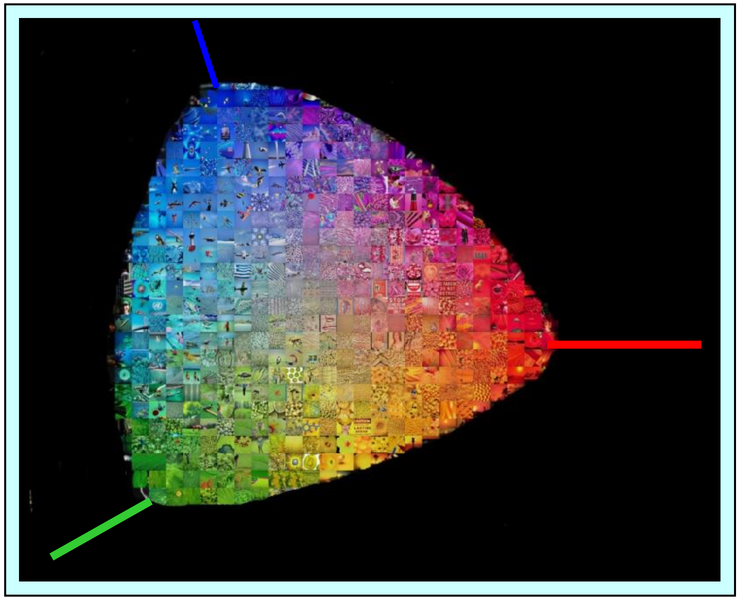
Color Basics

- human vision
- physics–based reflection model



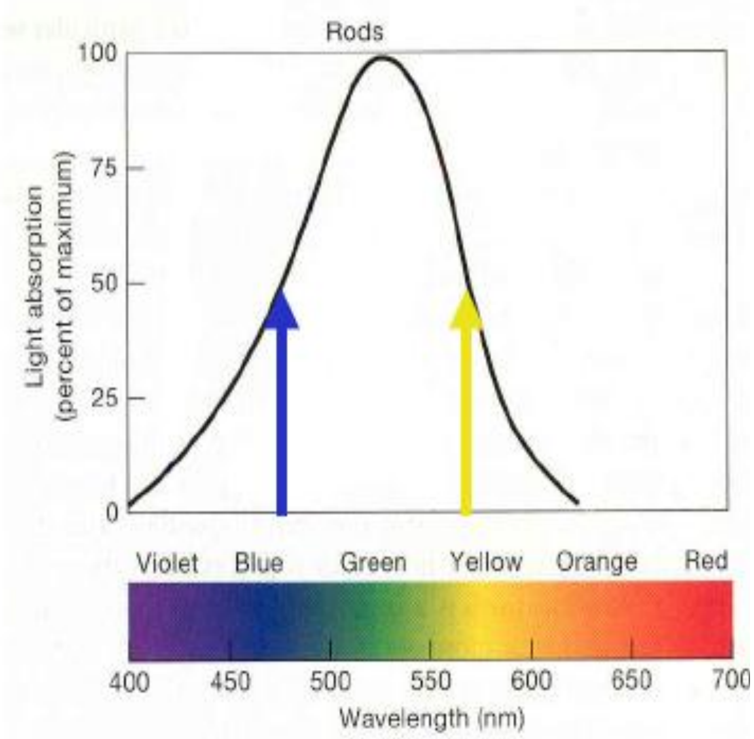
slides: Joost van de Weijer

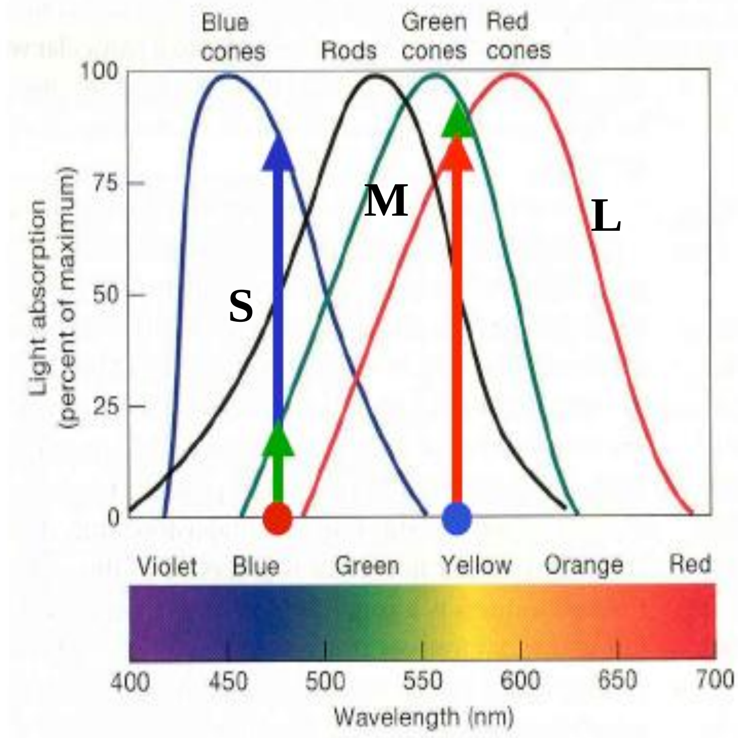
Human vision

Humans have two types of photoreceptors:

- **rods:** achromatic night time vision when light levels are low.
- **cones:** color vision during day time when light levels are high.

Normalized responsivity

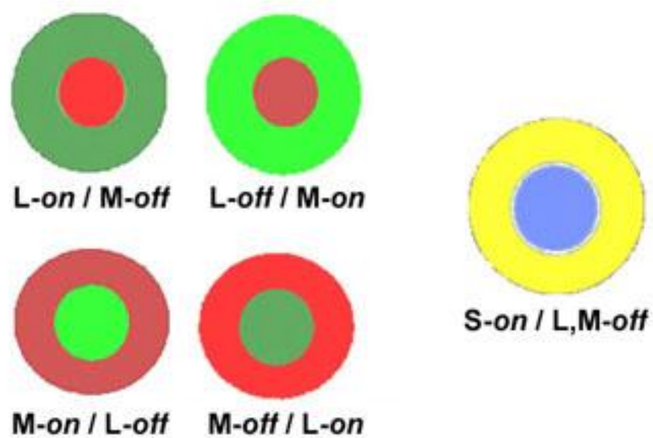




opponent color system

The information from these receptors is combined in the retina as colour opponent signals through the optic nerve.

Retinal neurons appear to encode both achromatic contrast systems and chromatic contrast systems.



$$R = r - \frac{g+b}{2} \qquad G = g - \frac{r+b}{2}$$

$$B = b - \frac{r-g}{2} \qquad Y = \frac{r+g}{2} - \frac{|r-g|}{2} - b$$

$$RG = R - G \qquad BY = B - Y$$

((r,g,b) normalized RGB)

Opponent mechanism **[Itti PAMI 95]**

opponent color system

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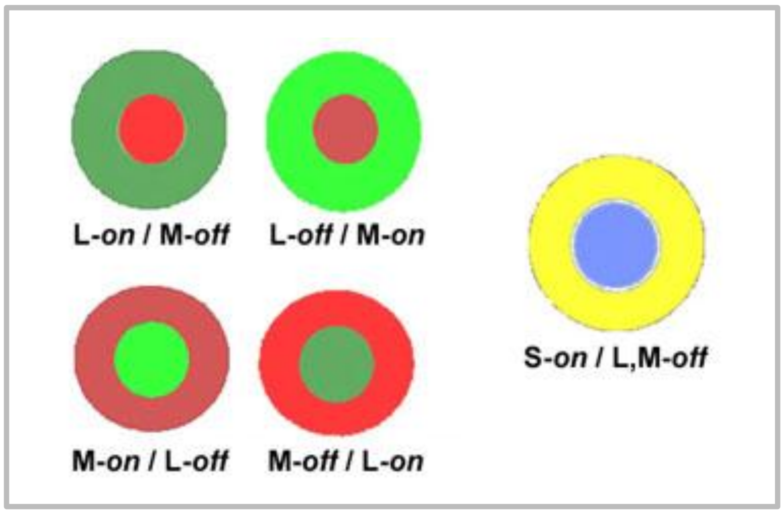
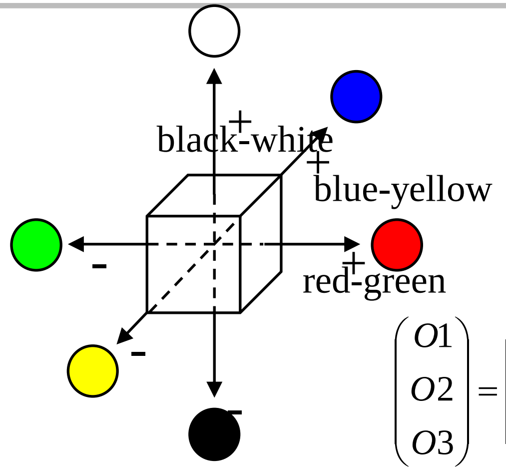


