The Electromagnetic Spectrum

- Visible light spectrum has wavelength form 350nm to 750nm.
Color Image Formation

- Light source ($\lambda$: wavelength of the source)
  - $E(x, y, z, \lambda)$: incident light on a point ($x, y, z$ world coordinates of the point)
- Each point of the scene has a reflectivity function.
  - $r(x, y, z, \lambda)$: reflectivity function
- Light reflects from a point and the reflected light is captured by an imaging device.
  - $c(x, y, z, \lambda) = E(x, y, z, \lambda) \cdot r(x, y, z, \lambda)$: reflected light.

![Image of light source and reflectivity]

Light Sources

- Illuminating sources:
  - emit light (e.g. the sun, light bulb, TV monitors)
  - perceived color depends on the emitted frequency
- Reflecting sources:
  - reflect an incoming light (e.g. the color dye, matte surface, cloth)
  - perceived color depends on reflected frequency (=emitted frequency - absorbed frequency)
Color Mixing

- Tri-chromatic color mixing theory
  - Any color can be obtained by mixing three primary colors with a right proportion
- Primary colors for illuminating sources:
  - Red, Green, Blue (RGB)
  - Color monitor works by exciting red, green, blue phosphors using separate electronic guns
  - follows additive rule: R+G+B=White
- Primary colors for reflecting sources (also known as secondary colors):
  - Cyan, Magenta, Yellow (CMY)
  - Color printer works by using cyan, magenta, yellow and black (CMYK) dyes
  - follows subtractive rule: R+G+B=Black

Light Sources and Color Mixing

- Primary Light
  - Emitting the EM wave (the sun, bulb, etc.)
  - Following the additive law
  - Primary colors
    - Red, Green, Blue
- Secondary Light
  - Reflecting an incident light (dye, object, etc.)
  - Following the subtractive law
  - Primary colors
    - Cyan, Magenta, Yellow
Light Sources and Color Mixing

Magenta = Red + Blue
Cyan = Blue + Green
Yellow = Green + Red

Magenta = White - Green
Cyan = White - Red
Yellow = White - Blue

The Human Eye

- Eye Anatomy
Light Reception in the Retina

- Rods
  - night vision
  - Low acuity
  - Achromatic

- Cones
  - Day vision
  - High acuity
  - Chromatic
  - Three sets
    • 700nm (R), 546nm (G), 435nm (B)

Light Reception in the Retina

- Color sensation
  - Luminance (brightness)
  - Chrominance
    • Hue (color tone)
    • Saturation (color purity)
Color Capture

- Each capture device has its sensitivity function $V(\lambda)$.

\[ \int_{\lambda} V(\lambda) \, d\lambda \]

- The result is an “image function” which determines the amount of reflected light that is captured at the camera coordinates $(x', y')$.

\[ f(x', y') = \int c_p(x', y', \lambda)V(\lambda) \, d\lambda \]

Digital Color Image

- Three components
  - $M = \{R, G, B\}$

\[
\begin{align*}
R &= \begin{bmatrix}
73 & \cdots & 87 \\
\vdots & \ddots & \vdots \\
27 & \cdots & 17
\end{bmatrix},
G &= \begin{bmatrix}
66 & \cdots & 98 \\
\vdots & \ddots & \vdots \\
36 & \cdots & 13
\end{bmatrix},
B &= \begin{bmatrix}
31 & \cdots & 61 \\
\vdots & \ddots & \vdots \\
36 & \cdots & 14
\end{bmatrix}
\end{align*}
\]
Tristimulus Values

- Tristimulus value
  - The amounts of red, green, and blue needed to form any particular color are called the **tristimulus values**, denoted by $X$, $Y$, and $Z$.
  - Trichromatic coefficients
    \[ x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z}. \]
  - Only two chromaticity coefficients are necessary to specify the chrominance of a light:
    \[ x + y + z = 1 \]

Color Representation Models

- Specify three primary or secondary colors
  - Red, Green, Blue.
  - Cyan, Magenta, Yellow.
- Specify the luminance and chrominance
  - HSB or HSI (Hue, saturation, and brightness or intensity)
  - YIQ (used in NTSC color TV)
  - YCbCr (used in digital color TV)
- Amplitude specification:
  - 8 bits per color component, or 24 bits per pixel
  - Total of 16 million colors
  - A 1kx1k true RGB color requires 3 MB memory
CMY(K) Color Model

- Conversion between RGB and CMY

\[
\begin{bmatrix}
C \\
M \\
Y
\end{bmatrix} = \begin{bmatrix}
1 & -1 & R \\
0 & 1 & G \\
0 & 0 & 1 & B
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 & C \\
0 & 1 & 0 & M \\
0 & 0 & 1 & Y
\end{bmatrix}
\]

- Equal amounts of Cyan, Magenta, and Yellow produce black. In practice, this produce muddy-looking black. To produce true black, a fourth color, black is added, which is CMYK color model.

HSI Color Model

- **Hue** represents dominant color as perceived by an observer. It is an attribute associated with the dominant wavelength.

- **Saturation** refers to the relative purity or the amount of white light mixed with a hue. The pure spectrum colors are fully saturated. Pink and lavender are less saturated.

