U2.3. Color

SJK002 Computer Vision

Master in Inteligent Systems

UNIVERSITAT JAUME I

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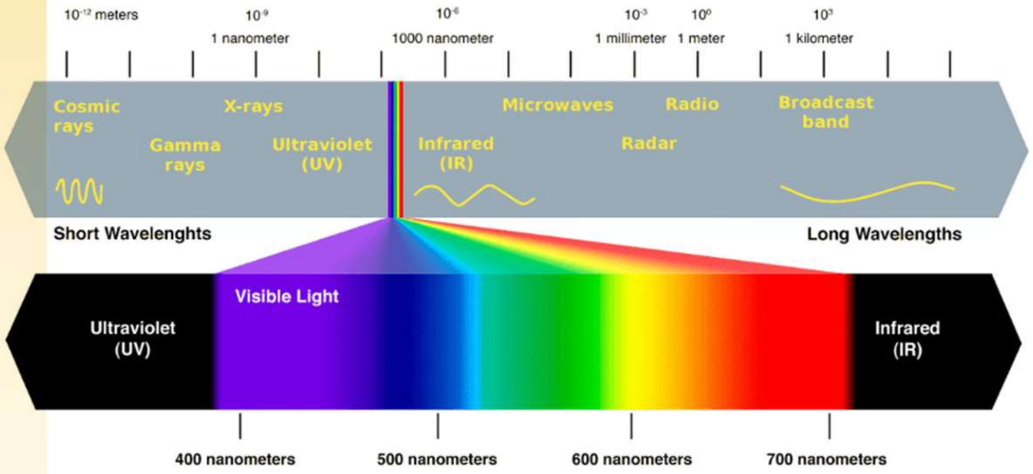
Color

"Color consists of those light features different from space-time, being light the characteristics of the radiant energy that humans perceive through the visual sensations that produce the retina excitation"

(*Optical Society of America*)

- Characteristics of the light:
  - Brightness (luminous flux).
  - Hue (dominant wavelength).
  - Saturation (purity).

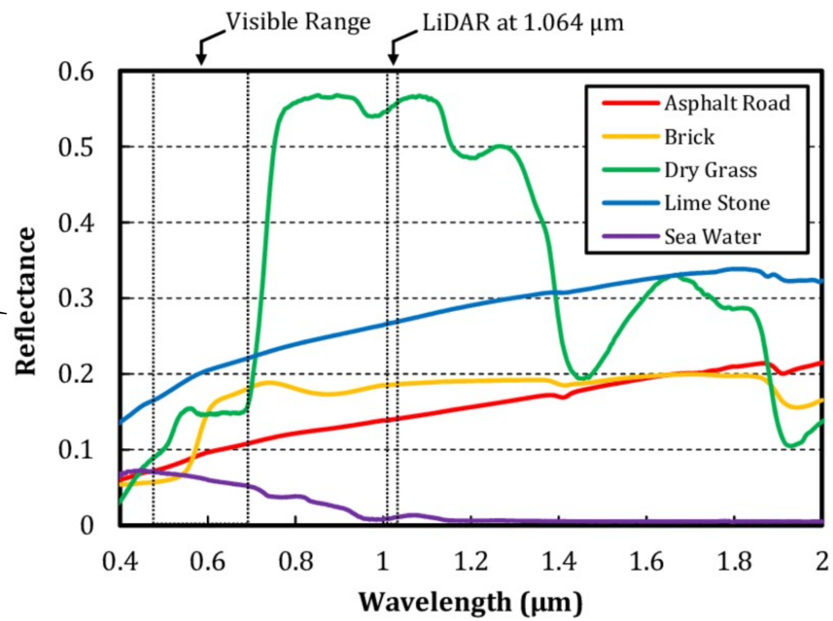
Electromagnetic radiation



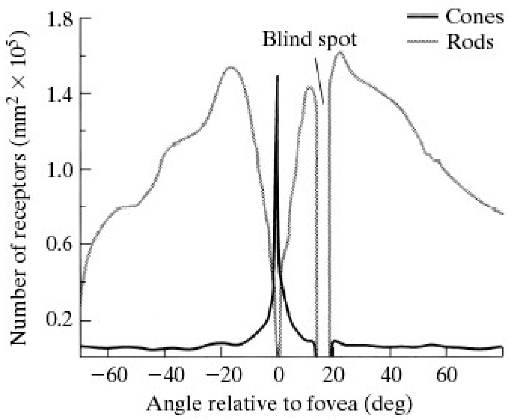
Electromagnetic radiation spectrum

Visible light spectrum

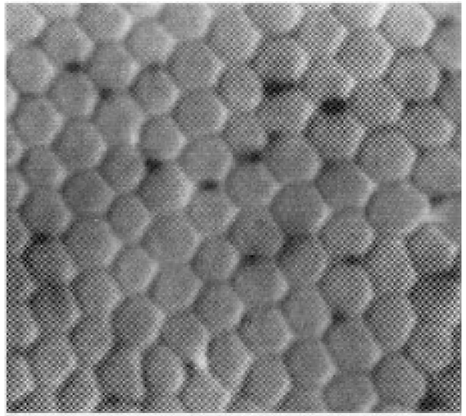
Spectral distribution of some materials reflectance