Opponent mechanism

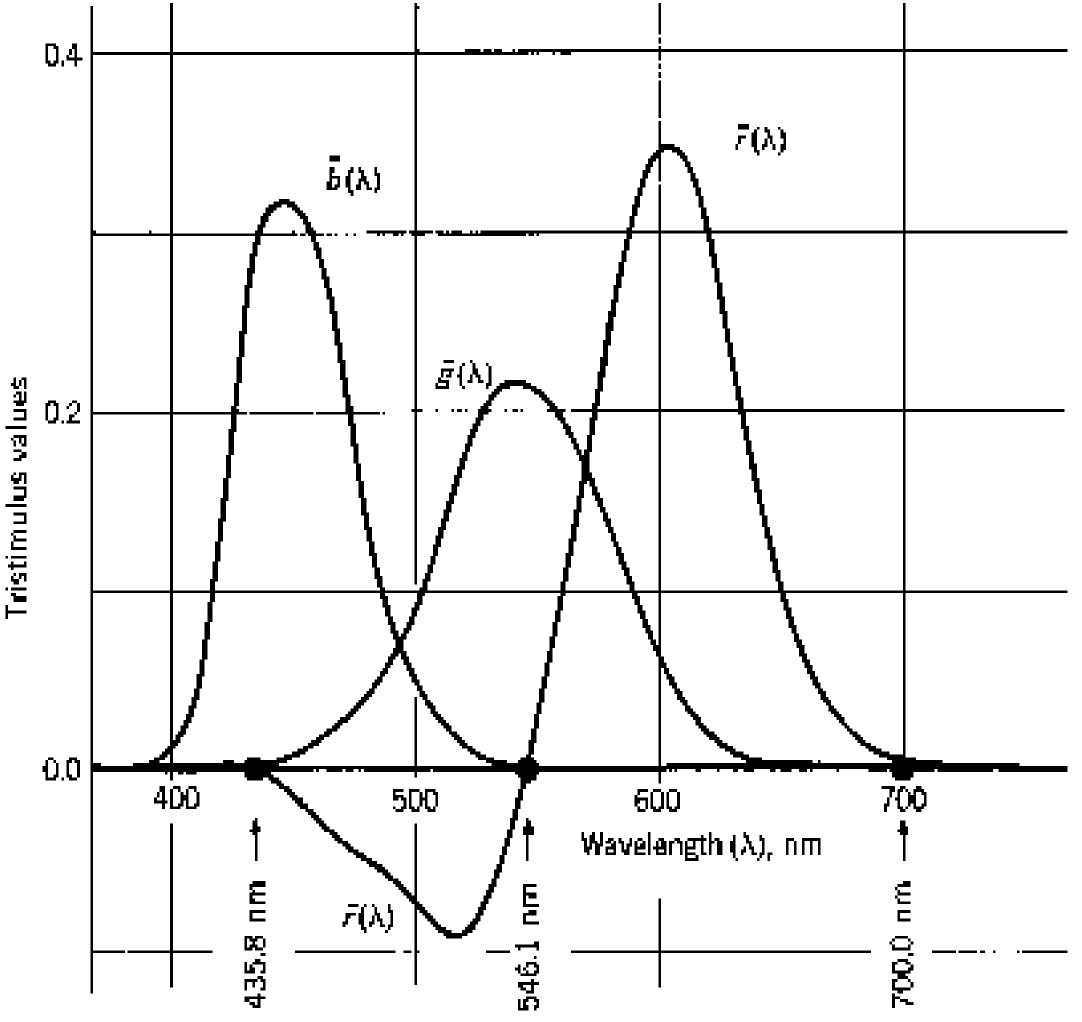


$$\begin{pmatrix} O1 \\ O2 \\ O3 \end{pmatrix} = \begin{pmatrix} 1 & -1 & 0 \\ 1 & 1 & -2 \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Linear combination of RGB

CIE 1931 standard observer

Experiment result
(*Commission International de l'Eclairage*)



- *Visuall field = 2 degrees*
- *Interval = [380,780]*
- *Sub-intervals = 5nm.*
- *primary stimuli:*

  R=700nm

  G=546.1nm

  B=435.8nm
- *Every position gives the mixing weights for the primary stimuli.*
- *The resulting functions are the color* ***matching functions***

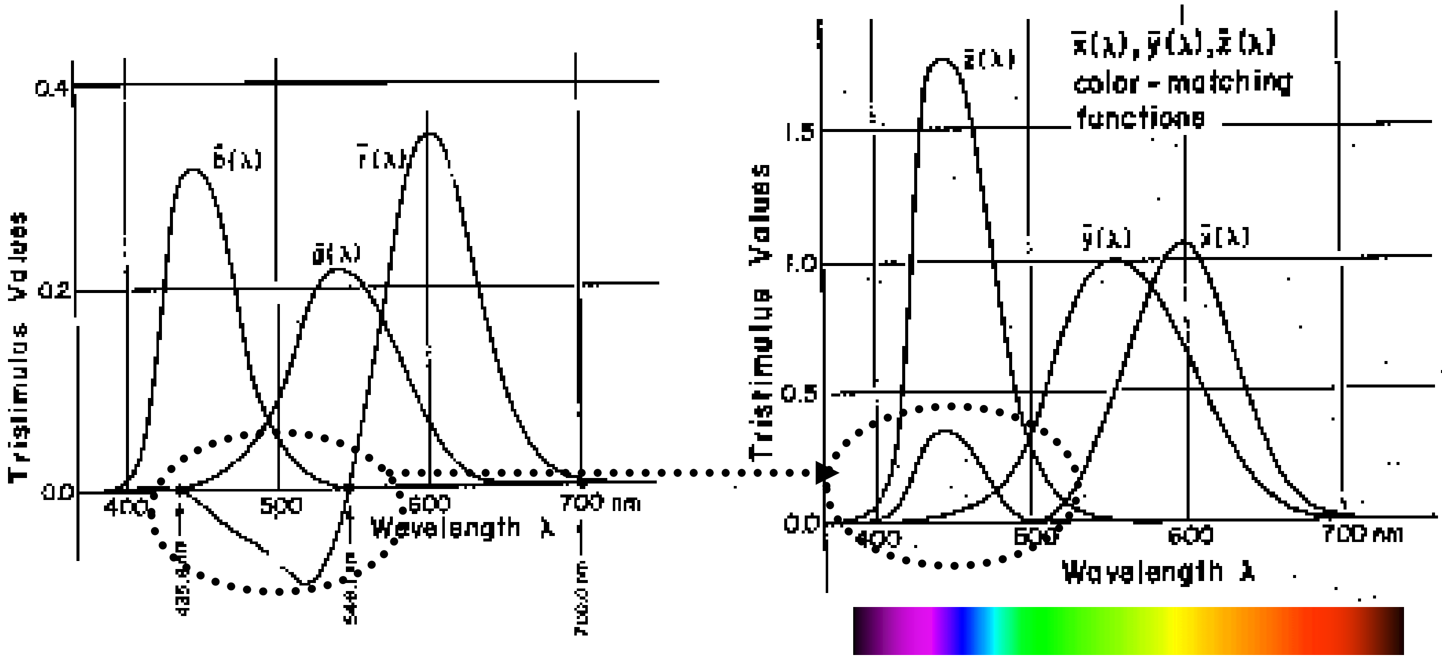
$$\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$$

