Optical imaging and image processing (IX)

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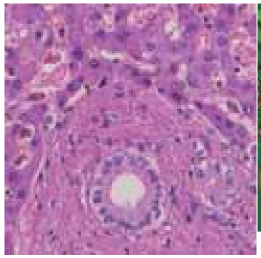
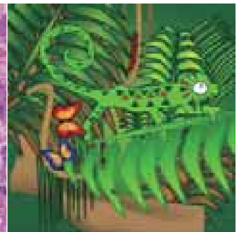
5. Color Imaging
5. カラー画像

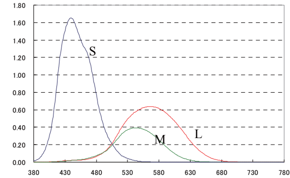




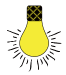
R, G, B
Luminance(Y), Chromaticity(C)
YCbCr, YPbPr, YUV, L*a*b*
Y, M, C, K
Hue(H), Saturation(S), Value(V), L*C*h

5.1 Color spaces
5.1 色空間

Color perception by human observer



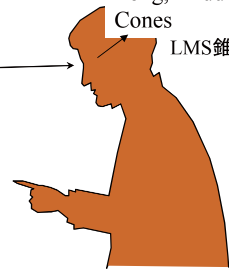
Spectral sensitivity of human visual system $C'_k(\lambda)$



illuminant
$E(\lambda)$
照明光源

分光反射率
Spectral reflectance
$f(\lambda)$

Object
物体



Long, Middle, Short (LMS) Cones
LMS錐体

輝度チャネル
反対色チャネル
Luminance Channel
Opponent Channel（R-G,Y-B）

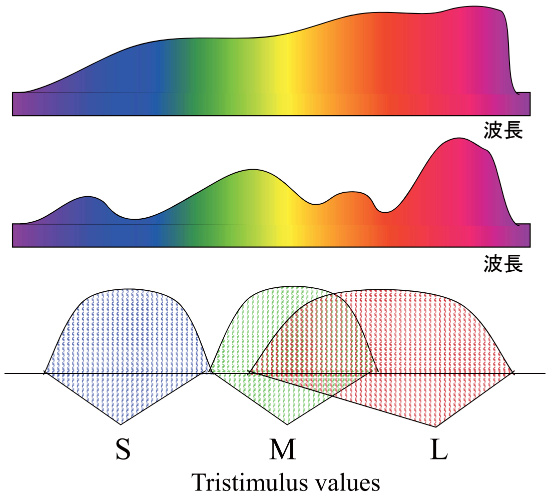
High–order color perception
(ex. Categorical color)
高次色知覚

Observer
観察者

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

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



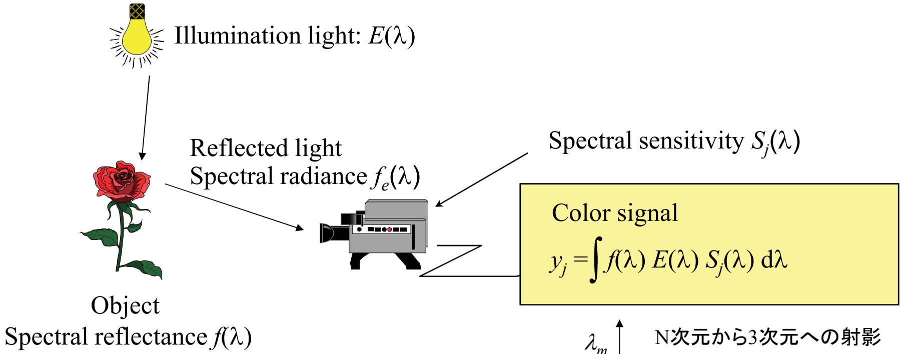
Spectral radiance of illumination light
照明光源の分光放射輝度

