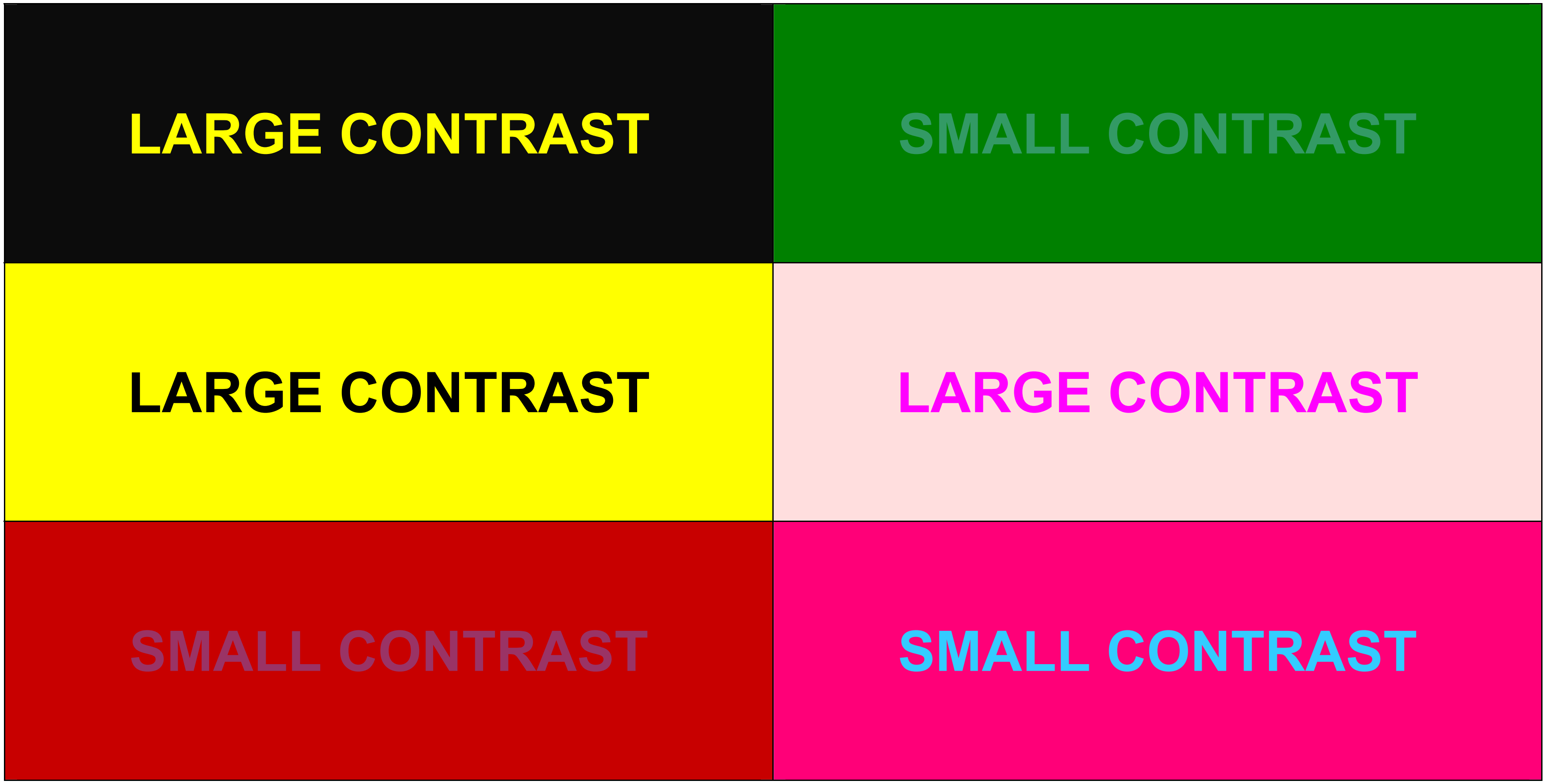
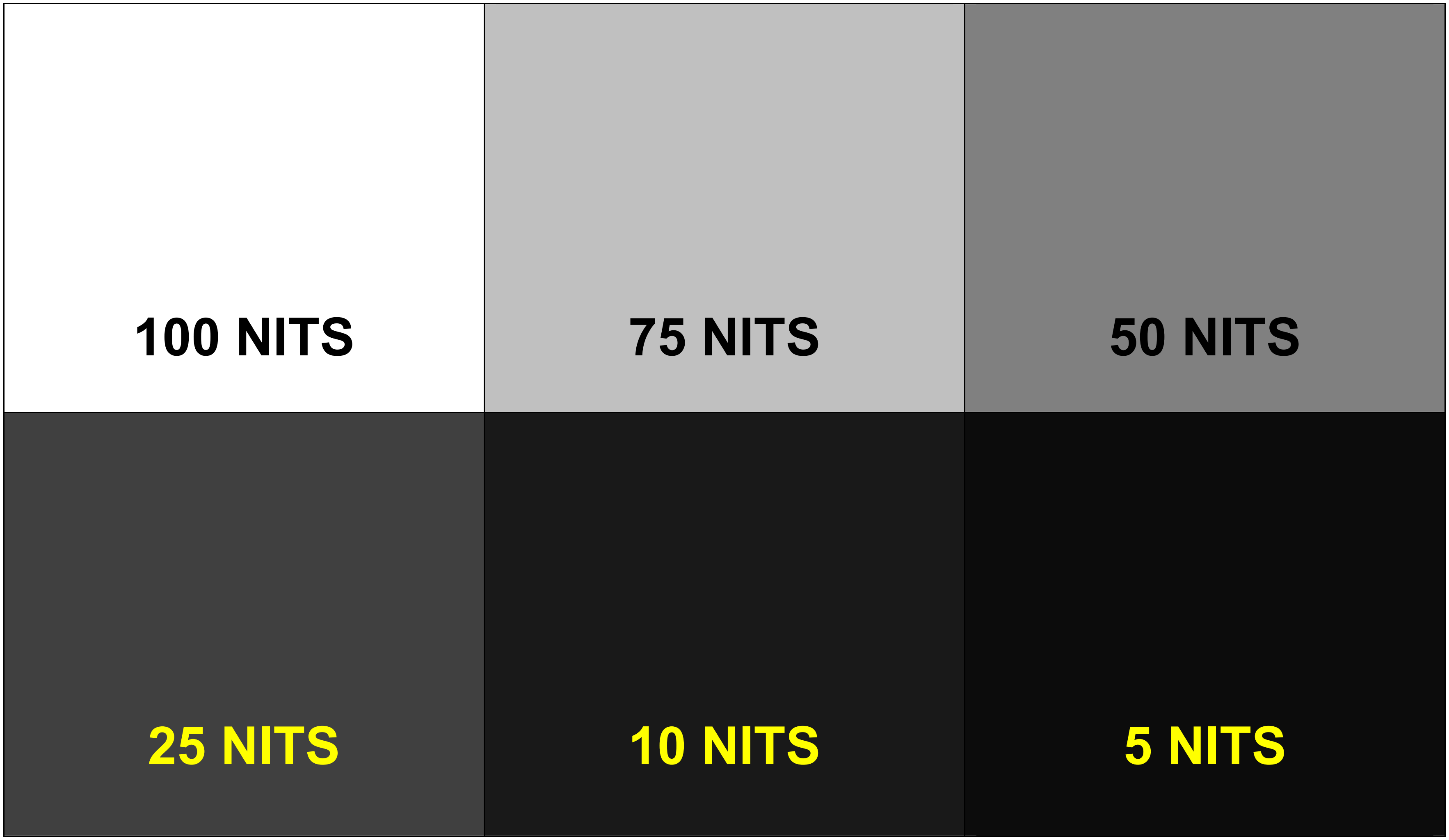
CONTRAST



LARGE CONTRAST	SMALL CONTRAST
LARGE CONTRAST	LARGE CONTRAST
SMALL CONTRAST	SMALL CONTRAST

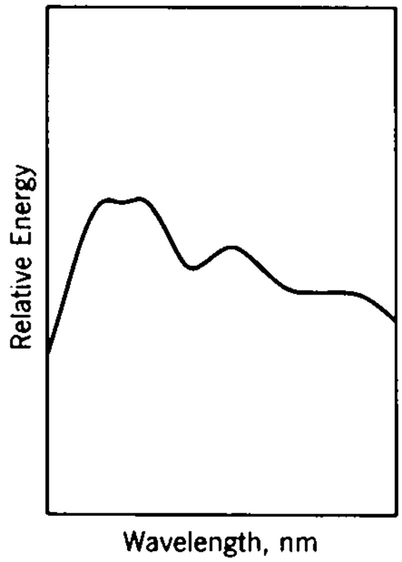
CONCLUSION: Difference in luminance more important than difference in hue