XYZ color space

Imaginary space: XYZ (Standard colorimètric Observer (CIE 1931)**)**

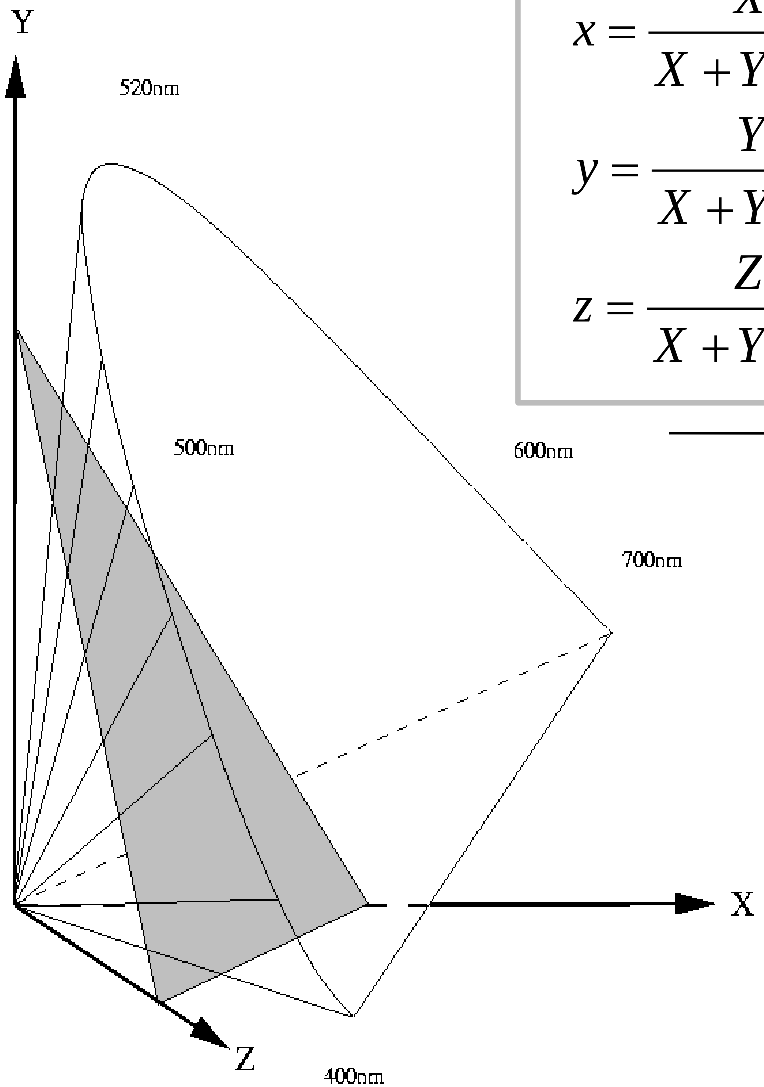
Goal:

- Avoid negative values in the color matching functions. This simplifies the constructions of color measurement devices.
- Correlate one of the functions to the intensity.



Chromaticity.exe

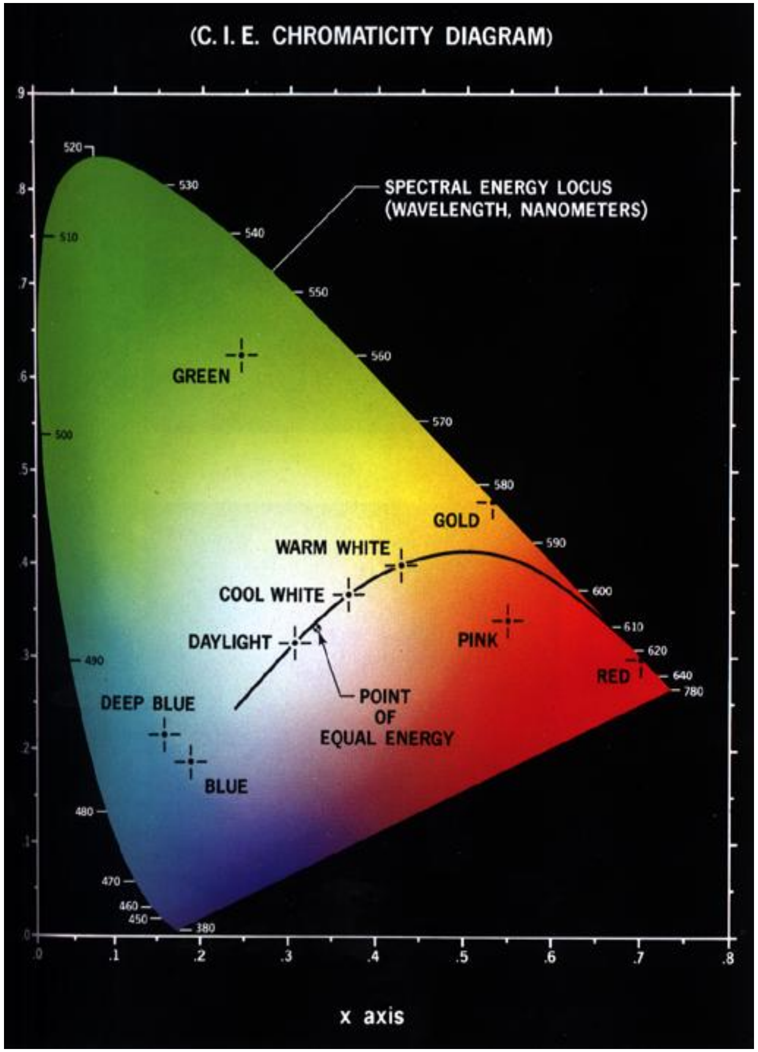
CIE diagram



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

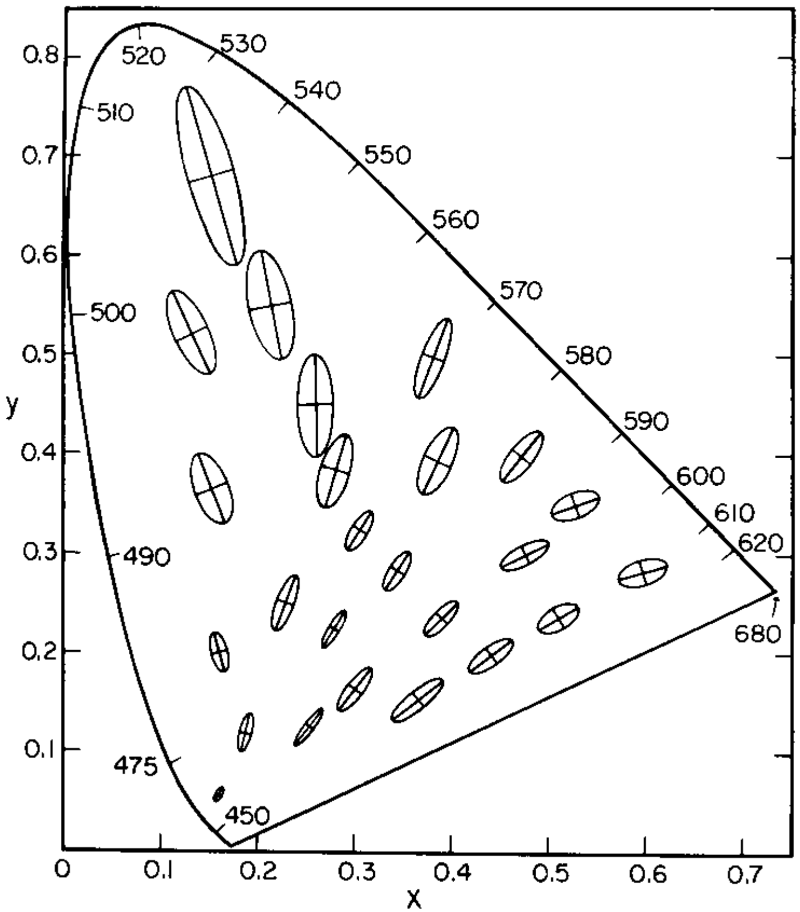
$$y = \frac{Y}{X+Y+Z}$$

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



$$white : (x, y, z) = \left(\tfrac{1}{3}, \tfrac{1}{3}, \tfrac{1}{3}\right)$$

MacAdam Ellipses



- If two stimuli are presented, one of them at the center of the ellipse, and the other one inside the ellipse, there is not a perceived difference.
- The space is not perceptually uniform (then the ellipses would be circles).

Perceptually uniform space

- CIELUV and CIELAB are examples of perceptually uniform color spaces.

$$L^* = \begin{cases} 116\left(\dfrac{Y}{Y_n}\right)^{\frac{1}{3}} - 16 & \text{if } \dfrac{Y}{Y_n} > k \\ 903.3\dfrac{Y}{Y_n} & \text{if } \dfrac{Y}{Y_n} \le k \end{cases}$$

