Lecture 4: Color Theory

Reading Materials: Chapter 4

http://dkclothing.com/blog/wp-content/uploads/2010/02/springcolors.jpg

Some slides taken shamelessly from Prof. Yao Wang's lecture slides

Recap

Definition of An Image

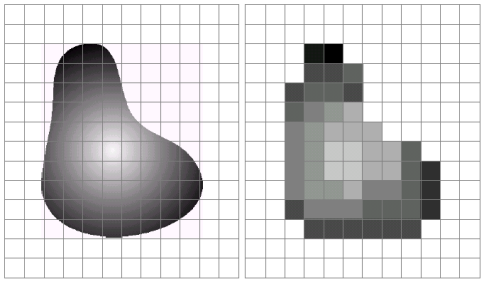
- Think an **image** as a function, f
  - $f(x, y)$ gives the **intensity** at position (x, y)
  - Realistically, we expect the image only to be defined over a rectangle, with a finite range:
    - f: $[a,b]$x$[c,d]$ → $[0,1]$

- A color image is just three functions pasted together
  - (R, G, B) components

$$f(x,y) = \begin{bmatrix} r(x,y) \\ g(x,y) \\ b(x,y) \end{bmatrix}$$

Sampling + Quantization

- We usually operate on **digital** (**discrete**) images:
  - **Sample** the 2D space on a regular grid → **Pixel**
  - **Quantize** each sample (round to nearest integer)



a b

FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.

1-bit Image

- Each pixel is stored as a single bit (0 or 1), so also referred to as **binary image**.
- Such an image is also called a 1-bit **monochrome** image or a pure black/white image since it contains no color.
- We show a sample 1-bit monochrome image "Lena"
  - A standard image used to illustrate many algorithms

8-bit Grayscale Image

* Each pixel has a gray-value between 0 and 255.
  * A dark pixel might have a value of 10, and a bright one might be 230.
* Each pixel is represented by a single byte;
* **Image resolution** refers to the number of pixels in a digital image
  * Higher resolution always yields better quality
  * Fairly high resolution for such an image might be 1600x1200, whereas lower resolution might be 640x480.
* Without any compression, a raw image's size = # of pixels x byte per pixel

24-bit Colored Image

* Each pixel is represented by **three bytes**, usually representing RGB
  * one byte for each R, G, B component
  * 256x256x256 possible combined colors, or a total of 16,777,216 possible colors.
  * However such flexibility does result in a storage penalty: A 640x480 24-bit color image would require 921.6 kB of storage without any compression.

x=imread('Filename')

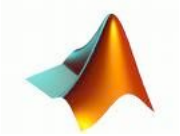
imshow(x)

image(x)

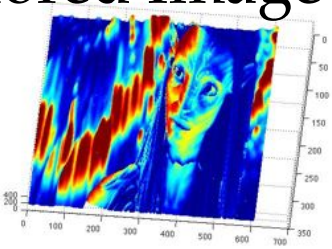
imwrite('Filename',x)

y=rgb2gray(x)

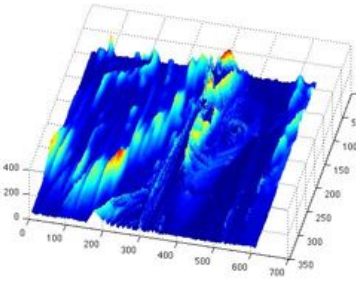
Processing Images in Matlab



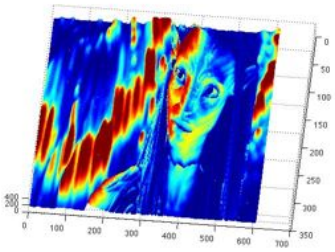
Colored Image



Blue-layer Pixel Strength



Red-layer Pixel Strength



Green-layer Pixel Strength

ans(:,:,1) =

17	16	14	15	17	19	19	18	13	12
17	15	14	14	16	17	17	16	14	13
19	18	16	16	16	17	17	16	15	14
21	20	19	18	18	17	17	16	16	15
17	17	16	15	16	14	14	13	15	14
16	17	17	17	17	15	15	15	14	13
14	16	17	17	16	15	15	15	13	12
11	13	15	15	14	13	13	14	12	11
15	14	14	13	13	11	11	10	13	11
16	16	15	15	15	14	14	14	10	8