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

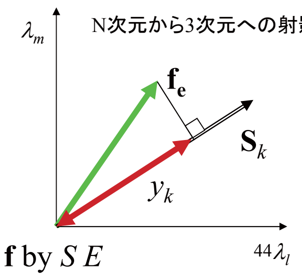
Color imaging system



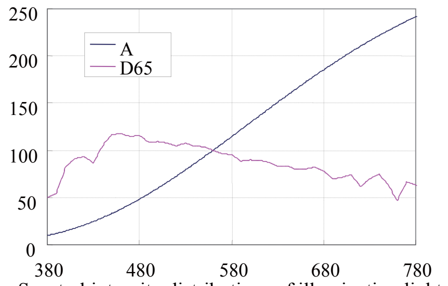
- Vector-matrix representation

  $\mathbf{y} = S\,E\,\mathbf{f}$

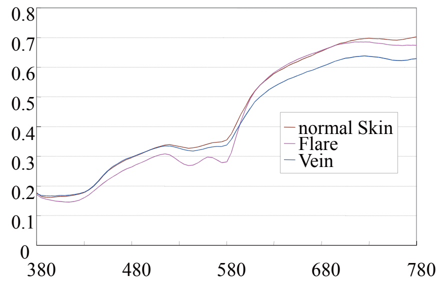
  $= S\,\mathbf{f_e}$
- $\mathbf{f_e}$: Spectral radiance
- Projection of $\mathbf{f_e}$ by S or Projection of $\mathbf{f}$ by $S\,E$



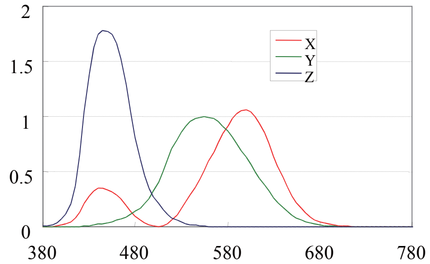
Examples



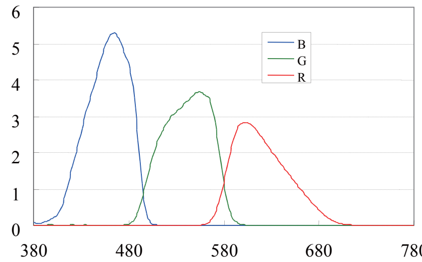
Spectral intensity distributions of illumination lights (CIE A and CIE D65 standard illuminants)



Example of spectral reflectance (Skin)



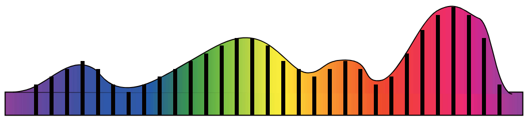
Color matching functions of human observer



Example of the spectral sensitivity of a color camera

Vector-matrix representation

Sampling of wavelengths



Spectral reflectance => **f** (N-dimensional vector)

$$\mathbf{f} = \begin{pmatrix} f(\lambda_1) \\ f(\lambda_2) \\ \vdots \\ f(\lambda_N) \end{pmatrix}$$

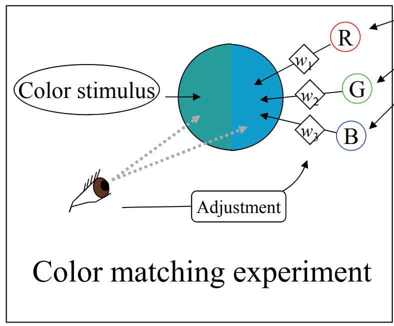
$$y_j = \int f(\lambda) E(\lambda) S_j(\lambda) d\lambda$$

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

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

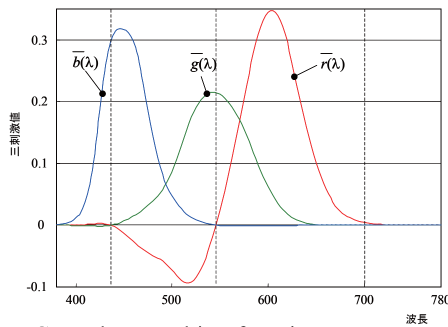


700nm, monochromatic light (red)

546.1nm monochromatic light (green)