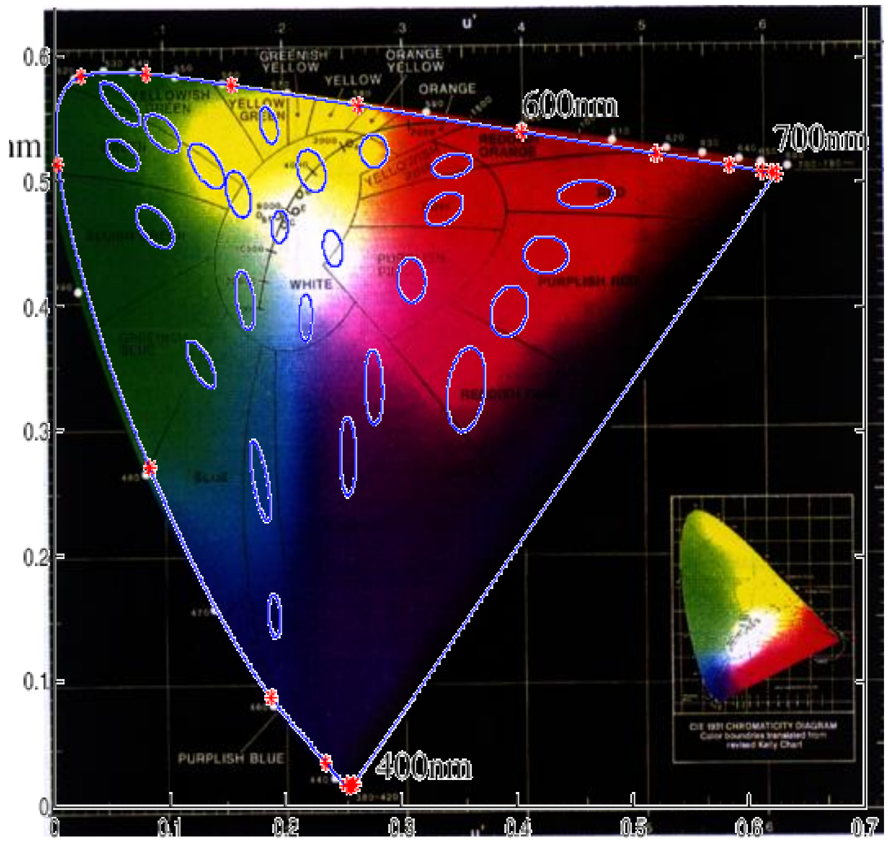
$$a^* = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right)$$

$$b^* = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right)$$

$$f(x) = \begin{cases} \sqrt[3]{x} & \text{if } x > k \\ 7.787x + \dfrac{16}{116} & \text{if } x \le k \end{cases}$$

$$k = 0.008856$$

CIELUV



$$\Delta E^*_{ab} = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$$

sRGB

- sRGB: standard RGB color space (HP, Microsoft, Pantone,Corel etc).

•Linear relation with XYZ space:

$$\begin{pmatrix} R_{linear} \\ G_{linear} \\ B_{linear} \end{pmatrix} = \begin{pmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.057 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

- sRGB images are assumed to have a gamma=2.2.

- In case of unknown origin people often assume sRGB. For example in the case of data sets collected from the internet.

Device dependent color spaces

- **RGB**: output of majority of cameras and is dependent on the camera sensitivity response.
- **CMY(K)**: Is the standard generally applied for printing devices.

HSI: human perception (others HSV, HSL)

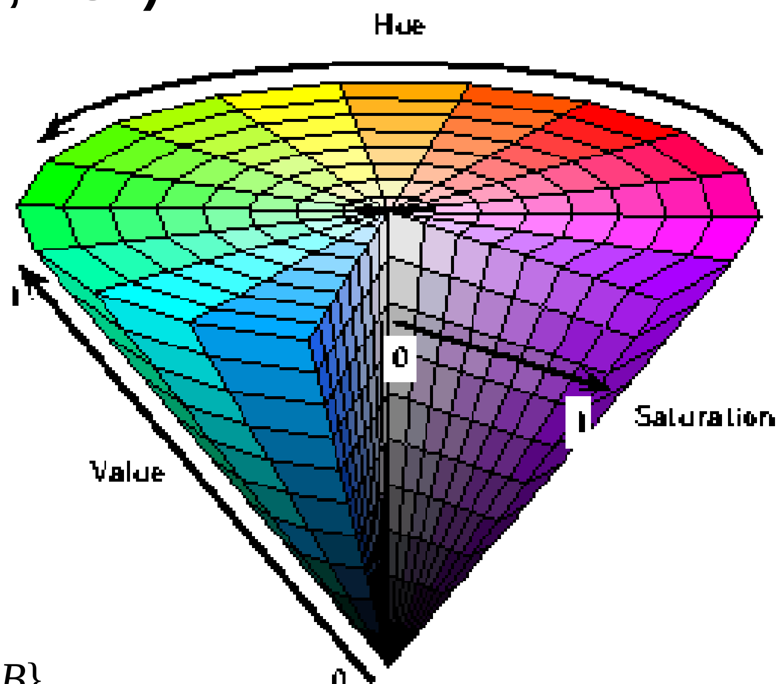
$$H = \begin{cases} \frac{\pi}{3}\left(\frac{G-B}{\Delta_2}\right) & si \quad R = max\{R,G,B\} \\ \frac{\pi}{3}\left(2.0+\frac{B-R}{\Delta_2}\right) & si \quad G = max\{R,G,B\} \\ \frac{\pi}{3}\left(4.0+\frac{R-G}{\Delta_2}\right) & si \quad B = max\{R,G,B\} \end{cases}$$

$$S = \begin{cases} \frac{\Delta_2}{\Delta_1} & si \quad L \leq 0.5 \\ \frac{\Delta_2}{2-\Delta_1} & si \quad L > 0.5 \end{cases}$$

$$I = \frac{1}{3}(R+G+B)$$

$$\Delta_1 = max\{R,G,B\} + min\{R,G,B\}$$

$$\Delta_2 = max\{R,G,B\} - min\{R,G,B\}$$



Device dependent color spaces

- **RGB**: output of majority of cameras and is dependent on the camera sensitivity response.
- **CMY(K)**: Es the standard generally applied for printing devices.

HSI: often used in computer vision

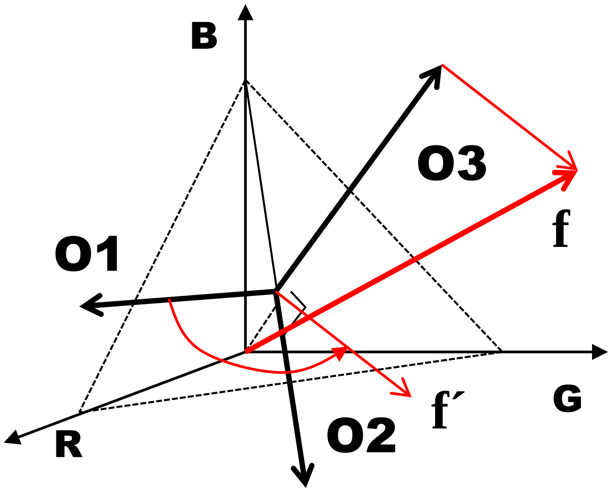
Orthonormal opponent space:

$$\begin{pmatrix} O1 \\ O2 \\ O3 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

$$H = \arctan\left(\frac{O1}{O2}\right)$$

$$S = \sqrt{O1^2 + O2^2}$$

$$I = O3$$



Projection of **f** on **O3** is the *intensity*. Let **f**´ the projection on the plane O1-O2, its length is the *satutation* and its angle the *hue*.

S is not normalized with intensity !

Guidelines application of color spaces

• be aware that many color spaces are devise dependent (industrial applications).

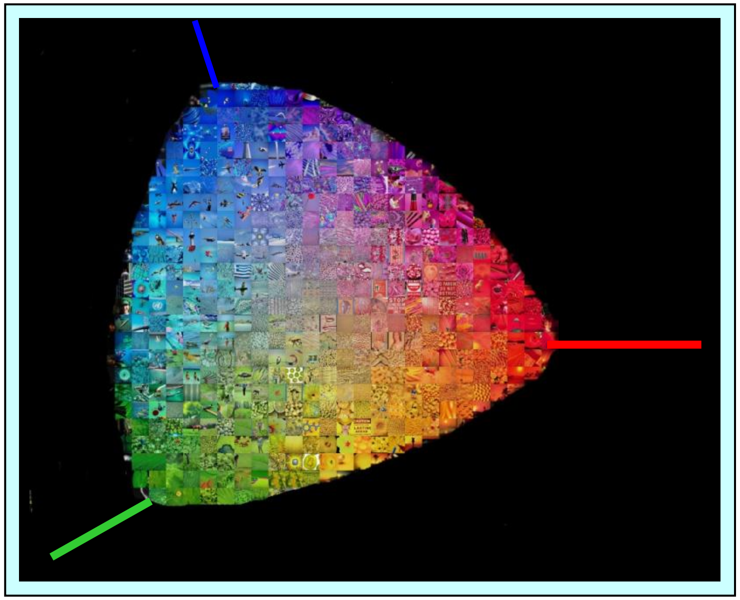
• apply CIELAB or CIELUV only when perceptually uniformity of the color space is relevant.

