Color

6.819/6.869, MIT
Bill Freeman

Sept. 13, 2018

Why does a visual system need color?

http://www.hobbylinc.com/gr/pll/pll5019.jpg

Why does a visual system need color? (an incomplete list…)

- To tell what food is edible. 
- To distinguish material changes from shading changes. 
- To group parts of one object together in a scene. 
- To find people's skin. 
- Check whether a person's appearance looks normal/healthy.

http://www.pouted.com/know-10-points-information-unicorn/sick-child/

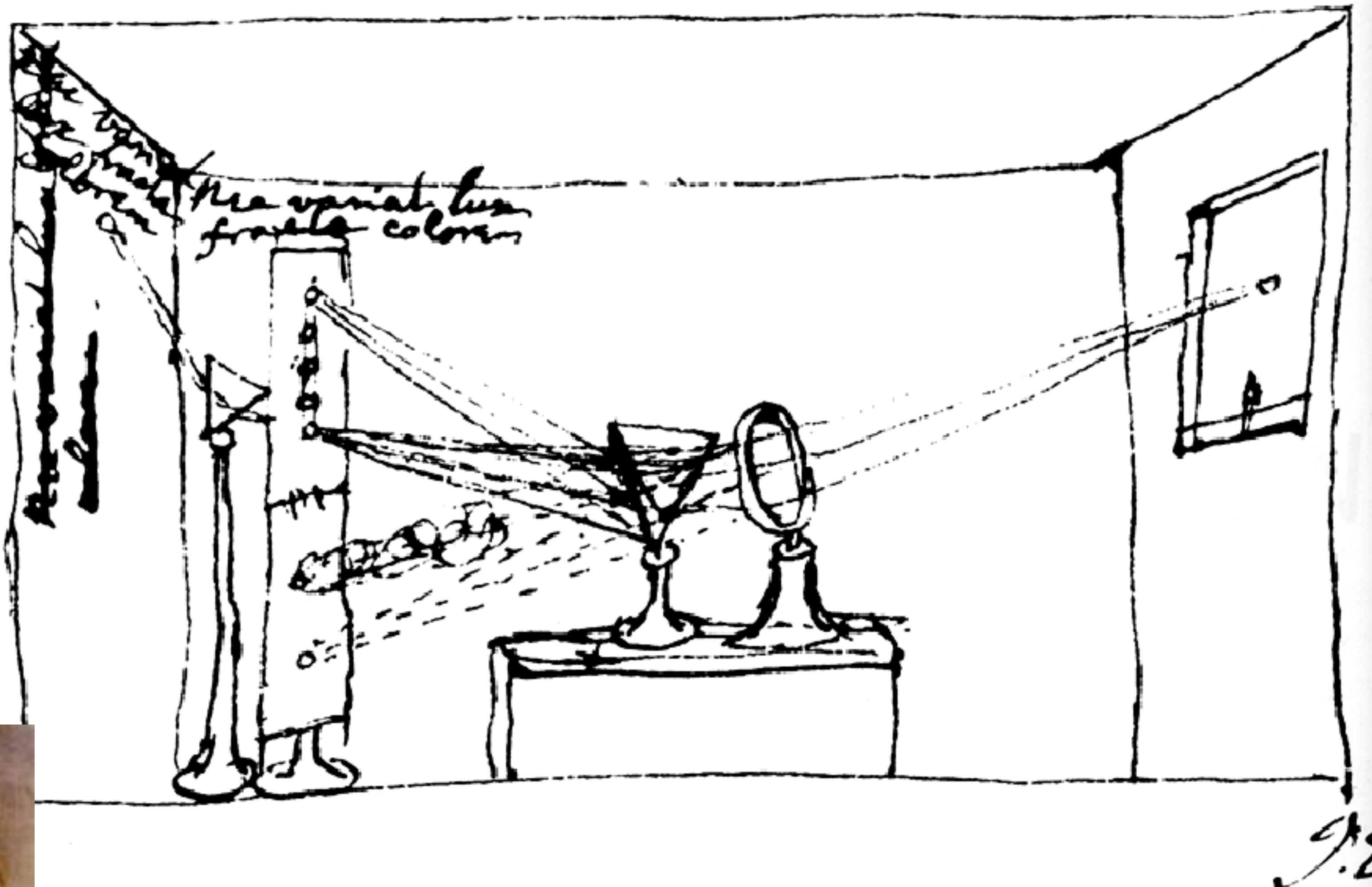
Lecture outline

- Color physics.
- Color perception.

Lecture outline

- Color physics.
- Color perception.

Color

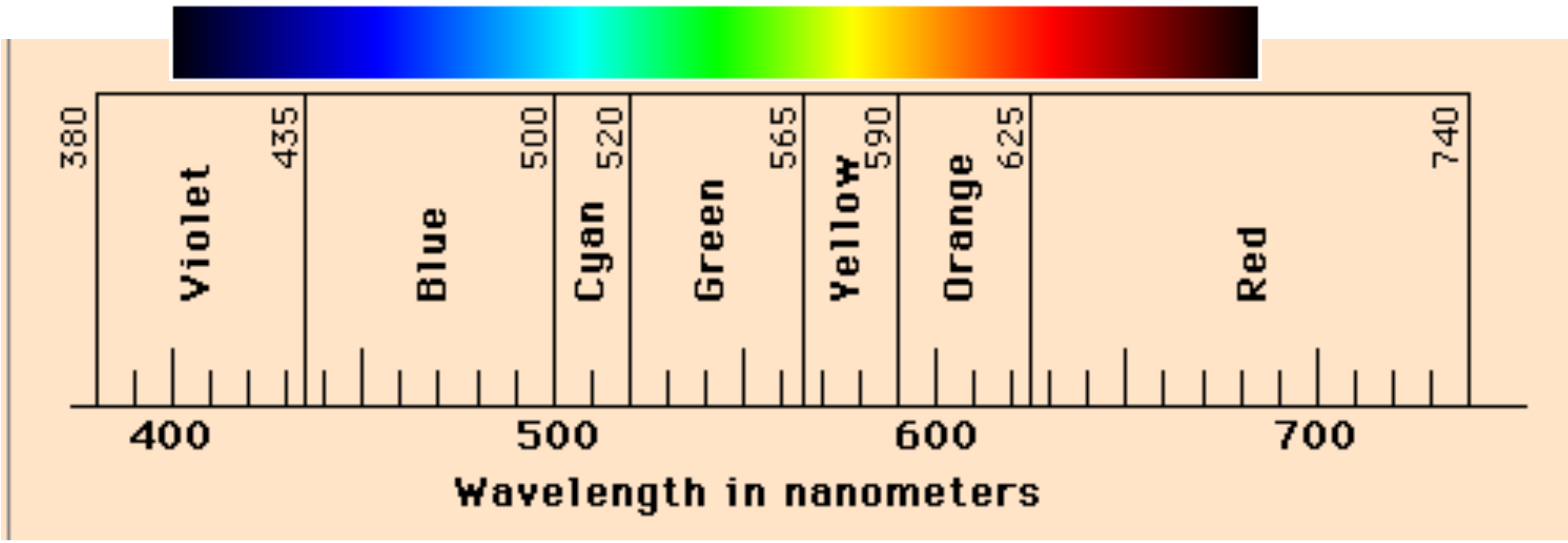


www.popularpersons.org

4.1 NEWTON'S SUMMARY DRAWING of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

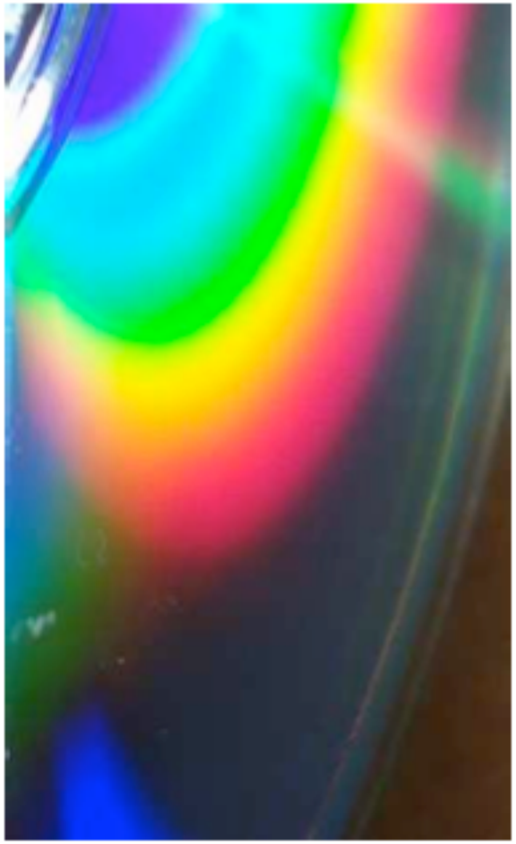
From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Spectral colors



http://hyperphysics.phy-astr.gsu.edu/hbase/vision/specol.html#c2

(a)



(b)

e 6.3: (a) A spectrograph constructed using a compact disk (CD). Light enters through a slit at diffracting from the narrowly spaced lines of the CD. (b) Photograph of diffraction pattern f ght, seen thorugh hole at bottom left.

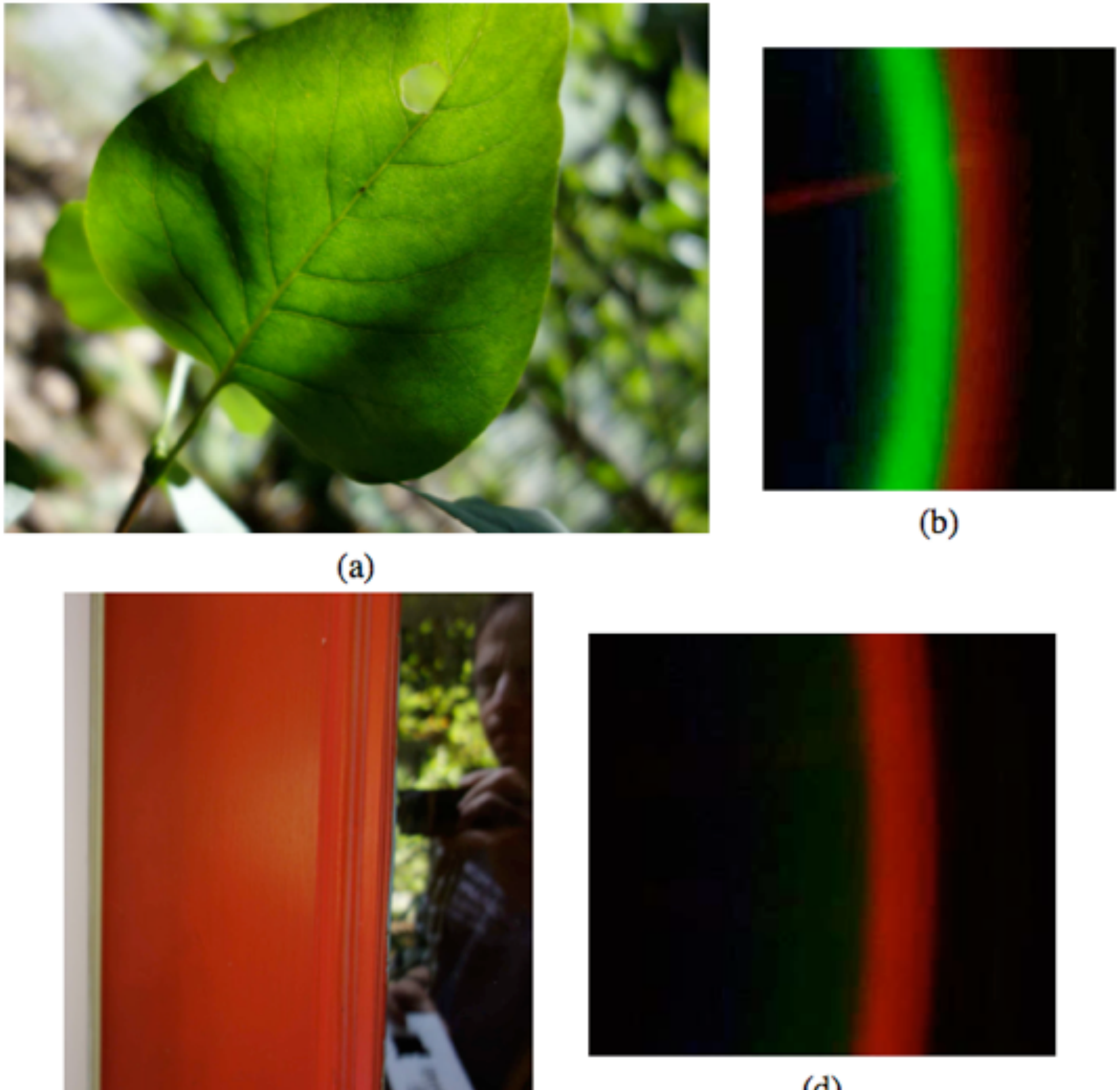
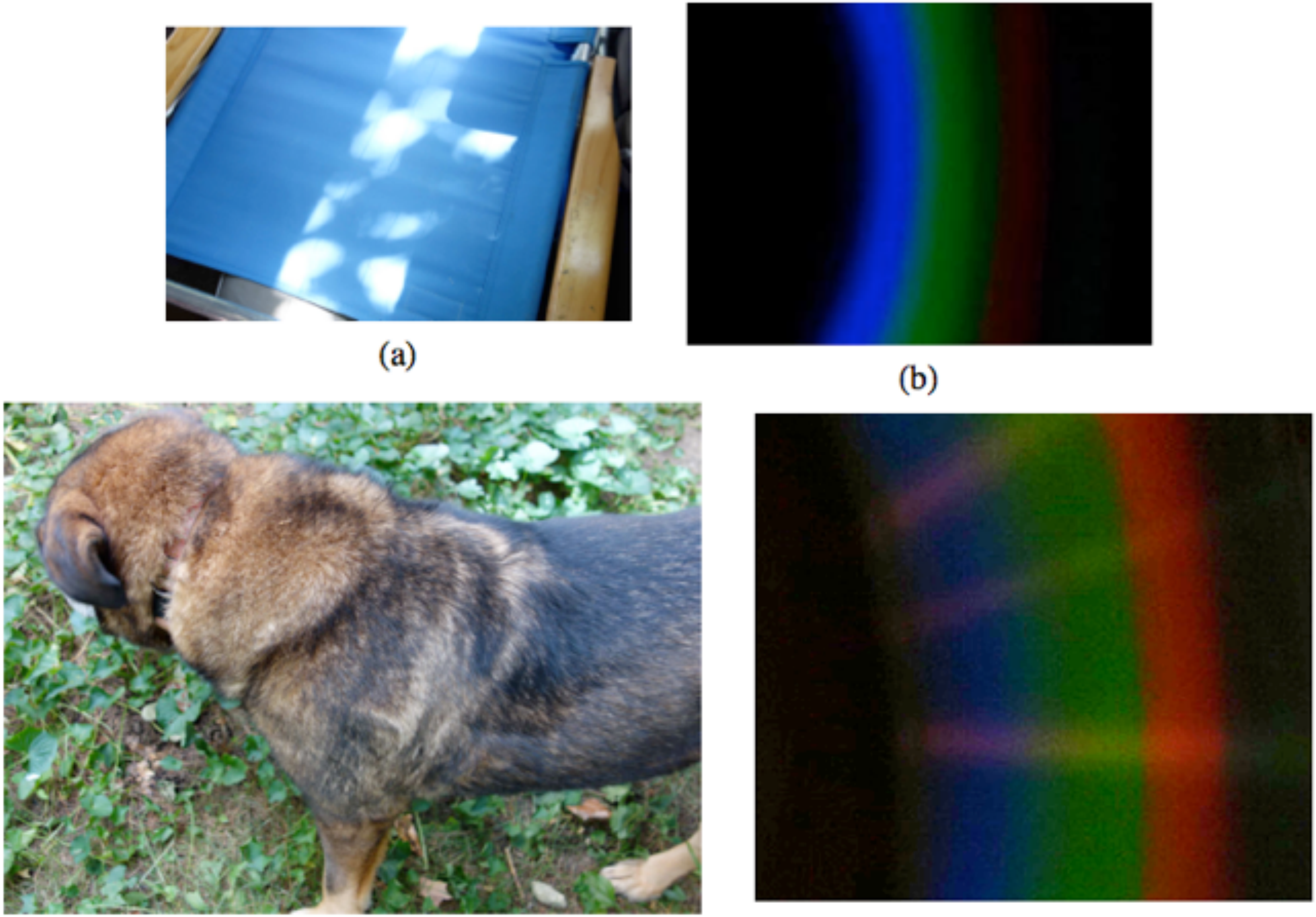
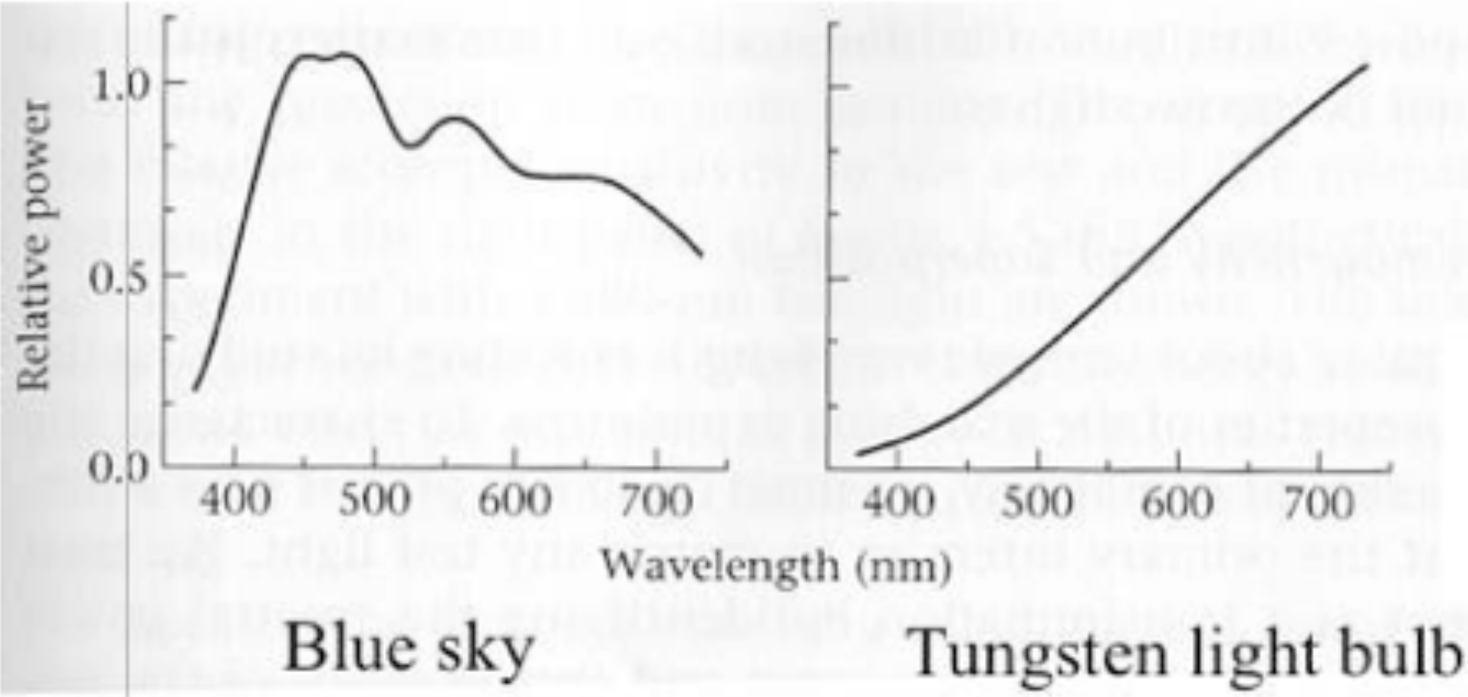


Figure 6.5: Some real-world objects and the reflected light spectra (photographed using Fig. (6.3) (a)) from outdoor viewing. (a) Leaf and (b) its reflected spectrum. (c) A red door and (d) its reflected



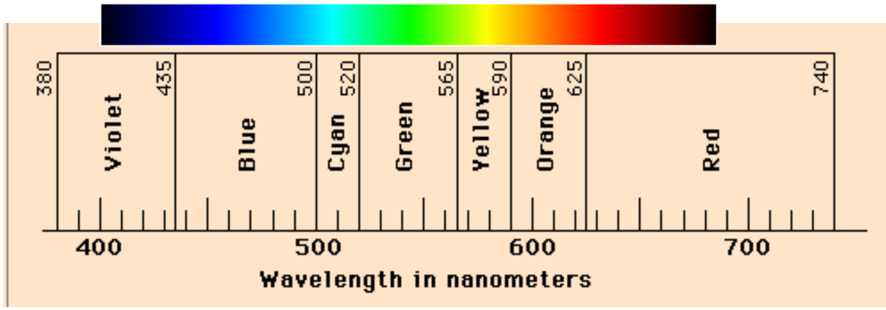
(a) (b) (c) (d)

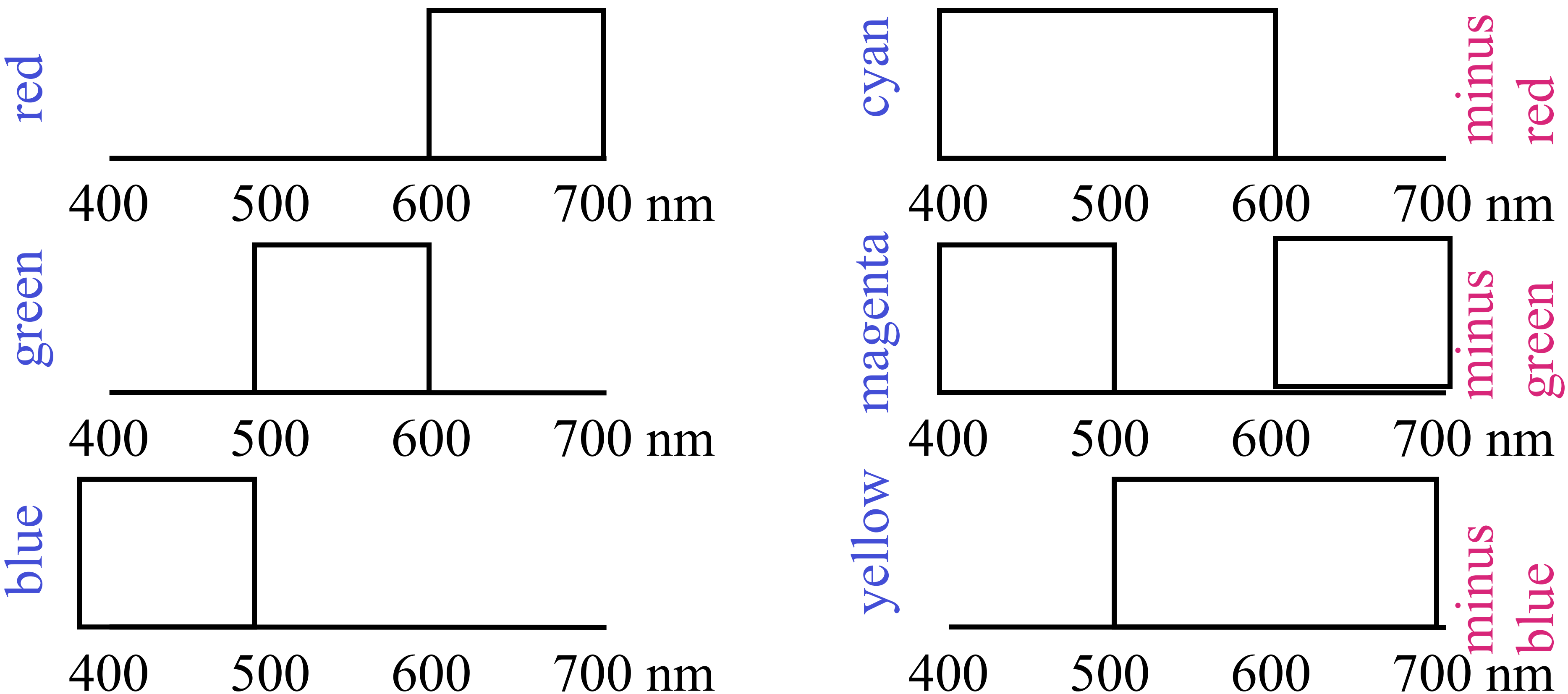
Figure 6.6: More real-world objects and the reflected light spectra. (a) Blue-green chair and (b) its reflected light. (c) Toby the dog and (d) his reflected spectrum.



