Digital Image Processing

6. COLOR SPACE
Session 6

Color Spaces:

- RGB Model
- CMY/K Model
- Human Vision
- Luminance and Chrominance
- HIS Model
- CIE XYZ Space
- Chromaticity Diagram
- YCbCr
- CIE LAB Space
Colors ?!

- Color is a powerful descriptor which can be used for various tasks:
  - simplify image analysis, segmentation, object detection, extraction and processing based on color, tracking and identification.
- The human visual system can distinguish hundreds of thousands of different color shades and intensities, but only around 100 shades of grey.
- Therefore, Color is a very important attribute in image processing with lots of extra information.
- We’ll cover some of the basic properties and ways to represent color in the segment.
- If color images are being acquired, it is first of all important to understand something about color representations.
Color Models and Spaces

- Color models provide a standard way to specify a particular color, by defining a 3D coordinate system, and a subspace that contains all constructible colors within a particular model.

- Any color that can be specified using a model will be represented by a single point within the subspace it defines.

- Each color model is oriented towards either specific hardware (RGB, CMY, YIQ), or image processing applications (HSI).
The “Box” and the “Balloon”

- Imagine a box containing all the visible colors.
- A color space can be represented as a balloon blown up inside the box with colors.
- Containing total number of visible colors that fall within the particular color space.
- The surface of the balloon has the most saturated colors that the color space can hold.
- Any colors falling outside the balloon can’t be reproduced in that color space.
- Larger color spaces such contain both more colors and more highly saturated colors.
The RGB Model

Is based in the Cartesian Coordinates system.

Blue (0,0,1)

White (1,1,1)

Black (0,0,0)

Red (1,0,0)

Green (0,1,0)

The greyscale spectrum, i.e. those colors made from equal amounts of each primary, lies on the line joining the black and white vertices.

Specifying a particular color is by specifying the amount of each of the primary components present.

16,777,216

The RGB model is used for color monitors and most video cameras.
RGB- Additive model

- The RGB model is used for color monitors and most video cameras.
- The colors present in the light add to form new colors, and is appropriate for the mixing of colored light for example.
- It can be viewed as 3 monochrome intensity images (red/green/blue).
- This is an additive model, it asks what is added to black to get a particular color.
Primary colors of light – Additive model

- The additive mixing of red, green and blue primaries to form the three secondary colors yellow (red + green), cyan (blue + green) and magenta (red + blue), and white ((red + green + blue).

Cyan, Magenta and Yellow are secondary colors
The CMY Model

- The CMY model is used for **printing devices and filters**.
- The surface covered with **pigments of colors**, illuminate the other colors in that surface.
- This is an **subtractive model** appropriate to absorption of colors, for example due to pigments in paints. It asks **what is subtracted from white to get a particular color**.
CMY Model – Subtractive Model

Secondary colors of light / Primary colors of pigments

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

**For example:** If a surface is coded with cyan pigments and illuminated with white light, no red light will be reflected from the surface.

- The figure on the right shows the three subtractive primaries, and their pairwise combinations to form red, green and blue, and finally black by subtracting all three primaries from white.

Cyan = 1-red (no red appear)  
Magenta = 1-Green (Blue+ Red)  
Yellow = 1-Blue (Green + Red)  
red, green and blue as secondary colors
The CMYK Model

Equal amounts of C,M,Y should produce black, but they produce instead in practice a muddy-looking black. Therefore, a fourth color “Black” – K is added to produce the CMYK color model.
Dr. Martine's Colors
Human Vision - Rods and Cones

Our eyes perceive light and dark as well as different color information through rods and cones. Together they allow us to see three components of color.

**Cones** are responsible for sensing color information (hue and saturation) and the *central fovea of the eye* is mostly cones. They are active when more light is present (photopic vision).

We have three types of cones, S-cones (blue), M-cones (green), and L-cones (red) for short, medium, and long wavelength.

**Rods** are responsible for seeing in low light (scotopic vision). To do this they need to be very sensitive to light and dark. However, they have a low visual acuity (low sharpness), making it difficult for rods to determine spatial relationships.
Human Vision – Luminance and Color

There are 20 times as many rods as cones.

