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Multimedia Systems

Algorithms, Standards, and Industry Practices

Chapter 4

Color Theory (part 1)

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Color Theory

- This chapter explains the role and significance of color, the physical basis of color vision and psycho physics of color perception.
- This result is used to calibrate the capture devices and display devices used in multimedia.
- Instrument capture multimedia signals and get rendered on different display devices.
- Color is,an intrinsic aspect of visual imagery that need to be captured and display faithfully.

1. The Color Problem

- Visual capture devices, such as cameras,video camcoders,capture visual signals and store them in digital formats and content is finally view by the end users.
- At the end user, this content is rendered on visual display devices.
- The expectation is that the rendered and reproduced color image on the end terminal should ‘look the same’ as the color image of the original object.
- This appear to be impossible task,as the signal reaching the capturing sensor is the result of a complex interaction between material observed and the (unknown) illuminating conditions.
- The signal that reach the eye is the result of the complex interaction between the observed image and the illuminating conditions.

The Color Problem..

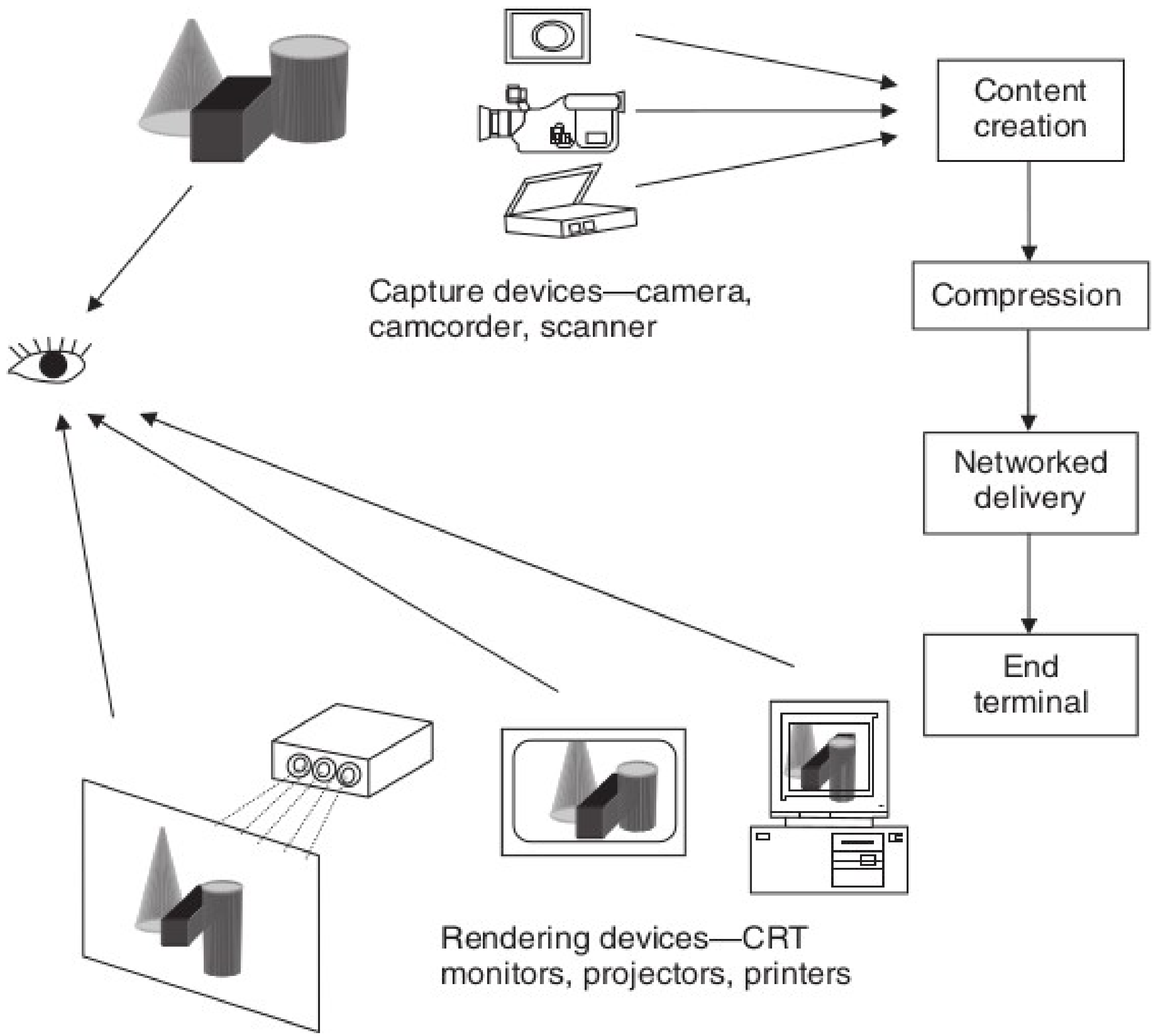


Figure 4.1 Illustration of color problem. Capture devices capture image of objects Having a variety of colors. These images, when rendered at the receivers display Terminal,such as projectors, printers, and CRTs, should “have the same color”, as The original objects as perceived by the human visual system.

History of Color and Light

- Defining color is not an easy task because is both a physical element and a perceptual sensation interpreted by our brains when light enter the eyes.
- Isaac Newton showed that sunlight could be separated into the various colors of the rainbow when passed through a prism and then recombined by passing through a second prism.

The Nature of Light

- Visible spectrum of white light contains all wavelengths from 400 to 700 nanometers.
- Wavelengths below 400 (known as ultraviolets) and those above 700 (known as infrared) cannot be sensed by the human visual system.
- The distribution of energy among the visual wavelengths or frequencies also varies,depending on illuminations.
- Spectral energy distribution is considered to be characteristic of the light source.
- Every light source has a unique spectral distribution.

The Nature of Light...