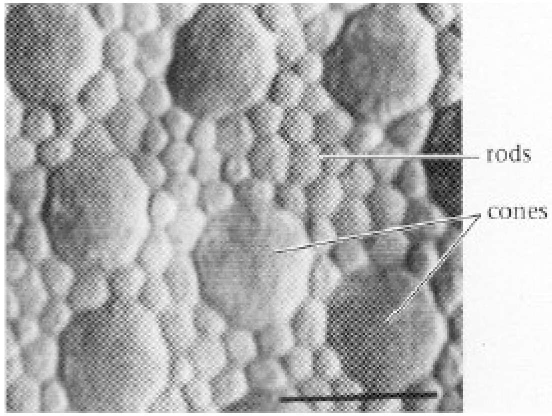
Human perception of color



Distribution of cones and rods in the retina



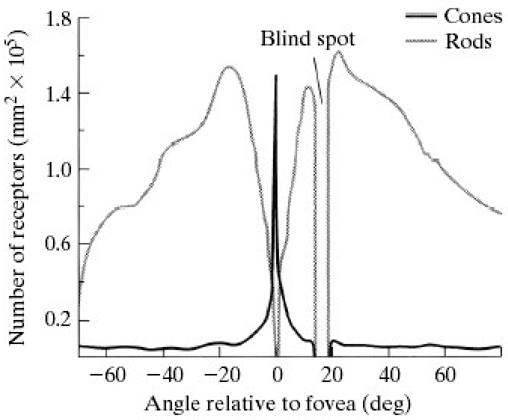
Cones in the fovea



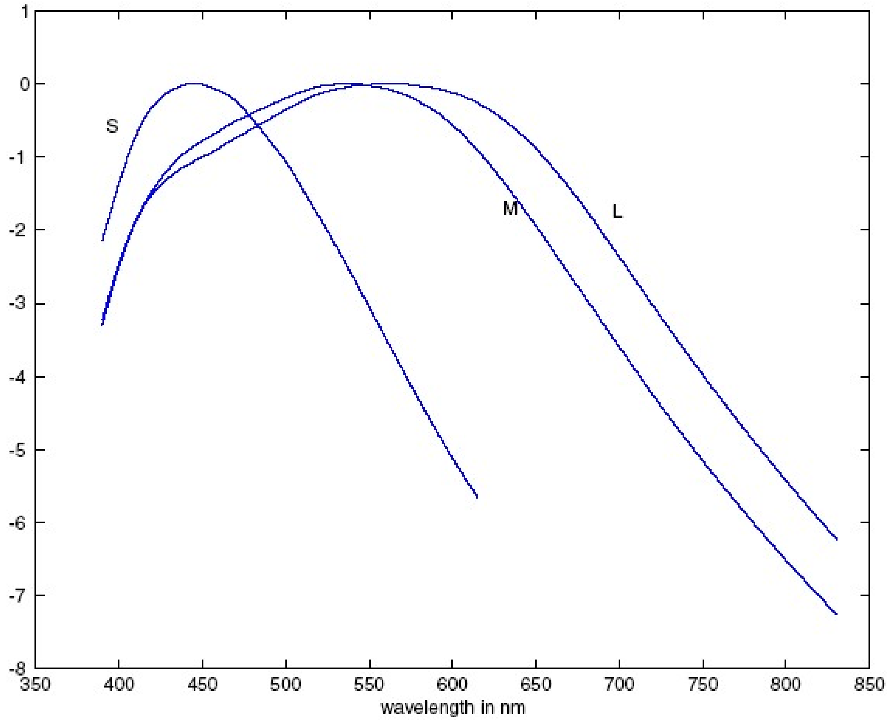
Cones (increase size with eccentricity) and rods in the periphery

- Photoreceptors [380,730] nm:
  - Rods: very sensitive. Monochrome vision (B/W).
  - Cones: Color vision.

Human perception of color



Distribution of cones and rods in the retina

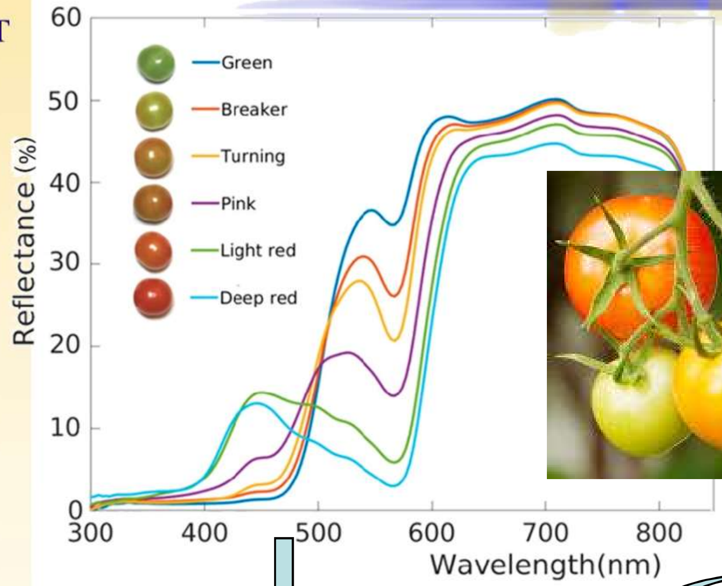


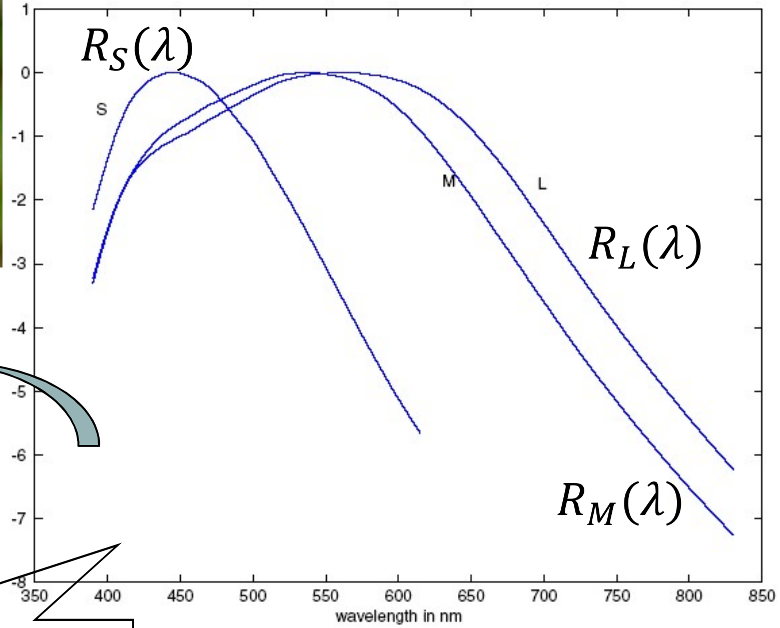
Relative sensitivity of cones types

- Three types of cones: S,M y L.
- Low levels of illumination:
  - Poor color vision.

