Colorimetry and Its Application

R. Chung, Professor

Colorimetry has become more and more useful in graphic arts imaging for color specification, process control, and quality assurance.

Topics Covered

- Light, object, and color vision
- Tristimulus integration
  - 1931 CIEXYZ color space
  - 1976 CIELAB color space
- Color matching and color difference
- Colorimetry application
Light and Color

- Light exists as a form of energy.
- Color is a visual sensation.
- Visual sensation requires
  - Light
  - Object
  - Observer

Human Color Vision

- Color perception is complex.
  - Even if we standardize the lighting condition, the color of the same object may be perceived differently by two people.
    - Perception is influenced by age, sex, cultural experiences
- CIE colorimetry standardizes how we measure color.
  - Color measurement may be able to predict color perception.
Color Vision Tests

- Ishihara’s test for color blindness
- Farnsworth-Munsell 100 Hue test

Color Vision Deficiency

- Anomalous trichromats
  - normal
  - deutan
  - tritan
- Statistics
  - 7% of male population have color vision defects
  - Less than 0.5% of female population have color vision defects
Standard Observer

- In 1931, CIE defined a set of mathematical functions which describe the sensitivity of the eye.
  - Based on two independent color matching experiments by Wright and Guild
  - To quantify how spectrum colors are matched rather than to specify a color sensation

Color Matching Experiment

- Three imaginary primaries (R, G, B) were used in the color matching experiments.
1931 2o Standard Observer

- The amount of tristimulus values required to match the equal-energy spectrum

Mathematics is used to transform color matching functions (x-bar, y-bar, z-bar) without negative portion.

Rods & Cones Distribution

- Color vision is centered around 2-degree fovea where cones are heavily concentrated.

Source: Leo Hurvich
Professor of Psychology
Univ. of Pennsylvania
Supplementary Observer

- A CIE 10o standard observer was established in 1964.
  - Larger visual field was used for color matching.
  - Suitable for paint, textile, and plastics applications

![Illustration of Supplementary Observer]

Spectral Power Distribution

- SPD is measured by a spectroradiometer.
  - Color temperature describes the hue of the light source.
    - Lamps with D50 color temperature can be different in spectral energy distribution.
      - A potential problem of metamerism
  - CRI describes its color rendering capability.
    - How complete spectral energies are across the visible spectrum
CIE Standard Illuminants

- **Illuminant A**
  - Tungsten
  - 2800oK

- **Illuminant D50**
  - Daylight
  - 5000oK

Source:
Hunt, R.W.G,
Measuring Colour (2nd edition, 1991)

SPD of F2 at 5 nm intervals (blue) shows spikes on top of the continuous emission.
- SPD of F2 at 10 nm intervals (red line) does not have sufficient resolution to show the spikes.
Object Color

- Measured by a spectrophotometer
  - A spectrophotometer measures the reflectance of a sample at many points across the visible spectrum.

Spectrophotometer

- Instrument design parameters
  - Geometry
    - 0 / 45
      - Measuring diffuse reflectance
    - Integrating sphere
      - Specular component included or excluded
  - Monochromator
    - Grating
    - Interference filters
  - Measurement spot size
Tristimulus Integration

- ISO 13655 (2009)
  - \( R(\lambda) \) is the reflectance factor at \( \lambda \).
  - \( WX(\lambda) \) is the weighting factor at \( \lambda \) for tristimulus value \( X \).
  - \( WY(\lambda) \) is the weighting factor at \( \lambda \) for tristimulus value \( Y \).
  - \( WZ(\lambda) \) is the weighting factor at \( \lambda \) for tristimulus value \( Z \).

\[
X = \sum_{400nm}^{700nm} R(\lambda) \times W_X(\lambda)
\]
\[
Y = \sum_{400nm}^{700nm} R(\lambda) \times W_Y(\lambda)
\]
\[
Z = \sum_{400nm}^{700nm} R(\lambda) \times W_Z(\lambda)
\]

XYZ-based TVI (ISO/TS 10128)

- Magenta and black
  \[
  TVI = 100 \left( \frac{Y_p - Y_t}{Y_p - Y_s} \right) - TV_{Input}
  \]

- Yellow
  \[
  TVI = 100 \left( \frac{Z_p - Z_t}{Z_p - Z_s} \right) - TV_{Input}
  \]

- Cyan
  \[
  TVI = 100 \left[ \frac{X_p - 0.55Z_p}{X_p - 0.55Z_s} - (X_t - 0.55Z_t) \right] - TV_{Input}
  \]