LUMINANCE



100 NITS	75 NITS	50 NITS
25 NITS	10 NITS	5 NITS

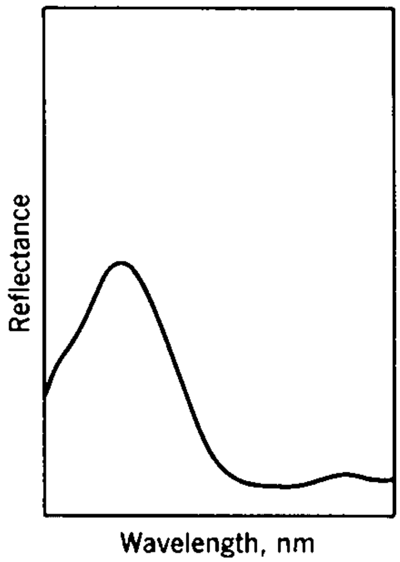
GENERATION OF STIMULUS



×

Spectral energy distribution

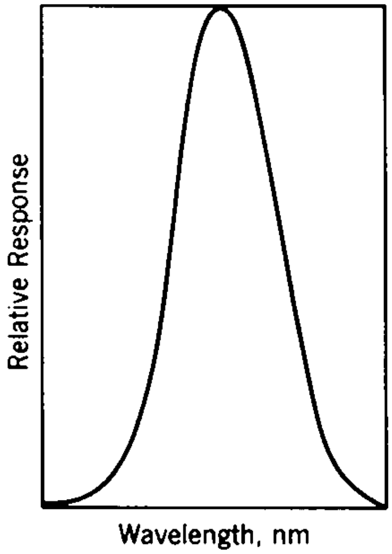
and



×

Spectral reflectance

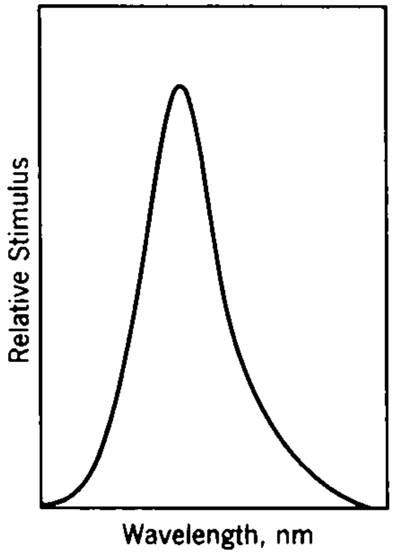
and



→

Spectral response

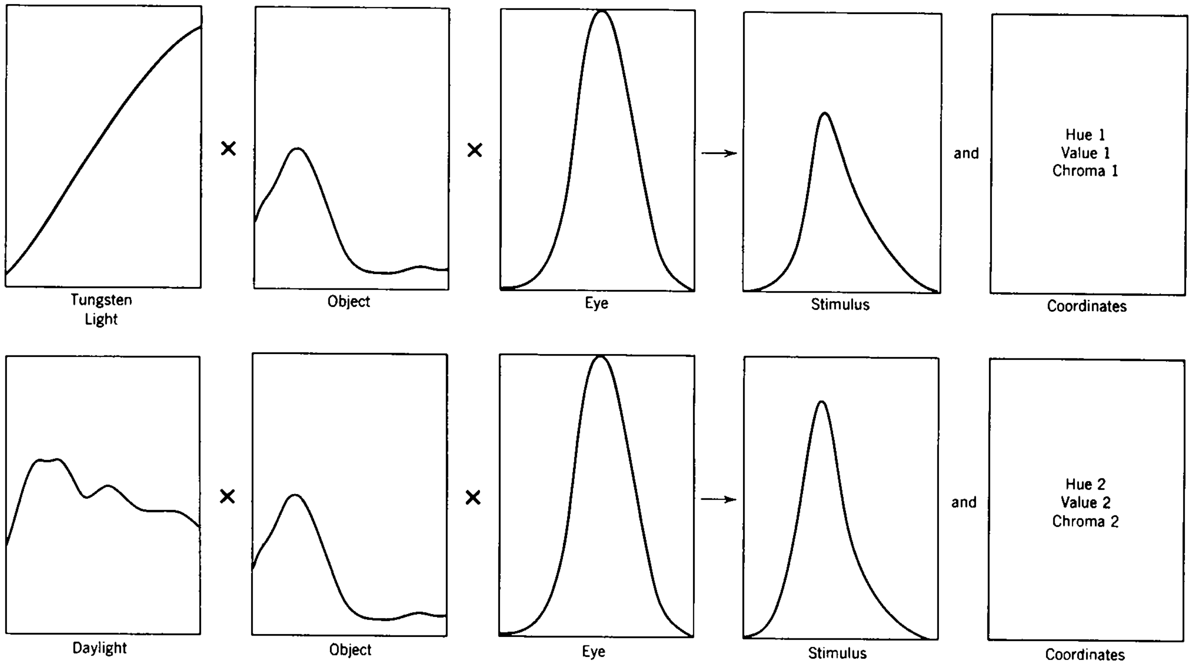
give



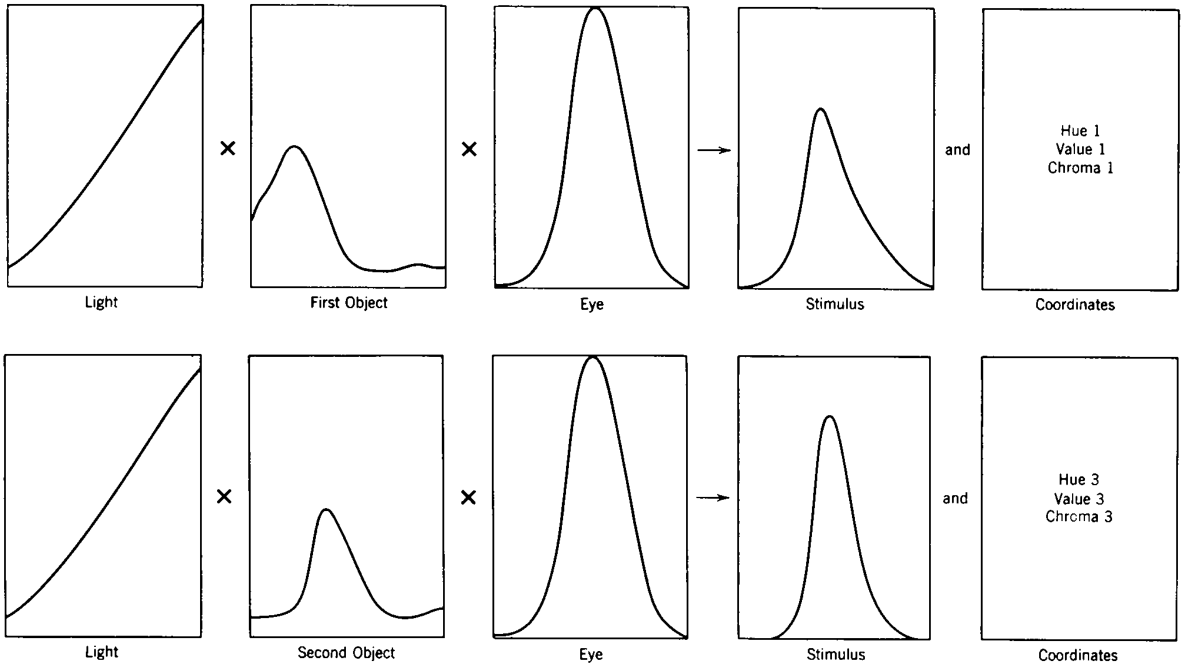
Stimulus for color

$$STIMULUS = \int L_{\lambda} \cdot \rho(\lambda) \cdot V(\lambda) \cdot d\lambda$$

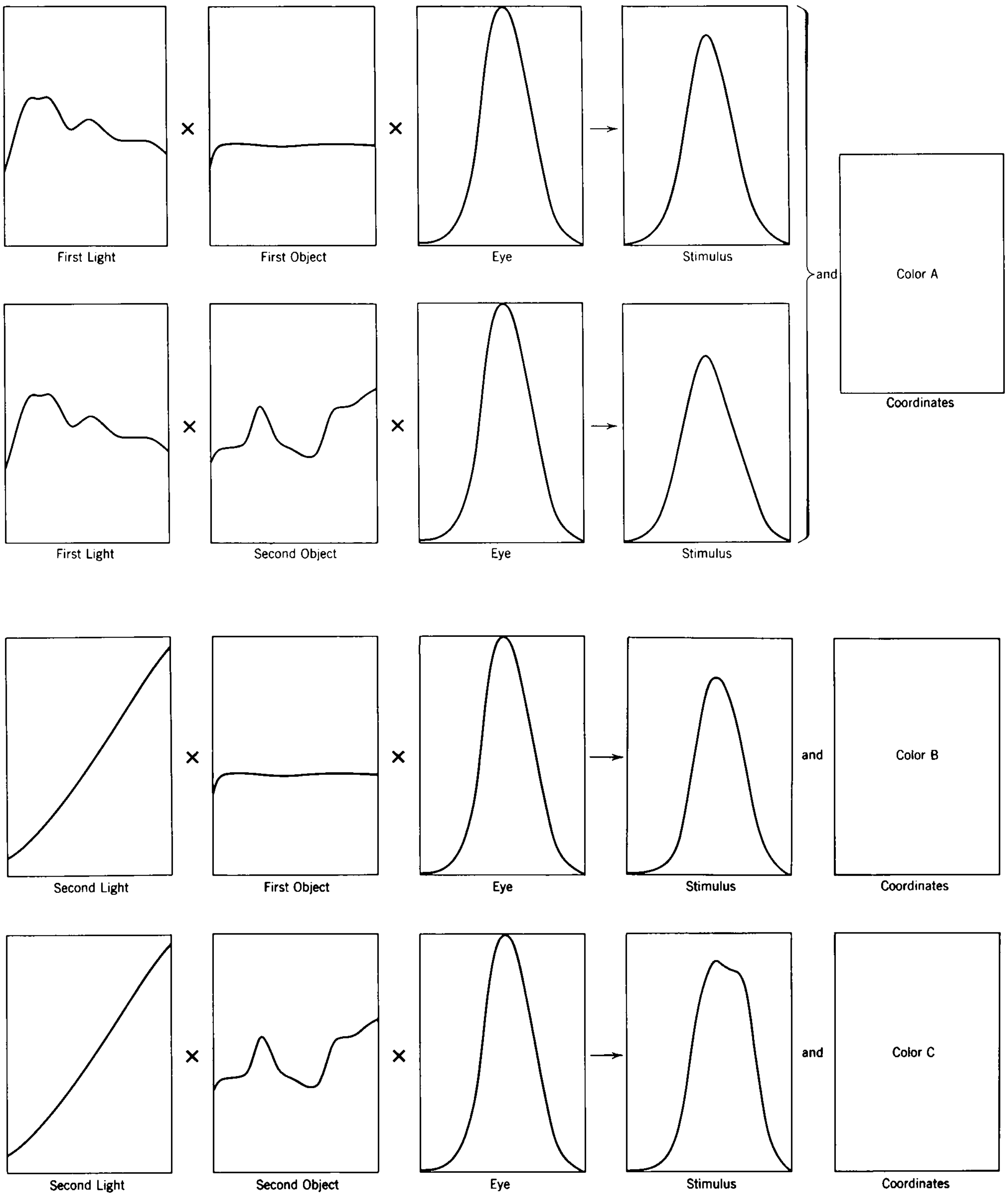
DEPENDENCE ON SOURCE



DEPENDENCE ON SPECTRAL REFLECTANCE



METAMERISM


First Light
×
First Object
×
Eye
→
Stimulus
First Light
×
Second Object
×
Eye
→
Stimulus
and
Color A
Coordinates
Second Light
×
First Object
×
Eye
→
Stimulus
and
Color B
Coordinates
Second Light
×
Second Object
×
Eye
→
Stimulus
and
Color C
Coordinates

COLOR MIXING

Newton started in 1730.

Grassman formulated acceptable laws in 1853

> [Symbols in square brackets are color names and not numeric values. The ⇔ sign indicates a color match.]

GRASSMAN'S FIRST LAW

Any color (source C) can be matched by a linear combination of three other colors (called primaries, e.g., RGB), provided than none of those three (primaries) can be matched by a combination of the other two.

This is fundamental to colorimetry. Any color C can be matched by R_c units of red, G_c units of green and B_c units of blue. The units can be measured in any form that quantifies light.

$$C \Leftrightarrow R_c[R] + G_c[G] + B_c[B]$$

GRASSMAN'S SECOND LAW

A mixture of any two colors (sources C_1 and C_2) can be matched by linearly adding together the mixtures of any three other colors that individually match the two source colors. It can be extended to any number of source colors.

$$\mathbf{C_3[C_3] \Leftrightarrow C_1[C_1] + C_2[C_2]}$$
$$\mathbf{\Leftrightarrow (R_1 + R_2)\,[R] + (G_1 + G_2)\,[G] + (B_1 + B_2)\,[B]}$$

GRASSMAN'S THIRD LAW

Color matching persists at all luminances.

$$kC_3(C_3) \Leftrightarrow kC_1(C_1) + kC_2(C_2)$$

It does fail at very low light levels where rod (scotopic) vision predominates over cone (photopic) vision.

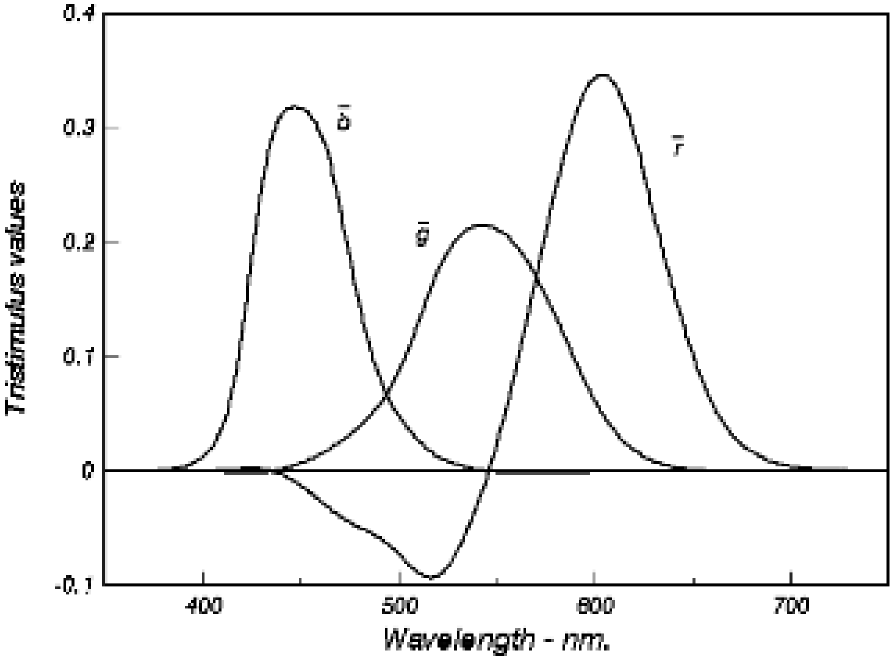
These laws govern all aspects of additive color work, but they apply only to signals in the "linear-light" domain. They can be extended into subtractive color work.

INITIAL EXPERIMENTS

Attempt to mix colors using three real primaries

R @ 700 nm (Tungsten lamp w/ long-pass filter)
G at 546 nm (Hg green line)
B @ 435 nm (Hg blue line)

Result is color-matching functions (approx. color sensitivity of the eye) that include negative values (not physically possible).

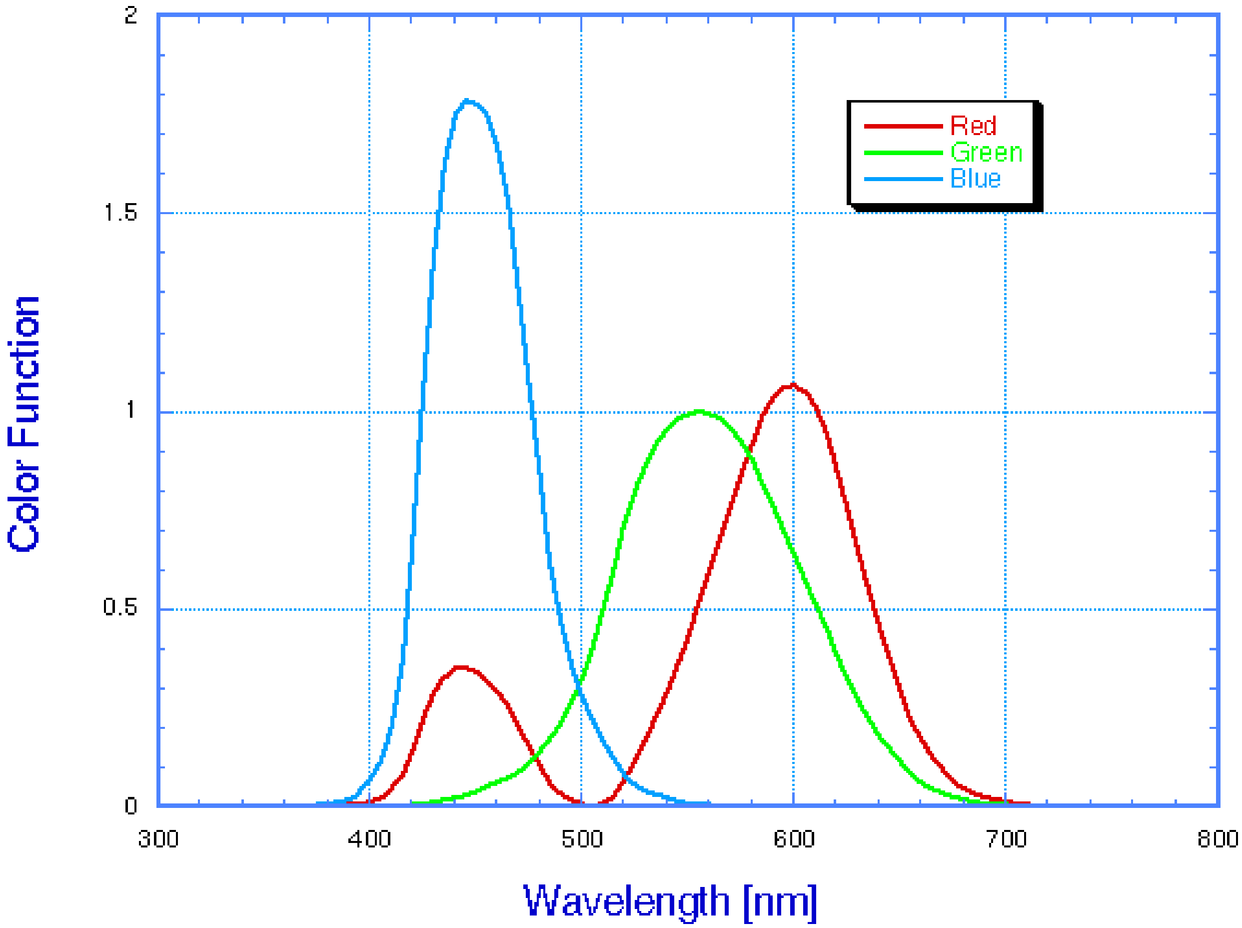


Conclusion: There is no set of real primaries that can match all real colors.

