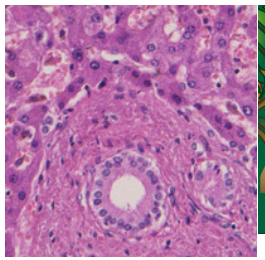
光画像工学
Optical imaging and image processing
(VII)

学術国際情報センター
山口雅浩

E-mail: yamaguchi.m.aa@m.titech.ac.jp
http://guchi.gsic.titech.ac.jp

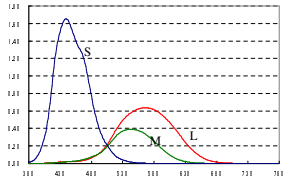
4. Color Imaging
4. カラー画像

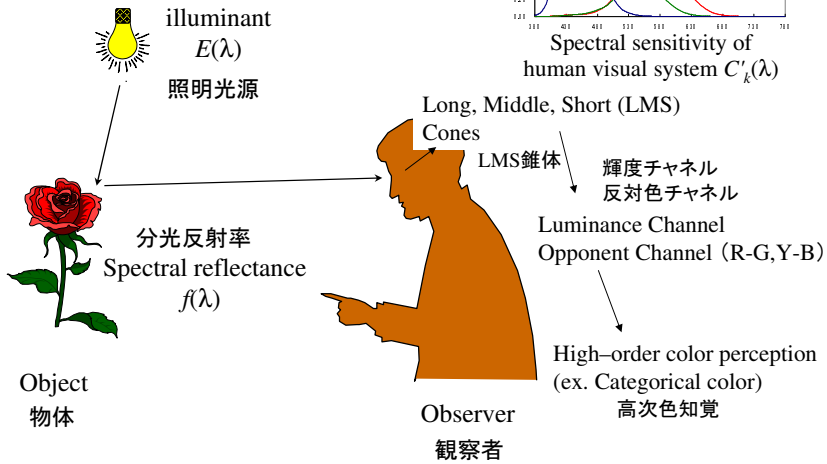

R, G, B
Luminance(Y), Chromaticity(C)
YCbCr, YPbPr, YUV, L*a*b*
Y, M, C, K
Hue(H), Saturation(S), Value(V), L*C*h

5.1 Color spaces
5.1 色空間

Color perception by human observer

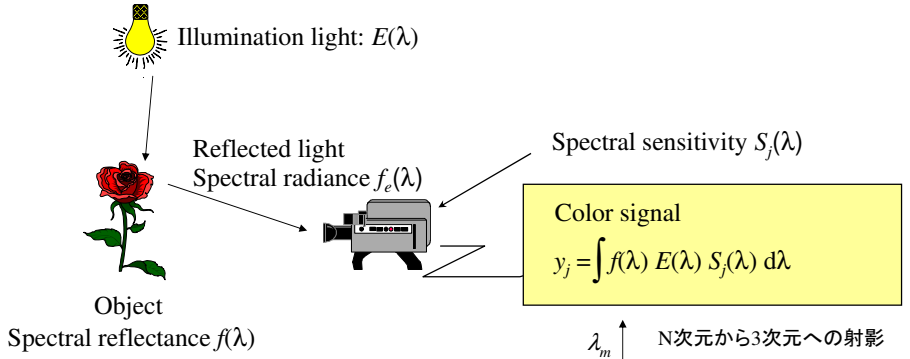


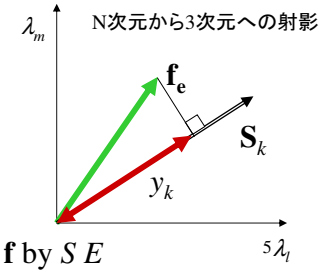
Spectral sensitivity of
human visual system $C'_k(\lambda)$



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 imaging system　カラーイメージングシステム

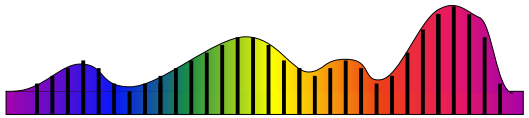




- Vector-matrix representation
  $\mathbf{y} = S\,E\,\mathbf{f}$
  $= S\,\mathbf{f_e}$
- $\mathbf{f_e}$: Spectral radiance
- Projection of $\mathbf{f_e}$ by S or Projection of $\mathbf{f}$ by $S\,E$