Subscripts:
- p: paper
- t: tint
- s: solid
Measuring Tristimulus Values

- **Spectro-colorimeter**
  - Computationally derived with spectral data
  - ANSI CGATS.5 - 1993
  - Suitable for critical color communication

- **Filter-colorimeter**
  - Derived by means of optical integration with the light-filter-detector combination
  - Spectral data are not used

Color Space Models

- **CIE Chromaticity coordinates, Yxy**
  - Y is the lightness of the color
  - x represents fractional redness
  - y represents fractional greenness
  - z or (1-x-y) is the fractional blueness

\[
\begin{align*}
  x &= \frac{X}{X + Y + Z} \\
  y &= \frac{Y}{X + Y + Z}
\end{align*}
\]
Chromaticity Diagram

- Spectrum colors form a horse shoe shaped locus.
  - Dominant wavelength
  - Purity

CIE Color Naming

- Different wavelength region represents color names of different hues.
Color Gamut Comparison

- A printer’s CMYK color gamut is different from a monitor’s RGB color gamut.

Uniform Color Space

- MacAdam ellipses
  - Equal visual difference should be plotted with equal distance.
    - Chromaticity diagram
    - did not do well.
1976 CIELAB Color Space

- Opponent color theory
  - L* is lightness
  - a* is redness or greenness
    - Redness (if a* is positive)
    - Greenness (if a* is negative)
  - b* is yellowness or blueness
    - Yellowness (if b* is positive)
    - Blueness (if b* is negative)

XYZ-to-Lab Formulas

- ISO 13655
  \[L^* = 116\left(f\left(Y/Y_n\right) - 16\right)\]
  \[a^* = 500\left(f\left(X/X_n\right) - f\left(Y/Y_n\right)\right)\]
  \[b^* = 200\left(f\left(Y/Y_n\right) - f\left(Z/Z_n\right)\right)\]

X, Y, Z are the tristimulus values
Xn, Yn, Zn are the white point
**Process Inks**

- Real inks have incomplete reflection and absorption.
  - CIELAB is used to specify the ink color.
  - Sample preparation
  - Measurement conditions

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<th>CIELAB (D50/2)</th>
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<td>Black</td>
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**CIE LCh Color Space**

- The vector equivalent of the CIELAB color space
  - Metric chroma
    \[ C^* = \sqrt{a^*2 + b^*2} \]
  - Hue angle
    \[ h = \tan^{-1}\left(\frac{b^*}{a^*}\right) \]
Hue Angle Calculations

- Given a* (cell D17) and b* (cell E17)
  - Hue angle in radian (cell H17)
    - If(ATAN2(D17, E17)>=0, ATAN2(D17, E17), 2*PI()+ATAN2(D17, E17))
  - Hue angle in degrees=DEGREES(H17)

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<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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Munsell Color Space

- Based on visual judgment
  - Hue
  - Value
  - Chroma

Notation: 5R 5/10
Device Dependent Color

- Computer graphics color space
  - RGB
- Designers color space
  - Swatchbook
- Printer color space
  - CMYK

Device Independent Color

- Act as a reference color (profile connection) space in color management systems
Color Matching

- **Invariant (or spectral) match**
  - When two colors have the same spectrophotometric curves (SPC), they will have the same tristimulus values.
  - Their match is invariant
  - If $(\text{SPC})_1 = (\text{SPC})_2$, then $(\text{XYZ})_1 = (\text{XYZ})_2$

- **Metameric (conditional) match**
  - When two colors have different spectrophotometric curves, but have the same tristimulus values
  - The color match is conditional.
  - The two objects are metamer.
  - $(\text{XYZ})_1 = (\text{XYZ})_2$, but $(\text{SPC})_1 \neq (\text{SPC})_2$
Color Difference

• For any two colors,
  - C1: L_1^*, a_1^*, b_1^*
  - C2: L_2^*, a_2^*, b_2^*
  - \( \Delta E \) is the total color difference
    \[
    \Delta E = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}
    \]

\( \Delta E \) is the abbreviation for ‘Empfindung’ in German, i.e., sensation.

