Overview of Human Color Perception

- History
- Anatomy of human eye
- Fundamentals of color measurement – colorimeter
- Additive/subtractive colors – rules for color mixing
- Color matching experiments
- Selected references

History of Color Perception
Major Contributors

- Groundwork for technically sound treatment of light and color was laid by Sir Issac Newton (1730s). Facts from Newton's observations
  - A given mixture of optical radiation versus wavelength creates a visual sensation which an observer associates with a particular color
  - Sensation of the same color can be created by a variety of mixtures of optical radiation versus wavelength
  - Color of objects is affected by the spectral content of the illumination source and selective transmission or reflection by the object
- Even before Newton, color experimenters knew that nearly all colors can be obtained by mixing only three pigments
  - Young (1807), Helmholtz (1850s), and Maxwell (1860s) laid the foundation of modern numerical three-color theory
  - Distinction between "additive" color primaries (colored lights) and "subtractive" color primaries (colored prints) not completely clarified until ~1900 (by F.E. Ives)

History of Color Perception

Newton

- **Issac Newton decomposed white light into different colors using prisms**

- **From his *Optiks*, published in 1730[1], we see that Newton appreciated the continuous spectral nature of the solar spectrum:**

> *The Spectrum did appear tinged with this Series of colours, violet, indigo, blue, green, yellow, orange, red together with all their intermediate Degrees in a continual succession perpetually varying. So that there appeared as many Degrees of Colours,as there were sorts of Rays differing in Refrangibility.*

- **Newton demonstrated that colors of objects are related to their spectral reflectances**

[1] Reprinted as a Dover classic (1979); IBSN 0-486-60205-2

Human Color Perception
General Comments

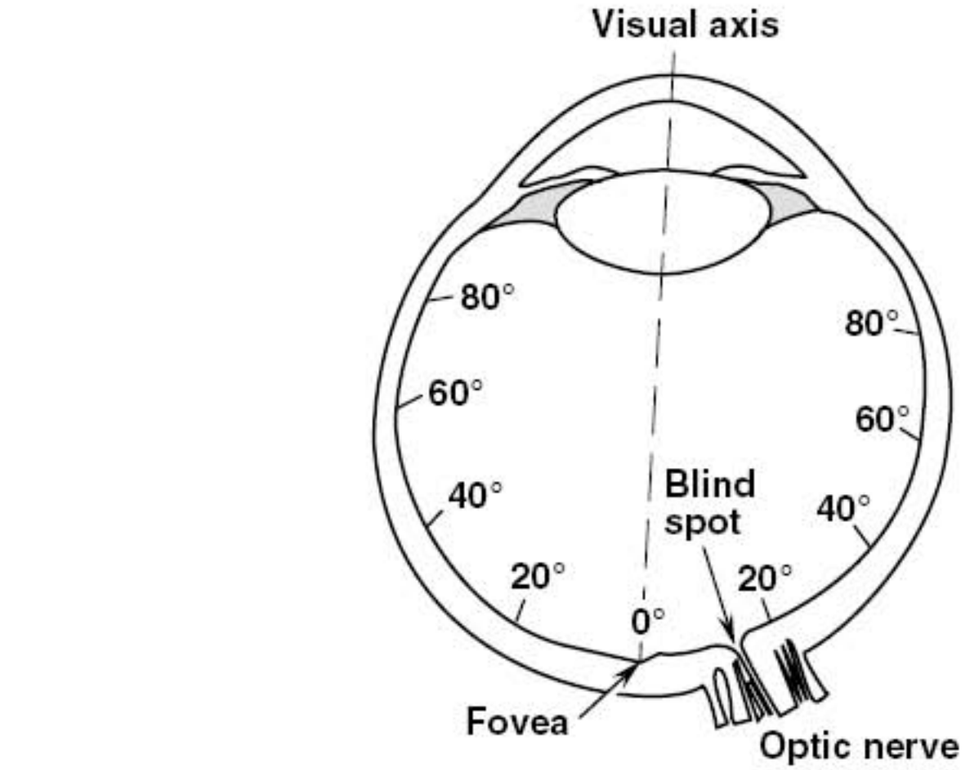
- Human visual system appears to behave as though it has three color detectors (roughly: red, green, and blue)
  - Thomas Young developed basic principles of trichromatic vision in 1801
  - Further developed by Hermann Helmholtz, who introduce trichromatic overlapping spectral sensitivity curves
- Human brain performs complex operations on color data, such as "correcting" overall color appearance of an object
  - What you "see" is not necessarily what you "measure"
  - "Color constancy" is the phenomenon of the *perceived* color of an object not changing, despite changing lighting and viewing conditions
  - Important for survival
- "Modes of color perception[1]
  - "Surface" mode – colors appear to be due to surface properties of objects
  - "Aperture" mode – color of a central region depends on surrounding colors
- Color described in terms of *hue, brightness, saturation*

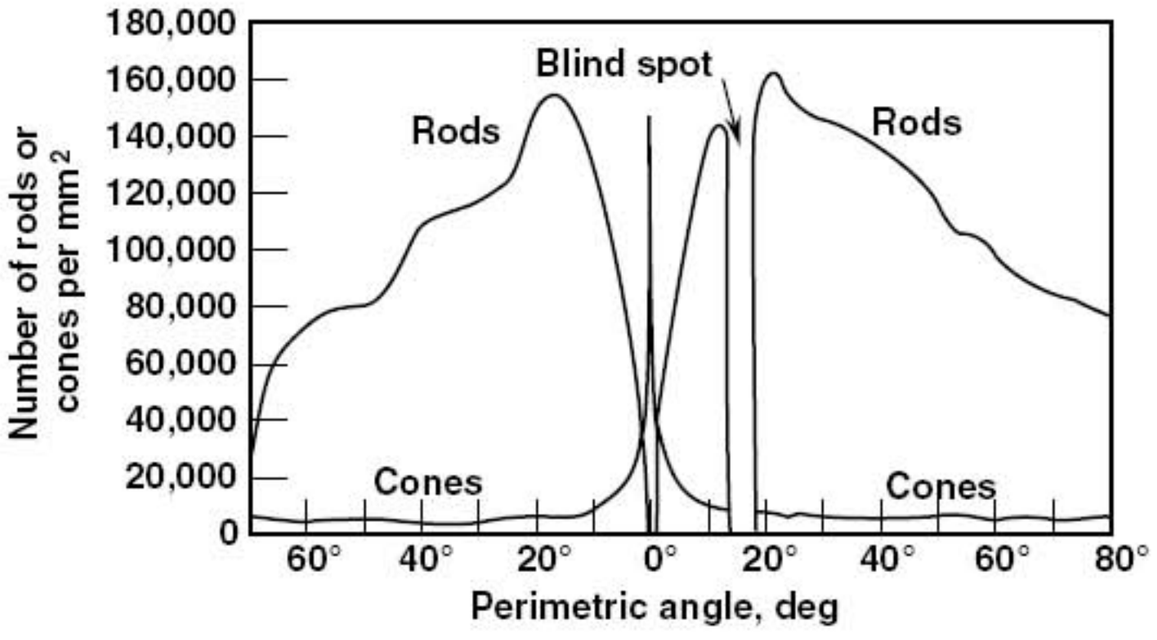
[1] R.M. Evans, "Variables of Perceived Color," JOSA, Vol. 54, pp. 1487-1474, 1964.

Anatomy of Human Eye

Rod and Cone Cells

Some Characteristics	
Rod Cells	**Cone Cells**
• "Black and white" receptors • One type • Photosensitive pigment "Rhodopsin" • Very sensitive (scotopic vision) • Responsible for night vision • Lower resolution • ~ 10^8 rods in human eye • Peripheral vision due to rod cells	• Primary color sensors • Three types identified by electron microscopy • Thinner and longer than rod cells – packed close together in fovea • Cone spacing in fovea ≈ 2.5 μm • Not sensitive – work with higher intensity light (photopic vision) • Photosensitive pigments of cone cells not all known

