Optical imaging and image processing (X)

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

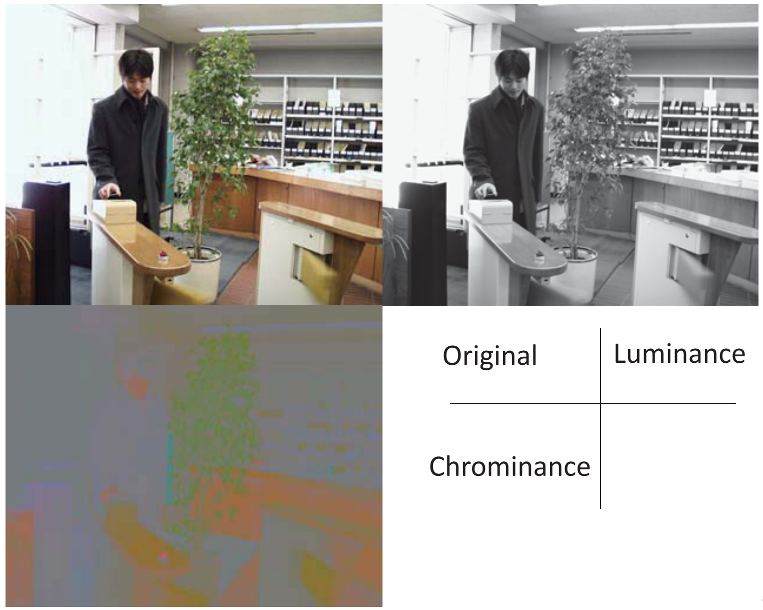
- Monochromatic image, B/W image = 1-dimensional
  ⇒ Color image = 3-dimensional
- larger bandwidth in the luminance signal, and smaller bandwidth in the chrominance signal
  - TV signal, Color image compression
- Resemblance in RGB primary component
  - The spectral reflectance of most objects are smooth
- 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)

Color

R

G

B



Original　　Smoothing only chrominance component

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

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

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

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

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

4.4.3 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

Wiener filtering in color images (Color image restoration)

カラー画像におけるウイナーフィルタ（カラー画像復元）

$$\mathbf{f_c}(x,y) = \sum_{j=R,G,B} f_j(x,y)\mathbf{e}_j$$

$$\mathbf{f_c} = \begin{pmatrix} \mathbf{f_R} \\ \mathbf{f_G} \\ \mathbf{f_B} \end{pmatrix}$$

$$\mathbf{g_c} = \mathbf{H_c}\mathbf{f_c} + \mathbf{n_c} = \begin{pmatrix} \mathbf{g_R} \\ \mathbf{g_G} \\ \mathbf{g_B} \end{pmatrix} = \begin{pmatrix} \mathbf{H_R}\mathbf{f_R} + \mathbf{n_R} \\ \mathbf{H_G}\mathbf{f_G} + \mathbf{n_G} \\ \mathbf{H_B}\mathbf{f_B} + \mathbf{n_B} \end{pmatrix}$$

$$e = E\{\| \mathbf{f_c} - \hat{\mathbf{f}}_\mathbf{c} \|^2\} = E\{\| \mathbf{f_c} - \mathbf{M}\mathbf{g_c} \|^2\} \to \min$$

In case of the 'Red' channel restoration

$$e = E\{\| \mathbf{f_R} - \mathbf{M_R}\mathbf{g_c} \|^2\} \to \min$$

Wiener filtering in color images
(Color image restoration)

