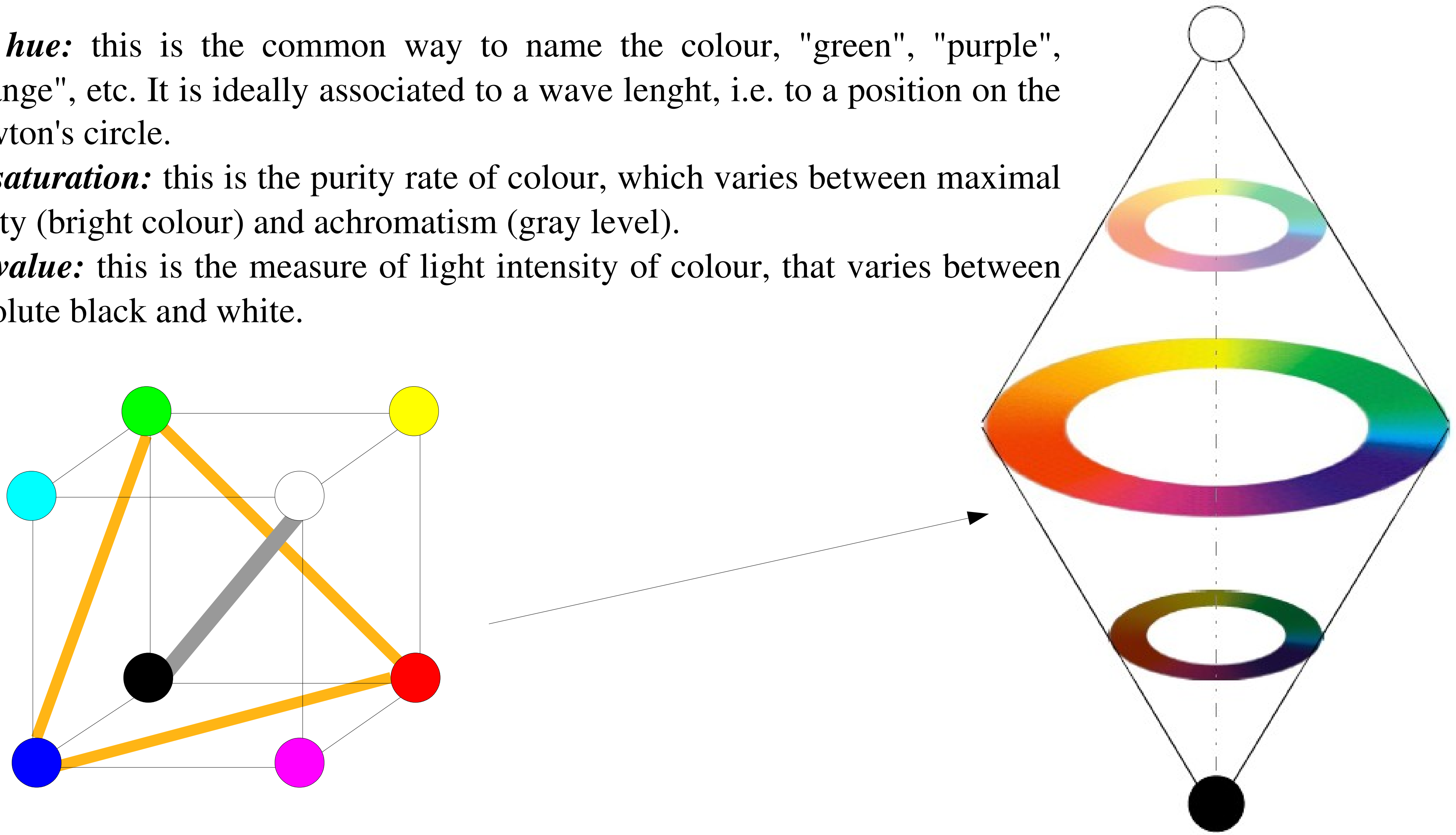
• Furthermore, some descriptive dimensions of colour are not available:

light/dark, bright/faded, etc.