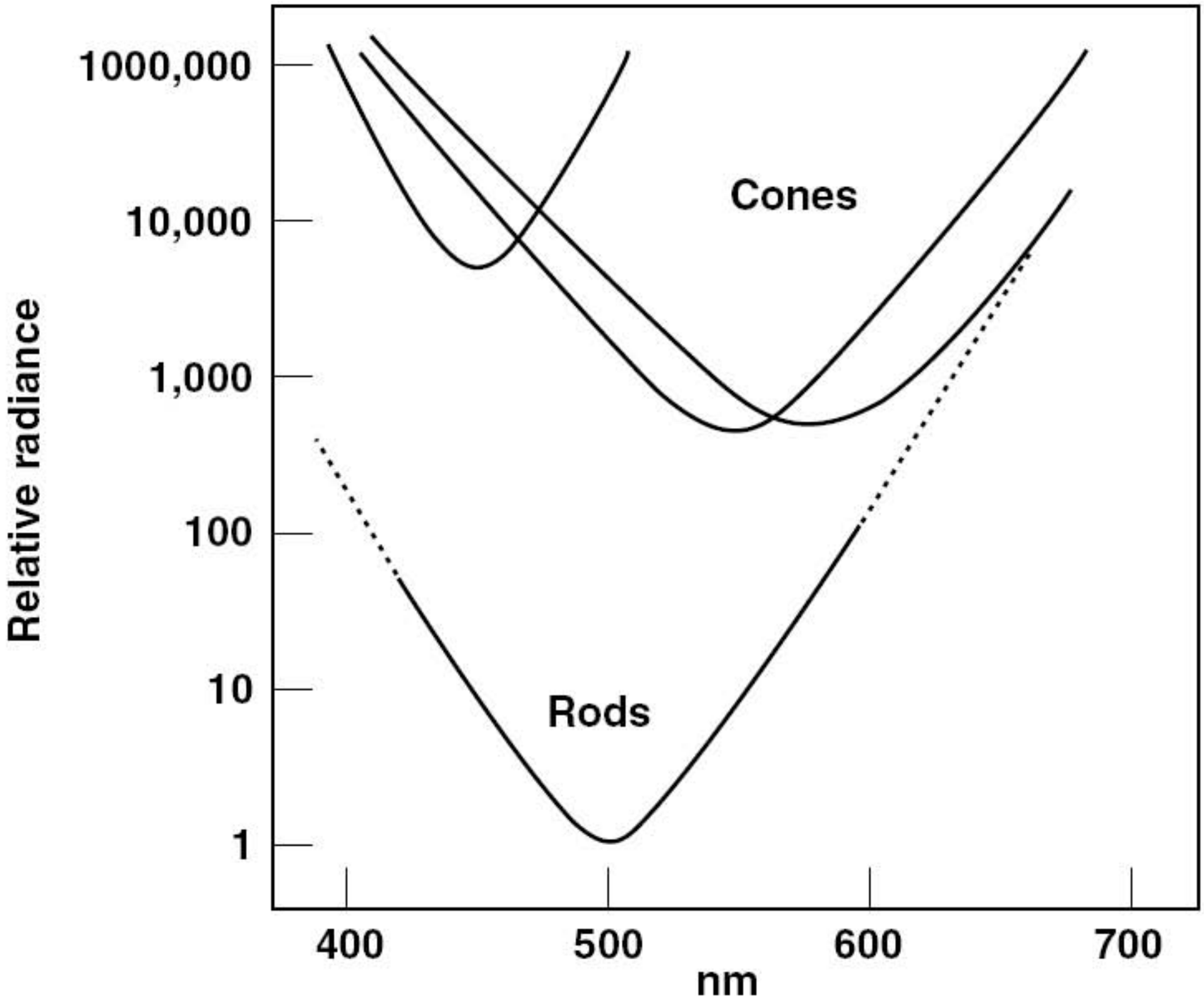




From T. N. Cornsweet, Visual Perception, New York, Academic Press, 1970, p. 137

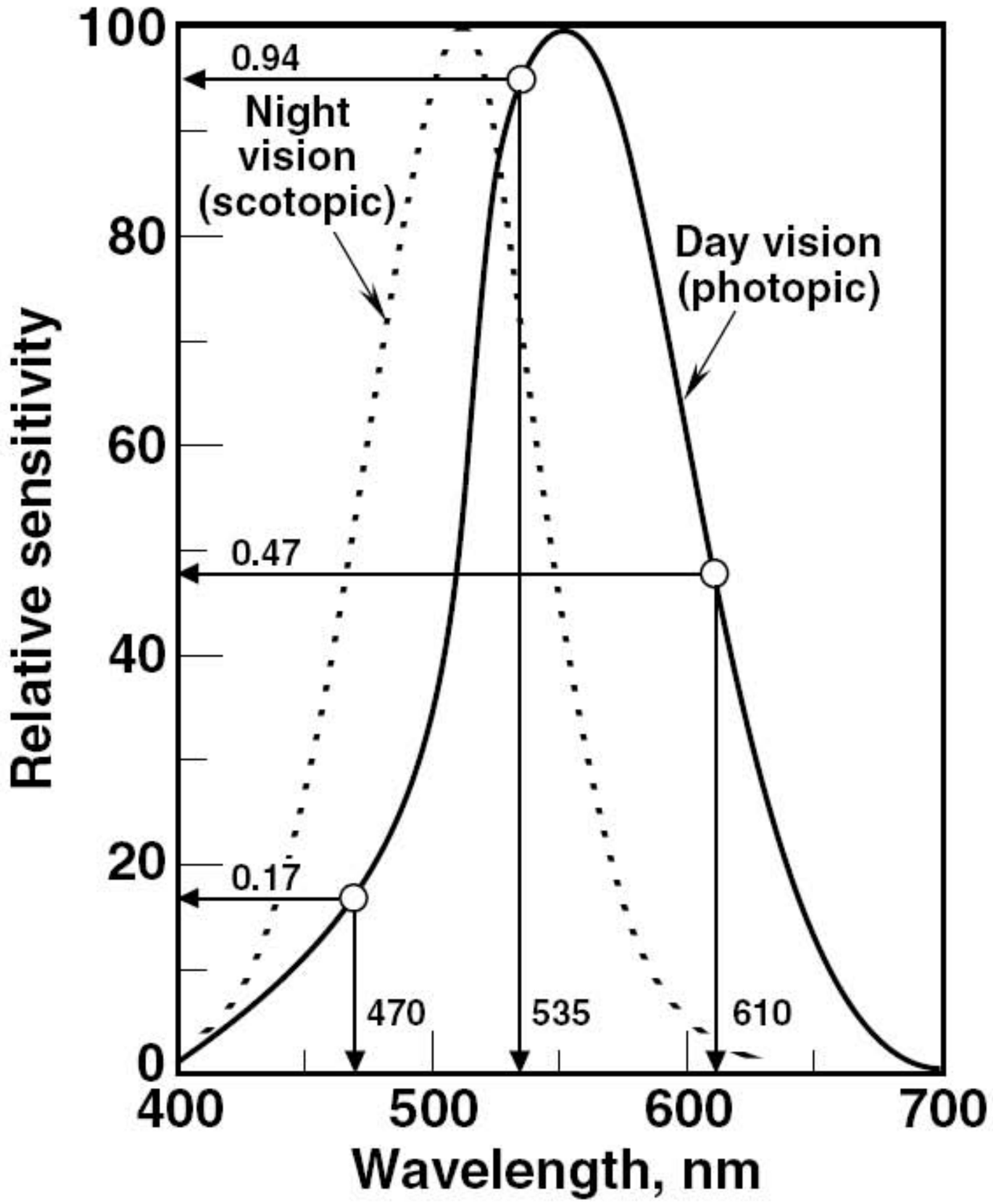
Anatomy of Human Eye

Radiance to produce threshold response versus wavelength for rods and three types of cones in human retina [1]



[1] R. A. Eynard, Ed., Color: Theory and Imaging Systems, Society of Photographic Scientists and Engineers, Washington, D.C., 1973

Nominal Luminosity Response of Human Eye(1)



- Daylight (or photopic) vision determined by cone cells
- Night (or scotopic) vision determined by rod cells
- *Television signal encoding and reconstruction are matched to human photopic vision*
  - $Ey = 0.30E_R + 0.59\ E_G + 0.11E_B$

Color signal	Normalized weighting	Weighting ratios relative to luminosity curve
E_R	0.30	0.47
E_G	0.59	0.94
E_B	0.11	0.17

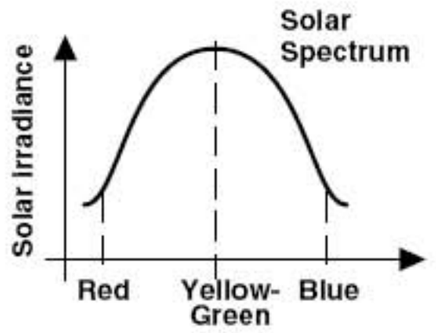
- Dominant wavelengths 470 nm, 535 nm, 610 nm based on NTSC color triangle receiver primaries(2)

(1) C. Bailey Neal, IEEE Trans. Broadcast Tele. Receiver, Vol. BTR-19, pp. 149 – 162, Aug. 1973, Figure 1.

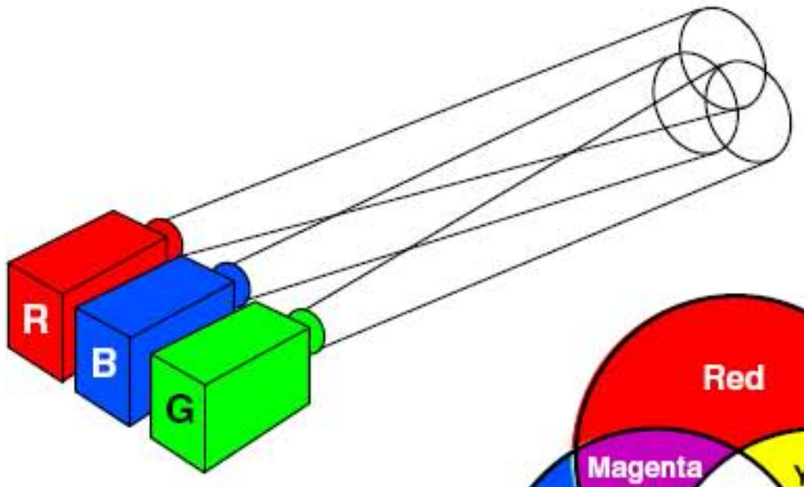
(2) P. C. Goldmark, et. al., Proceedings of the IRE, Vol. 39, pp.1288 – 1313, Oct., 1951, Fig. 2.

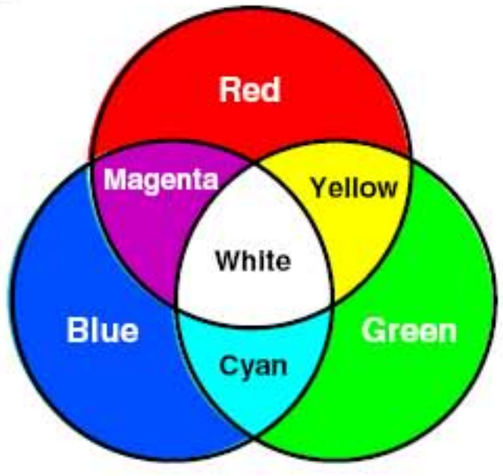
Additive Primary Colors

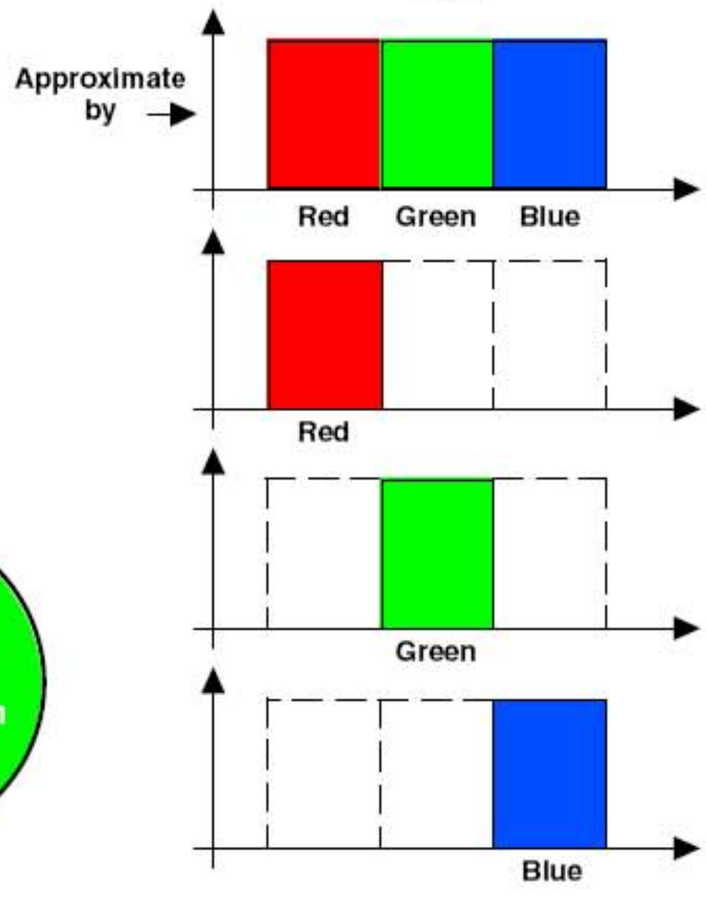
- Used in mixing of projected or emitted light
- Color TV tube, RGB projection system
- Weighted average of three primary colors (red, green, blue) can be used to produce any spectrum color plus white

