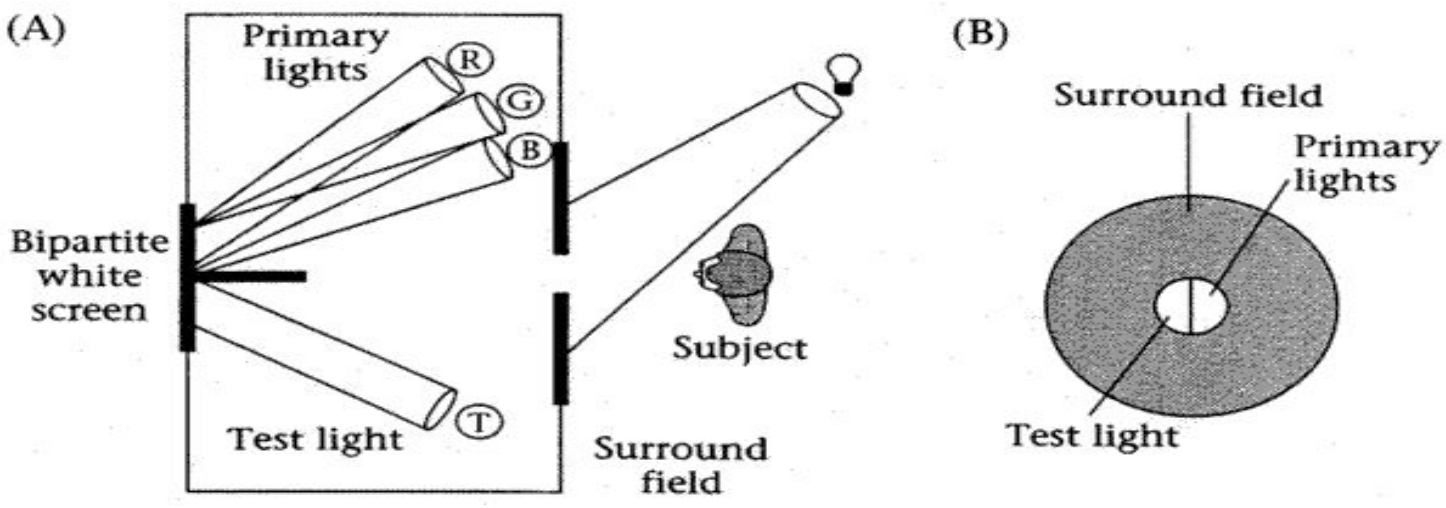
Color Matching Functions
From rgb to xyz

CIE -Commission Internationale de L'Éclairage

- INTERNATIONAL COMMISSION ON ILLUMINATION
- Advancing knowledge and providing standardisation to improve the lighted environment
- The International Commission on Illumination - also known as the CIE from its French title, the Commission Internationale de l´Eclairage - is devoted to worldwide cooperation and the exchange of information on all matters relating to the science and art of light and lighting, colour and vision, and image technology.
- With strong technical, scientific and cultural foundations, the CIE is an independent, non-profit organisation that serves member countries on a voluntary basis. Since its inception in 1913, the CIE has become a professional organization and has been accepted as representing the best authority on the subject and as such is recognized by ISO as an international standardization body.

Color Matching Experiment



http://www.ling.upenn.edu/courses/ling525/color_vision.html

Wright (1929) & Guild (1931)

- Published results of color matching experiments separately.

V. *The Colorimetric Properties of the Spectrum.*

By J. Guild, *A.R.C.S., F.Inst.P., F.R.A.S., National Physical Laboratory.*

(*Communicated by Sir* Joseph Petavel, *F.R.S.*)

(Received February 19, 1931—Read April 30, 1931.)

Introduction.

Those properties of the eye which determine its behaviour in the measurement of luminous intensity and colour are completely defined by two sets of numerical data which express, as functions of wave-length, its behaviour to monochromatic radiation throughout the visible spectrum in respect of these two aspects of the visual effect of a stimulus. The first of these functions is embodied in the " Relative Visibility "* curve of the spectrum, and the second is embodied in a curve showing the locus of the spectrum on the " colour triangle " of some trichromatic system.

These two functions may be combined to give the " mixture curves " of the spectrum, by means of which we can calculate both the photometric and colorimetric values of any stimulus from its spectral energy distribution.

The nature and significance of these various functions are sufficiently well understood to need no explanation here.

The visibility function of the normal human eye has been known to a high degree of accuracy for some time, and in 1924 the International Commission of Illumination agreed to accept, as representing the normal eye for photometric purposes, a set of data based on an analysis of all the modern determinations.† Except for some uncertainty at the two extremities of the spectrum these data are unquestionably closely representative of the normal eye.

