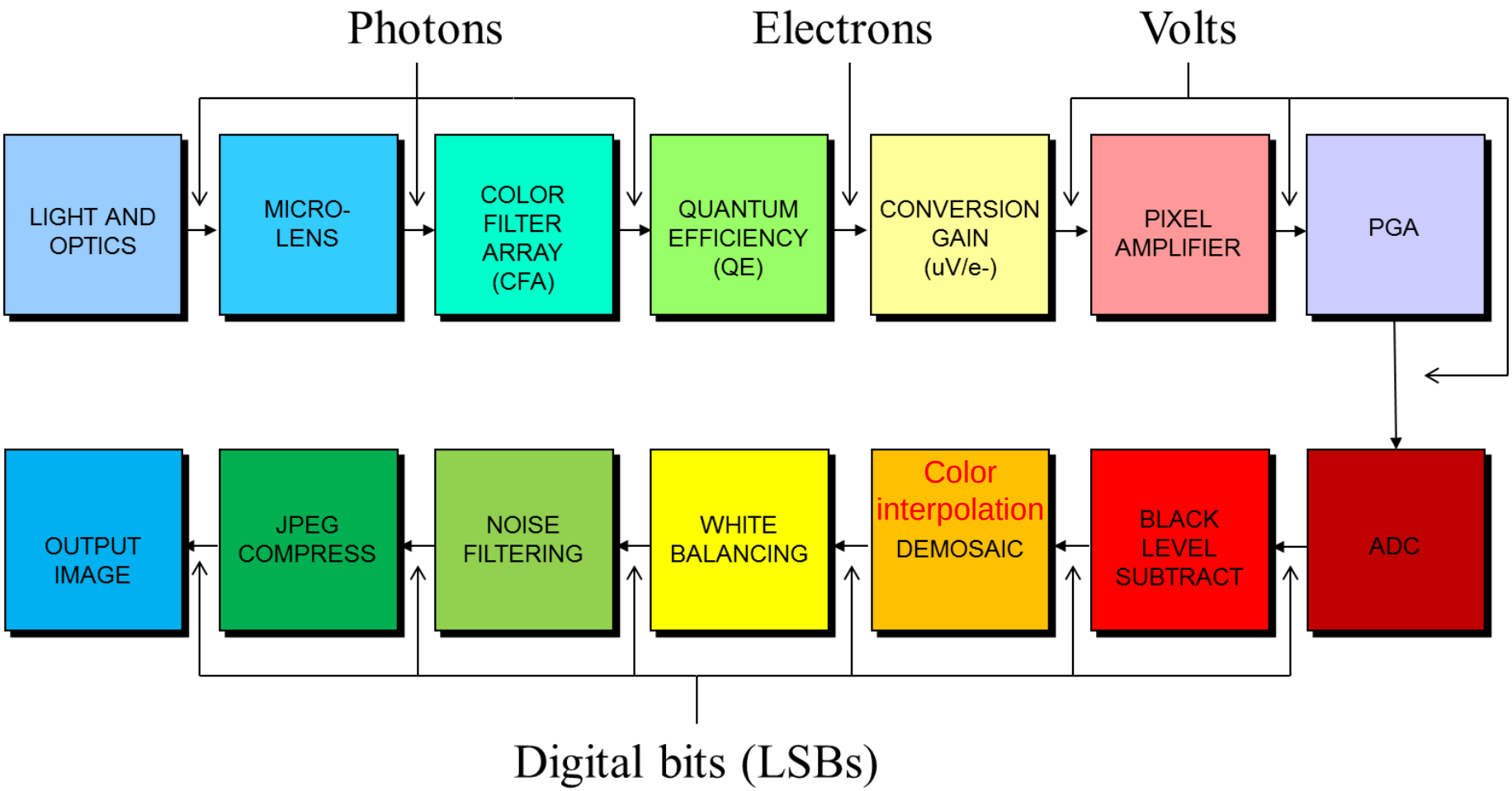
UiO : Department of Informatics
University of Oslo