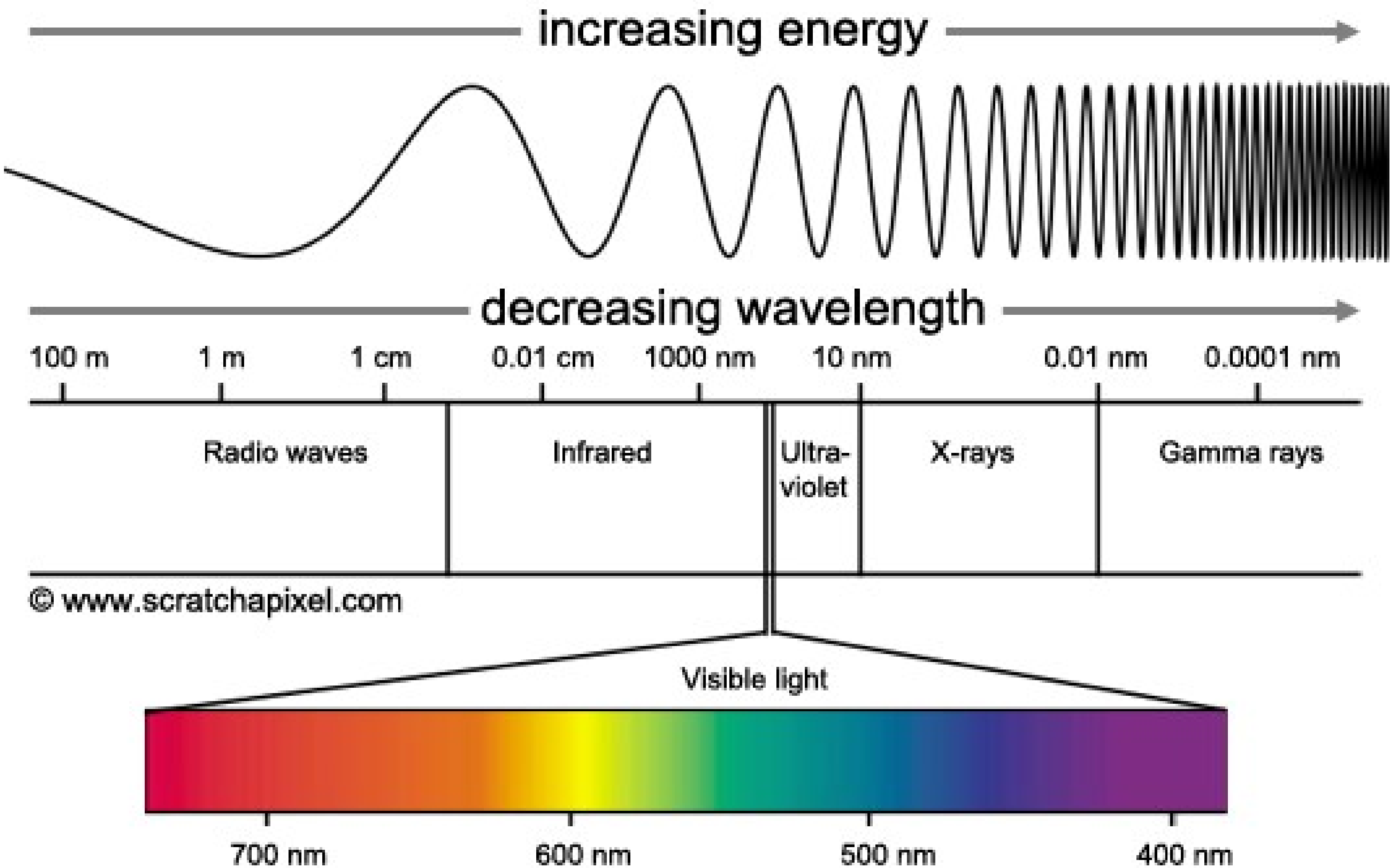


Figure 4.2 Visible Light Spectrum

The Nature of Light...

- Newton work helped analyze the visible spectrum but the generation of images involved the interaction of light with material.
- This interaction involves reflection and absorption.
- The ratio of reflected to absorbed energy depends on the material illuminated, and the wavelength of the illuminant, which will produces an energy field capture by the sensor.

Theories of Color Vision

- Eye have different kinds of color receptors. Red, green and blue primary colors (1802)
- James clerk Maxwell explore that the three primary color can be use to generate various colors by additive mixing.
- He experiment that other most colors can be matched by superimposing three separate light known as primaries.

Theories of Color Vision

- Experiment in 1920 showed that the red, green and blue primaries could match all visual colors.

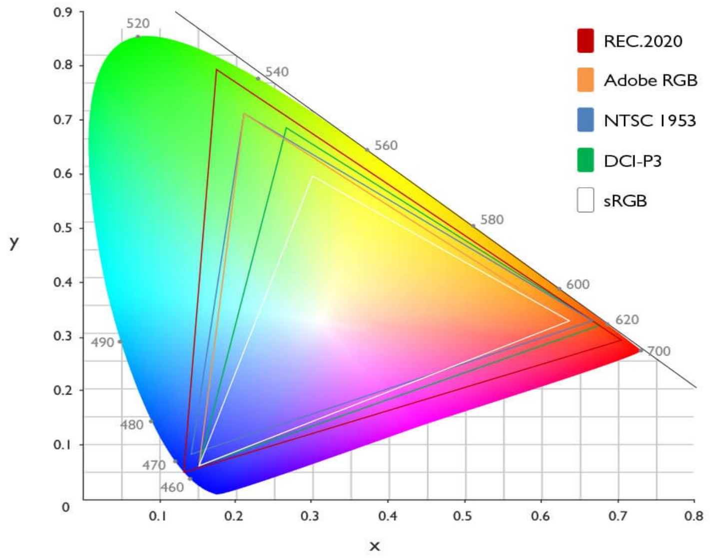


Figure 4.3 Color Gamut

Human Color Sensing

- Eye sense illumination using photoreceptors on the retina.
- Retina contains two types of photoreceptors, rods and cones, which vary in numbers as well as their sensations.
- There are more rods (120 millions) than cone (7 millions) and rods are more sensitive.
- Rods distributed more uniformly than cones.
- Rods are more than thousand times more responsive than cones, and respond primarily to change in illumination.

Human Color Sensing..

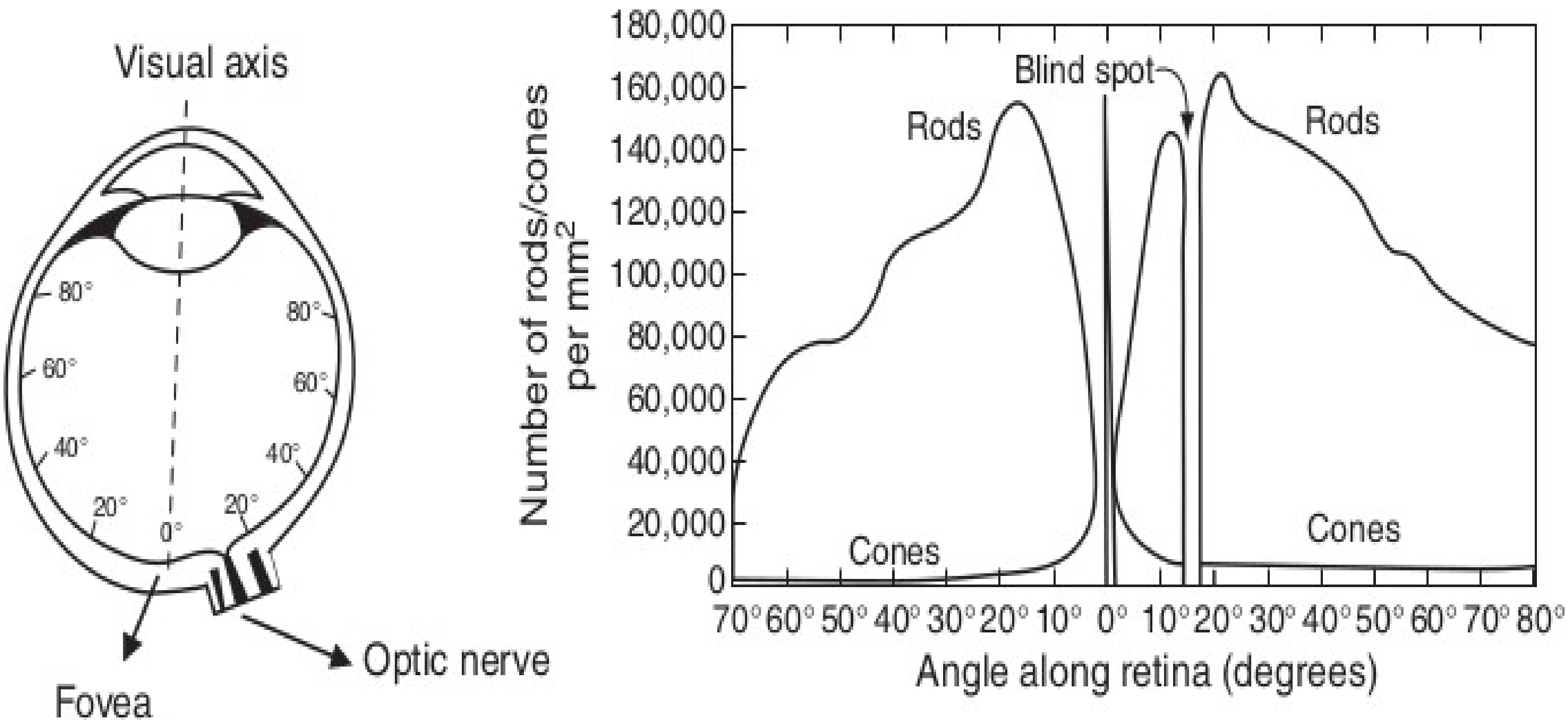


Figure 4.4 Left Figure shows the structure of the eye. The right figure shows the Distribution of rods and cones with respect to visual angle.

Human Color Sensing...

- The cones are responsible for the perception of color.
- The cones are of three different types, which selectively sense the spectrum.
- The cones can be divided into red cones,green cones and blue cones based on the different responses each generated when light is incident on them.
- Blue cones are distributed outside the fovea and have a larger spread and higher sensitivity.
- This selective sensing of the same spectrum is the physical basis for color.

Human Color Perception

- Color perception is not a strictly local process, but depends on a spatial neighborhood.
- Edwin land (1950) noticed that, unlike the eyes, a camera does not compensate for the color of light source.
- When we see white sheet of paper under different illuminating condition such as sunlight, a flash, or tungsten light, we perceive the paper to be white under all conditions.
- However, a picture taken with a camera of the same paper looks different.
- Camera setting need to be adjust while human does this automatically.
- This shows that as long as the image produce by the capture and rendering devices are the same,the user will ignore effects due to illumination.