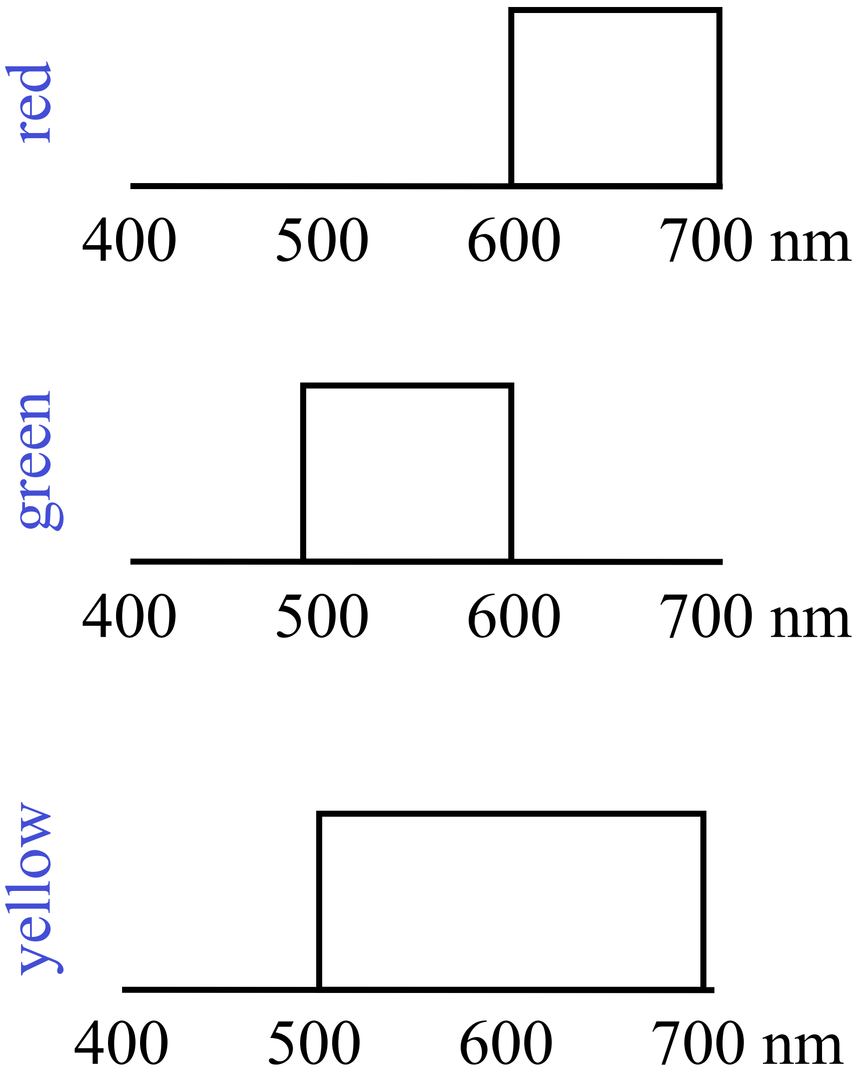
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Color names for cartoon spectra





Additive color mixing

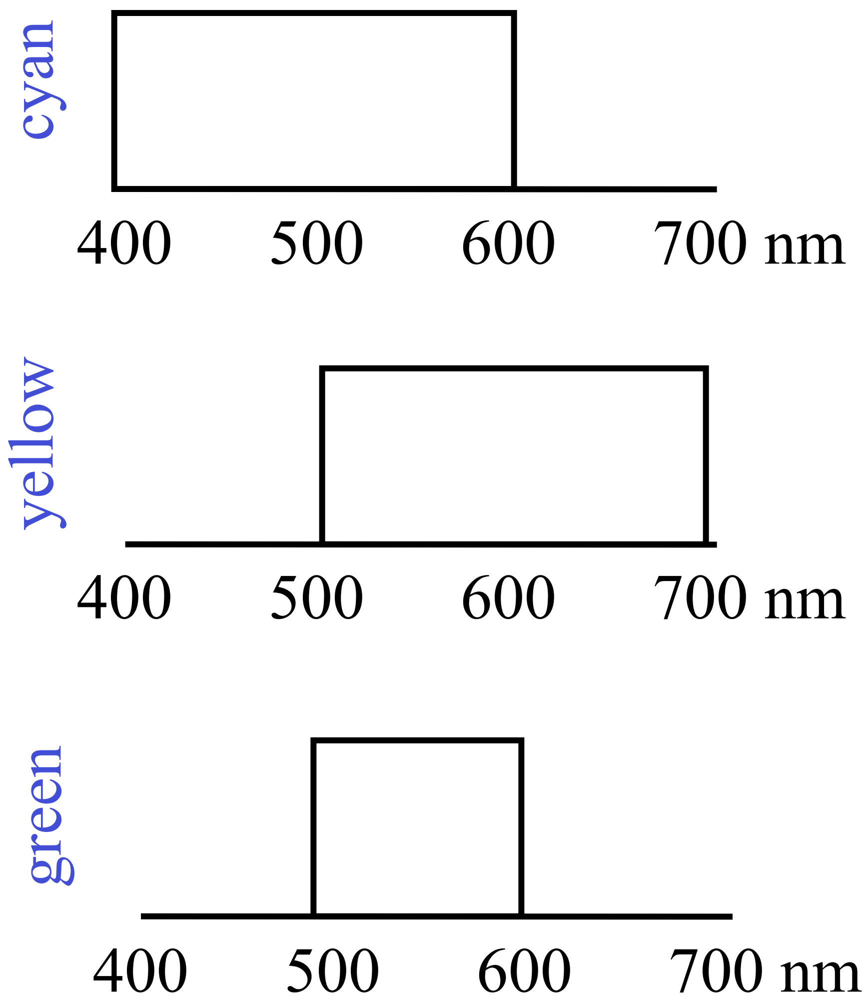


When colors combine by *adding* the color spectra. Example color displays that follow this mixing rule: CRT phosphors, multiple projectors aimed at a screen, Polachrome slide film.

Red and green make…

Yellow!

Subtractive color mixing

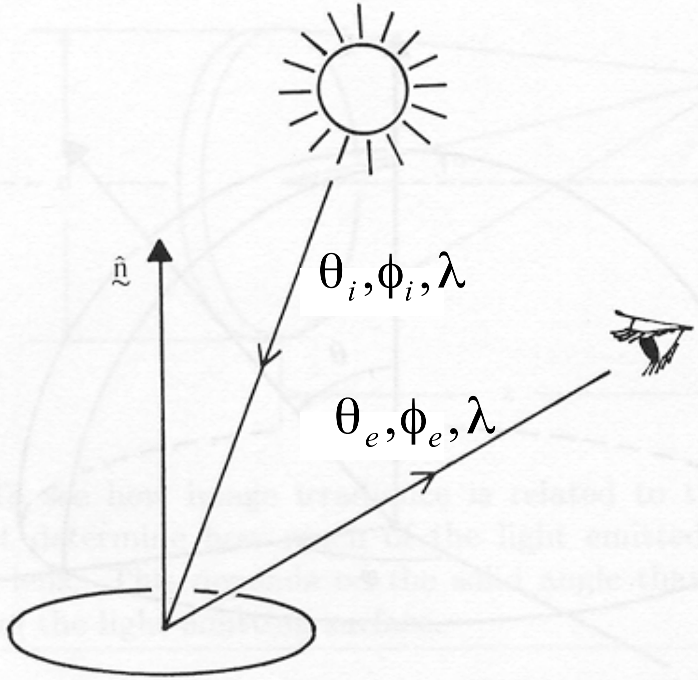


When colors combine by *multiplying* the color spectra. Examples that follow this mixing rule: most photographic films, paint, cascaded optical filters, crayons.

Cyan and yellow (in crayons, called "blue" and yellow) make…

Green!

The interaction of light with surfaces



Horn, 1986

Figure 10-7. The bidirectional reflectance distribution function is the ratio of the radiance of the surface patch as viewed from the direction (θ_e, ϕ_e) to the irradiance resulting from illumination from the direction (θ_i, ϕ_i).

Spectral radiance: power in a specified direction, per unit area, per unit solid angle, per unit wavelength

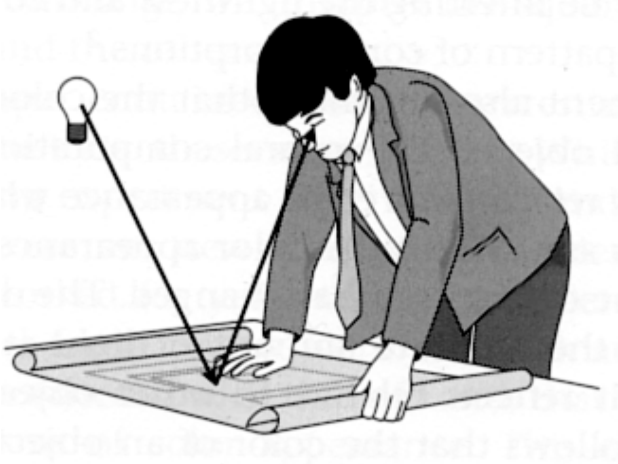
$$BRDF = f(\theta_i, \phi_i, \theta_e, \phi_e, \lambda) = \frac{L(\theta_e, \phi_e, \lambda)}{E(\theta_i, \phi_i, \lambda)}$$

Spectral irradiance: incident power per unit area, per unit wavelength

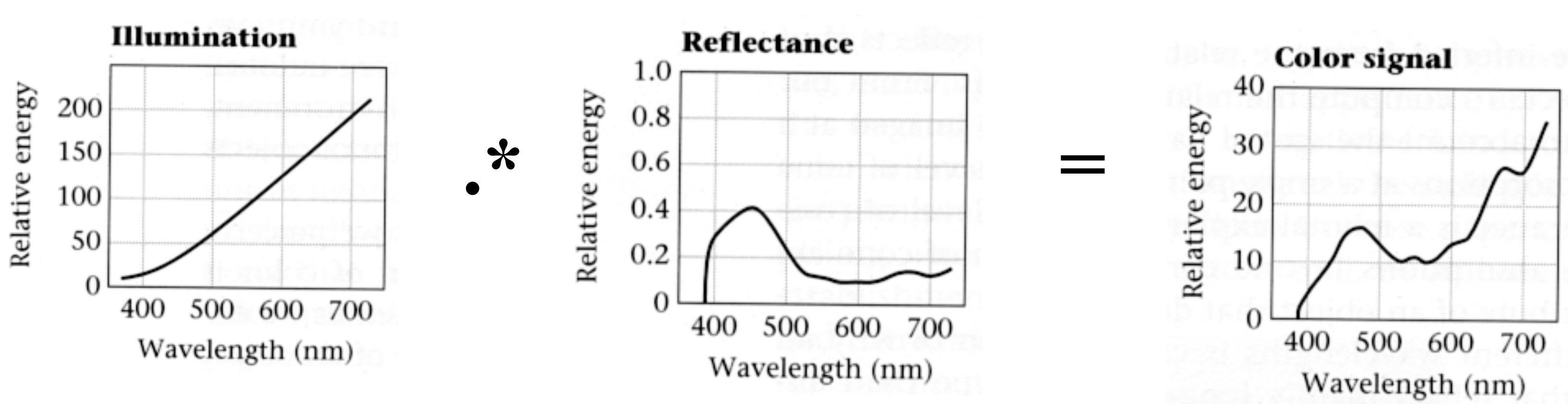
Effect of BRDF on sphere rendering

http://www.marmoset.co/toolbag/learn/pbr-practice

Simplified rendering models: BRDF → reflectance

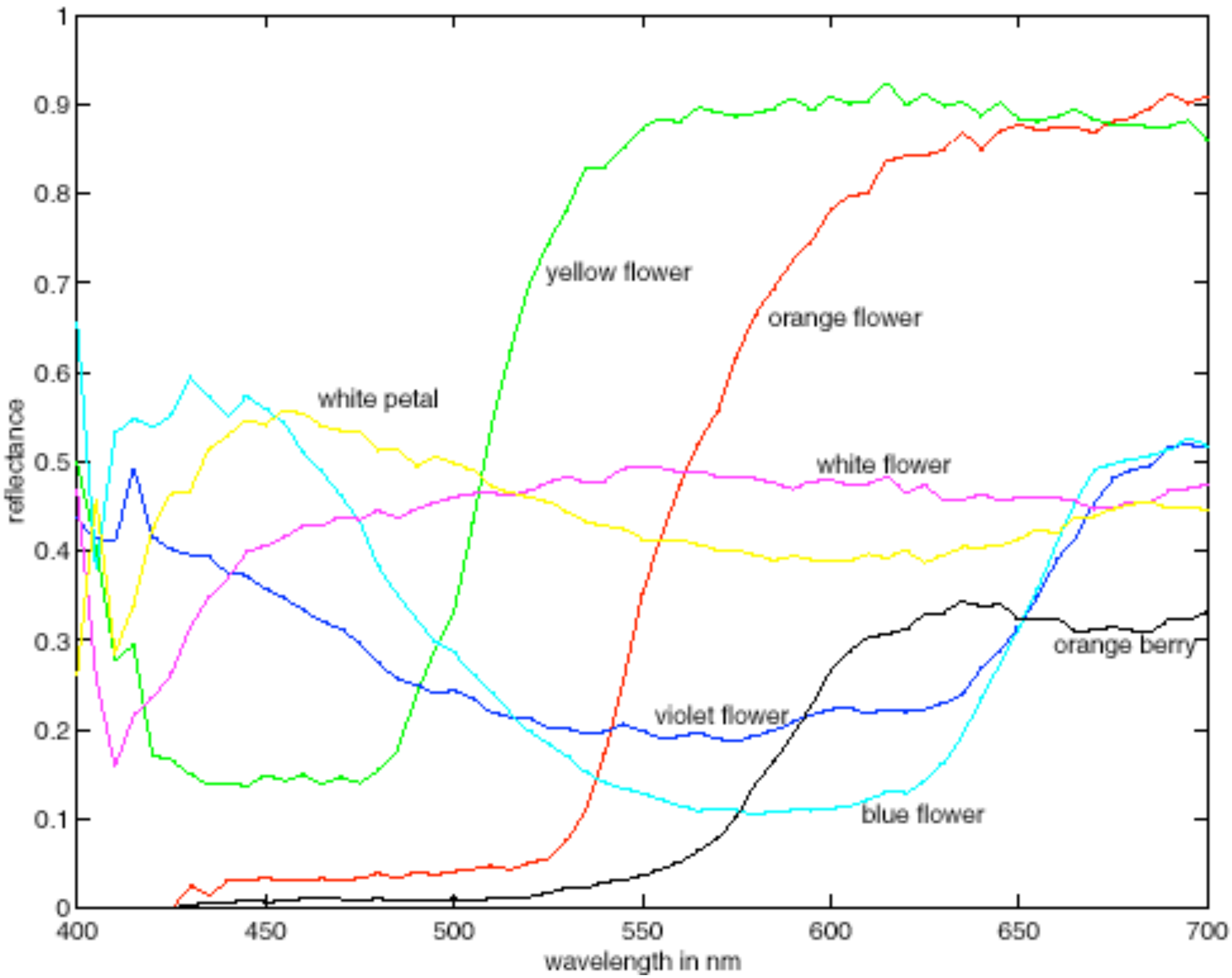


For diffuse reflections, we replace the BRDF calculation with a wavelength-by-wavelength scalar multiplication



Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

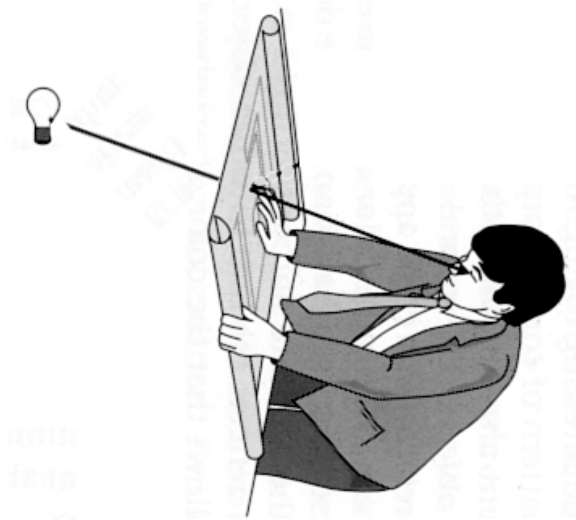
Some reflectance spectra

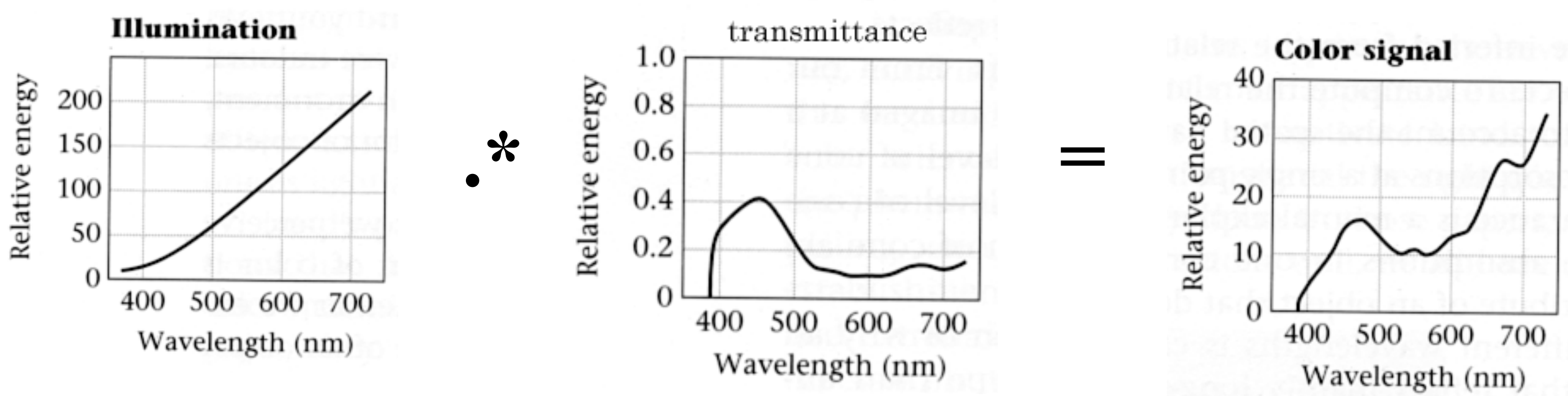


Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions. Measurements by E.Koivisto.