ans(:,:,2) =

10	9	7	8	10	12	11	10	5	4
10	8	7	7	9	10	9	8	6	5
14	13	11	11	11	12	9	8	7	6
16	15	14	13	13	12	9	8	8	7
14	14	13	12	10	8	8	7	9	8
13	14	14	14	11	9	9	9	8	7
13	15	16	16	13	12	12	12	7	6
10	12	14	14	11	10	10	11	6	5
15	14	14	13	11	9	8	7	10	8
16	16	15	15	13	12	11	11	7	5

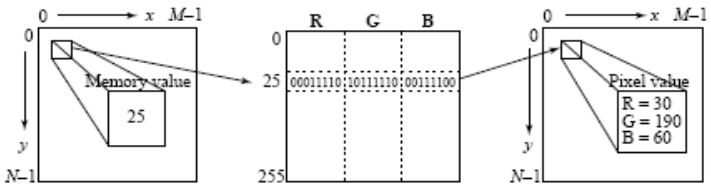
ans(:,:,3) =

17	16	14	15	18	20	22	21	18	17
17	15	14	14	17	18	20	19	19	18
20	19	17	17	18	19	20	19	20	19
22	21	20	19	20	19	20	19	21	20
21	21	20	19	20	18	18	17	21	20
20	21	21	21	21	19	19	19	20	19
21	23	24	24	22	21	23	23	19	18
18	20	22	22	20	19	21	22	18	17
25	24	24	23	22	20	19	18	21	19
26	26	25	25	24	23	22	22	18	16

8-bit Colored Image

* Many systems can make use of 8 bits of color information (the so-called "**256 colors**") in producing a screen image.

* Such images use the concept of a **lookup table** to store color information.
  * Basically, the image stores not color, but instead just a set of single bytes, each of which is actually an index into a table of 3-byte values that specify the pixel color for that lookup table



Progressive vs. Interlaced Frames

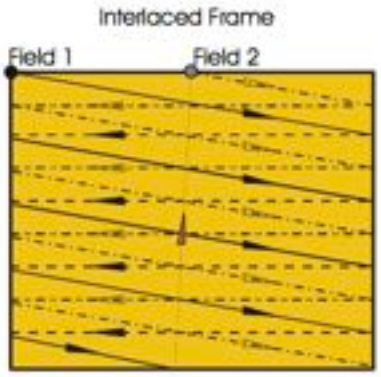
• Used in standard television formats (NTSC, PAL, and SECAM)

• Displays only half of the horizontal lines at a time

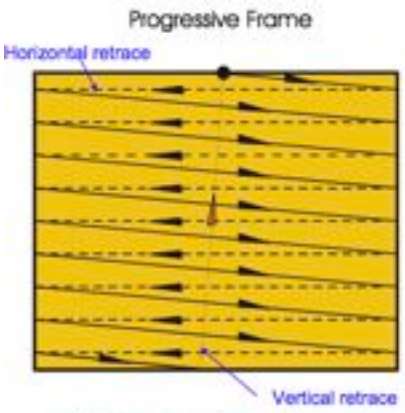
• The first *field* , containing the odd-numbered lines, is displayed, followed by the second field, containing the even-numbered lines

• Good: A high refresh rate (50 or 60 Hz) can be achieved with only half the bandwidth.

• Bad: The horizontal resolution is essentially cut in half.



