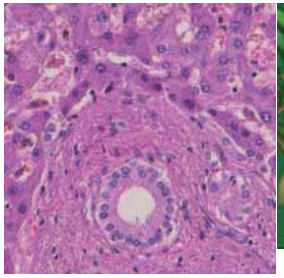
Optical imaging and image processing (IX)

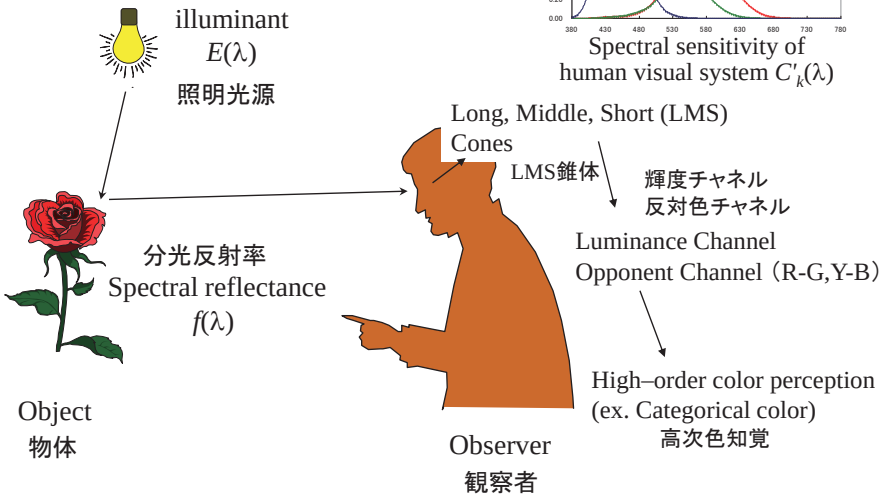
4. Color Imaging
4. カラー画像

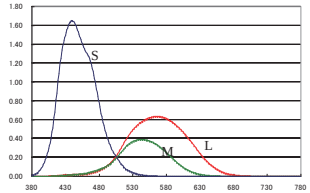




R, G, B
Luminance(Y), Chromaticity(C)
YCbCr, YPbPr, YUV, L*a*b*
Y, M, C, K
Hue(H), Saturation(S), Value(V), L*C*h

4.1 Color spaces
4.1 色空間

Color perception by human observer



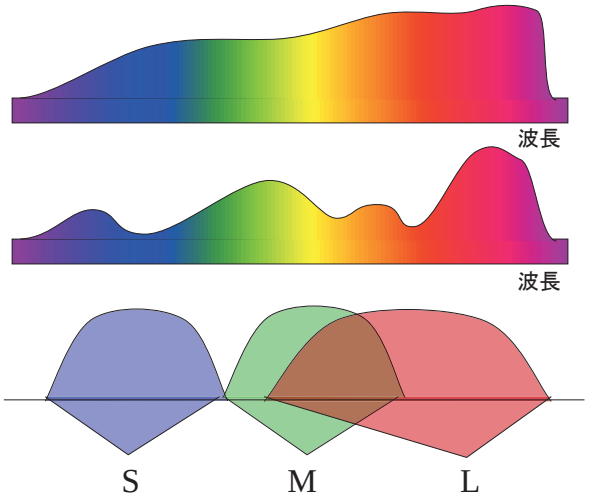


Spectral sensitivity of human visual system $C'_k(\lambda)$

LMS Cone Sensitivity
http://www.psychologie.uni-kiel.de/golz/publications/2003a/LMS.html
V.C. Smith and J. Pokorny, "Spectral sensitivity of the foveal cone photopigments between 400 and 500 nm," Vis. Res. 15, 161-171 (1975).