Forsyth, 2002

Simplified rendering models: transmittance





Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Overhead projector demo

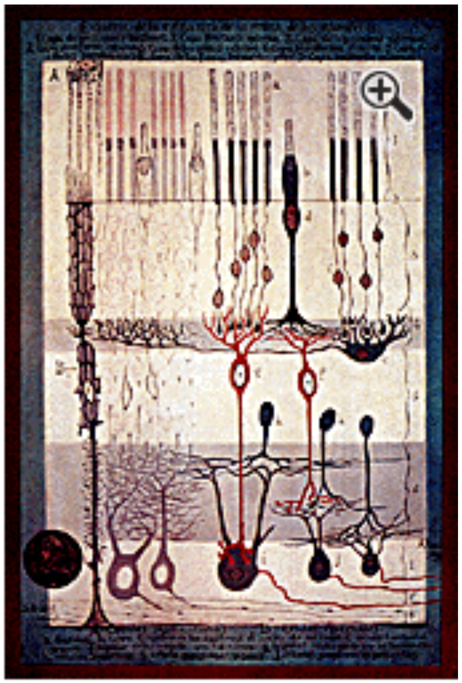
Subtractive color mixing

Lecture outline

- Color physics.
- Color perception.

What's the machinery in the eye?

Eye Photoreceptor responses

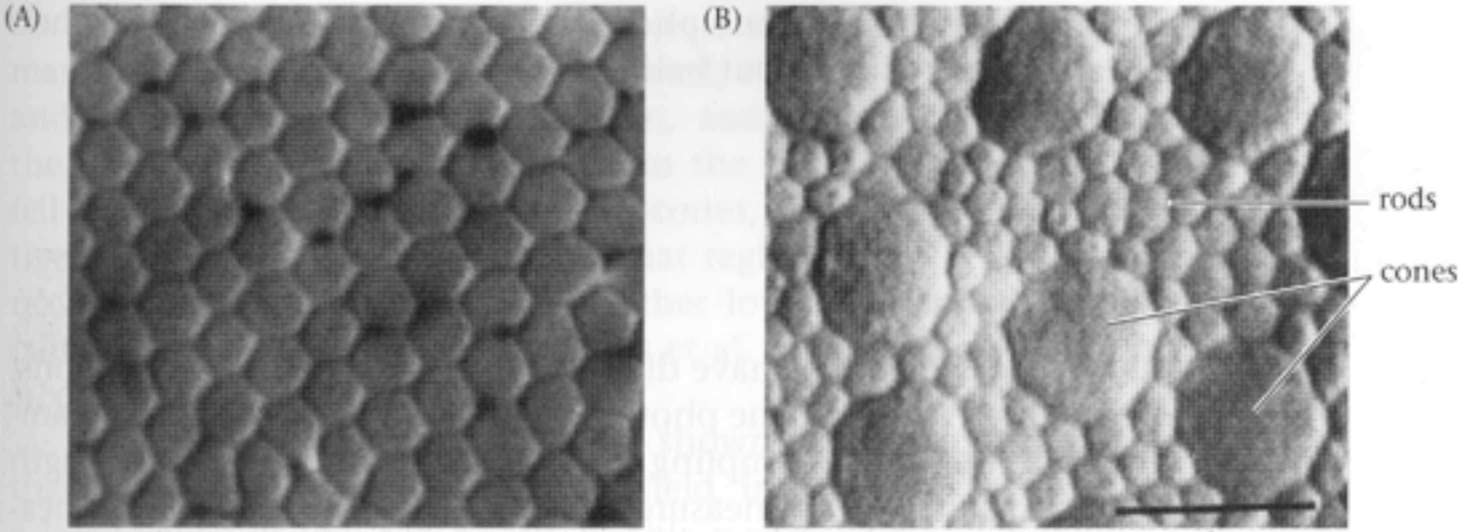


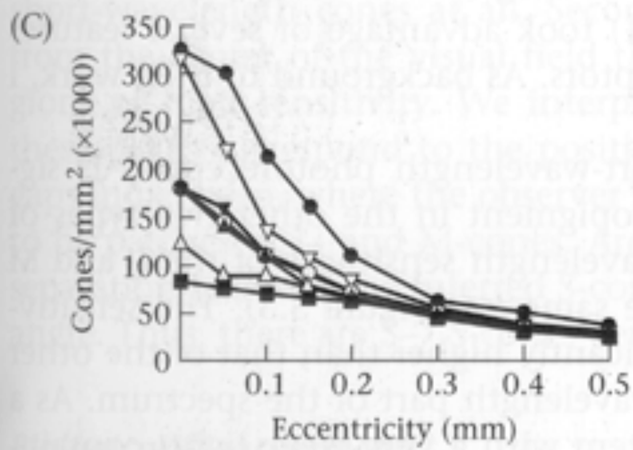
Instituto Cajal. CSIC. Madrid.

The intricate layers and connections of nerve cells in the retina were drawn by the famed Spanish anatomist Santiago Ramón y Cajal around 1900. Rod and cone cells are at the top. Optic nerve fibers leading to the brain may be seen at bottom right.

(Where do you think the light comes in?)

Human Photoreceptors



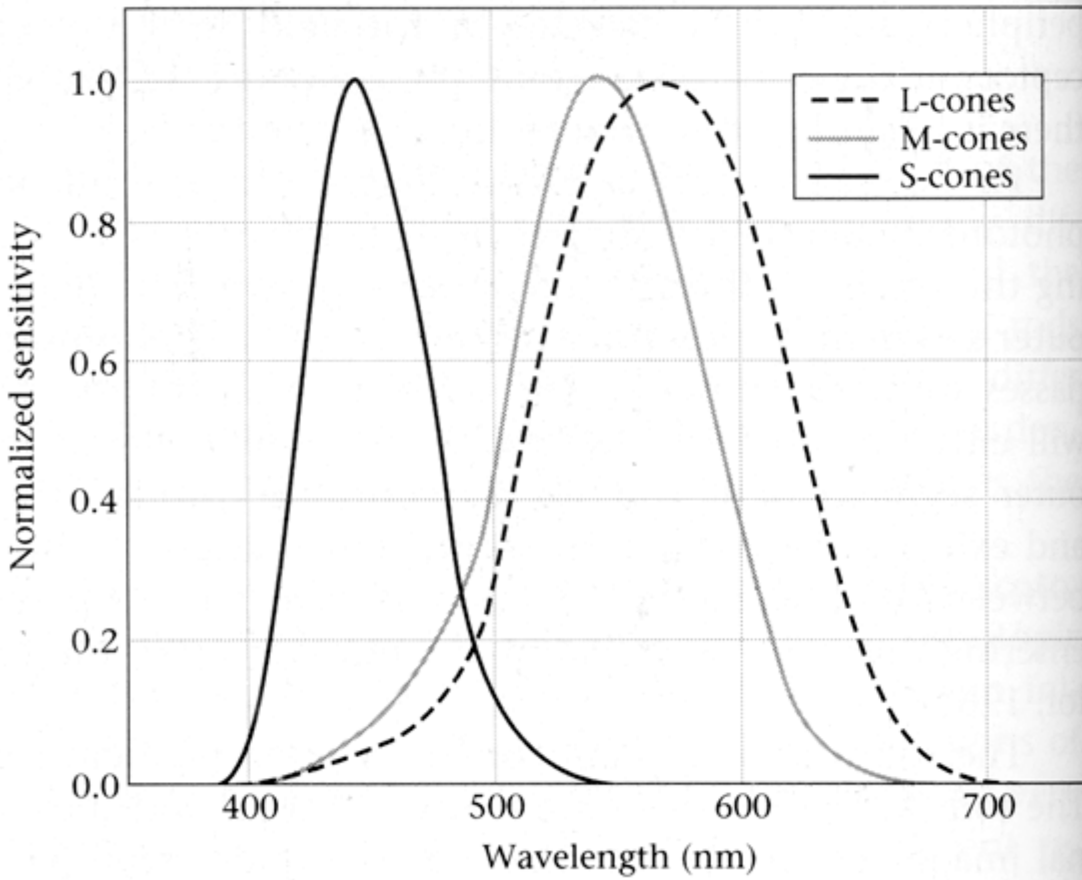


3.4 THE SPATIAL MOSAIC OF THE HUMAN CONES. Cross sections of the human retina at the level of the inner segments showing (A) cones in the fovea, and (B) cones in the periphery. Note the size difference (scale bar = 10 μm), and that, as the separation between cones grows, the rod receptors fill in the spaces. (C) Cone density plotted as a function of distance from the center of the fovea for seven human retinas; cone density decreases with distance from the fovea. Source: Curcio et al., 1990.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

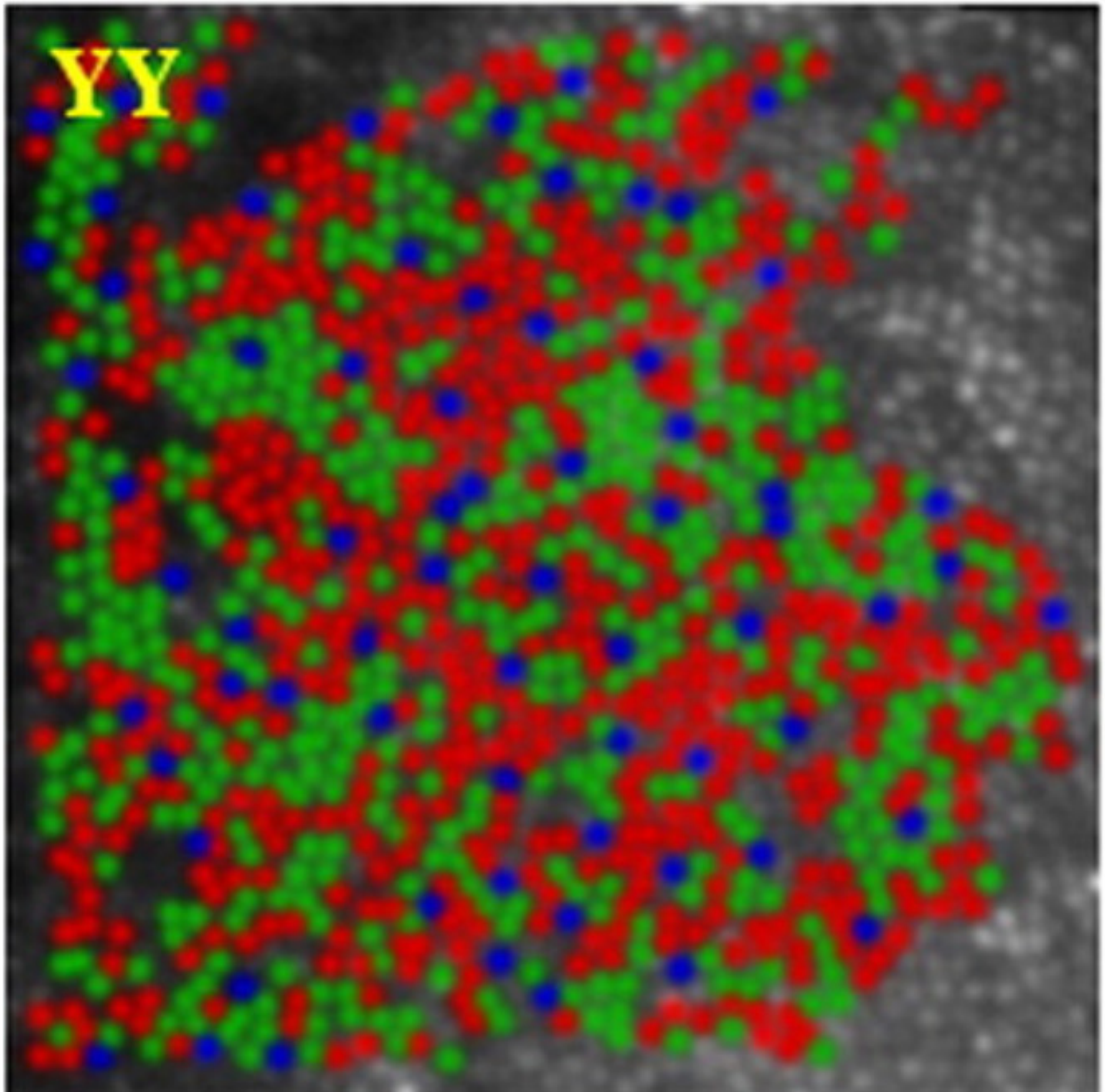
Human eye photoreceptor spectral sensitivities

3.3 SPECTRAL SENSITIVITIES OF THE L-, M-, AND S-CONES in the human eye. The measurements are based on a light source at the cornea, so that the wavelength loss due to the cornea, lens, and other inert pigments of the eye plays a role in determining the sensitivity. Source: Stockman and MacLeod, 1993.



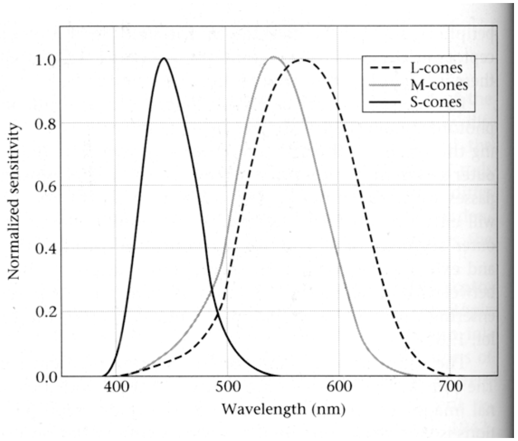
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

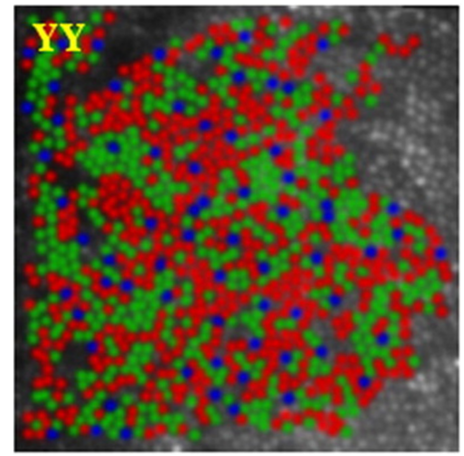
L, M, and S cone receptor types colored as R, G, B



What are some color artifacts we might expect our visual system to experience, based on this way of measuring the light spectra falling on our eye?

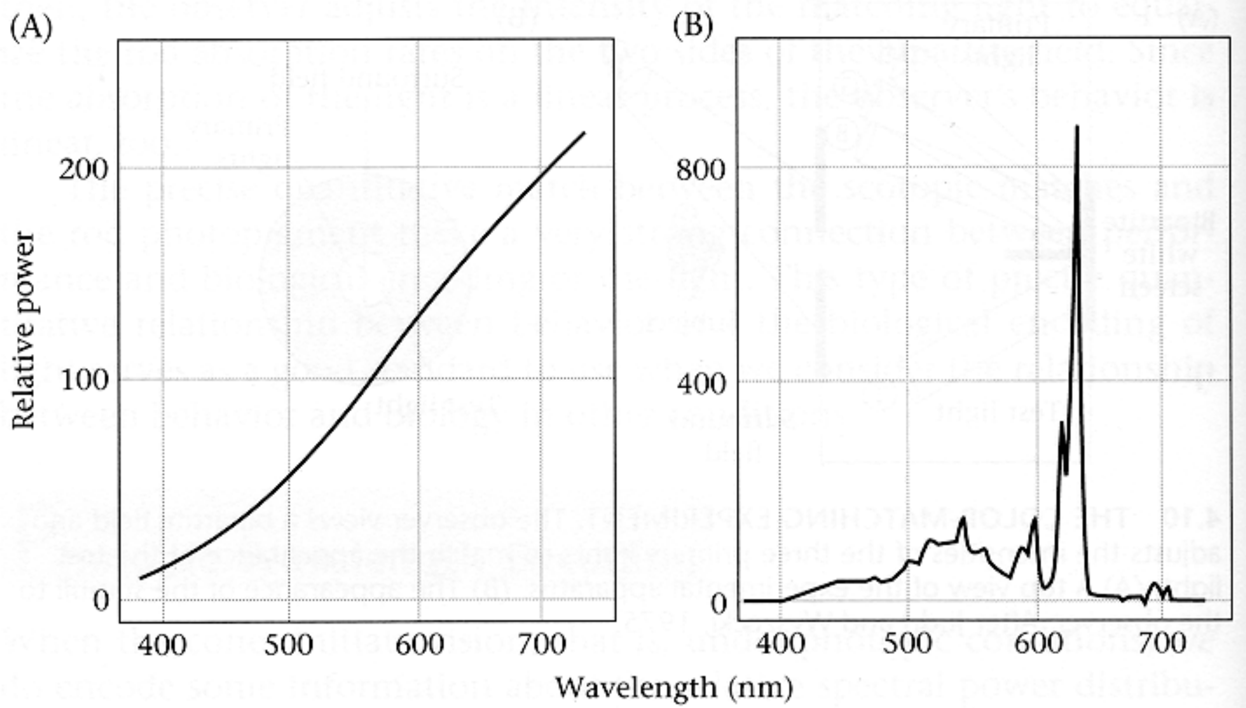
3.3 SPECTRAL SENSITIVITIES OF THE L-, M-, AND S-CONES in the human eye. The measurements are based on a light source at the cornea, so that the wavelength loss due to the cornea, lens, and other inert pigments of the eye plays a role in determining the sensitivity. Source: Stockman and MacLeod, 1993.



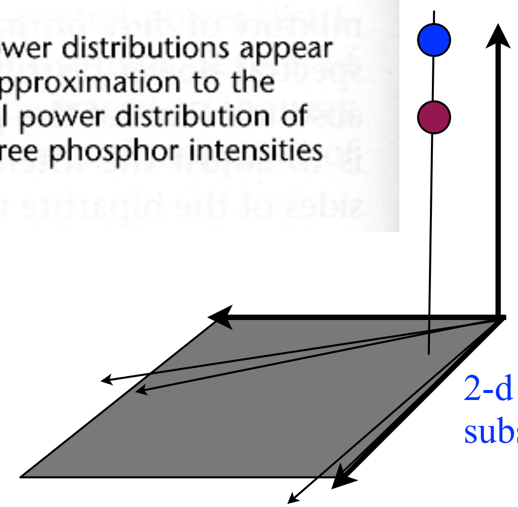


A property of our visual system: these two spectra look the same

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995



4.11 METAMERIC LIGHTS. Two lights with these spectral power distributions appear identical to most observers and are called metamers. (A) An approximation to the spectral power distribution of a tungsten bulb. (B) The spectral power distribution of light emitted from a conventional television monitor whose three phosphor intensities were set to match the light in panel A in appearance.



3-d depiction of the high-dimensional space of all possible power spectra

2-d depiction of the 3-d subspace of sensor responses

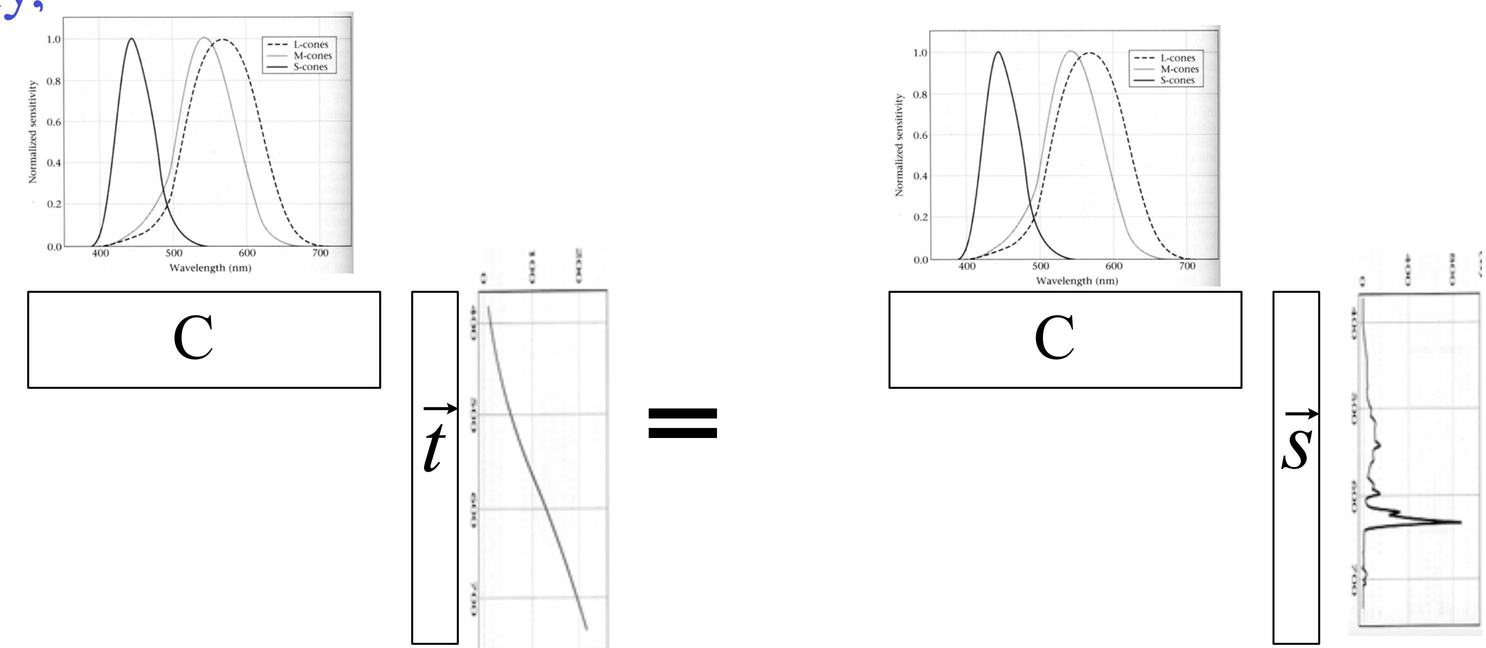
Color metamerism: different spectra looking the same color

Two spectra, t and s, perceptually match when

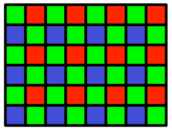
$$C\vec{t} = C\vec{s}$$

where C are the cone response curves.