Humans are much more sensitive to light information than to color information.

That means our eyes are much more sensitive to the luminance component of color than the chrominance component.

We also have a tendency to disregard some of the hue and saturation information. In fact, the details in what we see are carried mostly by the information we perceive about light and dark.
Question

Which color is brighter A or B?
Answer

Despite looking very different, squares A and B are the same medium gray. The image on the right connects them with a strip of the same color.
Light – Chromatic / Achromatic

- Achromatic light – without color
  Attributes = Intensity (the amount of light)
- Chromatic light – with color
- Isaac Newton – Mid 17th century

Discovered that when a beam of light passes through a glass prism, the light that comes out instead of having a continuous spectrum of colors ranges of:

Chroma components represent the color information.
Chromatic Light Attributes

- **Radiance**  total amount of energy that flows from the light source (watts).

- **Luminance**  is a measure of the **intensity of light that reaches the eye**. Its unit of measure is candela per square meter (cd/m²), which you don’t really need to know. What’s important is it’s an absolute measure of the intensity of light.

- **Brightness/Value** = The **perceived luminance** of an object. It’s how our eyes see the intensity of light.

- **Lightness**  is the brightness relative to the brightness of a similarly illuminated white. It’s perceived brightness with color information removed.
Our eyes allows us to see three components of color:
• Hue
• Saturation
• Some measure of light and dark (Brightness)
Luminance & Chrominance

**Luminance** refers to brightness
the "black-and-white" or achromatic portion of the image

**Chrominance** refers to color info
So we are talking about 2 different things

1. The distributions of wavelengths in the **electromagnetic visible spectrum**
2. The **physiological perceived colors** in human color vision

**Color spaces define quantitative links between those two!**

- They define mathematical relationships that are essential for color **management** dealing with image capture, presentation and processing on recording devices such as digital cameras, illuminated displays or color inks.

- They map a range of physically produced colors from mixed light, pigments etc. to an objective description of color sensations registered in the human eye.
SENSORS

- In digital cameras, most sensors record color images in terms of their red, green and blue intensities.

- Images are stored in the computer in terms of their red, green and blue (RGB) intensities, and displayed on CRT monitors with RGB phosphors or on LCD flat screens with RGB filters.

- In a typical sensor, white lights are filtered into RGB components and captured by individual sensor cells. Each cell captures only one of the 3 primary light colors.

- A typical grid pattern contains 50% green, 25% red and 25% blue cells. Because green is most representative (closest to the orientation) of luma, it serves as a stand-in for luma channel. In fact, luma is a mix of about 60% green, 30% red and 10% blue.
Color Properties

Three independent quantities are used to describe any particular color.

**Hue (H)** - This is the familiar color wheel children learn about and artists use. Physically – the dominant wave length in a mixture of light waves. Visible colors occur between about 400nm (violet) and 700nm (red) on the
Color Properties

**Saturation (s) / Colorfulness** – The relative purity, a measure of the amount of color/ inversely proportional to the amount of white light mixed with its hue. Full spectrum colors are fully saturated with no white light mixed in.

For example: A maximum saturation color such as pure red may be compared to a less saturated color such as **pink**.

**Chromaticity**

Hue and saturation together determine the **chromaticity** for a given color (the quality of color, independent of brightness).
Luminance (L)- Measures intensity and color sensation. Intensity is determined by the actual amount of light, with more light corresponding to more intense colors. The intensity is determined by the energy, and is therefore a physical quantity.

Intensity (I) / Brightness (B) - Measures the perceived amount of energy by human (lumen) but ignores color and measures the brightness of the pixels in the greyscale image.

Achromatic light has no color - its only attribute is quantity or intensity. Grey level is a measure of intensity.
Hue/Saturation/Intensity

Two of the most widely used are hue-saturation-intensity (HSI) and L

**HSI coordinates:**

**Hue (H)** - This is the familiar color wheel children learn about and artists use. The Hue is represented in this space as an angle, which progresses around the color wheel from red to yellow, then green, cyan, blue, magenta and back to red.