Color and the spectrum of light

$$g_k = \int f(\lambda)\, E(\lambda)\, C'_k(\lambda)\, d\lambda$$



Spectral radiance of illumination light
照明光源の分光放射輝度

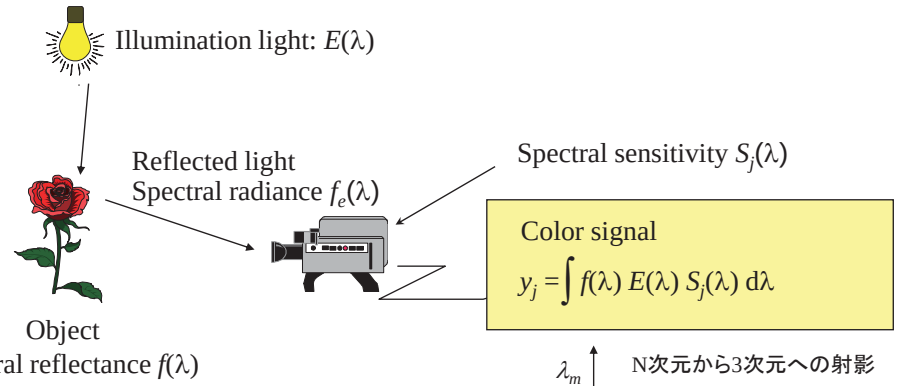
Spectral reflectance of the object
物体の分光反射率

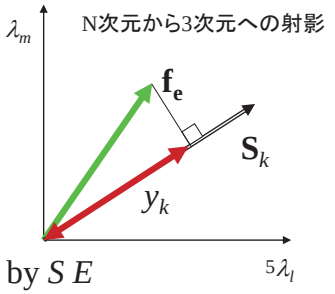
Spectral Sensitivity
分光感度

Output from the sensor
センサーの出力＝三刺激値

Tristimulus values

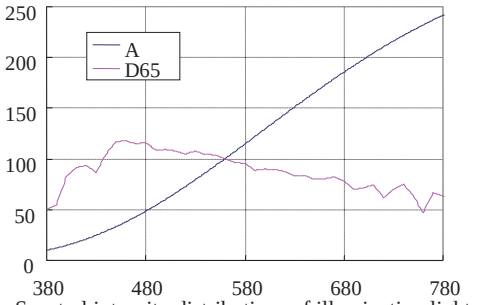
Color imaging system



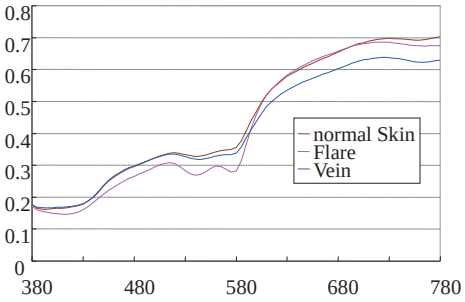


- Vector-matrix representation
  $\mathbf{y} = S\,E\,\mathbf{f}$
  $= S\,\mathbf{f_e}$
- $\mathbf{f_e}$: Spectral radiance
- Projection of $\mathbf{f_e}$ by S or Projection of $\mathbf{f}$ by $S\,E$

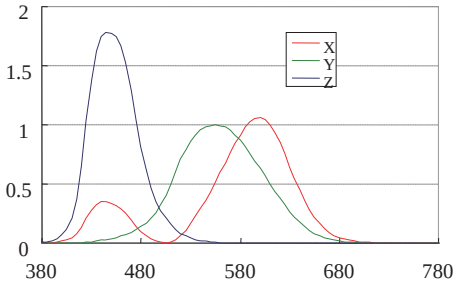
Examples



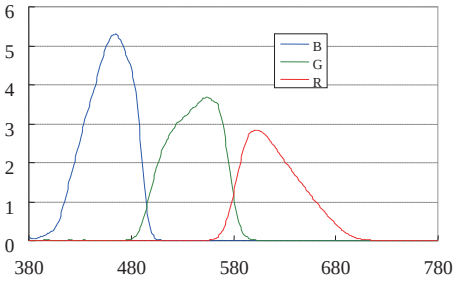
Spectral intensity distributions of illumination lights
(CIE A and CIE D65 standard illuminants)



Example of spectral reflectance (Skin)



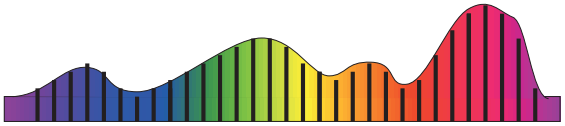
Color matching functions of human observer