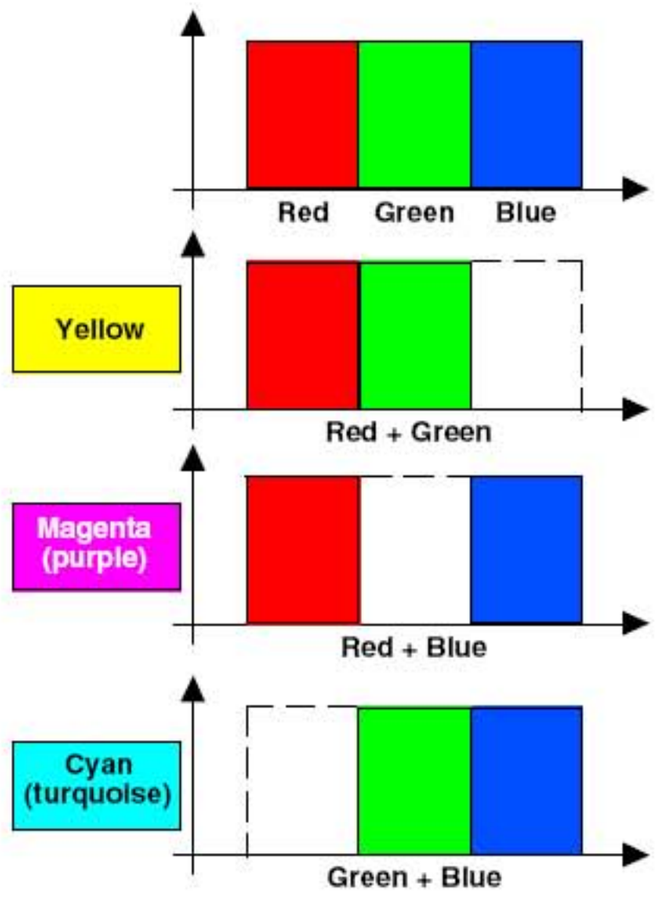


Color Addition







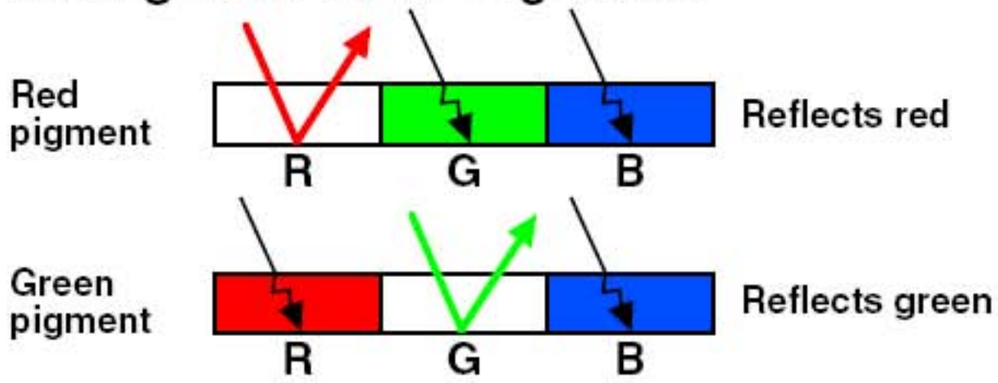


Magenta (purple) is a "non-spectral" color

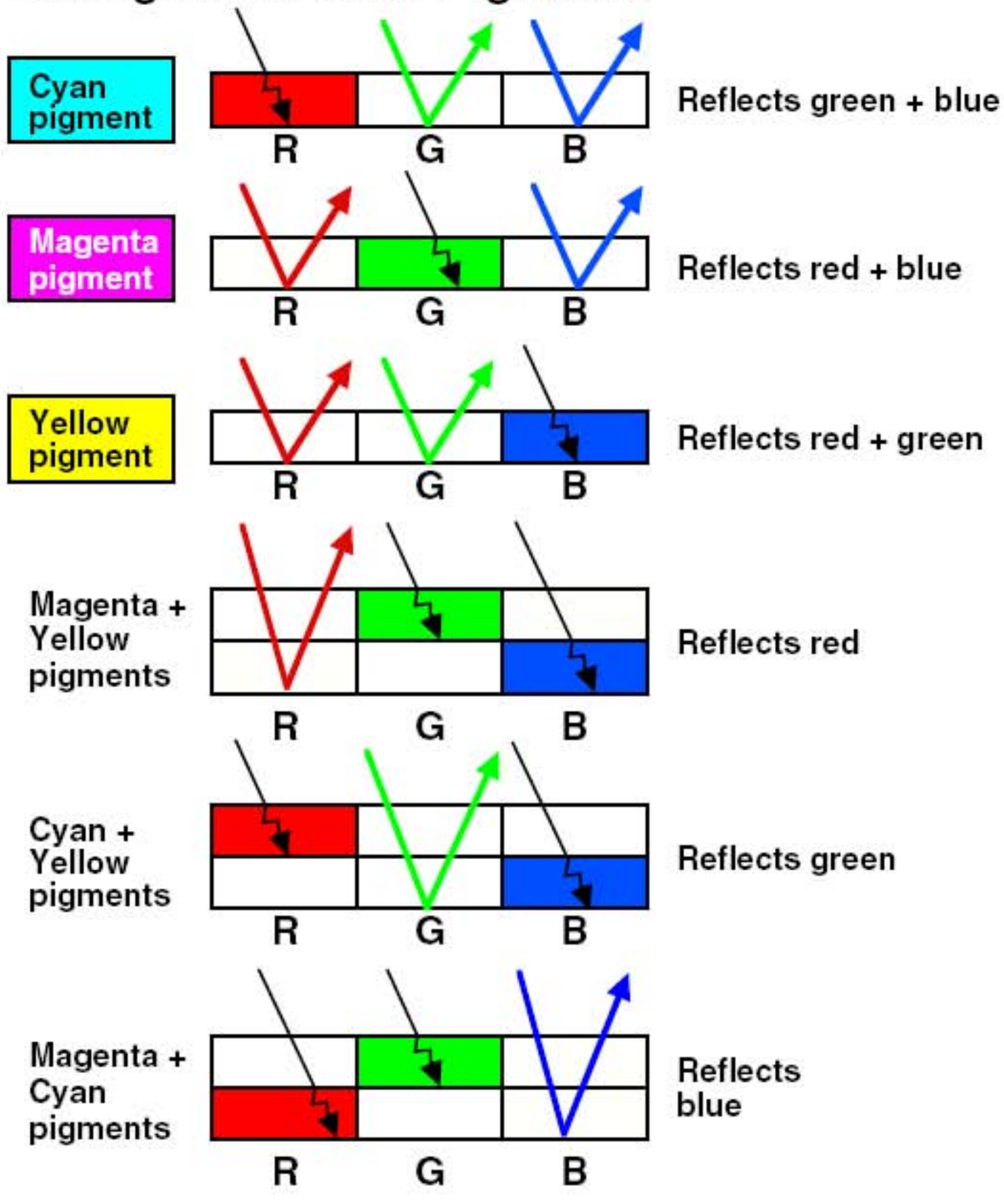
Subtractive Primary Colors

- Used for mixing color pigments
- Applicable to color printing
- Mixture of absorbing pigments results in subtraction of colors; observers sees light left over after absorption takes place