Solution: Adopt artificial primaries

CIE COLOR MATCHING FUNCTIONS

Adopt a set of real color matching functions



$\bar{y}$ (λ) (green curve) was deliberately chosen to equal V(λ), the relative spectral luminous efficiency for photopic vision.

CALCULATE TRISTIMULUS VALUES

$$X = c\int_{380}^{760} \Phi_\lambda \cdot \rho(\lambda) \cdot \bar{x}(\lambda)\, d\lambda$$

$$Y = c\int_{380}^{760} \Phi_\lambda \cdot \rho(\lambda) \cdot \bar{y}(\lambda)\, d\lambda$$

$$Z = c\int_{380}^{760} \Phi_\lambda \cdot \rho(\lambda) \cdot \bar{z}(\lambda)\, d\lambda$$

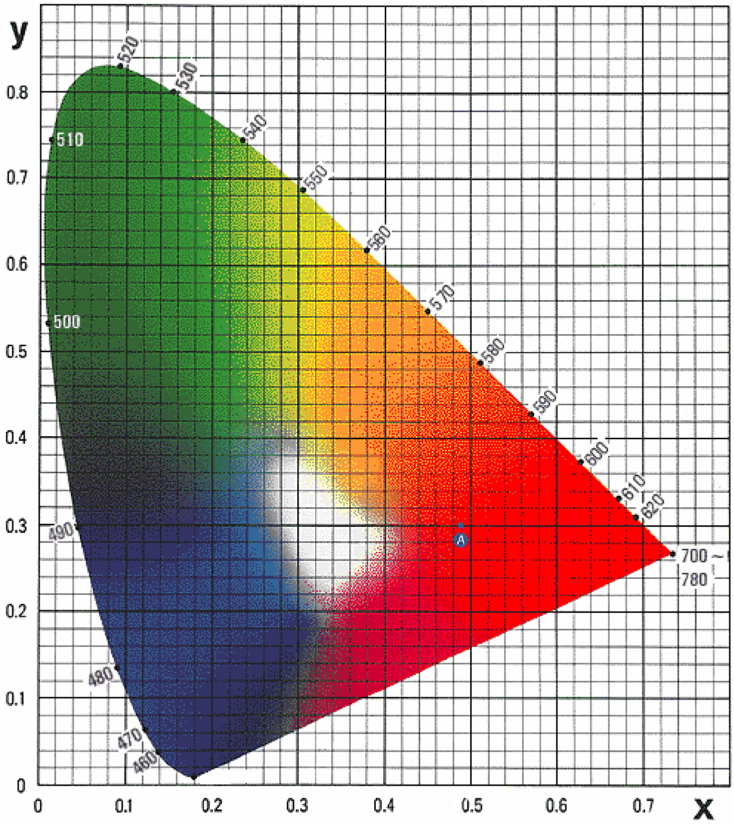
Φ_λ is the spectral power of the source, $\rho(\lambda)$ is the spectral reflectance of the object (may be replaced by $\tau(\lambda)$ if object is transmissive), and $\bar{x}$, $\bar{y}$ and $\bar{z}$ are the spectral tristimulus values or color matching functions (table look-up). The term $\bar{y}$ was deliberately chosen to equal $V(\lambda)$, the relative spectral luminous efficiency for photopic vision. Then $c = K_m =$ 683 lm/watt and Y is measured in lumens.

Since $\bar{y}$ (λ) deliberately chosen to equal $V(\lambda)$, $c = K_m = 683$ lm/W, and Y is measured in lumens.

NORMALIZE TO CHROMATICITY COORDINATES

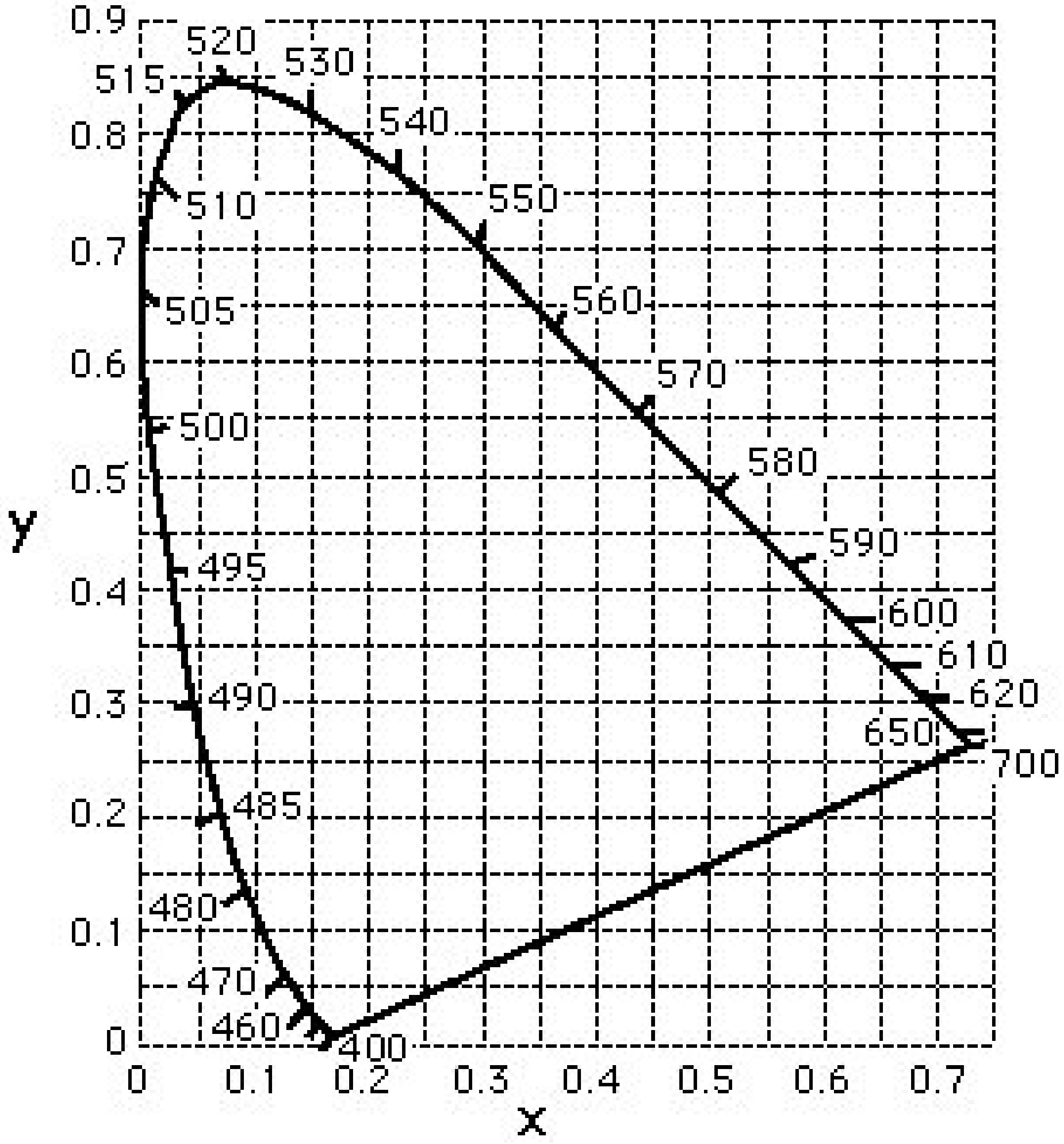
$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad z = \frac{Z}{X+Y+Z}$$

Since x, y and z range from 0 to 1, and $x + y + z = 1$, we can just plot x vs. y, and z is implied. Therefore a plot of x vs. y gives all information except Y. This is the chromaticity diagram. The primaries are located at the "corners"



PRIMARY	x	y	z
RED	1	0	0
GREEN	0	1	0
BLUE	0	0	1

1931 CIE CHROMATICITY DIAGRAM

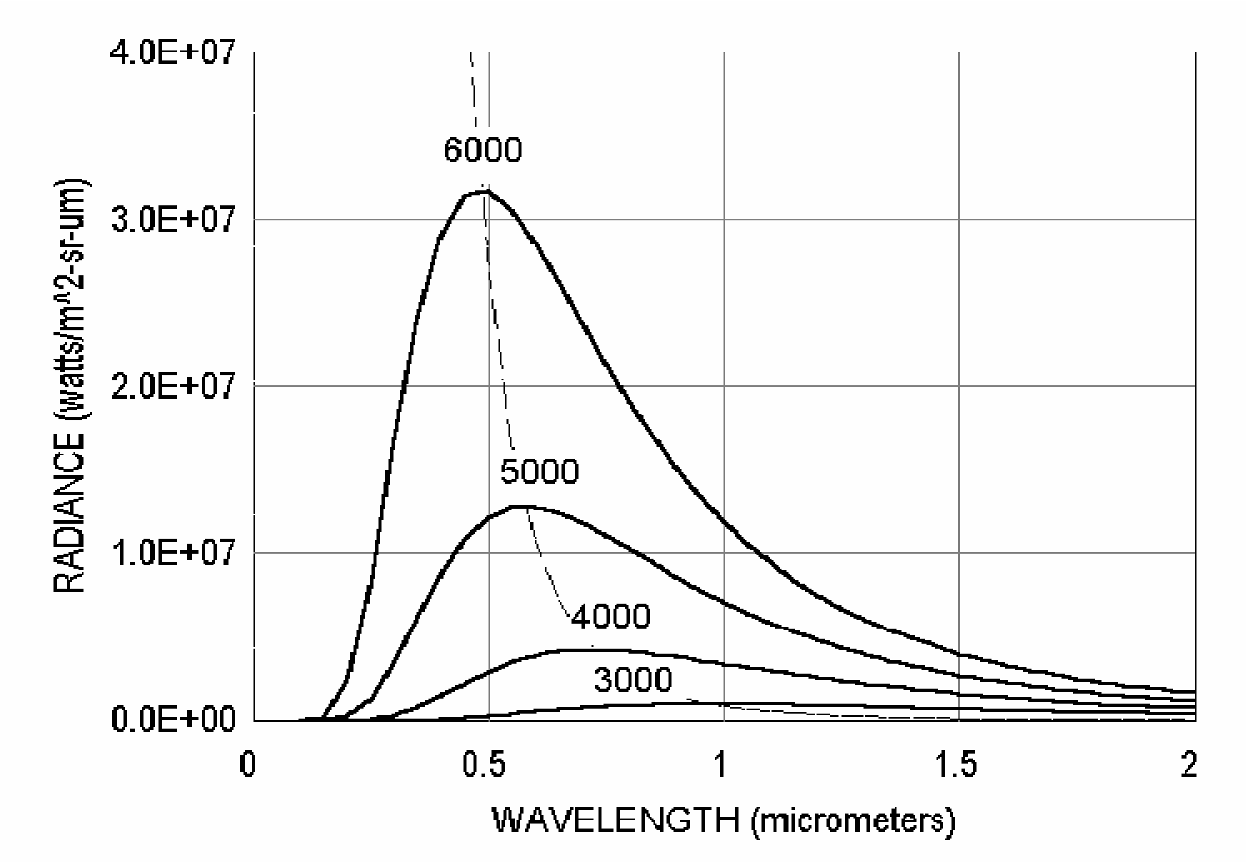


Outer curve is spectrum locus.

Equi-energy (white) at x=y=z=0.333…

BLACKBODY RADIATION

From perfect (Planckian) radiator. Absorbs all and emits all.