Example of the spectral sensitivity of a color camera

Vector-matrix representation

Sampling of wavelengths



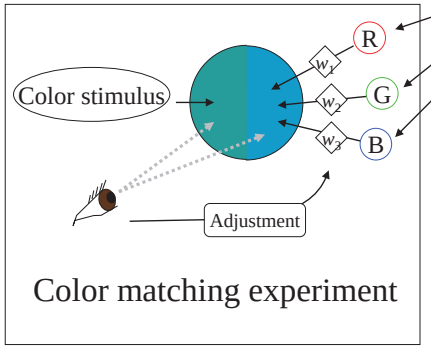
Spectral reflectance => **f** (N-dimensional vector) $\quad \mathbf{f} = \begin{pmatrix} f(\lambda_1) \\ f(\lambda_2) \\ \vdots \\ f(\lambda_N) \end{pmatrix}$

$$y_j = \int f(\lambda) E(\lambda) S_j(\lambda) d\lambda$$

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} = \begin{pmatrix} S_1(\lambda_1) & S_1(\lambda_2) & \cdots & S_1(\lambda_N) \\ S_2(\lambda_1) & S_2(\lambda_2) & \cdots & S_2(\lambda_N) \\ S_3(\lambda_1) & S_3(\lambda_2) & \cdots & S_3(\lambda_N) \end{pmatrix} \begin{pmatrix} E(\lambda_1) & & \cdots & 0 \\ & E(\lambda_2) & & \vdots \\ \vdots & & \ddots & \\ 0 & \cdots & & E(\lambda_N) \end{pmatrix} \begin{pmatrix} f(\lambda_1) \\ f(\lambda_2) \\ \vdots \\ f(\lambda_N) \end{pmatrix} \quad (5.3)$$

色空間はどのようにして定められたのか？
How were color spaces defined?

- Additive mixture of three-primary colors　3原色の加法混色

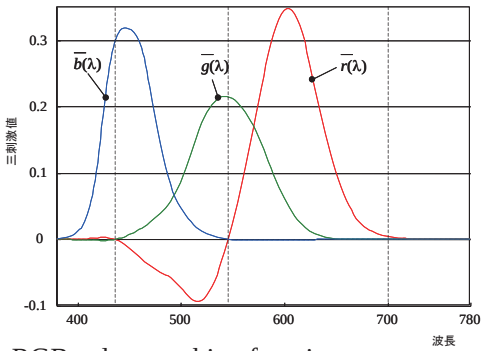


Color matching experiment

700nm, monochromatic light (red)
546.1nm monochromatic light (green)
435.8nm monochromatic light (blue)

w_1, w_2, w_3: tristimulus values
三刺激値

※三刺激値が負になる場合

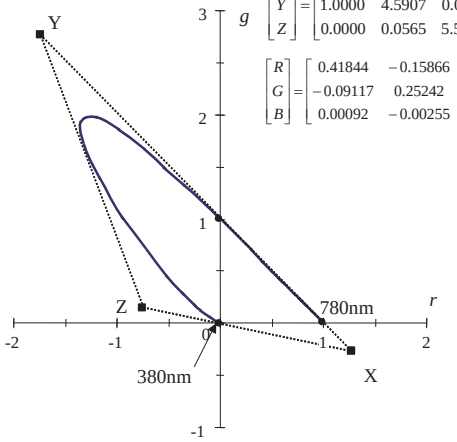


RGB color matching functions
各波長の三刺激値：スペクトル三刺激値

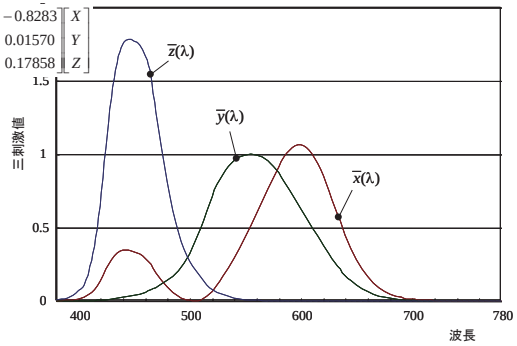
XYZ Color Matching Functions (CMF)
Color is represented by three positive variables
XYZ等色関数:3つの正の数で色を表す