2. Trichromacity Theory

- Three type of receptors are necessary to generate the perception of the variety of colors in the visible spectrum.
- In human, these three receptors are called red, green and blue and they selectively sense the spectral distribution entering the eye.
- This selective sensitivity leads to the perception of color.
- The condition of having three receptors is known as trichromacy, exhibit by human and few primates.
- Most mammals exhibit dichromacy (two receptors) only.
- Monochromacy (one receptor) is common among sea mammals and does not result in any color perception, only intensity variations sensed by rods.
- Color blind also cause human to exhibit dichromacy.

Cone Response

- Cones are measured in different response curves.
- Each cones have a different spectral absorption.
- Selective sensing of a cone is model mathematically produce the energy of the spectrum, which is sensed by the sensitivity curve of that cone.

Cone Response

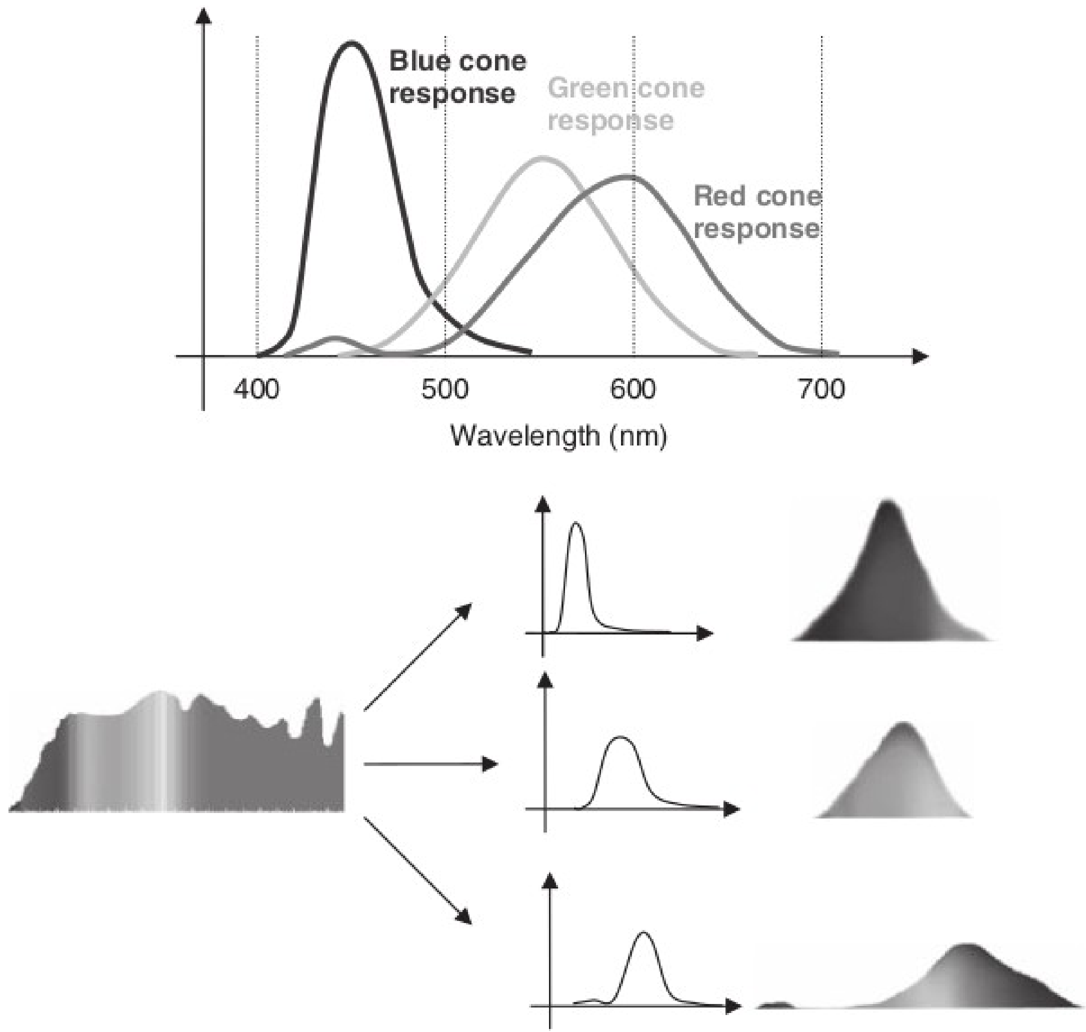


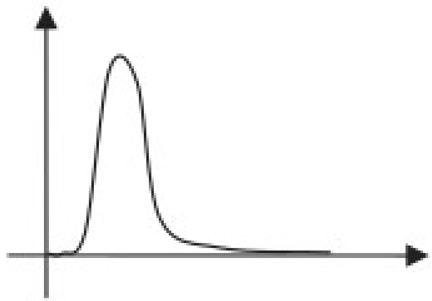
Figure 4.5 Top figure shows the cone response curve for blue,green and red. The bottom Figure shows the selective sensitivity for the white light spectrum.

The Tristimulus Vector

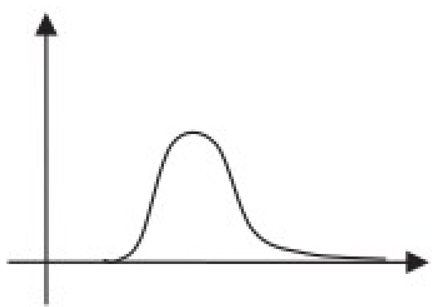
- Tristimulus vector represent the parametrics curve function and convolved with the spectral representation.
- Integral shown in figure 4.6 evaluate within the limit of the visible spectral wavelenghts, gives the energy of the spectrum, which is sensed by sensitivity curve of that cone.
- The different response are not the same for all people,but they do have similar overall structure.
- Two different people cant agree on which tomato from two tomatoes have reddest color.
- This is because the red cones can have minor differing responses in both individuals.

The Tristimulus Vector..

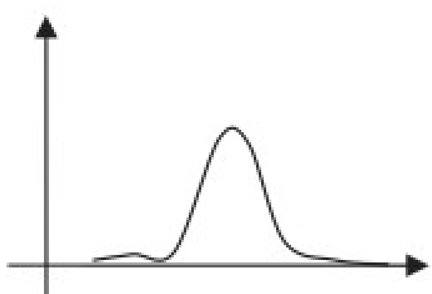
$$c = \int_{\lambda=400}^{\lambda=700} s(\lambda)\, f(\lambda)\, d\lambda$$



$$c_1 = \int_{\lambda=400}^{\lambda=700} s_1(\lambda)\, f(\lambda)\, d\lambda$$



$$c_2 = \int_{\lambda=400}^{\lambda=700} s_2(\lambda)\, f(\lambda)\, d\lambda$$



$$c_3 = \int_{\lambda=400}^{\lambda=700} s_3(\lambda)\, f(\lambda)\, d\lambda$$

Figure 4.6 Top equation shows a model of estimating the energy response of a cone with a response curve *s* for a give spectrum *f*. The following equations show the energy response From the blue,green and red cones. This three values are called the tristimulus vector.

The Tristimulus Vector...