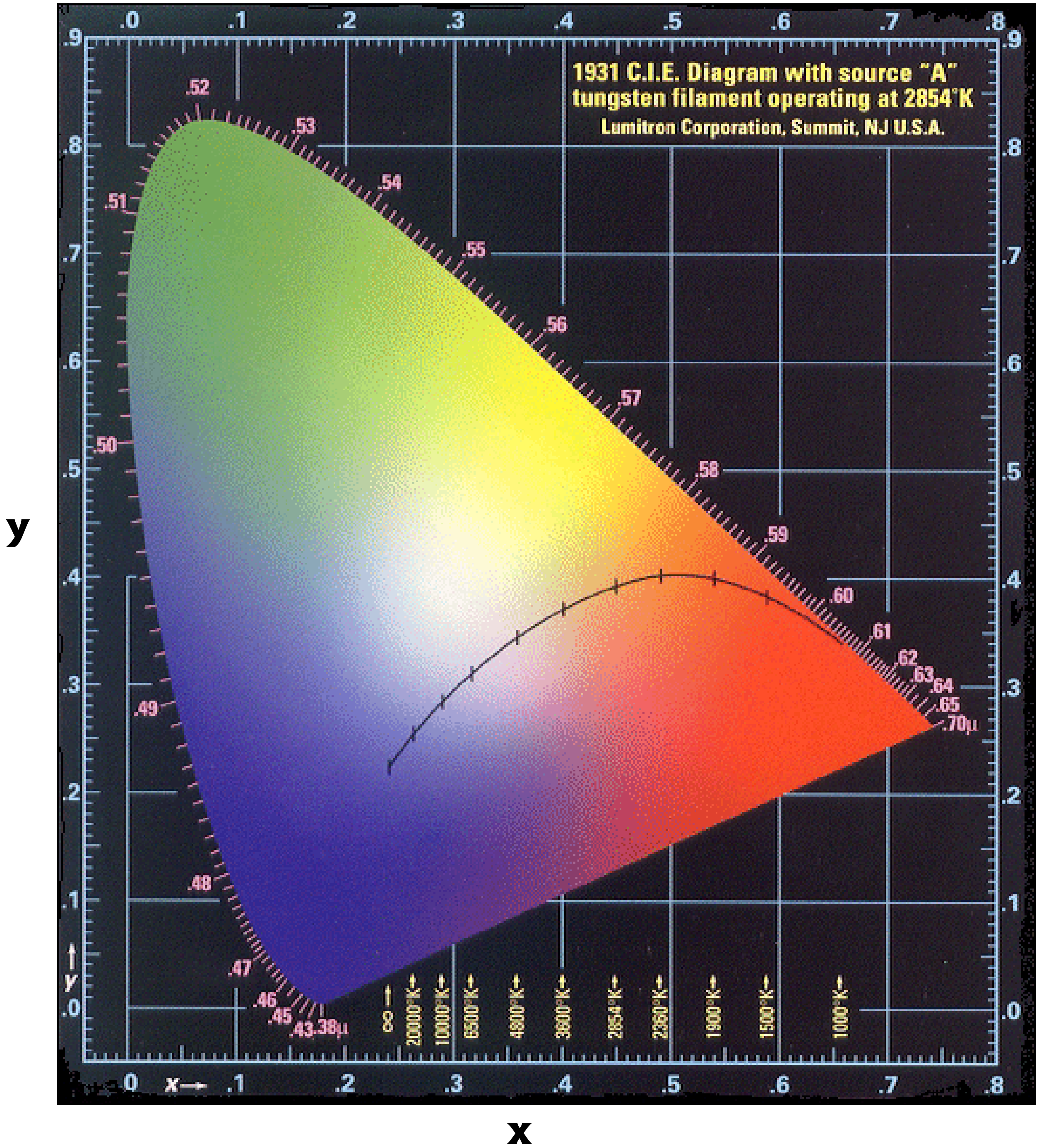


The peak wavelength is inversely related to the temperature:

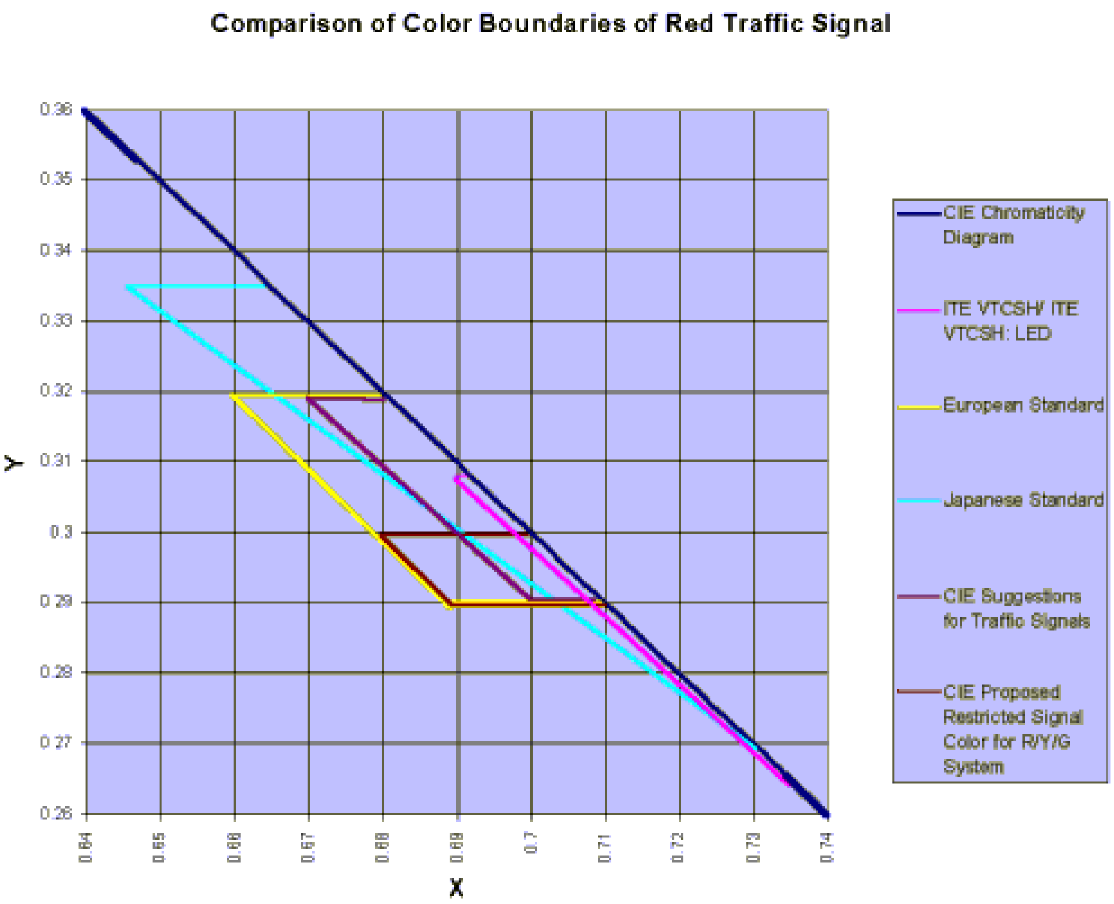
$$\lambda_{\max} = \frac{2898000}{T} \quad \lambda \, in \; nm$$

The fraction in the visible ranges from 40% for 6000K (sunlight) to less than 10% for 2854K (incandescent).

1931 CIE CHROMATICITY DIAGRAM

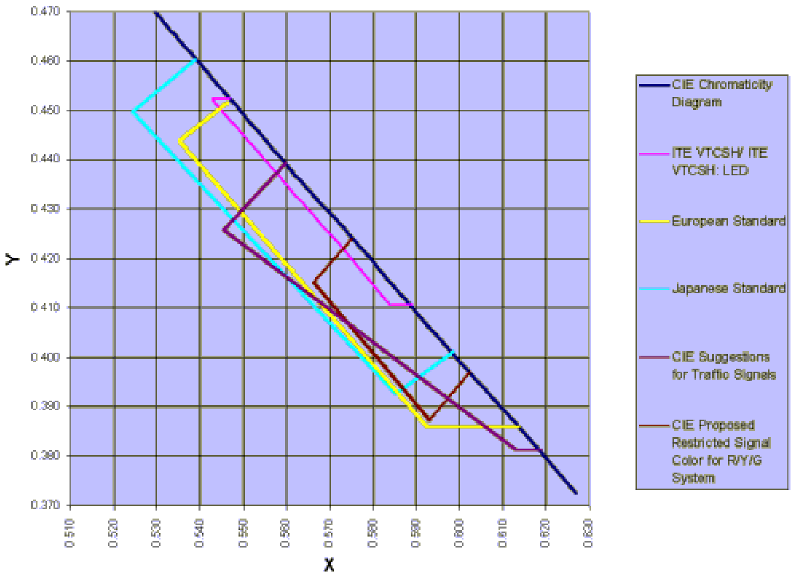


SIGNAL LIGHT SPECIFICATIONS - RED

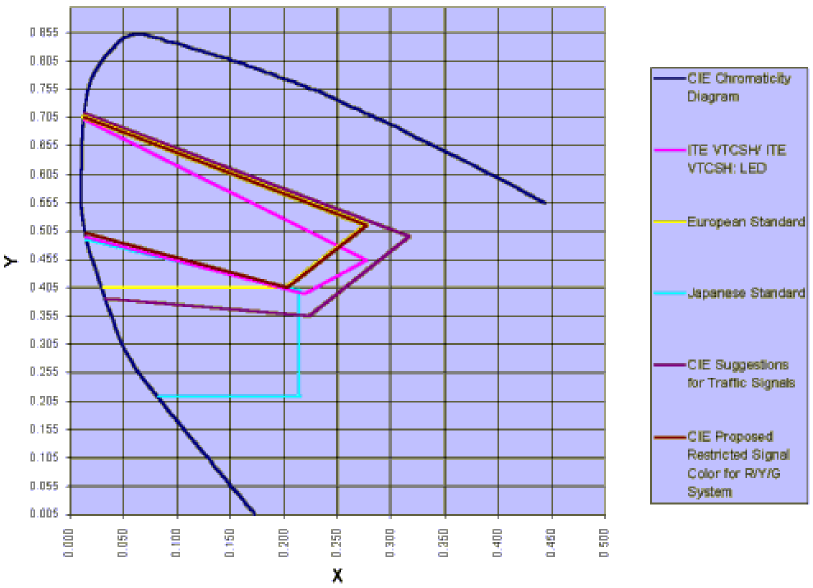

Comparison of Color Boundaries of Red Traffic Signal

x and y data refers to 1931 CIE diagram.

SIGNAL LIGHT SPECIFICATIONS
YELLOW AND GREEN



Comparison of Color Boundaries of Yellow Traffic Signal

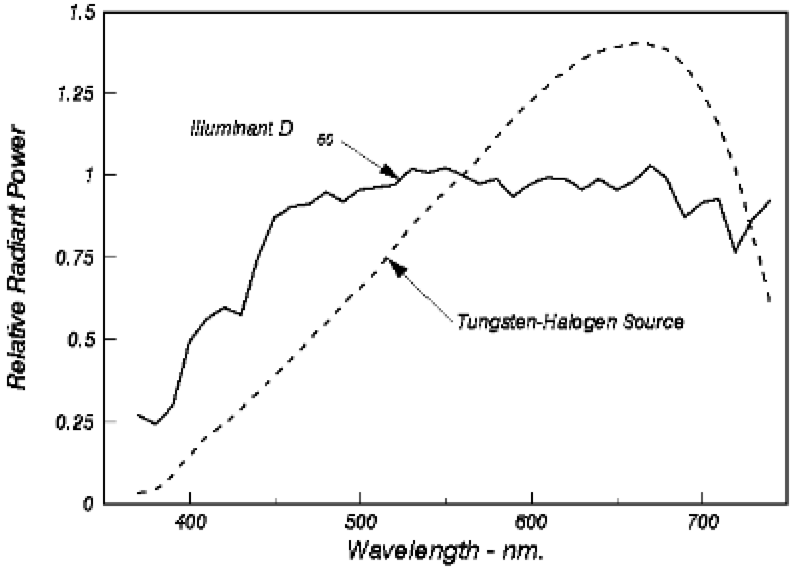


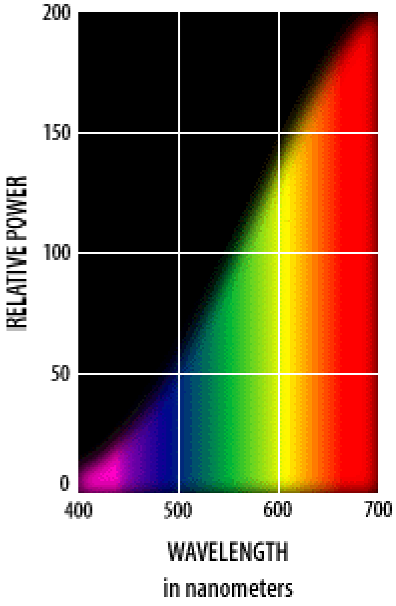
Comparison of Color Boundaries of Green Traffic Signal

STANDARD SOURCES

Illuminant A (2854K, represents incandescent lighting)

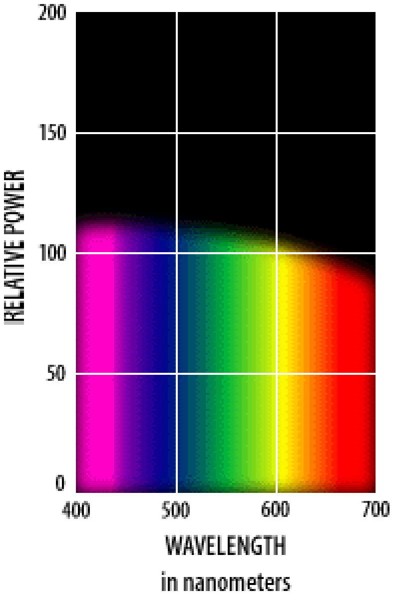
Illuminant D65 (6500K, represents daylight)