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2.7689 & 1.7517 & 1.1302 \\ 1.0000 & 4.5907 & 0.0601 \\ 0.0000 & 0.0565 & 5.5943 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 0.41844 & -0.15866 & -0.8283 \\ -0.09117 & 0.25242 & 0.01570 \\ 0.00092 & -0.00255 & 0.17858 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$



XYZ primary colors on
r-g color coordinates

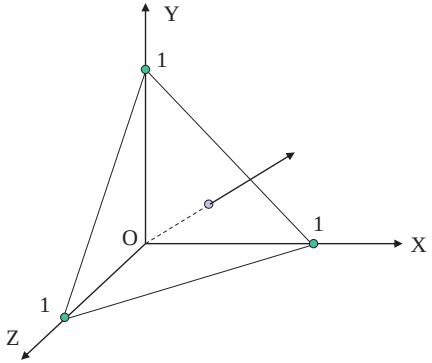


各波長の三刺激値

CIE 1931 XYZ CMF

CIE 1931XYZ CMF (2 degrees)
CIE 1964XYZ CMF (10degrees)

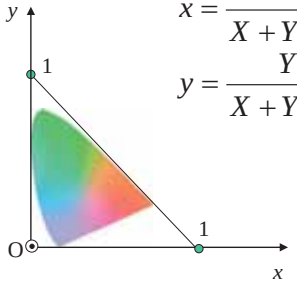
XYZ color space, *xy*-chromaticity diagram
XYZ色空間、xy-色度図



XYZ color space

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

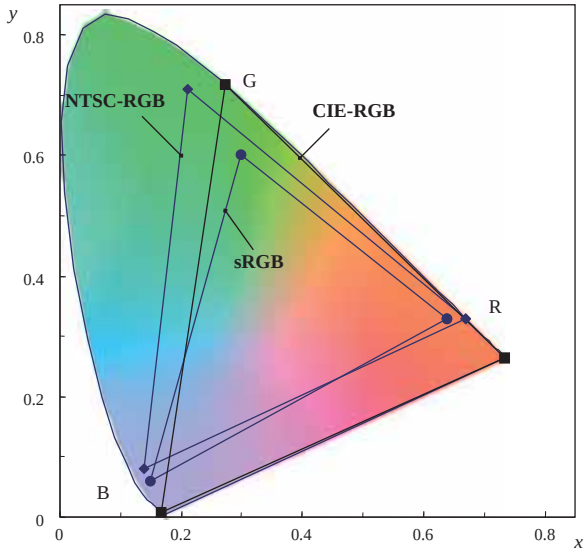
$$y = \frac{Y}{X+Y+Z}$$



xy-chromaticity diagram

RGB three primary colors
RGB 3原色

→12/3



- Linear combination of a set of color matching functions yields another set of color matching functions