Progressive vs. Interlaced Frames



• Used in CRT, LCD, DTV, HDTV
  • 720p, 1024p

• Displays all the horizontal lines at a time

• Good: Higher resolution at the same refresh rate, no blurring

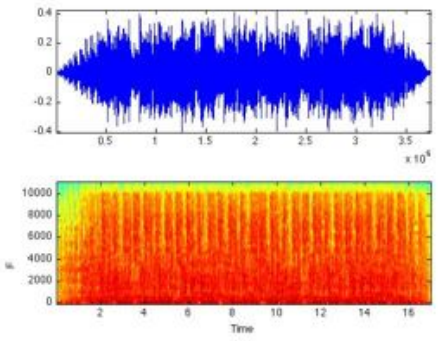
• Bad: Higher bandwidth

Bandwidth of 1920x1080 (1080**i**60)
= Bandwidth of 1280x720(720**p**60)

Interlaced scan is developed to provide a trade-off between temporal and vertical resolution, for a given, fixed data rate (number of line/sec).

Digital Audio

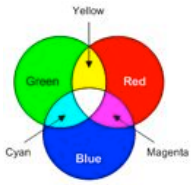
- Audio= collection of waveforms
- Sampling + quantization



- Matlab demo
  - [audio,Fs]=wavread(file)
  - sound(audio,Fs)
  - Can only read some .wav files

Outline

- Color perception and specification
  - Color as EM waves
  - Human perception of color
  - Trichromatic color mixing theory
- Different color representations
  - Primary color (RGB, CMY)
  - Luminance/chrominance
- Color image capture and display
  - 3D to 2D projection
  - Analog vs. digital camera
- Color quantization
  - Uniform
  - Adaptive
  - Dithering



Color = EM Waves

- Light is an **electromagnetic wave**. Its color is characterized by the **wavelength** content of the light.
  - Most light sources produce contributions over many wavelengths.
  - Laser light consists of a single wavelength
  - Short wavelengths produce a blue sensation, long wavelengths produce a red one
- Human can not detect light, but its contributions that fall in the visible wavelengths (**400—700nm**)
  - Nanometer: 1nm=10^{-9} meter

color	wavelength interval
red	~ 700–635 nm
orange	~ 635–590 nm
yellow	~ 590–560 nm
green	~ 560–490 nm
blue	~ 490–450 nm
violet	~ 450–400 nm

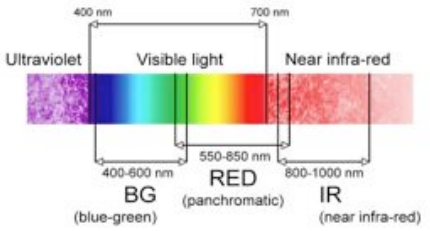
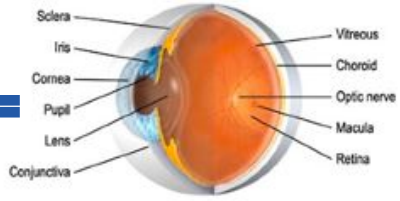


Image from http://hirise.lpl.arizona.edu/HiBlog/tag/color/

Human Vision

Like a Camera!!

=



Mapping camera components to the eyes

Lens → Lens, cornea

Shutter → Iris, pupil

Film → Retina

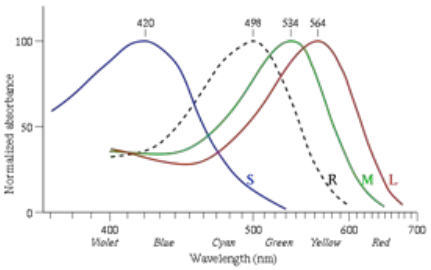
Retina: a light sensitive tissue lining the inner surface of the eye.
The optics of the eye create an image of the visual world on the retina.

Cable to transfer images → Optic nerve send info to the brain

Human Perception of Colors

- Retina contains photo receptors
  - Cones: day vision, can perceive color tone
    - **Red**, **green**, and **blue** cones
    - cones have different frequency responses
    - Tri-receptor theory of color vision
  - Rods: night vision, perceive brightness only
    - produce a image in shades of gray ("all cats are gray at night!")

color	wavelength interval
red	~ 700–635 nm
orange	~ 635–590 nm
yellow	~ 590–560 nm
green	~ 560–490 nm
blue	~ 490–450 nm
violet	~ 450–400 nm