2854 K

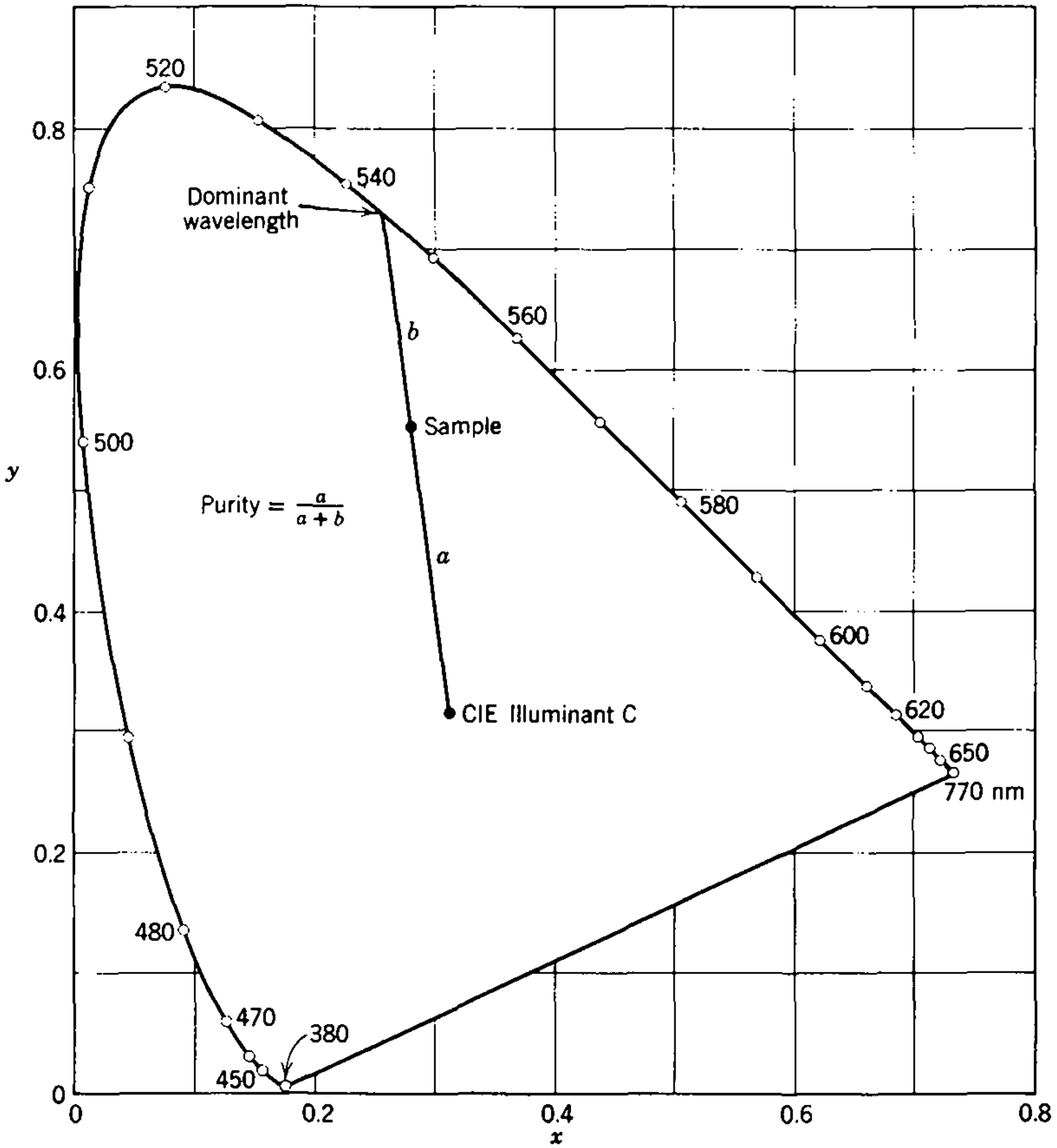
CIE Source A



6500 K

CIE Illuminant D_{65}

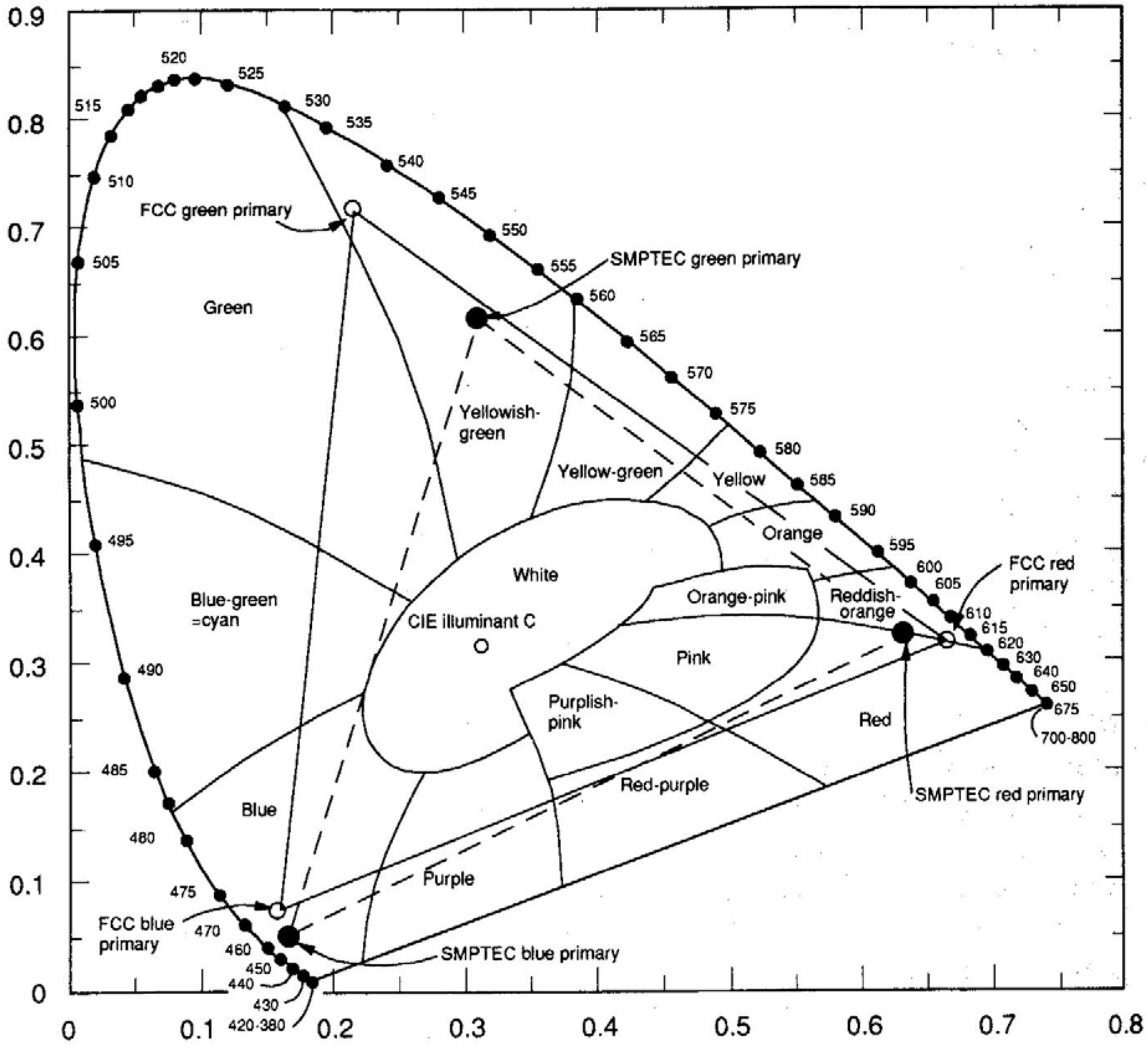
DOMINANT WAVELENGTH AND PURITY



Mix with a spectral color and white

For magenta region, add complementary wavelength to color being matched.

RGB TELEVISION

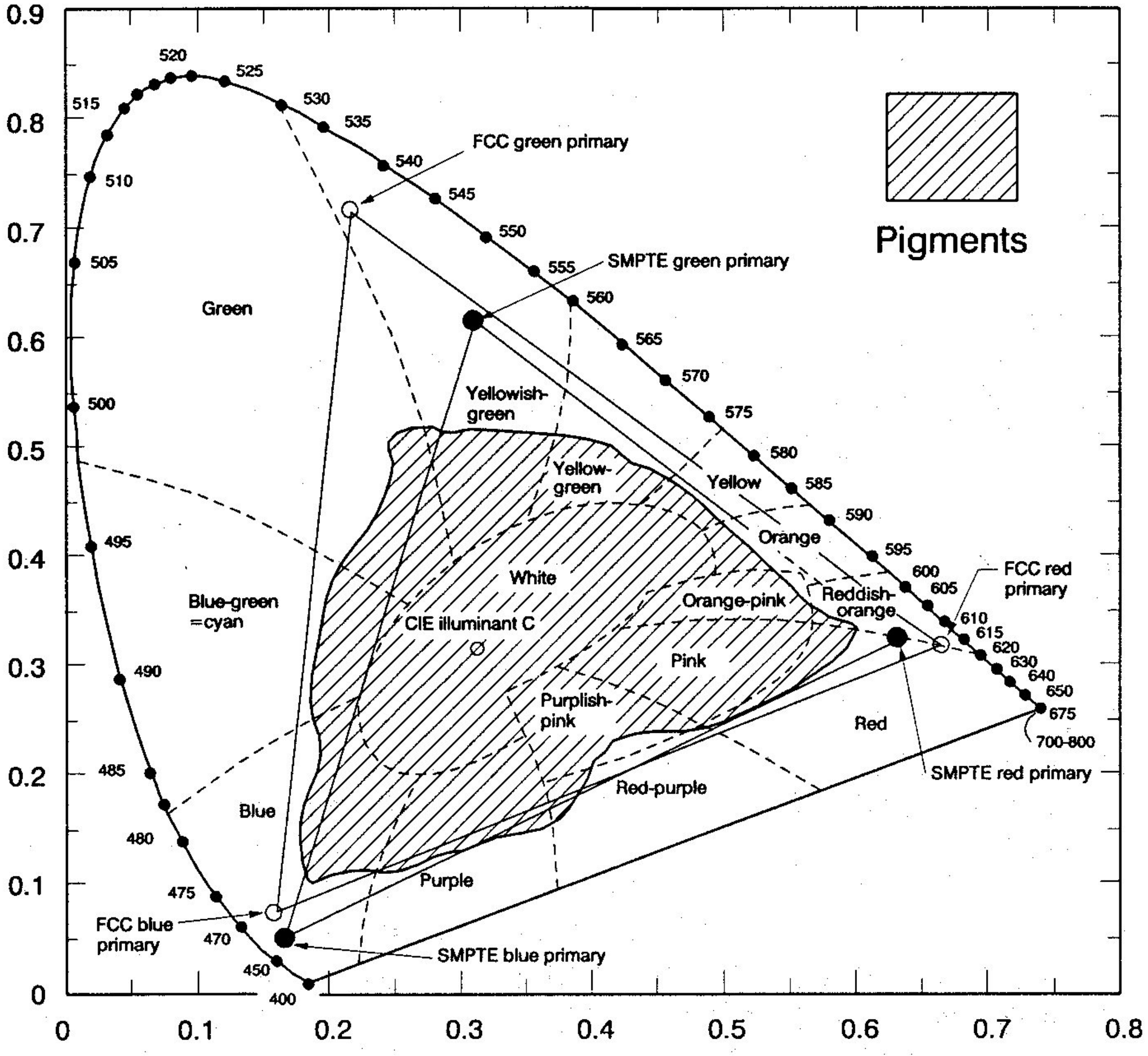


FCC/NTSC RGB PRIMARIES (1953)

SMPTEC RGB PRIMARIES (1982)

Adopted to give greater screen brightness
at expense of range of colors attainable.