Mixing RGB Color Pigments



Mixing CMYe Color Pigments



Fundamentals of Color

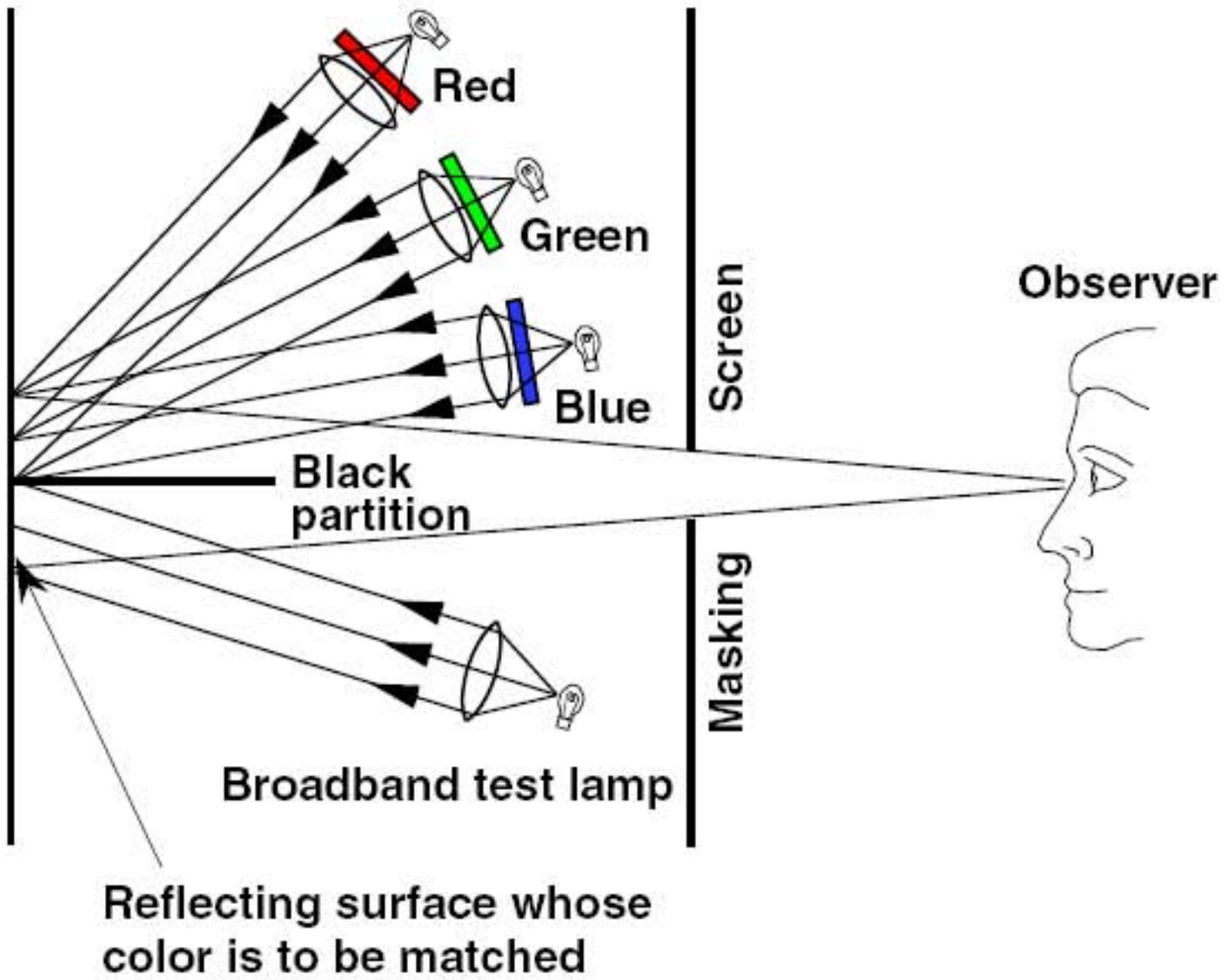
Colorimetry[1]

- Science of additive and subtractive color reproduction and matching
- All rules and laws of colorimetry are empirically based and depend specifically on color-matching experiments carried out on a population of human observers under appropriate illumination conditions
- Empirical observations are made using a device called a colorimeter
  - Device has a divided visual field, where a color to be matched is presented to one side of the field and a mixture of three primaries is presented to the other side
  - Optical field of colorimeters is limited to 2 degrees *or* 10 degrees to recognize variation in color over area of human retina

[1]W.T. Wintringham, Proceedings of the IRE, Vol. 39, pp 1135-1172, 1951

Schematic of a Colorimeter

CIE Method of Matching Colors



- Narrowband color filters(1) are placed over test lamps to give "pure" spectral primaries
  - Red = 700.0 nm
  - Green = 546.1 nm
  - Blue = 435.8 nm
- Intensities of three lamps are adjusted to produce color match on both sides of black partition
- Color "subtraction" corresponds to moving one of the narrow band lamps to the same side as the broadband lamp
- Field-of-view of masking screen is
  - 2° for 1931 CIE standard observer
  - 10° for 1964 CIE supplementary observer

Figure from *Principles of Color Technology by* F.W. Billmeyer and M. Saltzmann, Wiley, New York, 1981

(1) Spectral primaries chosen based on available technology in early 1930s (e.g. spectral lines of a high pressure mercury arc lamp)

Color Matching Measurements

Color Subtraction

- (C) + r(R) = b(B) + g(G)

mixture of unknown color C with r "Red"

mixture of b "Blue" and g "green"

Equality means color match

R = red
B = blue
G = green

r,b,g, = multiplicative factors which scale radiance of reflected colors

- Can be written as

(C) = -r(R) + b(B) + g(G)

"Negative" light has no physical meaning – however, interpretation of a negative term is that it belongs on the other side of matching equation

Fundamentals of Color

Rules of 3-Component Color

- Any color can be matched by a mixture of no more than three colored lights
- A color match made at one radiance level holds over a wide range of radiance levels
- The spectral components of a mixture of colored lights cannot be resolved by the human eye
- The luminance of a mixture of spectral components is equal to the sum of the component luminances
- Color matching obeys the laws of algebra
  - Interpretation of “positive” and “negative” amounts of light is crucial

References/Resources for Human Color Perception

- **SPIE short courses**
  - **"Color Perception and Measurements,"** Labrum, J.H.
  - **"Device-Independent Color: Myth or Reality,"** Giorgianni, E.

- ***Human Color Perception*,** Boynton, R.M., Optical Society of America, 1992

- ***Color: Theory and Imaging Systems*,** Eynard, R.A. (ed.), Society of Photographic Scientists and Engineers, Chapters 1 and 2, 1973

- ***Principles of Color Technology*,** Billmeyer, F.W. and Saltzman, M., Wiley, New York, 1981

- ***The Perception of Color*,** Evans, R.M., Wiley, New York, 1974

- ***Color Measurement: Theme and Variations*,** Second Revised Edition, MacAdam, D.L., Springer-Verlag, New York, 1985

CIE Standardized System for Colorimetry

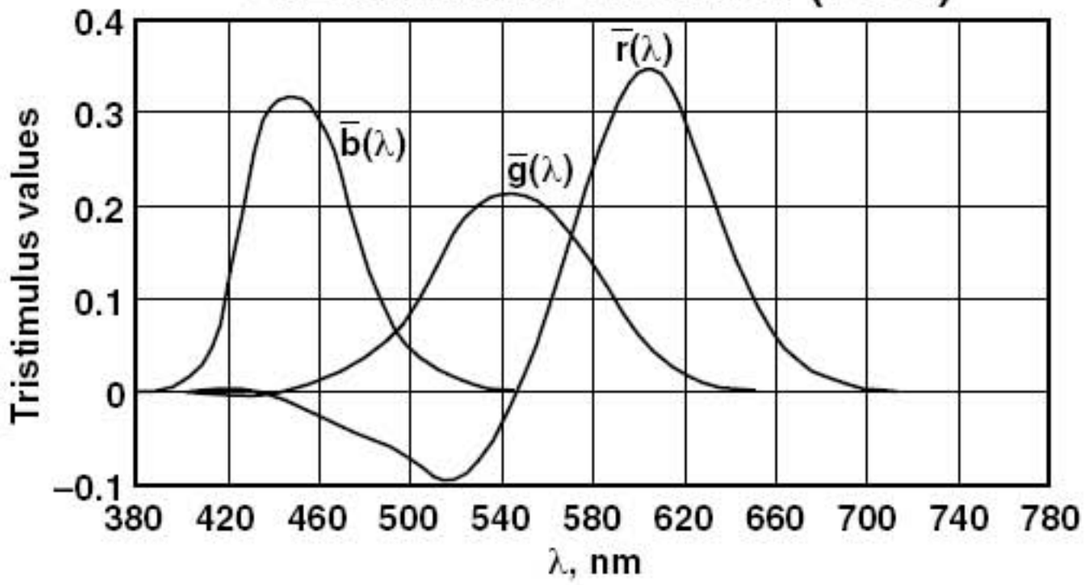
- CIE chromaticity diagram
- CIE standard illuminants
- Color correction matrix

CIE System: Physical and Non-Physical Primaries(1)

Color-Matching Functions

- Any set of <u>three</u> colored illumination sources can be used as primaries for the generation of a gamut of colors provided <u>no two of them, when mixed, will match the third</u>

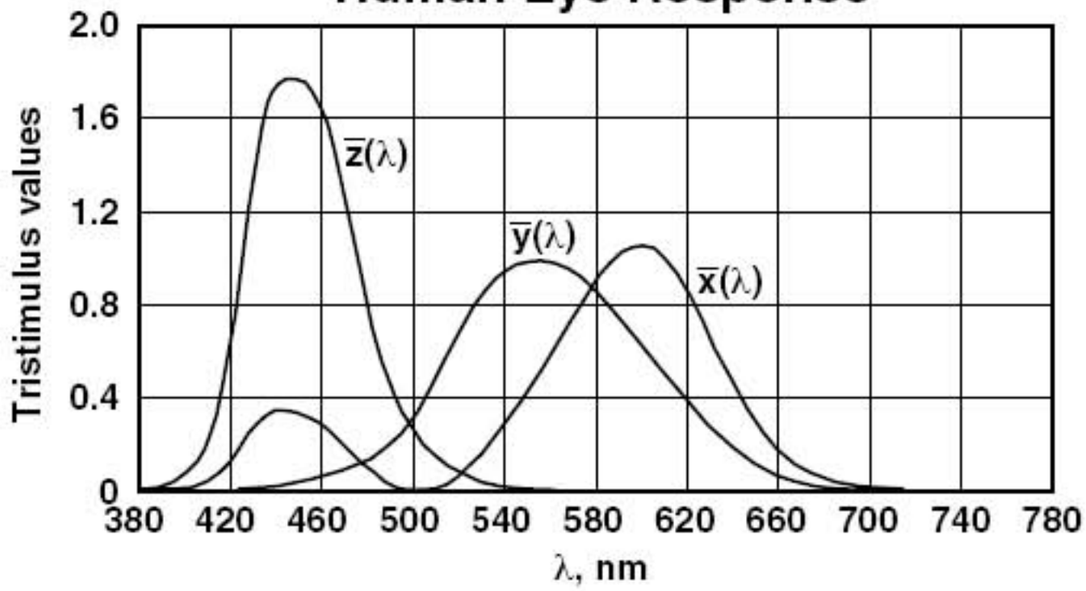
Human Eye Response:
CIE standard observer (1939)



RGB color matching functions –
CIE standard observer

Spectrum primaries { Red = 700 nm; Green = 546.1 nm; Blue = 435.8 nm

Transformed version of
Human Eye Response



XYZ color matching functions –
CIE standard observer

Spectrum primaries { x_c, y_c, z_c Non-physical

Chosen by CIE as "standard" in 1931; system adopted by NTSC for color television in 1954