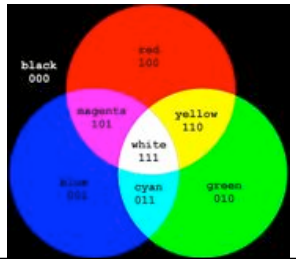
http://en.wikipedia.org/wiki/Trichromacy

Define Colors via RGB

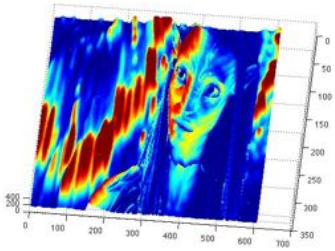
- **Trichromatic** color mixing theory
  - Any color can be obtained by mixing three primary colors with a right proportion

- Primary colors for illuminating sources:
  - **Red**, **Green**, **Blue** (RGB)
  - Example: CRT works by exciting red, green, blue phosphors using separate electronic guns
  - R+G+B=White

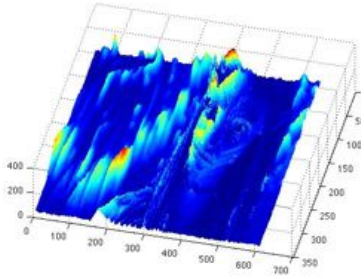
Used in digital images



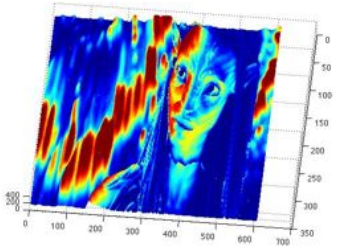
Recap: Color Images



Blue-layer Pixel Strength

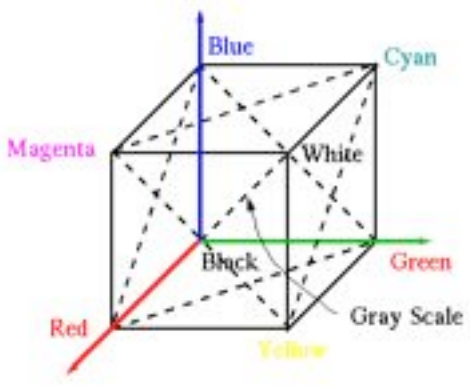


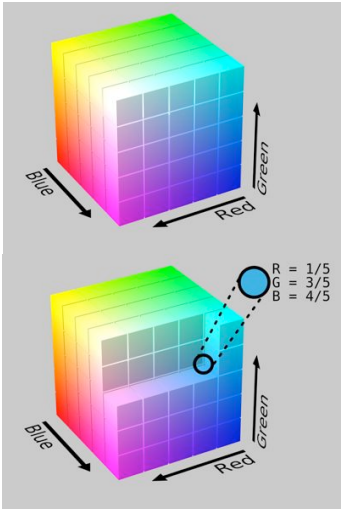
Red-layer Pixel Strength



Green-layer Pixel Strength

RGB Coordinate

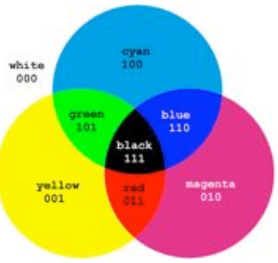




http://en.wikipedia.org/wiki/HSL_and_HSV

Define Colors via CMY

- Primary colors for **reflecting** sources (also known as secondary colors):
  - Cyan, Magenta, Yellow (CMY)
  - Example: Color printer works by using cyan, magenta, yellow and black (CMYK) dyes
  - Subtractive rule: R+G+B=Black
  - **CMYK: use K to save CMY inks**



Used in printing

RGB ⟷ CMY(K)

Normalize each R, G, B component to a value within [0,1]

C_{RGB}=[R, G, B]

C_{CMY}=[C, M, Y]=[1-R, 1-G, 1-B]

or [255-R, 255-G, 255-B] if not normalized

C_{CMYK}= [C, M, Y, K]

if min(C, M, Y)=1

then C_{CMYK}=[0,0,0,1]

else

K=min(C, M, Y)

