Color Spaces and Color Encodings and Color Image Processing

Color Imaging Course
EPFL
Winter semester 2005/2006

Color Spaces [ISO 22028-1]

Color Image Encoding

=  

Color Space Encoding

=  

Color Space

+  

Digital Encoding Method

+  

Information necessary to properly interpret the color values (image state, viewing environment, etc.)

Color Space

• According to the CIE [CIE87], a color space is a "geometric representation of colors in space, usually of three dimensions."
  – colorimetric, color appearance, and device dependent.

• Colorimetric Color Space:
  – The relationship between the color space and CIE colorimetry is clearly defined.
  – Additive RGB color spaces
    • Primaries, linear transform to XYZ, color space white-point, and color component functions are defined.
    – CIEXYZ, CIELAB, CIELUV
    • XYZ under D65 is different from XYZ under D50.
    – YCC, YC/CB, etc.
  – Linear transforms from RGB to more de-correlated, opponent color

• Such color spaces are generally the basis for color image encodings used in compression.
Lecture 4 - Color Spaces, Encodings, and Image States

Color Space

- **Color Appearance**
  - Output of color appearance models, such as CIECAM97s or CIECAM02.

- **Device Dependent**
  - No direct relationship with CIE colorimetry.
  - Examples: Camera color space, printer color space
  - Spectral characteristics, color component function, and white-point of an actual or idealized input or output device needs to be specified.

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Example: color space characteristics

<table>
<thead>
<tr>
<th>Color space type</th>
<th>Colorimetric RGB color space</th>
<th>Colorimetric RGB color space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color component transfer function</td>
<td>( C'=\begin{cases} 12.92C &amp; \text{for } C \leq 0.0031308 \ 1.055(C^{1/2.4} - 0.055) / 1.402 &amp; \text{for } C &gt; 0.0031308 \end{cases} )</td>
<td>( C'=\begin{cases} 12.92C &amp; \text{for } C \leq 0.0031308 \ 1.055(C^{1/2.4} - 0.055) / 1.402 &amp; \text{for } C &gt; 0.0031308 \end{cases} )</td>
</tr>
<tr>
<td>Luma-Chroma matrix</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Color space white point luminance</td>
<td>80 cd/m²</td>
<td>15'000 cd/m²</td>
</tr>
<tr>
<td>Color space white point chromaticity</td>
<td>D65</td>
<td>D65</td>
</tr>
</tbody>
</table>

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Linear Transform to XYZ

\[
\begin{bmatrix}
R \\
C \\
B
\end{bmatrix} =
\begin{bmatrix}
m_{11} & m_{12} & m_{13} \\
m_{21} & m_{22} & m_{23} \\
m_{31} & m_{32} & m_{33}
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]

Equivalently:

\[
\begin{bmatrix}
R \\
C \\
B
\end{bmatrix} = \mathbf{M} \begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]

\( \mathbf{M} \) is non-singular. The inverse transform is:

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \mathbf{M}^{-1} \begin{bmatrix}
R \\
C \\
B
\end{bmatrix}
\]
Lecture 4 - Color Spaces, Encodings, and Image States

**XYZ and sRGB CMF’s**

**Example sRGB**

\[
\begin{bmatrix}
R_{sRGB} \\
G_{sRGB} \\
B_{sRGB}
\end{bmatrix} =
\begin{bmatrix}
3.2406 & -1.5372 & -0.4986 \\
-0.9689 & 1.8758 & 0.0415 \\
0.0557 & -0.2040 & 1.0570
\end{bmatrix}
\begin{bmatrix}
X_{\text{ref}} \\
Y_{\text{ref}} \\
Z_{\text{ref}}
\end{bmatrix}
\]

\(X_{\text{ref}}, Y_{\text{ref}}, Z_{\text{ref}}\) normalized (divided by \(Y_{\text{wD65}}\)).