√ Learning color names	✗ tracking

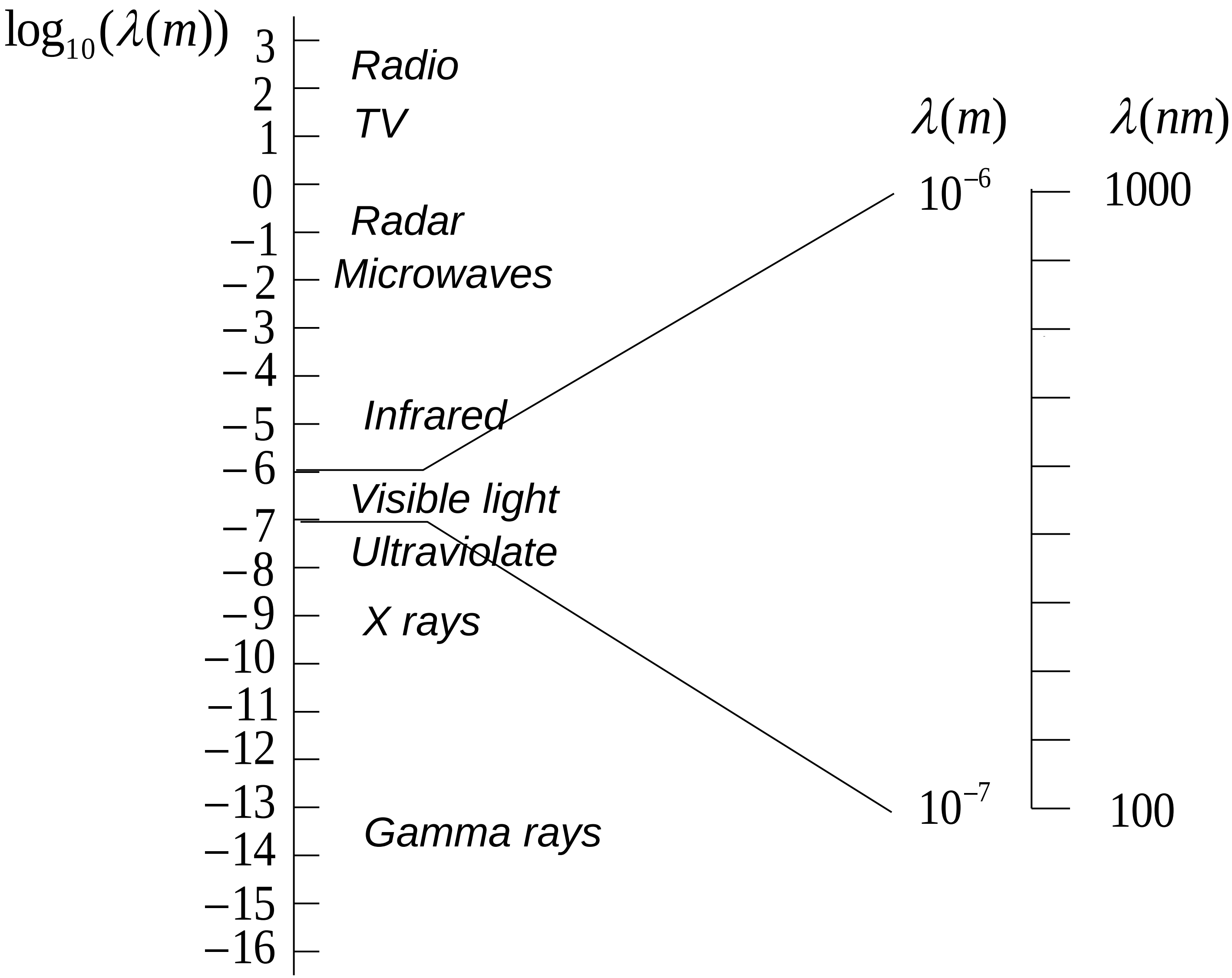
• when you want to decorrelate only luminance use opponent color space. HSI spaces introduces non-linearities.

•Choose the color space which fits the photometric invariants your application requires.