$$C'_j(\lambda) = \sum_{k=1}^{3} a_{jk} C_k(\lambda)$$

ある等色関数のセットの線形結合により、別の3つの等色関数のセットを導出できる

$$g'_j = \int f(\lambda) E(\lambda) C'_j(\lambda) d\lambda$$

$$= \int f(\lambda) E(\lambda) \sum_{k=1}^{3} a_{jk} C_k(\lambda) d\lambda$$

$$= \sum_{k=1}^{3} a_{jk} \int f(\lambda) E(\lambda) C_k(\lambda) d\lambda$$

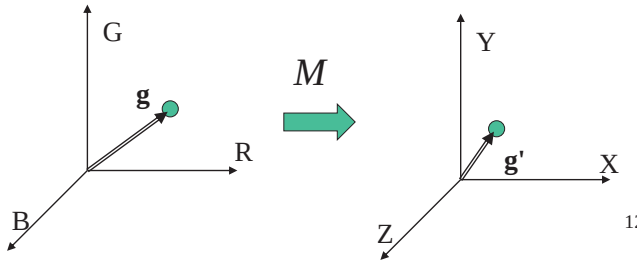
$$= \sum_{k=1}^{3} a_{jk}\, g_k$$

↓

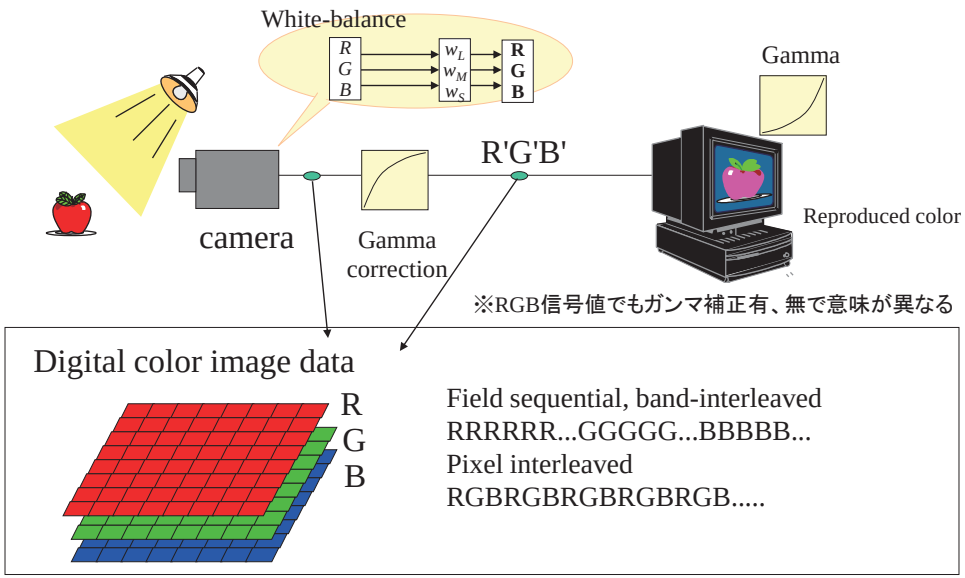
3×3の行列を用いて、ある色空間の三刺激値から別の色空間の三刺激値に変換できる

Color space can be converted using a 3x3 matrix.

$$\mathbf{g}' = M\,\mathbf{g}$$

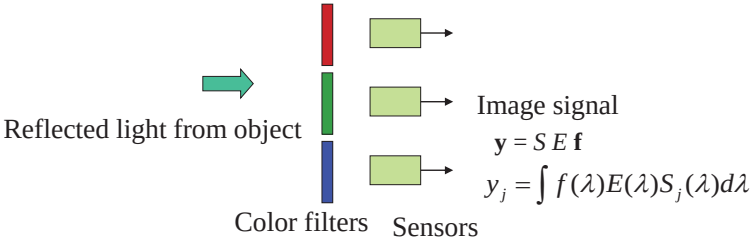


4.2 Color imaging and display systems
4.2 カラーイメージングとディスプレイシステム

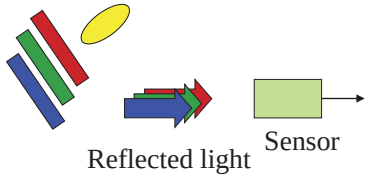


4.2.1 Input of color images　　カラー画像の入力
Color image input devices

- Color camera, scanner, …, endoscopy

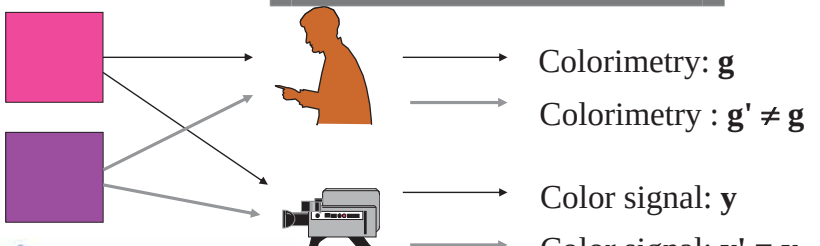


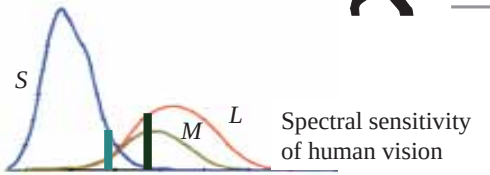
(Modulation of illumination light)