**Color Component Transfer Function**

- for perceptual encoding
- Non-linear to mimic the sensitivity of the human visual system.
- Common encoding strategies:
  - \(C = \log_{10}(C)\)
  - \(C = aC\)
  - \(\gamma = 1/3\) for \(L^*\)
  - \(\gamma = [1/1.8 - 1/2.4]\) for common color spaces
  - \(\forall C=R,G,B\)
Luma-Chroma Example

- From (non-linear) sRGB to sYCC:

\[
\begin{bmatrix}
Y \\
C_b \\
C_r
\end{bmatrix} =
\begin{bmatrix}
0.299 & 0.587 & 0.114 \\
0.1687 & -0.3313 & 0.5000 \\
0.5000 & 0.4187 & 0.0813
\end{bmatrix}
\begin{bmatrix}
H \\
C'_b \\
C'_r
\end{bmatrix}
\]

Color Space Encoding [ISO 22028-1]

- Color Image Encoding = Color Space + Digital Encoding Method + Information necessary to properly interpret the color values (image state, viewing environment, etc.)

Color Encodings

- Color Space plus digital encoding method
  - Digital code value range (8-bit, [0..255]) associated to color space range (RGB, [0..1])
  - Values outside of the minimum and maximum color space range are clipped to the minimum and maximum values.
  - The same color space can result in different color encodings.
  - Example: sRGB and sCRGB, ROMM RGB (ProPhoto RGB): 8-bit, 12-bit, 16-bit.
For example, the non-linear sRGB values \( (C' = R', G', B') \) are quantized to 8-bit/channel \( (C'' = R''_{8-bit}, G''_{8-bit}, B''_{8-bit}) \) as follows:

\[
C'' = \text{round}(255 \times C')
\]

The non-linear sYCC values are quantized to 8-bit as follows:

\[
Y_{sYCC}, 8\text{-bit} = \text{round}(255 \times Y) \\
C_b_{sYCC}, 8\text{-bit} = \text{round}(255 \times C_b + 128) \\
C_r_{sYCC}, 8\text{-bit} = \text{round}(255 \times C_r + 128)
\]
Color Image Encoding [ISO 22028-1]

\[
\text{Color Image Encoding} = \\
\text{Color Space Encoding} = \\
\text{Color Space} + \\
\text{Digital Encoding Method} + \\
\text{Information necessary to properly Interpret the color values (image state, viewing environment, etc.)}
\]

Color Image Encoding

- Color Space Encoding plus parameters necessary to interpret the color values:
- Image State (color rendering of the image data):
  - input-referred (scene or original): image data represents an estimate of the scene or original colorimetry (scRGB, RIMM RGB)
  - output-referred: image data represents the colorimetry of the original data color rendered to a real or virtual output device (sRGB, ProPhoto).

Color Workflow
Color Image Encoding

- Reference Viewing Conditions:
  - Surround, adapted white-point, luminance of the adapting field, viewing flare
  - Output-referred additionally needs a reference imaging medium, either a real or virtual monitor or print.

Example: color image encoding characteristics

<table>
<thead>
<tr>
<th></th>
<th>sRGB</th>
<th>RIMM RGB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image state</td>
<td>Output-referred (CRT)</td>
<td>Scene-referred</td>
</tr>
<tr>
<td>Image background / surround</td>
<td>20% of display white-point luminance (16 cd/m²)</td>
<td>Surround: 20% of adapted white-point</td>
</tr>
<tr>
<td></td>
<td>20% reflectance of ambient luminance level (4.1 cd/m²)</td>
<td></td>
</tr>
<tr>
<td>Adapted white-point luminance</td>
<td>Not specified</td>
<td>15'000 cd/m²</td>
</tr>
<tr>
<td>Adapted white-point chromaticity</td>
<td>Not specified</td>
<td>D50</td>
</tr>
<tr>
<td>Luminance of adapting field</td>
<td>Not specified</td>
<td>Not specified (20% of adapted white-point luminance)</td>
</tr>
</tbody>
</table>