435.8nm monochromatic light (blue)

w_1, w_2, w_3: tristimulus values
三刺激値



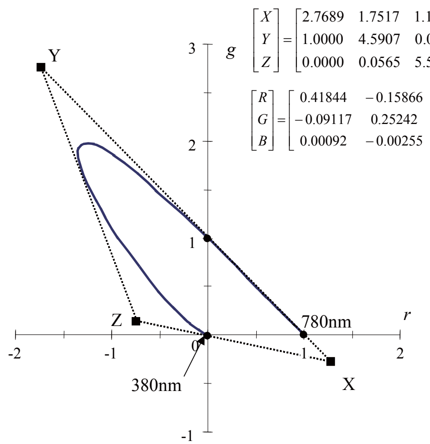
RGB color matching functions
各波長の三刺激値：スペクトル三刺激値

※三刺激値が負になる場合

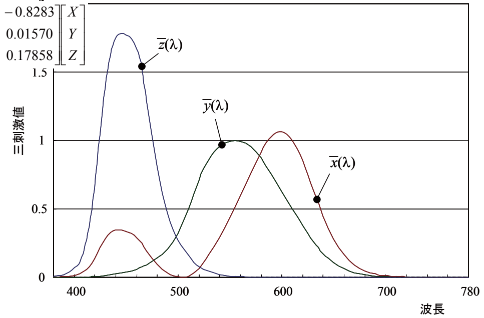
XYZ Color Matching Functions (CMF)
Color is represented by three positive variables
XYZ等色関数:３つの正の数で色を表す

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

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



XYZ primary colors on r-g color coordinates

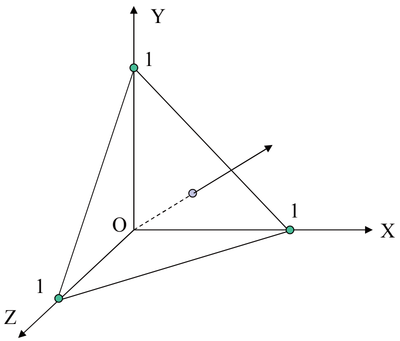


各波長の三刺激値

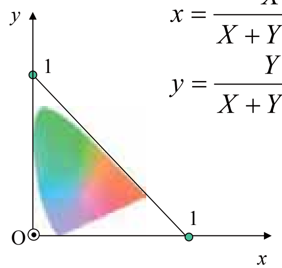
CIE 1931 XYZ CMF

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

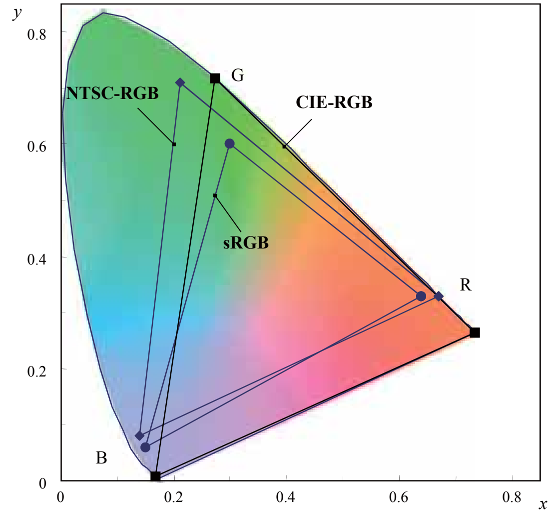


$$x = \frac{X}{X+Y+Z}$$

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

xy-chromaticity diagram

RGB three primary colors
RGB　3原色



- 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

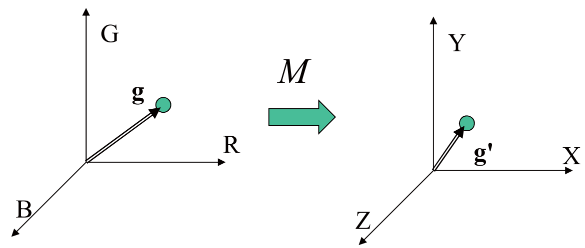
$$\begin{aligned} g'_j &= \int f(\lambda)E(\lambda)C'_j(\lambda)d\lambda \\ &= \int f(\lambda)E(\lambda)\sum_{k=1}^{3} a_{jk} C_k(\lambda)d\lambda \\ &= \sum_{k=1}^{3} a_{jk} \int f(\lambda)E(\lambda)C_k(\lambda)d\lambda \\ &= \sum_{k=1}^{3} a_{jk}\, g_k \end{aligned}$$

↓

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.