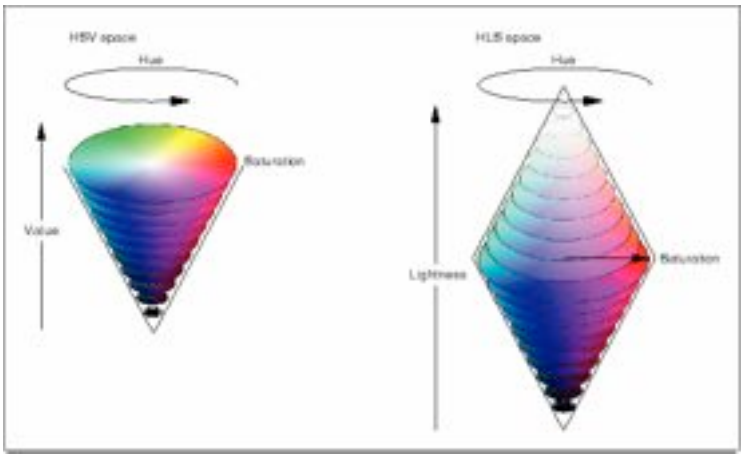
C_{CMYK}=[(C-K)/(1-K), (M-K)/(1-K), (Y-K)/(1-K), K]

Luminance & Chrominance

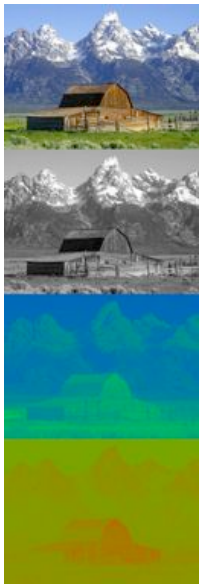
- Color sensation can also be characterized by
  - Luminance (brightness): e.g.**Y = 0.2126 R + 0.7152 G + 0.0722 B**
  - Chrominance
    - Hue (color tone)
    - Saturation (color purity)
- Hue, saturation, and intensity (HSI)
  - typically used by artists.
  - HSB (brightness), HSV(value), HSL(light)
- Intensity-chromaticity color spaces, YUV and YIQ,
  - Used for television broadcast.

HSV (HSB) and HSL

- **Hue, saturation, and intensity** (brightness/ value/ light)



Intensity-chromaticity based

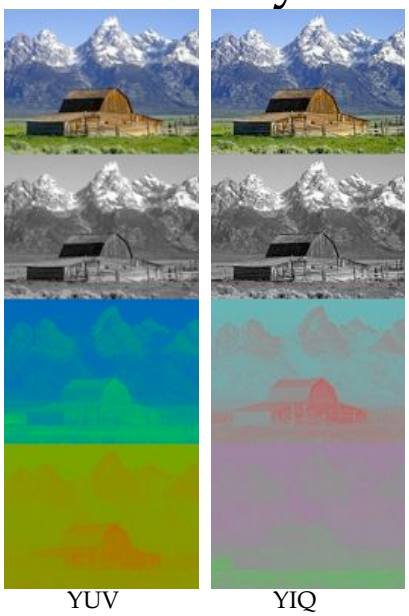


* **YUV (PAL TV broadcast, Europe & Asia, and some forms of NTSC)**
  * Code a **luminance** signal (often gamma-corrected signals) equal to **Y'**, the "luma".
  * **Chrominance** refers to the difference between a color and a reference white at the same luminance. –> use color differences **U, V**
  * Also known as Y'UV, YCbCr, YPbPr (component video)