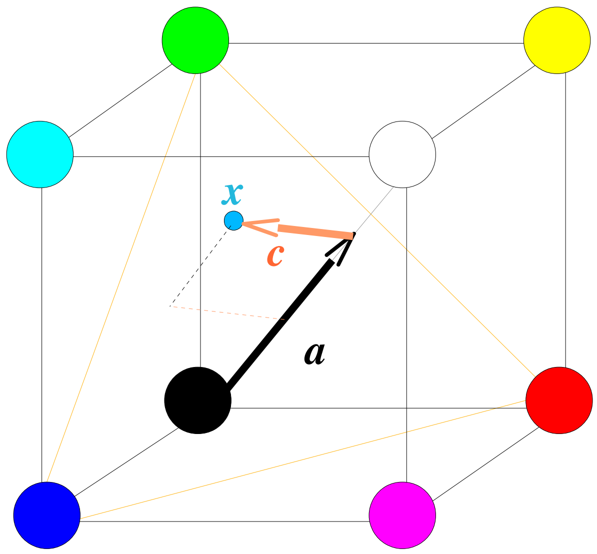
The HSV colour space

The interest of the HSV colour space is to characterise colours in a more intuitive way, according to the natural perception of colours, in terms of:

1 - hue: this is the common way to name the colour, "green", "purple", "orange", etc. It is ideally associated to a wave lenght, i.e. to a position on the Newton's circle.
2 - saturation: this is the purity rate of colour, which varies between maximal purity (bright colour) and achromatism (gray level).
3 - value: this is the measure of light intensity of colour, that varies between absolute black and white.



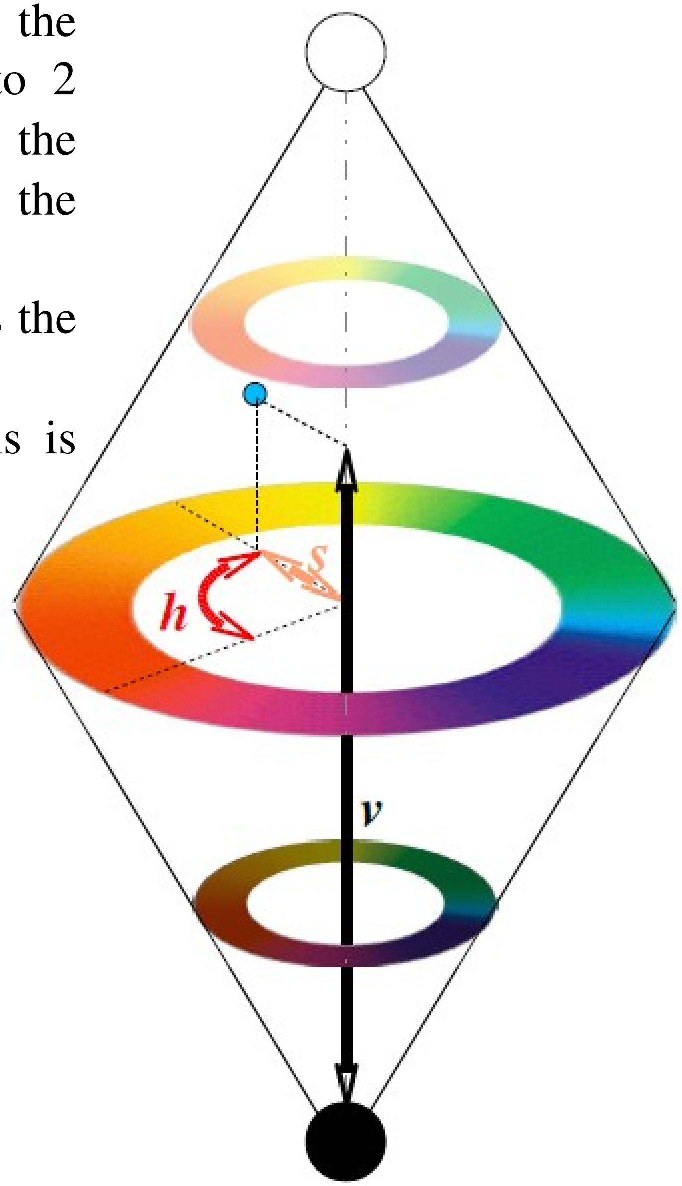
The HSV colour space



A point *x* of coordinates (*r*,*g*,*b*) in the RGB cube can be decomposed into 2 components (***c***,***a***). Let *y* be the orthogonal projection of *x* on the achromatic axis.

• The chromatic component ***c***: this is the vector *yx*.

• The achromatic component ***a***: this is the vector Oy.