REAL-LIFE COLOR RANGE

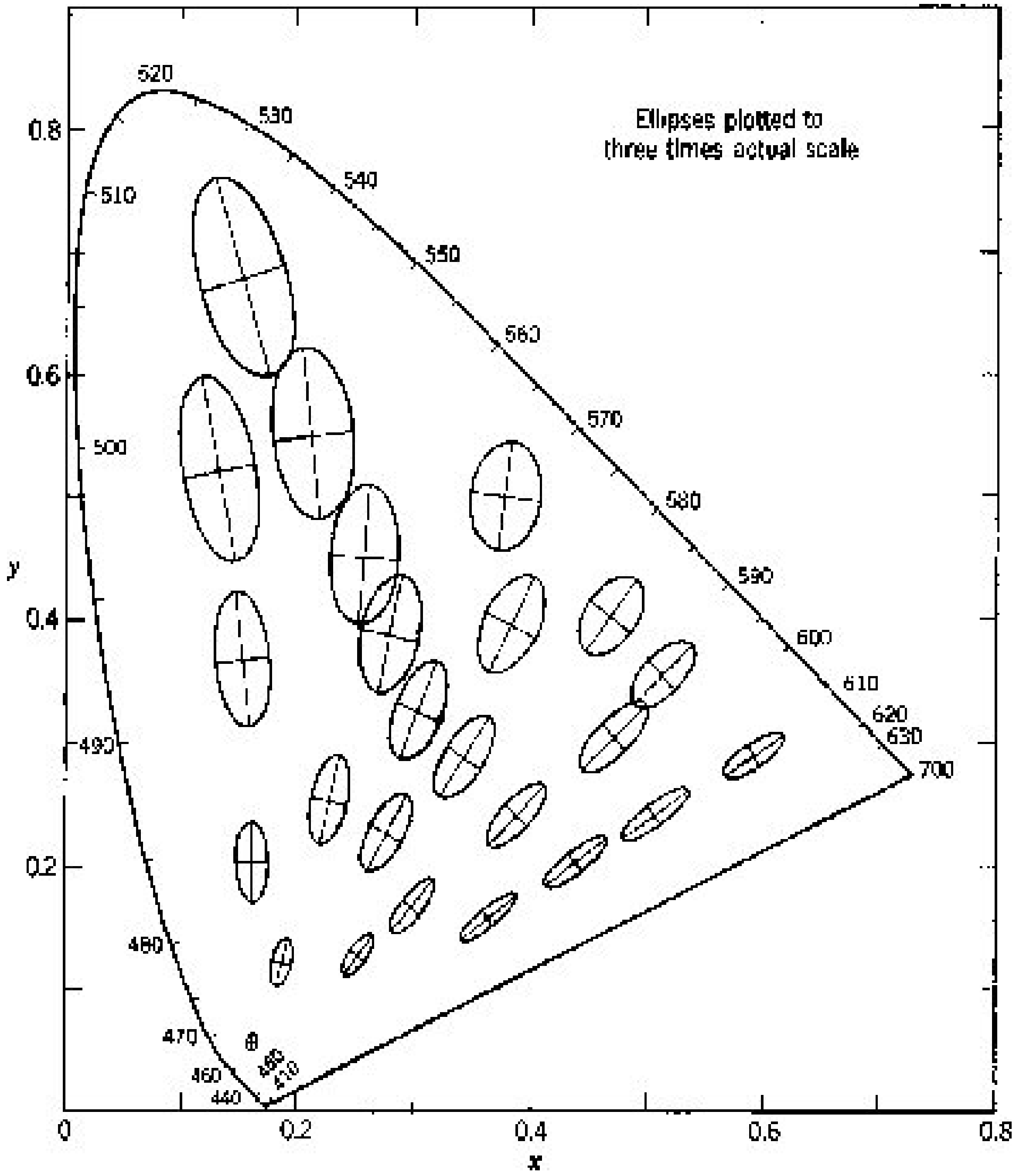


Range of FCC/NTSC primaries encompasses

nearly all of pigment and dye color gamut,

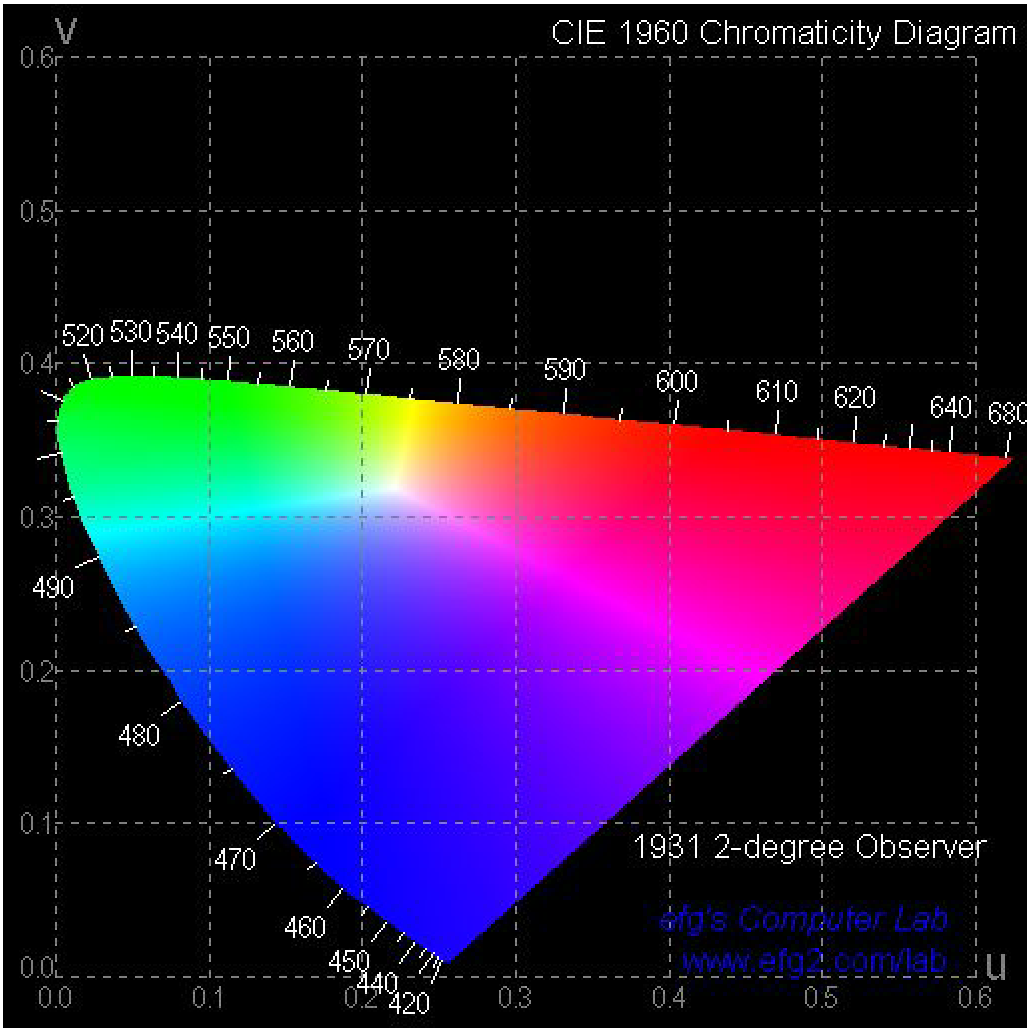
SMPTE primaries somewhat less

UNIFORM COLOR SPACE



Ellipses represent three times the minimum perceptible color difference. A uniform chromaticity scale would be much nicer.

1960 CIE UCS CHROMATICITY DIAGRAM



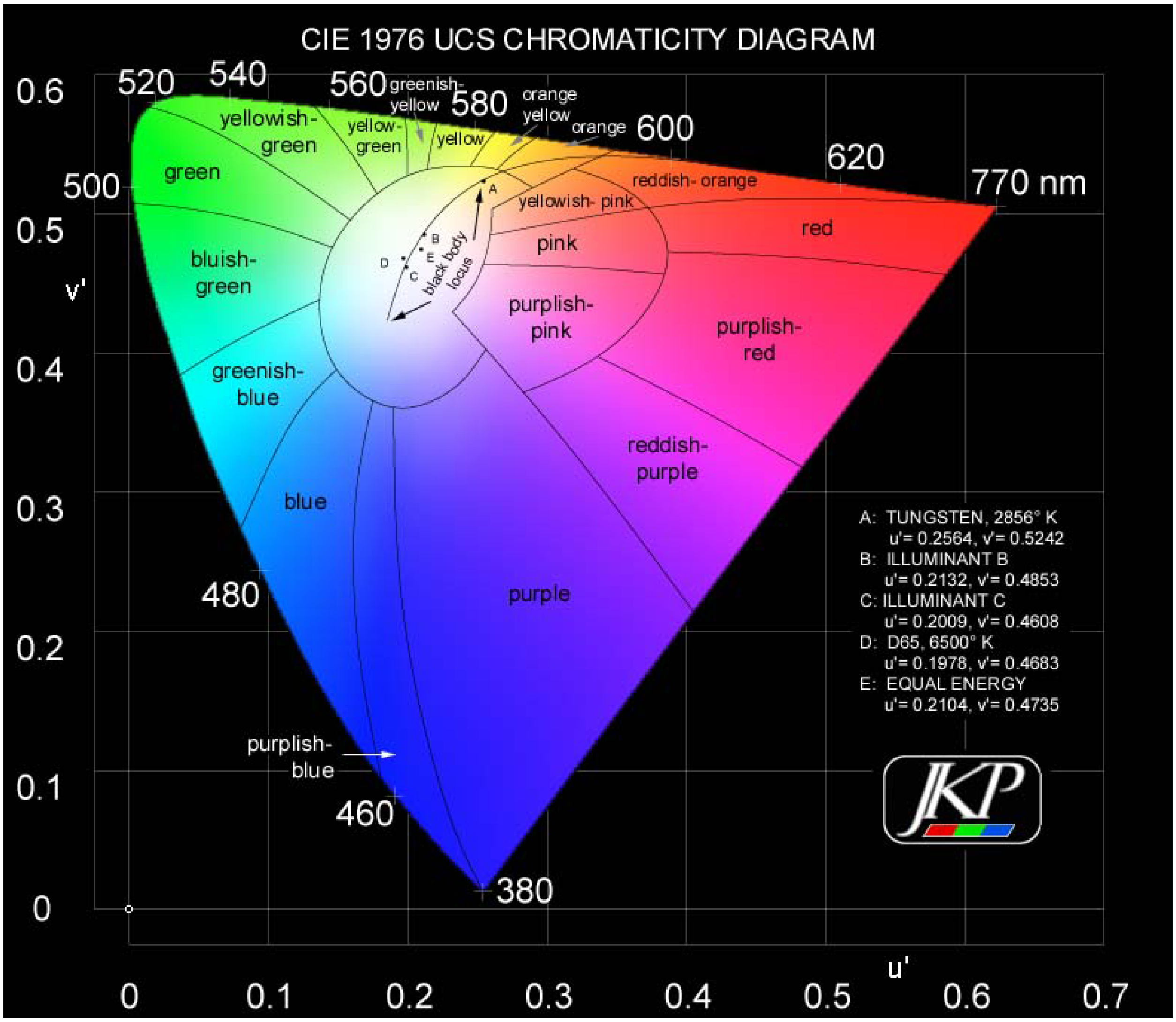
$$u = \frac{4x}{-2x + 12y + 3} \qquad v = \frac{6y}{-2x + 12y + 3}$$

Location of primaries: RED u = 4 v = 0

GREEN u = 0 v = 0.4

BLUE u = 0 v = 0

1976 CIE UCS CHROMATICITY DIAGRAM



$$u' = \frac{4x}{-2x + 12y + 3} \qquad v' = \frac{9y}{-2x + 12y + 3}$$

Location of primaries: RED u = 4 v = 0
GREEN u = 0 v = 0.6
BLUE u = 0 v = 0

A SAMPLING OF COLOR SPACES

- **CIE-XYZ** - the international standard capable of representing all colors.
- **CIE-xyY** - a variant of the CIE standard using two color components plus luminance (Y).
- **CIE-uvY** - Another variation of the CIE standard using two color components plus luminance (Y).
- **PhotoYCC**™ - Kodak system for PhotoCDs™
- **CIE L*u*v*** - A popular perceptually uniform space i.e., numerical distance in the space is proportional to perceived color difference. Used for additive applications.
- **L*a*b*** - A popular perceptually equalized space, i.e., numerical distance in the space is proportional to perceived color difference. Used for subtractive applications.
- **CMY** - Cyan, magenta, yellow, for low-end color printing.
- **CMYK** - Cyan, magenta, yellow, key (black); for high-end four-color printing.

A FEW MORE COLOR SPACES

- **DIN FSD** - German standard
- **Munsell HVC** - US standard; hue, value, and chroma
- **RGB** - Red, green, blue; for color monitors and scanners
- **HSV** - Hue, saturation, value
- **HLS** - Hue, lightness, and saturation
- **YIQ** - Luminance, in-phase, quadrature; NTSC color TV broadcasting. Made by a linear transformation of the RGB cube.
- **YUV** - Also called YCbCr. Initially for PAL analog video, now used in CCIR 601 standard for digital video
- **National Bureau of Standards Dictionary of Color Names** - Thousands of popular and commercial color names (like mauve, teal, cobalt, etc.)
- **National Bureau of Standards Color System** - A stylized system of about two hundred names encompassing all colors.

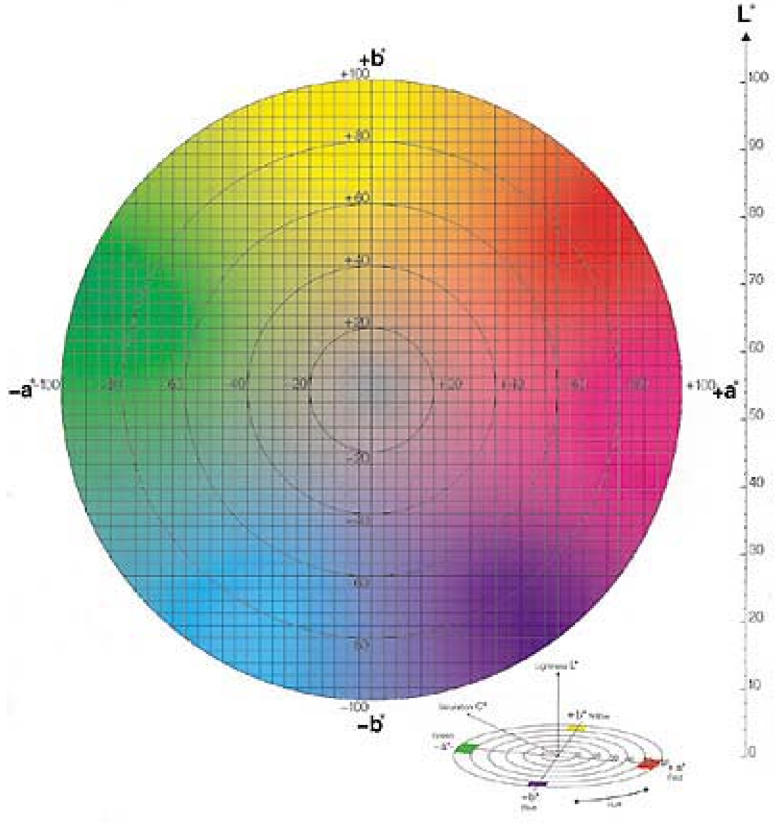
COLOR DIFFERENCES

In many applications, color differences with respect to a standard are more important than absolute values of x and y.

