Chapter 16

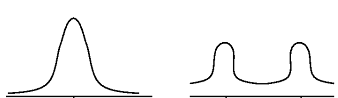
Color Theory

Physical Color

- Visible energy - small portion of the electro-magnetic spectrum
- Pure *monochromatic* colors are found at wavelengths between 380nm (violet) and 780nm (red)

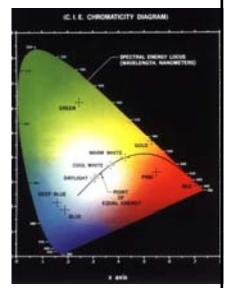
Visible Color

- Eye can perceive other colors as combination of several pure colors
- Most colors may be obtained as combination of small number of *primaries*
- Output devices use this approach



CIE Diagram (1931 & 1976)

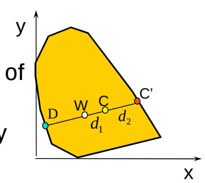
- Universal standard
- Color (ignoring intensity) - affine combination of 3 primaries X, Y, Z
  - 3D vector (x,y,z) s. t. $x+y+z=1$
- Colors inside right-angle unit triangle formed by two of the primaries
- Not all "possible" colors visible
- Visible colors contained in horse-shoe region
- Pure colors (*hues*) located on region boundary



The CIE Diagram (cont'd)

- Color "white" is point W=(1/3,1/3,1/3)
- Any visible color C is blend of hue C' & W
- Purity of color measured by its *saturation*:

$$\text{saturation (C)} = \frac{d_1}{d_1 + d_2}$$



- *Complement* of C is (only) other hue D on line through C' and W

The CIE Diagram (cont'd)

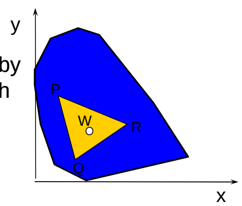
- Color enhancement of image
  - increasing the saturation of the colors
  - moves them towards the boundary of the visible region

unsaturated

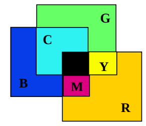
saturated

Color Gamuts

- Most color output devices can not generating all visible colors in CIE diagram
- Possible colors bounded by triangle in XYZ space with vertices P, Q, R
  - Color = barycentric combination of P, Q, R
- This triangle is called the *device gamut*



The RGB Color Model



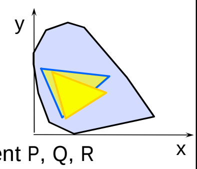
$Col = rR + gG + bB \qquad r, g, b \in [0,1]$

- Yellow= Red+Green (1,1,0)
- Cyan = Green+Blue (0,1,1)
- White = Red+Green+Blue (1,1,1)
- Gray = 0.5 Red+0.5 Blue+0.5 Green(0.5,0.5,0.5)
- Main diagonal of RGB cube represents shades of gray

Color Gamuts (cont'd)

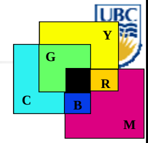
- Example: Primaries of low quality color monitor:

$$\begin{bmatrix} RED \\ GREEN \\ BLUE \end{bmatrix} = \begin{bmatrix} P \\ Q \\ R \end{bmatrix} = \begin{bmatrix} .628 & .346 & .026 \\ .286 & .588 & .144 \\ .150 & .070 & .780 \end{bmatrix}$$



- Different color displays use different P, Q, R
- Same RGB image data, displayed on two monitors will look different !!
- Questions - Given P,Q & R of two color monitors & image I
  - How to make I looks the same on both monitors?
  - Is it always possible?

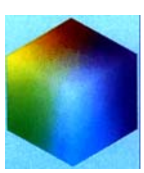
The CMY Color Model

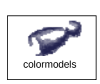


- Used mainly in color printing, where light is absorbed by dyes
- Cyan, Magenta and Yellow primaries are complements of Red, Blue and Green
- Primaries (dyes) subtracted from white paper which absorbs no energy
  - Red = White-Cyan = White-Green-Blue (0,1,1)
  - Green = White-Magenta = White-Red-Blue (1,0,1)
  - Blue = White-Yellow = White-Red-Green (1,1,0)
  - (r,g,b) = (1-c,1-m,1-y)

The RGB Color Model

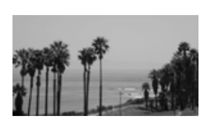
- Common in describing *emissive* color displays
- Red, Green and Blue are primaries in this model
- Color (including intensity) described as combination of primaries





Luminance

- Color "brightness/darkness"
  - Easiest to quantify on greyscale
  - Harder to quantify on full color



- Human eye more sensitive to changes in luminance than to changes in hue or saturation

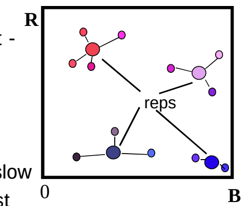
Setting Luminance

- Based on human perception
- Example tool to set luminance value:

Color Quantization Issues

- How representative colors are chosen?
  - Fixed representatives, image independent - fast
  - Image content dependent - slow
- Which image colors are mapped to which representatives?
  - Nearest representative - slow
  - By space partitioning - fast

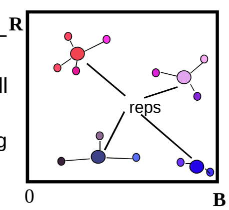
quantization to 4 colors



Color Quantization

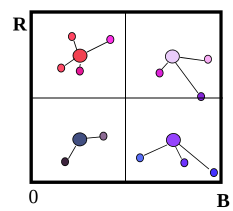
- High-quality color resolution for images - 8 bits per primary = 24 bits = 16.7M colors
- Reducing number of colors – select subset (colormap/palette) & map all colors to them
  - Device capable of displaying only a few different colors simultaneously
  - E.g. an 8 bit display
  - Storage (memory/disk) cost

quantization to 4 colors



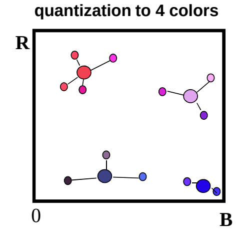
Choosing the Representatives

uniform quantization to 4 colors



large *quantization error*

image-dependent quantization to 4 colors



small *quantization error*

Color Quantization Example

256 colors

64 colors

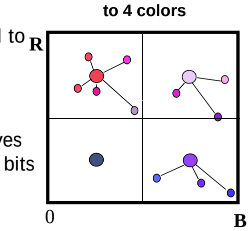
16 colors

4 colors

Uniform Quantization

- Fixed representatives - lattice structure on RGB cube
- Image independent - no need to analyze input image
- Some representatives may be wasted
- Fast mapping to representatives by discarding least significant bits of each component
- Common way for 24→8 bit quantization
  - retain 3+3+2 most significant bits of R, G and B components

uniform quantization to 4 colors

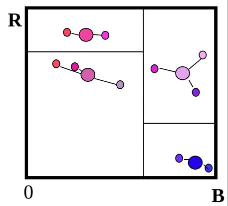


large *quantization error*

Median-Cut Quantization

- Image colors partitioned into *n* cells, s.t. each cell contains approximately same number of image colors
- Recursive algorithm
- Image representative
  - Average of image colors in each cell
- Image color mapped to rep. of containing cell
  - not necessarily nearest representative

image-dependent quantization to 4 colors



small *quantization error*

Quantization

256 colors

uniform

median-cut

8 colors