- A spectrum is represented as an array of numbers that measured intensities at different wavelengths.
- This is analogous to a two dimensional plot with the x-axis showing the wavelengths present in the spectrum,and the y-axis showing the energy each wavelengths carries, in spectral power densities (SPD).

$$c_i = \sum_{j=400}^{j=700} s_i(\lambda_j) f(\lambda_j), \text{ defined for the three cones } i = 1, 2, 3$$

Figure 4.7 Tristimulus Vector Equation

The Tristimulus Vector....

$$f(\lambda) = \begin{bmatrix} f(\lambda_1) \\ f(\lambda_2) \\ .. \\ f(\lambda_n) \end{bmatrix} \qquad S = \begin{bmatrix} s_1(\lambda_1) & s_2(\lambda_1) & s_3(\lambda_1) \\ s_1(\lambda_2) & s_2(\lambda_2) & s_3(\lambda_2) \\ .. & .. & .. \\ s_1(\lambda_n) & s_2(\lambda_n) & s_3(\lambda_n) \end{bmatrix}$$

$$\begin{aligned} S^T f &= \begin{bmatrix} s_1(\lambda_1) \times f(\lambda_1) + s_1(\lambda_2) \times f(\lambda_2) + \ \ldots \ + s_1(\lambda_n) \times f(\lambda_n) \\ s_2(\lambda_1) \times f(\lambda_1) + s_2(\lambda_2) \times f(\lambda_2) + \ \ldots \ + s_2(\lambda_n) \times f(\lambda_n) \\ s_3(\lambda_1) \times f(\lambda_1) + s_3(\lambda_2) \times f(\lambda_2) + \ \ldots \ + s_3(\lambda_n) \times f(\lambda_n) \end{bmatrix} \\ &= \begin{bmatrix} \sum_i s_1(\lambda_i) f(\lambda_i) \\ \sum_i s_2(\lambda_i) f(\lambda_i) \\ \sum_i s_3(\lambda_i) f(\lambda_i) \end{bmatrix} \\ &= \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} \end{aligned}$$

Figure 4.8 c1, c2 and c3 is calculated from the spectral density and frequency wavelengths

The Tristimulus Vector…..

- The equation give the result of color sensation for the spectrum defined by *f*.
- It should be clear that if we have two spectral distribution *f1* and *f2,* and *f1=f2,* then this necessarily means that *f1* and *f2* give same sensation of color.
- This result is important because it now allows the color problem to be simplified.
- If the recording instrument is recording a spectral energy distribution f and the rendering device is generating s spectral energy distribution *g*, we g has to be generated with this equation and get the same result as *f*.

3. Color Calibration

- The previous part is used to calibrate capture devices and rendering devices.
- First we need to understand the working of capture device such as camera and any rendering device such as CRT or a projector.

Color Cameras

- Charge Couple Camera (CCD) proposed in 1970s and now is common in most modern applications.
- CCD sensor consist of a rectangular grid of electron-collection sites laid over a thin silicon wafer to record the amount of light energy reaching each of them.
- When light photons strikes the silicon, a charge is released proportional to the amount of light energy incident on the sensor area.
- Image is read out of the CCD one row at time,being transferred to serial output registers.
- Each sensor produce on value, which typically stored in 8 bit black and white images.
- For color images, each pixel location needs to have three samples based on trichromacity theory discuss before.

Charge Couple Device – CCD

- Ideally, each CCD sensor should sense all three filtered results, but practically only one of either red, green or blue filters is placed over each pixel area, allowing each CCD sensor to sense one part of the spectrum that is falling on it.
- The filter are not equally distributed but organized in a pattern known as bayer filter pattern, which has more green filters than red or blue.
- The bias toward green is because of the increased sensitivity needed for the green parts of the spectrum.

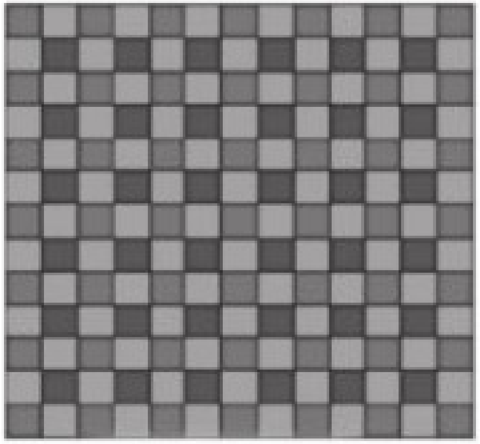
Bayer Filter

- The advantage of the bayer filter pattern method is that only one sensor is required and all color information (red, green, blue) is recorded simultaneously.
- One captured and digitized, the digital cameras need to use specialized demosaicing algorithms to convert the mosaic of separate colors recorded at each pixel into equally sized mosaic of true colors having a red, green and blue value at each pixel.
- The values are determined by averaging the values from the closest surrounding pixels.

Fovean and SONY RGBE System

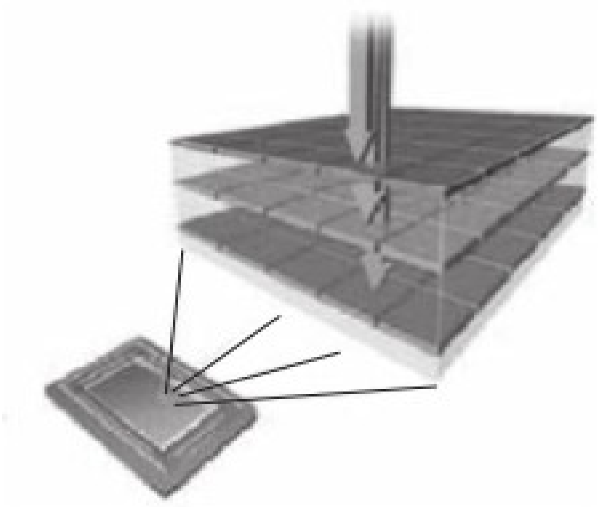
- The foveon systems capture red,green and blue values by embedding these different spectral photo detectors in the same location at all pixels on the silicon wafer.
- Fovean X3 technology works because red,green and blue light components each penetrate silicon to different depths to release the appropriate electrical charges.
- SONY use four filter,RGBE which bayer green filter have been split into two different filter to sense the green part of the spectrum more definitively by using additional emerald filter.

Color Cameras..

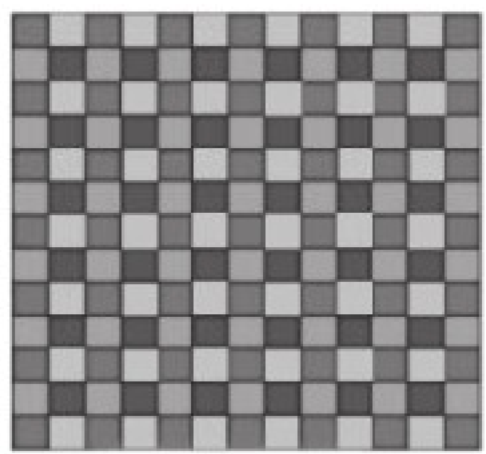


Bayer mosaic pattern

Bayer mosaic pattern overlaid on a CCD chip



Fovean X3 technology



RGBE mosaic pattern

Figure 4.9 Filters used in CCD imaging devices to Capture color. Upper left Is traditional bayer pattern. Upper right image shows The bayer overlaid on a silicon CCD image capture plane. The lower left image shows A tricolor capture at every Pixel using Fovean X3. The lower right image shows SONY’s modified beyer filter known as RGBE filter.

CCD Light Filter and Sensing

- CCD need to filter incoming light ray, before sensing.
- Filters are physically manufactured elements, which are transparent and coated with material that blocks a certain part of the spectrum.
- The output of these filters is then further sampled and quantized producing values a_1,a_2,$a_{3.}$ (remember a_1,a_2 and a_3 are the output of the filter)
- The filter have response, which is shown as m_1,m_2 and m_3 for three different filter.
- Different filter m_1,m_2,m_3 will produce different value a_1,a_2,a_3.
- Thus, how a spectrum is translated into a trinumber representation largely depends on the filter used and their response.

Rendering Devices

- Visual display devices attempt to create various spectra, using three electron guns in the case of CRT.
- The guns p_1,p_2,p_3 correspond to a monochromatic wavelength in the red, green and blue areas of the spectrum,respectively.
- The output that generated is a monochromatic spectra g_1,g_2,g_3.
- This known as RGB system,where all three guns simultaneously focus on a particular area of the phosphor screen and combine to produce a spectrum $g = g_1 + g_2 + g_3$.
- The spectrum is perceived by the observer to have color corresponding to $S^T g$.

Rendering Devices..

- Rendering devices produce different spectra that correspond to different colors.
- This is done by applying voltage gains v_1, v_2, v_3 to the guns p_1, p_2 *and* p_3.

$$g = g_1 + g_2 + g_3 = v_1p_1 + v_2p_2 + v_3p_3 = vp$$

- P1,p2 and p3 are known as primaries and correspond to fixed wavelengths.
- Every display device has a fixed set of primaries.
- Changing this primaries will lead to changing the spectrum and consequently with voltage gains it will, different perception of colors produced by the display system.

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Rendering Devices...