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



CIE 1976 L*a*b* Uniform Chromaticity Space (UCS)
均等色空間

$$L^* = \begin{cases} 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16, & \frac{Y}{Y_n} > 0.008856 \\ 903.29\frac{Y}{Y_n} & \frac{Y}{Y_n} \le 0.008856 \end{cases}$$

= Lightness

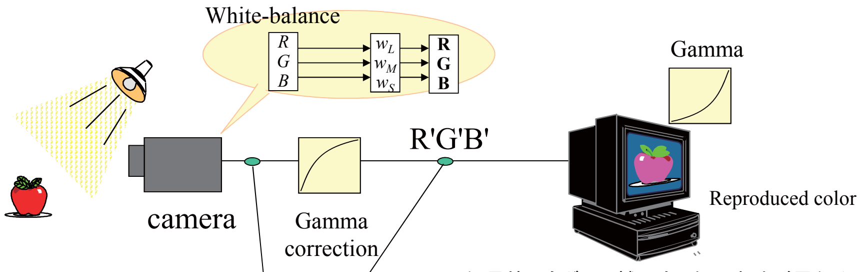
$$a^* = 500\{\phi(\frac{X}{X_n}) - \phi(\frac{Y}{Y_n})\}$$

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

where $\phi(a) = \begin{cases} a^{1/3} & \frac{Y}{Y_n} > 0.008856 \\ 7.78a + 16/116, & \frac{Y}{Y_n} \le 0.008856 \end{cases}$

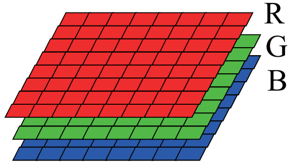
CIELAB color difference $\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$

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



※RGB信号値でもガンマ補正有、無で意味が異なる

Digital color image data



Field sequential, band-interleaved
RRRRRR...GGGGG...BBBBB...
Pixel interleaved
RGBRGBRGBRGBRGB.....

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

- Color camera, scanner, …, endoscopy

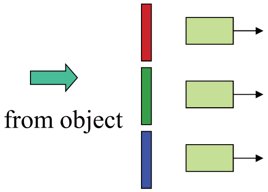


Image signal

$\mathbf{y} = S\,E\,\mathbf{f}$

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

(Modulation of illumination light)

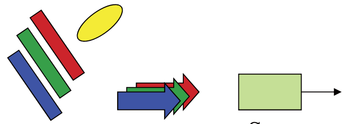


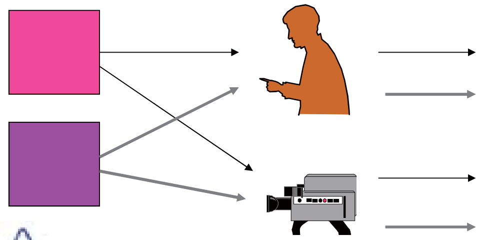
Image signal

$\mathbf{y} = S\,E\,\mathbf{f}$

$y_j = \int f(\lambda)E_j(\lambda)S(\lambda)d\lambda$

Problem

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

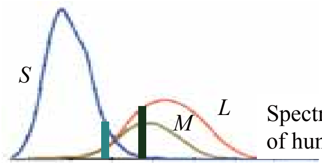


Colorimetry: **g**

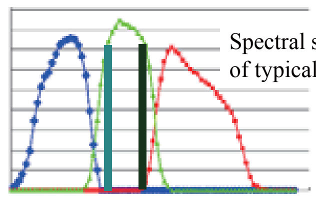
Colorimetry : **g' ≠ g**

Color signal: **y**

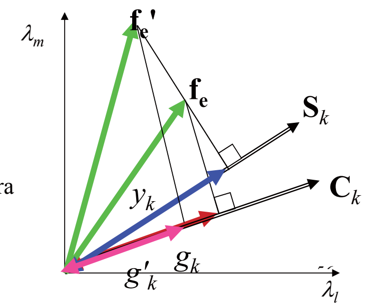
Color signal: **y' = y**



Spectral sensitivity of human vision



Spectral sensitivity of typical HDTV camera



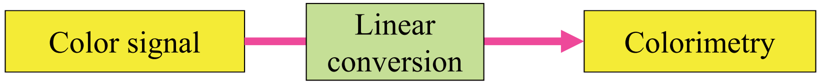
Luther condition

- If the space spanned by $\mathbf{S}_k$ covers the space spanned by $\mathbf{C}_k$