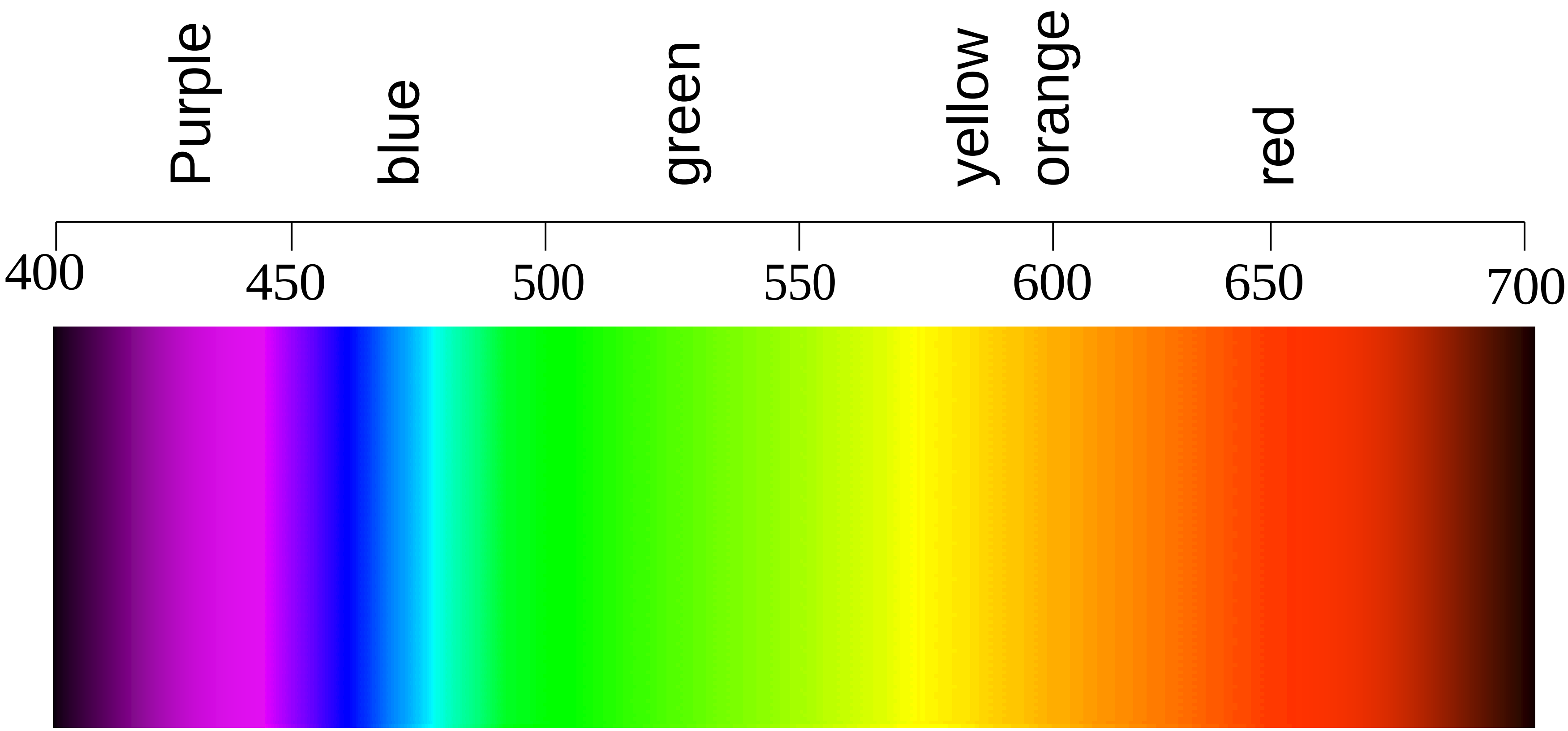
Reflection Models



Electromagnetic radiation spectrum



visible light spectrum



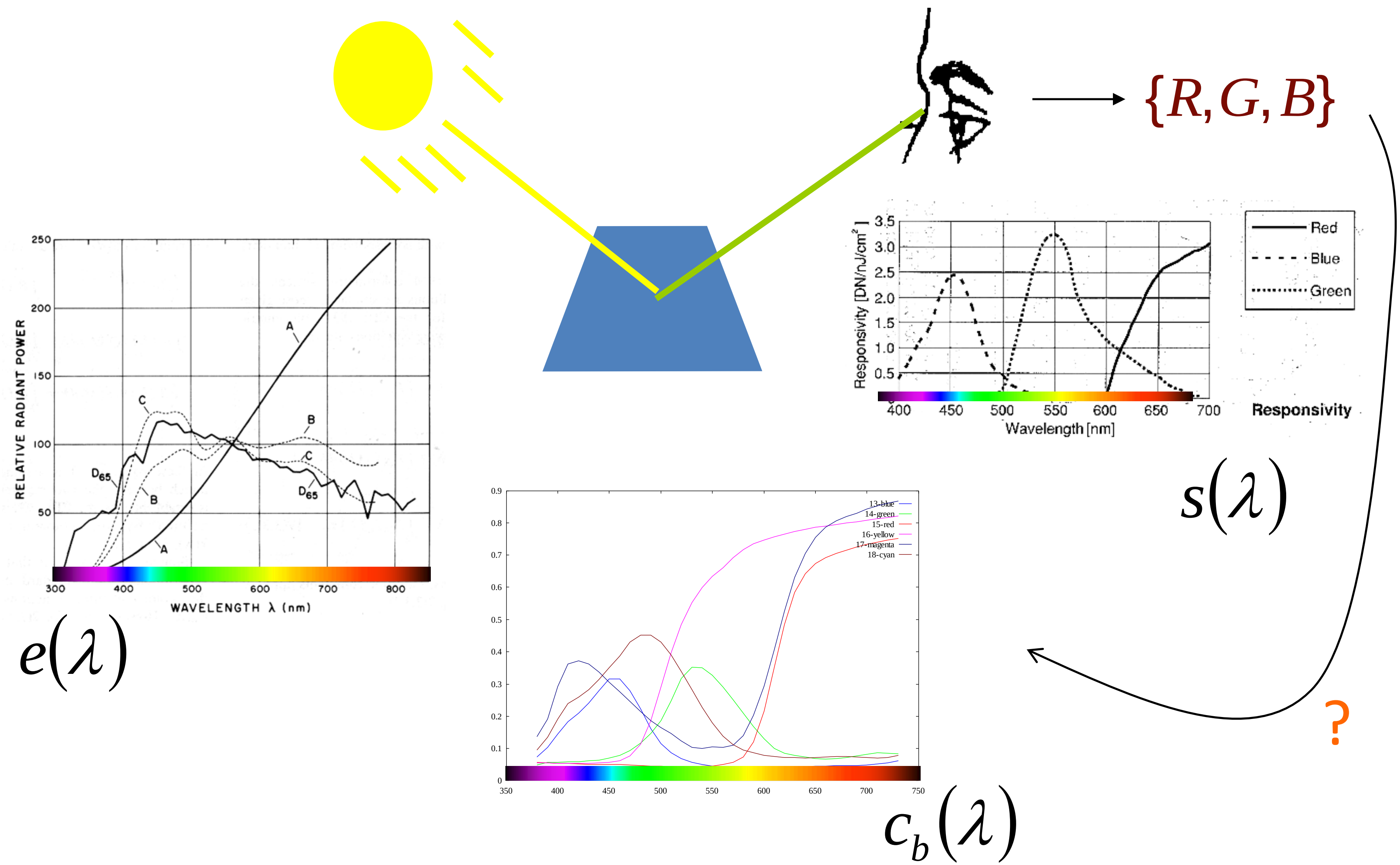
nanometers ⇨ $1nm = 10^{-9}m$

Spectra.exe

http://askabiologist.asu.edu/research/seecolor/atable.html

slide credit: R. Baldrich

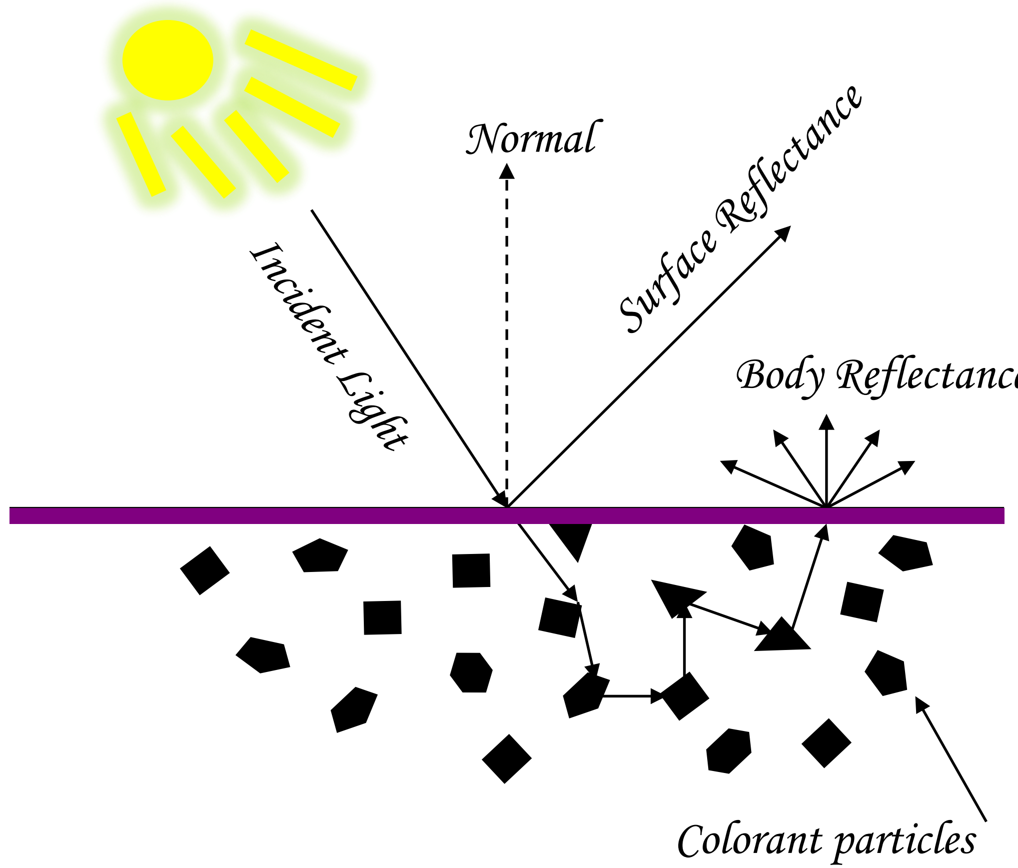
Surface reflectance



Dichromatic reflection model

Two types of reflection:

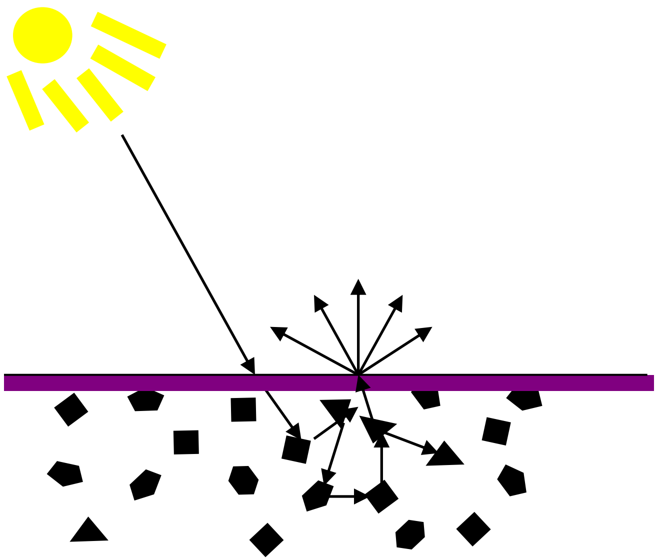
- Body reflection
- Surface reflection

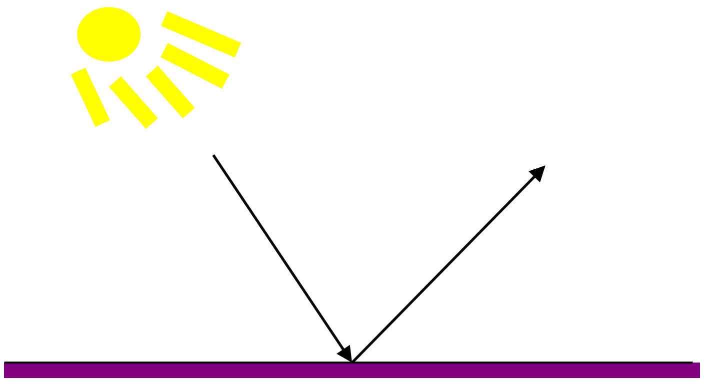


Metals: mainly specular reflection.

Dielectric: specular and diffuse reflection. It includes materials that are coloured using pigments: paints, plastic, ceramic, fabric, paper, etc.

Reflecting materials





Body Reflectance

Diffuse reflection, isotropic reflection. The spectral distribution depends on colorants.