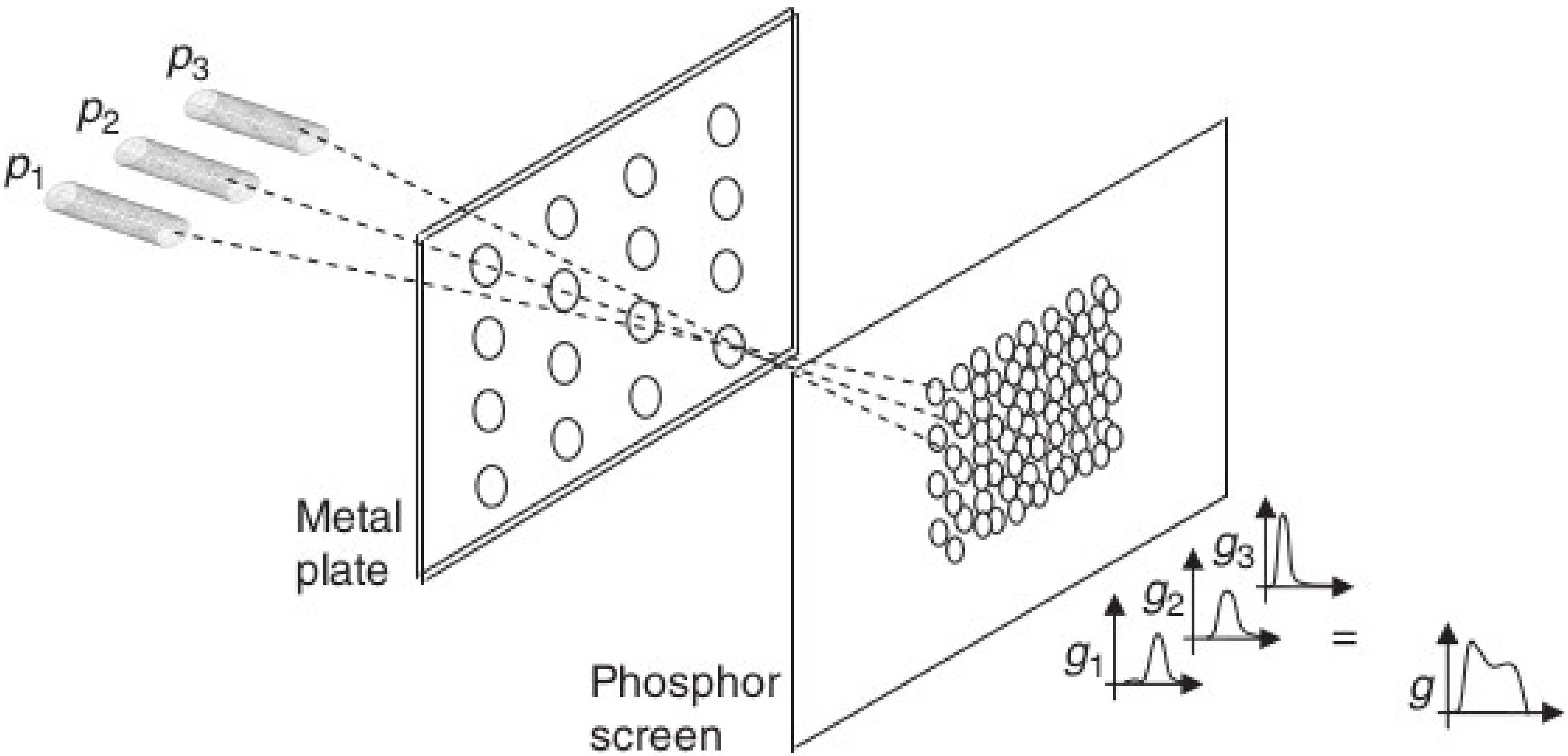


Figure 4.10 A Typical CRT system showing primaries p_1,p_2,p_3. The individual spectra g_1,g_2 and g_3 produced by them get additively mixed to produce a combined spectrum g, which the observer will perceived as a color.

LCD and Plasma Display Technology

- Plasma technology works by sending electric pulses to individual pixel cells.
- These pulses excite xenon and neon gases,which then emit light.
- This light activates the proper ratio (software defined) of red, green and blue phosphors in each cell.
- Liquid crystal filled cells sandwitched between two sheet of glass receive voltage from an array of thin film transistor (TFT).
- LCD TV use a subtractive color process. They selectively block wavelengths from the broad spectrum to achieve the right color mix.

LCD and Plasma Display Technology..

- Plasma screen have a better, darker black and the dynamic range (between white and black), also called contrast is higher.
- The viewing angle is wider for plasma than for LCD screen.
- Plasma screen are better in than LCDs at playing fast moving video.
- Plasma TVs consume about 33% more power than LCD at equivalent resolution

The Calibration Process

- Objectives of calibration process is to ensure that the spectrum g, which is produce by the display device, generate the same color perception as the spectrum f, which was captured by the camera. So we need:

$$S^T g = S^T f$$

- Camera capture a1,a2,a3 for a spectrum f falling at a pixel location.
- This use as voltage gain for the primaries in the display devices to produce the spectrum g.

$$g = g_1+g_2+g_3 = a_1 p_1 + a_2 p_2+a_3 p_3$$

$$g=Pa$$

- Display devices have a choice of primaries, whereas cameras have a choice of filters.

The Calibration Process..

- To make $S^T g = S^T f$, the primaries p_1, p_2, p_3 and the filter outputs a_1, a_2, a_3 have the following relationship.

  $S^T g = S^T f$ *and* $g = Pa$

  $S^T Pa = S^T f$

  $a = (S^T P)^{-1} S^T f$

- To achieve the same color sensation,the primaries and the filters (m_1, m_2, m_3) have to be related.
- The CIE – commission Internationale de I'Eclairage solves this by fixing primaries to predefined standard values.
- If p_1, p_2 and p_3 are fixed for all devices, the filter responses m_1, m_2, m_3 can be computed.
- This require unknown value of *S* matrix, m_1, m_2 *and* m_3 can be computed by having and observer perform the function of *S*.
- This is done by color matching experiment.

$$a_i = \int_{\lambda=400}^{\lambda=700} m_i(\lambda) f(\lambda)\, d\lambda, \text{ or in discrete quantities}$$

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = M^T f = \begin{bmatrix} \sum_i m_1(\lambda_i) f(\lambda_i) \\ \sum_i m_2(\lambda_i) f(\lambda_i) \\ \sum_i m_3(\lambda_i) f(\lambda_i) \end{bmatrix}, \text{ where } M = \begin{bmatrix} m_1(\lambda_1) & m_2(\lambda_1) & m_3(\lambda_1) \\ m_1(\lambda_2) & m_2(\lambda_2) & m_3(\lambda_3) \\ .. & .. & .. \\ m_1(\lambda_n) & m_2(\lambda_n) & m_3(\lambda_n) \end{bmatrix}.$$

CIE Standard and Color-Matching Function

- The variation of primaries in the display devices, with the variation of filters in capture devices makes it impractical to manufacture standardized capture and display devices such that colors captured by any capture device match the color rendered by any display device.
- CIE solved this problem by proposing that the primaries p1,p2,p3 be fixed and open for the way to establishing an internationally agreed upon system for color.
- The primaries selected by CIE were p_1=700.0 nanometers (red), p_2 = 546.1 nanometers (green) and p_3 = 435.8 nanometers (blue).
- The fixed p1,p2 and p3 primaries values made it possible to calibrate filter responses.
- This need color matching experiment.

Color-Matching Experiment

- Has a setup where CRT based rendering device is capable of rendering colors using fixed primaries.
- This color is perceived as $S^T g$, where the spectrum g is generated as $g = a_1 p_1 + a_2 p_2 + a_3 p_3$.
- Here a_1,a_2 and a_3 are gains applied to primaries.
- Observer can control all this a to generate different spectra and observe different colors.
- In the experiment, observer is shown a spectrum f and is made to adjust a_1, a_2 *and* a_3 so that the spectrum generated at the CRT using CIE defined primaries and the observer inputs a_1, a_2 *and* a_3 have the same color sensation as the spectrum f shown to him.
- In other words,the observer is ensuring that $S^T g = S^T f$.

Color-Matching Experiment..

