Color fidelity and Color spaces

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What is a color?

• physical description: wavelengths
• psychological perception: stimulus
• computer description:
  – different sets of basis and coordinates
  – dithering/halftoning
• color correction:
  – ensure that perceived colors are correct
Map of the lecture

• Physical and biological description of colors:
  – wavelength, CIE color space…

• Computer description of colors:
  – color spaces: RGB, CMYK, HSV,…
  – color fidelity
  – gamma correction
  – halftoning and dithering
Physical and Biological

- wavelengths/spectrum
- hues, tints, shades, saturation, brightness
- cones on the retina, perception
- display independant description:
  - Commission Internationale de l’Éclairage
Computer description

- Display based color-spaces: RGB, CMYK, YIQ, YCbCr...
- Perception based color-spaces: HSV
- Color correction:
  - gamma correction
- Conversion between these color descriptions
Spectral Distribution

- One color = one spectral distribution

![Graph showing spectral distribution with peaks at 400 nm (Violet) and 760 nm (Red)]
"Pure" colors, shades and hues

- Initially: artist perception

![Diagram showing the relationships between brightness, saturation, white, tints, tones, grays, and shades.](image)

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Colors, shades and hues (2)

• Physical definition:
  – Hue = dominant wavelength
  – Saturation = excitation purity
  – Luminance, brightness: amount of light
  – Pure color: one single wavelength
Hue, Saturation and Brightness

Energy $P(\lambda)$

Saturation

Dominant wavelength

Brightness = area under the curve

400 nm Violet

Hue

760 nm Red

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Retina Response

• Three types of cones on the retina:

- Violet: 400 nm
- Green: 540 nm
- Red: 760 nm

Light absorbed $L(\lambda)$

400 nm Violet

760 nm Red

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Retina Luminous Efficiency

Sensitivity $S(\lambda)$

- 400 nm Violet
- Yellow-Green 550 nm
- 760 nm Red

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Color Definition

• Define a color by its spectral distribution:
  – memory requirements…
  – non unicity (see next slide)

• Need for simpler bases:
  – describing all colors
  – with a unique set of coordinates
Non Unicity

Same orange-like color

Energy $P(\lambda)$ vs wavelength $\lambda$

400 nm Violet to 760 nm Red
Using Primary Colors

• Use the three primary colors:
  – Red, Green and Blue

• Describe all colors as a linear combination of red, green and blue
  – three coordinates by color

• Simple model, but...
Using Primary Colors (2)

Values $V(\lambda)$

400 nm Violet

760 nm Red
Commission Internationale de l’Éclairage

• CIÉ: 1931
• Three standard primary functions:
  – X, Y, Z
  – defines all visible colors
  – with only positive coefficients
• Y = retina luminance perception
• x and y = chromaticity
CIÉ Base Functions

Values $V(\lambda)$

400 nm Violet

760 nm Red

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CIÉ Chromaticity Diagram

All visible colors

- Green
- Red
- Purple
- Yellow
- Cyan
CIÉ Chromaticity Diagram (2)
CIÉ Chromaticity Diagram (3)

Mixing colors

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CIÉ Chromaticity Diagram (4)

Displayable colors

Color Film

RGB Color display
Beyond CIÉ 1931...

- Distance in chromaticity diagram:
  - not linked to perceptual distance
- CIÉ 1976: perceptually uniform
- LUV:
  - L for lightness
  - U and V for chromaticity
- L*a*b: perceptually uniform and orthogonal
Colors in computer graphics

• How to specify a color?
  – set of coordinates in a color space

• Several “Color spaces”

• Color fidelity?
  – why is my orange blue?

• Relation to the task/perception
  – blue for hot water
Color spaces

• Device based color spaces:
  – color spaces based on the internal of the device: RGB, CMYK, YCbCr

• Perception based color spaces:
  – color spaces made for interaction: HSV

• Conversion between them?
• Conversion to device independant?
Red-Green-Blue

- Most commonly known color space
  - used (internally) in every monitor
  - additive
Cyan-Magenta-Yellow

- Used internally in color printers
- Subtractive
- Complementary to RGB:
  - $C = 1 - R$
  - $M = 1 - G$
  - $Y = 1 - B$
- Also CMYK (black)
  - mostly for printer use
CMYK

- K is for blacK
- Save on color inks, by using black ink preferably
- $K = \min(C,M,Y)$
- $C = C - K$
- $M = M - K$
- $Y = Y - K$
The RGB/CMY cube
The RGB/CMY cube
“Class Y” Color space

• YIQ, YUV, YcbCr…

• Used in television sets and videos
  – Y is luminance
  – I and Q is chromaticity

• BW television sets display only Y

• Color TV sets convert to RGB

• YUV=PAL, YIQ=NTSC
YCbCr Color Spaces

• Y must be equal to luminance:
  \[ Y = \text{LumaRed} \times R + \text{LumaGreen} \times G + \text{LumaBlue} \times B \]

• Cb is blue chromaticity:
  \[ Cb = (B-Y)/(2-2\times\text{LumaBlue}) \]