INF5442 – Lecture 4

Color theory and color processing

Ref: Nakamura et al, Ch-7 and Ch-8

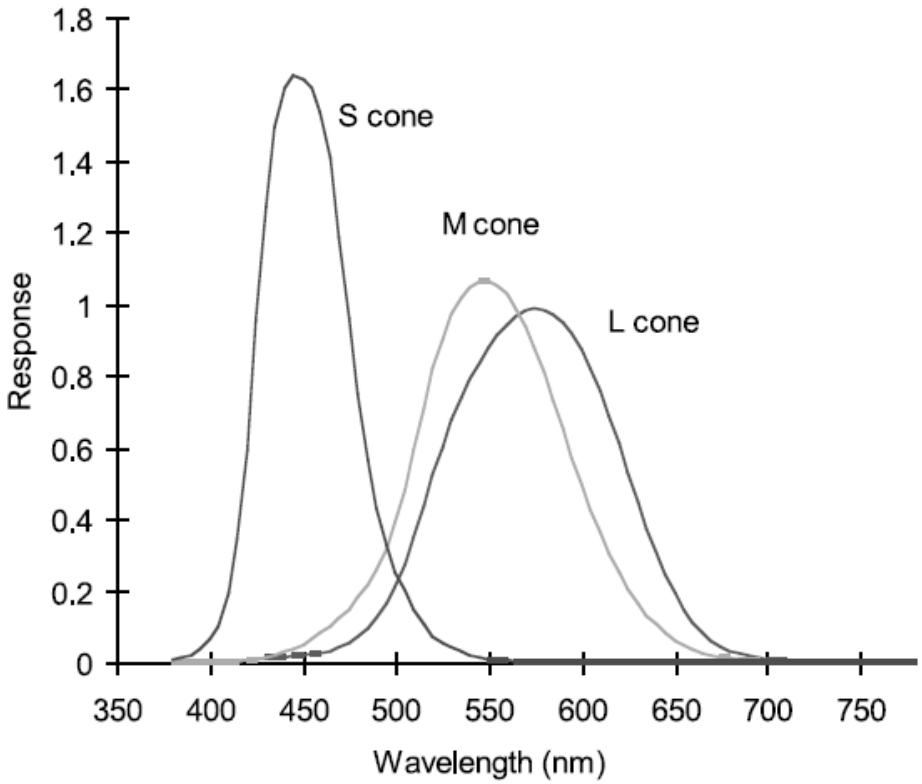
Digital camera signal chain



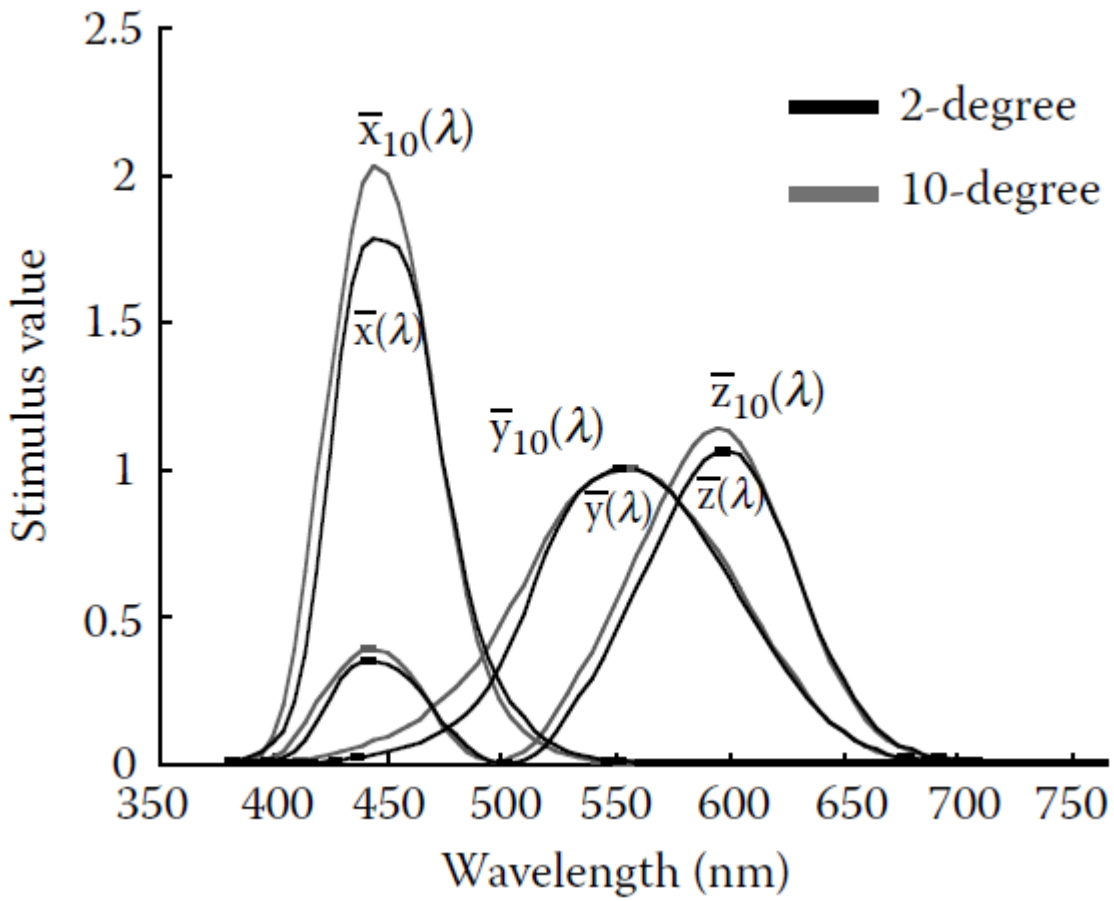
The human visual system

- Daylight: 3 cones activated
  - Different spectral responsivity
  - Translated into (i) Luminance, (ii) Red-Green, (iii) Yellow-Blue which is transmitted to the brain
- Darkness: 1 rod activated
  - Not sensitive to color, only luminance

Human cone sensitivity



CIE color matching functions



CIE standard colorimetric system