Vector-matrix representation

Sampling of wavelengths



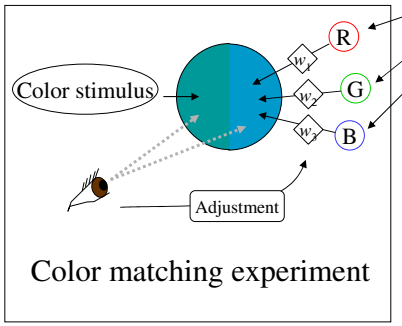
Spectral reflectance => **f** (*N*-dimensional vector) $\mathbf{f} = \begin{pmatrix} f(\lambda_1) \\ f(\lambda_2) \\ \vdots \\ f(\lambda_N) \end{pmatrix}$

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

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

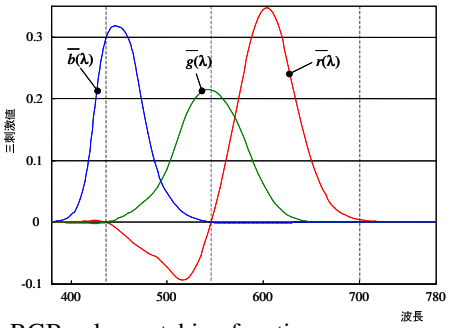
色空間はどのようにして定められたのか？
How were color spaces defined?

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



Color matching experiment

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

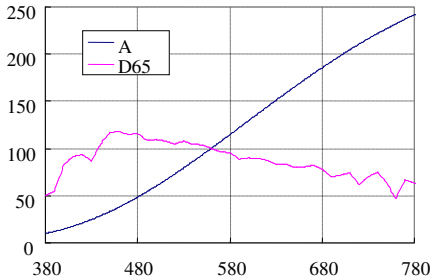


RGB color matching functions
各波長の三刺激値:スペクトル三刺激値

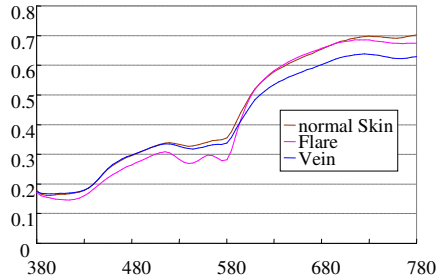
w_1, w_2, w_3: tristimulus values
三刺激値

※三刺激値が負になる場合

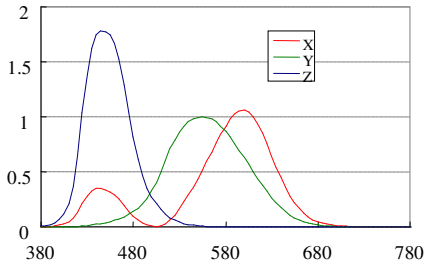
Examples



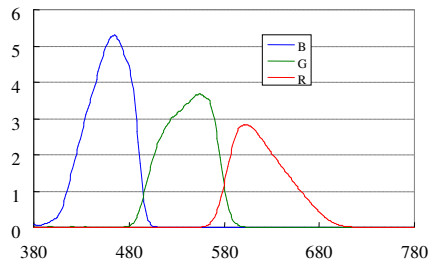
Spectral intensity distributions of illumination lights
(CIE A and CIE D65 standard illuminants)



Example of spectral reflectance (Skin)



Color matching functions of human observer

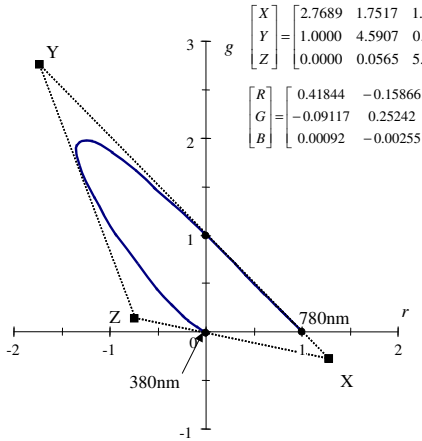


Example of the spectral sensitivity of a color camera

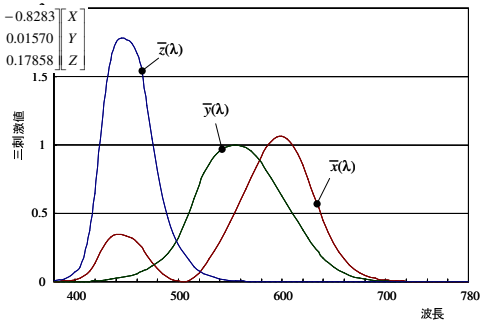
XYZ Color Matching Functions (CMF)
Color is represented by three positive variables
XYZ等色関数:３つの正の数で色を表す