- **Intensity** reflects the brightness.
HSI Color Space

CIE Color Specification

x axis: red
y axis: green

The point marked with GREEN
x: 25%, y: 62%, z: 13%.
YIQ Color System

- YIQ is defined by the National Television System Committee (NTSC)
  - Y describes the luminance, I and Q describes the chrominance.
  - A more compact representation of the color.
  - YUV plays similar role in PAL and SECAM.
- Conversion between RGB and YIQ

\[
\begin{bmatrix}
Y \\
I \\
Q
\end{bmatrix} =
\begin{bmatrix}
0.299 & 0.587 & 0.114 \\
0.596 & -0.274 & -0.322 \\
0.211 & -0.523 & 0.311
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
= \begin{bmatrix}
1.0 & 0.956 & 0.621 \\
1.0 & -0.272 & -0.649 \\
1.0 & -1.106 & 1.703
\end{bmatrix}
\begin{bmatrix}
Y \\
I \\
Q
\end{bmatrix}
\]

YUV (YCrCb) Domain

- Important properties
  - RGB components are highly correlated
  - HVS perception differs for luminance than for chrominance
- Goal: Convert RGB to a different color space where these properties can be exploited
- 3x3 Linear color-space transformation:
  - \( R \ G \ B \rightarrow Y \ U \ V \)
  - Y: Luminance
  - U & V: Chrominance
Advantages of YUV

Advantages of color space conversion:

- HVS has lower spatial frequency response to U and V than to Y
  - → Reduce sampling density for U and V
- HVS has lower sensitivity to U and V than to Y
  - → Quantize U and V more coarsely

- Reasonable assumption: An RGB image requires 3x bit rate of B&W image (single-color image)
- Key result: RGB image only requires ~1.25x bit rate

Which Color Representation to Use?

- The type of representation depends on the applications at hand.
  - For display or printing, choose primary colors so that more colors can be produced. E.g. RGB for displaying and CMY for printing.
  - For analytical analysis of color differences, the difference in the tristimulus values are linearly related to the chrominance differences. HSI is more suitable.
  - For transmission or storage, choose a less redundant representation, eg. YIQ or YUV
An Example of Color Spaces

Use this if you’re going to process the image in grayscale!

Color Image Display and Printing

- **Display**:  
  - Need three light sources projecting red, green, blue components respectively at every pixel  
  - Analog display: raster scan  
  - Digital display: directly projecting at all pixel locations

- **Printing**:  
  - Need three (or more) color dyes (Cyan, Magenta, Yellow, and Black)  
  - Analog printing  
  - Digital printing  
  - Out of gamut color
Color Display

Input

<table>
<thead>
<tr>
<th></th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>255</td>
<td></td>
</tr>
</tbody>
</table>

Note Gamma correction needed.

Red signal

Green signal

Blue signal

Color Gamut

Each color model has different color range (or gamut). RGB model has a larger gamut than CMY. Therefore, some color that appears on a screen may not be printable and is replaced by the closest color in the CMY gamut.
Color Quantization and Contouring

24 bits -> 8 bits

Adaptive (non-uniform) quantization
(vector quantization)

Uniform quantization
(3 bits for R,G, 2 bits for B)

Pseudo-Color Images (Coloring gray pictures)

• Why?
  – Human eye is more sensitive to changes in the color hue than in brightness.

• How?
  – Use different colors (different in hue) to represent different image features in a monochrome image.
Different Methods for Pseudo Coloring

- **Intensity slicing**: Display different gray levels as different colors
  - Can be useful to visualize medical / scientific / vegetation imagery
    - E.g. if one is interested in features with a certain intensity range or several intensity ranges

- **Frequency slicing**: Decomposing an image into different frequency components and represent them using different colors.

Intensity Slicing

Pixels with gray-scale (intensity) value in the range of \((f_{k+1}, f_k)\) are rendered with color \(C_f\)
Example

(a) Monochrome image of the Picker Thyroid Phantom. (b) Result of density slicing into eight colors. (Courtesy of Dr. J. L. Blankenship, Instrumentation and Controls Division, Oak Ridge National Laboratory.)

Another Example

(a) Gray-scale image in which intensity (in the lighter horizontal band shown) corresponds to average monthly rainfall. (b) Colors assigned to intensity values. (c) Color-coded image. (d) Zoom of the South American region. (Courtesy of NASA.)
Pseudo-Color for Multiple Images

- Display multi-sensor images as a single color image
  - Multi-sensor images: e.g. multi-spectral images by satellite

![Diagram](image)

**FIGURE 6.26** A pseudocolor coding approach used when several monochrome images are available.

---

**Example**

Multispectral Images

Pseudo-color Image
Color Image Enhancement

- How should we apply the previous techniques to color images
  - To all three color components (RGB or CMY) separately
  - To the Intensity component only while keeping the Hue and Saturation in the HSI coordinate
  - Can also enhance saturation for more vivid colors
  - Can change individual color components to add certain tone to an image

Color Image Enhancement

- Enhance each primary color component independently using the techniques for monochrome images
  - Will change the color hue of the original image
- Convert the tri-stimulus representation into a luminance / chrominance representation, and enhance the contrast of the luminance component only.
  - Use HSI representation, where I truly reflects the luminance information.
Examples

Examples
Examples

FIGURE 6.37
Histogram equalization (followed by saturation adjustment) in the HSI colorspace.