**Saturation (S)** - The distance that they are displaced is a measure of the amount of color. When color is present, pixel values move off the axis. A maximum saturation color such as pure red may be compared to a less saturated color such as pink (percentage 0-100%).

**Intensity/Brightness (I)** - a central axis that ignores color altogether and measures the brightness (sometimes described as intensity or luminance) of the pixels in the image. For a monochrome or gray scale image, with no color, all of the pixel values would plot along that central axis.
The HSI Model

- So, color may be specified by the three quantities hue, saturation and intensity.
- Decouples the Intensity component from the color caring information.
- It’s an ideal tool for developing image processing algorithms based on color descriptions that are natural, and intuitive to humans.
- Such a decomposition is quite natural in graphics applications such as color picking
- There are non-linear expressions that allows us to go from RGB to HSI and back.
- With this model we can manipulate the hue, saturation and intensity.
The HSI SPACE

- HSB/V is measuring the amount of light
- HSL is measuring the amount of white

Hue is measured from red, and saturation is given by distance from the axis.

Colors on the surface of the solid are fully saturated (pure)
The greyscale spectrum is on the axis of the solid. For these colors, hue is undefined.
Conversion from RGB to HIS (each pixel)

The Intensity is given by:

\[
I = \frac{R+G+B}{3}
\]

Saturation: the amount of white present. If any of R, G or B are zero, there is no white and we have a pure color.

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

\[
H = \begin{cases} 
\theta & \text{if } B \leq G \\
360 - \theta & \text{if } B > G
\end{cases}
\]

\[
\theta = \cos^{-1}\left\{\frac{\frac{1}{2}[(R - G) + (R - B)]}{[(R - G)^2 + (R - B)(G - B)]^{1/2}}\right\}
\]
Conversion from HSI to RGB (each pixel)

First Multiply H by 360... then

\[
\begin{align*}
\text{RG sector (}0^\circ \leq H < 120^\circ) & \\
B &= I(1 - S) \\
R &= I \left[1 + \frac{S \cos H}{\cos(60^\circ - H)}\right] \\
G &= 3I - (R + B). \\
\end{align*}
\]

\[
\begin{align*}
\text{GB sector (}120^\circ \leq H < 240^\circ) & \\
R &= I(1 - S) \\
G &= I \left[1 + \frac{S \cos H}{\cos(60^\circ - H)}\right] \\
B &= 3I - (R + G). \\
\end{align*}
\]

\[
\begin{align*}
\text{(}240^\circ \leq H \leq 360^\circ) & \\
H &= H - 240^\circ \\
R &= I(1 - S) \\
G &= I \left[1 + \frac{S \cos H}{\cos(60^\circ - H)}\right] \\
B &= 3I - (R + G). \\
\end{align*}
\]
CIELAB and CIEXYZ

- Color spaces which were specifically designed to encompass all colors the average human can see.
- It’s the usual reference standard for defining a color space.
- They resulted from a series of experiments done
The CIE XYZ color space

- Encompasses all color sensations that are visible to a person with average eyesight.
- It is a device-invariant representation of color.
- It serves as a standard reference against which many other color spaces are defined.
- The idea: humans tend to perceive light within the green parts of the spectrum as brighter than red or blue light of equal power.
- The perceived brightness is described in a “Luminosity function”
- In the model $Y = \text{luminance}$.
- $Z$ is quasi-equal to blue stimulation (s-cone)
- $X$ is a mix (a linear combination) of cone response curves chosen to be nonnegative.
CIE XYZ - The Tristimulus Values

Defining $Y$ as luminance has the useful result that for any given $Y$ value, the XZ plane will contain all possible chromaticity (colors) at that luminance (perceived brightness). The tristimulus values for a color with a spectral radiance $L_{e,\Omega,\lambda}$, are given in terms of the standard observer by:

\[
X = \int_{\lambda} L_{e,\Omega,\lambda}(\lambda) \bar{x}(\lambda) \, d\lambda,
\]
\[
Y = \int_{\lambda} L_{e,\Omega,\lambda}(\lambda) \bar{y}(\lambda) \, d\lambda,
\]
\[
Z = \int_{\lambda} L_{e,\Omega,\lambda}(\lambda) \bar{z}(\lambda) \, d\lambda.
\]

where $\lambda$ is the wavelength of the equivalent monochromatic light (in nm) and the standard limits are in [380,780]. The values of $X$, $Y$, and $Z$ are bounded if the radiance spectrum $L_{e,\Omega,\lambda}$ is bounded.
Trichromacy