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

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



XYZ primary colors on
r-g color coordinates

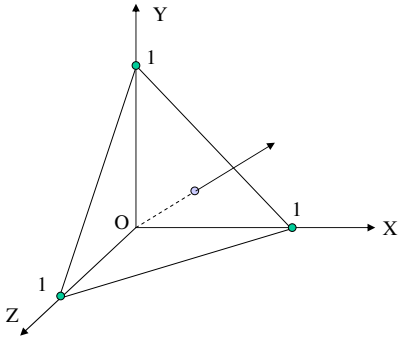


各波長の三刺激値

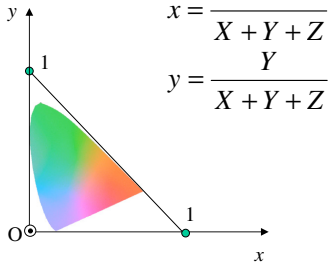
CIE 1931 XYZ CMF

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

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



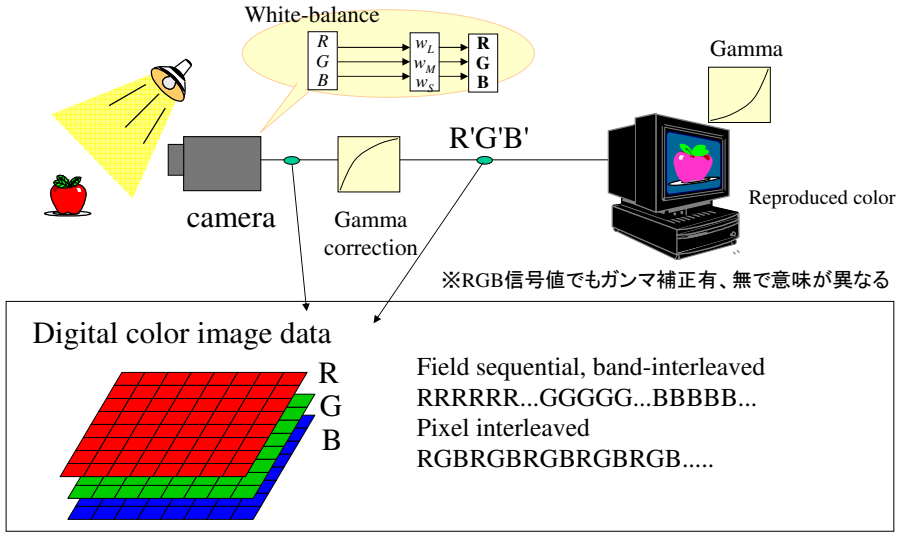
XYZ color space



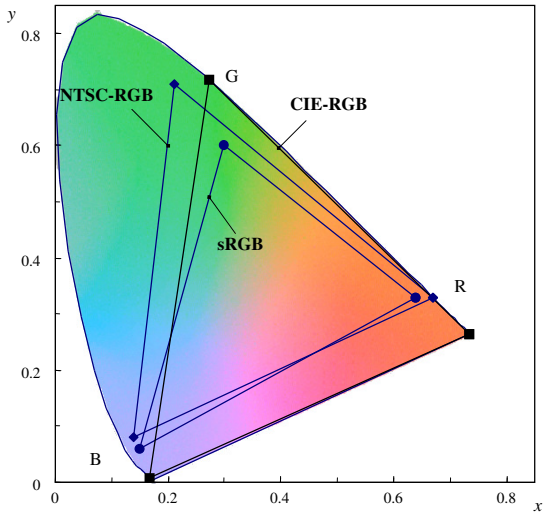
$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z}$$

xy-chromaticity diagram

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

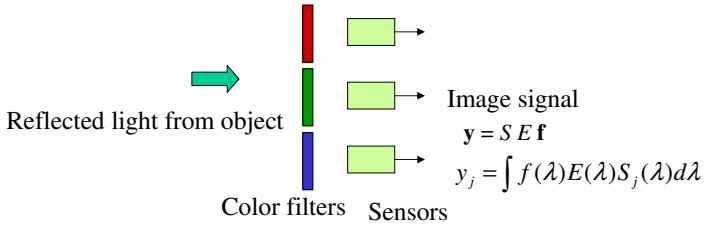


RGB three primary colors
RGB　3原色

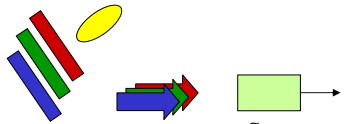


5.2.1 Input of color images　　カラー画像の入力
Color image input devices

- Color camera, scanner, …, endoscopy



(Modulation of illumination light)