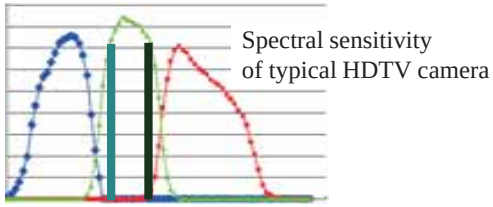


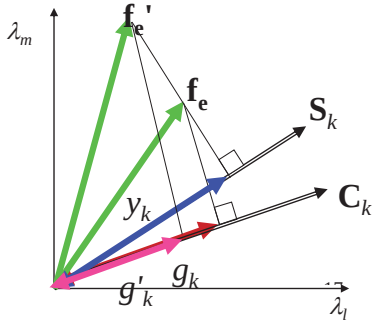
Problem

- Two color objects　**Impossible to discriminate !**









Luther condition

- If the space spanned by $\mathbf{S_k}$ covers the space spanned by $\mathbf{C_k}$

　⇒

　g is derivable from **y** for arbitrary $\mathbf{f_e}$

　$\mathbf{g} = M\,\mathbf{y}$

任意の分光分布を持つ物体に対して、色信号値から三刺激値を誤差なく求めるための条件

Color signal → Linear conversion → Colorimetry

3×3 matrix multiplication

- Conversion matrix

　$\mathbf{y} = S\,E\,\mathbf{f}$

　$\mathbf{g} = C\,E\,\mathbf{f}$

$$M = C\,S^t\,(S\,S^t)^{-1}$$

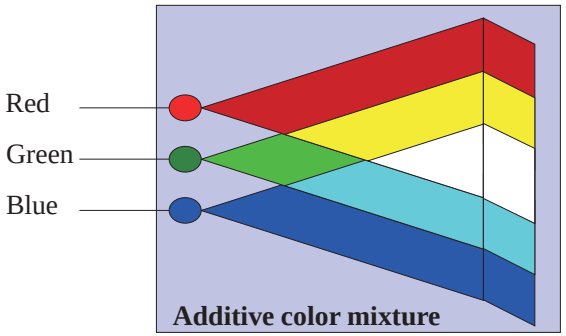
$$\mathbf{g_e} = M\,\mathbf{y} = C\,S^t\,(S^t\,S)^{-1}\,S\,E\,\mathbf{f} = C\,E\,\mathbf{f} = \mathbf{g}$$

4.2.2 Color display　　カラーディスプレイ

- Spectral radiance of *j*-th primary color : $P_j(\lambda)$
- Color signal for j-th primary color: $\{ \mathbf{r} \}_j = r_j$
- Spectral radiance of reproduced color : $Q(\lambda) = \sum_{j=R,G,B} r_j P_j(\lambda)$
- Reproduced color **q**

$$q_k = \int Q(\lambda) C_k(\lambda) d\lambda = \int \sum_{j=R,G,B} r_j P_j(\lambda) C_k(\lambda) d\lambda = \sum_{j=R,G,B} \alpha_{jk} r_j \qquad (5.13)$$