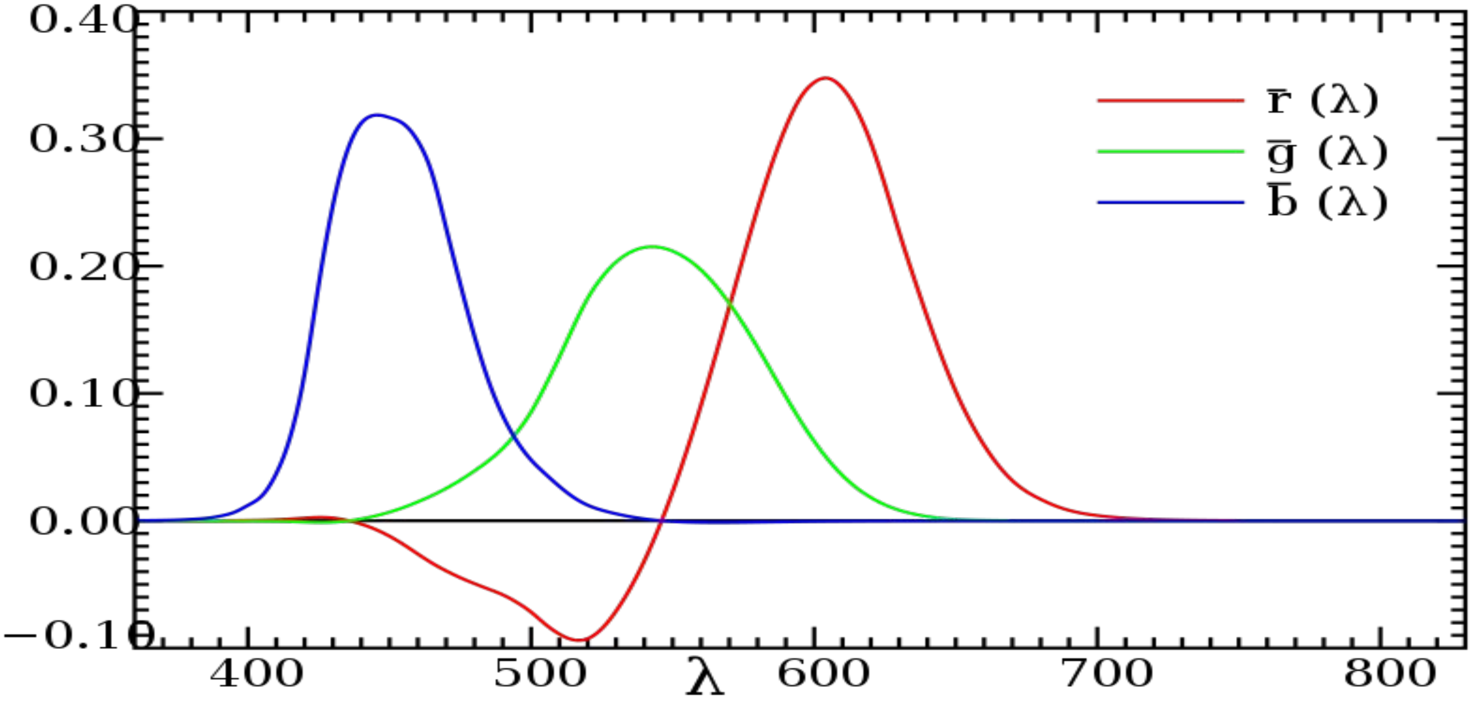
No such accumulation of data exists for the colorimetric properties of the eye. Clerk Maxwell‡ first determined the spectrum locus on a colour triangle constructed in accordance with Newton's law of colour mixture, and also deduced mixture curves of the spectrum for himself and his assistant, using as primaries spectral radiations of wave-lengths 0·6307 μ, 0·5286 μ and 0·4573 μ, approximately.

* The writer is not alone in objecting to the use of the word " visibility " in connection with the luminosity function, but prefers to continue its use under protest until some more acceptable term is substituted by general agreement.

† ' Recuil des Travaux ' p. 67 (1924) ; see also K. S. Gibson and E. P. Tyndall, ' Bur. Stds. Sci. Papers,' No. 475 (1923).

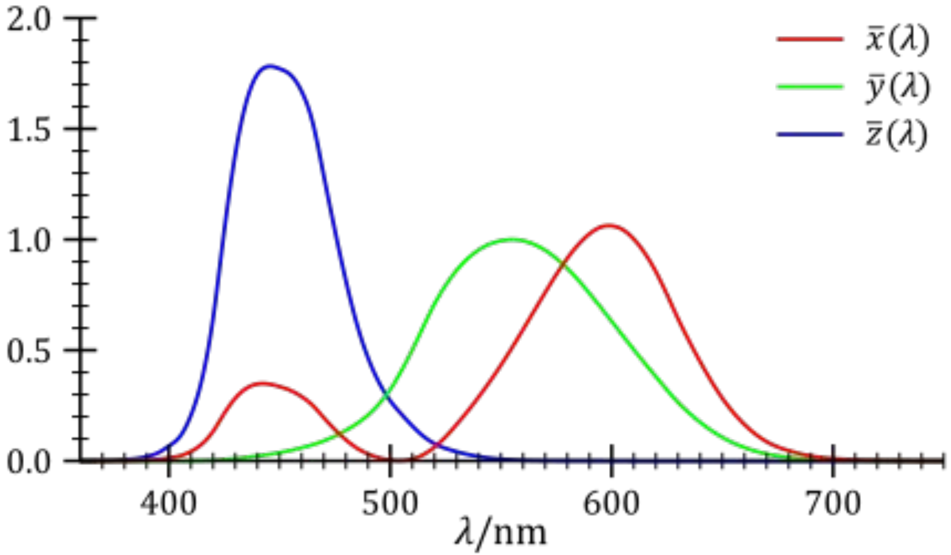
‡ ' Sci. papers,' vol. 1, pp. 410–444 ; ' Phil. Trans.,' vol. 150, p. 67 (1860).

Color Matching Functions



Due to the analytic limitations of the times, there was a need to recast the CMF's into an all-positive set

- This led to the establishment in 1931 of the CIE Standard Human Observer



Conversion from rgb to xyz

$$\begin{bmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{bmatrix} = \begin{bmatrix} 0.49000 & 0.31000 & 0.20000 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00000 & 0.01000 & 0.99000 \end{bmatrix} \begin{bmatrix} \bar{r}(\lambda) \\ \bar{g}(\lambda) \\ \bar{b}(\lambda) \end{bmatrix}$$

An interesting account of the CIE Meeting in which the proposed XYZ color matching functions was discussed by Brill et al. (1997)

How the CIE 1931 Color-Matching Functions Were Derived from Wright–Guild Data

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Abstract: The principles that guided the founders of the CIE 1931 system for colorimetry are examined. The principles are applied to the Wright–Guild experimental determinations of the color mixture data to show in detail how and why each step in the development of the CIE 1931 system for colorimetry came about. These steps are examined in the light of 65 years advanced knowledge of colorimetry. The necessity for each of these principles in the modern world is examined critically to determine whether one might hold to the same principles if the system were being freshly formulated today. © 1997 John Wiley & Sons, Inc. Col Res Appl, 22, 11–23, 1997.