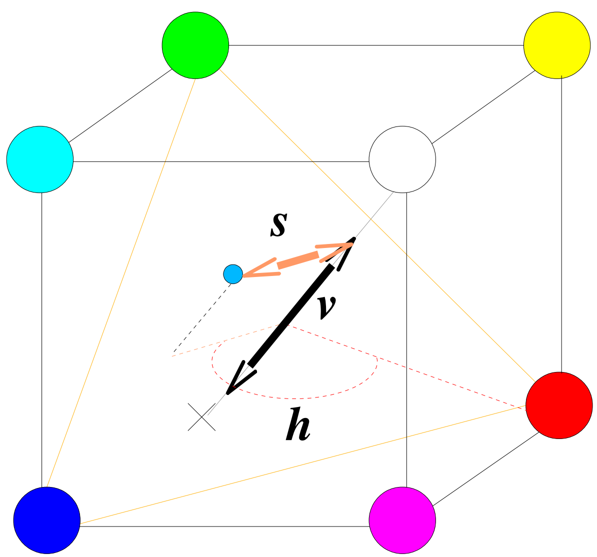
This decomposition associates the HSV components to geometric measures:

• The **value**: this is the norm of the achromatic component **‖a‖**

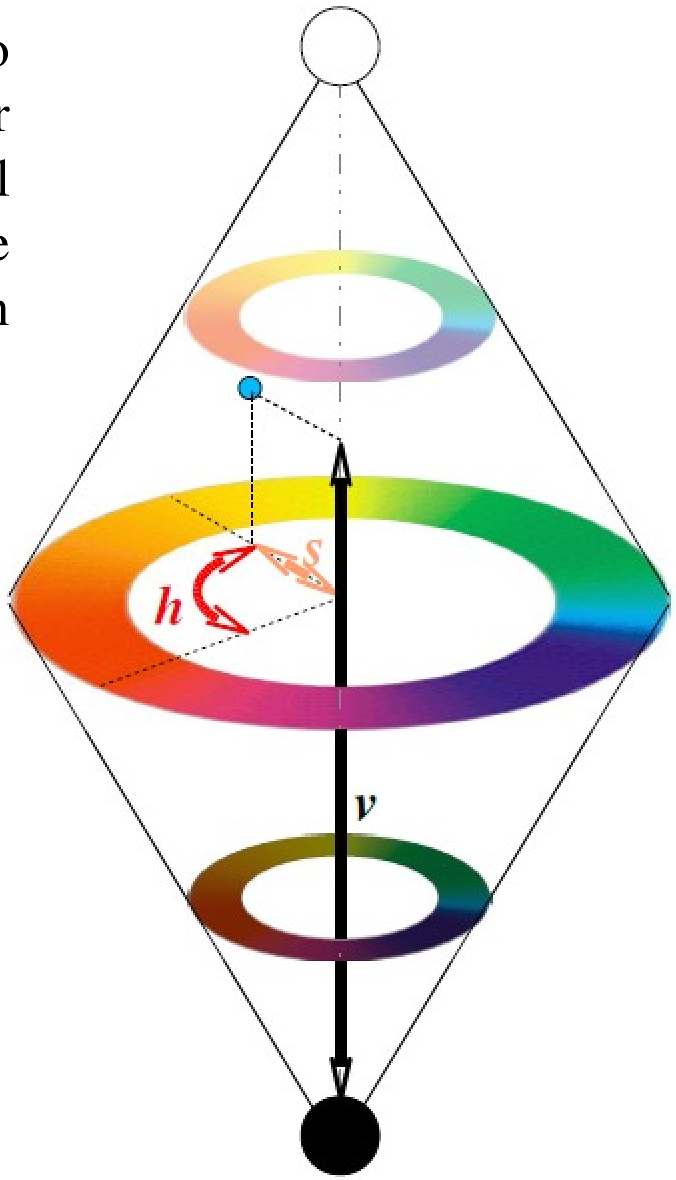
• The **saturation**: this is the norm of the chromatic component **‖c‖**

• The **hue**: this is the argument (with respect to an arbitrary direction of the chromatic circle), of the chromatic component **arg(c)**.

The HSV colour space



The passage from RGB to HSV is made by a non linear transformation. Several conversion operators have been proposed. Here is an example:

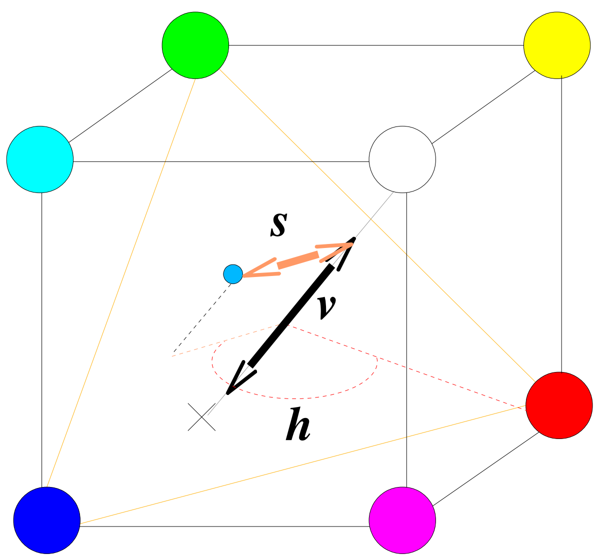


$$v = \frac{r+g+b}{3}$$

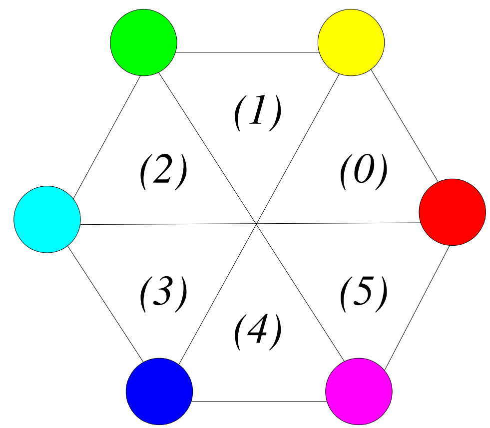
$$s = 1 - \frac{3\,min(r,g,b)}{r+g+b}$$

$$h = \begin{cases} \theta & if \quad b \leqslant g \\ 2\pi - \theta & if \quad b > g \end{cases} \quad \theta = \arccos\left(\frac{(r-g)+(r-b)}{2\sqrt{(r-g)^2+(r-b)(g-b)}}\right)$$

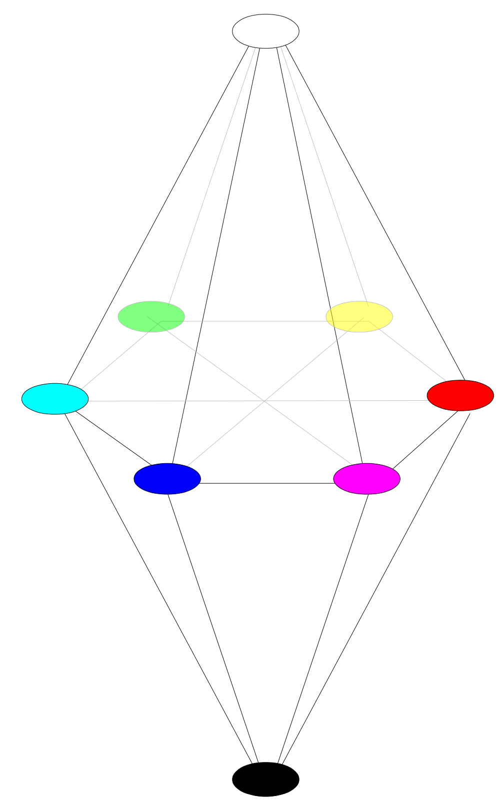
The HSV colour space



This is another example, without using the Arc Cosine:



The chromatic hexagon with associated λ values.