Human perception of color

- Sensor integration





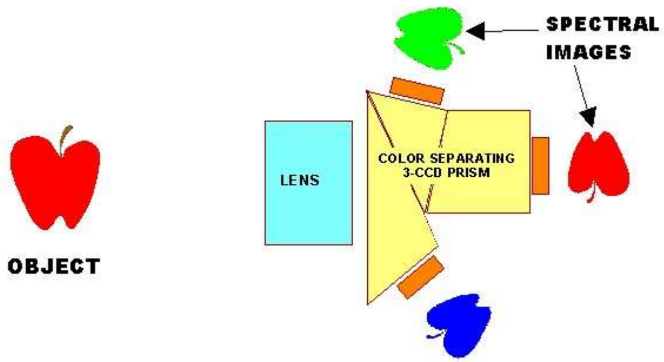
$$Q(x',y') = \int_t \int_\lambda E(x',y',\lambda,t)\, R(\lambda)\, d\lambda\, dt$$

Sensor spectral response

- A unique response for each type of photoreceptor.
- Tri-chromatic Representation.

Colorimetry

- Tri-chromatic generalization:
  - In a wide range of conditions, most of colors can be defined by additive mixtures of 3 colors:
- Tri-stimulus values:
  - Vectorial representation of color (3D).
- Example:
  - C=r R + g G + b B
  - C=(R,G,B)
  - R,G,B primary colors.



Colorimetry

- Tri-chromatic generalization (*Grassman* laws):
  1. Four colors are linearly dependent.
  2. Two colors are equal if they come from the same mixture, in spite of having different spectral representations.
  3. A continuous change in the spectral representation produces a continuous change in the tri-stimulus values.

- Symmetry: $U=V \Leftrightarrow V=U$
- Transitivity: $U=V$ and $V=W \Rightarrow U=W$
- Proportionality: $U=V \Leftrightarrow tU=tV$
- Aditivity: $U=V \quad W=X \Rightarrow U+W=V+X$

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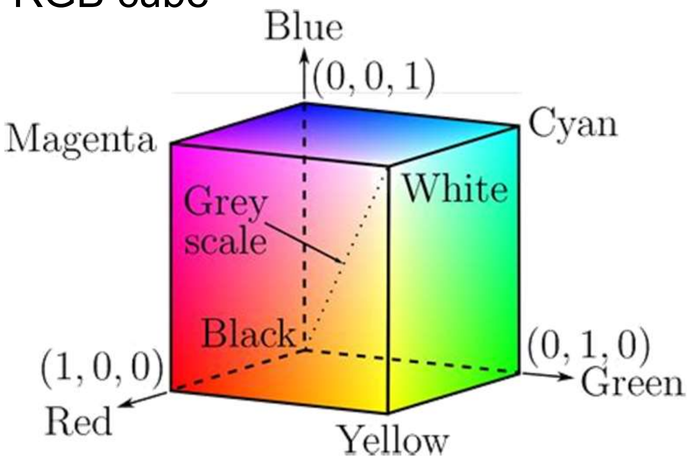
Colorimetry

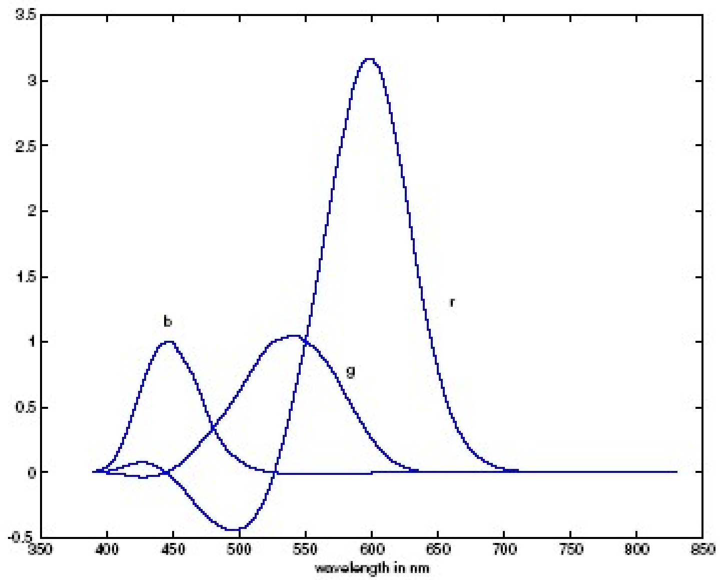
- Set of primary colors:
  - Additive mixtures of three colors.
  - Linear color space.

- Metamerism: several and different spectral representations with an unique finite color space representation:
  - Projection of a space with infinite dimensions (spectral distribution of light),
  - In a finite three-dimensional system.

Primary color RGB

RGB cube





Base of functions of the RGB system

Sensor spectral response

$$R = \int_t \int_\lambda E(x', y', \lambda, t)\, r(\lambda)\, d\lambda\, dt$$

$$G = \int_t \int_\lambda E(x', y', \lambda, t)\, g(\lambda)\, d\lambda\, dt$$

$$B = \int_t \int_\lambda E(x', y', \lambda, t)\, b(\lambda)\, d\lambda\, dt$$

$$C(x', y') = (R, G, B)$$

Primary colors CIE-XYZ

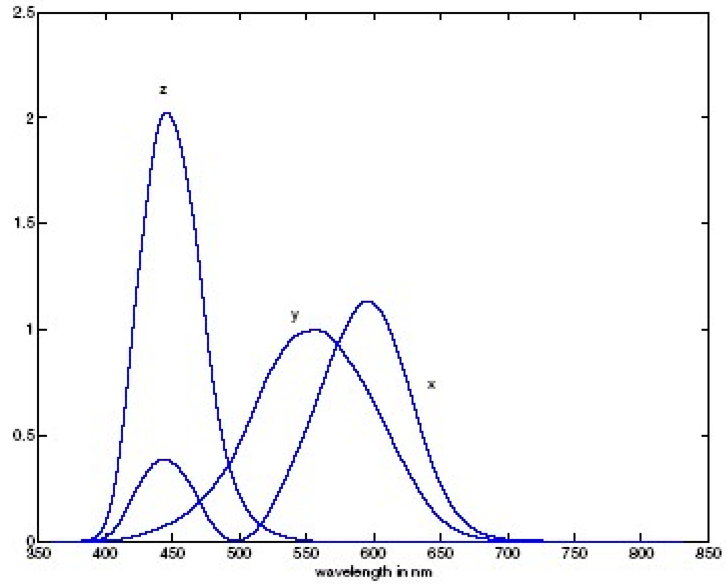
- Avoid negative values in base functions:
  - Always positive coefficients.
  - Positive tri-chromatic values.

