Digital image

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Image formation

Light is an electromagnetic wave. Its color is characterized by the wavelength content of the light.

\[ \text{L}(x,y;t) = \int \Phi(x,y;t;\lambda) \ E(\lambda) \ d\lambda \]

Monochromatic receptor
Trichromatic receptor

Human vision system
Scotopic vision (monochromatic)
Photopic vision (trichromatic)

Visible spectrum
The retina consists of an array of rods and three kinds of cones.

Rods (scotopic vision) : 100 millions
Cones (photopic vision) : 6 millions

Central vision : space
Peripheric vision : motion
Eye sensitivity

The sensitivity of our receptors is a function of wavelength

Primary colours

<table>
<thead>
<tr>
<th>Colour</th>
<th>Symbol</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>R</td>
<td>575</td>
</tr>
<tr>
<td>Green</td>
<td>G</td>
<td>535</td>
</tr>
<tr>
<td>Blue</td>
<td>B</td>
<td>445</td>
</tr>
</tbody>
</table>
A linear mixing of three colors gives every spectral distribution

Three reference stimuli

<table>
<thead>
<tr>
<th>Color</th>
<th>Symbol</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>R</td>
<td>700</td>
</tr>
<tr>
<td>Green</td>
<td>G</td>
<td>546</td>
</tr>
<tr>
<td>Blue</td>
<td>B</td>
<td>436</td>
</tr>
</tbody>
</table>

\[
R = \int \bar{r}(\lambda) \, d\lambda \\
G = \int \bar{g}(\lambda) \, d\lambda \\
B = \int \bar{b}(\lambda) \, d\lambda
\]
Color matching

Diagram showing color matching setup with light sources, a black partition, and an eye. The diagram includes CIE color matching functions graph with tristimulus values and wavelengths.

R.G.B values at specific wavelengths are also shown.
Color matching

![Color matching diagram](image)

- p1
- p2
- p3
Color system XYZ (C.I.E.)

Y : luminance

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.490</td>
<td>0.310</td>
<td>0.200</td>
</tr>
<tr>
<td>0.177</td>
<td>0.813</td>
<td>0.011</td>
</tr>
<tr>
<td>0</td>
<td>0.010</td>
<td>0.990</td>
</tr>
</tbody>
</table>

White : X=Y=Z
Chromaticity diagram (C.I.E.)

Trichromatic coefficients

Pure colors
Linear mixing
Saturated/Non-saturated

\[
X = \frac{X}{X + Y + Z} \\
y = \frac{Y}{X + Y + Z} \\
z = \frac{Z}{X + Y + Z}
\]

Ανάκτηση συνιστωσών

\[
X = \frac{x}{y} \\
Z = \frac{(1 - x - y)}{y}
\]
RGB color components
sRGB color components

Primary
R₀ : x = 0.64, y = 0.33, z = 0.03
G₀ : x = 0.30, y = 0.60, z = 0.10
B₀ : x = 0.15, y = 0.06, z = 0.79

White : x = 0.3127, y = 0.3290, z = 0.3583
C.I.E. D65

Y = 0.21 R₀ + 0.72 G₀ + 0.07 B₀

R = 1.055 R_L^{(1/2.4)} - 0.055
G = 1.055 G_L^{(1/2.4)} - 0.055
B = 1.055 B_L^{(1/2.4)} - 0.055

\( R_L = ((R + 0.055)/1.055)^{2.4} \)
\( G_L = ((R + 0.055)/1.055)^{2.4} \)
\( B_L = ((R + 0.055)/1.055)^{2.4} \)
Lab color system

\[ L^* = 116 \left( f \left( \frac{Y}{Y_n} \right) \right) - 16 \]

\[ X_n, Y_n, Z_n \]

\[ a^* = 500 \left( f \left( \frac{X}{X_n} \right) - f \left( \frac{Y}{Y_n} \right) \right) \]

\[ b^* = 200 \left( f \left( \frac{Y}{Y_n} \right) - f \left( \frac{Z}{Z_n} \right) \right) \]

\[ \sqrt{(a^*)^2 + (b^*)^2} \]

\[ \arctan\left( \frac{a^*}{b^*} \right) \]

Euclidean distance (just perceived distance 2,3)
HSL color system

\[ H = \cos \left( \frac{1}{3} \left[ \frac{(R - G) + (R - B)}{((R - G)^2 + (R - B)(G - B))^{1/2}} \right] \right) \]

\[ 0^\circ \leq H \leq 180^\circ \]

\[ S = 1 - \frac{3}{(R + G + B)} \left[ \min(R, G, B) \right] \]

\[ I = \frac{1}{3} (R + G + B) \]
YCbCr color system

\[ Y = 0.299 R + 0.587 G + 0.114 B \]
\[ Cb = -0.169 R - 0.331 G + 0.500 B \]
\[ Cr = 0.500 R - 0.419 G - 0.081 B \]