(1) Also called "imaginary" or "hypothetical" in the literature

(2) $\bar{x}, \bar{y}, \bar{z}$ and $\bar{r}, \bar{g}, \bar{b}$ color matching plots from W. T. Wintringham, Proceedings of the IRE, <u>Vol. 39</u>, pp. 1135–1171, 1951, Figures 4 and 10

Standardized System for Colorimetry
CIE[(1)] or ICI[(2)] Color Standards

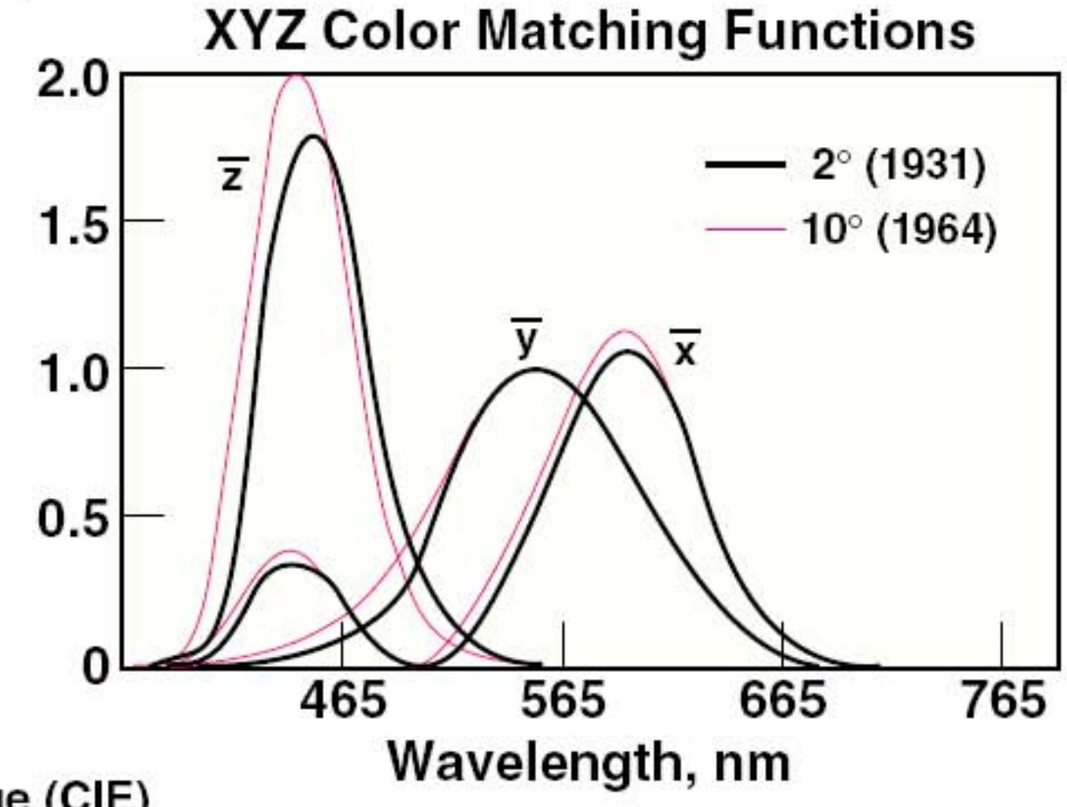
- CIE recommended use of <u>non-physical</u> spectrum primaries X, Y, Z instead of R, G, B
  - Set a common standard for color specification for television
  - Simplify and minimize errors in calculating spectrally weighted integrals involving color-matching functions
  - Use system which defines luminance in a single primary (Y)

- X, Y, Z non-physical primary system uses <u>all-positive</u> color-matching (or tristimulus) matching functions, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$

- "Standard observer" characteristics captured by all positive tristimulus functions for
  - 2-degree FOV observers (1931)
  - 10-degree FOV observers (1964)

- Specification of <u>four</u> standard spectral illumination sources: Illuminants A, B, C, D_{65}

- Specification of specific illumination and viewing geometries



(1)In French: Commission Internationale de L'Eclairage (CIE)
(2)In English: International Commission on Illumination (ICI)

CIE System: Physical and Non-Physical Primaries

Tristimulus Values and Chromaticity Coordinates

<table>
<tr><th></th><th>R G B – Physical primaries</th><th>X Y Z – Non-physical primaries</th></tr>
<tr><td>Tristimulus values</td><td>R, G, B ≡ tristimulus values
$\bar{r}(\lambda)$, $\bar{g}(\lambda)$, $\bar{b}(\lambda)$ ≡ color matching functions
$R = \int \rho(\lambda)\, P_I(\lambda)\, \bar{r}(\lambda)\, d\lambda$
$G = \int \rho(\lambda)\, P_I(\lambda)\, \bar{g}(\lambda)\, d\lambda$
$B = \int \rho(\lambda)\, P_I(\lambda)\, \bar{b}(\lambda)\, d\lambda$</td><td>X, Y, Z ≡ tristimulus values
$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ ≡ color matching functions
$X = \int \rho(\lambda)\, P_I(\lambda)\, \bar{x}(\lambda)\, d\lambda$
$Y = \int \rho(\lambda)\, P_I(\lambda)\, \bar{y}(\lambda)\, d\lambda$
$Z = \int \rho(\lambda)\, P_I(\lambda)\, \bar{z}(\lambda)\, d\lambda$
Note:
Y ≡ luminance (photometric brightness)</td></tr>
<tr><td colspan="3">$\rho(\lambda)$ ≡ Spectral reflectance of colored object
$P_I(\lambda)$ ≡ Spectral illumination function
$\rho(\lambda)\, P_I(\lambda)$ is replaced by $E(\lambda)$ for purely emitting source</td></tr>
<tr><td>Chromaticity coordinates[1] (also call trichromatic coordinates)</td><td>r, g, b ≡ Chromaticity coordinates for R G B
$r = \frac{R}{R+G+B}$
$g = \frac{G}{R+G+B}$
$b = \frac{B}{R+G+B}$
$r + g + b = 1$</td><td>x, y, z ≡ Chromaticity coordinates for X Y Z
$x = \frac{X}{X+Y+Z}$
$y = \frac{Y}{X+Y+Z}$
$z = \frac{Z}{X+Y+Z}$
$x + y + z = 1$</td></tr>
<tr><td>Comments</td><td>• Since $\bar{r}(\lambda)$ has negative values, r can be negative</td><td>• Since color matching functions are all positive, x, y, z are all positive</td></tr>
</table>

[1] Normalization of coordinates (by R + G + B or X + Y + Z) removes dependence on luminance

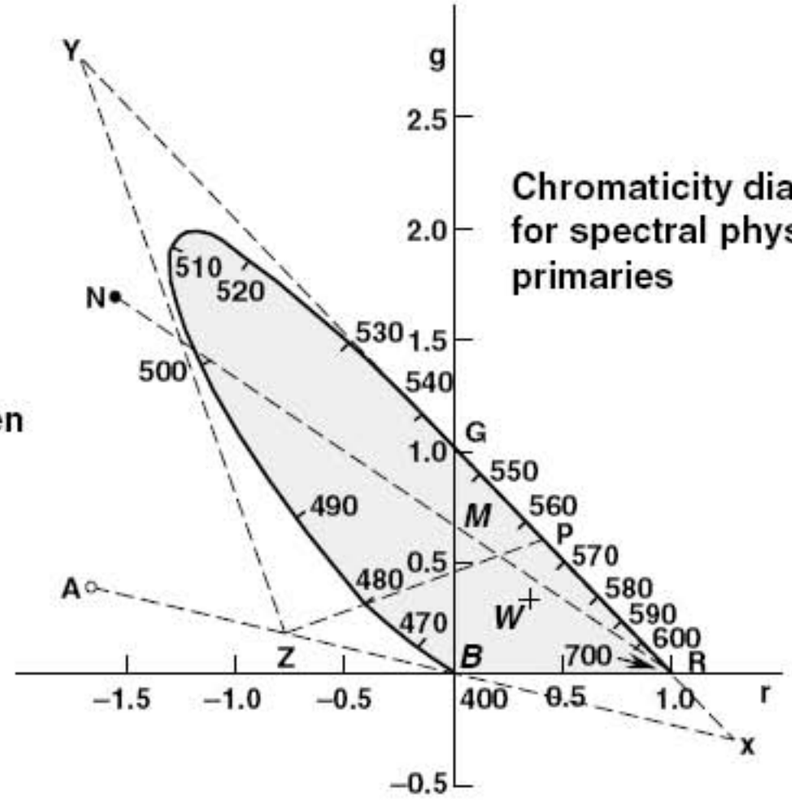
CIE System: Physical and Non-physical Primaries

Chromaticity Diagrams

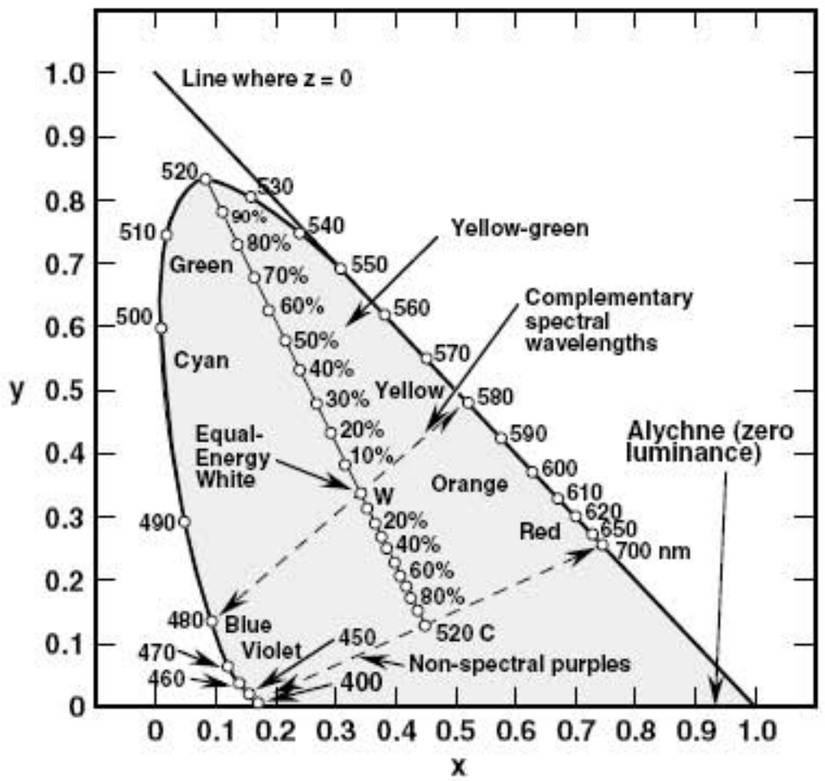
- Since r + b + g = 1 and x + y + z = 1, only two coordinates are needed to describe color behavior using chromaticity coordinates
  - Normalization removes dependence on intensity (or luminance)
- If we assume that $\rho(\lambda)P_I(\lambda) = \delta(\lambda)$ ["pure spectral stimulus" per Dirac delta function] then at λ'
  - $x = \overline{x}(\lambda') / \Sigma_c$, $y = \overline{y}(\lambda') / \Sigma_c$, $z = \overline{z}(\lambda') / \Sigma_c$; $\Sigma_c = \overline{x}(\lambda') + \overline{y}(\lambda') + \overline{z}(\lambda')$
    $r = \overline{r}(\lambda') / \Sigma_w$, $g = \overline{g}(\lambda') / \Sigma_w$, $b = \overline{b}(\lambda') / \Sigma_w$; $\Sigma_w = \overline{r}(\lambda') + \overline{g}(\lambda') + \overline{b}(\lambda')$
  - Plot all values of x, y, z or r, b, g for 400 nm $<\lambda'<$700 nm to form a <u>spectral locus</u>; a continuous curve called a <u>chromaticity diagram</u> (1)