Example: color image encoding characteristics

<table>
<thead>
<tr>
<th></th>
<th>sRGB</th>
<th>RIMM RGB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viewing flare (typical viewing conditions)</td>
<td>0.9% of color space white-point luminance</td>
<td>N/A</td>
</tr>
<tr>
<td>Valid relative luminance range (without flare or glare)</td>
<td>0.0 to 1.8</td>
<td>0.0 to 2.0</td>
</tr>
<tr>
<td>Reference medium white point luminance</td>
<td>80 cd/m²</td>
<td>N/A</td>
</tr>
<tr>
<td>Reference medium white point chromaticity</td>
<td>D65</td>
<td>N/A</td>
</tr>
<tr>
<td>Reference medium black point luminance</td>
<td>1 cd/m²</td>
<td>N/A</td>
</tr>
<tr>
<td>Reference medium black point chromaticity</td>
<td>D65</td>
<td>N/A</td>
</tr>
</tbody>
</table>
1) "Raw" data from the sensor (sensor encoding)
2) Device color encoding, after non-uniformity illumination correction (sensor encoding)
3) Color rendered to sRGB (the rendering intent was to minimize colorimetric errors ($\Delta E$)

Sensor Encoding
Raw sensor data encoding

- Device specific
- Linear with respect to scene irradiance (if flare is removed) or linear with respect to focal plane irradiance
- Good for archival and image processing tasks (panorama stitching) if the camera characterization data is maintained
  - exposure condition, sensor characterization, etc.

Input-referred Encoding

- Represents an estimate of the scene’s or the original’s colorimetry.
  - Maintains the relative dynamic range and gamut
  - Scene-referred, original-referred.
- The quality of the colorimetric estimate can vary:
  - scene illuminant, transformation from device coordinates to standard input-referred encoding,
  - The transforms are usually not reversible.
- Advantageous if facsimile reproductions have to be created.
- Color image encodings based on CIE XYZ, CIE Lab, CIE Luv, Photo YCC, RIMM RGB
Output-referred Encoding

- Represents the desired image colorimetry on a real or virtual output devices.

- Image-dependent transforms from device- or input-referenced encoding. The color rendering is dependent on the reproduction intent, the original, and the output-referred encoding specifications.

- Most common encoding for master and derivative images
  - Commercially available hard-/software

- Appropriate for images whose purpose is reproduction and not replacement of the original.

Output-device specific encoding

- Represents output device coordinates.

- Not recommended for master file encoding.

- Legacy files: “Reverse Transform” to new derivatives
  - Apple RGB, CMYK
Color Image Workflow from Capture to Display

Color Processing to Sensor Encoding

Noise

\[ X = X_{\text{mean}} \pm \sigma_X \]

- Noise Sources in Sensors:
  - Dark current
  - Fixed Pattern noise
  - Read-out noise
  - Shot noise (Photon noise)
Dark Current

• Due to excitation other than light (temperature and time)
  - Dark current doubles with each ~5 K temperature increase
• Subtract dark current:
  - Dark frame subtraction
  - Optical black subtraction

Fixed Pattern Noise

• Due to different pixel sensitivities (filter thickness, amplifier differences in case of CMOS sensors)
  - Can be removed by subtracting a reference frame

Shot noise

• Poisson distribution:

\[ f = \rho T \pm \sqrt{\rho T} \]

\( f \): pixel response
\( \rho \): photon rate /second
\( T \): time
Total noise

- If errors are independent and random:

\[ \sigma_n = \sqrt{\sigma_{dc}^2 + \sigma_i^2 + \sigma_{fp}^2 + \sigma_p^2 + \ldots} \]

**Note:** \( \sigma_n \): total amount of noise for a pixel value

Linearization

- Sensors are inherently linear with respect to focal plane illuminance.
- If support electronics introduce non-linearities, compensate with the inverse OECF.
- OECF: opto-electronic conversion function (A/D)

OECF

- EOCF: Electro-Optical Conversion Function (D/A)
- Can be changed through image processing steps.
Veiling Flare

- The relatively uniform but unwanted illuminance in the image plane of an optical system, caused by the scattering and reflection of a portion of the illuminance which enters the system through its normal entrance aperture.