Key words: CIE; CIE 1931 system; colorimetry; transformation; Wright–Guild data; color-matching; spectrum locus; alychne; primary colors; chromaticity diagram

INTRODUCTION

At 9:30 a.m. on September 18, 1931, a meeting of the Colorimetry Committee of the Commission Internationale de l'Éclairage convened at Trinity College, Cambridge, England.[1] Present were 21 delegates from six countries: France, Germany, Great Britain, Japan, the Netherlands, and the United States. John Guild opened the meeting with apologies that the agendum circulated in advance was by then out of date. He noted, however, that CIE rules then in effect allowed countries four months after the vote for national consideration. Then he presented five revised resolutions to the Committee. Those five resolutions would prove in retrospect to be the most important single event ever to occur in colorimetry, because they would set the colorist's agenda for the next 65 years, and into the foreseeable future. In fact, resolutions of any sort could have been adopted only if the two English-speaking nations could come to agreement upon them. This was because in the period after the First World War, with the devastation of the European continent, colorimetry did not have a very prominent position in Europe. Virtually all seminal writings from this period came either from the United States or from Great Britain. In the week previous to the Cambridge meeting, Guild, T. Smith (his deputy at the National Physical Laboratory), and Irwin G. Priest (Chief of the Colorimetry Division of the U.S. National Bureau of Standards) hammered out the differences between the views of the delegates of these two nations. This agreement set the stage for the presentation of the revised resolutions.

First Resolution

The first of the resolutions offered to the 1931 meeting defined the color-matching functions of the soon-to-be-

* Correspondence to: Mr. Hugh S. Fairman

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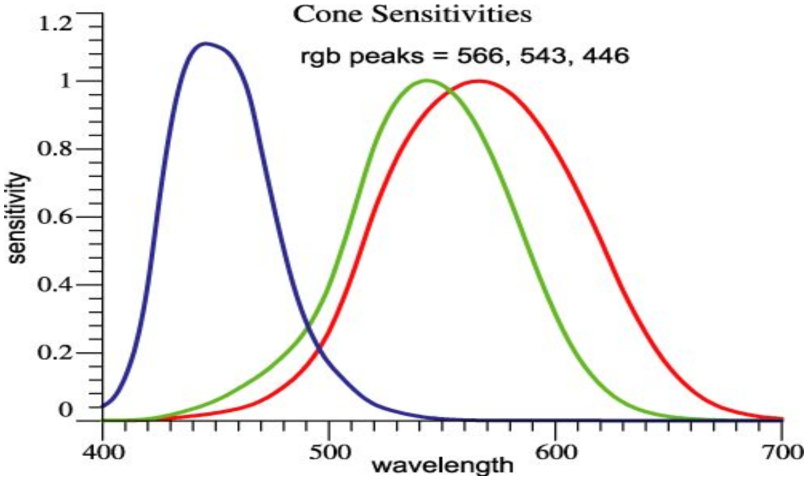
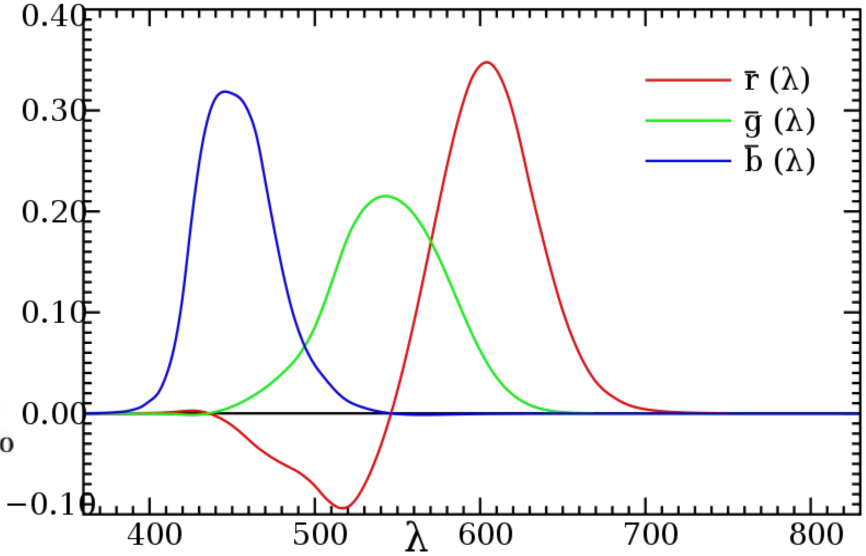
Cones vs CMF