Spectral primaries

- r = 1, g = 0, b = 0 } Red
- r = 0, g = 1, b = 0 } Green
- r = 0, g = 0, b = 1 } Blue



Chromaticity diagram for spectral physical primaries



Non-physical primaries

- x = 1, y = 0, z = 0
- x = 0, y = 1, z = 0 } Points do not fall on locus
- x = 0, y = 0, z = 1

Chromaticity diagram for non-physical spectral primaries

(1) Interior points to spectral locus occur for $\rho(\lambda)P_I(\lambda) \rightarrow$ spectrally broad

CIE Chromaticity Diagram with Color (Hue) Names and Location

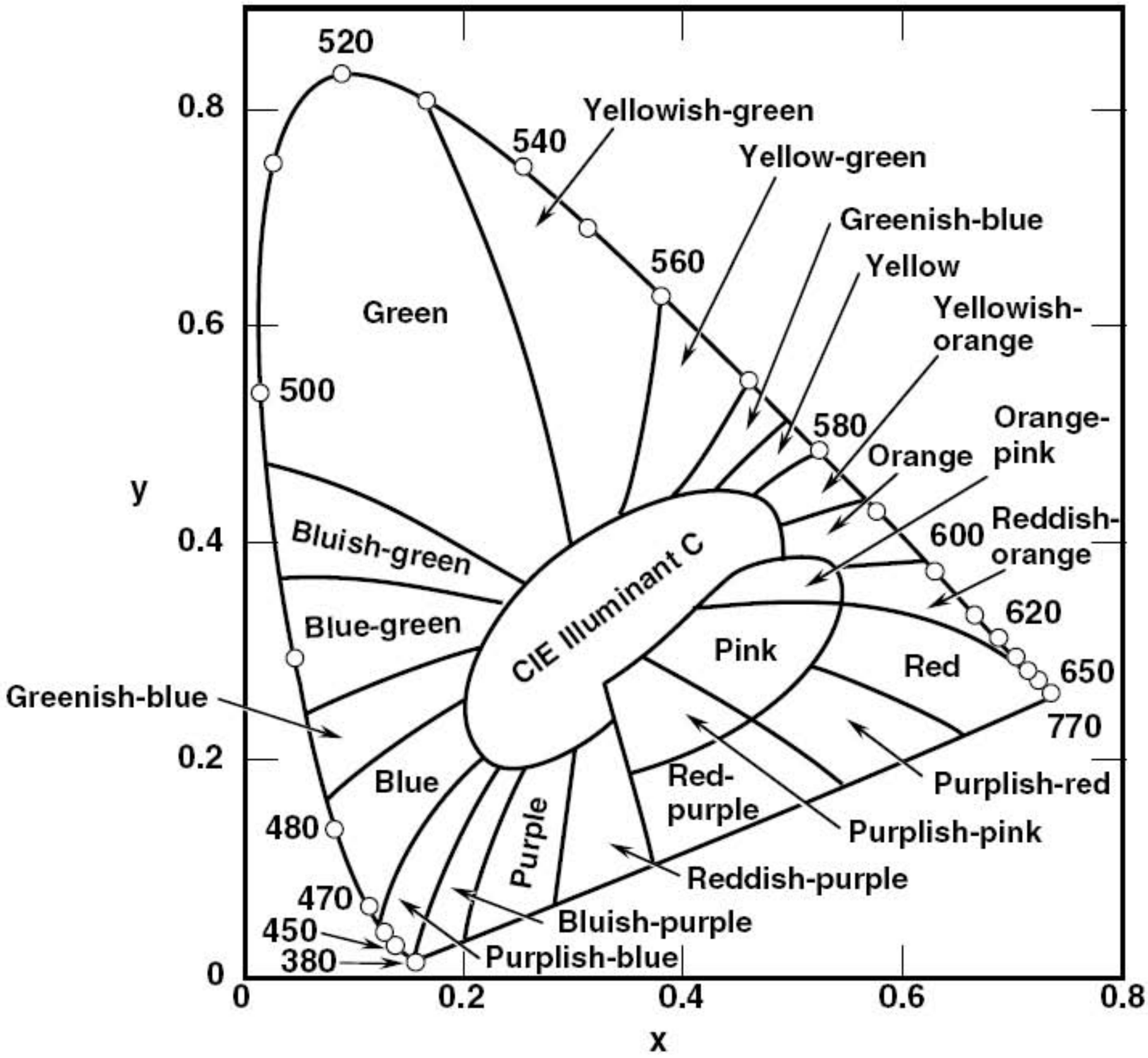
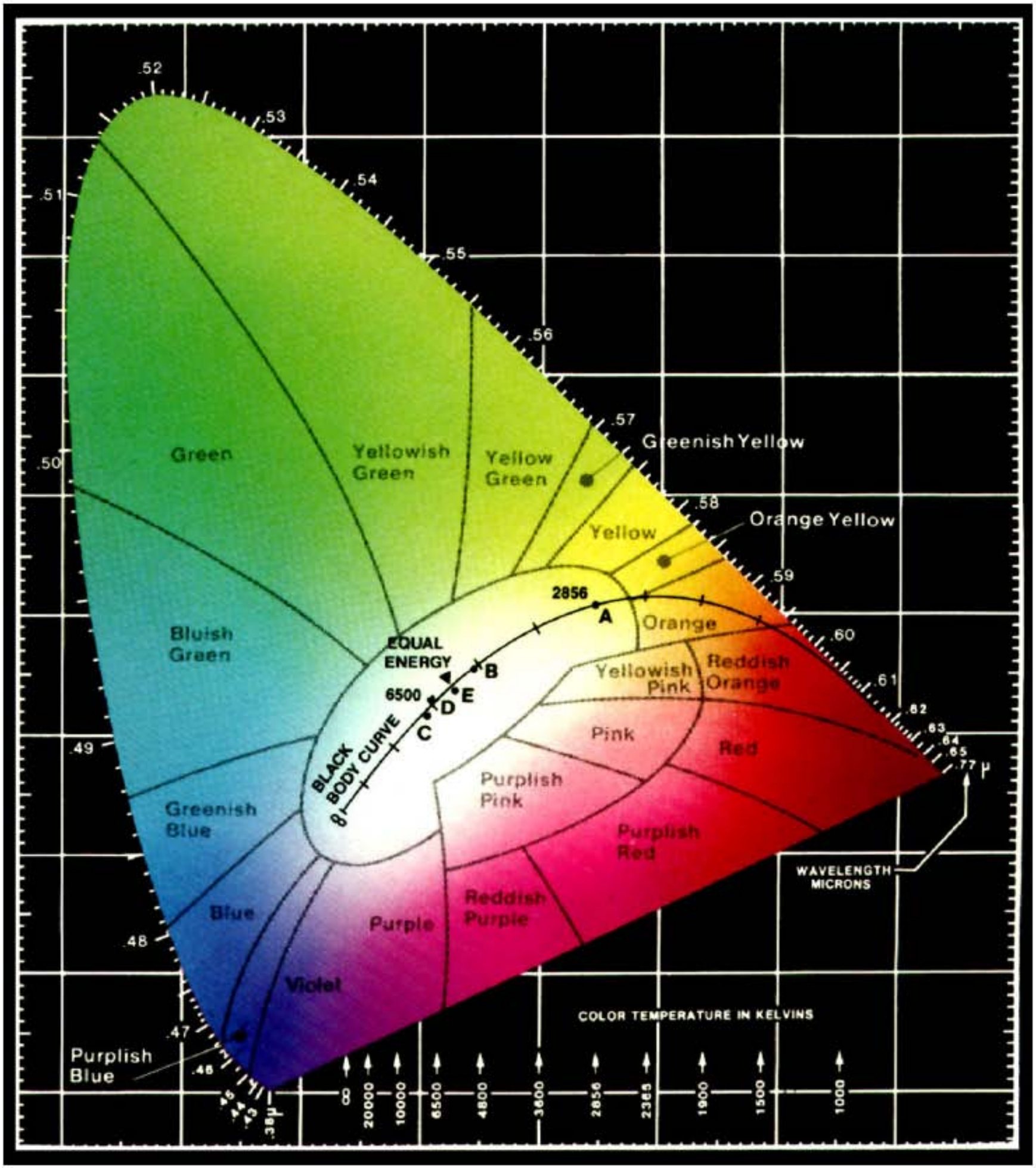


Diagram from *Principles of Color Technology* , by F.W Billmeyer and M. Saltzmann, Wiley, New York, 1981