  ⇒

  $\mathbf{g}$ is derivable from $\mathbf{y}$ for arbitrary $\mathbf{f}_e$

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



3×3 matrix multiplication

- Conversion matrix

  $\mathbf{y} = S\,E\,\mathbf{f}$

  $\mathbf{g} = C\,E\,\mathbf{f}$

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

$\mathbf{g}_e = M\,\mathbf{y}$

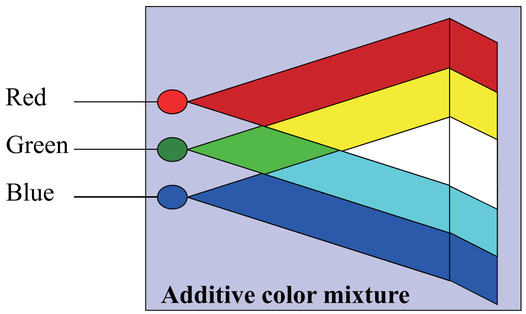
$= C\,S^t\,(S^t\,S)^{-1}\,S\,E\,\mathbf{f} = C\,E\,\mathbf{f} = \mathbf{g}$

5.2.2 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 $\mathbf{q}$

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

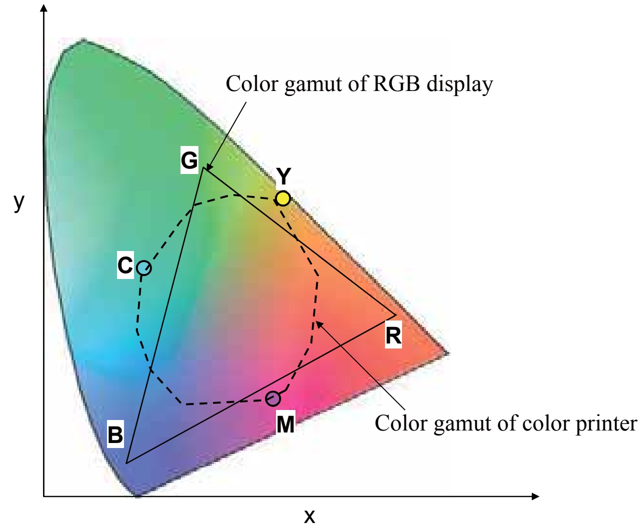
- $\mathbf{q} = \mathbf{A}\,\mathbf{r}$



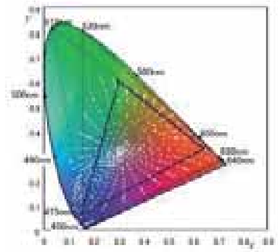
加法混色の原理

※ 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

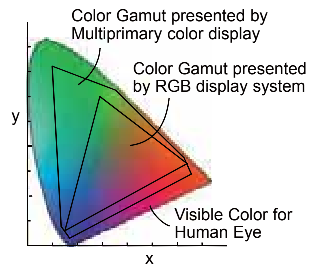


- Wide gamut televisions