Color tolerance specifications generally written in terms of differences.

Many attempts to define a uniform chromaticity color space so Δx and Δy are consistent across color space

CIELAB COLOR SPACE



$$L^* = 116\left(\frac{Y}{Y_0}\right)^{1/3} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_0}\right)^{1/3} - \left(\frac{Y}{Y_0}\right)^{1/3}\right]$$

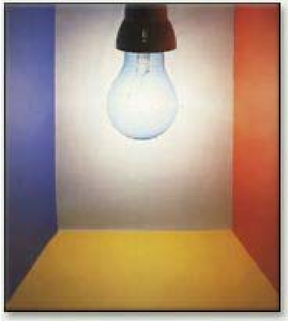
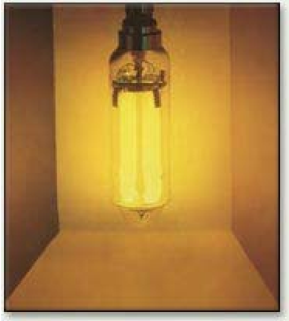
$$b^* = 200\left[\left(\frac{Y}{Y_0}\right)^{1/3} - \left(\frac{Z}{Z_0}\right)^{1/3}\right]$$

X, Y and Z are tristimulus values of sample

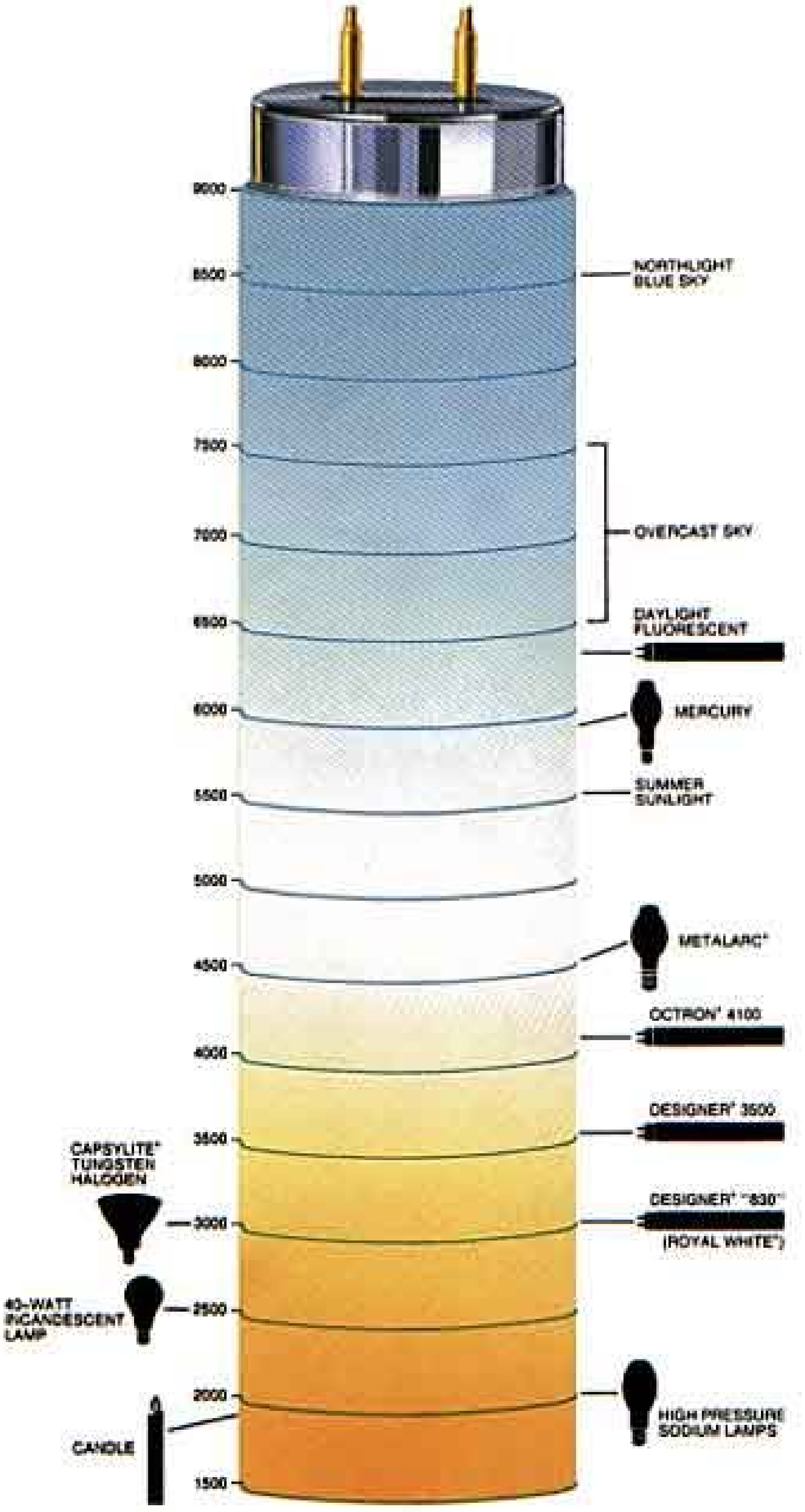
X_0, Y_0 and Z_0 are tristimulus values of illuminant

APPEARANCE UNDER VARIOUS LIGHT SOURCES

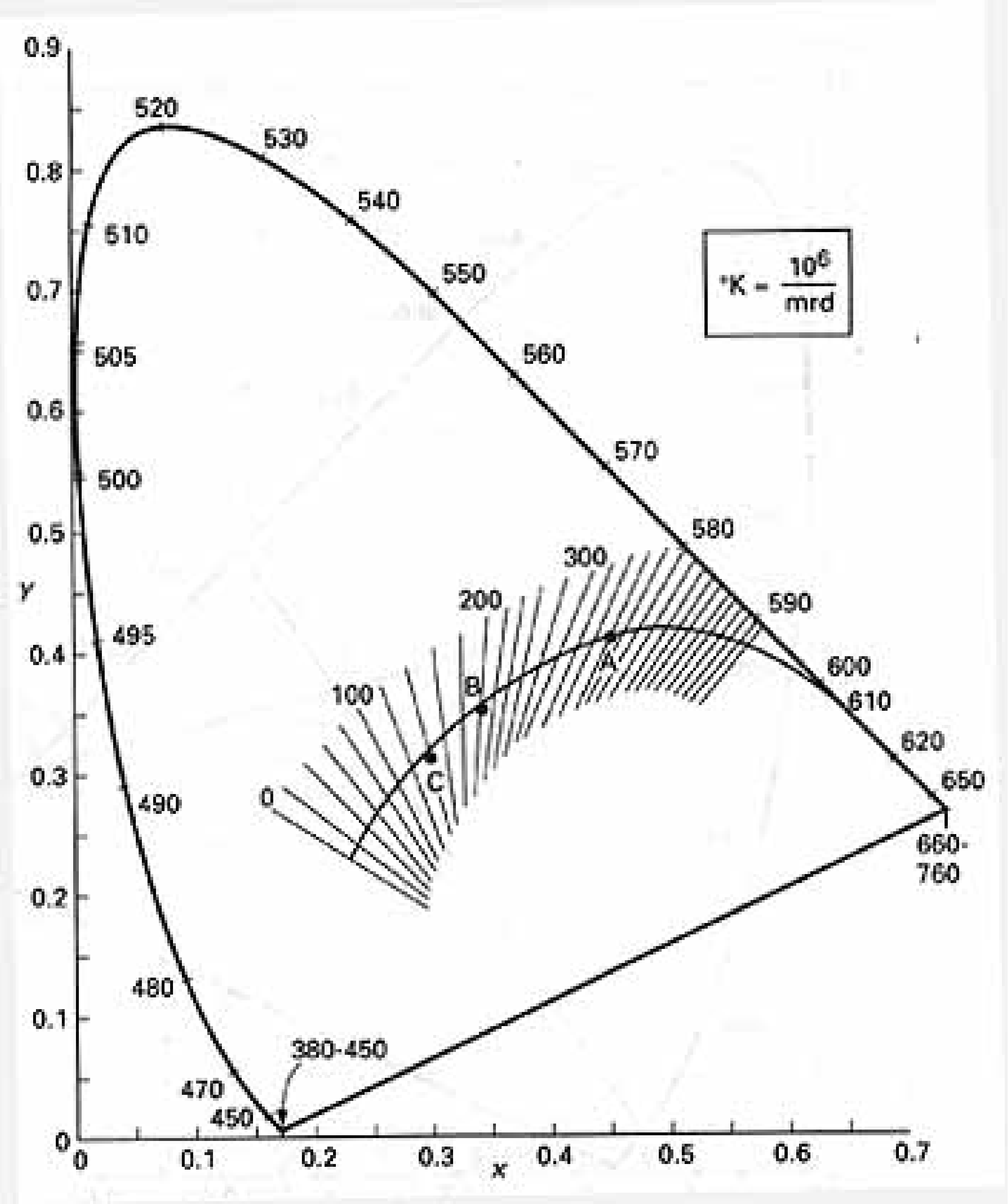
In the box below, the left wall is painted blue, the right wall is painted red, the floor is painted yellow, and the back wall is painted white.

Bulb	**Daylight bulb**	**Incandescent bulb**	**Mercury vapor lamp**	**Low-pressure sodium lamp**	**Hi-pressure sodium lamp**
Purpose	Imitates natural daylight	Common household light bulb	First HID lamps, now obsolete.	Sometimes used for street lighting	Street lighting in cities, sports arenas
In the light box...	Walls around bulb appear like they would in daylight.	Filament emits yellowish-white light; walls have a strong yellow tint.	Left wall is blue; right is blue-grey. Lamp has no red, so right wall can't reflect it. Light has some yellow, seen on bottom wall.	Colors around lamp show that light is almost pure yellow. Controls light pollution.	Give most objects a similar color as daylight.
Appears					

COLOR TEMPERATURE



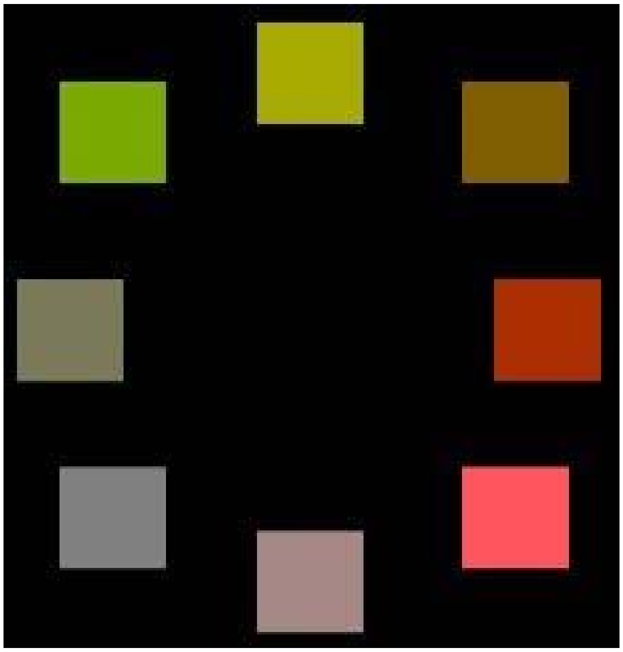
CORRELATED COLOR TEMPERATURE



COLOR RENDERING INDEX (CRI)

A scheme to compare light sources as to how they modify color. Scale runs from 0 (stinks, no color fidelity) to 100 (perfect, colors not distorted). Reference sources are sunlight and incandescent.

Uses 8 color tiles (standard) or 16 color tiles (extended)

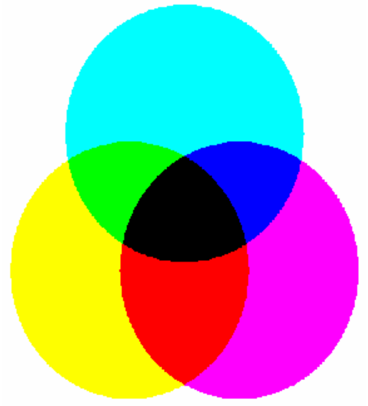


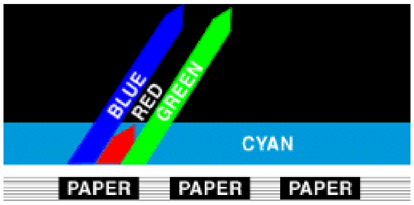
Over 90 is considered excellent, less that 60 is lousy.