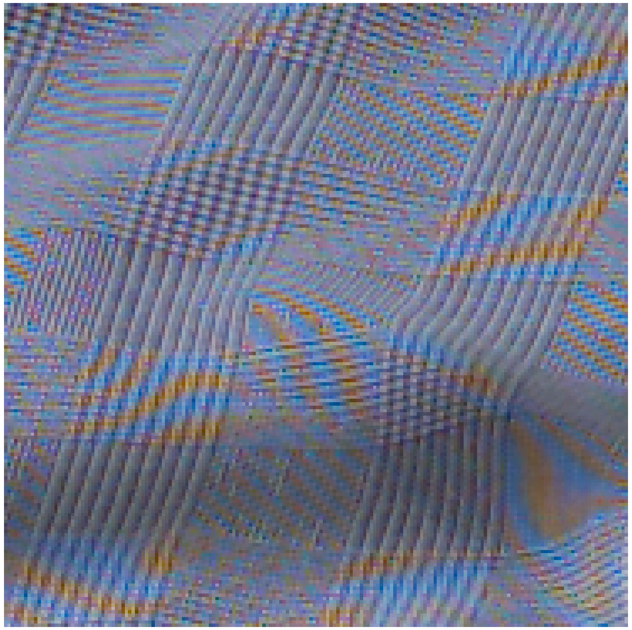
Graphically,

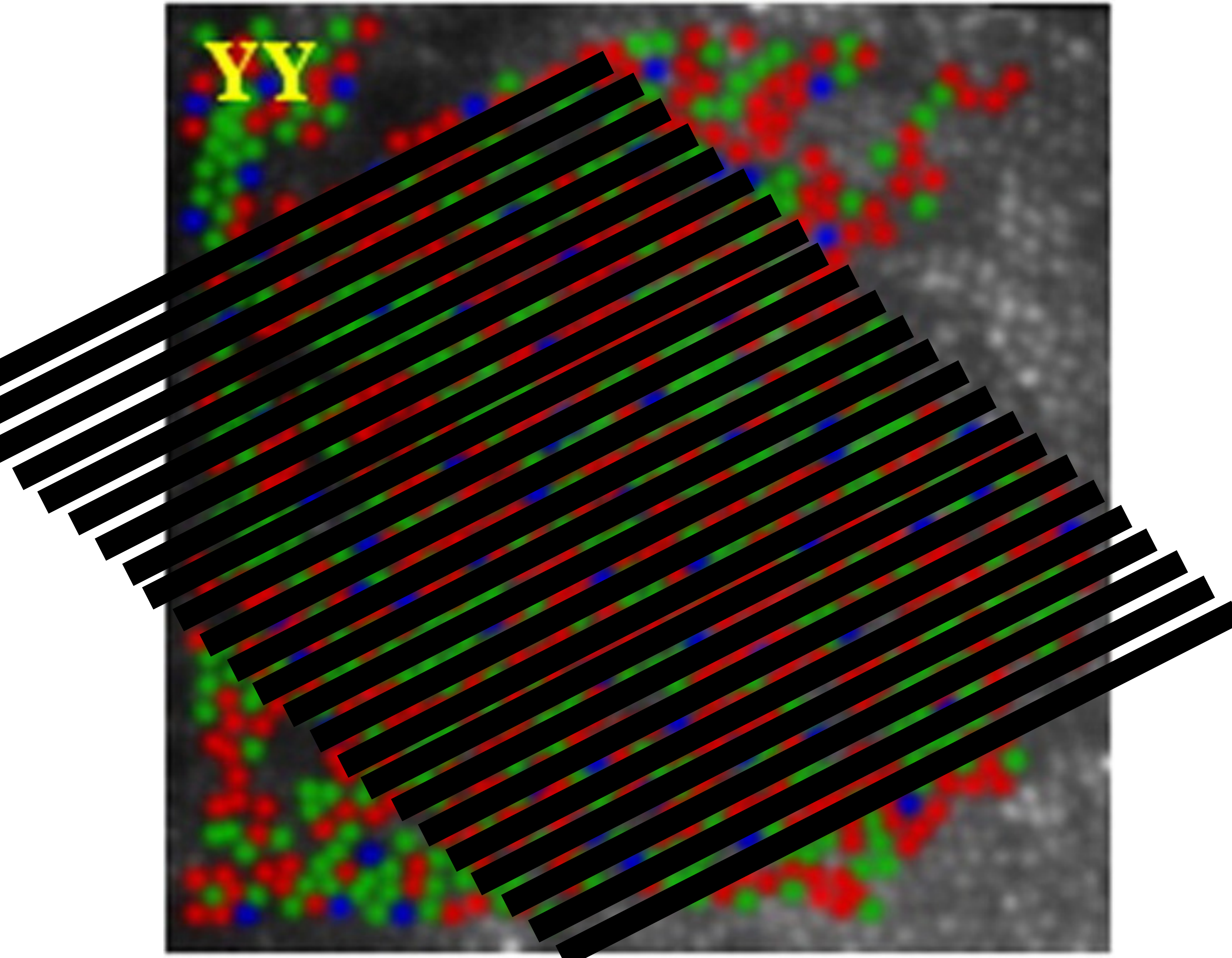


Evidence of spatially offset color sampling in an old digital camera

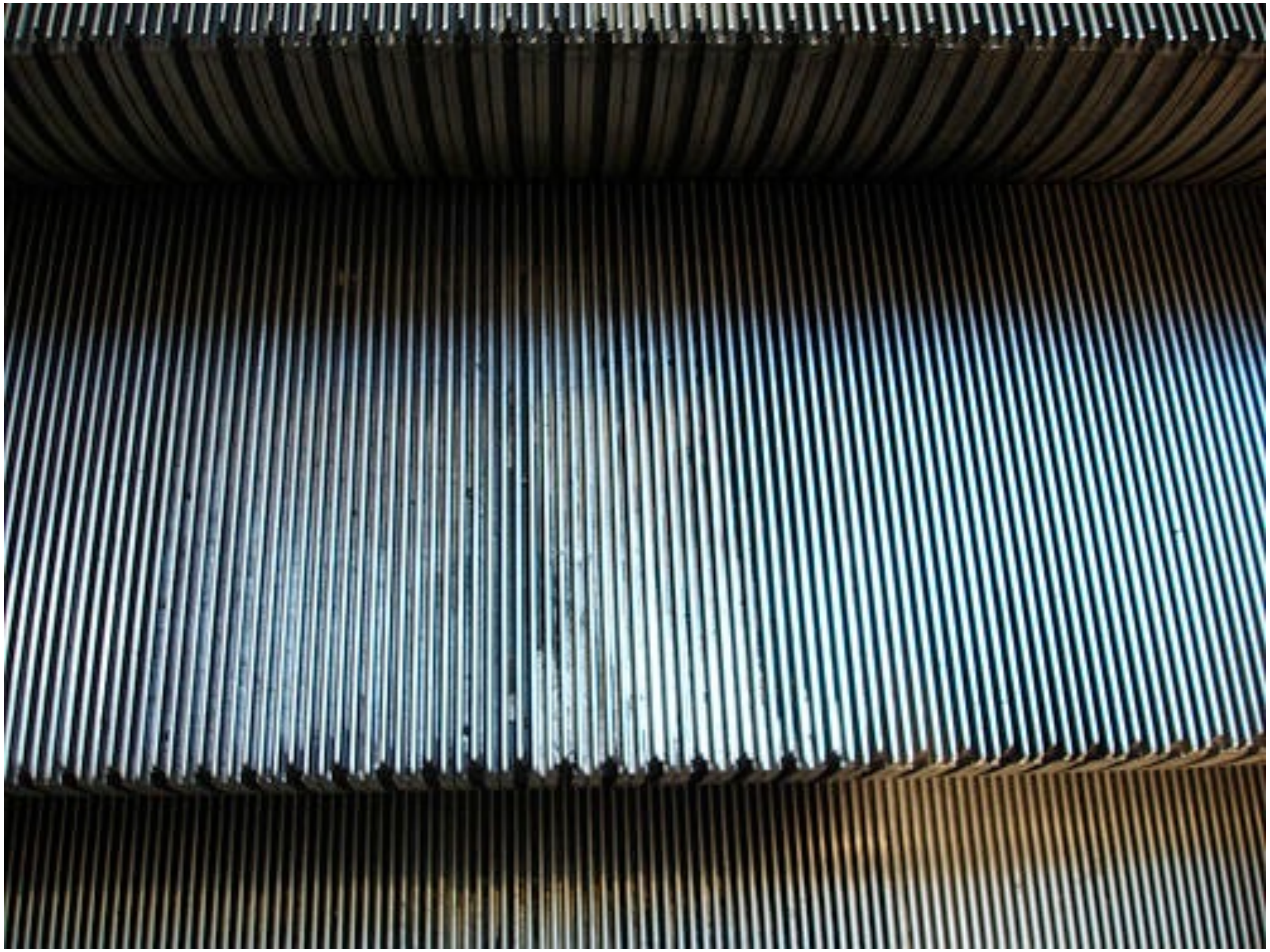

sensor color sampling pattern

- Color fringes or jaggies




YY

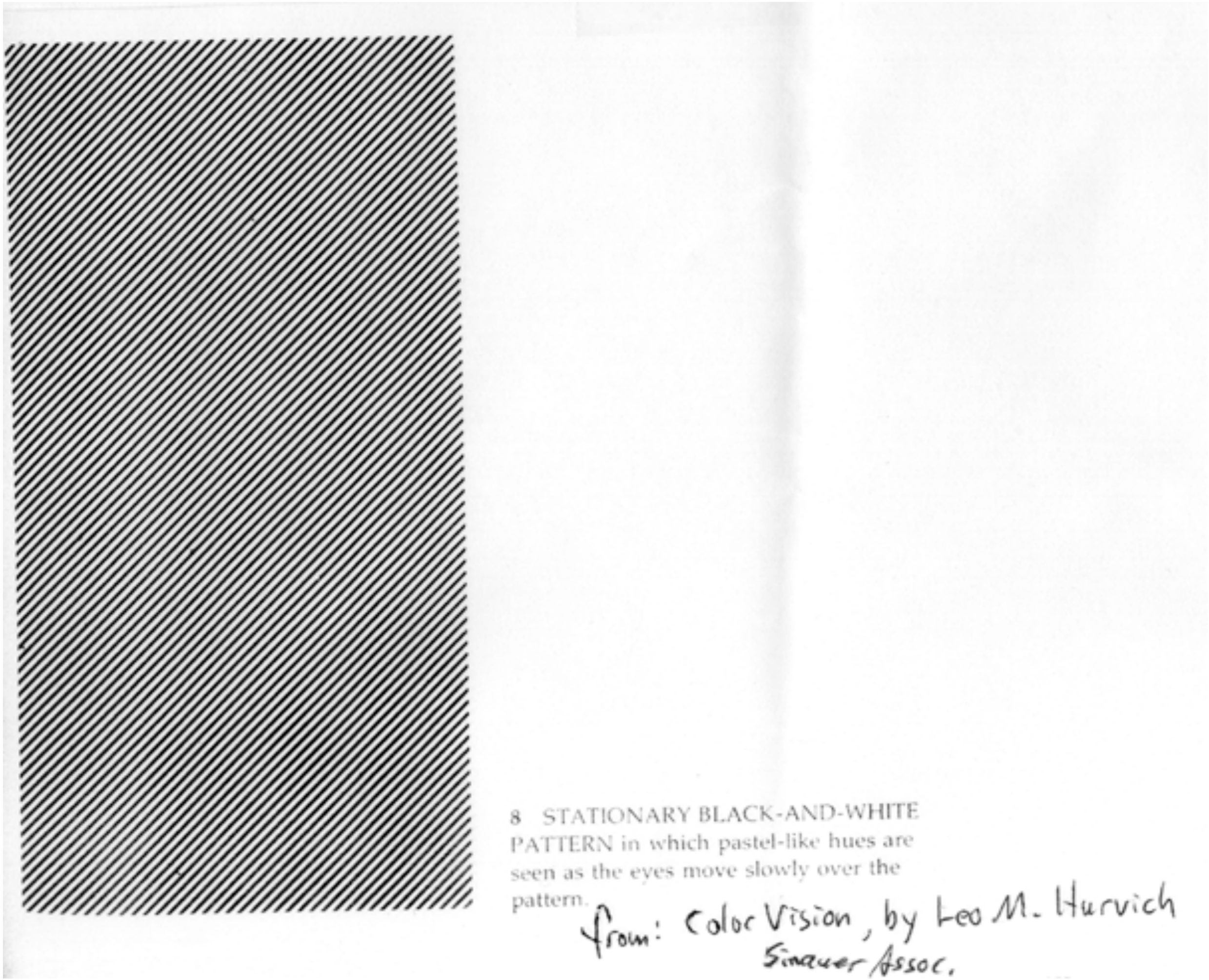
Where you can see color fringe reconstruction artifacts from your own eye



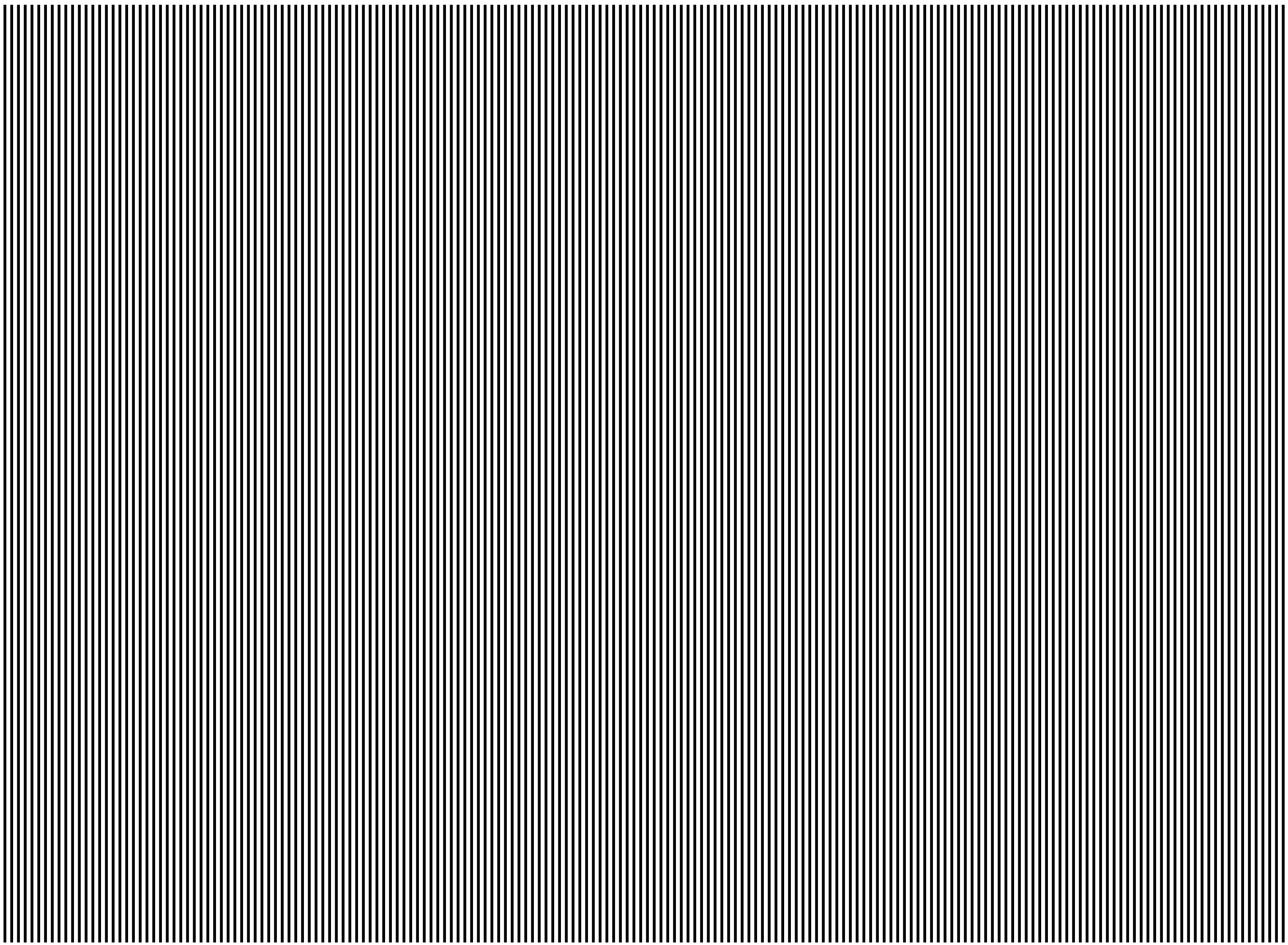
http://static.flickr.com/21/31393422_23013da003.jpg

Brewster's colors—evidence of interpolation from spatially offset color samples

Scale relative to human photoreceptor size: each line covers about 7 photoreceptors.



Brewster's colors—evidence of interpolation from spatially offset color samples



Lecture outline

- Color physics.
- Color perception
  - part 1: assume perceived color only depends on light spectrum.
  - part 2: the more general case.

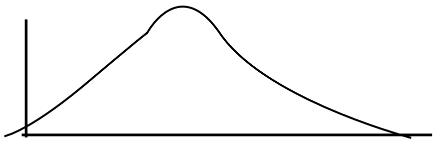
The assumption for color perception, part 1

- We know color appearance really depends on:
  - The illumination
  - Your eye's adaptation level
  - The colors and scene interpretation surrounding the observed color.

- But for now we will assume that <u>the spectrum of the light arriving at your eye completely determines the perceived color</u>.

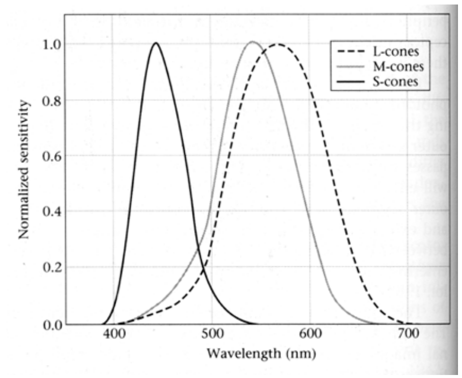
How we sense light spectra

test light, t



project →

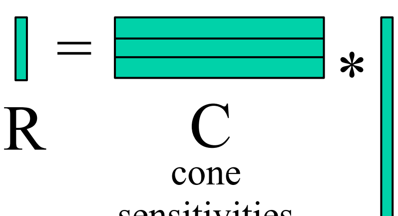
Cone sensitivities, in matrix, C



→ L, M, S responses

<u>biophysics:</u> integrate the response over all wavelengths, weighted by the photosensor's sensitivity at each wavelength.

<u>mathematically:</u> take dot product of input spectrum with the cone sensitivity basis vectors. Project the high-dimensional test light into a 3-d space. $R = C\,t$



cone responses R

C cone sensitivities

t input spectrum

UNITED STATES DEPARTMENT OF AGRICULTURE

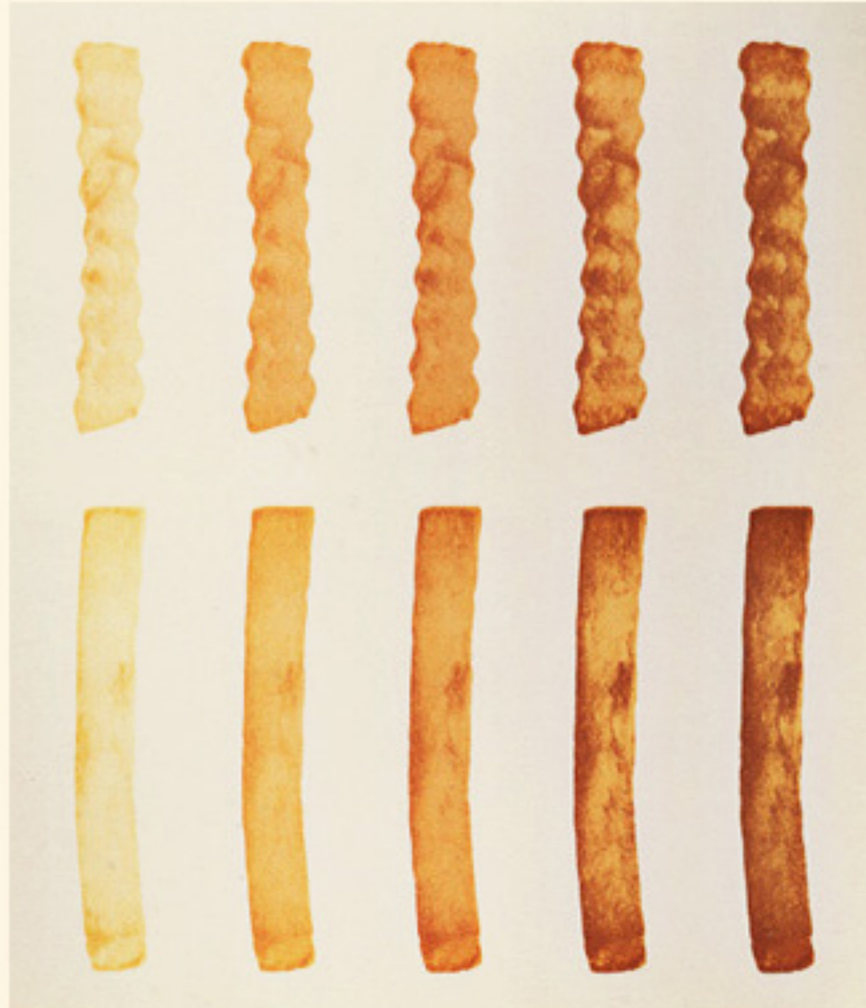
COLOR STANDARDS

for

FROZEN FRENCH FRIED POTATOES

FOURTH EDITION, 1988

MUNSELL COLOR
BALTIMORE, MARYLAND
64-1



Color trademarks

T-Mobile's magenta

Lilac of Milka-chocolate

Blue of Tiffany & Co., Pantone 1837

Orange of Fiskars scissors

Again, the color orange in Reese's.