The image of red channel is restored using other channel components

$$\mathbf{M}_R = E\{\mathbf{f}_R\mathbf{g}_c^{\,t}\}E\{\mathbf{g}_c\mathbf{g}_c^{\,t}\}^{-1}$$

$$\mathbf{M}_R = E\{\mathbf{f}_R\mathbf{f}_c^{\,t}\}\mathbf{H}_c^{\,t}\left[\mathbf{H}_c E\{\mathbf{f}_c\mathbf{f}_c^{\,t}\}\mathbf{H}_c^{\,t} + E\{\mathbf{n}_c\mathbf{n}_c^{\,t}\}\right]^{-1}$$

$$E\{\mathbf{f}_R\mathbf{f}_c^{\,t}\} = \mathbf{R}_{Rc} = \left(E\{\mathbf{f}_R\mathbf{f}_R^{\,t}\} \quad E\{\mathbf{f}_R\mathbf{f}_G^{\,t}\} \quad E\{\mathbf{f}_R\mathbf{f}_B^{\,t}\}\right) = \left(\mathbf{R}_{RR} \quad \mathbf{R}_{RG} \quad \mathbf{R}_{RB}\right)$$

$$E\{\mathbf{f}_c\mathbf{f}_c^{\,t}\} = \mathbf{R}_{cc} = \begin{pmatrix} \mathbf{R}_{RR} & \mathbf{R}_{RG} & \mathbf{R}_{RB} \\ \mathbf{R}_{GR} & \mathbf{R}_{GG} & \mathbf{R}_{GB} \\ \mathbf{R}_{BR} & \mathbf{R}_{BG} & \mathbf{R}_{BB} \end{pmatrix}$$

$$\mathbf{M}_R = \mathbf{R}_{Rc}\mathbf{H}_c^{\,t}\left[\mathbf{H}_c\mathbf{R}_{cc}\mathbf{H}_c^{\,t} + \mathbf{R}_{ncc}\right]^{-1}$$

Wiener filtering in color images
(Color image restoration)

If spatial correlation is $\mathbf{R}_j$, and no correlation between channels,
(Intra-channel correlation = $\mathbf{R}_j$, inter-channel correlation = 0

$$\mathbf{R}_{Rc} = \left(\mathbf{R}_{RR} \quad \mathbf{R}_{RG} \quad \mathbf{R}_{RB}\right) = \left(\mathbf{R}_{RR} \quad 0 \quad 0\right)$$

$$\mathbf{R}_{cc} = \begin{pmatrix} \mathbf{R}_{RR} & \mathbf{R}_{RG} & \mathbf{R}_{RB} \\ \mathbf{R}_{GR} & \mathbf{R}_{GG} & \mathbf{R}_{GB} \\ \mathbf{R}_{BR} & \mathbf{R}_{BG} & \mathbf{R}_{BB} \end{pmatrix} = \begin{pmatrix} \mathbf{R}_{RR} & 0 & 0 \\ 0 & \mathbf{R}_{GG} & 0 \\ 0 & 0 & \mathbf{R}_{BB} \end{pmatrix}$$

$$\mathbf{H}_c\mathbf{R}_{cc}\mathbf{H}_c^{\,t} = \begin{pmatrix} \mathbf{H}_R & 0 & 0 \\ 0 & \mathbf{H}_G & 0 \\ 0 & 0 & \mathbf{H}_B \end{pmatrix}\begin{pmatrix} \mathbf{R}_{RR} & 0 & 0 \\ 0 & \mathbf{R}_{GG} & 0 \\ 0 & 0 & \mathbf{R}_{BB} \end{pmatrix}\begin{pmatrix} \mathbf{H}_R^{\,t} & 0 & 0 \\ 0 & \mathbf{H}_G^{\,t} & 0 \\ 0 & 0 & \mathbf{H}_B^{\,t} \end{pmatrix}$$

$$\mathbf{M}_R = \left(\mathbf{R}_R \quad 0 \quad 0\right)\begin{pmatrix} \mathbf{H}_R^{t} & 0 & 0 \\ 0 & \mathbf{H}_G^{t} & 0 \\ 0 & 0 & \mathbf{H}_B^{t} \end{pmatrix}\left[\begin{pmatrix} \mathbf{H}_R\mathbf{R}_R\mathbf{H}_R^{\,t} & 0 & 0 \\ 0 & \mathbf{H}_G\mathbf{R}_G\mathbf{H}_G^{\,t} & 0 \\ 0 & 0 & \mathbf{H}_B\mathbf{R}_B\mathbf{H}_B^{\,t} \end{pmatrix} + \begin{pmatrix} \mathbf{R}_{nR} & 0 & 0 \\ 0 & \mathbf{R}_{nG} & 0 \\ 0 & 0 & \mathbf{R}_{nB} \end{pmatrix}\right]^{-1}$$

$$\mathbf{M}_R = \mathbf{R}_{RR}\mathbf{H}_R^{\,t}\left[\mathbf{H}_R\mathbf{R}_{RR}\mathbf{H}_R^{\,t} + \mathbf{R}_{nR}\right]^{-1}$$

Each channel is restored independently.