$$v=\frac{r+g+b}{3}$$

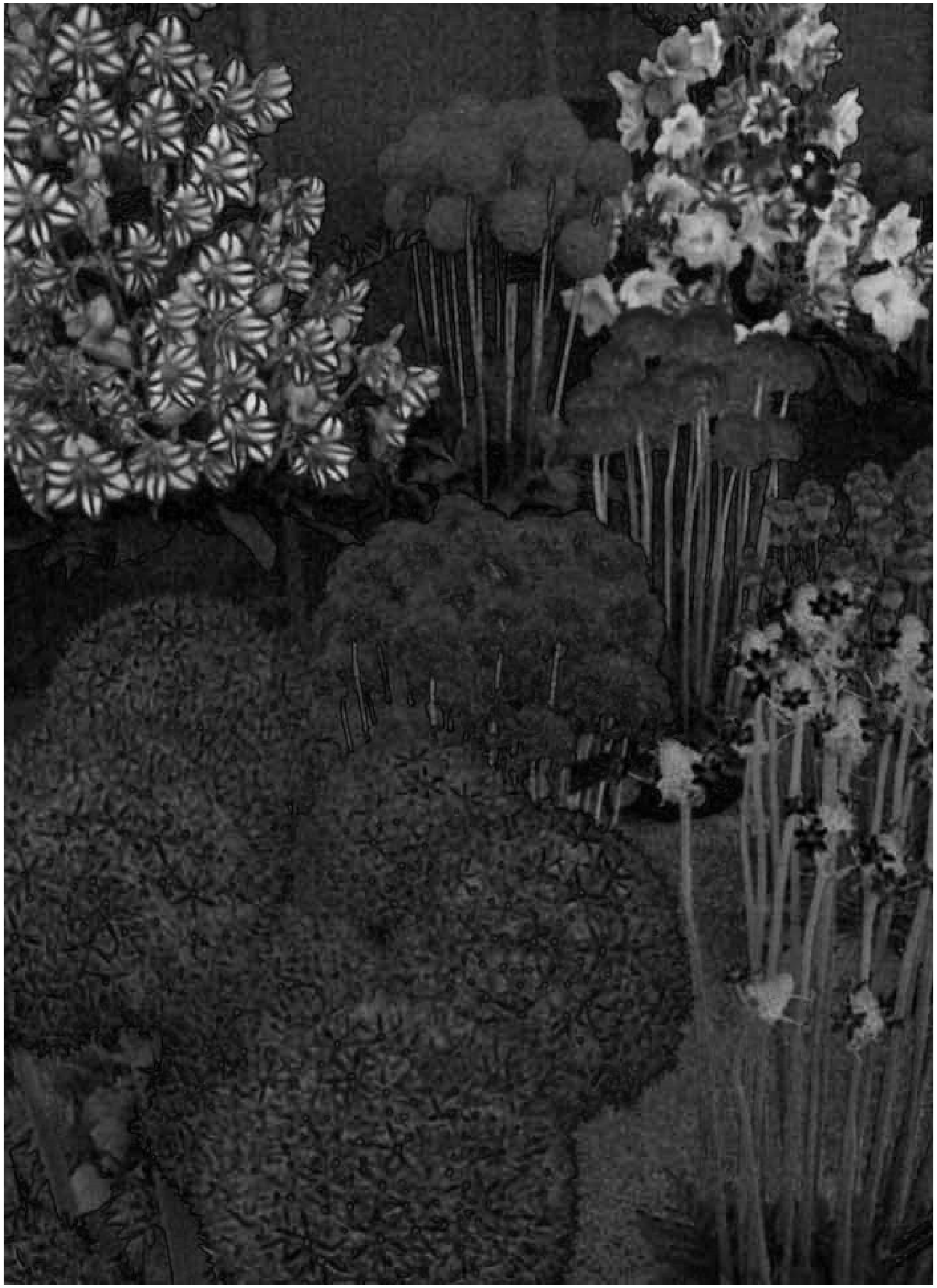
$$s=\begin{cases}\frac{3}{2}(M-v) & \text{if} \quad v\geqslant med\\ \frac{3}{2}(v-m) & \text{if} \quad v\leqslant med\end{cases}\quad\left|\quad\begin{aligned}M&=max(r,g,b)\\ m&=min(r,g,b)\\ med&=median(r,g,b)\end{aligned}\right.$$

$$h=\frac{\pi}{3}\left(\lambda+\frac{1}{2}-(-1)^{\lambda}\frac{M+m-2\,med}{2v}\right);\lambda=\begin{Bmatrix}0 & \text{if} & r\geqslant g\geqslant b;1 & \text{if} & g\geqslant r\geqslant b\\ 2 & \text{if} & g\geqslant b\geqslant r;3 & \text{if} & b\geqslant g\geqslant r\\ 4 & \text{if} & b\geqslant r\geqslant g;5 & \text{if} & r\geqslant b\geqslant g\end{Bmatrix}$$

Colour Image

Value Component

Colour Image



Saturation Component

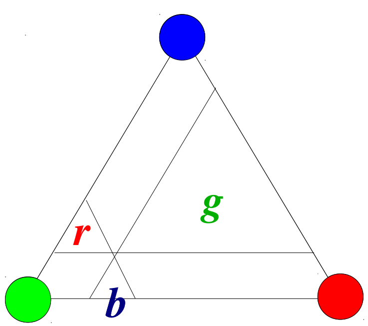
Colour Image

Hue Component

(Note the colour quantisation effect, typical of compressed images)