A display, which creates most visible colors through combinations and different levels of the three primary colors: red, green and blue
CIE primaries

Although nearly all visible colors can be matched by the Tristimulus model, some cannot. So the Commission Internationale de l'Éclairage (international commission of illumination) suggested to use three standard primaries, called $X$, $Y$ and $Z$, that can be added to the Trichromatic model to form all visible colors.

If one of the primaries is added to one of the unmatchable colors, it can be matched by a mixture of the other two, and so the color may be considered to have a negative weighting of that particular primary.
Chromaticity Diagram

- The chromaticity diagram is a tool to specify how the human eye will experience light with a given spectrum.
- Represents all of the chromaticity visible to the average person called the gamut of human vision.
- The curved edge of the gamut is called the *spectral locus* and corresponds to monochromatic light (each point representing a pure hue of a single wavelength), with wavelengths listed in nanometers.
- Note that the chromaticity diagram is a tool to specify how the human eye will experience light with a given spectrum. It cannot specify colors of objects (or printing inks), since the chromaticity observed while looking at an object depends on the light source as well.
The diagram shows all visible colors.

The primary $Y$ was chosen so that its color matching function exactly matches the **luminous-efficiency function for the human eye** given the sum of the colors in the tristimulus model.

Chromaticity depends on dominant wavelength and saturation, and is independent of luminous energy

The standard white light has color defined to be near (but not at) the point of equal energy $x = y = z = \frac{1}{3}$

colors with the same chromaticity, but different luminance all map to the same point within this region.
Complementary colors, = add to give white, lie on the endpoints of a line through the point of equal energy.

Color composition as a function of
x = Red
Y = Green
Z = (1-x-y) = Blue

The pure colors:
Max x = 780 nm
Min z = 480

The middle = Equal energy = white light.
Tristimulus Model Limitations

Although nearly all visible colors can be matched by the Tristimulus model, some cannot.

All the colors along any line in the chromaticity diagram may be obtained by mixing the colors on the end points of the line.

All colors within a triangle may be formed by mixing the colors at the vertices.

This property illustrates graphically the fact that all visible colors cannot be obtained by a mix of R, G and B (or any other three visible) primaries alone, since the diagram is not triangular!
The Chromaticity Values

The \( Y \) parameter is a measure of the luminance of a color.

The chromaticity of a color is then specified by the two derived parameters \( x \) and \( y \), two of the three normalized values being functions of all three tristimulus values \( X \), \( Y \), and \( Z \):

\[
x = \frac{X}{X + Y + Z}
\]
\[
y = \frac{Y}{X + Y + Z}
\]
\[
z = \frac{Z}{X + Y + Z} = 1 - x - y
\]
**YCbcCr**

- Video systems can store and transmit chromatic information at lower resolution.
- Certain color encoding system for television color transformation (PAL, NTSC, and SECAM) separate between those two.
- TCbcCr - Similar to lab color, the color space is specified in luminance, blue and red components.

\[
\begin{align*}
Y &= 0.299R + 0.587G + 0.114B \\
Cb &= 128 - 0.168736R - 0.331264G + 0.5B \\
Cr &= 128 + 0.5R - 0.418688G - 0.081312B
\end{align*}
\]

- Luma / Brightness
- Blue Channel
- Red Channel

The advantage from the HIS is that there is a linear transformation from RGB while from HSI to RGB is no-linear.
YCbCr Cont.

- Y- The luminance component - contains all the information required for black and white television, and captures our perception of the relative brightness of particular colors.

- That we perceive green as much lighter than red, and red lighter than blue, is indicated by their respective weights of 0.587, 0.299 and 0.114 in the first row of the conversion matrix.

- These weights should be used when converting a color image to greyscale if you want the perception of brightness to remain the same.

