https://www.smpte.org/sections/united-kingdom
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What We’re Going to Cover

- Fundamentals of Colour Science
  - Imaging Systems
  - Colour Spaces
- Motivation and Derivation of IC\textsubscript{T}C\textsubscript{P}
- Colour Differences and $\Delta E_{\text{ITP}}$
DEMO

Universe
Fundamentals of an “Imaging System”

- Light Source
- Reflecting/Transmitting surface
- Imaging Device
Light Source
Reflecting Object
Imaging “Device”
Same Color: Metamerism

$XYZ = XYZ$
\[ X = k \int \bar{x} \ast SPD \]
\[ Y = k \int \bar{y} \ast SPD \]
\[ Z = k \int \bar{z} \ast SPD \]
Chromaticity Coordinates

Tristimulus (3D)

\[ X = k \int \bar{x} \cdot SPD \]
\[ Y = k \int \bar{y} \cdot SPD \]
\[ Z = k \int \bar{z} \cdot SPD \]

Chromaticity (2D)

Top Down View

\[ x = \frac{X}{X + Y + Z} \]
\[ y = \frac{Y}{X + Y + Z} \]
Colour Gamuts

Colour gamuts are defined with xy chromaticity coordinates for red, green, blue and white:

- ITU-R BT.709
- ITU-R BT.2020
- DCI-P3
- ITU-R BT.2100
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Colour Volumes

Colour volumes are defined based on colors and luminance level:

- ITU-R BT.709
- ITU-R BT.2020
- DCI-P3
- ITU-R BT.2100
DEMO

Gamut
Chroma Subsampling

Simple way of reducing the amount of information you need to send.

- 4:4:4
- 4:2:2
- 4:2:0
DEMO

Subsampling
What Makes HDR/WCG More Challenging?

- Small errors in SDR are now exaggerated
  - Design decisions
- Closer to visual threshold
  - Less bits per color step
Chroma Subsampling

Start with 10 bit BT.2020 RGB Image

Subsample 4:2:0 10 bits
Chroma Subsampling

Start with 10 bit BT.2020 RGB Image

Subsample 4:2:0 10 bits

- Crosstalk with chroma and luminance
The Design of ICₜCₚ
Start with the Human Visual System

Cone Response

Transduction

Color Opponency

Intensity

Tritan Axis

Protan Axis
Use $Y' C'_B C'_R$ Operations
Optimize for constant luminance, hue linearity, and uniformity
Constant Luminance

$IC_{T}C_{P}$

$Y'C_{B}C_{R}$
Hue Linearity

$Y' C_B C_R$

$I_C T C_P$

$\max |\text{Hue Deviation}| = 23.16$ degrees

$\max |\text{Hue Deviation}| = 8.05$ degrees

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Uniformity
Uniformity

$IC_T C_P$

$YC_B C_R$

$C_P$

$C_T$

$C_R$

$C_B$
Practical Benefits of $IC_T C_P$
Chroma Subsampling

Start with 10 bit BT.2020 RGB Image

Subsample 4:2:0 10 bits
Chroma Subsampling

Start with 10 bit BT.2020 RGB Image

Subsample 4:2:0 10 bits

- Crosstalk with chroma and luminance
Chroma Subsampling

Start with 10 bit BT.2020 RGB Image

Subsample 4:2:0 10 bits

- Decorrelated chroma and luminance
Chroma Subsampling 4:2:0

Original

$IC_T C_P 4:2:0$

$YC_B C_R 4:2:0$
Chroma Subsampling 4:2:0

Original

$\text{IC}_{\text{T}} \text{C}_p$ 4:2:0

$\text{YC}_B \text{C}_R$ 4:2:0
Chroma Subsampling 4:2:0

Original  ICₜCₚ 4:2:0  YCₜCᵣ 4:2:0
Quality of Resizing in $Y'C_B'C_R$?
Quality of Resizing in IC_{T\text{C}_P} ?

Up-Scaled IC_{T\text{C}_P} Image

↑ Red Edge

Blue Edge ↑
Uniformity: Colour Differences
Colour Differences

• Measuring colour differences allows us to make imaging systems more efficient
• We want to allocate space to where it counts in the HVS
• It is possible to have a CV difference of 10 and not see a difference, or a CV difference of 1 and see a difference.
How Do We Measure Colour Differences?

\[
\begin{align*}
X &= k \int \bar{x} \cdot SPD \\
Y &= k \int \bar{y} \cdot SPD \\
Z &= k \int \bar{z} \cdot SPD
\end{align*}
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How Do We Measure Colour Differences?

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XYZ reference

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\]

XYZ measured
Colour Difference Metrics

- PSNR
- DeltaE_2000 (CIE)
- DeltaE_ITP (ITU BT.2124)

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XYZ reference

XYZ measured
Colour Differences Metrics

A colour difference metric should match human vision

Subjective

AGREE

Colour Difference Metric
Colour Differences Metrics

If a colour difference metric does NOT match human vision

a) Inaccuracy

Value is too small
Colour Differences Metrics

If a colour difference metric does NOT match human vision

a) Inaccuracy

Value is too small

b) Inefficiency

Value is too large
DEMO

Adaptation
Colour Difference Metrics: $\Delta E_{00}$

Based on CIE $L^*a^*b^*$ colour space

Accounts for adaptation

Common practice is to use:
- $100\text{cd/m}^2$ D65

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{K_C S_C}\right) \left(\frac{\Delta H'}{K_H S_H}\right)}$$