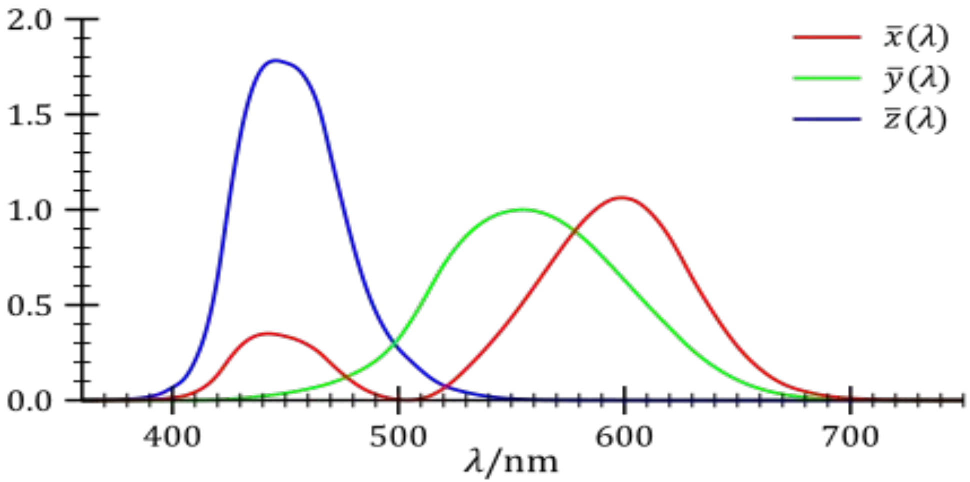


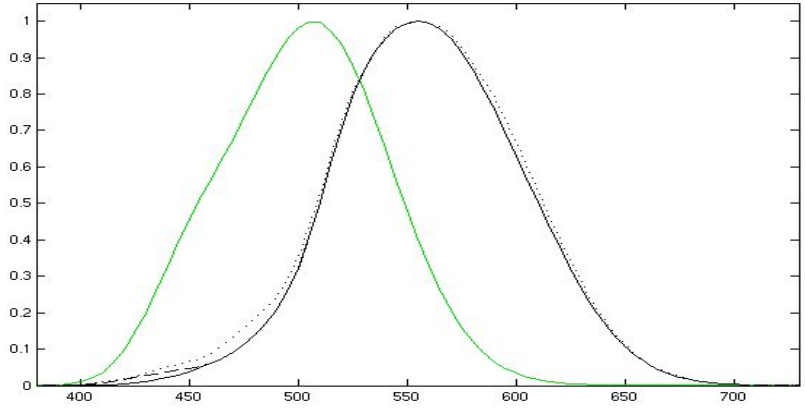
Cone sensitivities



Color Matching Functions

V – Luminance Function



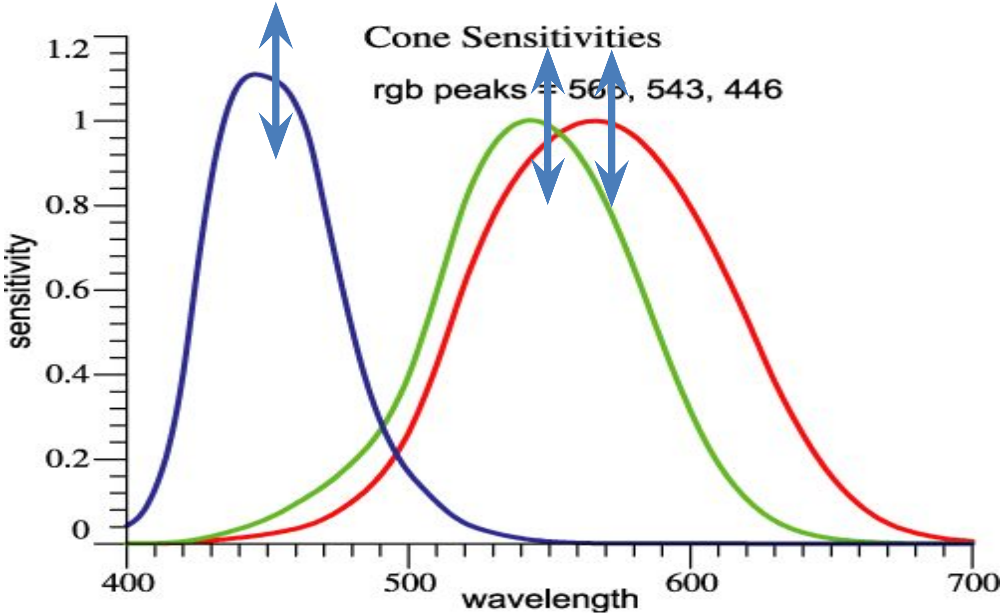


CIE xbar ybar zbar color matching functions

Luminance function V

Chromatic Adaptation

The brain can adjust the gain of the cone sensitivities independently.



Given a light spectrum P(λ) we can compute the Tristimulus Values XYZ

$$X = \int P(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int P(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int P(\lambda)\bar{z}(\lambda)d\lambda$$

Normalizing each tristimulus value by their sum we get the CIE xy Chromaticity Coordinates

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

$$z = \frac{Z}{X+Y+Z}$$

CIE xy

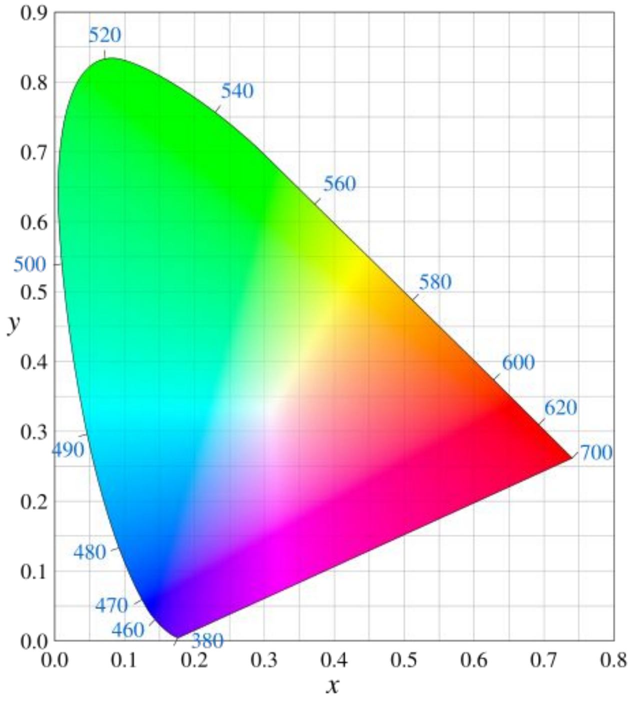
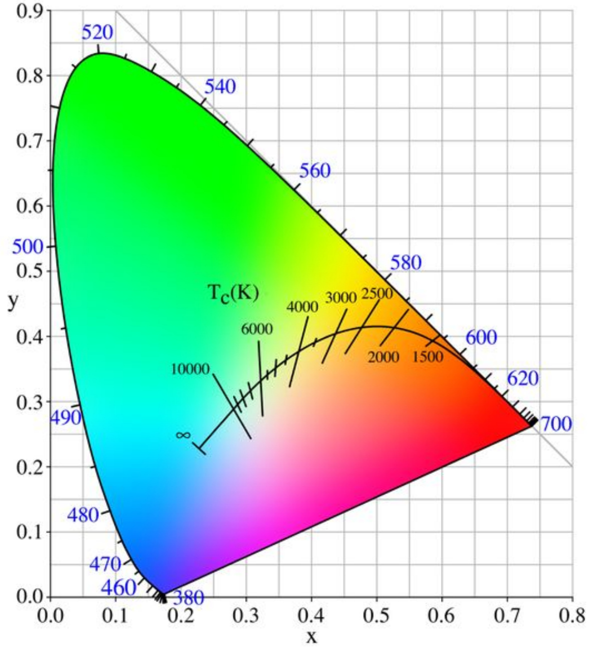