Used in digital video and in standards JPEG and MPEG

Recommendation ITU-R BT.601-4
Color quantization

Color palette
Dominant colors

Uniform quantization (3-3-2)

Popular colors

Median cut algorithm

Vector quantization
Palette

Look-up table

Memory value

Pixel value

Indexed colour

Palette

Alpha table

Spring 2018
Color quantization / color system

RGB, HSI, YIQ, XYZ, Lab, Luv
Median cut algorithm

Color_quantization(Image, n)
{
    For each pixel in Image with color C, map C in RGB space;

    P = {RGB space partition};
    While (n-- > 0) {
        L = Heaviest (P);
        Split L into L1 and L2;
        Remove L from P, and add L1 and L2 instead;
    }

    For all boxes in B do
        assign a representative (color centroid);

    For each pixel in Image do
        map to one of the representatives;
}

Median cut (1/6)

Partition according to the largest deviation
Median cut (2/6)
Median cut (3/6)
Μεσαία τομή (4/6)
Median cut (5/6)
Median cut (6/6)
Vector quantization

Minimization of the mean square quantization error

**k-means algorithm**

**Necessary conditions:**
- Best cluster representative = cluster centroid
- Best partition = minimization of distance to centroid
K-means algorithm
Named colors (Web)
Image digitalization

- **Sampling**
  periodic, rectangular (pixel = picture element)
samples’ density related to image details (ppi)

- **Quantization**
  discrete values, uniform quantization
  (256 values or 8 bits)
Sampling (1/3)

- sampling
- scanning
- sensors
  - electrical signal proportional to the luminance
    - CCD (charge-coupled device)
    - CMOS (complementary metal-oxide semiconductor)
  
- Pixel size
- Digital image size
Sampling (2/3)

Resolution depends on image signal content: more details in the image, more dense are the samples.

Otherwise, sampling results in distortion.

If the maximum resolution is not needed, details are filtered and sampling density is adapted to the desired resolution.

FIGURE 2.22 (a) Image with a low level of detail. (b) Image with a medium level of detail. (c) Image with a relatively large amount of detail. (Image (b) courtesy of the Massachusetts Institute of Technology.)
Sampling (3/3)

72 ppi

300 ppi
Subsampling / resize

[Images of a rose at different resolutions: 32x32, 128x128, 256x256, 512x512, 1024x1024]
Subsampling / reconstruction
Subsampling / reconstruction

128                           64                             32

Bilinear interpolation

Nearest
Data types

Binary images

Gray scale images

Color images

Spring 2018
### Portable PBM / PGM / PPM

<table>
<thead>
<tr>
<th>Format</th>
<th>Type</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBM</td>
<td>binary images</td>
<td>1</td>
</tr>
<tr>
<td>PGM</td>
<td>Gray scale images</td>
<td>8, 16, 1-16</td>
</tr>
<tr>
<td>PPM</td>
<td>Color images</td>
<td>1-16 / component</td>
</tr>
</tbody>
</table>

![Example Images](image1.png)  ![Example Images](image2.png)  ![Example Images](image3.png)
Graphics Interchange Format (GIF)

Images up to 8 bits/pixel
Compression algorithm Lempel-Ziv-Welch
Transparency is possible
Animation is possible
Portable Network Graphics (PNG)

- Grayscale images 1, 2, 4, 8, 16 bits/pixel
- Grayscale images with transparency 16, 32 bits/pixel
- Color images with palette 1, 2, 4, 8 bits/pixel
- True color images 24, 48 bits/pixel
- True color images with transparency 32, 64 bits/pixel

Compression algorithm Lempel-Ziv (1977) and Huffman

Animation is possible (MNG)
Windows bitmap (BMP)

- Grayscale images 1, 4, 8 bits/pixel
- Color images with palette 1, 4, 8 bits/pixel
- True color images 16 (=5+6+5), 24 bits/pixel
- True color images with transparency 32 bits/pixel

Compression option (RLE)
Joint Photographic Experts Group (JPEG)

- Lossless or lossy compression
- Chromatic system YCbCr
- Subsampling of chromatic components

Block → Discrete cosine transform → Quantization → Coding

Quantization according to human visual system
Scanner

Moving optical array CCD
Tri-chromatic (filters RGB)

Optical resolution (ppi)

Scaling

Color depth

Optical character recognition

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 ppi</td>
<td>Display, Web</td>
</tr>
<tr>
<td>100 ppi</td>
<td>Printer 300 dpi</td>
</tr>
<tr>
<td>150 ppi</td>
<td>Printer 600 dpi</td>
</tr>
<tr>
<td>300 ppi</td>
<td>Printer 1200 dpi</td>
</tr>
</tbody>
</table>
Digital camera

CCD or CMOS sensors (RGB)

Typical resolution
1280 x 1024
2048 x 1536
3072 x 2048
3520 x 2344
4256 x 2832
4992 x 3328

Pixel aspect
4:3 ή 3:2

Anti-aliasing filter

Compression JPEG