$$X = \int L(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int L(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int L(\lambda)R(\lambda)\bar{z}(\lambda)d\lambda$$

- $R(\lambda)$ = spectral reflectance of scene object
- $L(\lambda)$ = spectral luminance on the scene (W/m)
- Y = luminance
- (X and Z mathematical terms with no physical meaning)

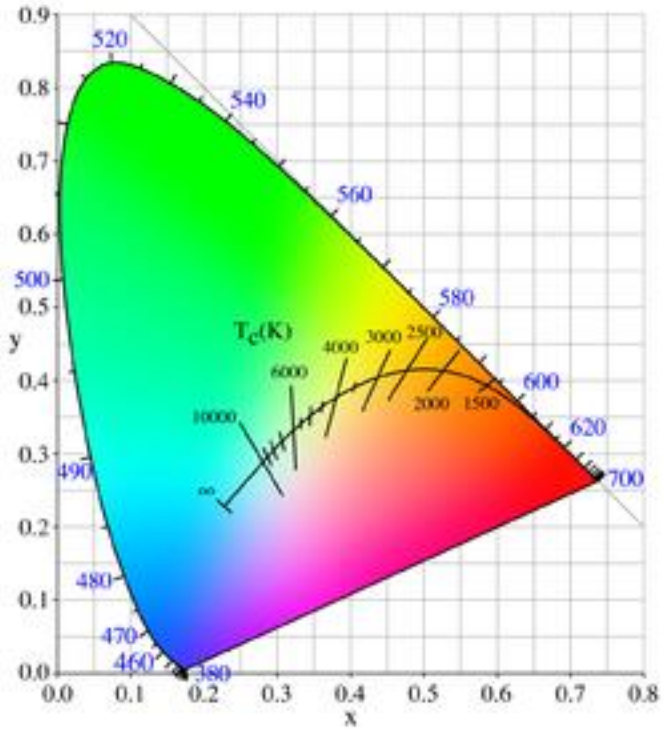
Chromatisity coordinates

- 2-dimensional color representation (ignoring luminance). Easier to interpret than XYZ.
- Two popular schemes widely used:

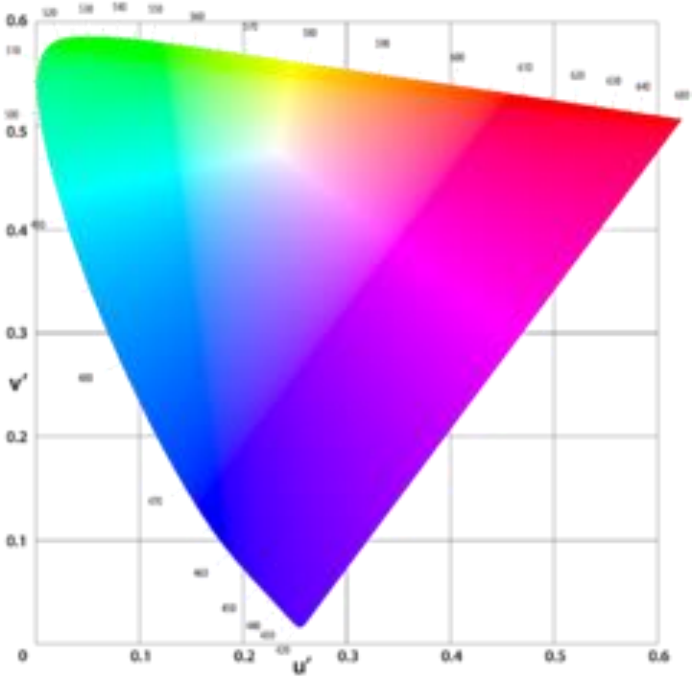
$$x = \frac{X}{X+Y+Z}, \; y = \frac{Y}{X+Y+Z}$$ CIE 1931

$$u' = \frac{4X}{X+15Y+3Z}, \; v' = \frac{9Y}{X+15Y+3Z}$$ CIE 1976

Diagrams of xy and u'v' chromaticity



CIE 1931



CIE 1976

Uniform color space standard (L*a*b*)

$$L^* = \begin{cases} 116\left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} - 16 & \frac{Y}{Y_0} > 0.008856 \\ 903.29\left(\frac{Y}{Y_0}\right) & \frac{Y}{Y_0} \le 0.008856 \end{cases} \quad X_n = \begin{cases} \left(\frac{X}{X_0}\right)^{\frac{1}{3}} & \frac{X}{X_0} > 0.008856 \\ 7.787\left(\frac{X}{X_0}\right) + \frac{16}{116} & \frac{X}{X_0} \le 0.008856 \end{cases} \quad Y_n = \begin{cases} \left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} & \frac{Y}{Y_0} > 0.008856 \\ 7.787\left(\frac{Y}{Y_0}\right) + \frac{16}{116} & \frac{Y}{Y_0} \le 0.008856 \end{cases}$$