$$X = \int_t \int_\lambda E(x', y', \lambda, t)\, x(\lambda)\, d\lambda\, dt$$

$$Y = \int_t \int_\lambda E(x', y', \lambda, t)\, y(\lambda)\, d\lambda\, dt$$

$$Z = \int_t \int_\lambda E(x', y', \lambda, t)\, z(\lambda)\, d\lambda\, dt$$

$$C(x', y') = (X, Y, Z)$$



Base functions of the CIE XYZ system

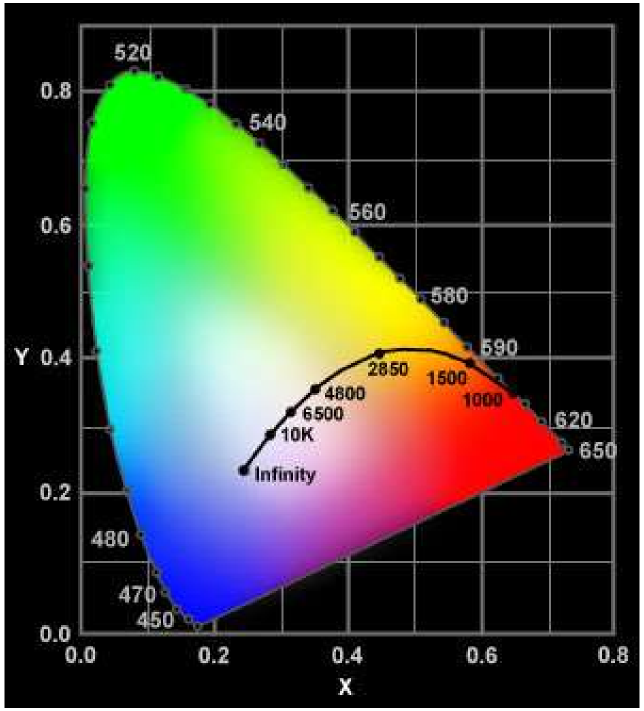
- Chromaticity:
  - Color values independent from luminance.
  - Depends on dominant wavelength and saturation

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

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

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

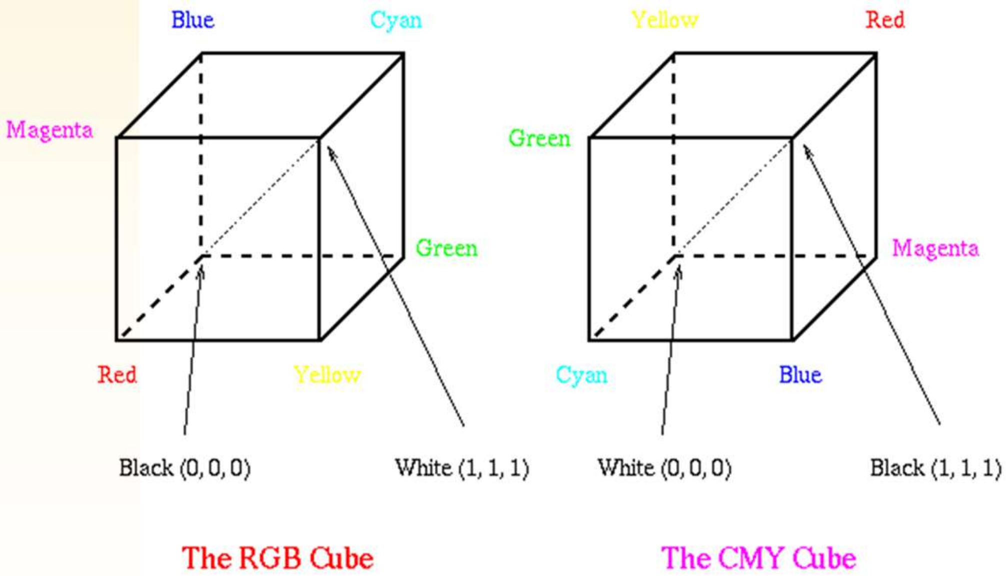
$$x + y + z = 1$$



xy chromatic diagram

Secondary colors

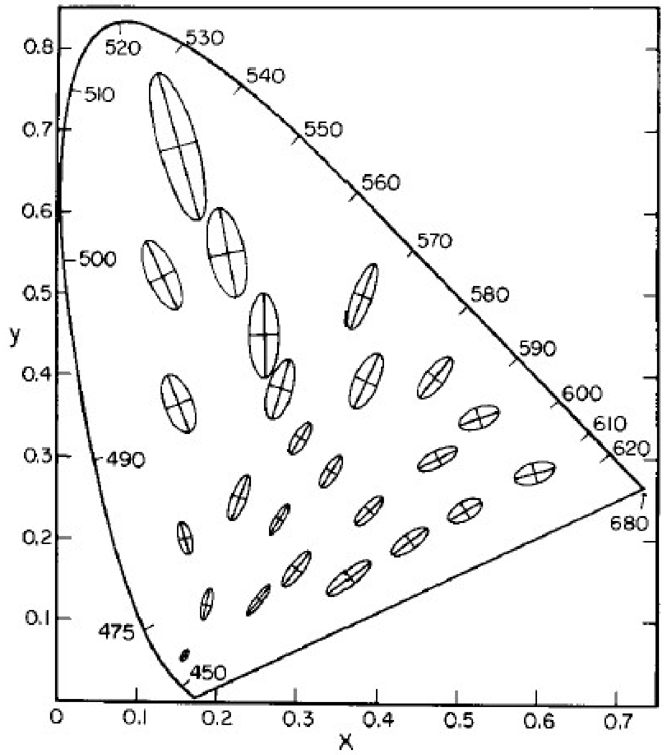
- Subtractive color system:
  - CMY (*Cyan-Magenta-Yellow*)
  - Represent absorption codification.
  - Subtraction from white color:
    - Opposite to primary colors (addition to black).