Y = 0.299R + 0.587G + 0.114B
U = -0.147R - 0.289G + 0.437B= 0.492(B-Y)
V = 0.615R - 0.515G - 0.100B= 0.877 (R-Y)

http://commons.wikimedia.org/wiki/File:Barn-yuv.png

Intensity-chromaticity based



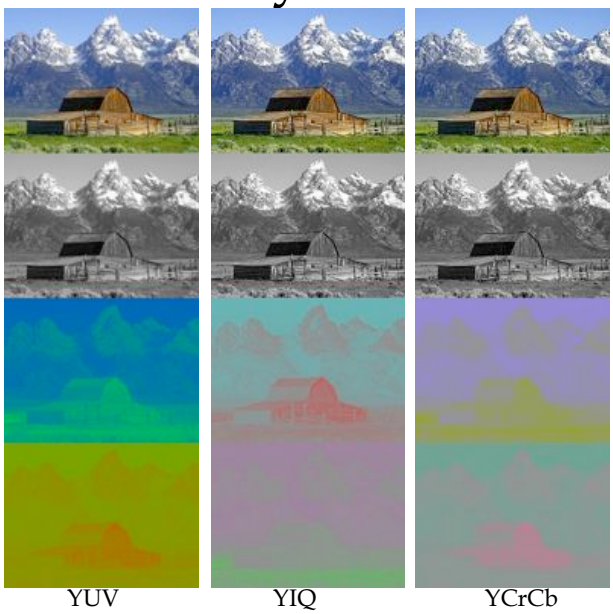
YUV YIQ

* **YIQ (NTSC TV broadcast, north America)**
  * *I* : *in-phase*
  * *Q*: *quadrature*
  * **U, V rotated 33º**

RGB-to-YIQ

Y = 0.299R +0 .587G +0.114B
I = 0.596R - 0.274G - 0.322B
Q = 0.211R - 0.523G - 0.312B

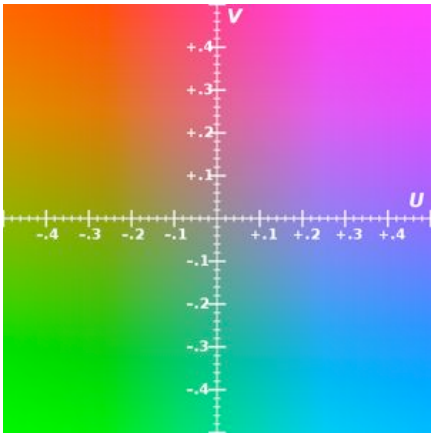
Intensity-chromaticity based

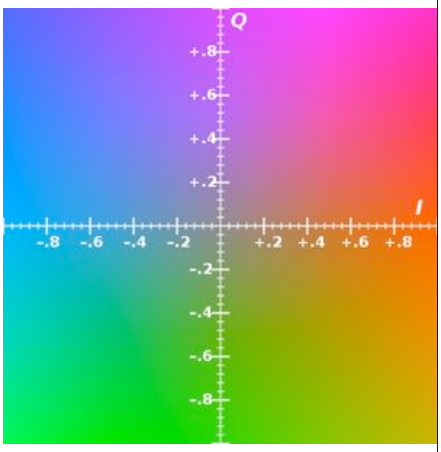


YUV YIQ YCrCb

* **YCrCb**
* **Digital image/video**
* Cb= blue-difference
* Cr=red-difference
* Similar to YUV

YUV vs. YIQ





RGB –YUV & YIQ

* *RGB-to-YUV*

  Y = .299R + .587G + .114B
  U = -.147R - .289G + .437B=0.492(B-Y)
  V = .615R - .515G - .100B=0.877 (R-Y)

* *RGB-to-YIQ*

  Y = .299R + .587G + .114B
  I = .596R - .274G - .322B
  Q = .211R - .523G - .312B

* *YUV-to-RGB*

  R = 1.00Y + .000U + 1.403V
  G = 1.00Y - .344U - .714V
  B = 1.00Y + 1.773U + .000V

* *YIQ-to-RGB*

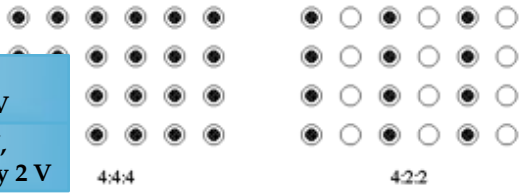
  R = -1.129Y + 3.306I - 3.000Q
  G = 1.607Y - .934I + .386Q
  B = 3.458Y - 3.817I + 5.881Q