Surface Reflectance

Specular reflection. The reflection angle is similar to the incident angle. Its spectral distribution depends on the illuminant.

$$f_b(\lambda,\Theta) = m_b(\Theta)c_b(\lambda)$$

$$f_s(\lambda,\Theta) = m_s(\Theta)c_s(\lambda) \approx m_s(\Theta)h$$

slide credit: R. Baldrich

Dichromatic reflection model:

$$f(\lambda,\Theta) = f_b(\lambda,\Theta) + f_s(\lambda,\Theta)$$

$f_b(\lambda,\Theta)$: Reflected light by the object body. It depends on the pigments used to colour the object and it's the one that makes the object look coloured. (Diffuse reflectance)

$f_s(\lambda,\Theta)$: Reflected light from the surface. It has a SPD nearly the same as the incident light. (Specular or regular reflectance)

Θ : Angles that depend on light source position, observer and surface

The spectral and geometrical terms can be separated:

$$f(\lambda,\Theta) = m_b(\Theta)c_b(\lambda) + m_s(\Theta)c_s(\lambda)$$

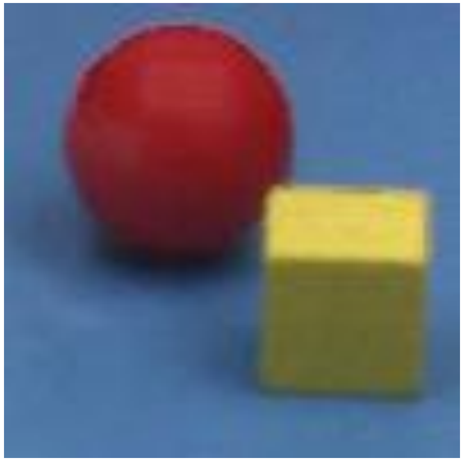
$$\mathbf{f} = m_b\mathbf{c_b} + m_s\mathbf{c_s}$$

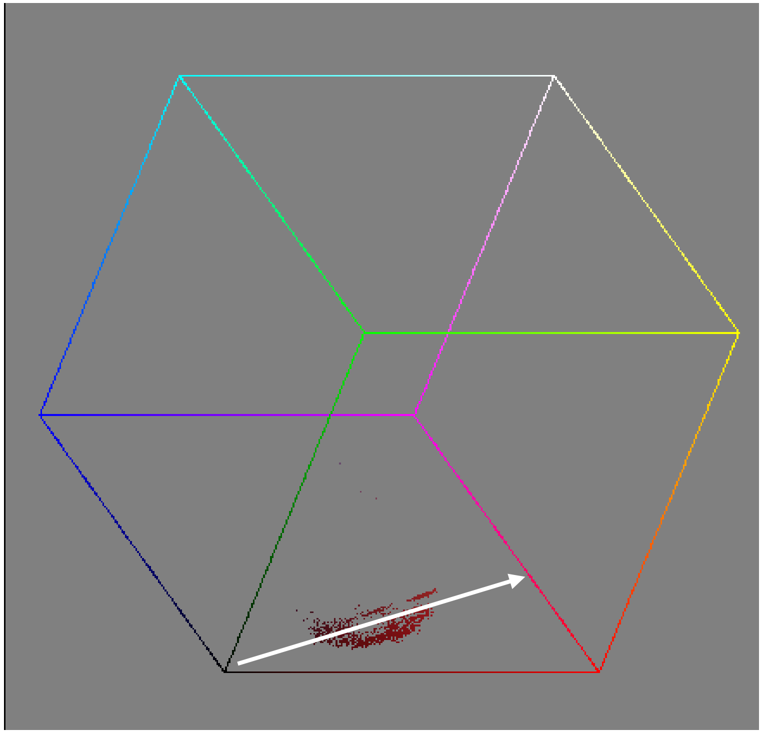
slide credit: R. Baldrich

Dichromatic Reflection Model

dichromatic model for matte surfaces:

$$\mathbf{f} = m_b \mathbf{c_b}$$



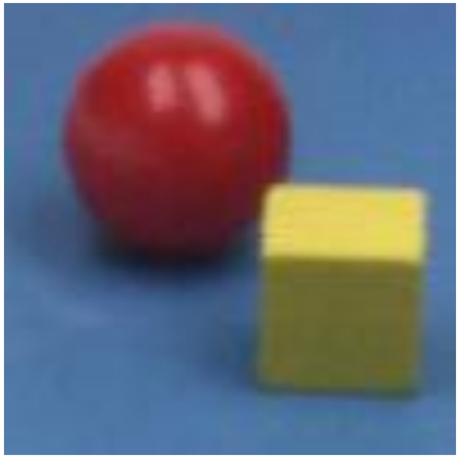


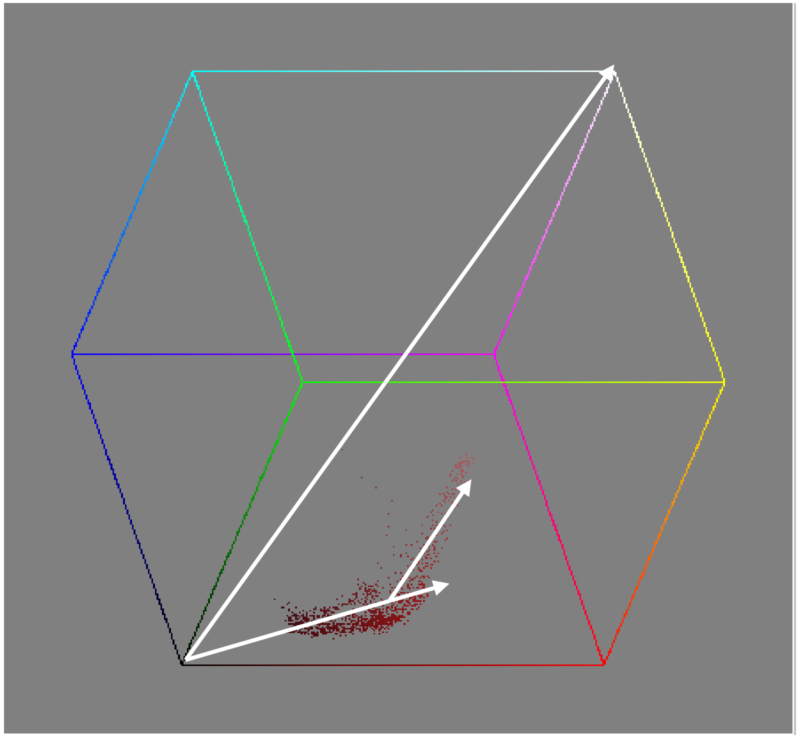
RGB-histogram

Dichromatic Reflection Model

dichromatic model for specular surfaces:

$$\mathbf{f} = m_b \mathbf{c_b} + m_s \mathbf{c_s}$$





RGB-histogram

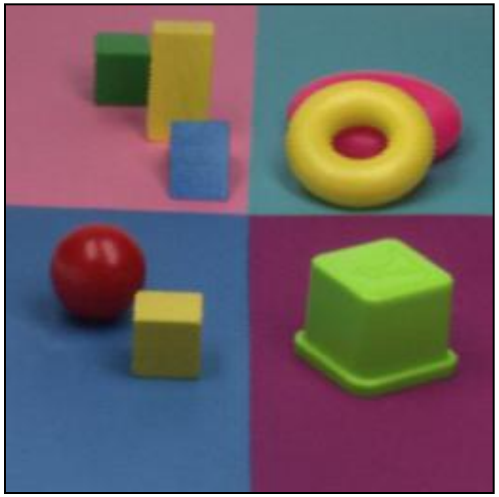
color spaces: normalized RGB

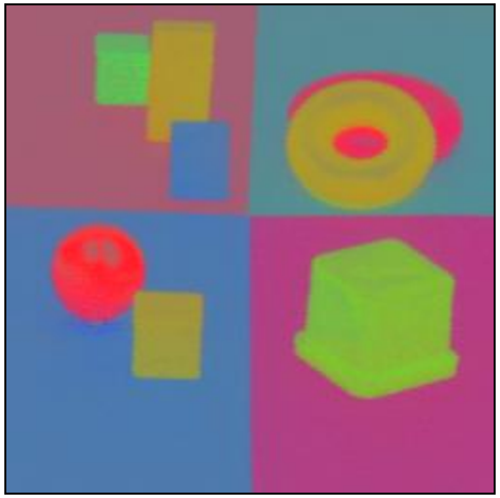
- normalized RGB is given by:

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

- invariant for shadow and shading variations (matte surfaces):

$$r = \frac{R}{R+G+B} = \frac{m_b c_R^b}{m_b c_R^b + m_b c_G^b + m_b c_B^b} = \frac{c_r^b}{c_r^b + c_g^b + c_b^b}$$