Wiener filtering in color images
(Color image restoration)

In case of no intra-channel correlation, and high inter-channel correlation
(almost monochromatic)

$$\mathbf{R}_{Rc} = \left(\mathbf{R}_{RR} \quad \mathbf{R}_{RG} \quad \mathbf{R}_{RB}\right) = \left(\mathbf{I}_n \quad \mathbf{I}_n \quad \mathbf{I}_n\right)$$

$$\mathbf{R}_{cc} = \begin{pmatrix} \mathbf{R}_{RR} & \mathbf{R}_{RG} & \mathbf{R}_{RB} \\ \mathbf{R}_{GR} & \mathbf{R}_{GG} & \mathbf{R}_{GB} \\ \mathbf{R}_{BR} & \mathbf{R}_{BG} & \mathbf{R}_{BB} \end{pmatrix} = \begin{pmatrix} \mathbf{I}_n & \mathbf{I}_n & \mathbf{I}_n \\ \mathbf{I}_n & \mathbf{I}_n & \mathbf{I}_n \\ \mathbf{I}_n & \mathbf{I}_n & \mathbf{I}_n \end{pmatrix}$$

$$\mathbf{H}_c\mathbf{R}_{cc}\mathbf{H}_c^{\,t} = \begin{pmatrix} \mathbf{H}_R & 0 & 0 \\ 0 & \mathbf{H}_G & 0 \\ 0 & 0 & \mathbf{H}_B \end{pmatrix}\begin{pmatrix} \mathbf{R}_{RR} & \mathbf{R}_{RG} & \mathbf{R}_{RB} \\ \mathbf{R}_{GR} & \mathbf{R}_{GG} & \mathbf{R}_{GB} \\ \mathbf{R}_{BR} & \mathbf{R}_{BG} & \mathbf{R}_{BB} \end{pmatrix}\begin{pmatrix} \mathbf{H}_R^{\,t} & 0 & 0 \\ 0 & \mathbf{H}_G^{\,t} & 0 \\ 0 & 0 & \mathbf{H}_B^{\,t} \end{pmatrix}$$

$$= \begin{pmatrix} \mathbf{H}_R\mathbf{H}_R^{\,t} & \mathbf{H}_R\mathbf{H}_G^{\,t} & \mathbf{H}_R\mathbf{H}_B^{\,t} \\ \mathbf{H}_G\mathbf{H}_R^{\,t} & \mathbf{H}_G\mathbf{H}_G^{\,t} & \mathbf{H}_G\mathbf{H}_B^{\,t} \\ \mathbf{H}_B\mathbf{H}_R^{\,t} & \mathbf{H}_B\mathbf{H}_G^{\,t} & \mathbf{H}_B\mathbf{H}_B^{\,t} \end{pmatrix}$$