YUV Subsampling

* Human eyes are more sensitive to changes in luminance than in chrominance → opportunity for reducing bandwidth → UV subsampling

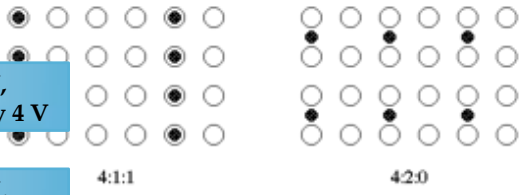
4:4:4 → 24 bits
8 for Y, 8 for U, 8 for V

4:2:2 → 16 bits, 8 for Y,
8 for every 2 U, 8 for every 2 V



4:1:1 → 12 bits, 8 for Y,
8 for every 4 U, 8 for every 4 V

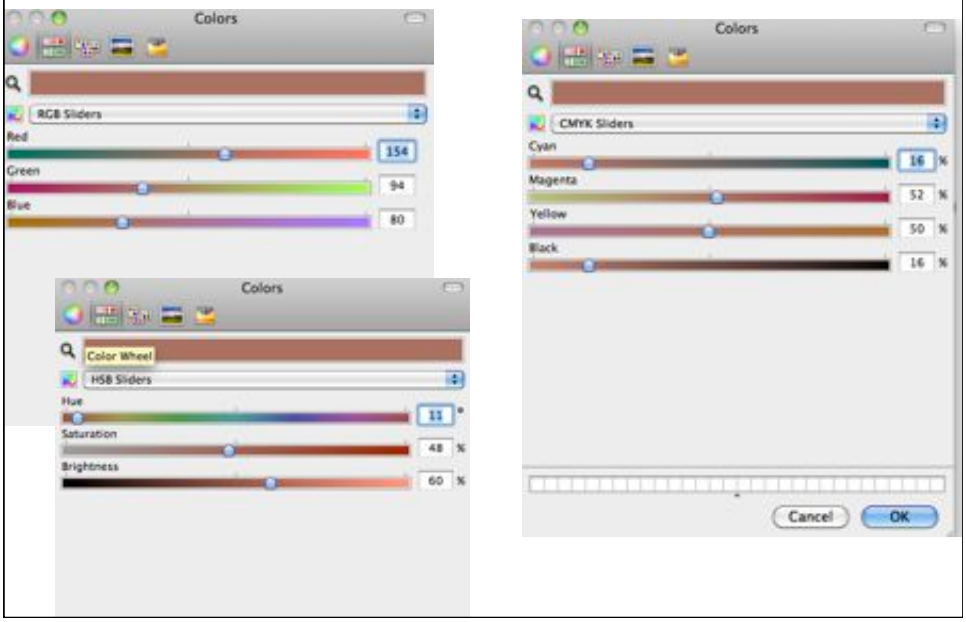
4:2:0 → 12 bits, 8 for Y,
8 for avg 2x2 U, 8 for avg 2x2 V



Summary: Color Specification

- Specify three primary or secondary colors
  - **RGB** & **CMY**
- Specify the luminance and chrominance
  - **HSB** or **HSI** (Hue, saturation, and brightness or intensity)
  - **YUV, YIQ** (used in NTSC color TV or analog color TV)
  - **YCbCr** (used in digital color TV, image, video)
- **Amplitude specification:**
  - In general **8 bits** for each color component (0, 255), and **24 bits** total for each pixel
  - Total of 16 million colors
  - A true RGB color display of size 1000x1000 requires a display buffer memory size of 3 MB