The Yuv colour space

The principle of the Yuv colour space is to represent colours using one *luminance* component *Y*, and two *chrominance* components (*u*,*v*) corresponding to the *blue* and *red* components in the reduced chromatic coordinates:



$$Cb + Cr + Cg = \mathrm{Cte}$$
$$Cg = \mathrm{Cte} - Cb - Cr$$

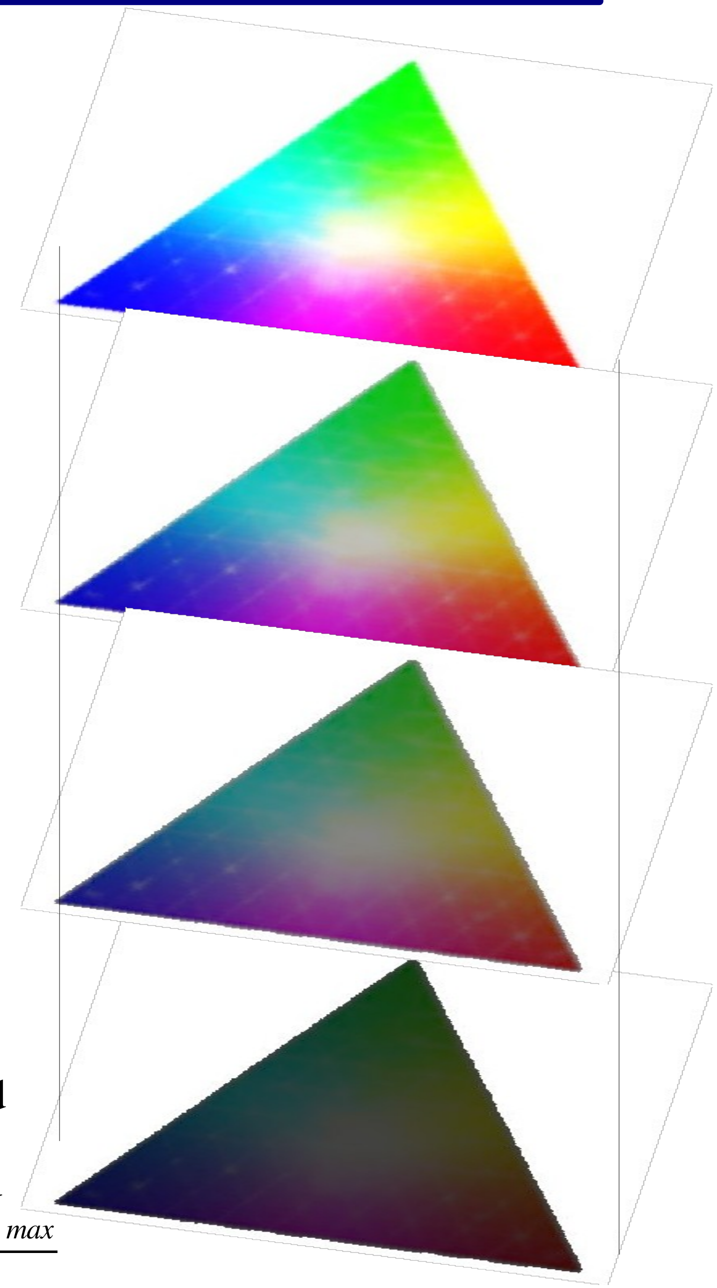
The luminance component is a linear combination of primary colours, weighted by the relative human sensitivity.

$$0 \leqslant Y \leqslant N_{max}$$

$$Y = 0{,}2989\, r + 0{,}5866\, g + 0{,}1145\, b$$
$$u = 0{,}5647(b - Y) = -0{,}1687\, r - 0{,}3312\, g + 0{,}5000\, b$$
$$v = 0{,}7132(r - Y) = 0{,}5000\, r - 0{,}4183\, g - 0{,}0817\, b$$

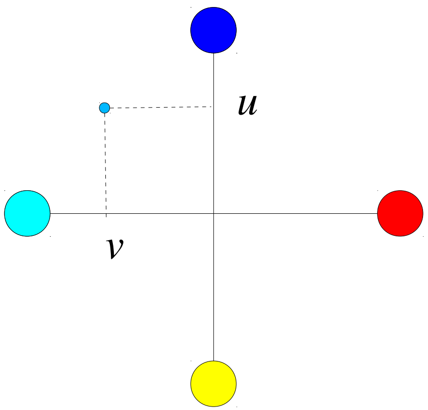
The chrominance component correspond to the normalised difference between the primary component and the luminance.

$$\frac{-N_{max}}{2} \leqslant u \leqslant \frac{+N_{max}}{2} \qquad \frac{-N_{max}}{2} \leqslant v \leqslant \frac{+N_{max}}{2}$$