- *Cyan* : subtract red to white.
- *Magenta*: subtract green to white.
- *Yellow*: subtract blue to white.

Uniform color space

- McAdam ellipses:
  - With respect to a human observer.
  - Differences in xy space are not uniform.

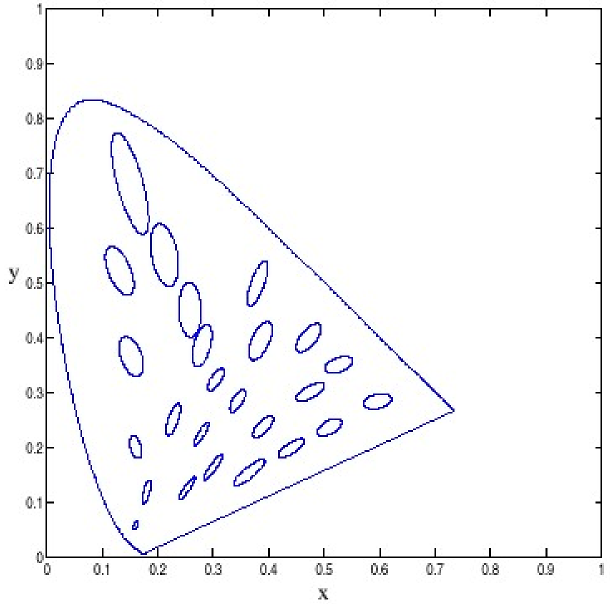


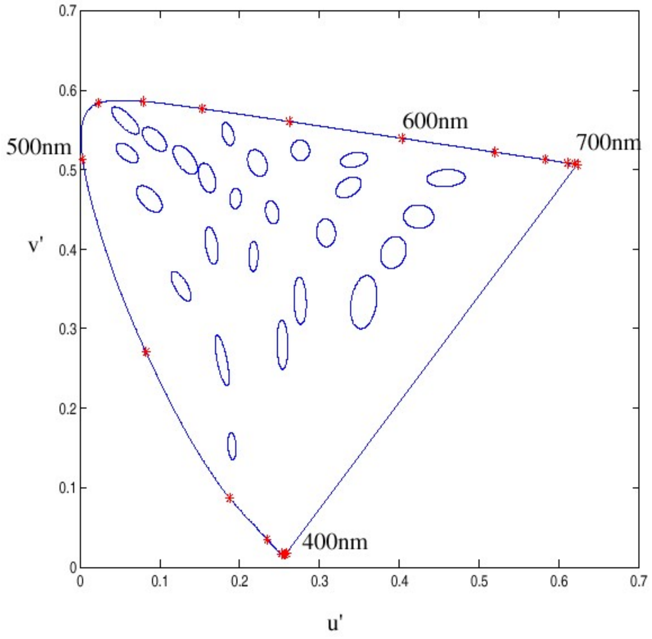
- Uniform color spaces:
  - Uniform color differences.

Uniform color space

- CIE u'v':
  - Transformation of XYZ to deform ellipses.
  - Omit luminance differences (brightness).

$$(u', v') = \left(\frac{4X}{X + 15Y + 3Z}, \frac{9Y}{X + 15Y + 3Z}\right)$$





Uniform color space

- CIE LAB:
  - More popular and used.
  - Non-linear transformation of XYZ.
  - Good reference of human observer differences.

$$
\begin{aligned}
L^* &= 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16 \\
a^* &= 500\left[\left(\frac{X}{X_n}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right] \\
b^* &= 200\left[\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}}\right]
\end{aligned}
$$

Non-linear spaces

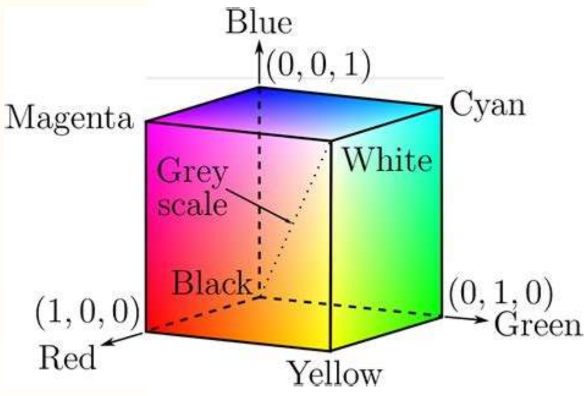
- HSI (HSV):

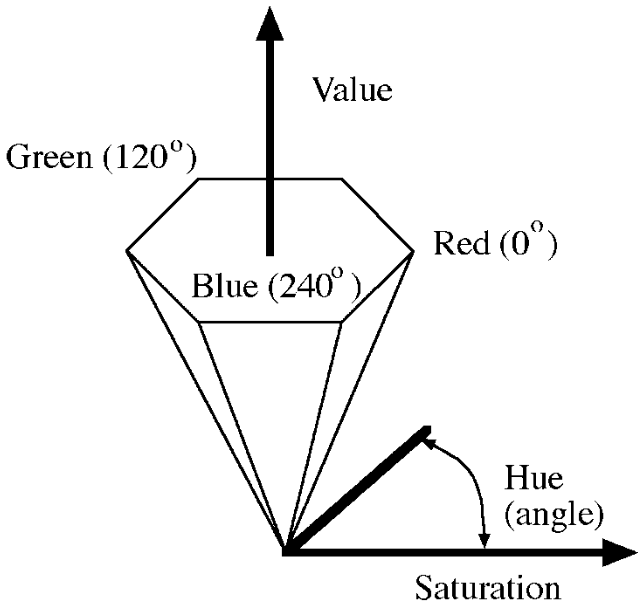
$$
\begin{bmatrix} I \\ U \\ V \end{bmatrix} = \begin{bmatrix} 1/3 & 1/3 & 1/3 \\ 2/3 & -1/3 & -1/3 \\ -1/3 & 2/3 & -1/3 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}
$$