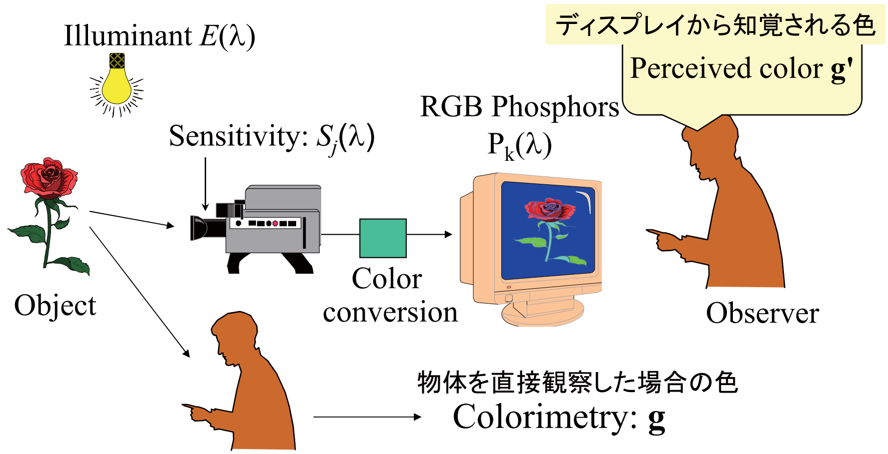


Ex.Laser display

- Expanding Color Gamut: Multiprimary color display



5.3 Color reproduction
5.3 色再現



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

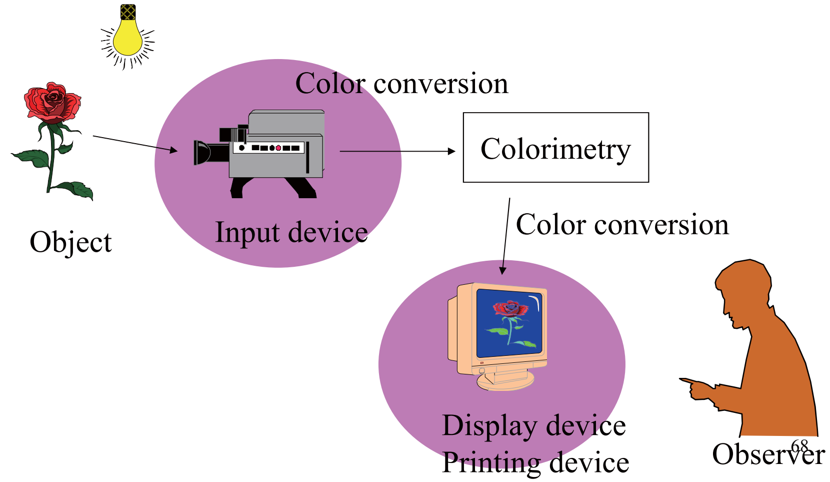
5.3.1 Objectives in color reproduction
色再現の分類 (R. W. G. Hunt)

- 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！

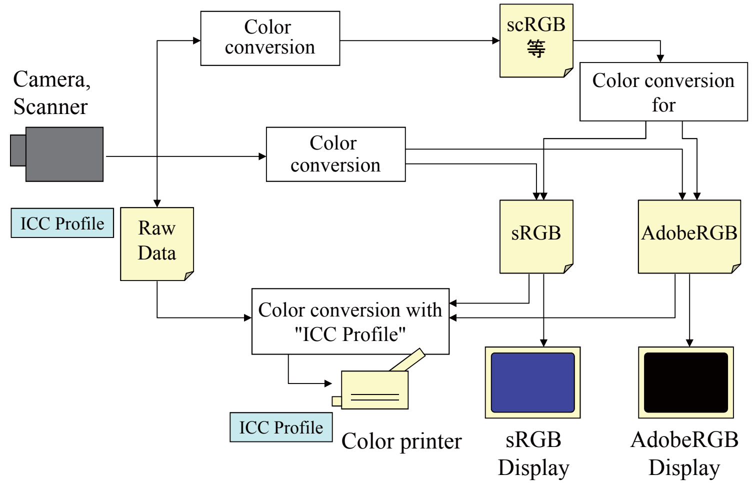
5.3.2 Color management
カラーマネージメント、色管理

- Device independent color reproduction
  - Device characterization



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

Color spaces for input device
ex., 12bit, Negative RGB values supported



Color spaces for output device.
ex., sRGB, AdobeRGB

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) ※現在のNTSCはBT.709に近い
- ITU-R BT.709 RGB (HDTV)
- IEC 61966-2-1 (sRGB)
- IEC 61966-2-2 (scRGB)
- Adobe RGB