Image from Wikipedia

Individual Activity 6

1. Download the table for CIE Standard Human Observer 1964. Compute the CIE-xy chromaticity coordinates of monochromatic lights (Dirac delta) from 380nm to 780 nm in steps of 10nm and reproduce the boundaries of the CIExy Chromaticity Diagram. Embed an image of the color “tongue” on your plot.
2. Compute the CIE-xy chromaticities of a blackbody emitting from 1000K to 10,000K in steps of 1000K and plot in your CIExy chromaticity diagram. The collection of points showing the range of colors of a blackbody radiator is known as the Planckian Locus .

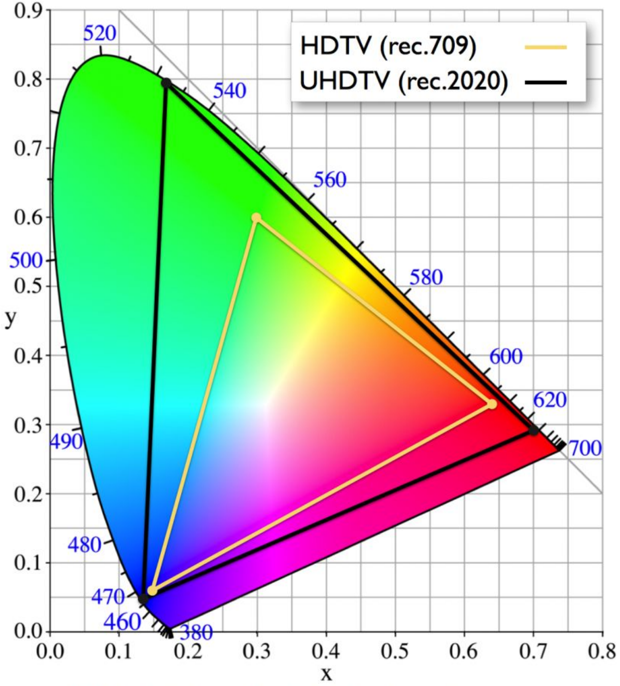


Expected result

Color reproduction

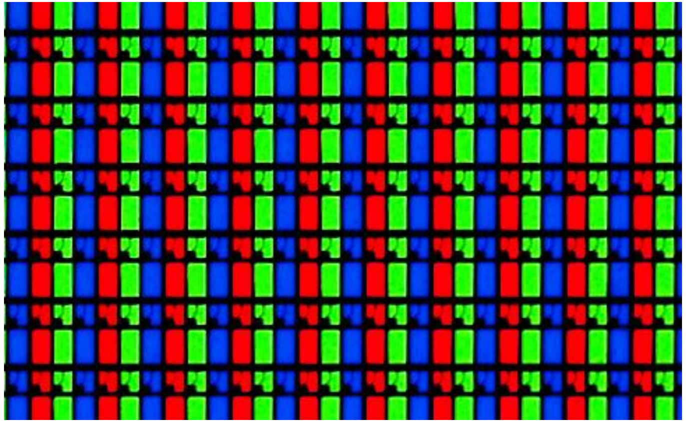
Recall Trichromaticity

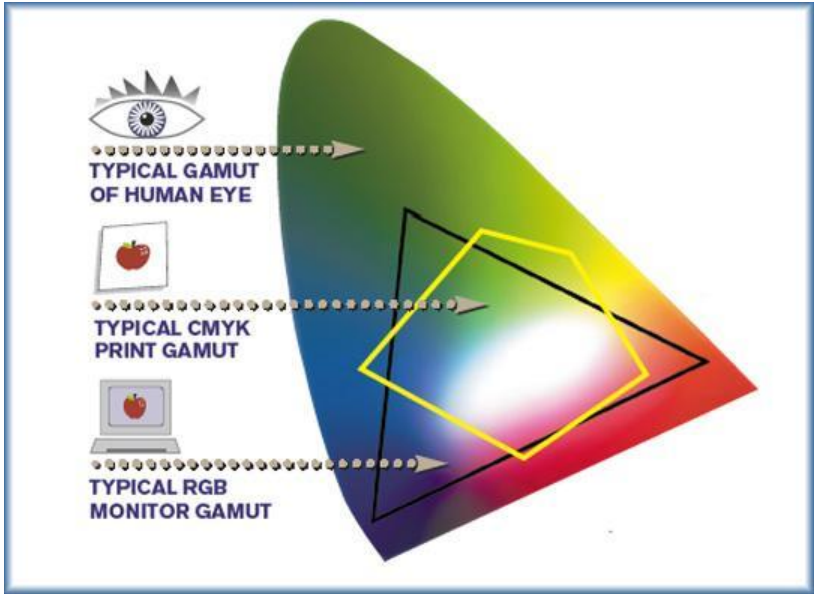
Gamut



UHDTV vs HDTV Color Gamuts

Primaries and Pigments




TYPICAL GAMUT
OF HUMAN EYE
TYPICAL CMYK
PRINT GAMUT
TYPICAL RGB
MONITOR GAMUT

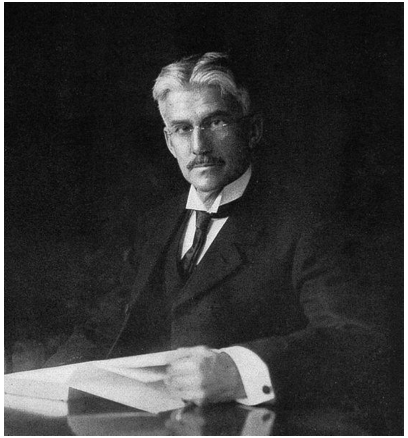
Group Activity 7

1. Set your laptop or computer monitor to display its primaries and measure the irradiance spectrum.
2. Compute the CIE chromaticity coordinates of the primaries and plot in the CIE tongue.