\[ E_{\text{total}} = E_{\text{image}} + E_{\text{flare}} \]

- Veiling Flare reduces the contrast in the shadows.
Veiling Flare (Positive) (simulation)

No Flare  Little Flare  Lots of Flare

\[ F_{\text{total}} = F_{\text{image}} + F_{\text{flare}} \]

Flare Correction

- The amount of flare depends on the scene luminance and the optics.
  - The exact flare values are estimated through testing

Color processing from sensor encoding to input-referred encoding

- Pixel interpolation (if needed)
- Select scene adopted white
- Transform to standard color space

Image representation in input-referred color encoding (estimate of scene or original colorimetry)
Scene Analysis

- Transformation from camera response to tristimulus values:
  \[ s = f(p) \]
  
  \( s \) = \( X,Y,Z \) tristimulus values
  \( p \) = \( R,G,B \) camera response values

Find \( f \)

- Simple Method: Assume that the camera response is a linear transformation of the color matching functions:
  \[ S = PM \]
  
  \( S(3x3) = [X,Y,Z] \)
  \( P(3x3) = [R,G,B] \)

- In reality, camera response functions do not fulfill the Luther condition: \( S - PM \)

Error Minimization

- Find the linear transform such that an error is minimized:
  \[ M = f(S, P) \quad s.t. \quad \min \| PM - S \| \]

- least squares error:
  - Pseudoinverse: \( M = P' S \)
  - Moore-Penrose: \( M = (PP')^{-1}P' S \)
Error Minimization

- Dependent on the samples:
  \[ M = [(S^T T) S^T]^{-1} (S^T T) S^T C \]
  \[ M = (T^T S S^T T)^{-1} T^T (S S^T T) C \]

- \( C(mx3): \) xyz CMFs multiplied by the illuminant spectral power distribution.
- \( S(mxn): \) set of reflectances (n surfaces, sampled at m wavelengths).
- \( T(mx3): \) Transfer matrix of reflectances to camera values.

Reflectances

- Reflectance charts:
  - MacBeth (scene)
  - Digital ColorChecker (scene)
  - IT-8 (scanner)

- The reflectance charts should be representative of the actual reflectances:
  - Pigments of paintings

Other Error Minimizations

- Minimize perceptual attributes:
  - Achromatic colors (white): Finlayson and Drew, 1997 (see reading assignment)

\[ t = [P^T P]^T P^T s + \frac{1 - s^T P^T P^{-1} u}{u^T [P^T P]^{-1} u} [P^T P]^{-1} u \]
Comparison

<table>
<thead>
<tr>
<th>Data sets</th>
<th>LS mean</th>
<th>LS sd</th>
<th>LS white*</th>
<th>WPPLS mean</th>
<th>WPPLS sd</th>
<th>WPPLS white*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Munsell</td>
<td>1.54</td>
<td>1.45</td>
<td>1.71</td>
<td>1.75</td>
<td>1.57</td>
<td>0.41</td>
</tr>
<tr>
<td>Macbeth</td>
<td>2.01</td>
<td>1.29</td>
<td>1.55</td>
<td>1.86</td>
<td>1.51</td>
<td>0.40</td>
</tr>
<tr>
<td>Object</td>
<td>1.53</td>
<td>1.63</td>
<td>1.51</td>
<td>1.60</td>
<td>1.72</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Error: ΔE
* this is the whitest patch of the data set (not a perfect diffuser)

Other Error Minimizations

- Minimize other perceptual errors
  - Delta E (94, CMC): non-linear with respect to XYZ. Close to HVS perceptual uniformity.
Camera Sensitivity to Color Space Transforms

- Some comments:
  - The camera to XYZ and the XYZ to color space transforms are both linear, and usually concatenated.
  - The off-diagonal coefficients of the transformation matrix give an indication about the noise amplification.
    - The smaller the coefficients, the less noise is amplified.

Reading Assignment (see web)

- Lecture Notes

References (see web)