• Cr is red chromaticity:
  \[ Cr = (R-Y)/(2-2\times\text{LumaRed}) \]

• \text{LumaRed, LumaGreen, LumaBlue} values given by measurements
Class Y values

• Values depend on standard:
  – CCIR 601: \( L_r=0.299, L_g=0.587, L_b=0.114 \)
  – CCIR 709: \( L_r=0.2125, L_g=0.7154, L_b=0.0721 \)

• YIQ color space:
  \[
  \begin{bmatrix}
  Y \\
  I \\
  Q \\
  \end{bmatrix}
  =
  \begin{bmatrix}
  0.299 & 0.587 & 0.114 \\
  0.596 & -0.275 & -0.321 \\
  0.212 & -0.528 & 0.311 \\
  \end{bmatrix}
  \begin{bmatrix}
  R \\
  G \\
  B \\
  \end{bmatrix}
  \]
Interests of “Class Y”

• Sometimes you have to use it
  – video input/output

• Makes sense in image compression:
  – better compression ratio if changing class Y before compression
  – High bandwidth for Y
  – Small bandwidth for chromaticity
  – Lab is fine for that too
Hue-Saturation-Value

• Nice for user interface:
Hue-Saturation-Value

- \( V = \max(r, g, b) \)
- \( S = (\max - \min) / \max \)
- \( H = \ldots \)

- Excellent for interpolations
- Color effects for visualization:
  - change saturation, at constant hue
  - change hue, at constant saturation (maps)
The HSV cone
The HSV cone
Color Fidelity

• Problem: ensure that colors look the same when changing device
• Sample the RGB phosphors
• Convert to XYZ:

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = 
\begin{bmatrix}
Xr & Xg & Xb \\
Yr & Yg & Yb \\
Zr & Zg & Zb
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]
Color Fidelity (2)

- Device description available from manufacturers
- Extract $X_r, X_g, X_b, \ldots$
- For other devices: multi-dimensional lookup-tables
- Convert to and from device independant
Intensity Perception

- Human perception is logarithmic
- Cause for Mach-Banding
- Perceptual “just noticeable differences”

$$I(j) \propto r^j$$
Gamma Correction

• Human perception is logarithmic:
  \[ I(j) \propto r^j \]

• CRT intensity related to voltage:
  \[ I \propto V^\gamma \]

• Need correction for both:
  \[ V = (kr^j)^{1/\gamma} \]
Gamma Correction

• Hardware in Graphics Workstations:
  – Silicon Graphics, HP, some monitors
  – graphics accelerators
• Extremely useful if well used
• Can lead to strange effects if forgotten
  – transfer of a picture between monitors with different gamma values = oups!
Displaying colors

- Color ability of the display
  - measured in bits:
    - 1 bit=2 levels, 8 bits=256 levels
  - bits per color primitive:
    - 24 bits=256 levels for each of R,G,B
- Depends on the medium:
  - TV Screen: 30 dpi, 8bits color
  - Computer Screen: 70-100 dpi, 24 bits color
  - Laser Printer: 300-2400 dpi, 3 bits color (8 colors)
  - Photo: 800 dpi, 36 bits color
Gaining color resolution

• Sometimes, this color resolution is not enough
• How to display more colors?
• Basic idea: sacrifice some of the spatial resolution
  – halftoning and dithering
Gaining color resolution

• For top-quality printers:
  – discs of size varying inversely with $I$
  – pattern angle (called *screen angle*)
  – halftone resolution (different from spatial resolution)
    • 60-80 dpi for newspapers, 120-200 for books

• Called “Halftoning”
Simulating halftoning

• If you don’t have halftoning
  – wrong printer, or computer screen

• Use dither patterns
  – groups of $n \times n$ pixels = $n \times n + 1$ intensity levels
Simulating Halftoning (2)

• Example for 2x2:

```
0 1 2 3 4
0 2
3 1
```

• Matrix notation:

```
[0 2]
[3 1]
```
Matrix notation

- For level $i$, display pixels with $v<i$
- Requirement on matrix depend on device:
  - dispersed dots for CRT
  - clustered dots for printers

$$\begin{bmatrix}
6 & 8 & 4 \\
1 & 0 & 3 \\
5 & 2 & 7
\end{bmatrix}$$  

$$\begin{bmatrix}
0 & 8 & 2 & 10 \\
12 & 4 & 14 & 6 \\
3 & 11 & 1 & 9 \\
15 & 7 & 13 & 5
\end{bmatrix}$$
Halftoning: the next step

• One image pixel = 4 or 9 printer pixels
• What if I want one image pixel = one printer pixel?
• Use modulo:
  – i = x modulo n
  – j = y modulo n
  – Lit the pixel if point (i, j) in dithering matrix is smaller than I(x, y)
Halftoning, the next step (2)

- There is an error at each pixel
- Dithering pattern is sometimes visible
- Floyd-Steinberg: spread the error to neighbouring pixels
Conclusion

• Several ways to represent colors
• Each one fitted for a special task
• Easy conversion between them
• Conversion is often required:
  – for color fidelity:
    • convert to CIE, and back to device-space
  – for showing the image