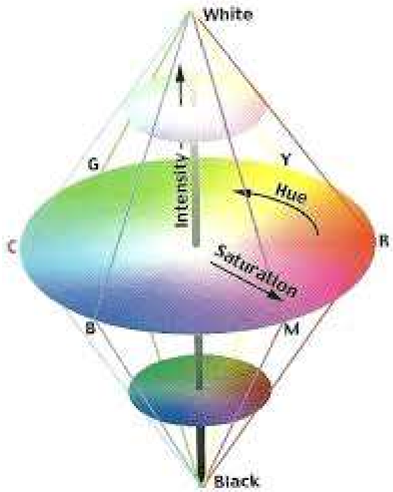
$$
H = \arctan\left(\frac{V}{U}\right)
$$

$$
S = (U^2 + V^2)^{1/2}
$$

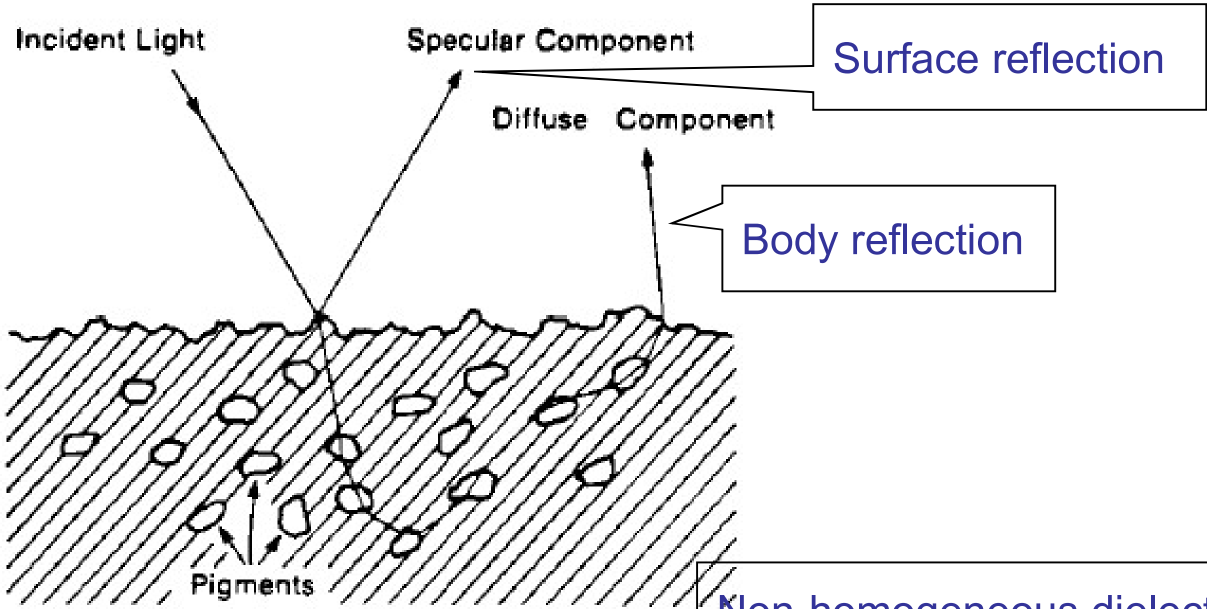
(H,S) are the polar coordinates values (U,V) in this reference system.







Color at object surfaces



Non-homogeneous dielectric and same properties in any point on the object surface

- Di-chromatic model:

$$L(\theta_i,\varphi_i,\theta_r,\varphi_r,\lambda) = L_s(\theta_i,\varphi_i,\theta_r,\varphi_r,\lambda) + L_b(\theta_i,\varphi_i,\theta_r,\varphi_r,\lambda)$$

$$L(\theta_i,\varphi_i,\theta_r,\varphi_r,\lambda) = m_s(\theta_i,\varphi_i,\theta_r,\varphi_r)\, c_s(\lambda) + m_b(\theta_i,\varphi_i,\theta_r,\varphi_r)\, c_b(\lambda)$$

Color at object surfaces

- Light integration in the sensor (in RGB)

$$C_f = \int_t \int_\lambda L(x', y', \lambda, t)\, f(\lambda)\, d\lambda\, dt \quad \Rightarrow \quad C(x', y') = (R, G, B)$$