$$a^* = 500(X_n - Y_n)$$

$$b^* = 200(Y_n - Z_n)$$

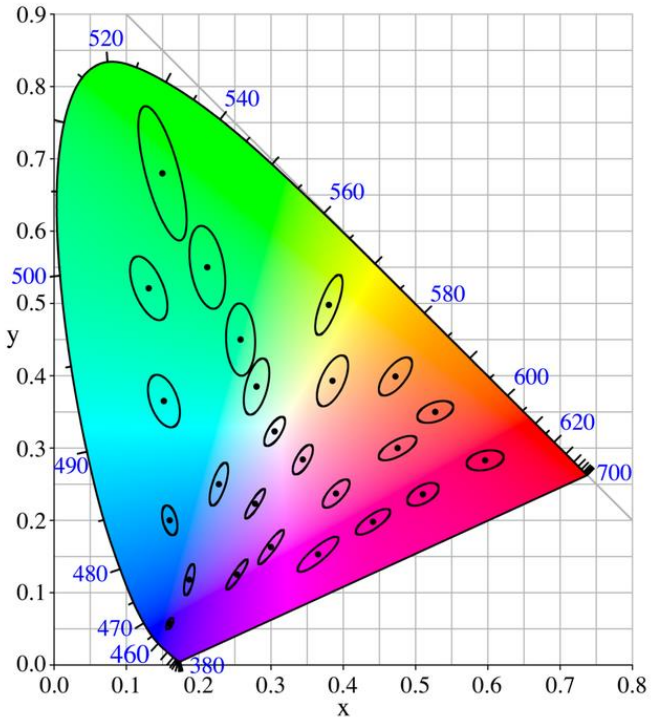
Color difference, delta-E

$$\Delta E^*_{ab} = \left[\left(L^*_1 - L^*_2\right)^2 + \left(a^*_1 - a^*_2\right)^2 + \left(b^*_1 - b^*_2\right)^2 \right]^{\frac{1}{2}}$$

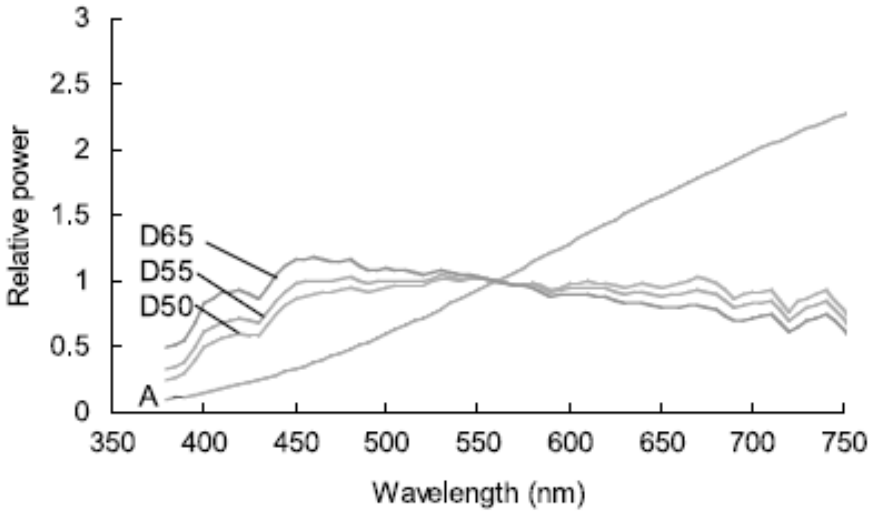
Just noticable difference (JND) between original and reproduced image:

$\Delta E \sim 2.3$

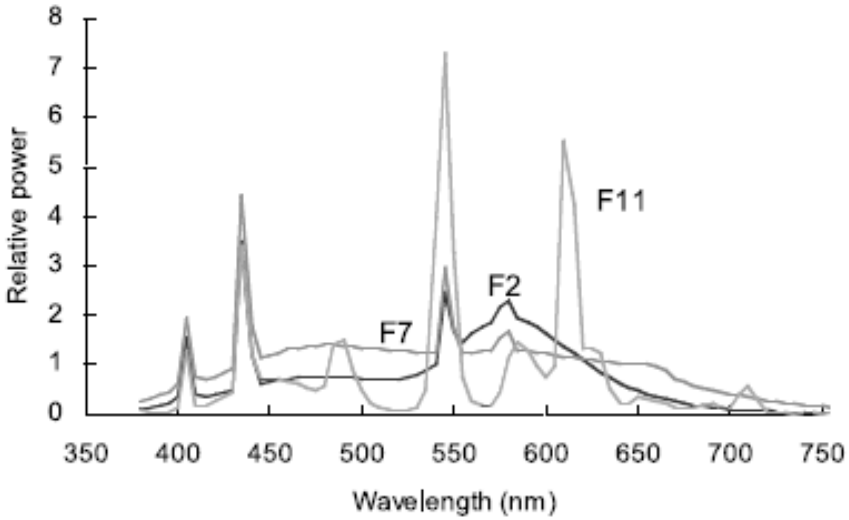
Example: MacAdam ellipse showing JND (ΔE~2.3) in xy color space