3. Display the gamut of your monitor display.
4. Measure the primaries of as many display devices as you can gather (laptop monitors, standalone monitors, projectors, smartphone displays) and compare their gamuts. Which display has the best color reproduction ability?

COLOR ORDER SYSTEM AND COLOR MATCHING FUNCTIONS

AP 187 Lecture

A. Color Order Systems



Albert H. Munsell
Image from Wikipedia

- Munsell Color Order System

Based on perceptual attributes of color.

- Hue
- Chroma (Saturation)
- Value (Lightness)

Munsell created his color atlas in conjunction with an artist who carefully painted samples to match Munsell's conception.

In 1929 the Optical Society of America commissioned a study to instantiate the Munsell colors into XYZ.

Munsell Color Order System

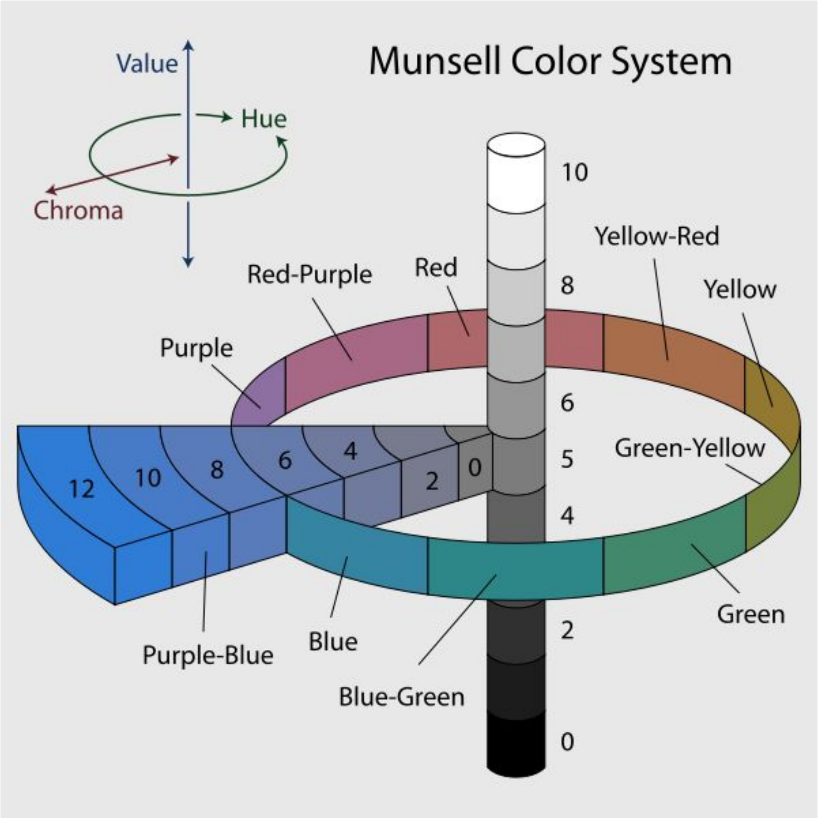
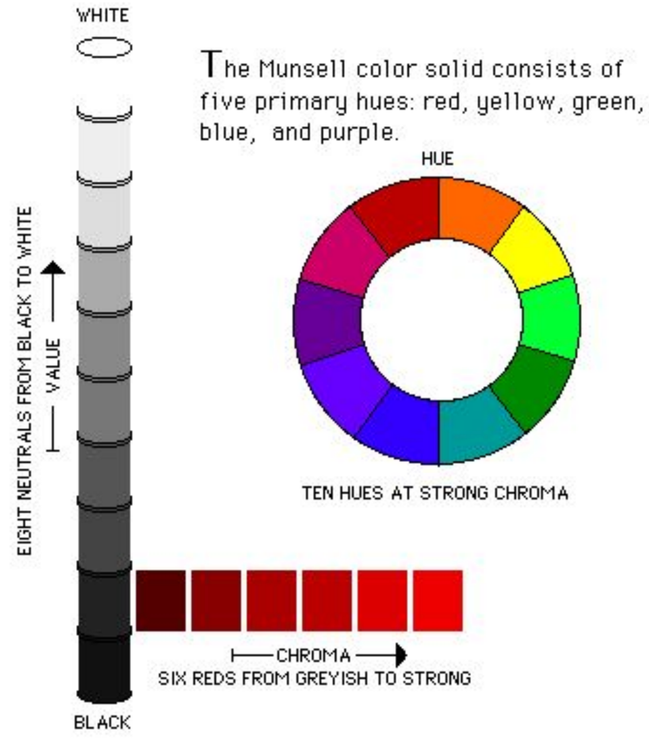


Image from Wikipedia

Munsell Hue

Circular scale based on 10 major hues

- Red (R)
- Yellow-Red (YR)
- Yellow (Y)
- Green-Yellow(GY)
- Green (G)
- Blue-Green(BG)
- Blue (B)
- Purple-Blue (PB)
- Purple(P)
- Red-Purple (RP)



Adapted with permission from San Diego Supercomputing Center, 1991.