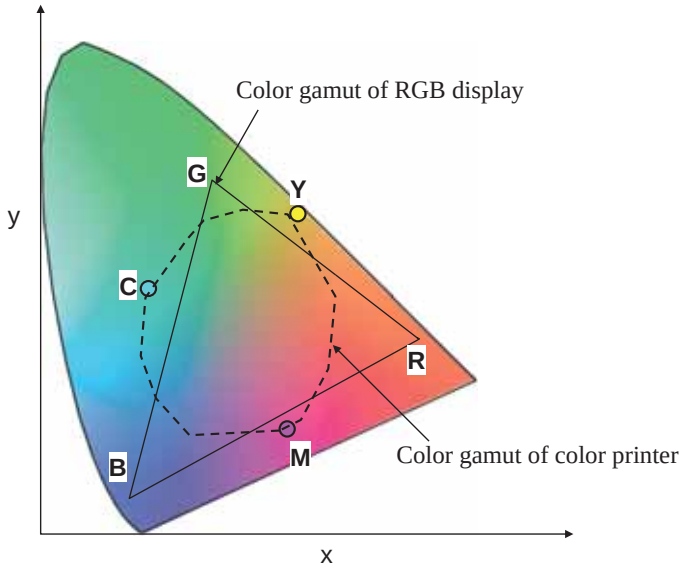
- **q = A r**



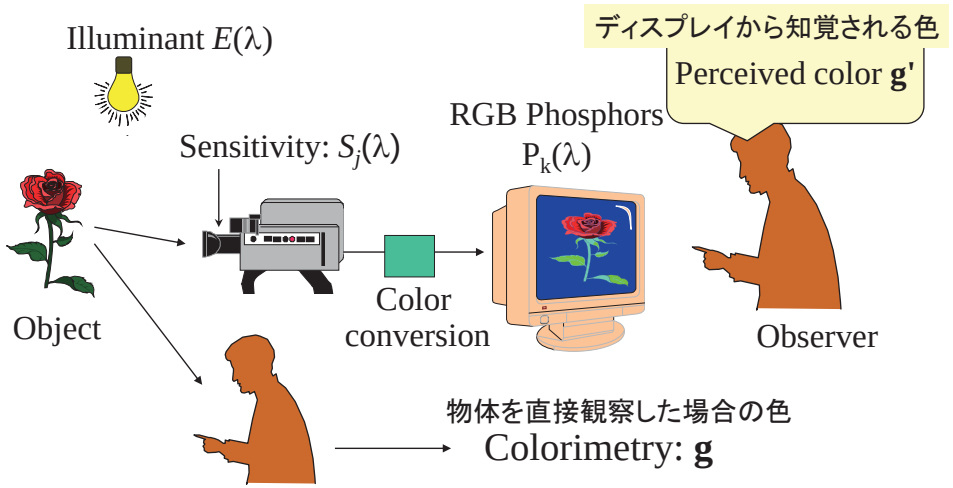
加法混色の原理

※　3原色の加法混色で全ての色を表示できる訳ではない！

Color gamut
色域



4.3 Color reproduction
4.3 色再現



Conversion such that **g** = **g**' : Colorimetric color reproduction
測色的色再現

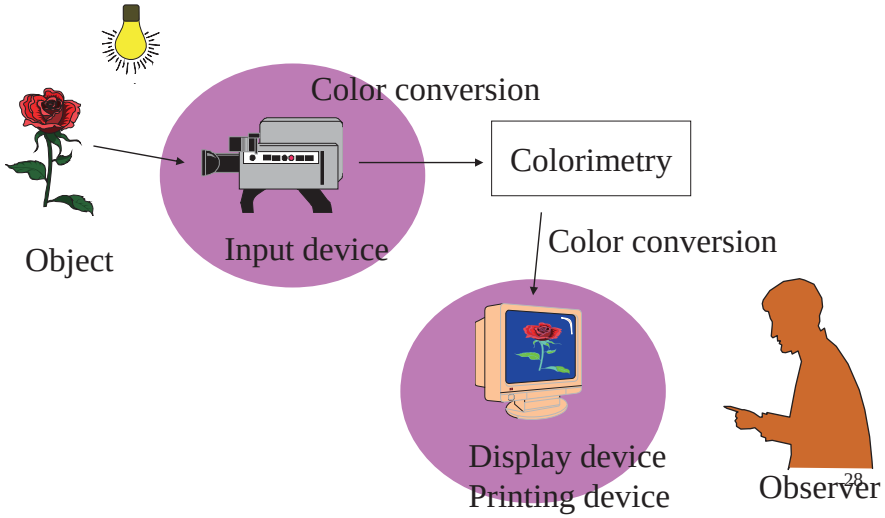
4.3.1 Objectives in color reproduction
色再現の分類　(R. W. G. Hunt)

- Spectral color reproduction　分光的色再現
- Exact color reproduction　正確な色再現
  - Tristimulus values are reproduced
- Colorimetric color reproduction　測色的色再現
  - Do not care luminance
- Equivalent color reproduction　等価な色再現
  - Tristimulus values do not agree with original, but matching the color appearance
  - Luminance should be similar to the original
- Corresponding color reproduction　対応する色再現
  - Tristimulus values do not agree with original, but matching the color appearance
- Preferred color reproduction　好ましい色再現