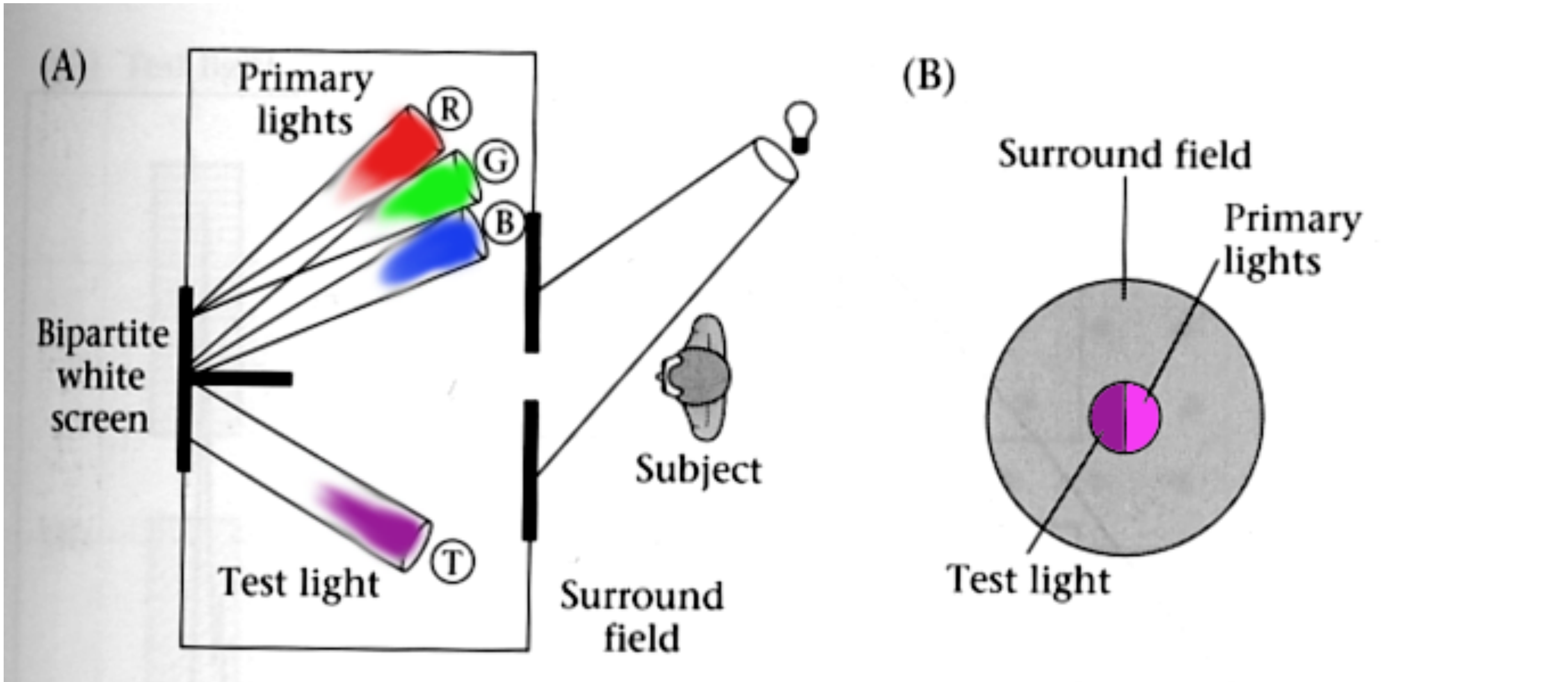
Brown of United Parcel Service

The yellow and black combination of DeWalt power tools

https://en.wikipedia.org/wiki/Colour_trade_mark

- How do we measure colors?
- How do we make systems that match colors?

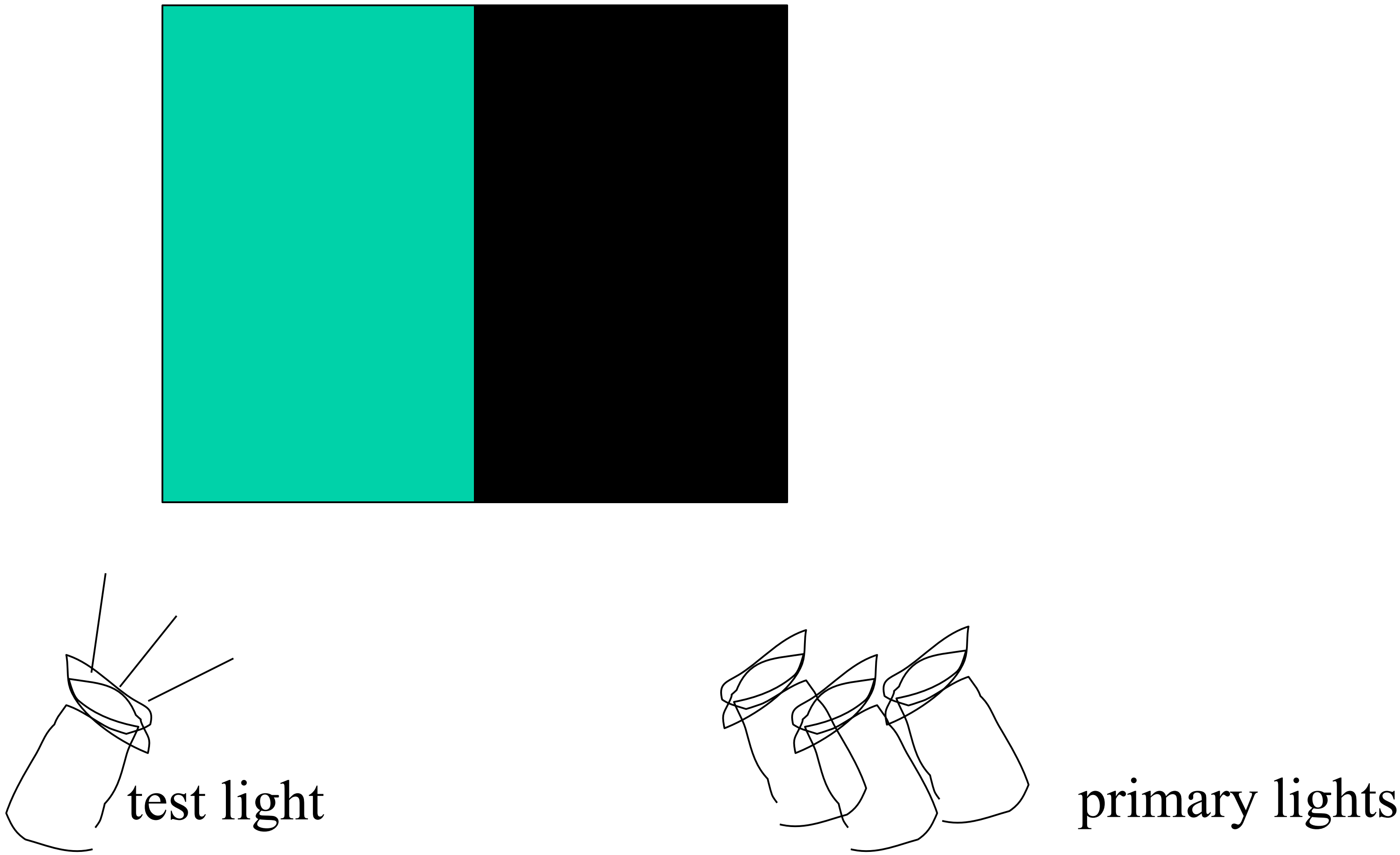
Color matching experiment



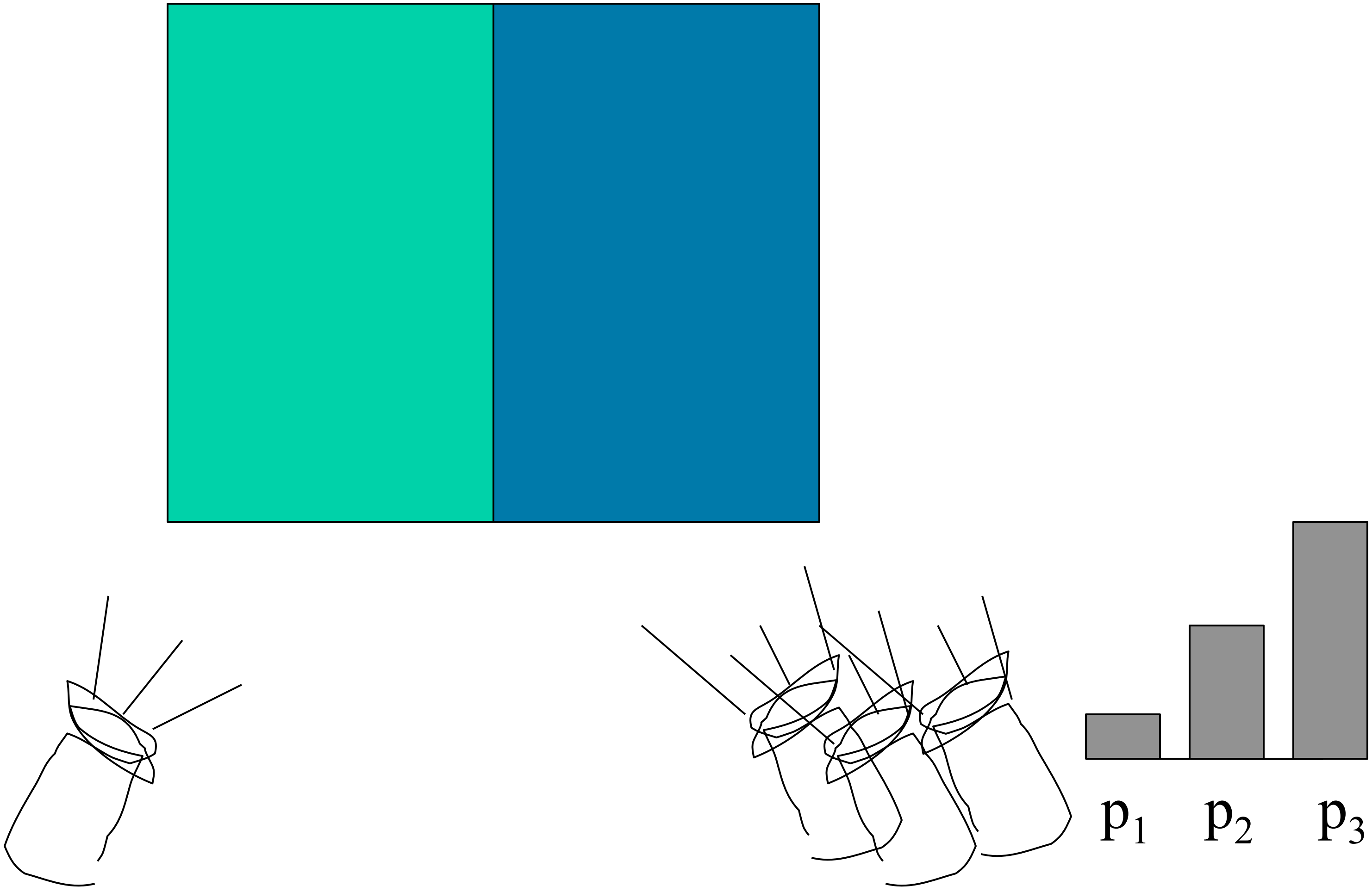
4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

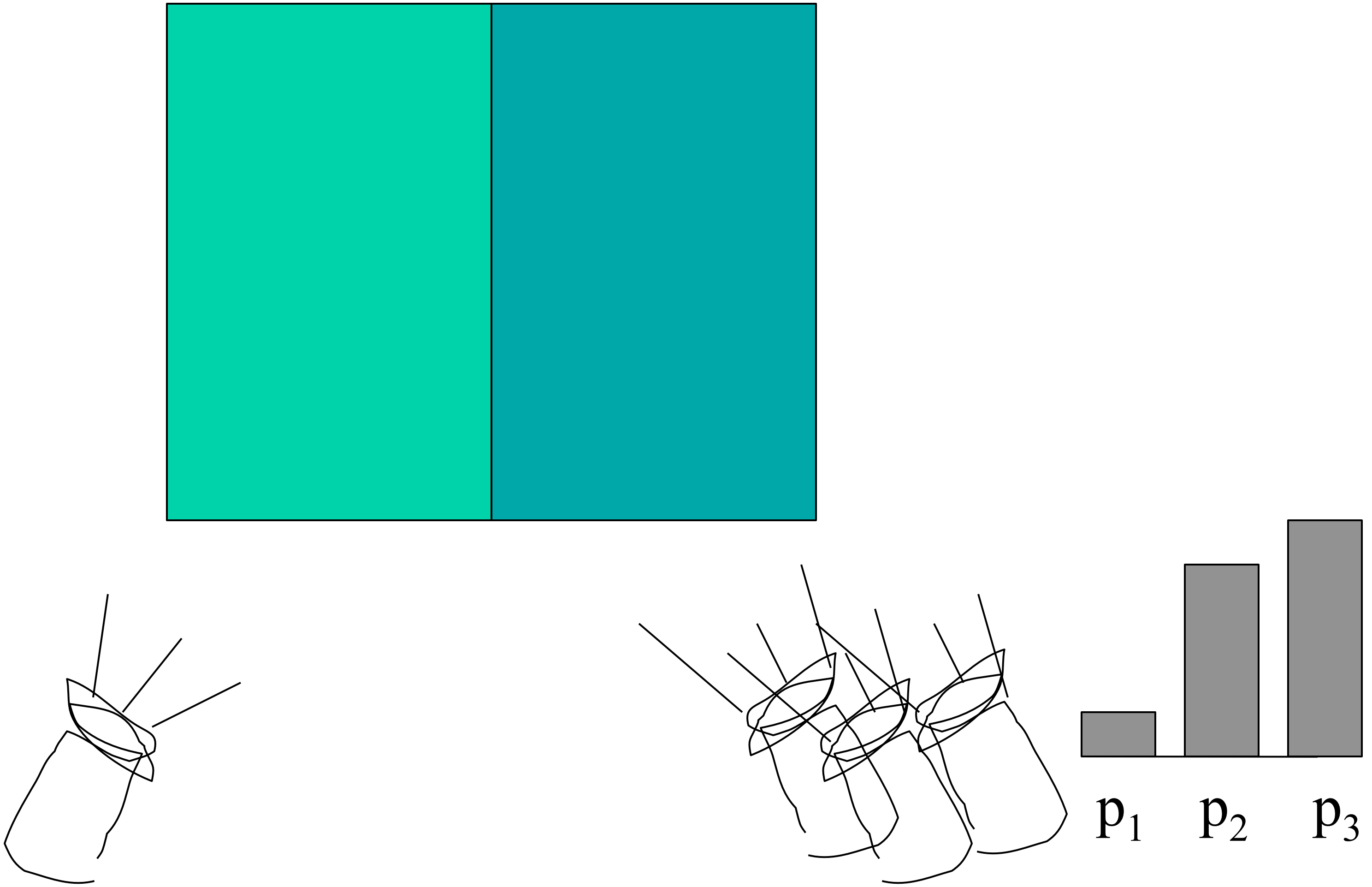
Color matching experiment 1



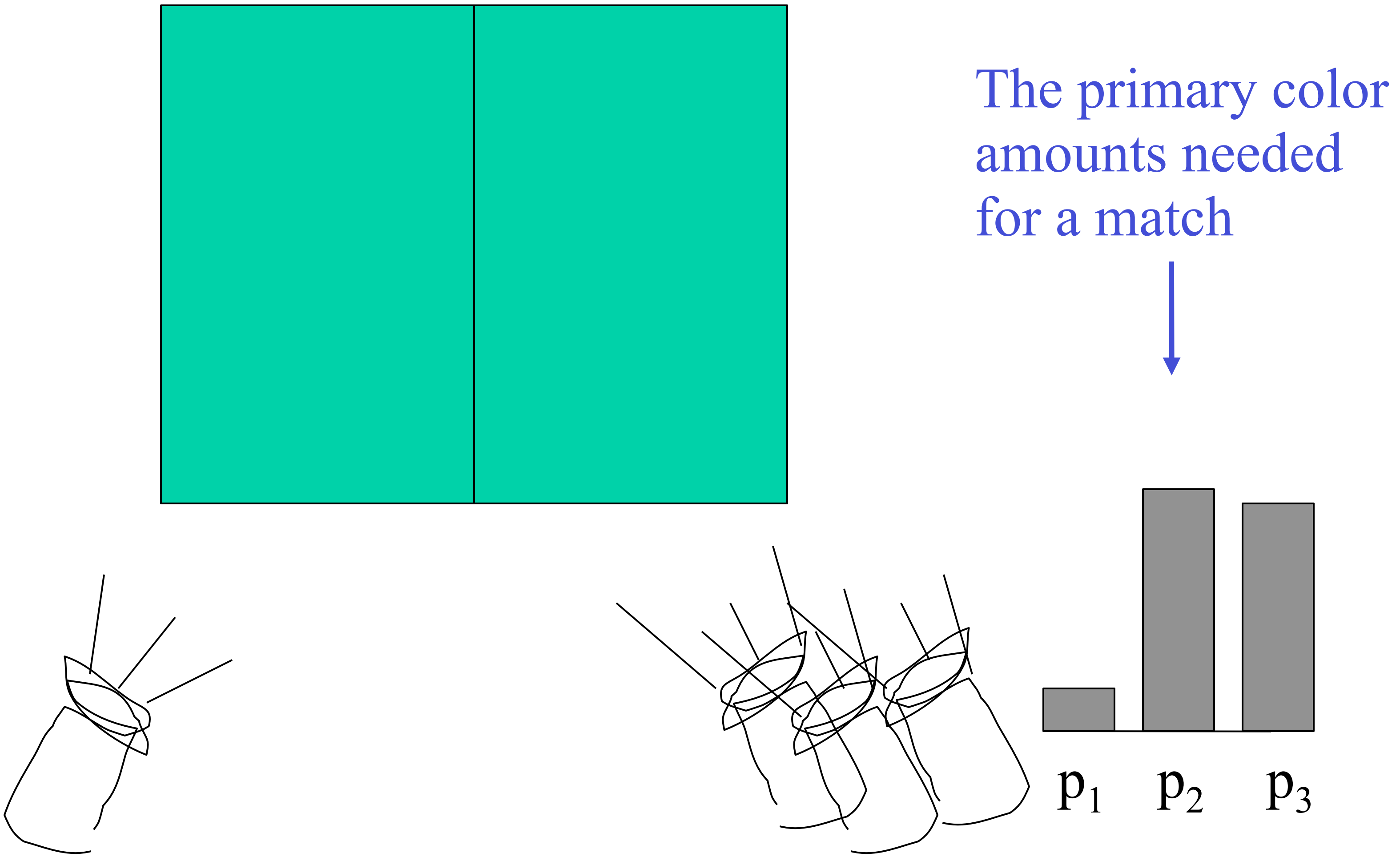
Color matching experiment 1



Color matching experiment 1



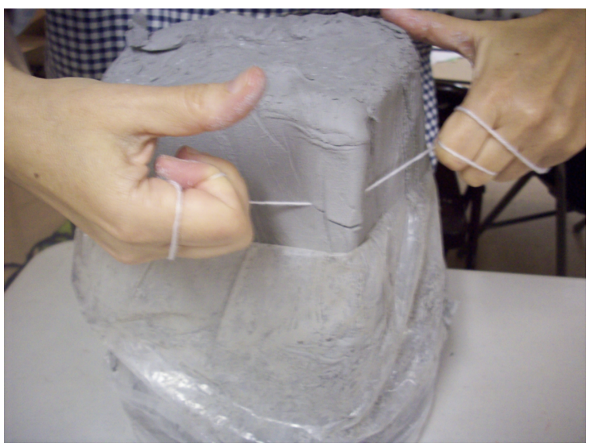
Color matching experiment 1



Relevant to color matching experiments, solve this puzzle:

http://commons.wikimedia.org/wiki/File:Balanced_scale_of_Justice.svg

uart4kids.com/wp-content/uploads/
/jmomys-about-us-picture-027.jpg



Want to measure out 7 lbs of clay

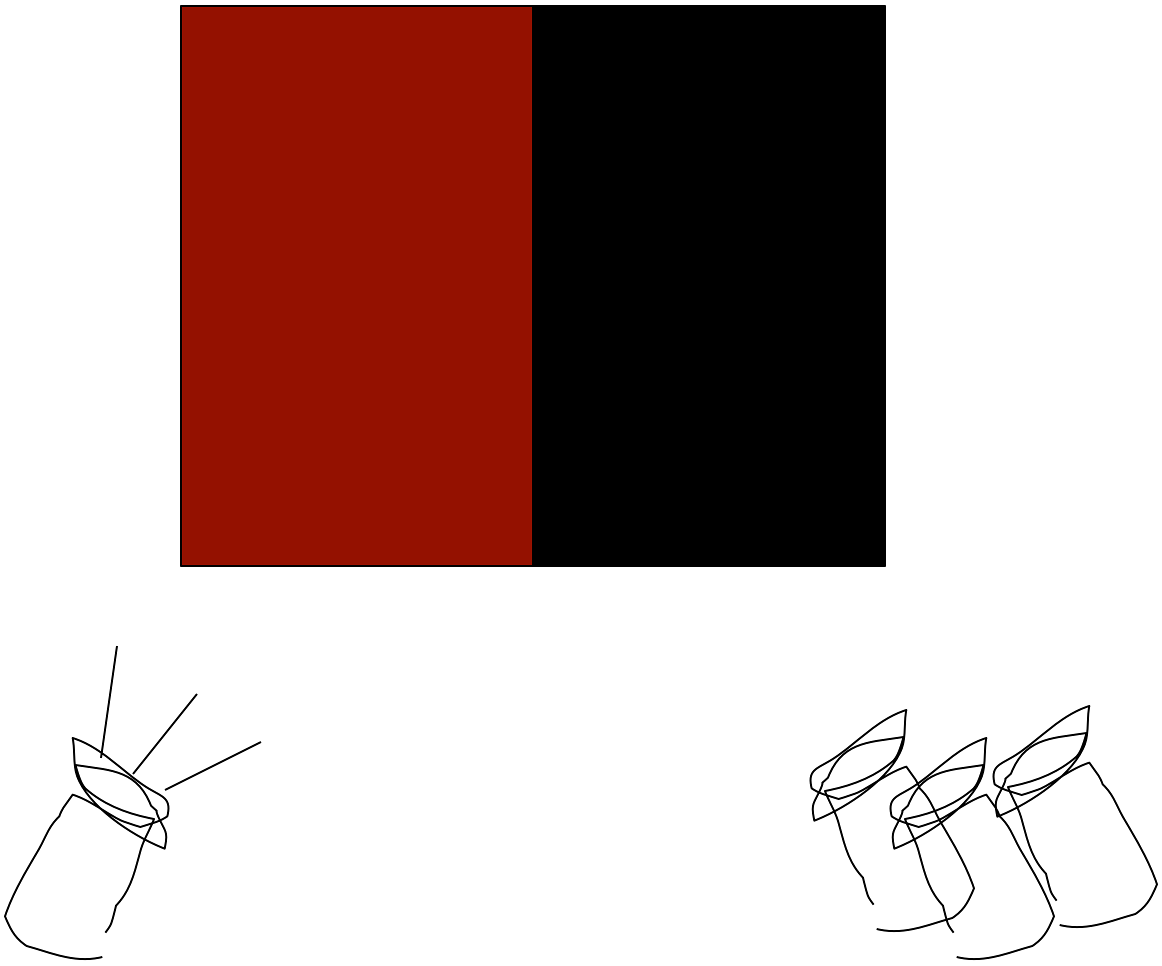
(we wish we could add a -1 lb mass to the 5 and 3 lb masses to weigh out 7 lbs of clay. But we don't have negative mass. Instead, we just add the 1 lb mass to the other side, where the clay is, to weigh out 7 lbs of clay)

http://www.retonthen
vintage-metric-brass-
weights-50-20--10-gr

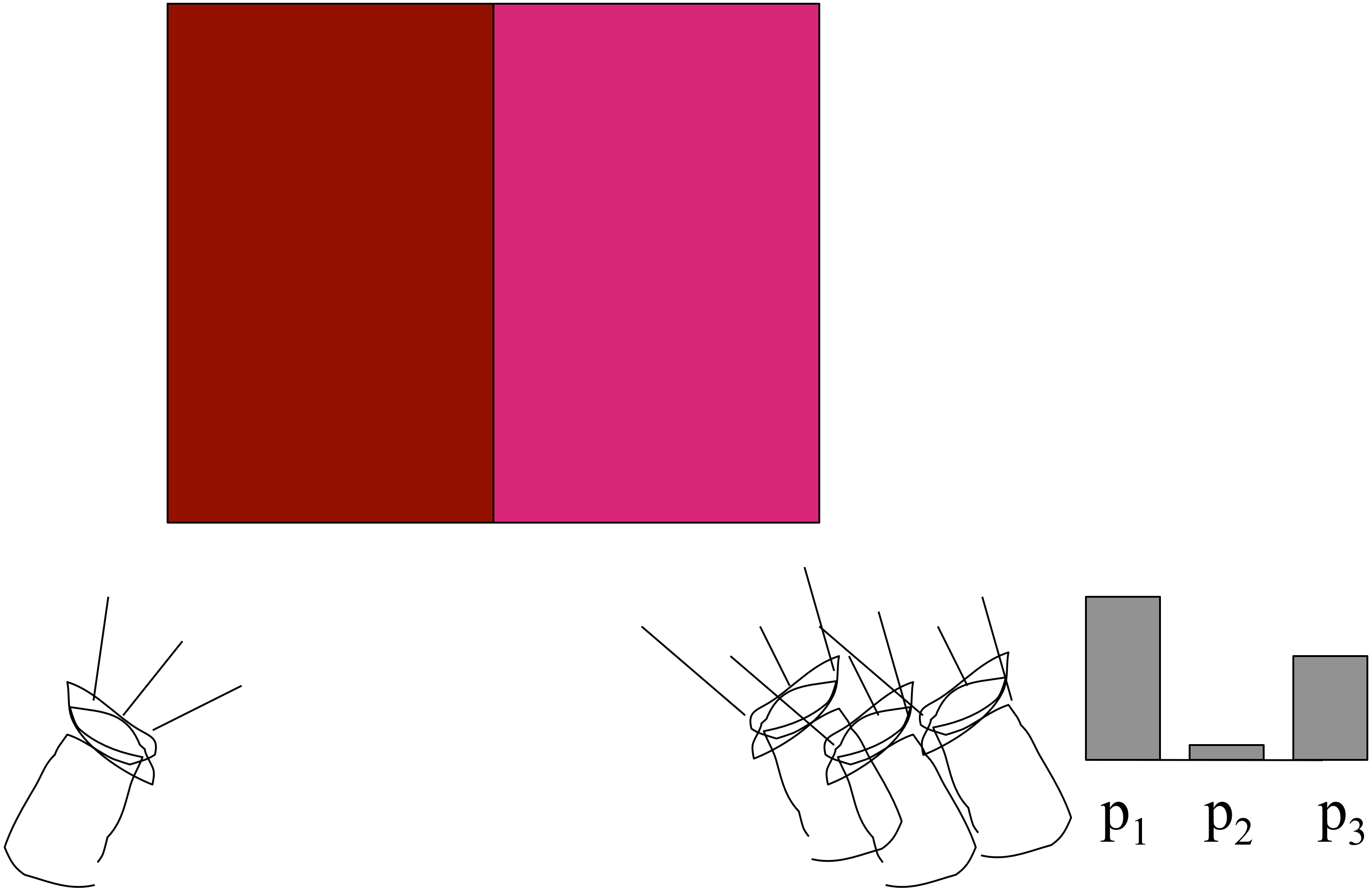
using 5, 3, 1 lb weights

Relevant to color matching experiments, solve this puzzle:

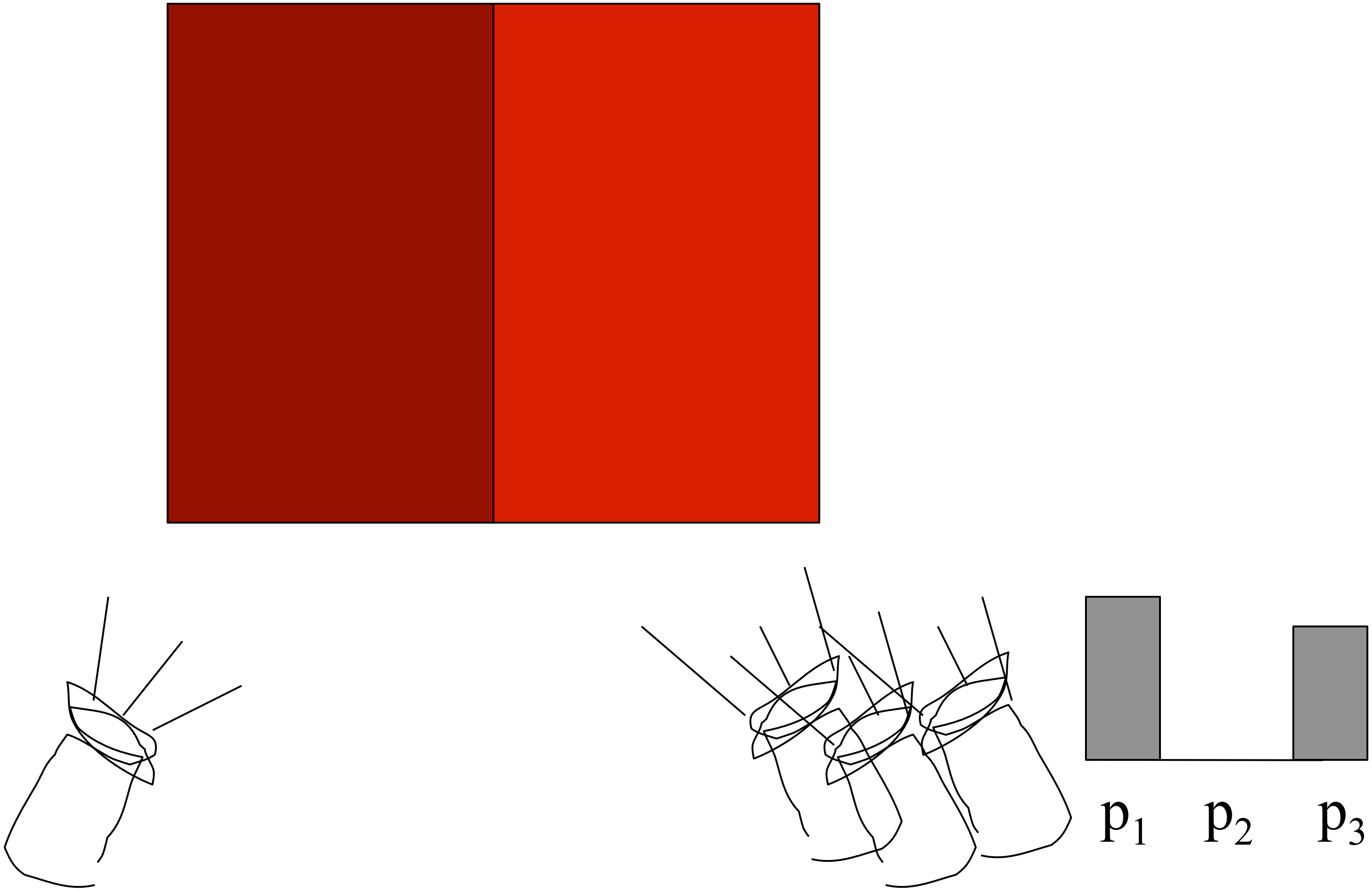
Color matching experiment 2



Color matching experiment 2

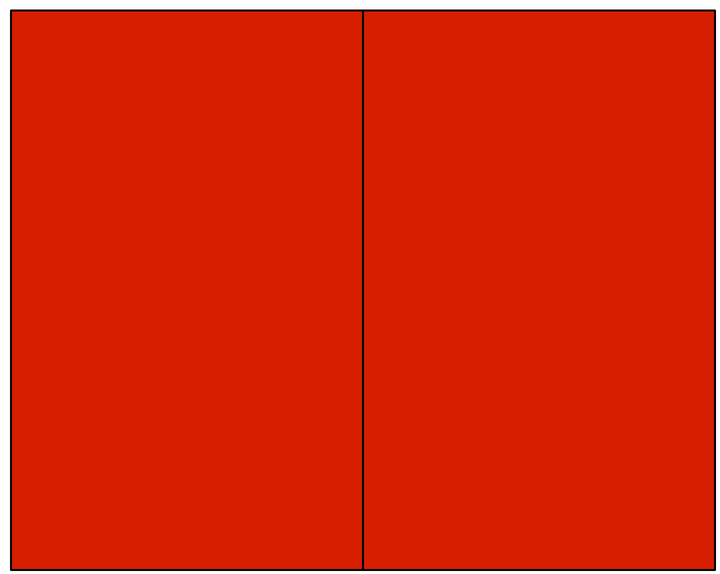


Color matching experiment 2

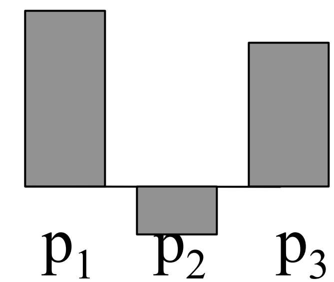


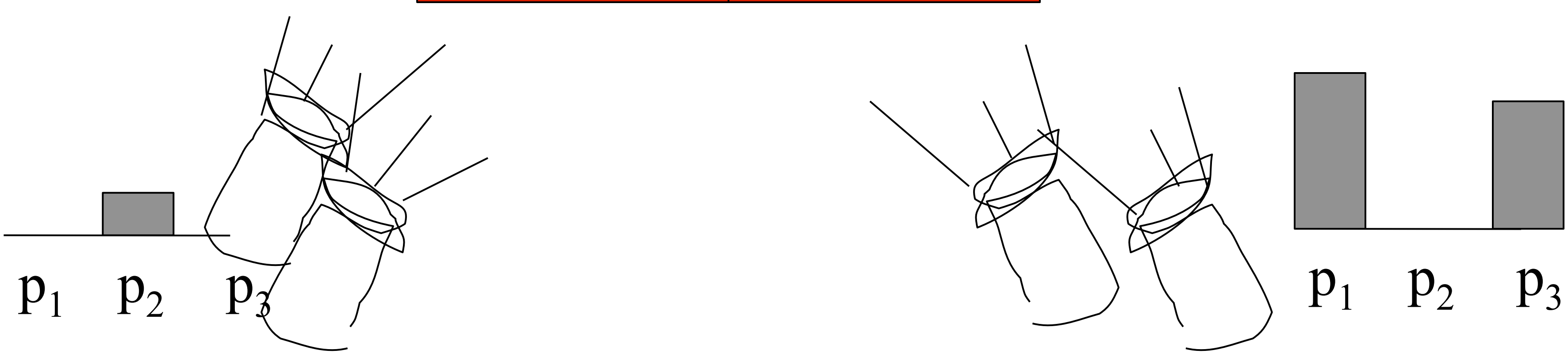
Color matching experiment 2

We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.

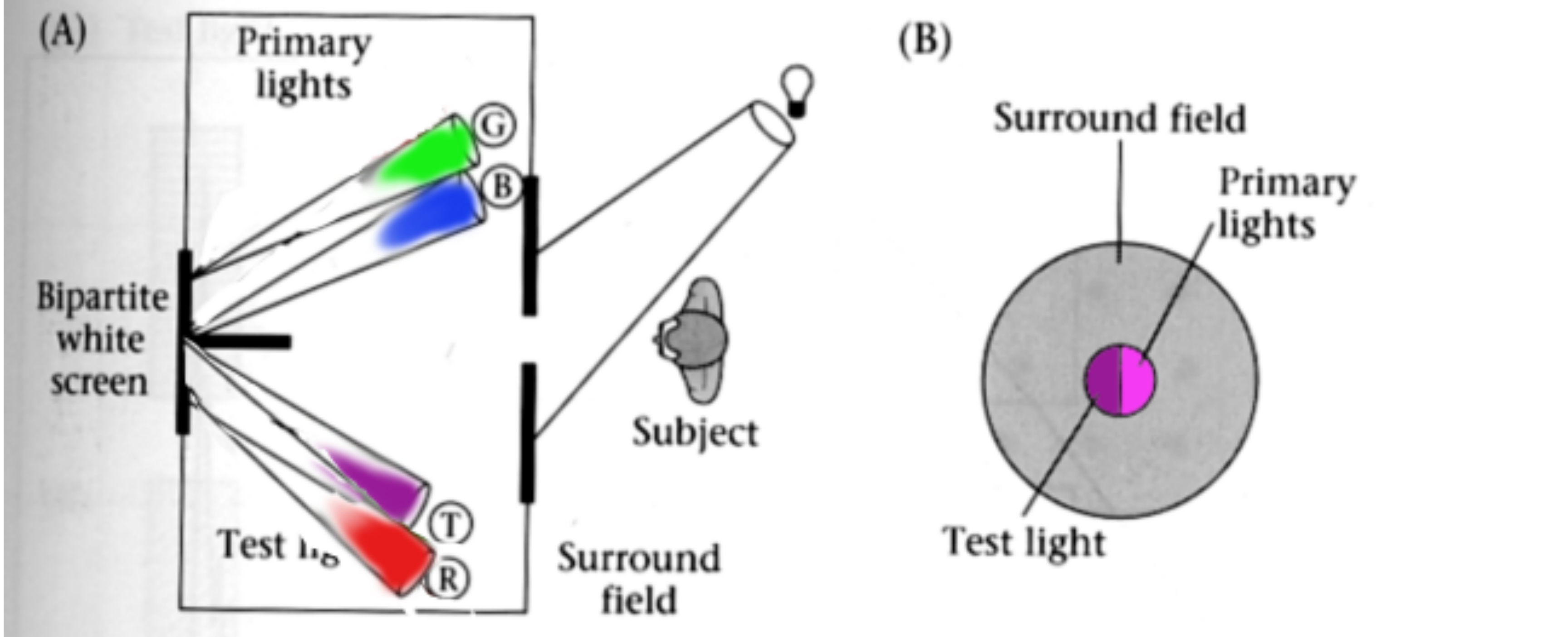


The primary color amounts needed for a match:





Color matching experiment--handle negative light by adding light to the test.



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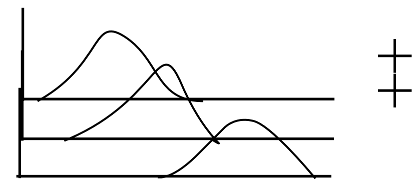
To measure a color

1. Choose a set of 3 primary colors (three power spectra).
2. Determine how much of each primary needs to be added to a probe signal to match the test light.

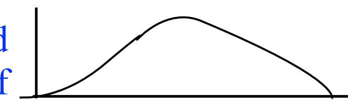
a_1
a_2
a_3



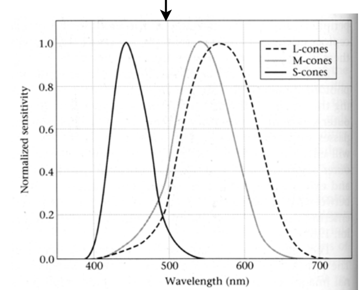
+
+

Primaries

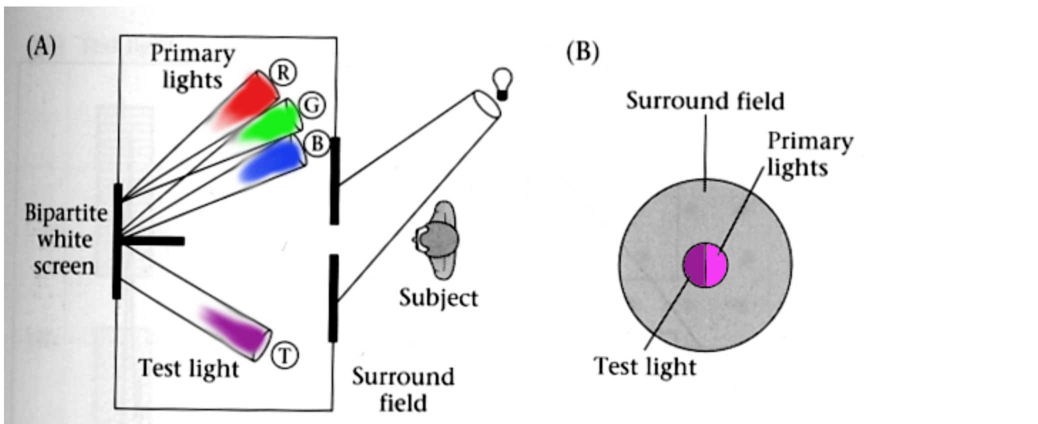
weighted sum of primaries



project



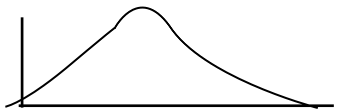
Cone sensitivities



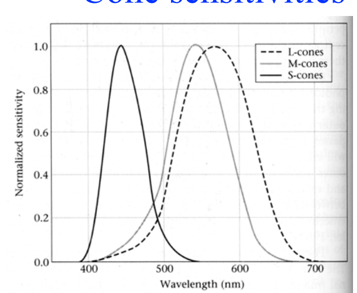
4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