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = M^T f = \begin{bmatrix} m_1(\lambda_1) & m_1(\lambda_2) & \ldots & m_1(\lambda_n) \\ m_2(\lambda_1) & m_2(\lambda_2) & \ldots & m_2(\lambda_n) \\ m_3(\lambda_1) & m_3(\lambda_2) & \ldots & m_3(\lambda_n) \end{bmatrix} \times \begin{bmatrix} f(\lambda_1) \\ f(\lambda_2) \\ \vdots \\ f(\lambda_n) \end{bmatrix}$$

- In above equation, the M matrix is unknown. We can compute $f(\lambda_1)$,$f(\lambda_2)$,….$f(\lambda_1)$ values via spectrometer.
- The observer adjust the a1,a2 and a3 values to make the colors match and each color reading yields three equations.
- From here we can obtain function m1,m2 and m3.
- There three responses provide a way to map any input spectrum to a tristimulus representation in a CIE based called the XYZ color space.

CIE based XYZ Color Space

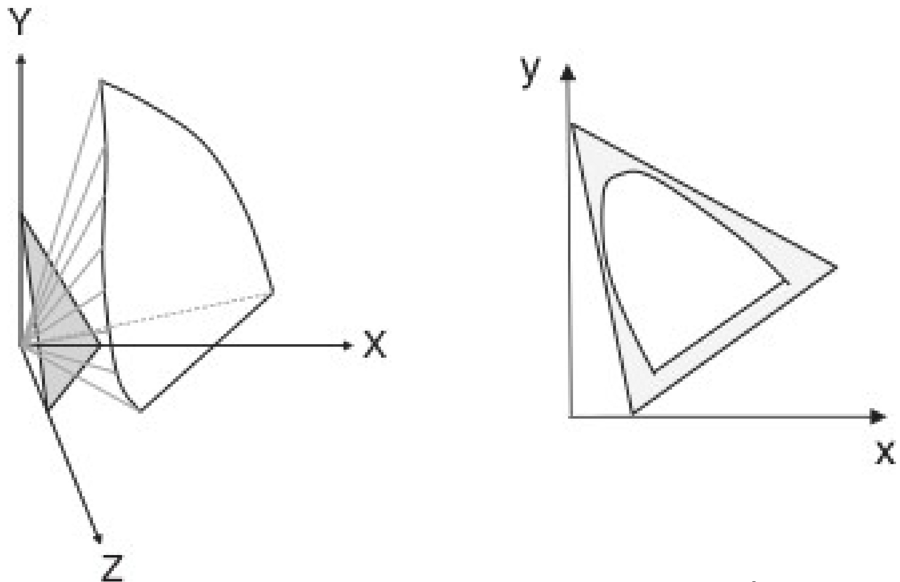


Figure 4.11 The left image shows the volume of all visible colors in CIE XYZ coordinate space. This is a cone with its vertex is at the origin. Usually, it is easier to suppress the brightness of a color, which we can do because perception of color is approximately linear. We do this by intersecting the cone with the plane X ⩽ Y ⩽ Z ⫽ 1 to get the CIE xy chromaticity space shown in the image to the right.

- Figure 4.11 shows a visualization of this XYZ color space, which arrived at when m_1,m_2 and m_3 values are plotted on three axes.
- XYZ color space are not physically realizable, only exists in a mathematical realm, but it can represent all the colors of the visible spectrum.
- This space is typically used to study color ranges and representations of other color spaces, but it cannot be used in practice. Next section present practical color space.

4. Color Space – CIE XYZ Color Space

- This space allows colors to be expressed as a mixture of the three tristimulus values x,y,z which are the color matching function.
- The CIE defined the primaries so that all visible light maps into positive mixture of X,Y and Z and so that Y correlates approximately to the apparent lightness of color.
- Other color space can be generated from XYZ color space. XY color space is generated which remove the luminous (lightness) from the space in the 2D space.
- Color is usually described by xyY coordinates,where x and y determine the chromaticity and Y the lightness component of color.

CIE XY Color Space..

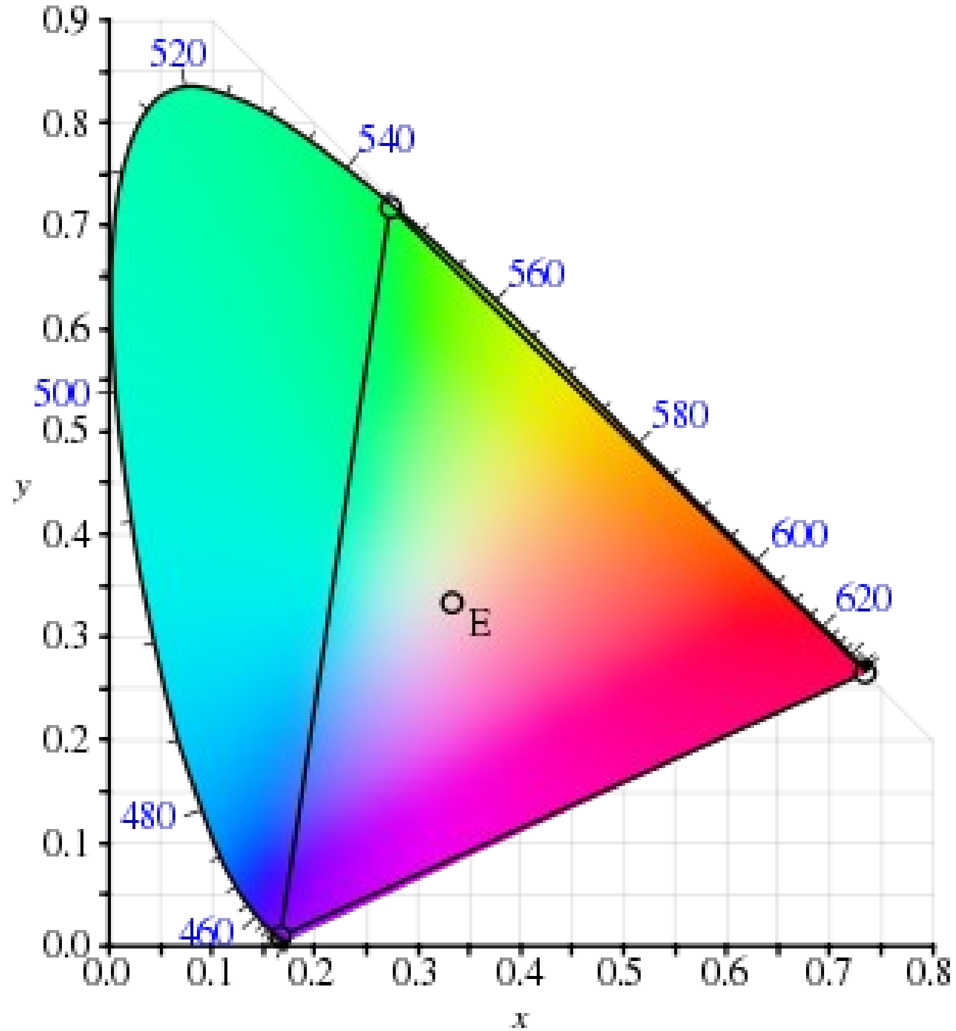
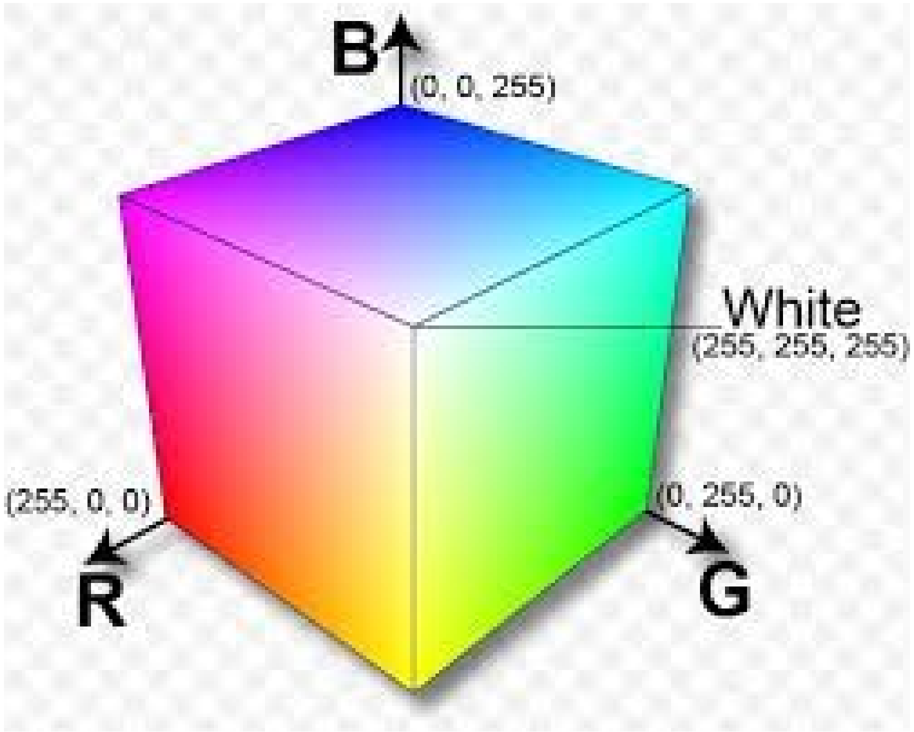