※消費者向け機器の開発では「好ましい色再現」が重要とされてきた！

4.3.2 Color management
カラーマネージメント、色管理

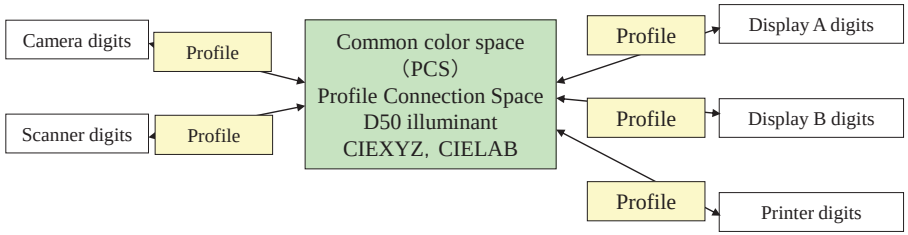
- Device independent color reproduction
  - Device characterization

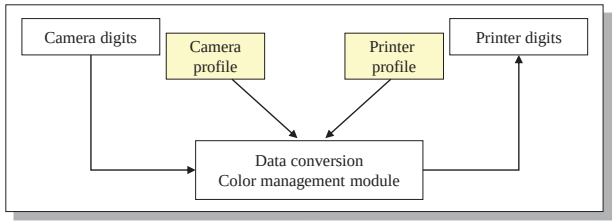


ICC Profile

ICC: International Color Consortium

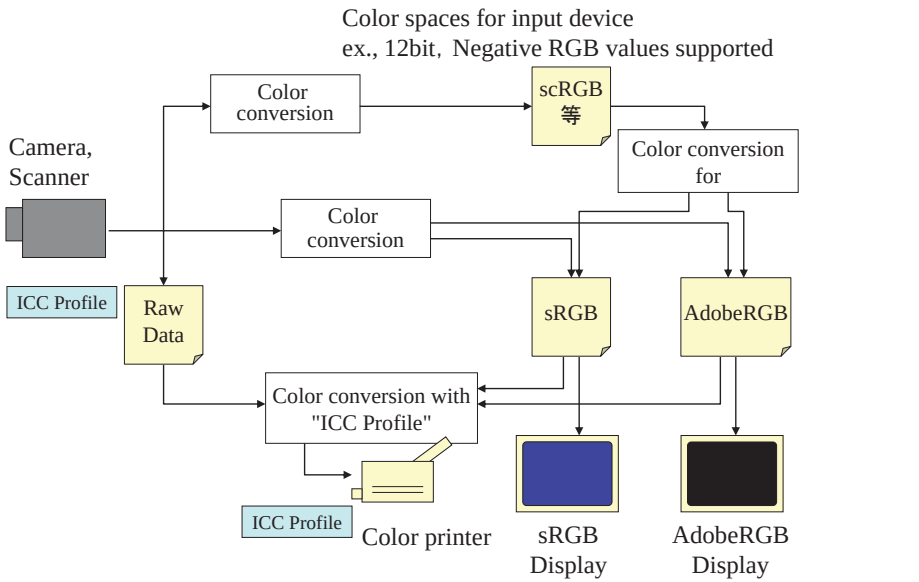
- Supported in PDF, TIFF, or Photoshop
- Tools for making ICC profile of a device using a color chart or color sensor.
- Note that the rendering intent includes not only colorimetric color reproduction but also perceptual color reproduction.





Rendering intent
- Media-relative colorimetric
- ICC-absolute colorimetric
- Perceptual (vendor specific)
- Saturation (vendor specific)

Color spaces for input and output devices
入力用の色空間、出力用の色空間



Color spaces used in color images
カラー画像に使われている各種の色空間

- NTSC RGB (1953)
- SMPTE 170M RGB (Current NTSC)
- ITU-R BT.709 RGB (HDTV)
- IEC 61966-2-1 (sRGB)
- IEC 61966-2-2 (scRGB)
- Adobe RGB

※現在のNTSCはBT.709に近い

- sYCC (sRGB to YCC)
- ITU-R BT.709 Y Cb Cr
- xvYCC

- Others

  Physical Standards: CIERGB, CIEXYZ, CIELAB

  Perceptual: Muncell Color Space, Natural Color System