RGB base functions $f = r, g, b$

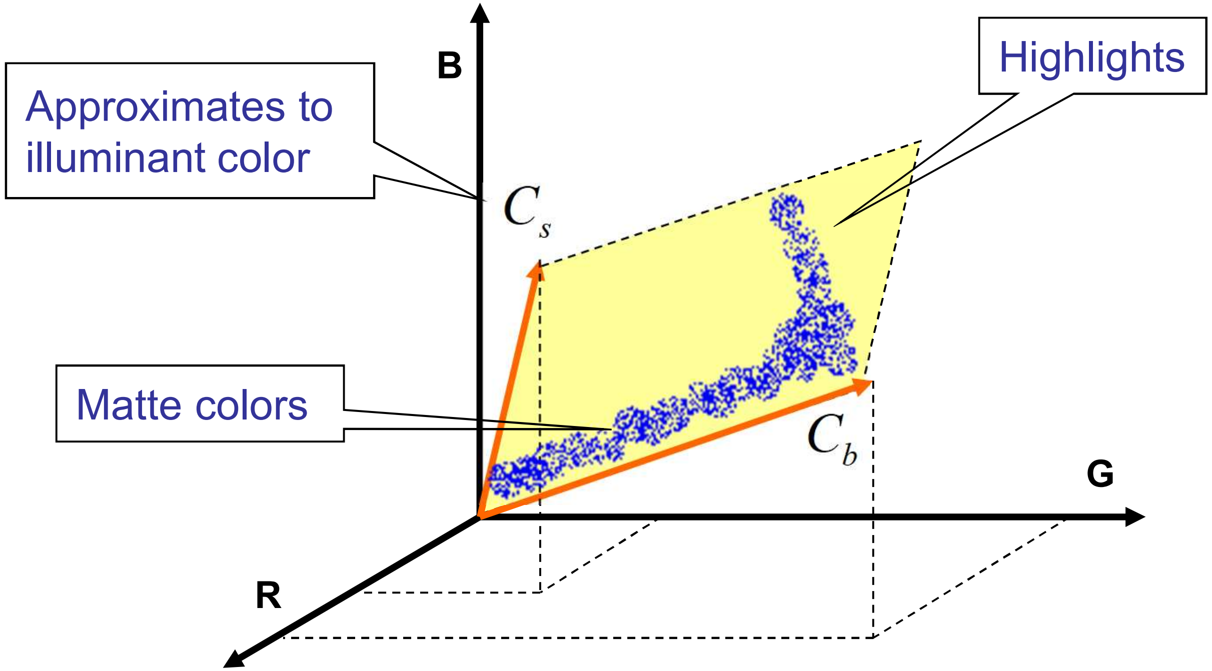
$$L(\theta_i, \varphi_i, \theta_r, \varphi_r, \lambda) = m_s(\theta_i, \varphi_i, \theta_r, \varphi_r)\, c_s(\lambda) + m_b(\theta_i, \varphi_i, \theta_r, \varphi_r)\, c_b(\lambda)$$

$$\Downarrow$$

$$C(x', y') = m_s(\theta_i, \varphi_i, \theta_r, \varphi_r)\, C_s(x', y') + m_b(\theta_i, \varphi_i, \theta_r, \varphi_r)\, C_b(x', y')$$

Color at object surfaces

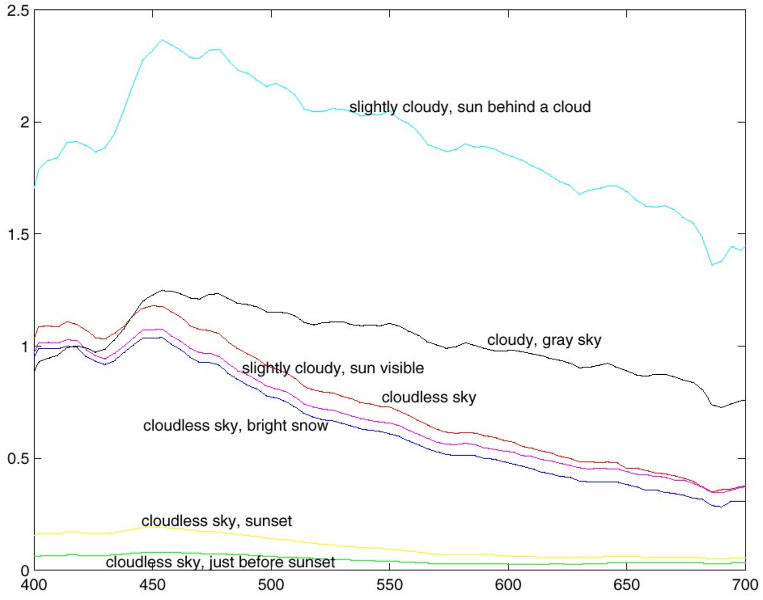
$$C(x',y') = m_s(\theta_i,\varphi_i,\theta_r,\varphi_r)\, C_s(x',y') + m_b(\theta_i,\varphi_i,\theta_r,\varphi_r)\, C_b(x',y')$$



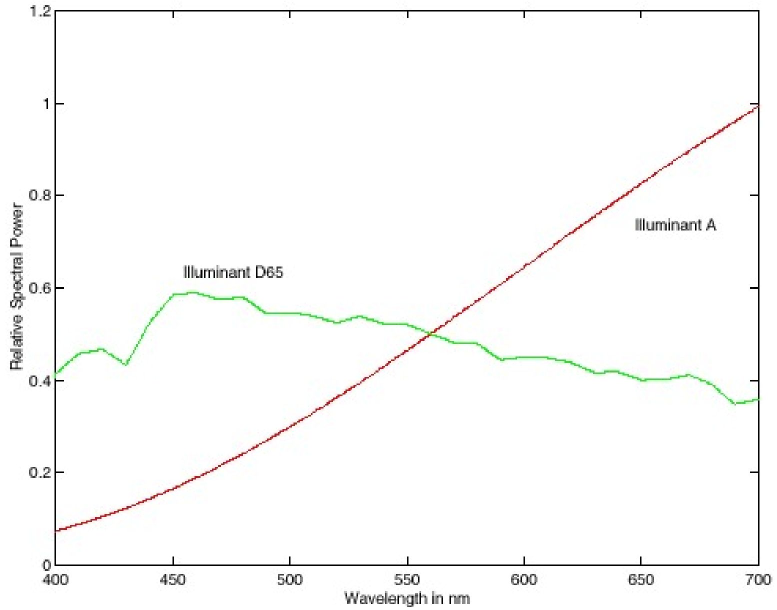
Di-chromatic plane in RGB space

Color constancy

- Object color perception independent from illuminant color.