Cone sensitivities

test light



project

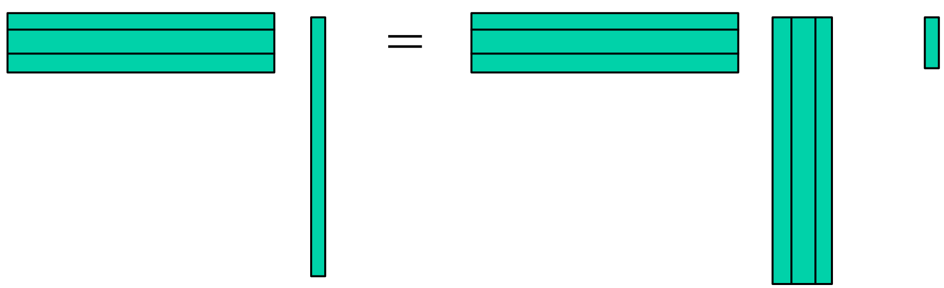


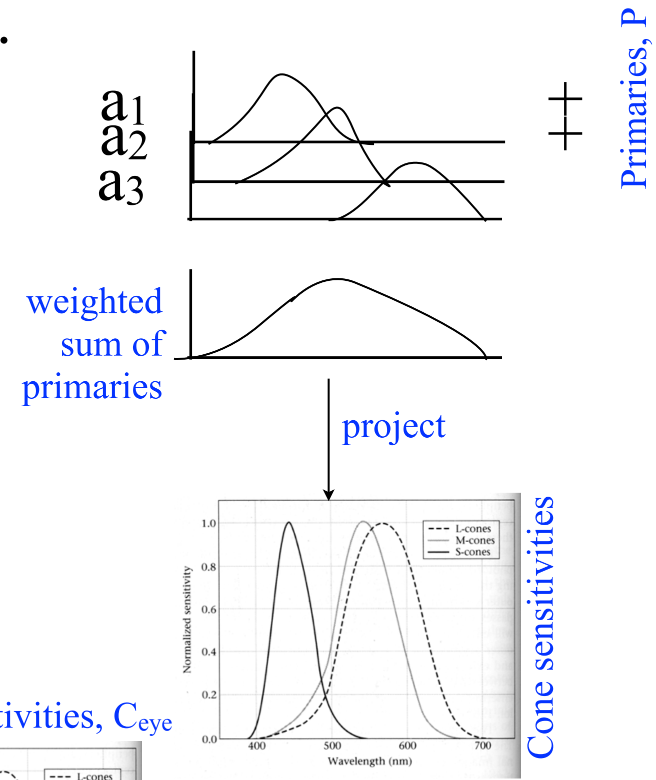
L, M, S responses

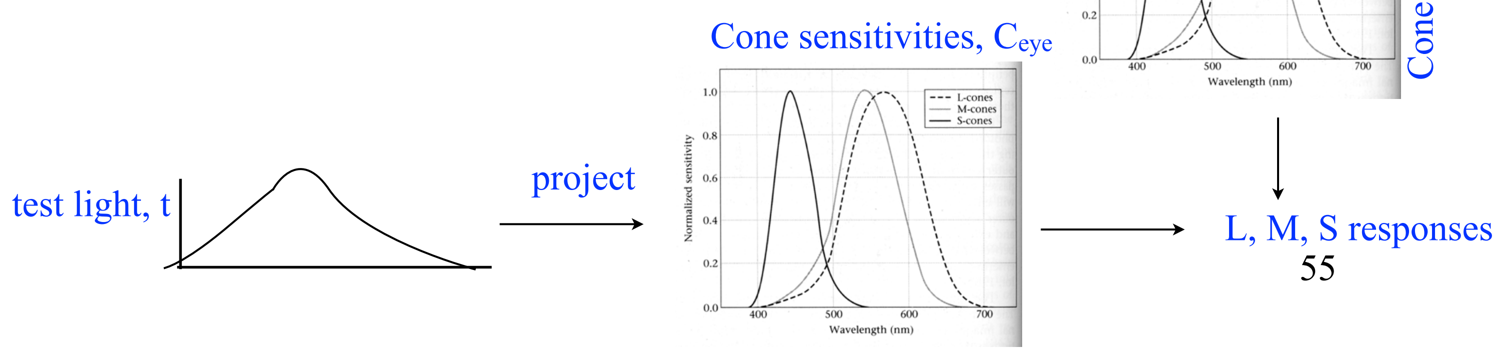
To measure a color

1. Choose a set of 3 primary colors (three power spectra).
2. Determine how much of each primary needs to be added to a probe signal to match the test light.

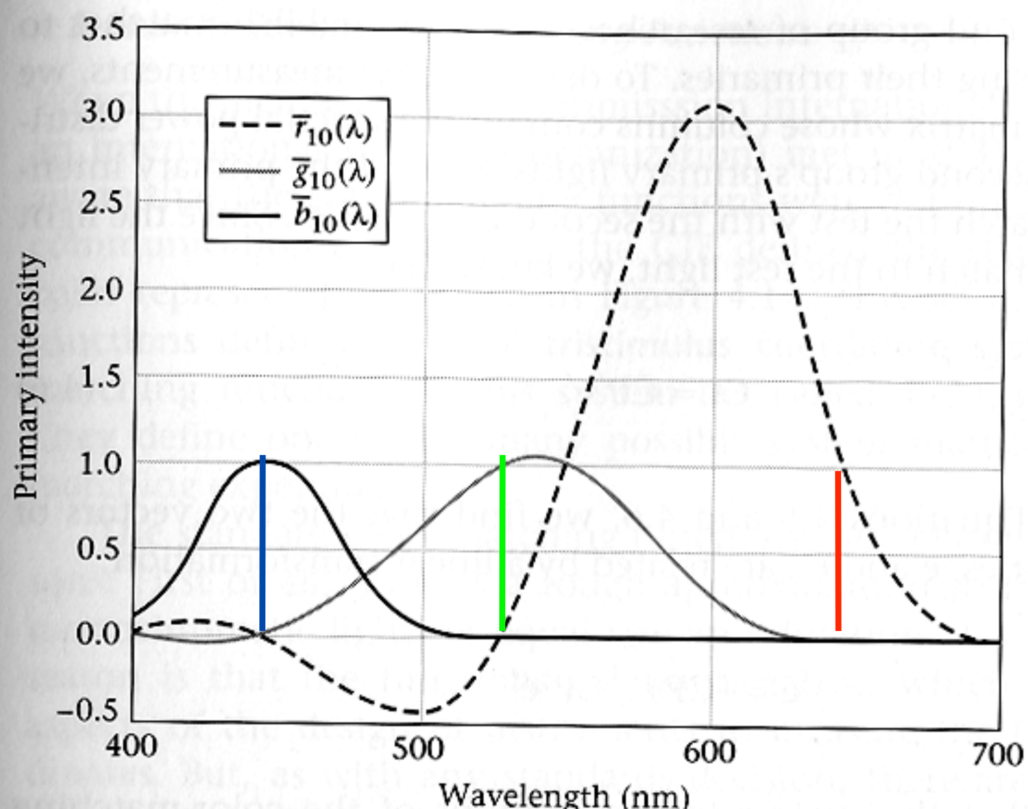
$$C_{eye} \; t = C_{eye} \; P \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}$$







“Color matching functions” tell us how to control primary lights in order to perceptually match a given spectrum



p_1 = 645.2 nm

p_2 = 525.3 nm

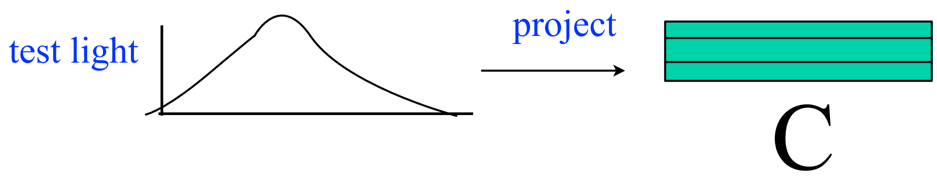
p_3 = 444.4 nm

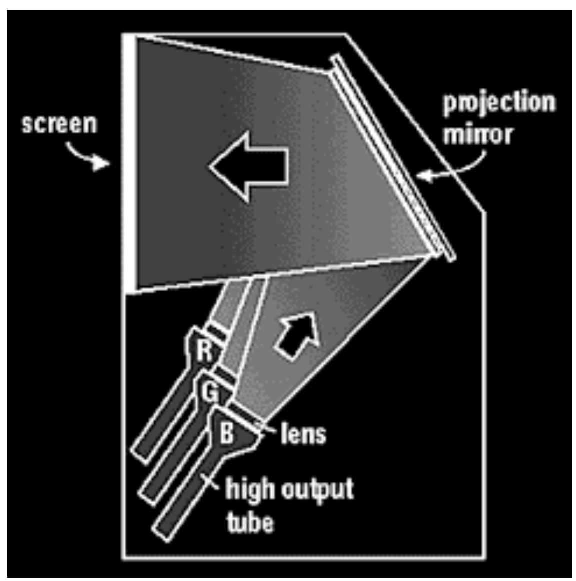
4.13 THE COLOR-MATCHING FUNCTIONS ARE THE ROWS OF THE COLOR-MATCHING SYSTEM MATRIX. The functions measured by Stiles and Burch (1959) using a 10-degree bipartite field and primary lights at the wavelengths 645.2 nm, 525.3 nm, and 444.4 nm with unit radiant power are shown. The three functions in this figure are called $\bar{r}_{10}(\lambda)$, $\bar{g}_{10}(\lambda)$, and $\bar{b}_{10}(\lambda)$.

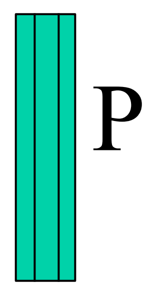
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

What we need from a color reproduction system

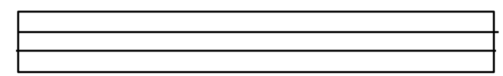
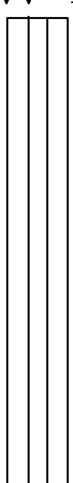
Given an input power spectrum, (a) how do we measure the color, then (b) how do we control our printing/projection/ cooking system to match it?



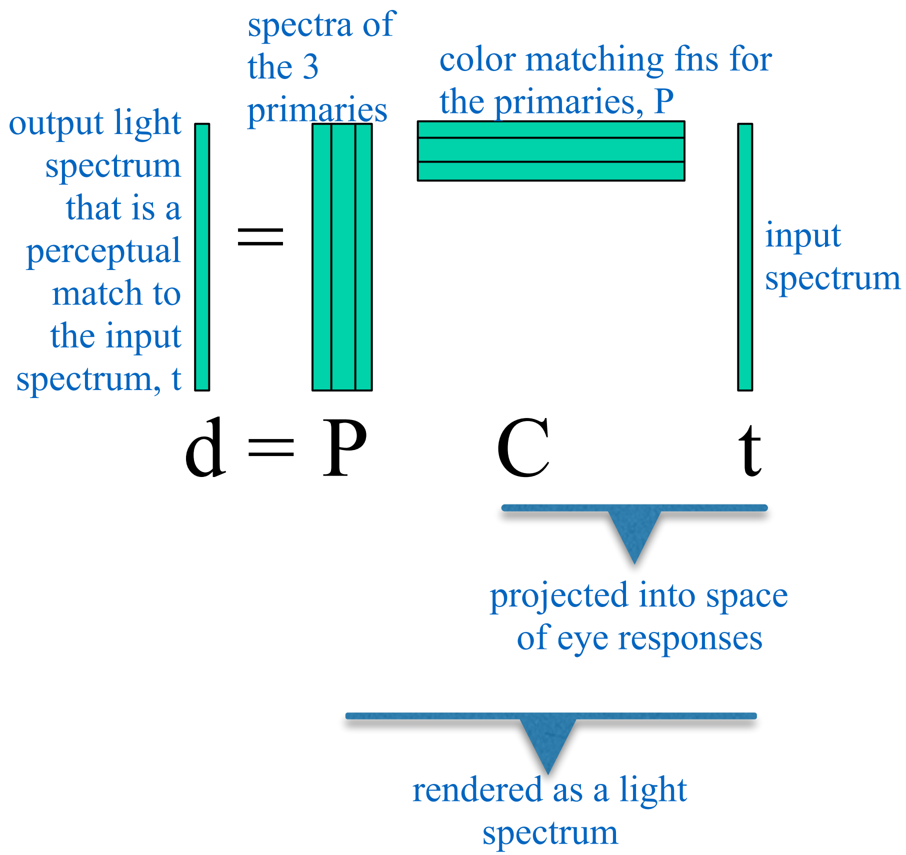




http://www.roobaroo.net/2006/06/25/how-to-clean-and-repair-projection-tv/

- We can measure a color by measuring how much of each primary is needed to match that color.
- Can we measure color without having to make psychophysical experiments each time?
- We'd like to find a matrix, C,  that we can project a spectrum onto, to tell us how much of each primary, in the columns of P,  , to use to match the spectrum.

How the color matching functions, C, and the corresponding primary spectra, P, relate to each other.



If the primaries, P, correspond to the color matching functions, C, then t and s are perceptual matches. When projected down by C they must give the same answer, so we must have,

$$C\,t = C\,d$$

Requirements on C, P to form a color matching system:

(1) the rows of C must be some (non-degenerate) linear combination of the eye photosensor response curves: $C = A\, C_{eye}$, where A is some 3x3 matrix.

That ensures that if two spectra match when projected into the subspace spanned by C, they will match when projected into the subspace of the eye response curves.

(2) C, P must satisfy:

$$C\,P = I$$

why must this hold? Because the amounts of the 3 primaries needed to match the spectrum of each primary (the columns of P) must be [1;0;0], [0;1;0], [0;0;1].

If those conditions hold, then the spectrum PCt will be a perceptual match to t, because

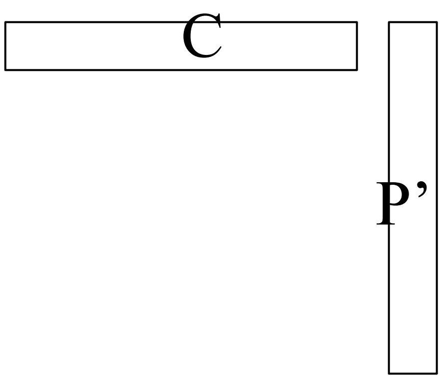
$Ct = CPCt$

How do color coordinates, and the color matching functions, C, translate between different sets of primaries?

From previous slide $$\underbrace{C\vec{t}}_{\text{Color in P primaries}} = CP'\underbrace{C'\vec{t}}_{\text{Color in P' primaries}}$$

But this holds for any input spectrum, t, so…

$$C = CP'C'$$



$$\underbrace{CP'}$$

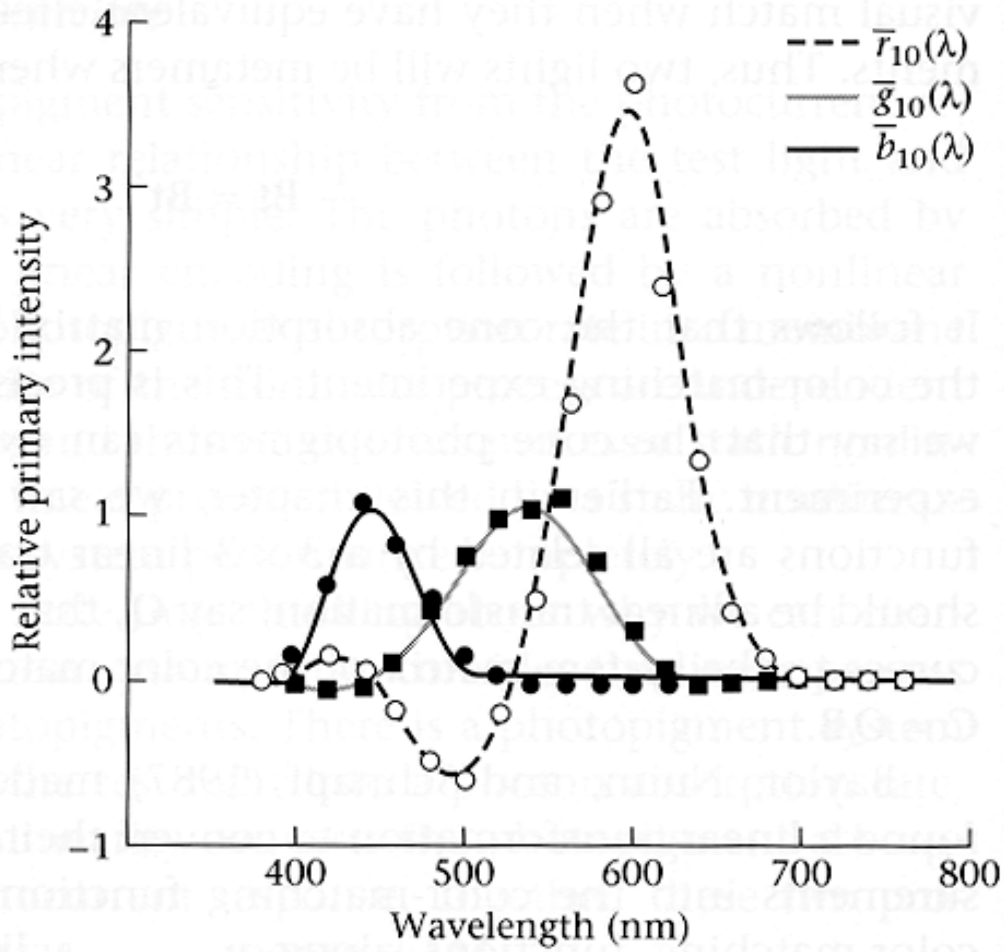
a 3x3 matrix that rotates the C’ color matching matrix into the C matrix. And it rotates a color coordinate from the primed to the unprimed system

P’ are the old primaries

C are the color matching functions for the new primaries, P

Comparison of color matching functions with best linear combination of cone response curves

4.20 COMPARISON OF CONE PHOTOCURRENT RESPONSES AND THE COLOR-MATCHING FUNCTIONS. The cone photocurrent spectral responsivities are within a linear transformation of the color-matching functions, after a correction has been made for the optics and inert pigments in the eye. The smooth curves show the Stiles and Burch (1959) color-matching functions. The symbols show the matches predicted from the photocurrents of the three types of macaque cones. The predictions included a correction for absorption by the lens and other inert pigments in the eye. Source: Baylor, 1987.



Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

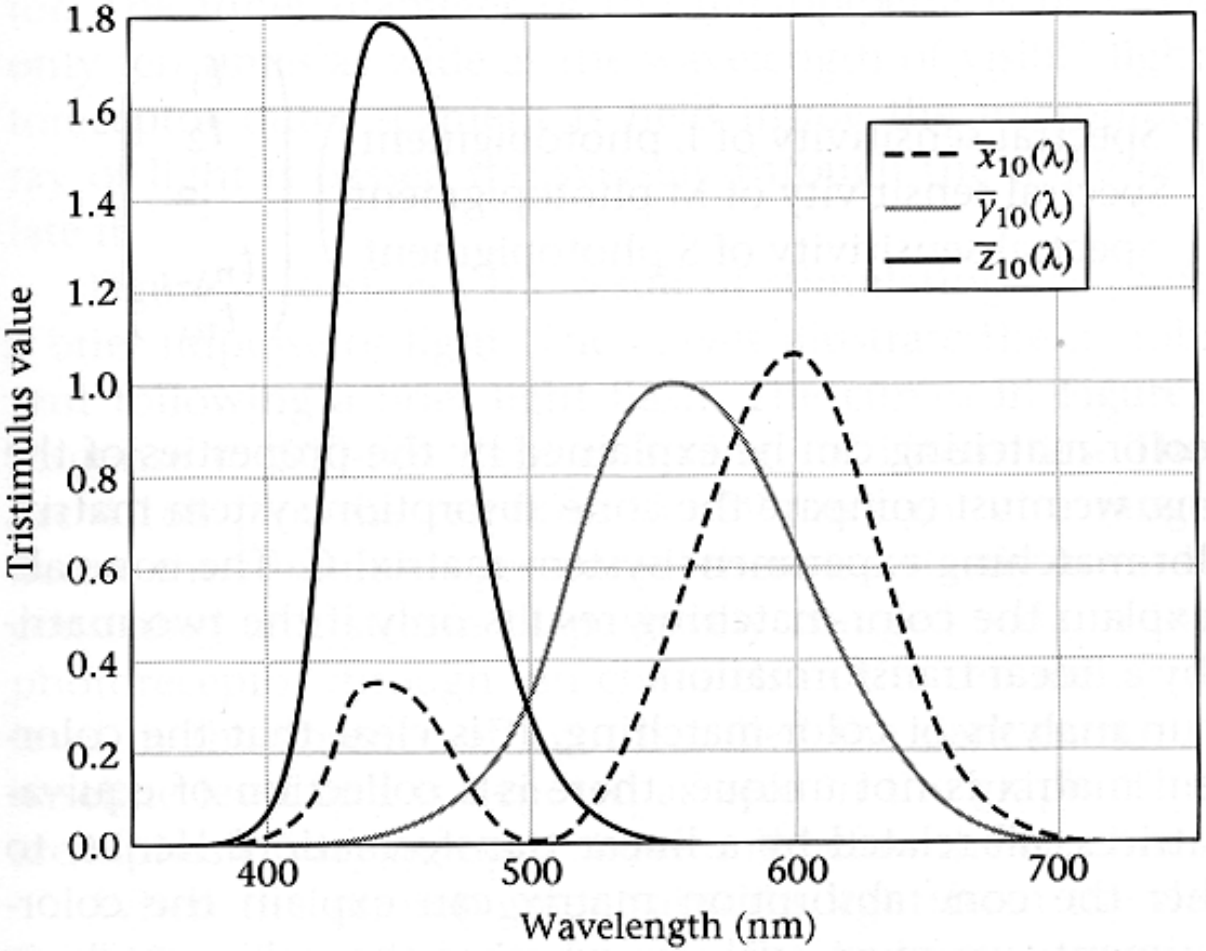
Standardization

- Now we know, for any given set of primaries, P, how to measure the color matching functions, C, corresponding to those primaries. And, knowing C, we know how to control the primaries P to match any given color spectrum. And we know how to translate from one set of color matching functions to another.
- Now we just need to standardize on a set of color matching functions, C, so that our color measurements are compatible.