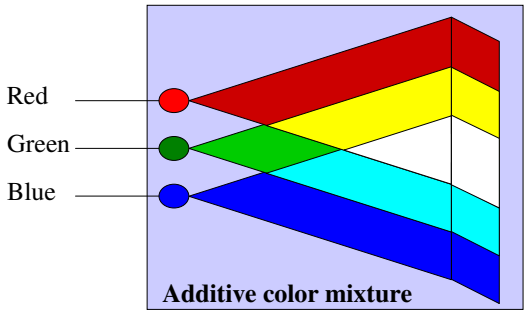


5.2.2 Color display　　カラーディスプレイ

- 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 **q**

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

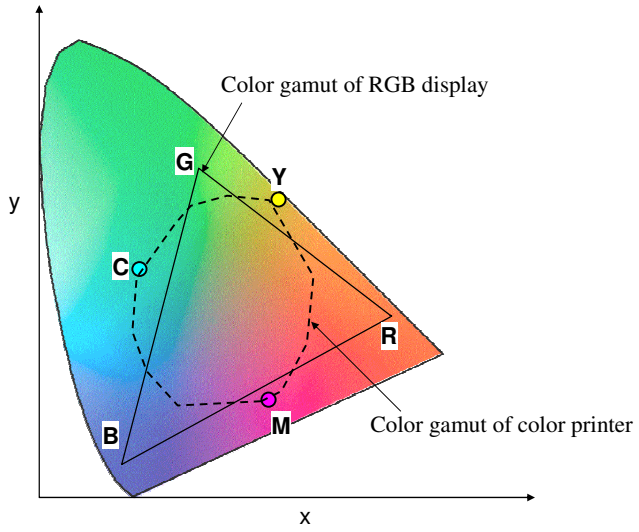
- **q = A r**



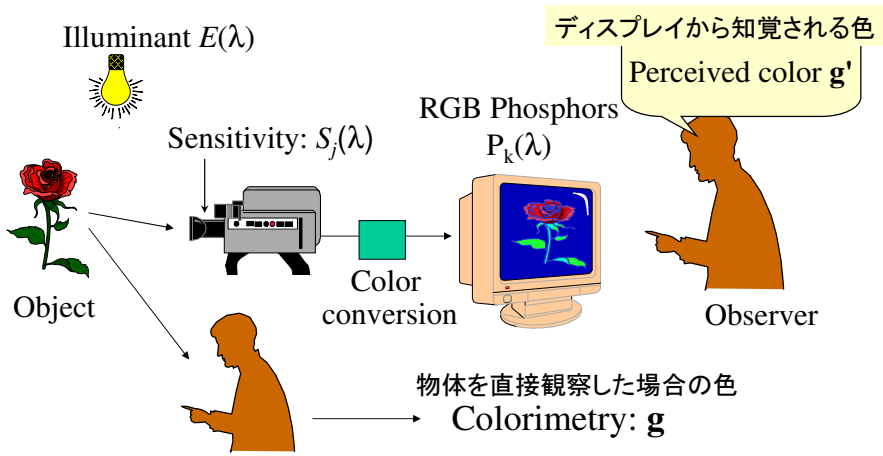
加法混色の原理

※ 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

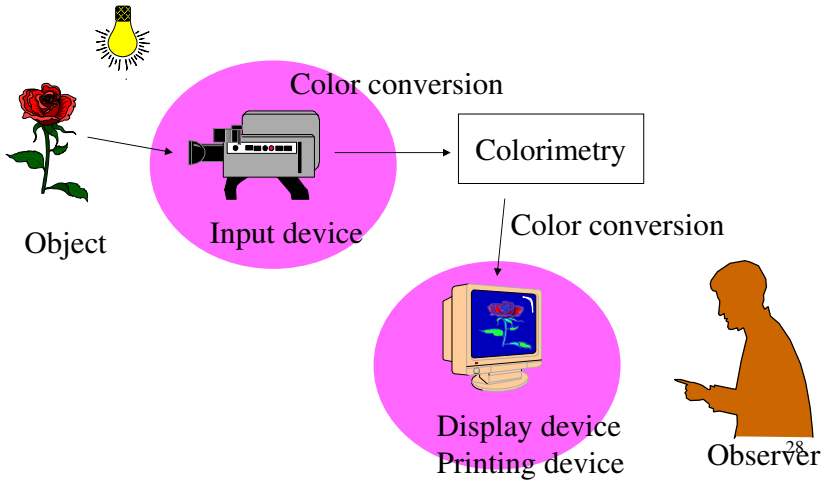
4.3.1 Objectives in color reproduction
色再現の分類 (R. W. G. Hunt)

- 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



4.4 Color image processing
4.4 カラー画像処理

4.4.1 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)

4.4.2 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 $\hat{\mathbf{g}} = \mathbf{M}\mathbf{y}$

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

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

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

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