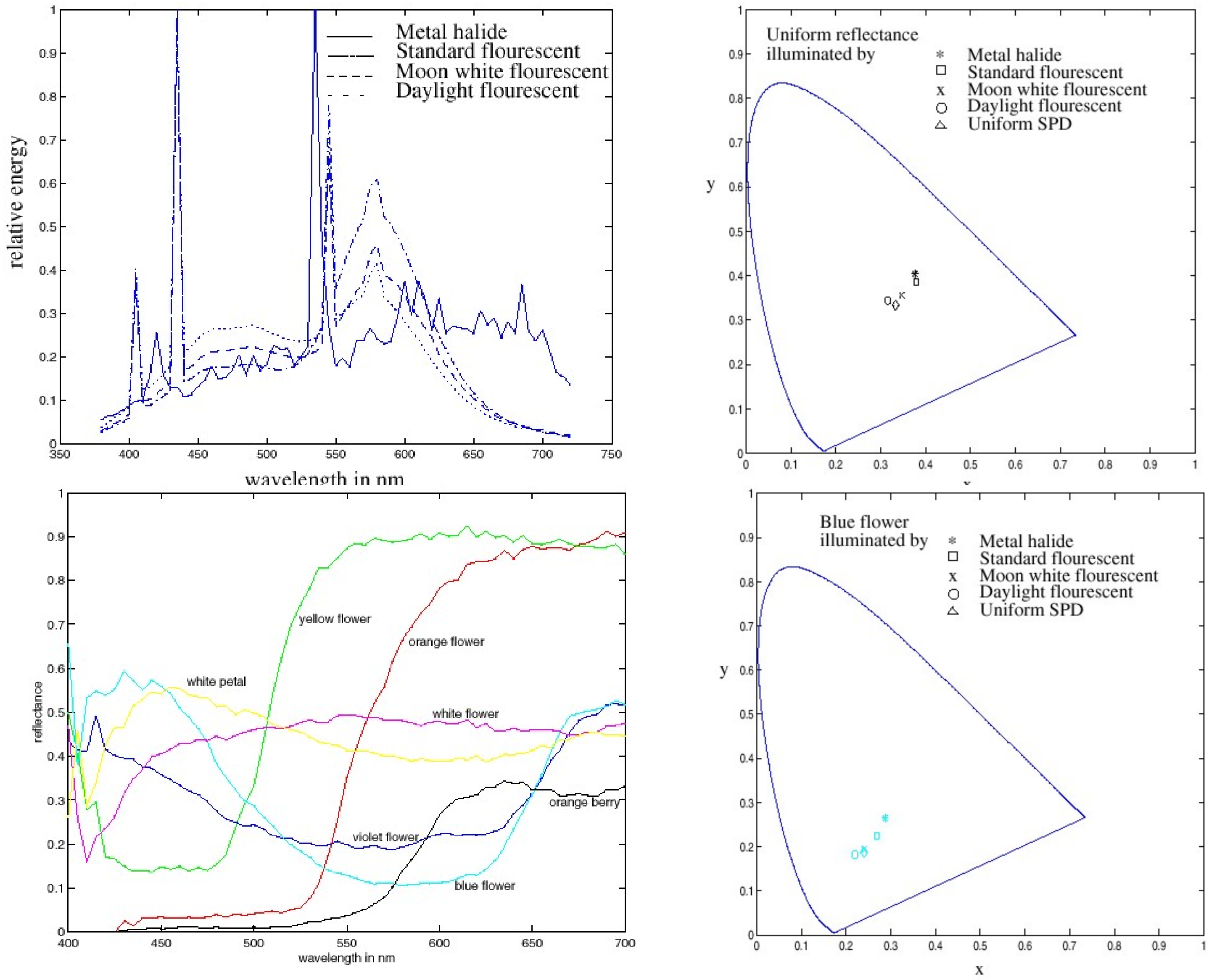


Relative spectral power distributions for different solor light variations



Standard illuminant models CIE D65 (solar light) and illuminant A (incandescent lamp)

Color constancy



Color constancy

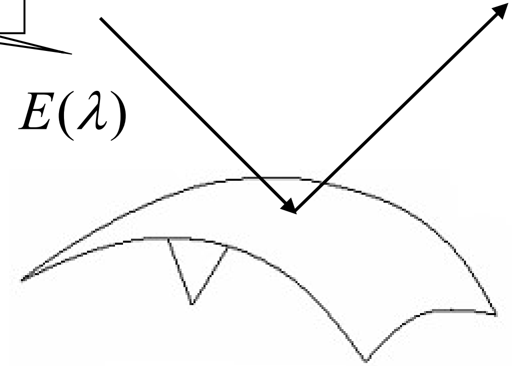
- Linear model of finite dimensionality:

Reflected light

$$E(\lambda)\, S(x', y', \lambda)$$

Illuminant

$$E(\lambda)$$



$$S(x', y', \lambda)$$

BRDF (albedo): only for areas free of specularities

Known function base

$$S(\lambda) = \sum_{i=1}^{n} \sigma_i S_i(\lambda)$$

Known function base

$$E(\lambda) = \sum_{j=1}^{m} \varepsilon_j E_j(\lambda)$$

$$\rho_k(x', y') = \int_t \int_\lambda R_k(\lambda)\, S(x', y', \lambda)\, E(\lambda)\, d\lambda\, dt$$

Sensor integration

Color constancy

$$\rho_k(x',y') = \int_t \int_\lambda R_k(\lambda)\left(\sum_{i=1}^{n}\sigma_i S_i(\lambda)\right)\left(\sum_{j=1}^{m}\varepsilon_j E_j(\lambda)\right) d\lambda\, dt$$

Matrix notation

$$\rho = \Lambda_\varepsilon \sigma$$

pxn matrix (p sensors and n base functions)

$$[\Lambda_\varepsilon]_{ki} = \int_t \int_\lambda R_k(\lambda)\, S_i(\lambda)\, E(\lambda)\, d\lambda\, dt$$

- If E(λ) is known ⇒ Λ_ε is known: $\sigma = \Lambda_\varepsilon^{-1}\rho$

For each (x',y') point

- If illuminant is unknown:
  - p=n+1 sensors are needed
  - s>m measures of different points
  - Solve equation system.

References

- Basic:
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  - Shapiro, L. and Stockman, G.; *Computer Vision*, Chapter 6, Prentice Hall, 2000.
  - Jähne, B.; Haubecker, H.; Geibler, P.; *Handbook of Computer Vision and Applications*, Chapter 11, Academic Press, 1999.