CIE Chromaticity Diagram

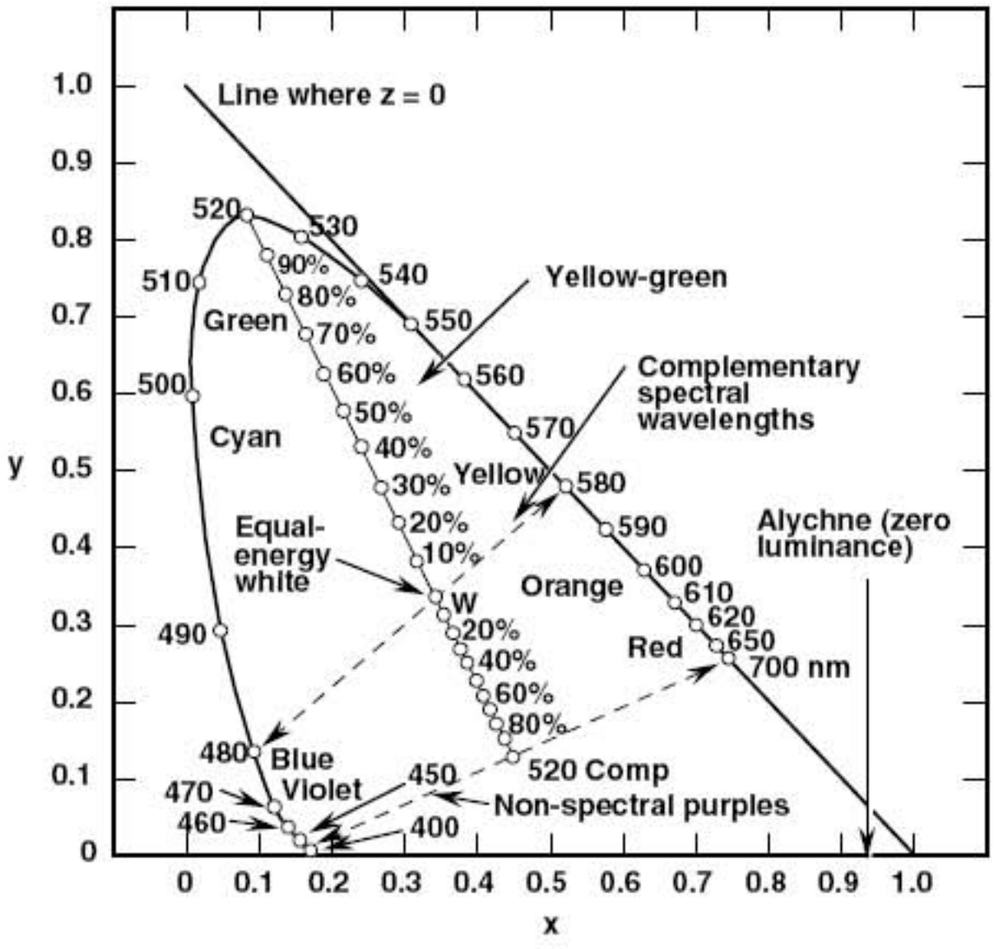
Taken from a Photo Research poster

Burbank, CA



CIE XYZ Chromaticity Diagram[1]

Discussion



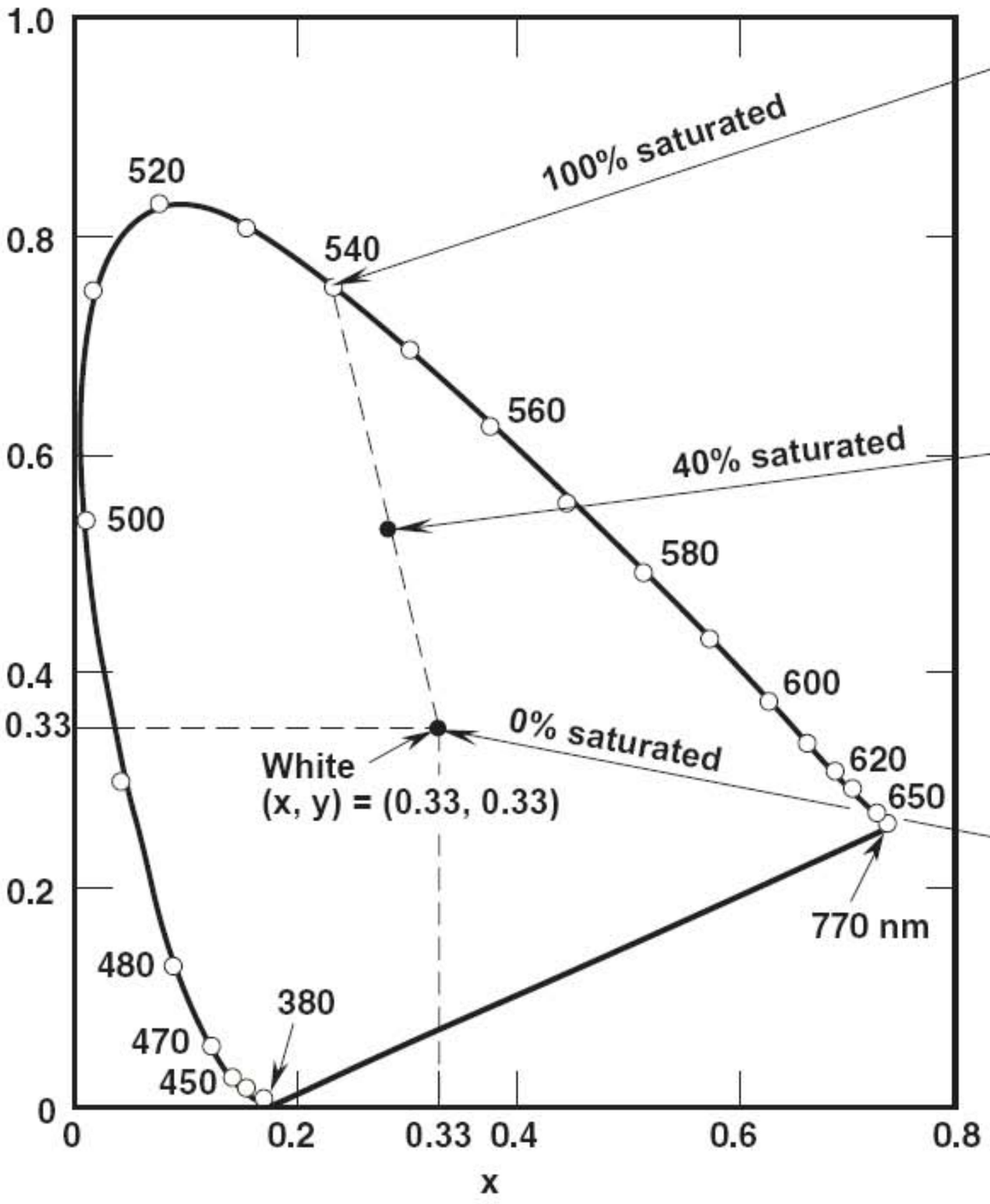
- Points inside spectral locus correspond to $\rho(\lambda)\ P_I(\lambda)$ which are spectrally broad
  - (x, y, z) = (0.33, 0.33, 0.33) corresponds to "equal energy" white near "center" of diagram
- Complementary spectral wavelengths are found at opposite intersections of the spectrum locus on a line passing through white (x = 0.33, y = 0.33)
- "Dominant wavelength" (or hue) of a sample with chromaticity = (x', y') is found at the intersection of spectrum locus by a line connecting "white" (x = 0.33, y = 0.33) and x', y'
- "Excitation purity" (EP) or *"saturation"* is

$$EP\ (\%) = \frac{\text{Distance from } x', y' \text{ to "white"}}{\text{Distance from spectrum locus to "white"}} \times 100$$

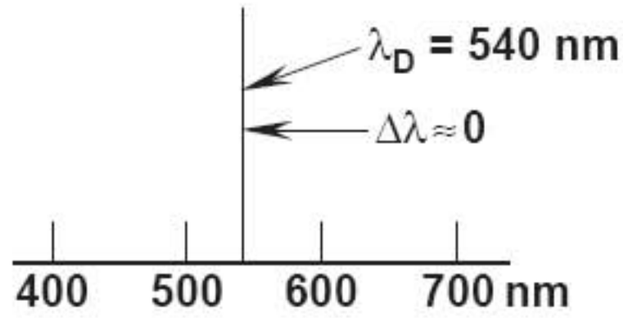
along a line containing "white", x', y',

[1] Chromaticity diagram from "Human Color Vision", R.M. Boynton, Optical Society of America, 1992, p. 394

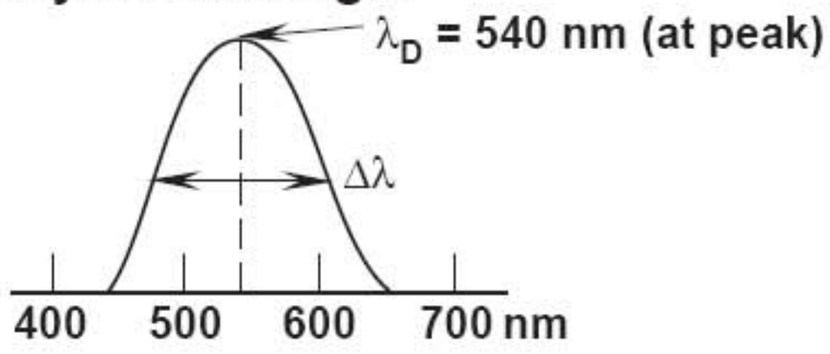
CIE Chromaticity Diagram—Intrepretation of Dominant Wavelength (λ_D) and Saturation ($\Delta\lambda$)



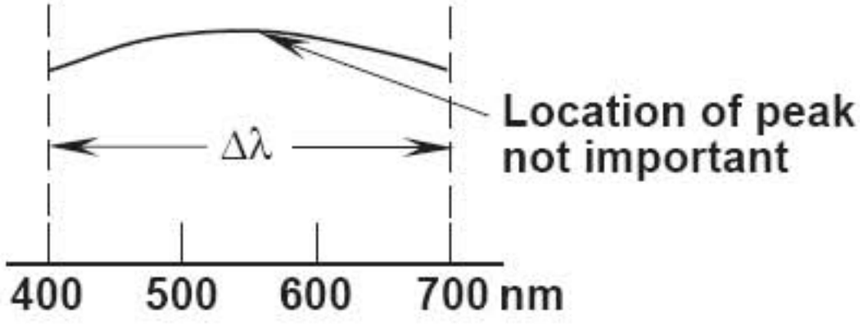
Points at locus of diagram correspond to "spectral delta function"