Color Difference

• \( \Delta L^* \), \( \Delta a^* \) and \( \Delta b^* \) expressed as human visual sensation
  - Between a sample and a reference
  - (sample-reference)

<table>
<thead>
<tr>
<th>When</th>
<th>The Sample is</th>
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<tr>
<td>( \Delta L^* ) is ‘+’</td>
<td>Lighter</td>
</tr>
<tr>
<td>( \Delta L^* ) is ‘-’</td>
<td>Darker</td>
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<tr>
<td>( \Delta a^* ) is ‘+’</td>
<td>Redder or less green</td>
</tr>
<tr>
<td>( \Delta a^* ) is ‘-’</td>
<td>Less red or greener</td>
</tr>
<tr>
<td>( \Delta b^* ) is ‘+’</td>
<td>Yellower or less bluer</td>
</tr>
<tr>
<td>( \Delta b^* ) is ‘-’</td>
<td>Less yellow or blue</td>
</tr>
</tbody>
</table>
Spot colors and trademark colors need to be matched closely.
- Small color difference is allowed

<table>
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<tr>
<th>ΔE</th>
<th>Perception</th>
<th>Interpretation</th>
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<tr>
<td>&lt; 1</td>
<td>No difference</td>
<td>Excellent match</td>
</tr>
<tr>
<td>1~2</td>
<td>Just noticeable</td>
<td>Good match</td>
</tr>
<tr>
<td>4~6</td>
<td>Noticeable</td>
<td>Fair match</td>
</tr>
<tr>
<td>&gt; 9</td>
<td>Strong difference</td>
<td>Poor match</td>
</tr>
</tbody>
</table>

- ΔE Magnitude, Perceptibility, and Acceptability

Acceptability
- Instrument error
- Ink verification

Perceptibility
- No difference
- Just noticeable
- Noticeable
- Strong difference

As interpreted as a simple field
Color Tolerance as a Volume

- Three color tolerancing models
  - $\Delta L^*$, $\Delta a^*$, and $\Delta b^*$ form a rectangular box.
  - $\Delta L^*$, $\Delta C^*$, and $\Delta hab^*$ form a wedge.
  - CMC takes on an ellipsoidal-shaped volume.

CMC Tolerancing

- The eye is better at detecting hue differences in the orange than in the green.
- The eye is more sensitive to low chroma difference than high chroma difference.
- The eye has greater acceptance for shifts in the lightness ($L$) than in the chromaticity ($C$) dimension.
Summary

- Color is a visual sensation.
  - Light, object, and human vision are involved.

- Tristimulus integration is the basis for color measurement.
  - CIELAB color space is the language for color specifications.

- Color matching is possible between metamers.
  - Color difference is useful for determining acceptability.

Colorimetry Application

- Material specifications
  - How inks are specified and compared

- Process characterization
  - How color gamut, color variations, and RGB-to-CMYK conversion are specified

- Color matching and image reproduction
  - \( \Delta E \) matters to color matching.
  - \( \Delta E \) does not matter to pleasing pictorial color image reproduction.
Material Specifications

- Colorimetric properties of halftone tints
  - Cyan screen tints

- Colorimetric differences
  - Rubine ink & rhodamine ink

- Colorimetric specifications
  - Standardized printing inks for offset lithography
    - ISO 2846

Colorimetric Properties

- Cyan halftone tints
  - Four levels of dot area coverage
    - 25%, 50%, 75%, & solid

  - Their SPCs are non-crossing
  - The wavelength of the max. absorption is at 630 nm
    - The SPC of the solid patch is situated in the bottom.
Colorimetric Properties

- Cyan halftone tints
  - Tints have similar hue angle in the a* b* diagram as the solid, but differ in metric chroma (C*)
  - When solid IFT increases, hue shift may result – the mass tone effect.

Colorimetric Differences

- Two magenta inks
  - Rubine is a reddish magenta ink.
    - Cost cheaper
  - Rhodamine a bluish magenta ink.
    - More expensive
Colorimetric Differences

- **Rubine & rhodamine**
  - Spectral reflectance in the blue region of SPC
  - Hue angle of the $a^* b^*$ diagram

```
% Reflectance

Wavelength (nm)

400 450 500 550 600 650 700

Rubine   Rhodamine

(Yellowish)

(Bluish)
```

Colorimetric Specifications

- **ISO 2846**—Standardized printing inks for offset lithography
  - C, M, Y, K
  - A single set of color coordinates could adequately represent standard inks around the world.
    - Endorsed by ink associations from Europe, America, and Japan

- Sample preparation
  - Should be made on the reference substrate
    - APCO II/II
  - The nominal ink film thickness for web heat-set ink is 1 mm.
    - 0.7-1.3 mm for cyan, magenta, and yellow
    - 0.9-1.3 mm for black

- Example of conformance
  - Ink 1

- Example of non-conformance
  - Ink 2—Deviation of ink color
  - Ink 3—correct in ink color, not in pigment concentration

Process Characterization

- Color gamut comparison
  - Monitor color gamut
  - Printer color gamut

- Color variations
  - Spatial uniformity within the sheet
  - Temporal consistency from sheet-to-sheet
  - XYZ-based TVI assessment
Monitor Color gamut

- Ambient lighting influences monitor color gamut.