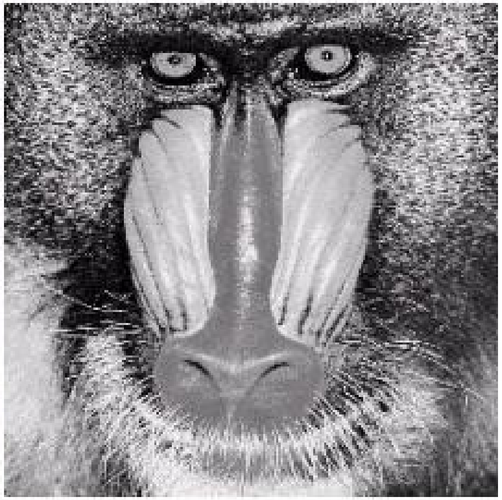


The Yuv colour space

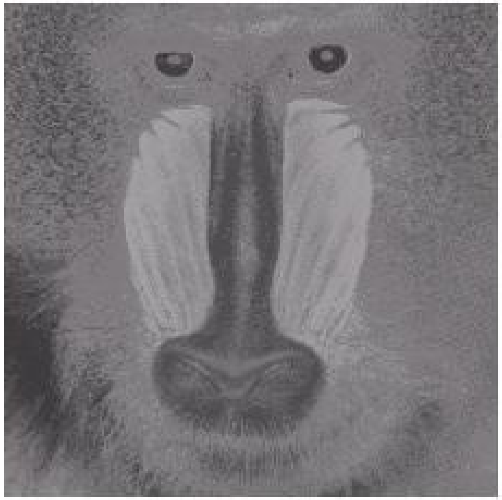
The chrominance components u and v respectively represent the Blue/Yellow and the Red/Cyan contrasts :



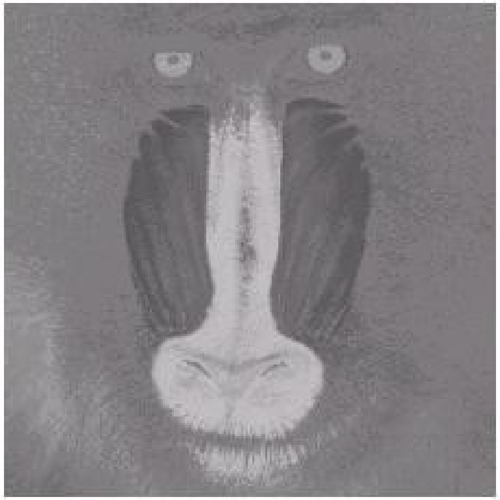
Colour Image



Luminance Y



Blue Chrominance u



Red Chrominance v

Colour Image Processing

OUTLINE OF THIS SECTION:

- Linear operations
- Non linear operations
- Contrast measures
- Shadow detections

Colour linear filters

A linear colour operator is defined in a vector base by a 3x3 matrix of *linear scalar operators*.
Translation invariant linear colour operators are then described by a convolution matrix:

General case

$$F = \begin{pmatrix} f_{11} & f_{12} & f_{13} \\ f_{21} & f_{22} & f_{23} \\ f_{31} & f_{32} & f_{33} \end{pmatrix}$$

Marginal processing

$$F = \begin{pmatrix} f_1 & 0 & 0 \\ 0 & f_2 & 0 \\ 0 & 0 & f_3 \end{pmatrix}$$

Identical processing

$$F = \begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & f \end{pmatrix}$$

ex:Gaussian filter identically applied to the 3 RGB components.

Non linear operations

Even if formally, any non linear operation can be applied marginally on every component of the vector space, the interprétation of the resulting vector may be hazardous.

For instance, in the case of order filtering (and then morphological operators), the order relation in the colour space is *a priori* undefined. Performing the erosion or dilation component by component is practically meaningless...

An order may be explicitely imposed on the vector space (e.g. lexicographic order).

Different operators may also be applied on the different component (e.g. erosion on Y, (u,v) unchanged, etc.)

Colour Contrast

How to characterise the spatial variations of a colour image I = (I_1, I_2, I_3)?

The 2 columns of the Jacobian matrix of I with respect to the space basis (x,y) are the spatial derivatives. These are colour images, making sense because partial derivation is a linear operator:

$$I^x = \left(\frac{\partial I_1}{\partial x}, \frac{\partial I_2}{\partial x}, \frac{\partial I_3}{\partial x} \right)$$

The 3 lines of the Jacobian are the gradient vectors of the 3 components. These values are also meaningful as variation measures of the components:

$$\nabla I_k = \left(\frac{\partial I_k}{\partial x}, \frac{\partial I_k}{\partial y} \right)$$

But what sense may be given to the colour gradient? In terms of contrast (modulus), a two-step approach is generally applied:

$$GI = \left(\|\nabla I_1\|_1, \|\nabla I_2\|_1 \|\nabla I_3\|_1 \right) \longrightarrow \|I\|_d = \|GI\|_2$$