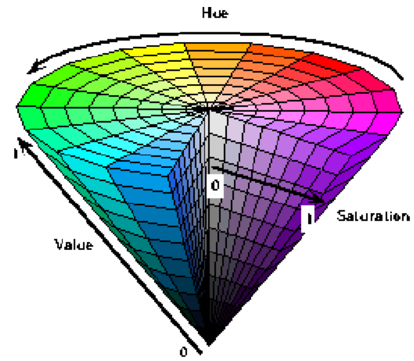




normalized RGB

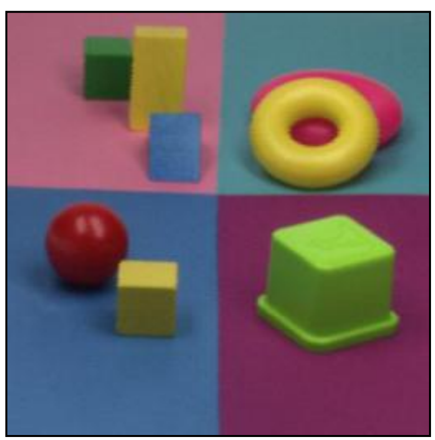
color spaces: hue-saturation-intensity

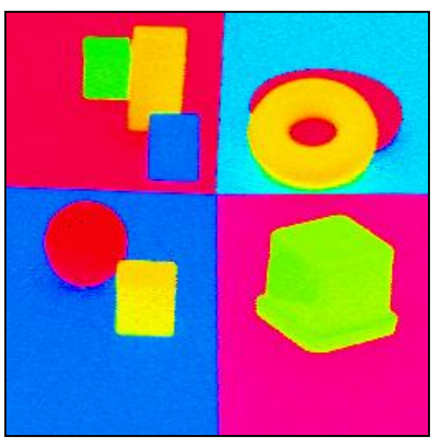
- defined as: $$hue = \arctan\left(\frac{\sqrt{3}(R-G)}{(R+G-2B)}\right)$$
$$sat = \sqrt{\tfrac{2}{3}\left(R^2+G^2+B^2-RG-RB-GB\right)}$$
$$i = \frac{R+G+B}{\sqrt{3}}$$



- hue is invariant for shading variations and specularities under white light:

$$hue = \arctan\left(\frac{\sqrt{3}\cancel{m^b}\left(c_R^b+\cancel{c^s}-c_G^b-\cancel{c^s}\right)}{\cancel{m^b}\left(c_R^b+\cancel{c^s}+c_G^b+\cancel{c^s}-2c_B^b-2\cancel{c^s}\right)}\right)$$

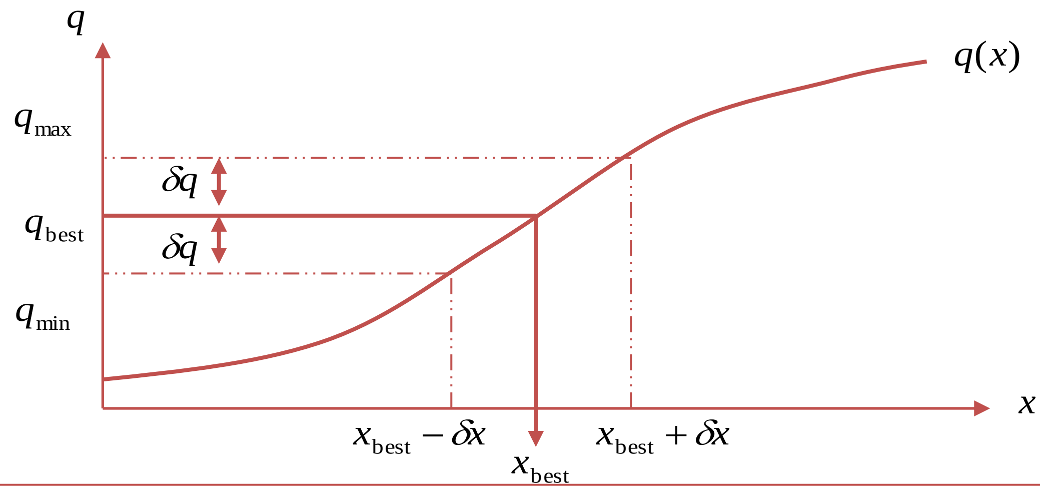




hue

Take care of instabilities

- when working in different color spaces always take instabilities into account !
- Error propagation is a convenient tool for instability evaluation:



Suppose that $u,\ldots,w$ are measured with corresponding uncertainties $\sigma_u,\ldots,\sigma_w$ to compute function $q(u,\ldots,w)$.

The predicted uncertainty is defined by :

$$\sigma_q = \sqrt{\left(\frac{\partial q}{\partial u}\sigma_u\right)^2 + \ldots + \left(\frac{\partial q}{\partial w}\sigma_w\right)^2}$$

Take care of instabilities

• when working in different color spaces always take instabilities into account !

• Error propagation is a convenient tool for instability evaluation:

Ex. 1

$$hue = \arctan\left(\frac{\sqrt{3}(R-G)}{(R+G-2B)}\right) \longrightarrow (\partial hue)^2 = \left(\partial\left(\arctan\left(\frac{\sqrt{3}(R-G)}{(R+G-2B)}\right)\right)\right)^2$$

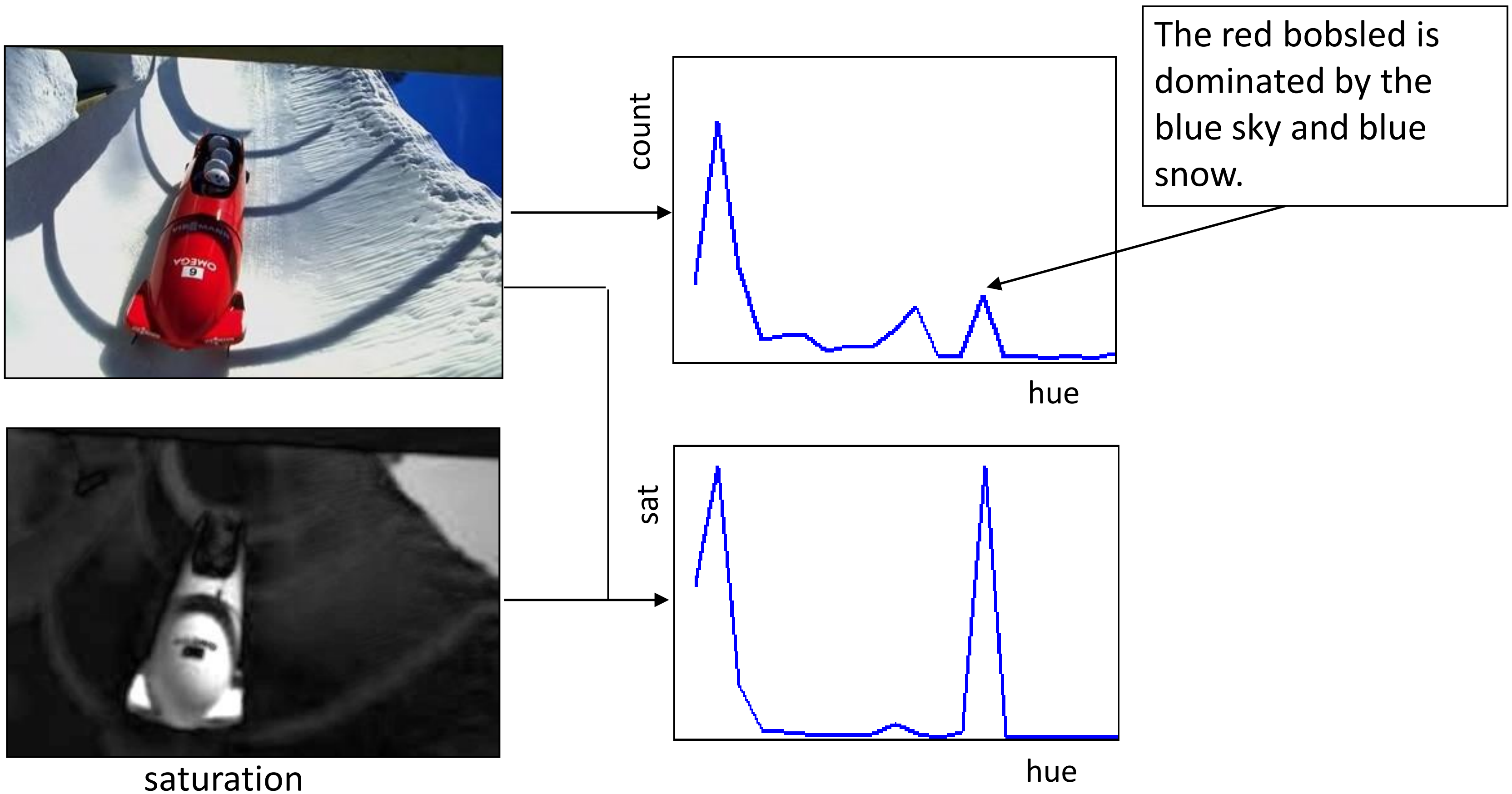
$$(\partial hue)^2 = \left(\frac{\partial hue}{\partial R}\right)^2 \partial^2 R + \left(\frac{\partial hue}{\partial G}\right)^2 \partial^2 G + \left(\frac{\partial hue}{\partial B}\right)^2 \partial^2 B$$

$$= \frac{1}{sat^2}\partial^2 R \text{ (assuming } \partial^2 R = \partial^2 G = \partial^2 B)$$

Take care of instabilities

- when working in different color spaces always take instabilities into account !

- Error analysis is a convenient tool for instability evaluation:



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