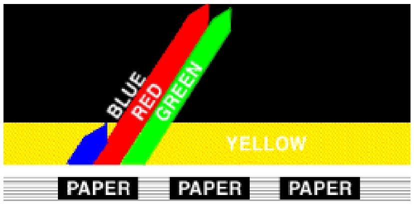
COLOR PRINTING

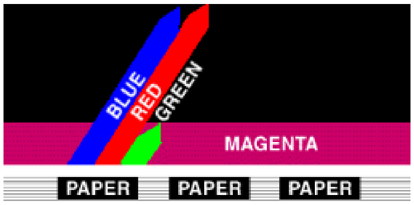
Start with white paper
Overlay with subtractive primary inks

CYAN (absorbs red)
YELLOW (absorbs blue)
MAGENTA (absorbs green)

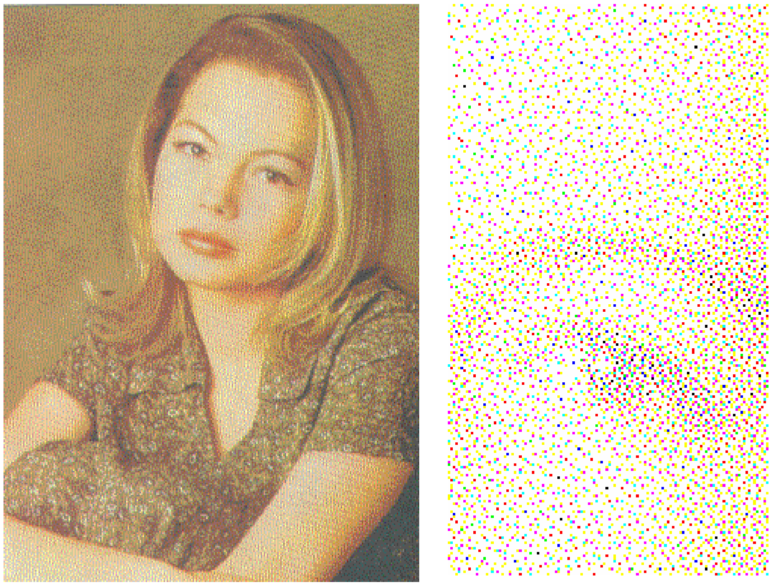






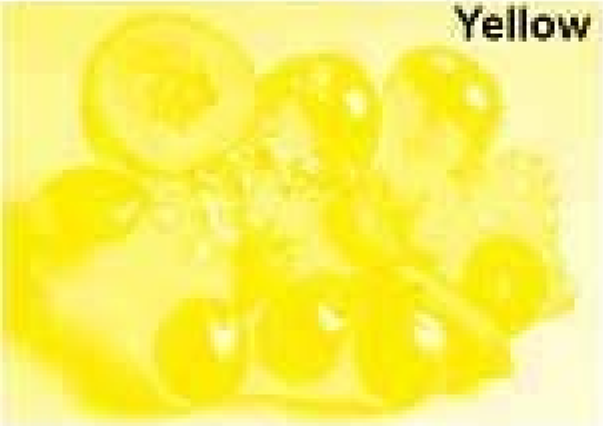


Available inks do not produce sufficiently dark color. So a layer of black ink added for better definition and darker blacks. This system is **CYMK**.

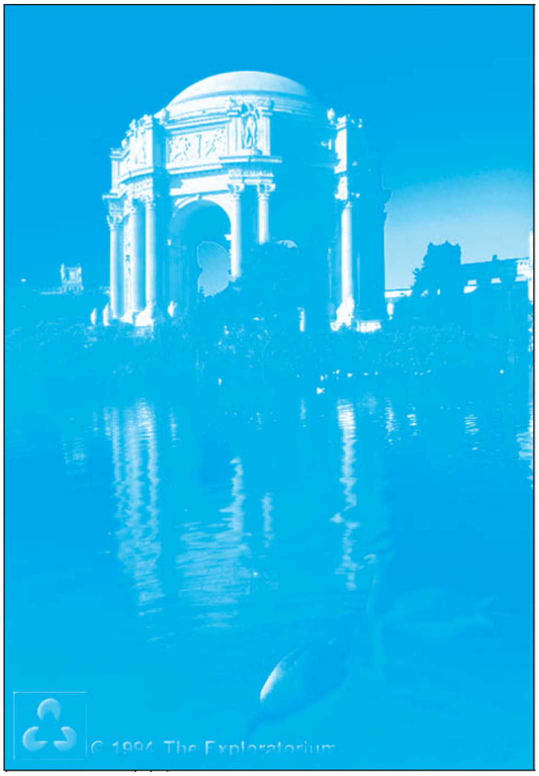


MICHELLE WILLIAMS

FOUR-COLOR CYMK PRINTING PROCESS



CYMK LAYERS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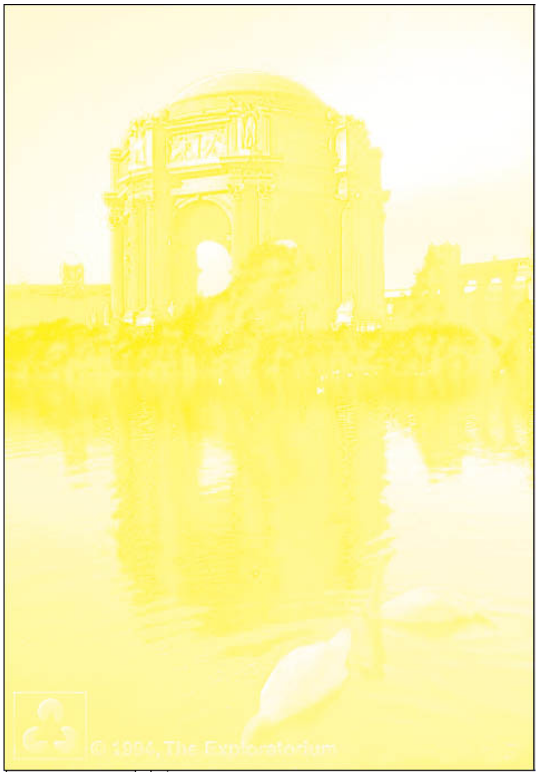
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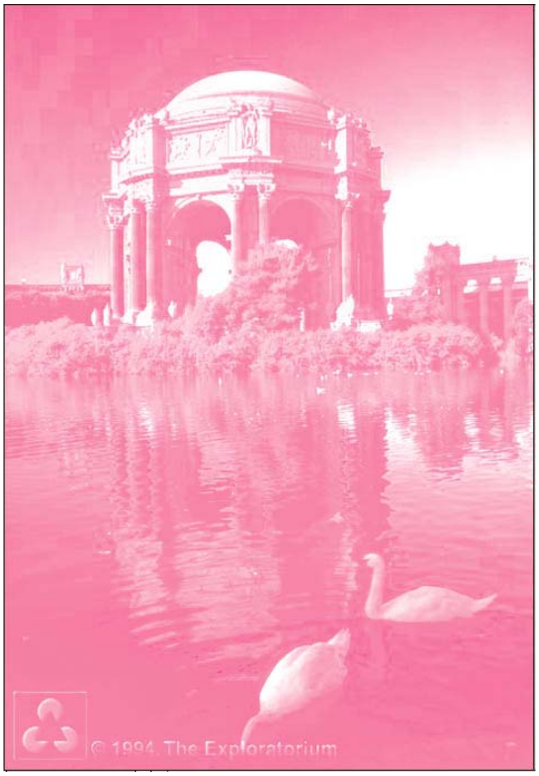
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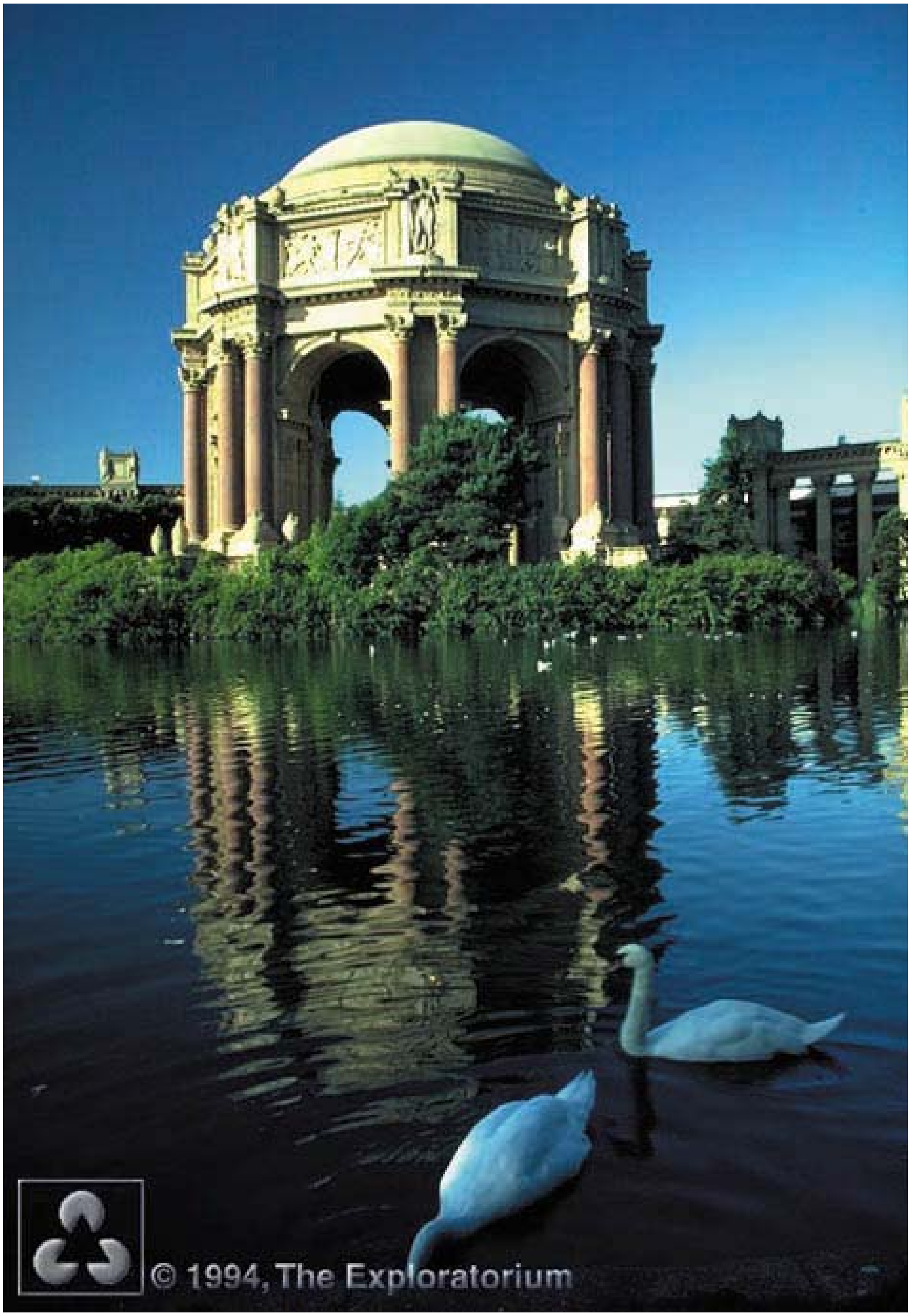
THE RESULT

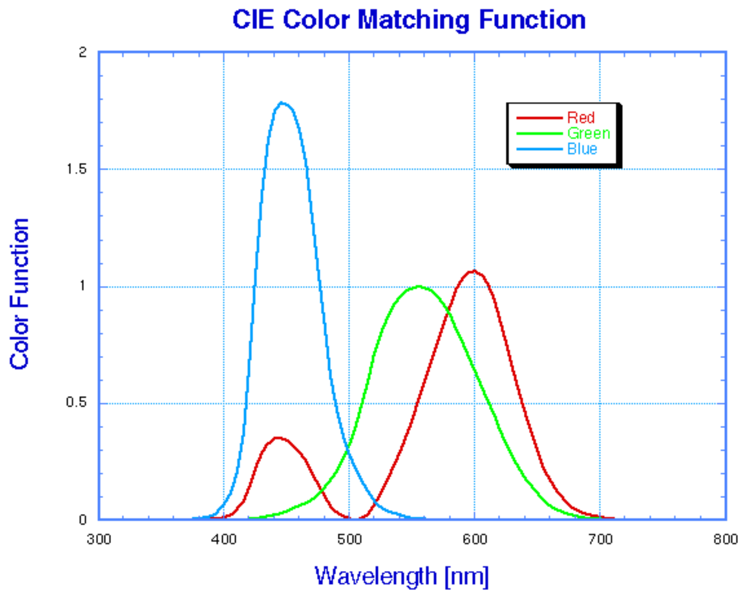


COLORIMETRY

Two classes of instruments
    Tri-stimulus colorimeters
    Spectroradiometers

TRI-STIMULUS COLORIMETERS

Most colorimeters of this configuration
Three detectors filtered to x, y and z
Signals proportional to X, Y and Z



Calculate x and y
If Y sensor calibrated to V(λ), can get xyY.
Use transformations to obtain other metrics

USE OF SPECTRORADIOMETERS FOR COLOR MEASUREMENTS

Two modes of operation:

Measurement of radiance:

- Determine relative spectral radiance over wavelength range 380 to 760 nm.
- Calculate X, Y and X
- Calculate x and y

Measurement of reflectance:

- Determine relative spectral reflectance over wavelength range 380 to 760 nm.
- Select source (standard illuminant A or D65)
- Calculate X, Y and X
- Calculate x and y