Points in the interior of diagram correspond to spectrally broader light

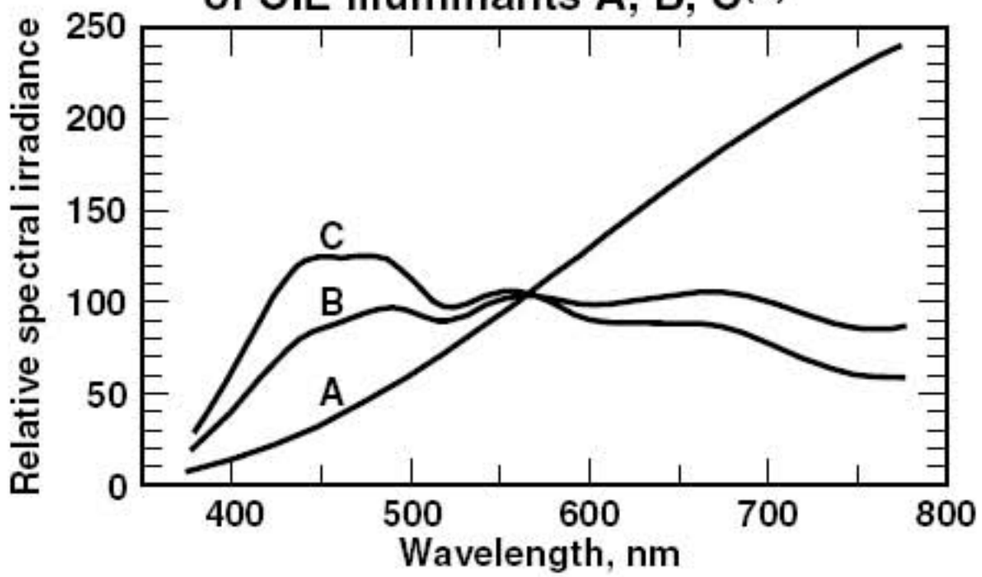


Point at (0.33, 0.33) of diagram is white; broadens to cover entire visual range

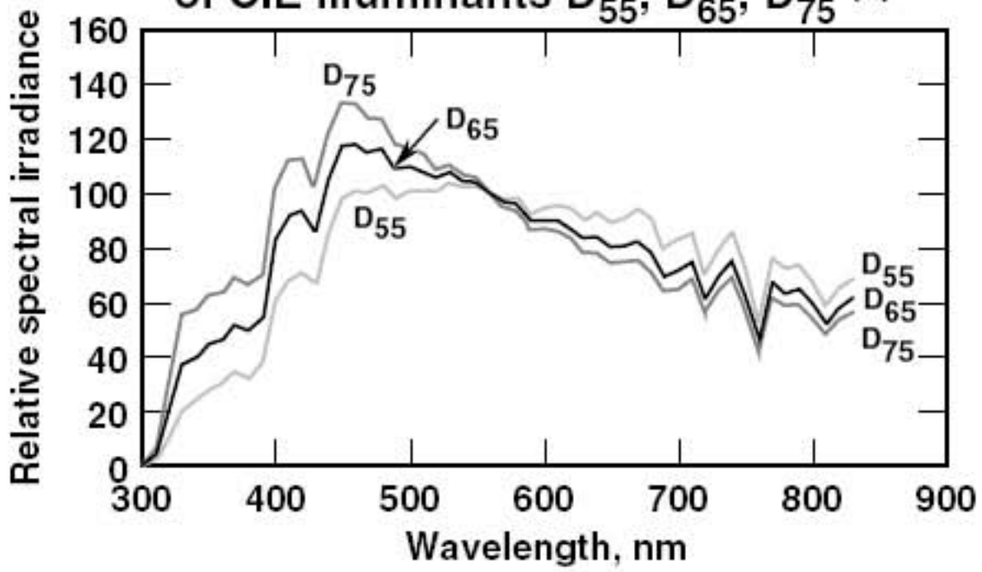


CIE Standard Illumination Sources

Relative spectral irradiances of CIE illuminants A, B, C[3]



Relative spectral irradiances of CIE illuminants D_{55}, D_{65}, D_{75} [3]



Standard illuminants[1]	Comments
A[2]	• Emulates artificial indoor lighting • 2856 K tungsten filament
B	• Emulates direct noon sunlight obtained by filtering illuminant A • Effective color temperature = 4870 K
C	• Emulates average daylight obtained by filtering illuminant A • Effective color temperature = 6770 K
D_{55}	• Emulates a phase of daylight • Effective color temperature
D_{65} [2]	• Emulates average daylight • Effective color temperature = 6500 K
D_{75}	• Emulates light overcast sky • Effective color temperature = 7500 K

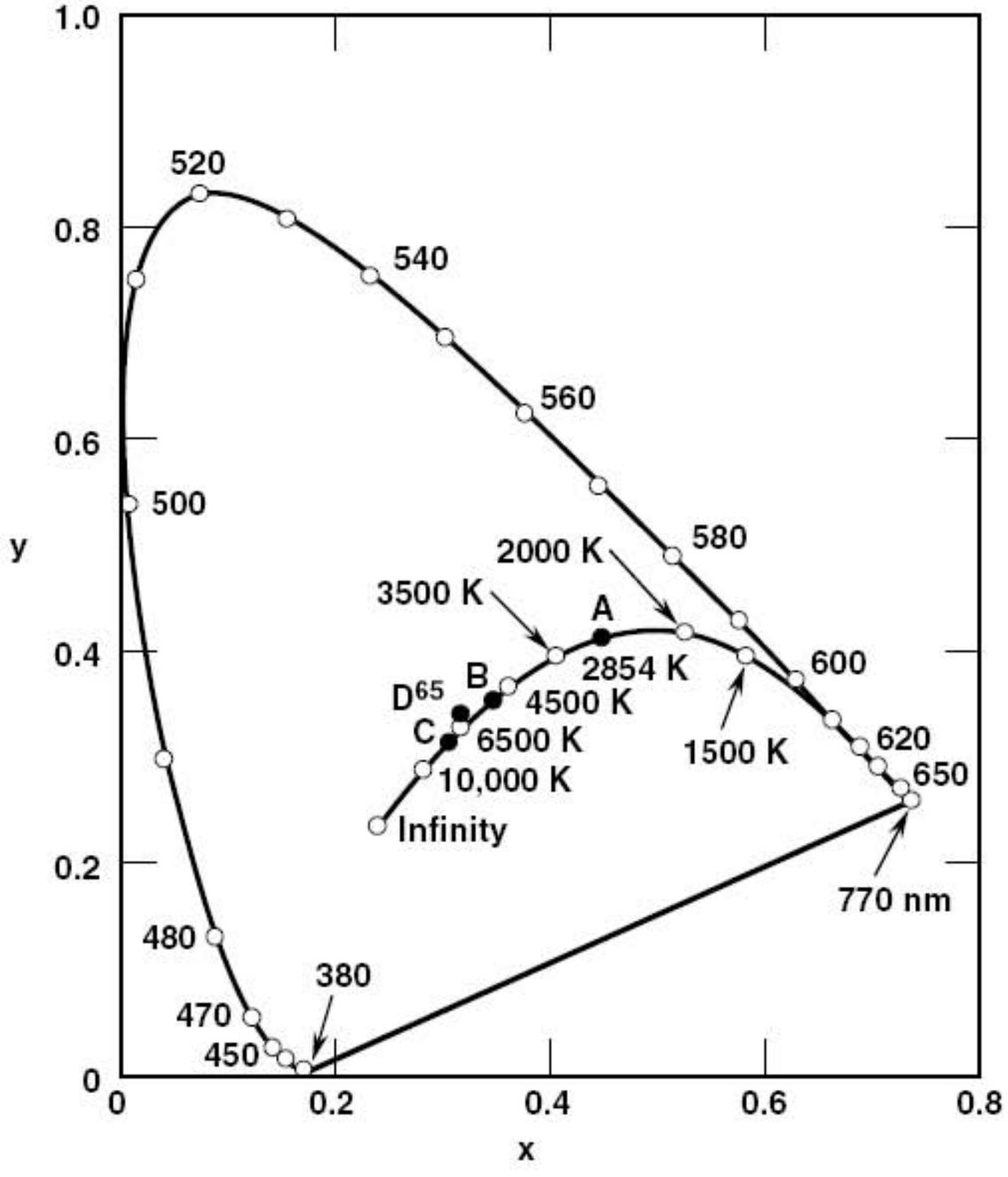
Some color temperatures	
Candle	1800 K
100W tungsten bulb	2875 K
Studio lighting	3200 K
Photographic white	5500 K
TV monitor white	6500 K
Equal energy white	5560 K

(1) Illuminants A, B, C defined by CIE in 1931; illuminants D_{55}, D_{65}, D_{75} based on experimental data ~1965

(2) Most commonly used

(3) Figures from *COLOR: Theory and Imaging Systems*, R.A. Eynard, Ed, SPSE, Washington, D.C., 1973, p. 35

Blackbody Radiators and CIE Standard Illuminants Plotted on CIE XYZ Chromaticity Diagram[1]



[1] D.B. Judd, Journal of Optical Society of America, Vol. 23, pp. 359 – 374, 1933, Figure 2

Blackbody color temperature (K)	Chromaticity coordinates		
	x	y	z
100	0.735	0.265	0.000
1000	0.652	0.345	0.003
1500	0.585	0.393	0.022
1900	0.537	0.411	0.052
2875	0.448	0.408	0.144
3500	0.405	0.391	0.204
4800	0.351	0.356	0.293
6500	0.313	0.323	0.364
10,000	0.280	0.288	0.432
∞	0.240	0.234	0.526

CIE standard illuminant/ color temperature		Chromaticity coordinates		
		x	y	z
A	2856 K	0.447	0.408	0.143
B	4870 K	0.348	0.351	0.301
C	6770 K	0.310	0.316	0.374
D_{55}	5500 K	0.332	0.340	0.328
D_{65}	6500 K	0.313	0.323	0.364
D_{75}	7500 K	0.303	0.313	0.384
Equal energy white	5560 K	0.333	0.333	0.333