Spectral distribution of illuminants

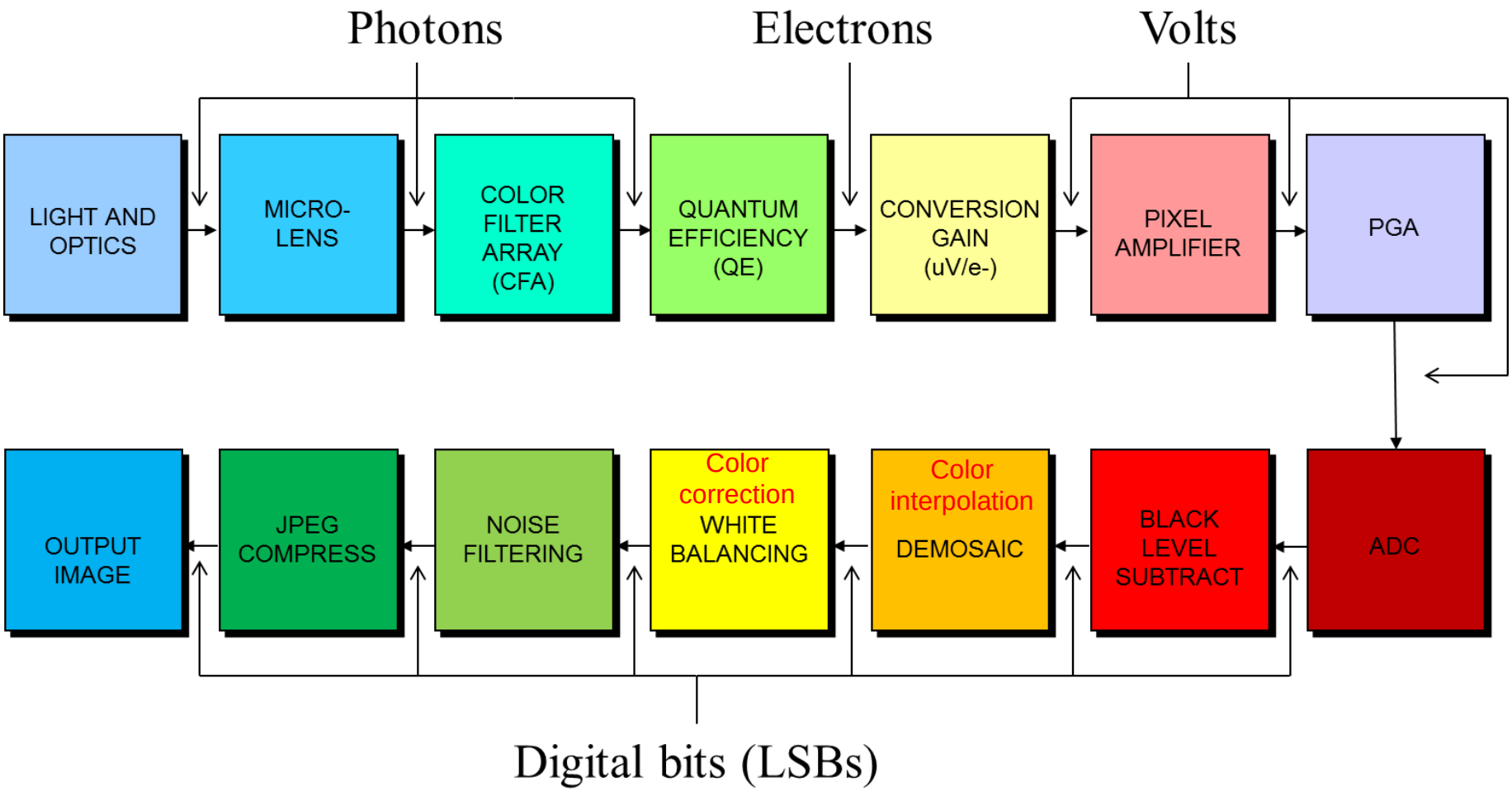


CIE standard light sources



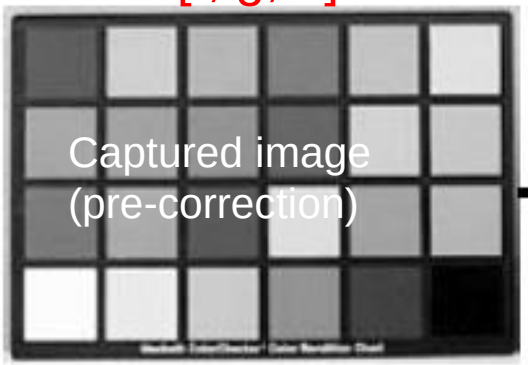
Fluorescent light sources

Digital camera signal chain



Camera color characterization

[r, g, b]



Internal data

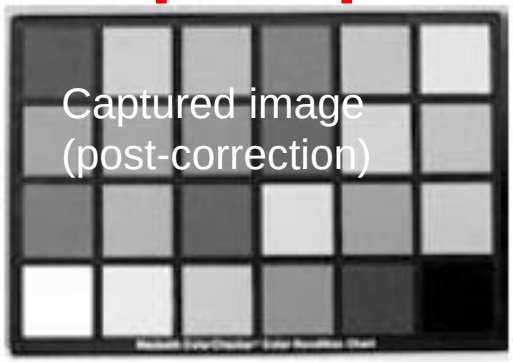
Linear matrix

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} r \\ g \\ b \end{bmatrix}$$

Matrix to minimize ΔE

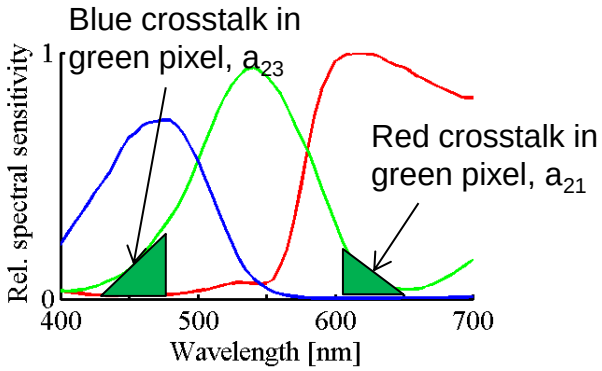
$$\sum_{i=1}^{3} a_i = \sum_{i=1}^{3} b_i = \sum_{i=1}^{3} c_i = 1 \ .$$

[R, G, B]



Reproduced color

Actual color

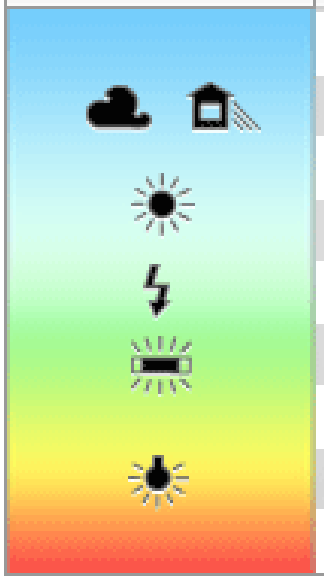


Automatic White Balance (AWB)

- Purpose: gain up/down the RGB color channels to compensate for color bias in scene illumination
  - Analog and/or digital gain (usually before CIP)
- 3 popular methods:

1. Grey world
   - Assumes average color of scene is grey (typically at 18% reflectance)
2. Brightest white point
   - Avoid light emitting sources (lamps) => pick only objects close to blackbody chromaticity
3. Color gamut of the scene
   - Analyse color distribution of scene
   - Correlate with color gamut database

Color temperatures (AWB settings)



WB Settings	Color Temperature	Light Sources
	10000 - 15000 K	Clear Blue Sky
	6500 - 8000 K	Cloudy Sky / Shade
	6000 - 7000 K	Noon Sunlight
	5500 - 6500 K	Average Daylight
	5000 - 5500 K	Electronic Flash
	4000 - 5000 K	Fluorescent Light
	3000 - 4000 K	Early AM / Late PM
	2500 - 3000 K	Domestic Lightning
	1000 - 2000 K	Candle Flame

Comparing three AWB settings