Figure 4.12 XY Color Space

RGB Color Space

- RGB color space is a linear color space that formally uses single wavelength primaries (645.16nm for R,526.32nm for G, 444.44nm for B).
- Different spectra are generated by voltage gains applied to these primaries, and resulting colors are represented as a unit cube, whose edges represent the R,G and B weights.
- Red usually shown as the x-axis,green being the y-axis and blue being the z-axis.
- RGB color is the system used in almost all color CRT and is device dependent.
- It is called additive because the three different primaries are added together to produce the desired color.

RGB Color Space..



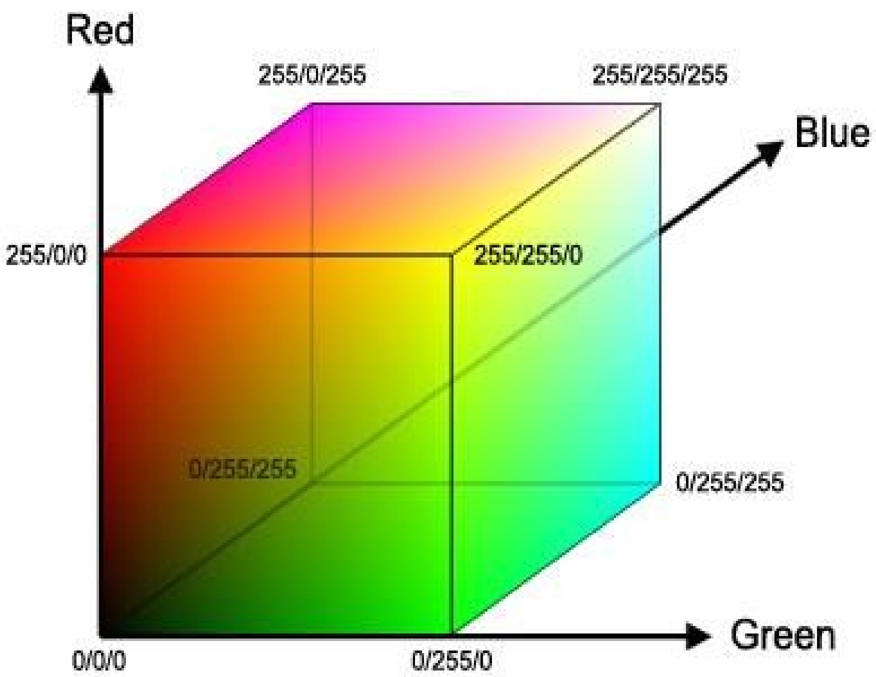


Figure 4.13 RGB Color Space. Black is 0,0,0 and white is 1,1,1

CMY or CMYK Color Space

- CMY color space stands for cyan,magenta and yellow, which are the complement of red, green and blue.
- This system is used for printing.
- It also referred as CMYK color space,when it refers to black as part of it.
- CMY colors are called subtractive primaries, white is (0,0,0) and black is (1,1,1)
- Using CMY is easier to print black pigments on paper.

CMY or CMYK Color Space..

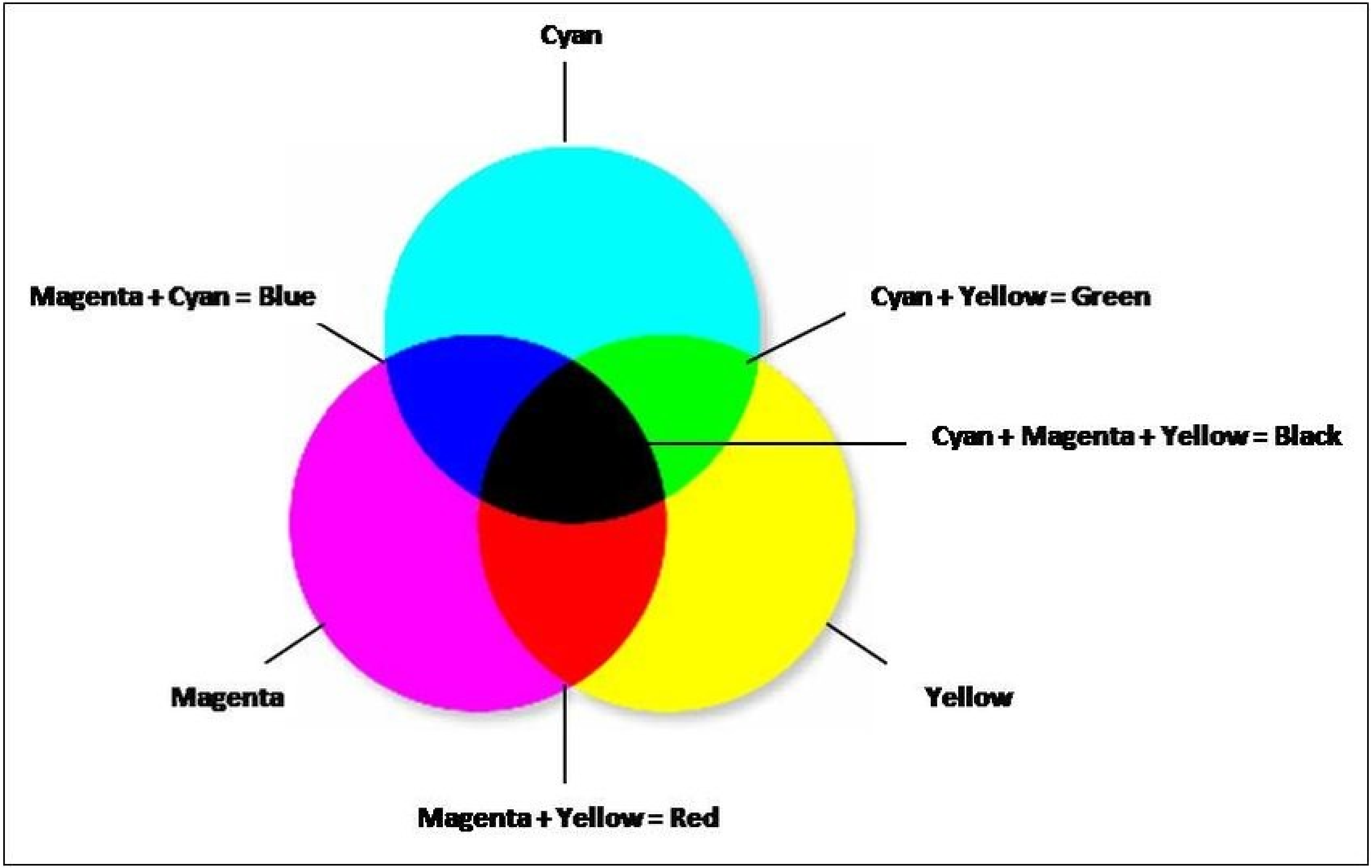


Figure 4.14 CMY color space

CMY or CMYK Color Space..