- 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

5.4 Color image processing
5.4 カラー画像処理

5.4.1 Properties of color images カラー画像の性質

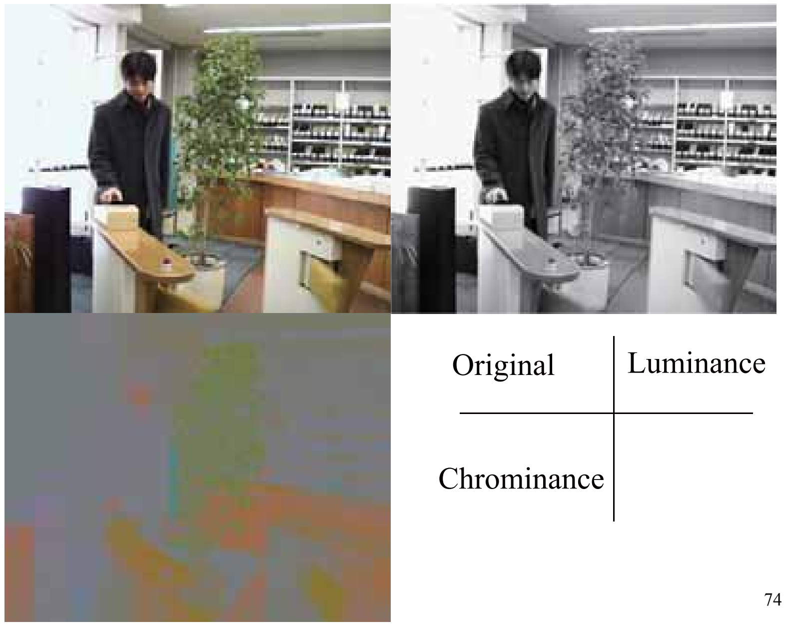
- Monochromatic image, B/W image = 1-dimensional
  ⇒ Color image = 3-dimensional
- larger bandwidth in the luminance signal, and smaller bandwidth in the chrominance signal
  - TV signal, Color image compression
- Resemblance in RGB primary component
  - The spectral reflectance of most objects are smooth
- The characteristics of human visual system (HVS)
  - HVS is not sensitive to the blur in the chrominance component
  - but is sensitive to the spatial color variation
  - It is difficult to memorize the color accurately
    (The memorized color shifts)

Color

R

G

B



Original	Luminance
Chrominance	

Original　　　　　Smoothing only chrominance component

5.4.2 Wiener filtering in color images (Color estimation)

カラー画像におけるウイナーフィルタ（色推定）

Image signal $\mathbf{y} = \mathbf{S}\,\mathbf{E}\,\mathbf{f} + \mathbf{n} = \mathbf{S}\,\mathbf{f_e} + \mathbf{n}$

Color (tristimulus values) $\mathbf{g} = \mathbf{C}\,\mathbf{E}\,\mathbf{f} = \mathbf{C}\,\mathbf{f_e}$

Estimated Color $\hat{\mathbf{g}} = \mathbf{M}\mathbf{y}$

$$e = E\{\|\mathbf{g} - \hat{\mathbf{g}}\|^2\} = E\{\|\mathbf{g} - \mathbf{M}\mathbf{y}\|^2\} \longrightarrow \text{min}$$

$$e = E\{tr[(\mathbf{g} - \mathbf{M}\mathbf{y})(\mathbf{g} - \mathbf{M}\mathbf{y})^t]\}$$

$$\frac{\partial e}{\partial \mathbf{M}} = 0$$

$$\frac{\partial}{\partial \mathbf{M}}(\mathbf{g} - \mathbf{M}\mathbf{y}) = \frac{\partial}{\partial \mathbf{M}}[\mathbf{CEf} - \mathbf{M}(\mathbf{SEf} + \mathbf{n})] = -(\mathbf{SEf} + \mathbf{n})$$

5.4.3 Color image restoration　　カラー画像の復元

- Restoration of R, G, B channels independently
- Restoration of luminance component only
  - Human vision is less sensitive to the high-frequency component of chrominance.
- Image restoration considering inter-channel correlation
  - Chromatic aberration => Different blur in each channel => It is effective to make use of the difference of the transfer functions in the R, G, B components.
- Color image captured by color filter array (demosaicing)
  - Color artifact sometimes appears at the edge of monochromatic object
  - Restoration using the inter-channel correlation

5.4.4 Color image analysis　　カラー画像解析（例）

- Color image segmentation
- The distribution of pixels values in the color space (color signal space)
- Selection of color space
  - Considering the characteristics of human vision: UCS, HSV
  - Discounting the illumination nonuniformity: 2-D subspace perpendicular to the illumination color (white)
- Vector quantization