Munsell Hue

The Hue Scale is further subdivided into a scale range of 1 to 10 with 5 the major hue itself.

A digit-letter notation is used to specify Munsell hue.

Example: 2.5R means the 2.5 step R in major hue category Red.

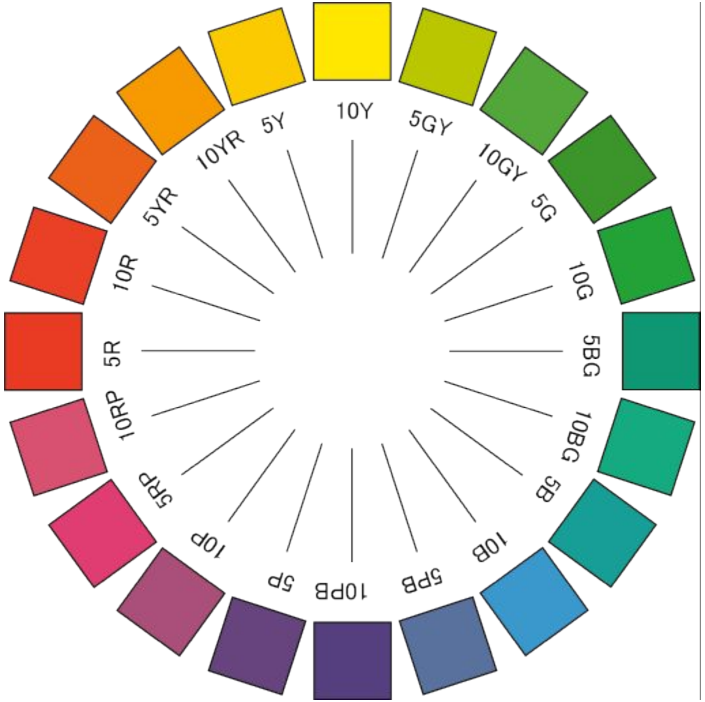


Image from http://igl.net.au

Munsell Chroma

- Starts from 0 to possible maximum chroma of each hue.
- O chroma indicates white, gray or black.
- The higher the chroma value, the purer the color.
- Equal steps on the chroma scale represent equal changes

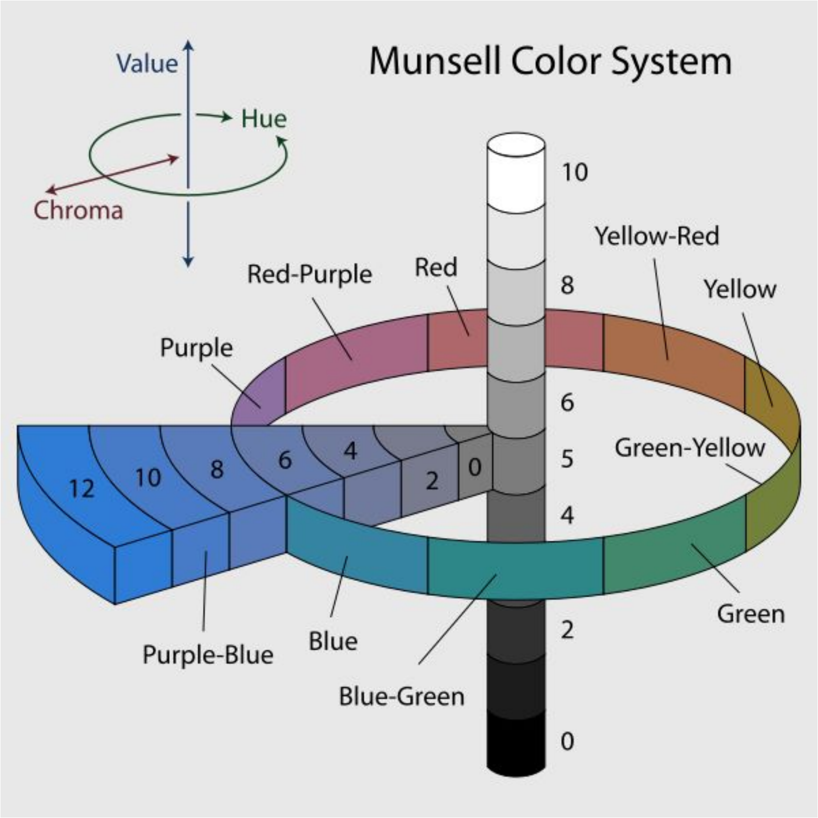
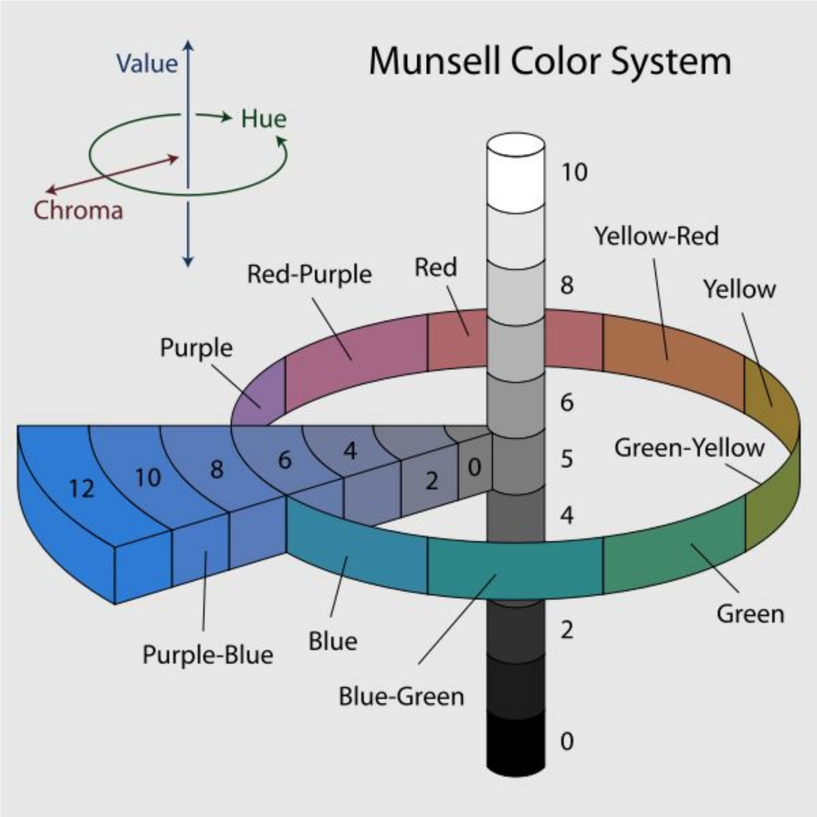