$$\Delta L' = L'_1 - L'_2$$

$$L = \frac{L'_1 + L'_2}{2}$$

$$\Delta E_{00} = \frac{C'_1 + C'_2}{2}$$

$$a'_1 = a'_1 + \frac{a'_2}{2} \left(1 - \sqrt{\frac{C'}{C^2 + 25}}\right)$$

$$a'_2 = a'_2 + \frac{a'_1}{2} \left(1 - \sqrt{\frac{C'}{C^2 + 25}}\right)$$

$$\Delta E' = \Delta E_{00}$$

$$L' = \frac{L'_1 + L'_2}{2}$$

$$a'_1 = a'_1 + \frac{a'_2}{2} \left(1 - \sqrt{\frac{C'}{C^2 + 25}}\right)$$

$$a'_2 = a'_2 + \frac{a'_1}{2} \left(1 - \sqrt{\frac{C'}{C^2 + 25}}\right)$$

$$\Delta E' = \frac{C'_1 + C'_2}{2}$$

$$h'_1 = \text{atan}2(b'_1, a'_1) \mod 360^\circ$$

$$h'_2 = \text{atan}2(b'_2, a'_2) \mod 360^\circ$$

$$\Delta H' = \begin{cases} 
    |h'_2 - h'_1| & |h'_2 - h'_1| \leq 180^\circ \\
    h'_2 - h'_1 + 360^\circ & |h'_2 - h'_1| > 180^\circ, h'_2 \leq h'_1 \\
    h'_2 - h'_1 - 360^\circ & |h'_2 - h'_1| > 180^\circ, h'_2 > h'_1
\end{cases}$$

$$\Delta H' = 2 \sqrt{C'_1 C'_2 \sin(\Delta H'/2)}$$

$$\tilde{H}' = \begin{cases} 
    (h'_2 + h'_1)/2 & |h'_2 - h'_1| \leq 180^\circ \\
    (h'_2 + h'_1 + 360^\circ)/2 & |h'_2 - h'_1| > 180^\circ, h'_2 + h'_1 < 360^\circ \\
    (h'_2 + h'_1 - 360^\circ)/2 & |h'_2 - h'_1| > 180^\circ, h'_2 + h'_1 > 360^\circ
\end{cases}$$

$$T = 1 - 0.17 \cos(\tilde{H}' - 30^\circ) + 0.24 \cos(2 \tilde{H}') + 0.32 \cos(3 \tilde{H}' + 60^\circ) - 0.20 \cos(4 \tilde{H}' - 63^\circ)$$

$$S_L = 1 + \frac{0.015 (L - 50)^2}{\sqrt{20 + (L - 50)^2}}$$

$$S_C = 1 + 0.045 C'^2$$

$$S_H = 1 + 0.015 C'T$$

$$R_T = -2 \sqrt{\frac{C'}{C^2 + 25}} \sin \left(60^\circ \cdot \exp \left(-\left(\frac{\tilde{H}' - 275}{25}\right)^2\right)\right)$$
Colour Difference Metrics: $\Delta E_{ITP}$

Based on $IC_T C_P$ colour space

Gives value under “highest sensitivity” scenario

A $\Delta E_{ITP}$ of 1 is a “just noticeable difference”

\[
\Delta E_{ITP} = 720\sqrt{(I_1 - I_2)^2 + 0.25 * (C_{T1} - C_{T2})^2 + (C_{P1} - C_{P2})^2}
\]
Colour Difference Metrics: $\Delta E_{ITP}$

Based on IC$_T$C$_P$ colour space

Gives value under “highest sensitivity” scenario

A $\Delta E_{ITP}$ of 1 is a “just noticeable difference”

$$\Delta E_{ITP} = 720\sqrt{(I_1 - I_2)^2 + 0.25 \times (C_{T1} - C_{T2})^2 + (C_{P1} - C_{P2})^2}$$

ITU-R BT.2124:

\begin{align*}
T &= C_T/2 \\
P &= C_P \\
\Delta E_{ITP} &= 720\sqrt{(I_1 - I_2)^2 + (T_1 - T_2)^2 + (P_1 - P_2)^2}
\end{align*}
Colour Difference Data Set

✓ Correct
Colour Differences Metrics

Adaptation Luminance Levels and Colors/Directions Tested

Test Color

Ref. Color

0.0039

0.016

0.063

0.25

1

4

16

64

Colour Differences

0.0009

0.0016

0.0025

0.004

0.008

0.016

0.032

0.064

0.128

0.256

1

2

4

8

16

32

64

128

256

512

2

4

8

16

32

64

128

256

512

2

4

8

16

32

64

128

256

512
Colour Differences Metrics

Adaptation Luminance Levels and Colors/Direcions Tested

PSNR Prediction
Colour Differences Metrics
Colour Differences Metrics

<table>
<thead>
<tr>
<th>Test Color</th>
<th>Ref. Color</th>
<th>Color Difference</th>
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<tbody>
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<td>0.016</td>
<td>0.0063</td>
</tr>
<tr>
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<td>0.0039</td>
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<tr>
<td>4</td>
<td>16</td>
<td>0.016</td>
</tr>
<tr>
<td>64</td>
<td>256</td>
<td>0.0039</td>
</tr>
</tbody>
</table>

Adaptation Luminance Levels and Colors/Directions Tested

PSNR Prediction

\( \Delta E \) Prediction

\( \Delta E \) Precinct
Wrap Up

• Fundamentals of colour science
• Seen how $I_{C_T}C_p$ was motivated and derived
• Artifacts can be avoided in chroma subsampling
• Hue remains constant during resizing
• $\Delta E_{ILT}$ is a useful measure of perceptual colour differences