PPT DEMO



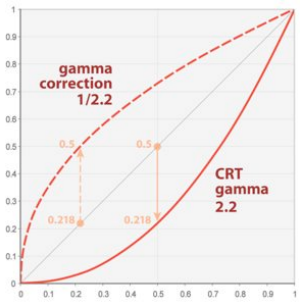
Displaying Images

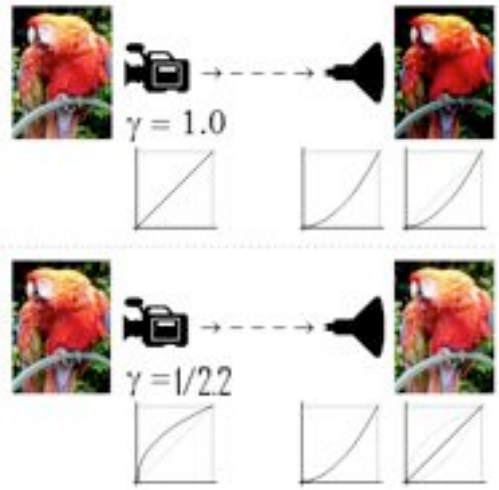
* The light entering the eye of the computer user is that which is emitted by the screen
* The screen is essentially a self-luminous source. It alters the color signals
  * The light emitted is in fact roughly proportional to the voltage raised to a power; this power is called gamma, with symbol γ.
* If the file value in the red channel is R, the screen emits light proportional to R^{γ}
  * The value of gamma is around 2.2.
* Need to pre-process signals by raising to the power $(1/\gamma)$ before transmission.

Gamma Correction

A nonlinear operation to code/decode luminance Y

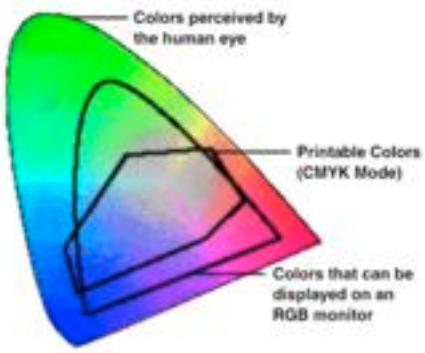
* $Y \rightarrow Y' = Y^{1/2.2}$





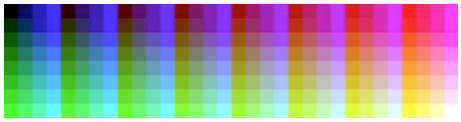
Color Gamut

* 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

* Select a set of colors that are most frequently used in an image, save them in a **look-up table** (also known as color map or color palette)
* Any color is quantized to one of the indexed colors
* Only needs to save the index as the image pixel value and in the display buffer
* Typically: k=8, m=8 (selecting 256 out of 16 million colors)
* Recall: Last Lecture: 24bit image → 8 bit image (3R, 3G, 2B)
  * Bit 7 6 5 4 3 2 1 0
  * Data R R R G G G B B

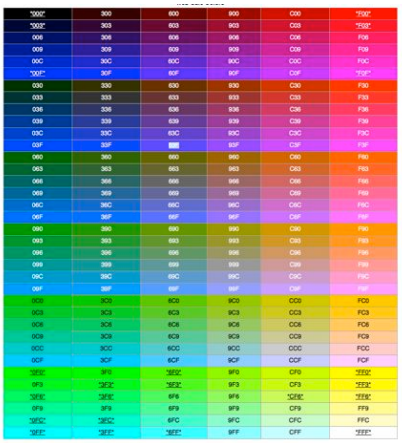


Web-Safe Colors

- A set of 216 color values as Web-safe color map
  - Developed when CRTs can display 256 colors
  - 6x6x6=216
  - Each R, G, B component has 6 shades

6 shades of each color

digit	hexadecimal	decimal
0	00	0
3	33	51
6	66	102
9	99	153
C or (12)	CC	204
F or (15)	FF	255



Today's Learning

- Each color is an EM wave at a certain wavelength in the visible light band
- How a human perceives color
  - Three types of cones sensitive to red, green, and blue respectively
- How to generate different colors in display and in printing
  - By mixing three primary colors
  - RGB for display, CMY+K for printing
- How to display images:
  - Gamma correction
- How is a color image stored
  - Consists of three separate component images: ex. R,G,B, YCbCr
- Color quantization
  - True color vs. index color image

Lab 1 Assigned

* From course website
* From facebook classjournal

* **Due: April 16, Friday 11:59pm via turnin**