Image from Wikipedia

Value (Lightness)



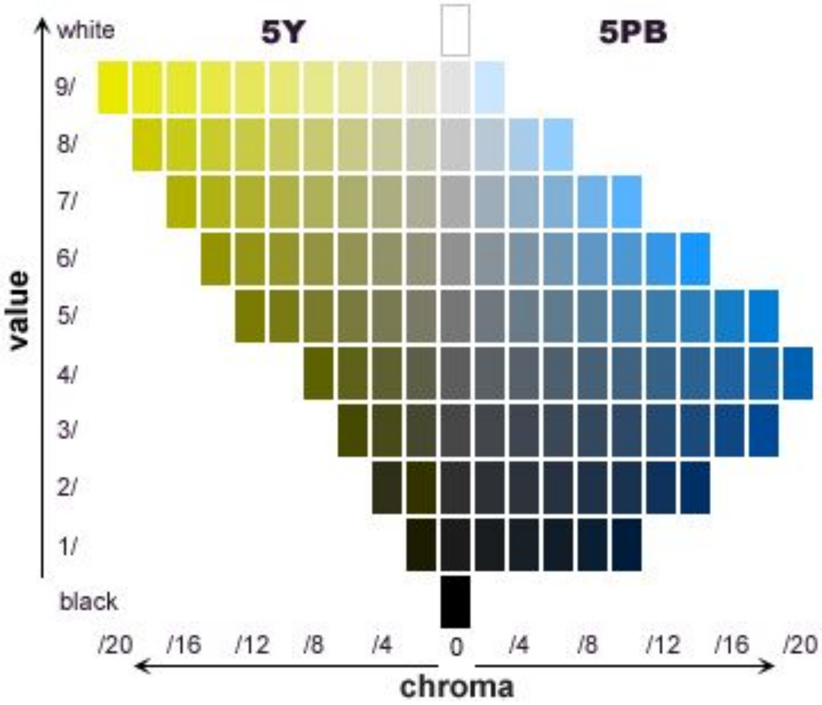
Numerical scale of lightness from 0 (black) to 10 (white)

Samples that differ in Munsell hue or chroma that have the same VALUE should be judged to represent equal changes in perceived lightness.

Image from Wikipedia

Munsell Notation

- Hue Value/Chroma
  - 2.5R 8/4 means
    - 2.5 Red
    - Value 8
    - Chroma 4

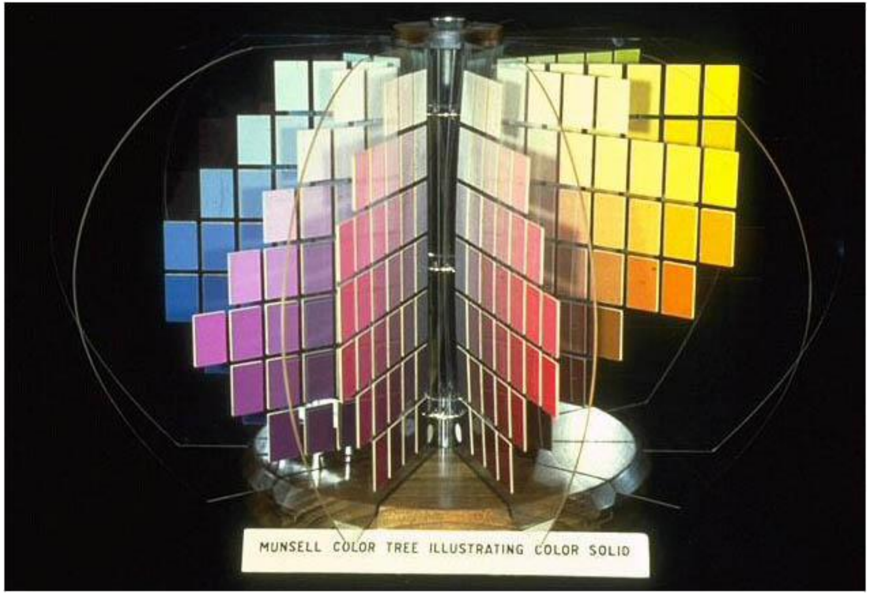


Letter N denotes neutral samples and chroma value is omitted
N 8/
Neutral sample value 8 chroma 0.

Munsell Color Tree

jiscdigitalmedia.ac.uk

urbanext.illinois.edu



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