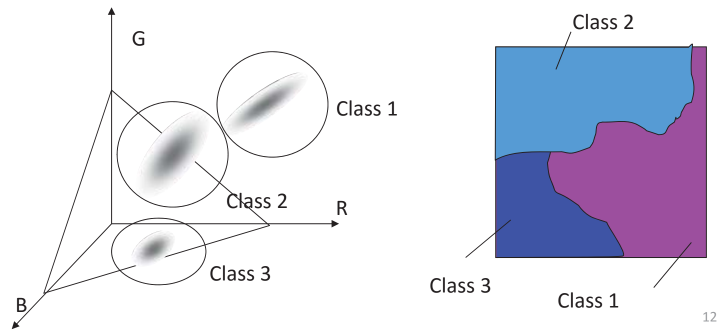
$$\mathbf{M}_R = \left(\mathbf{H}_R^{t} \quad \mathbf{H}_G^{t} \quad \mathbf{H}_B^{t}\right)\begin{pmatrix} \mathbf{H}_R\mathbf{H}_R^{\,t} + \mathbf{R}_{nR} & \mathbf{H}_R\mathbf{H}_G^{\,t} & \mathbf{H}_R\mathbf{H}_B^{\,t} \\ \mathbf{H}_G\mathbf{H}_R^{\,t} & \mathbf{H}_G\mathbf{H}_G^{\,t} + \mathbf{R}_{nG} & \mathbf{H}_G\mathbf{H}_B^{\,t} \\ \mathbf{H}_B\mathbf{H}_R^{\,t} & \mathbf{H}_B\mathbf{H}_G^{\,t} & \mathbf{H}_B\mathbf{H}_B^{\,t} + \mathbf{R}_{nB} \end{pmatrix}^{-1}$$

If inter-channel correlation = 1 $\longrightarrow$ $\mathbf{M}_R = \mathbf{M}_G = \mathbf{M}_B$

The intra- and inter-channel correlations are measured (or estimated) from the image and G and B components are used in accordance with the correlation characteristics.

4.4.4 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



4.5 Limitation of RGB-based color reproduction

Why RGB Imaging is not enough?

- <u>RGB does not represent the color attribute of an object.</u>

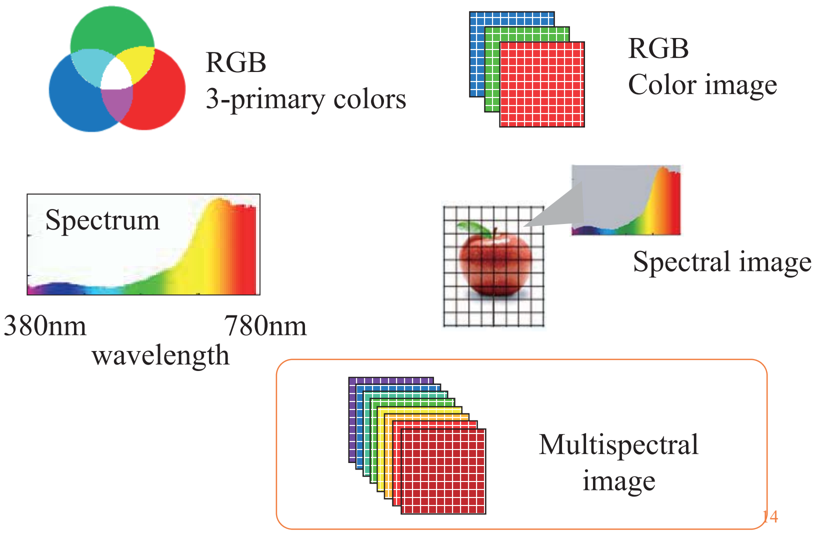
- Spectral sensitivity of conventional color imaging device is not equivalent to human vision
- Color reproduction under different illumination environment
- Is not "Quantitative" information for image analysis
- The color gamut of display does not cover all the existent colors
- Observer Metamerism: Color matching for different observers