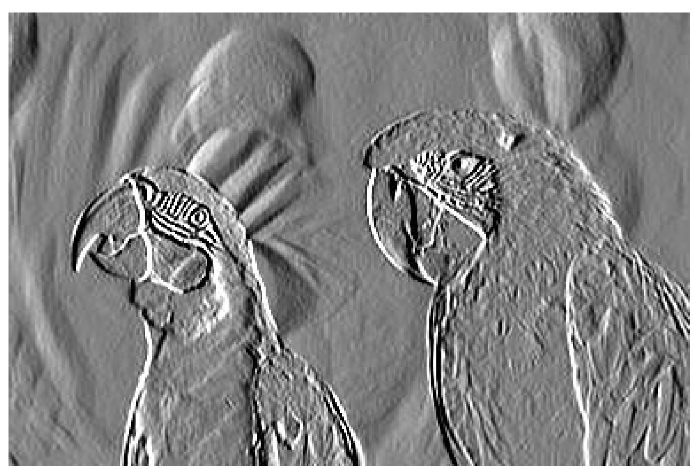
The norm (1) is generally a $\boldsymbol{L_1}$, $\boldsymbol{L_2}$ or $\boldsymbol{L_\infty}$ norm; the norm 2 is usually the $\boldsymbol{L_\infty}$ norm.

Colour Contrast

I

I^x

$\frac{\partial r}{\partial x}$



$\frac{\partial g}{\partial x}$

$\frac{\partial b}{\partial x}$

HSV Contrast

In HSV colour spaces, the *saturation* may be used as *weighting* factor to calculate a norm of colour gradient by linear combination of the gradient norms of *luminance* and *hue*:

$$\|I\|_{d'} = \frac{S}{K}\|\nabla H\|_1 + \frac{K-S}{K}\|\nabla V\|_1$$

V

S

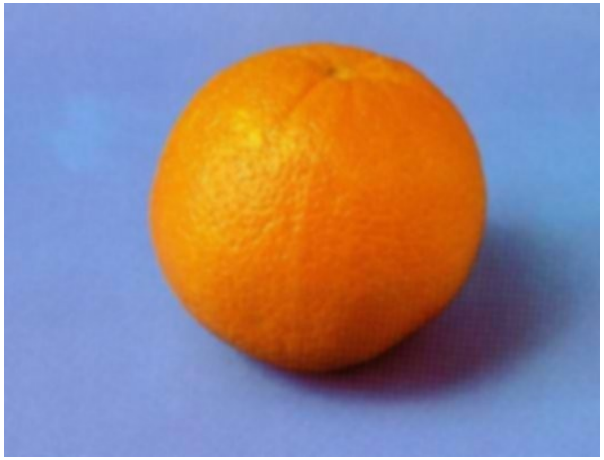
$\|\nabla V\|_1$

$\|\nabla H\|_1$

$\|I\|_{d'}$

Shadow Detecting and Removal

The colour allows to remove the shadows more easily thanks to colour invariants, i.e. values that remain unchanged while changing the intensity of the light source. The principle is that, in cast shadow areas, the 3 RGB components theoretically diminish in an identical fashion. Such invariant measures are: chromatic coordinates (u,v) or normalised (reduced) (r,g,b) coordinates.



Static case: the invariants are *spatially* compared near the contours of cast shadows.

Dynamic case: the invariant are compared in the *temporal dimension*.

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• Coll. University of Haïfa « Shadow Removal – Computer vision seminar » http://cs.haifa.ac.il/hagit/courses/seminar/shadowRemoval/shadowRemovalPapers.html

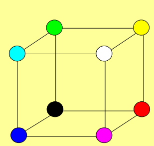
Conclusion / Course Highlights

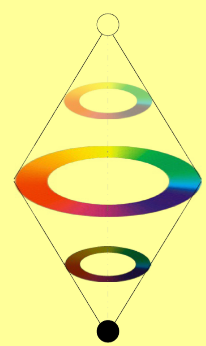
(1) Self shadows / Cast shadows

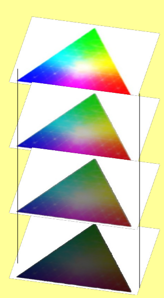
Homomorphic Filtering / Colour Invariants

(2) Colour Spaces

- RGB
- XYZ
- HSV
- Yuv







(3) Colour Processing

- Linear Filters
- Non linear Operators
- Contrast Measures