- The Y component is the same as the CIE primary Y
LAB Color Space

- describes mathematically all perceivable colors in the three dimensions:
  - $L$ for lightness
  - $a$ and $b$ for the color opponents green–red and blue–yellow
- The Lab color space exceeds
- The Lab color space is used when graphics for print have to
  - be converted from RGB to CMYK as the Lab gamut includes both the RGB and CMYK gamut.
- One of the most important attributes of the Lab model
  - is device independence.
- The space itself is a three-dimensional real number space that contains an infinite number of color representations. However, in practice, the space is usually mapped onto a three-dimensional integer space for device-independent digital representation, and for these reasons, the $L^*$, $a^*$, and $b^*$ values are usually absolute, with a pre-defined range.
Calculating the LAB coordinates

- The lightness, $L^*$, represents the darkest black at $L^* = 0$ and the brightest white at $L^* = 100$.
- The color channels, $a^*$ and $b^*$, will represent true neutral gray values at $a^* = 0$ and $b^* = 0$.
- The red/green opponent colors are represented along the $a^*$ axis, with green at negative $a^*$ values and red at positive $a^*$ values.
- The yellow/blue opponent colors are represented along the $b^*$ axis, with blue at negative $b^*$ values and yellow at positive $b^*$ values.
Calculating the LAB coordinates

- The CIELAB coordinates are created by a cube root transformation of the CIE XYZ color data.
- \(X, Y, Z\) the values from the RGB Model, \(X_n, Y_n\) and \(Z_n\) are the CIEXYZ tristimulus values.
- The scaling and limits of the \(a^*\) and \(b^*\) axes will depend on the specific implementation of Lab color, as described below, but they often run in the range of ±100 or −128 to +127 (signed 8-bit integer).

\[
\delta = \frac{6}{29}
\]

\[
f(t) = \begin{cases} 
\frac{\sqrt[3]{t}}{3\delta^2} + \frac{4}{29} & \text{if } t > \delta^3 \\
\text{otherwise}
\end{cases}
\]

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

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

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

CIELAB-CIEXYZ conversions
In Processing color Images

1. Choose the appropriate color space.

- Choosing an RGB image and applying the transformations (for example sharpen) to each color plane Problem: might result in quite different colors in our transformed image or leaking contours.

- You might want to choose a color space where luminance and chrominance channels are separated (HSI/YCbCr/LAB).

- The alternative space should be chosen according to your computational abilities, the transformation complexity and your processing purpose.
2. Decide whether to process the channel/representation independently or jointly.

- You might want to process the brightness/Luminance channels (I/B/Y) and Chrominance channels separately (Maybe you won’t need to process the chrominance).

- Usually we’ll handle the a-chromatic channels separately very gently and the chromatic channels can be handled roughly.
In Processing color Images cont.

- In RGB usually we will apply the same algorithms as in grey scale for every channel 3 times. Alternatively we can utilize a malty channel processing when there is a need to look at the correlation/complementary components of channels (for example in image compression). Restoration is also done through malty-channel processing. We try to capitalize the between channel correlation and cross channel smoothness.

3. Recombine the modified channel with the other channels (for example modified brightness channel with original color channels)

4. Convert back to RGB.
Original
Very close to the Intensity / The Greyscale of the image.
CMY

C=1-R -> Look at the sun...
Operations on color spaces

If a simple operation like filtering is required,

It will be more simple to do the HIS operation, filter only 1 channel and then add the other 2 instead of RGB filtering with 3 channels.
HIS (L/H Separation #1)

Color components of the original image

Intensity = Grey Scale version
YCbCr (L/H Separation #2)

Luminance (GREYSCALE) (I+G)  Differential color components
RGB Might Leak Sometimes...

- Processing the individual RGB channels alters the proportions of those colors and produces color shifts and distortions that are visually distracting.

**RGB** - the result of individually processing each color channel.
The use of alternative color coordinates offers opportunities for filtering to achieve improved contrast, both to visually reveal structures that are present and potentially to make them easier to discriminate for subsequent measurement.

**LAB** - displays the result of processing the intensity or luminance information (only L channel separately), which preserves the colors of the original specimen image.
Thank you!