Different illuminant


Under incandescent lamp

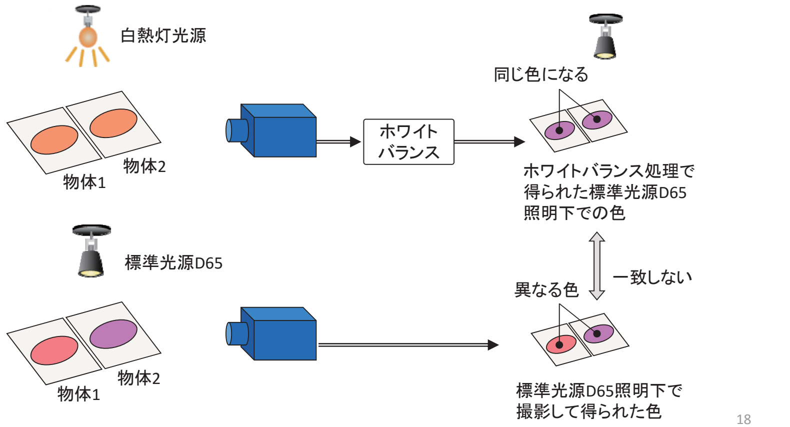

Under fluorescent lamp

Color image / Spectral image



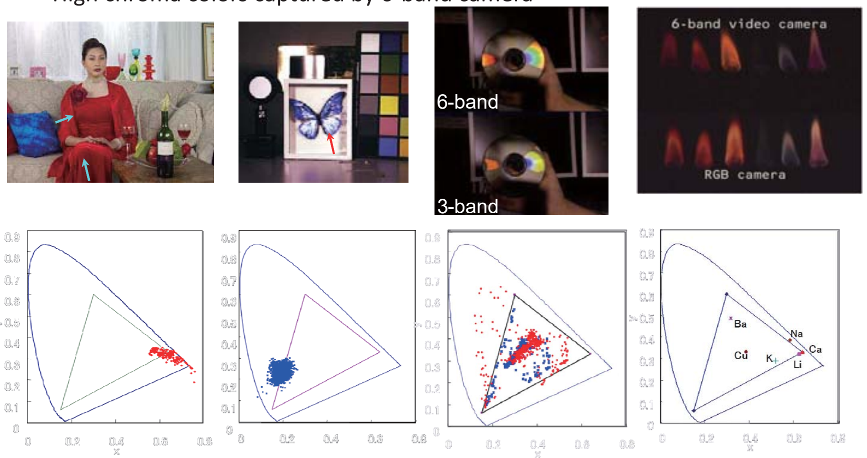
Different illuminant
Metamerism

白熱灯光源の下でスペクトルは異なるがXYZが等しくなる二つの物体が、標準光源D65の下では異なる色になる例。ホワイトバランスによって白は正確に補正されるが、他の色は正しく求めることができない。このような現象はメタメリズムと呼ばれている。



Wider color gamut

High chroma colors captured by 6-band camera



Solution
Spectrum-based color reproduction

- Multispectral imaging:
  Capture more than 3 channels
- Illumination spectrum measurement
- Spectrum-based color conversion
- Utilization of wide-gamut displays

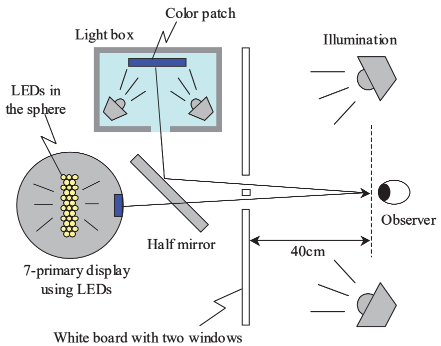
Enables high-fidelity color reproduction as if the subject were placed at the observer site.

Cf. International Color Consortium, ICCMax
CIE Division 8, TC 8-07 Multispectral Imaging

Observer metamerism

Spectral display with spectral approximation

For the applications that need very high-accuracy



Visual experiment using 7-P LED color patch

Y. Murakami, et. al., JEI, Vol.13, No.4, 701-708, (2004)

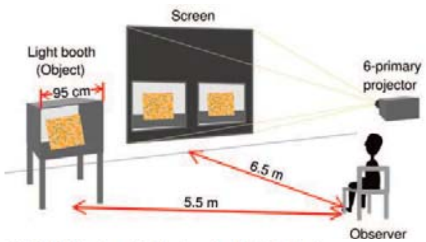


TABLE I. Number of Selections for Each Method

Compared methods	Number of selections	Standardized variable, z	p value
Linear interpolation / Spectral-approx.	8 / 32	3.79	0.015%
Matrix switching / Spectral-approx.	3 / 40	5.64	< 0.0001%
Three-primary / Spectral-approx.	3 / 32	4.90	0.01%

Visual experiment using 6P display

T. Uchiyama et. al., JIST, Vol.49, No.4, 410-417, (2005)

Spectrum-based color reproduction system