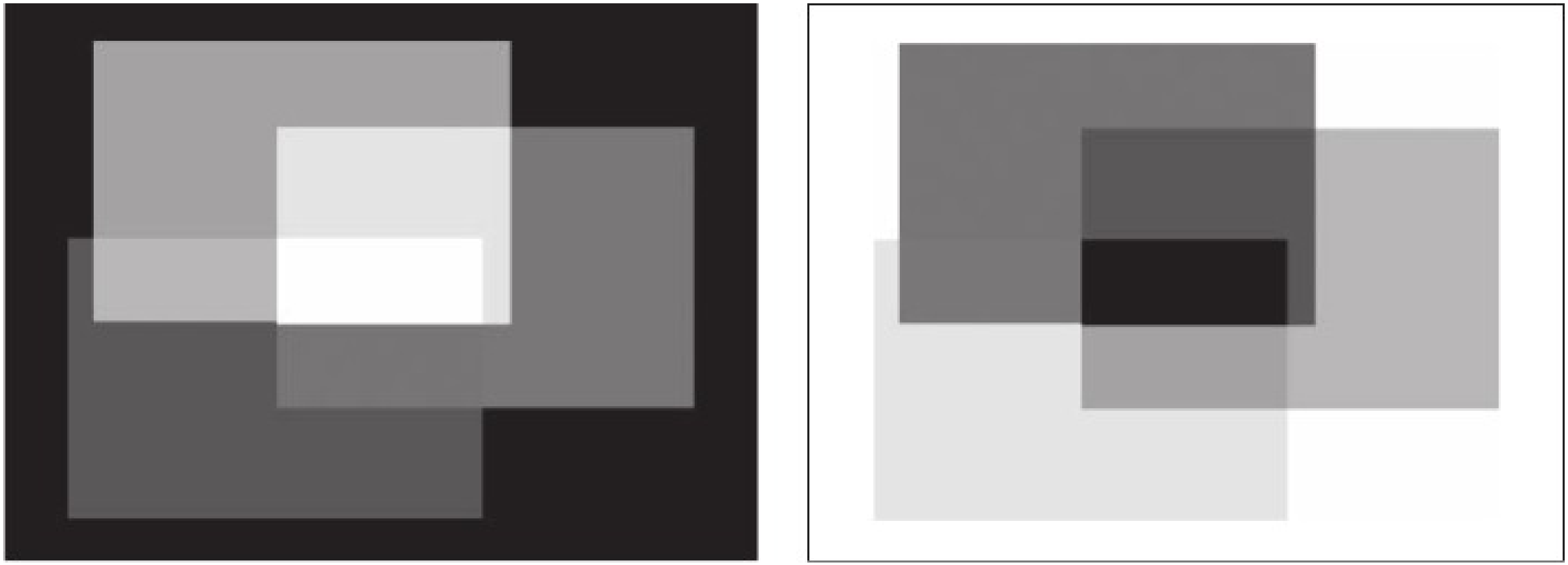


Figure 4.15 Additive (left) and subtractive (right) color mixing. In additive color mixing, the left Figure shows the outer black (no color) rectangle with three primary RGB rectangles. Their additive effects are shown. In the substractive case (right), the outer rectangle is white (no color) and the three CMY rectangle have subtractive effect as shown.

CMY in Printing

- All document normally stored in RGB.
- For printing, this document need to be converted to CMYK color space.
- Printing device use inks that correspond to cyan,magenta, yello and black pigments.
- The final image is achieved by printing each color plate,one on top of another in a sequential manner.

CMY in Printing..

- All document normally stored in RGB.
- For printing, this document need to be converted to CMYK color space.
- Printing device use inks that correspond to cyan,magenta, yello and black pigments.
- The final image is achieved by printing each color plate,one on top of another in a sequential manner.

YUV Color Space

- YUV and YIQ are standard color spaces used for analog tv transmission.
- Y is linked to the component of luminance and U and V or I and Q are linked to the components of chrominance.
- Y comes from from XYZ standard explained before.
- YUV space have very practical bandwidth saving usage.
- RGB space can be transformed easily into these sets of spaces by a simple linear transform.

HSV Color Space

- The representation of colors in the linear space mention before – XYZ,RGB,CMY are designed for devices to make capture,rendering and printing possible.
- But for human observer, the color properties that important are:
  - ***Hue*** – The property of a color that varies in passing from red to green. Roughly speaking, hue represents the dominant wavelength in spectral power density of that color.
  - ***Saturation*** – The property of a color that defines the colorfullness of an area judged in proportion to its brightness. Eg: Red is more saturated than pink. The more spectral energy concentrated at one wavelength, the more saturated the color. The color can be desaturated by adding light that contains power power at all wavelength (white).
  - ***Brightness/Value*** – is the property that varies in passing from black to white.

HSV Color Space..

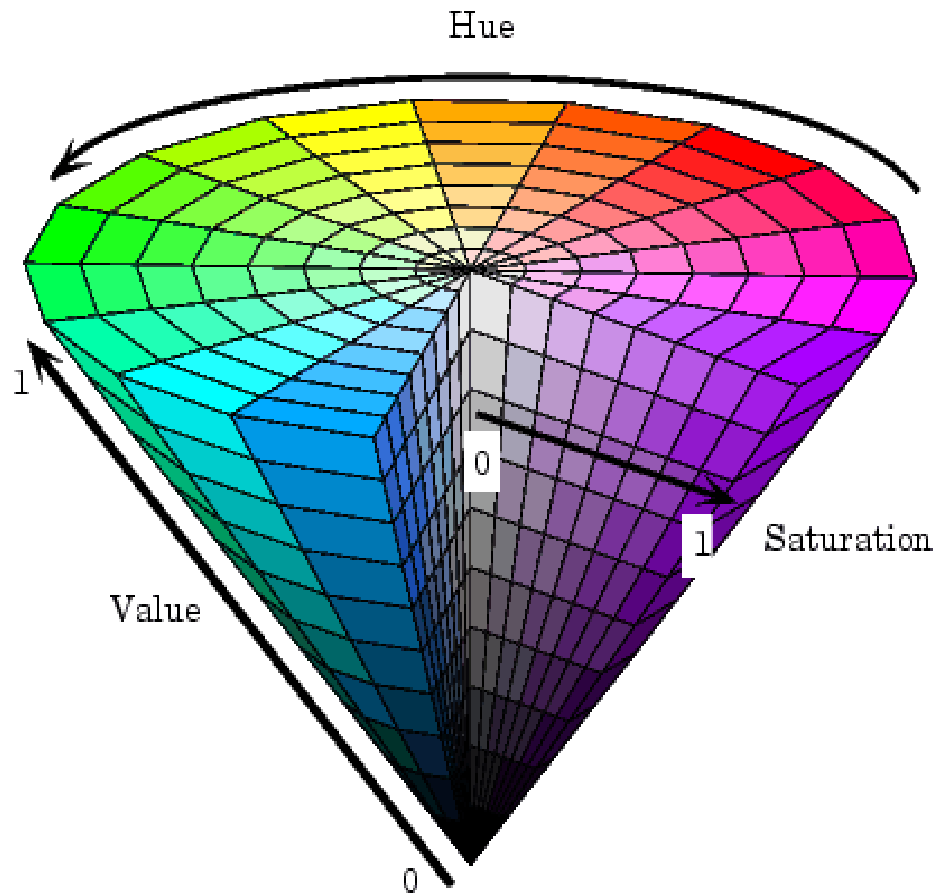


Figure 4.16 HSV Color Space

Uniform Color Space

- A uniform color space is one in which the distance in coordinate space accurately reflects the perceived difference between the colors.
- In such a space,if the distance in coordinate space were below some threshold, a human observer would not be able to tell these colors is different.
- CIE LUV and CIE LAB are examples or uniform color space that obtained from transforming (X,Y) color space.

5. Gamma Correction and Monitor Callibration

- The displayed color tends to look dimmer than in the original photograph.
- Brighter colors are perceived to be dimmer than darker colors.
- Generated color is normally adjusted by nonlinearly increasing (or decreasing) the voltage applied to the primaries of the device.
- This adjusting process is called gamma correction Typical CRT displays have gamma values between 1.5 and 3.0 and the value is constant for all the channels; 2.2 is a frequently used standard. Some graphics hardware partially compensates for this response function, bringing the effective system gamma down to 1.8 or 1.4. The correct display of images, whether computer-generated or captured, requires proper correction for the system’s gamma response.

Conclusion

- This chapter present the fundamentals idea and theories in understanding colors.