Monitor Color Gamut

- Ambient lighting also influences lightness range of the monitor.
  - High ambient lighting
    - Adds flare in the black point
    - Reduces lightness range

Hard copy has brighter white point
Printer Color Gamut

- Chromaticity / a*b* diagram can be deceiving.
  - Expressed in two dimensions without lightness

Printer Color Gamut Slice

- Chromaticity at constant lightness plane requires special test targets.
Color Variation Rules

- All imaging processes have color variations.
  - Some processes have more variations than other processes.

Sources of variability

- Uniformity within the sheet
- Sheet-to-sheet
- Run-to-run

Assignable variations can be corrected for; random variations cannot.

Uniformity within the Sheet

Spot color by flexo (30 measurements across)
### Consistency from Sheet-to-sheet

#### Spot color by flexo (30 consecutive sheets)

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<thead>
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<th>Sample</th>
<th>72_Brown</th>
<th>Sample</th>
<th>75_Red</th>
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<td>a*</td>
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#### XYZ-based TVI (ISO/TS 10128)

- **Magenta and black**
  \[
  TVI = 100 \left( \frac{Y_p - Y_s}{Y_p - Y_s} \right) - TV_{Input}
  \]

- **Yellow**
  \[
  TVI = 100 \left( \frac{Z_p - Z_s}{Z_p - Z_s} \right) - TV_{Input}
  \]

- **Cyan**
  \[
  TVI = 100 \left[ \frac{(X_s - 0.55Z_s) - (X_s - 0.55Z_s)}{(X_s - 0.55Z_s) - (X_s - 0.55Z_s)} \right] - TV_{Input}
  \]

**Subscripts**
- \(p\): paper
- \(t\): tint
- \(s\): solid
Color Matching

- Spot color printing vs. CMYK printing
  - Avoid out-of-gamut color
  - Small $\Delta E$ matters

Pantone swatchbook is printed by dry offset using special formulated inks.

Pantone-to-digital printing uses a RIP-based look-up table.

Pictorial Color Image

- Pleasingness of the reproduction matters.
  - Minimum $\Delta E$ is not important
    - Particularly when $\Delta E$ is due to gamut clipping
### Color Image Reproduction

- **Color Research & Appl. (Pearson, 1986)**
  - Large $\Delta Es$ exist between the original and a very acceptable photographic print
  - Tone reproduction and gamut compression are key factors for pleasing reproduction

<table>
<thead>
<tr>
<th>statistics</th>
<th>All patches in Macbeth colorchecker</th>
<th>Std. Observer from 1931 to 1964</th>
<th>Geometry 0/45 to sphere</th>
<th>color temp. difference by 4000K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>15.9</td>
<td>1.4</td>
<td>3.2</td>
<td>3.1</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>6.8</td>
<td>1.6</td>
<td>3.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Min.</td>
<td>4.4</td>
<td>0</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Max.</td>
<td>31.7</td>
<td>4.7</td>
<td>12.3</td>
<td>8.4</td>
</tr>
<tr>
<td>Range</td>
<td>27.3</td>
<td>4.7</td>
<td>12.1</td>
<td>7.9</td>
</tr>
</tbody>
</table>

### Summary

<table>
<thead>
<tr>
<th></th>
<th>Densitometer</th>
<th>Spectro-colorimeter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>density</td>
<td>XYZ, Yxy, CIELAB</td>
</tr>
<tr>
<td>Difference (Single number)</td>
<td>none</td>
<td>$\Delta E$</td>
</tr>
<tr>
<td>Spectral response</td>
<td>match to peak absorption of process inks</td>
<td>match the 1931 CIE standard observer</td>
</tr>
<tr>
<td>Geometry</td>
<td>0/45</td>
<td>0/45, integrating</td>
</tr>
<tr>
<td>Color perception</td>
<td>anomalous trichromat</td>
<td>color-normal observer</td>
</tr>
<tr>
<td>Dark shade discrim.</td>
<td>good</td>
<td>okay</td>
</tr>
<tr>
<td>Light shade discrim.</td>
<td>poor</td>
<td>good</td>
</tr>
<tr>
<td>Standardization</td>
<td>ANSI status T</td>
<td>CIE</td>
</tr>
<tr>
<td>Applications</td>
<td>process control for CMYK printing only</td>
<td>color specification process control quality assurance</td>
</tr>
</tbody>
</table>
Summary

- Colorimetry has multiple uses in graphic arts imaging practices.
  - Ink specifications and standardization
  - Process characterization and standardization
  - Spot color matching

- Colorimetry cannot judge pleasingness of pictorial color images.
  - Only the human color perception can