CIE XYZ color space

- Commission Internationale d'Eclairage, 1931 (International Commission on Illumination).
- "…as with any standards decision, there are some irratating aspects of the XYZ color-matching functions as well…no set of physically realizable primary lights that by direct measurement will yield the color matching functions."
- "Although they have served quite well as a technical standard, and are understood by the mandarins of vision science, they have served quite poorly as tools for explaining the discipline to new students and colleagues outside the field."

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

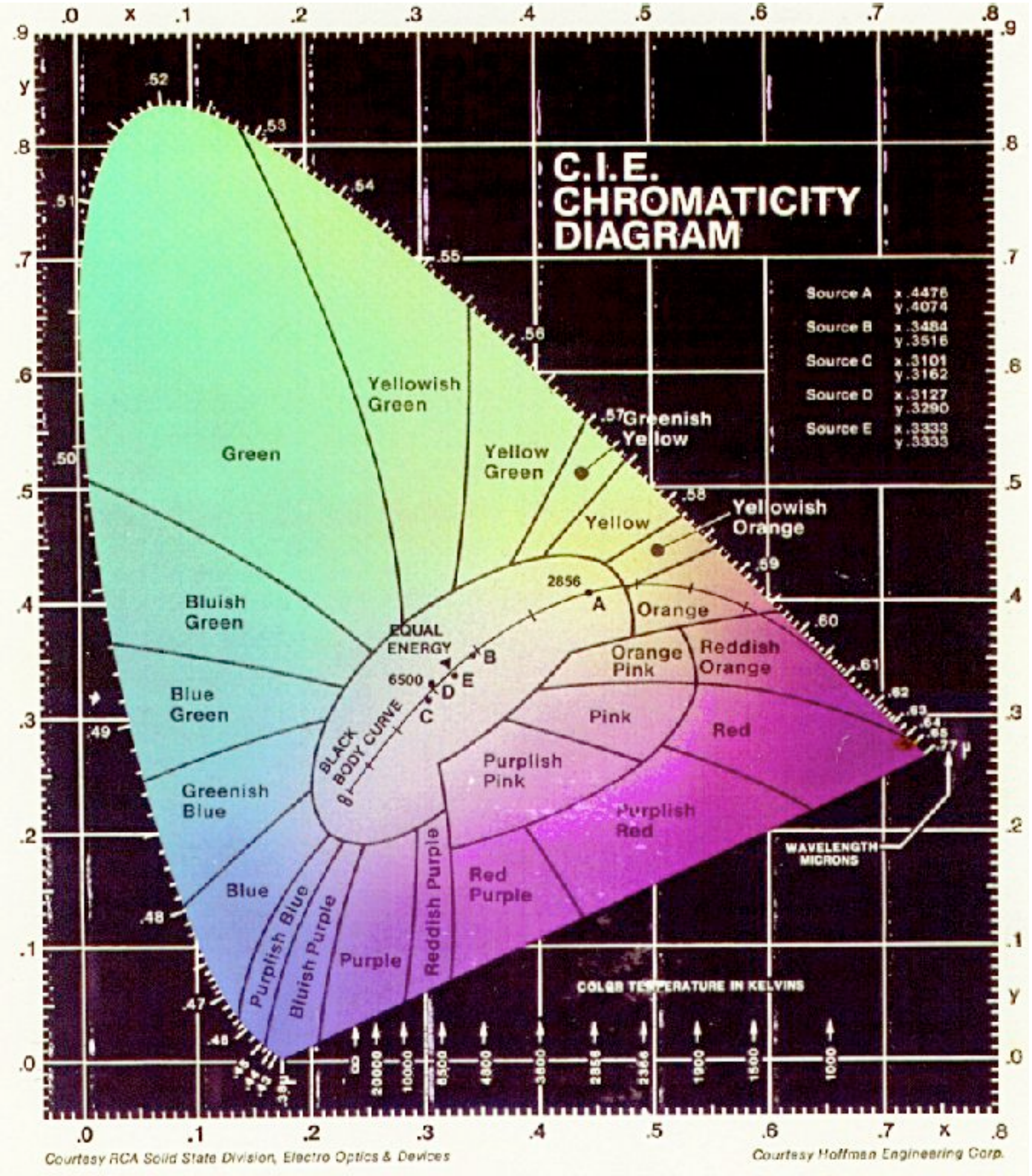


4.14 THE XYZ STANDARD COLOR-MATCHING FUNCTIONS. In 1931 the CIE standardized a set of color-matching functions for image interchange. These color-matching functions are called $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$. Industrial applications commonly describe the color properties of a light source using the three primary intensities needed to match the light source that can be computed from the XYZ color-matching functions.

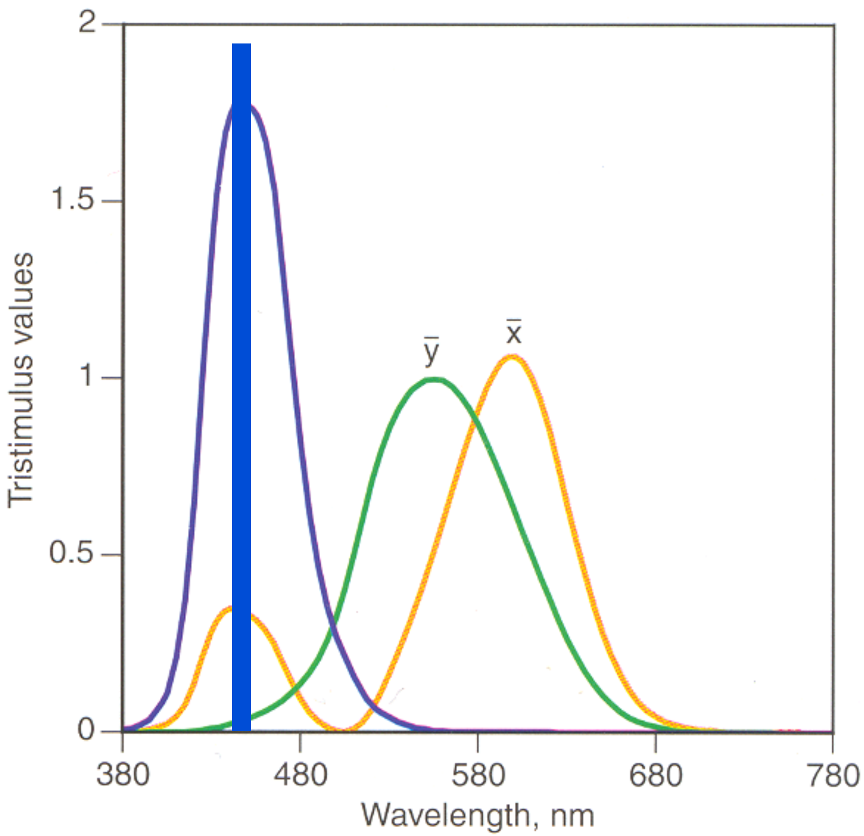
CIE XYZ: Color matching functions are positive everywhere, but primaries are "imaginary" (require adding light to the test color's side in a color matching experiment). Usually compute x, y, where $x=X/(X+Y+Z)$

$y=Y/(X+Y+Z)$

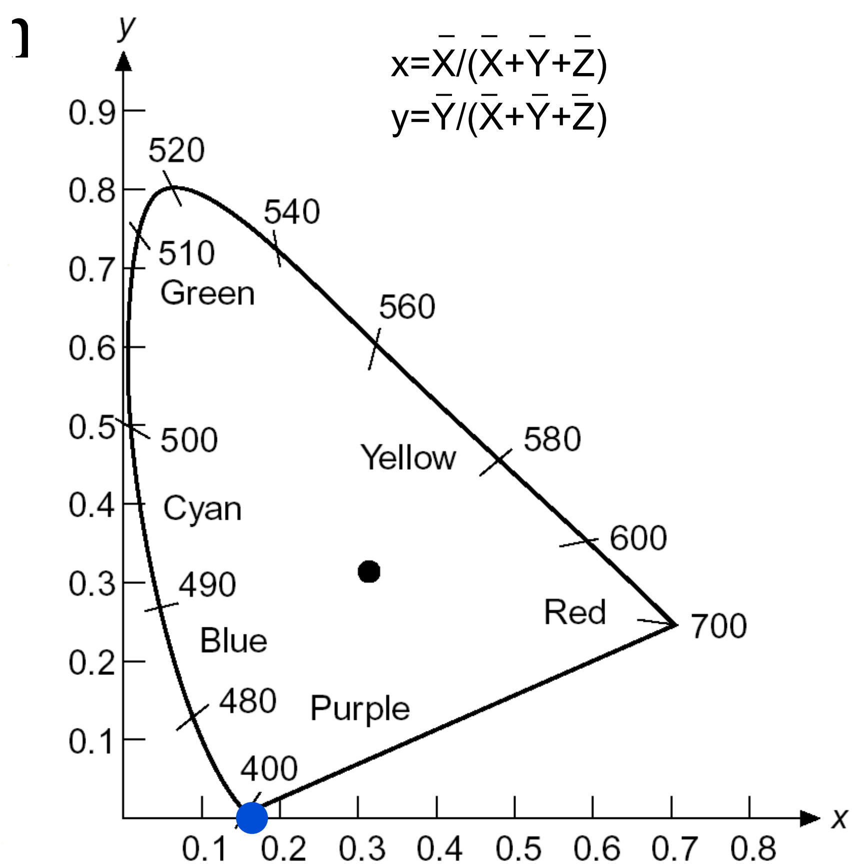
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995


C.I.E.
CHROMATICITY
DIAGRAM
Source A x .4476 y .4074
Source B x .3484 y .3516
Source C x .3101 y .3162
Source D x .3127 y .3290
Source E x .3333 y .3333
Green
Yellowish Green
Yellow Green
Greenish Yellow
Yellow
Yellowish Orange
Orange
Orange Pink
Reddish Orange
Pink
Red
Purplish Pink
Purplish Red
Red Purple
Reddish Purple
Purple
Bluish Purple
Purplish Blue
Blue
Greenish Blue
Blue Green
Bluish Green
EQUAL ENERGY
BLACK BODY CURVE
6500
2856
WAVELENGTH MICRONS
COLOR TEMPERATURE IN KELVINS
Courtesy RCA Solid State Division, Electro Optics & Devices
Courtesy Hoffman Engineering Corp.

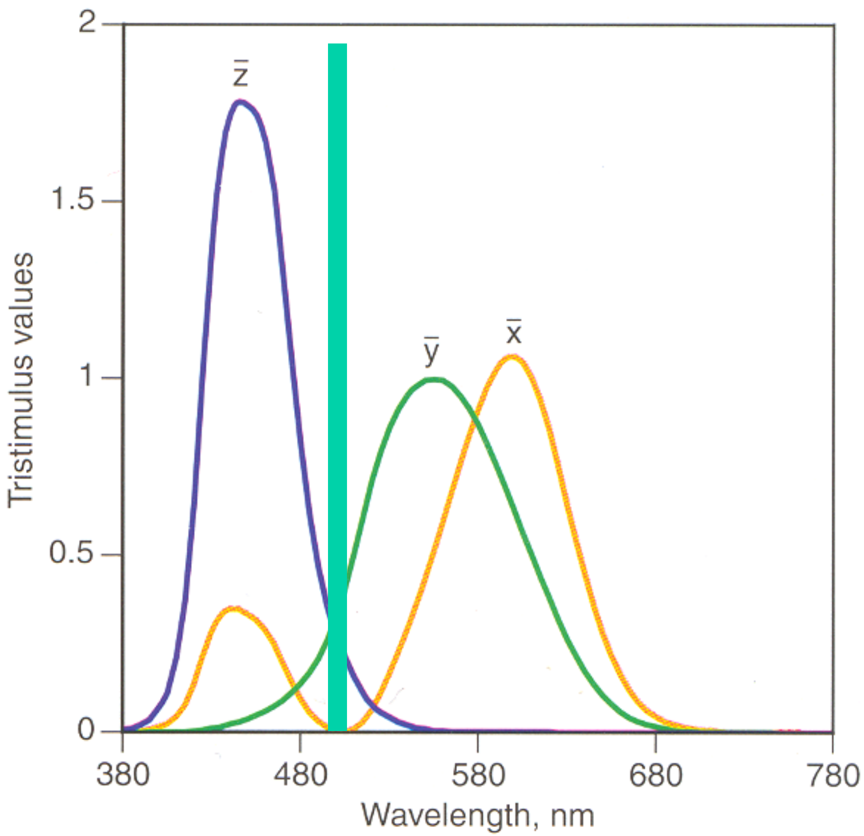
Pure wavelength in chromaticity diagram



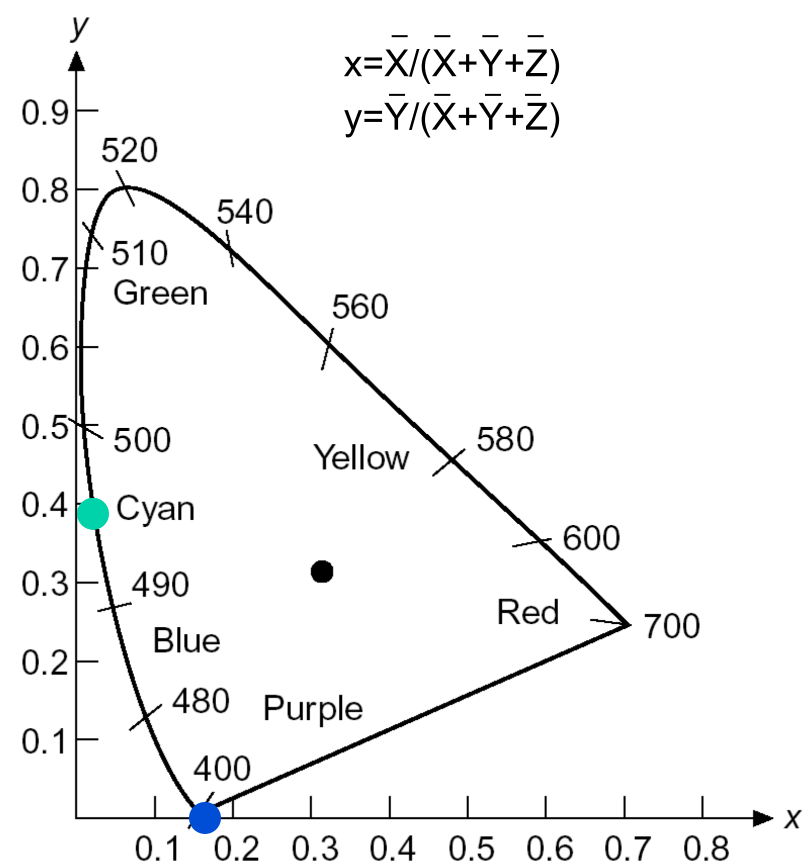
The 1931 standard observer, as it is usually shown.



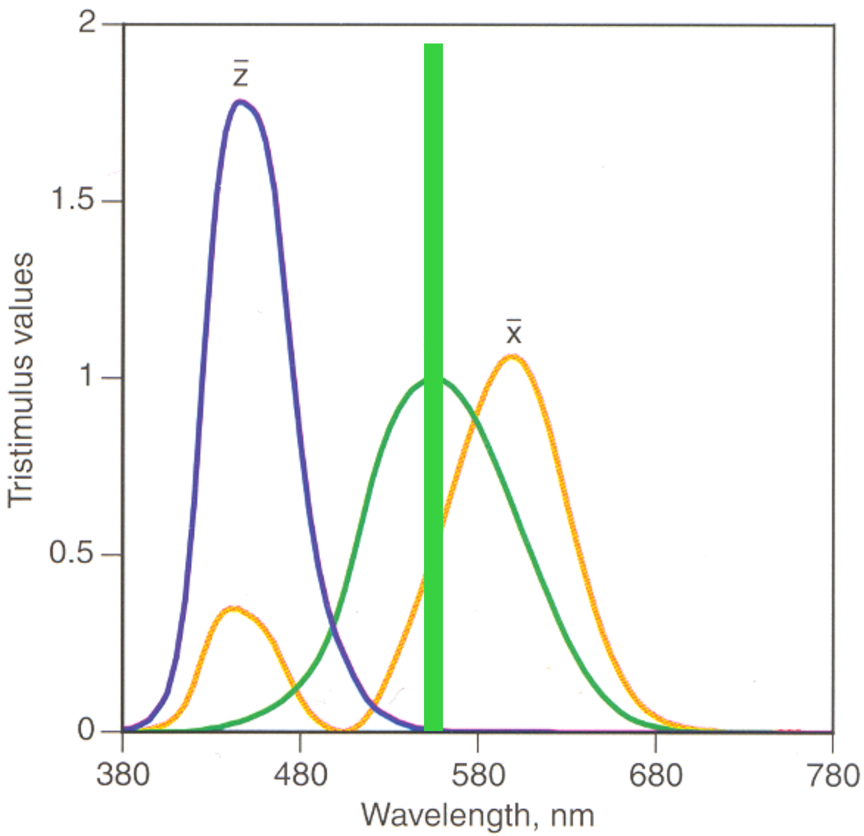
Pure wavelength in chromaticity diagram



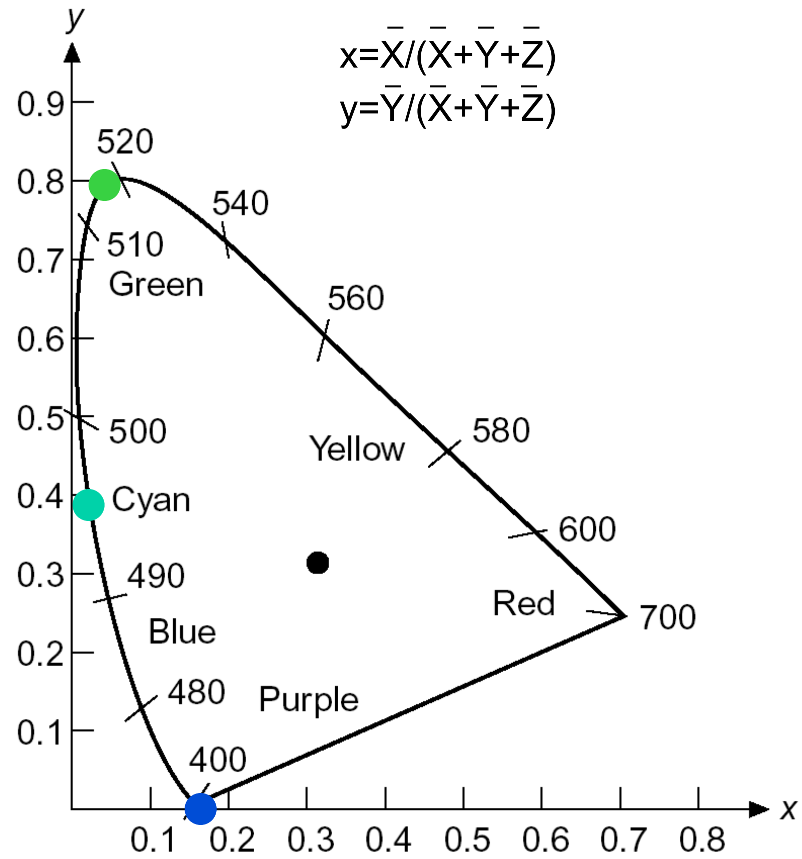
The 1931 standard observer, as it is usually shown.



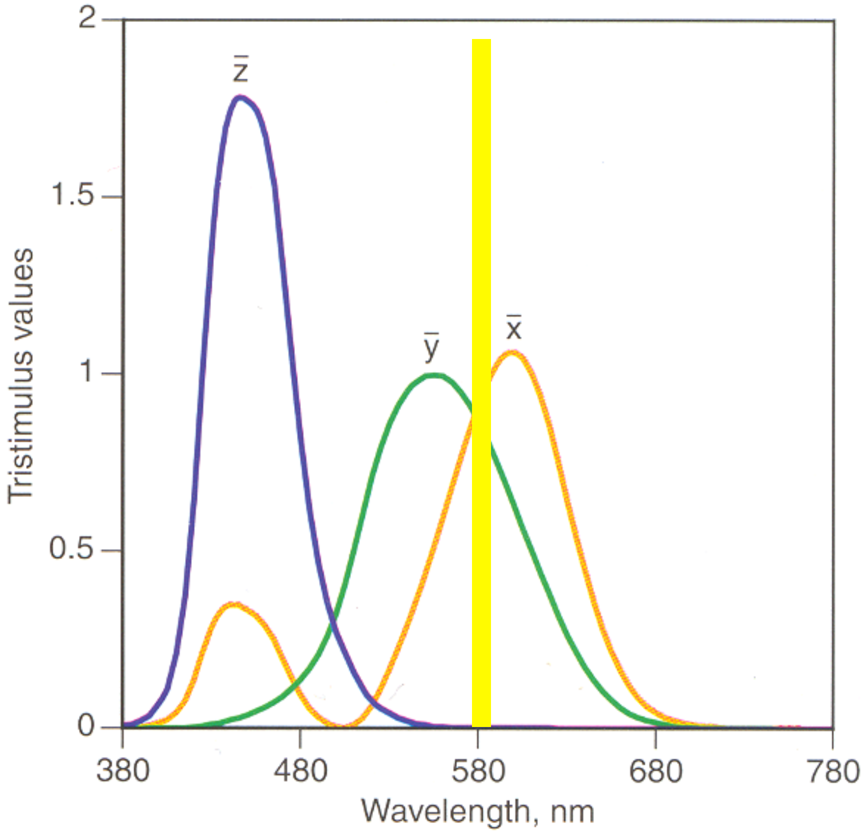
Pure wavelength in chromaticity diagram



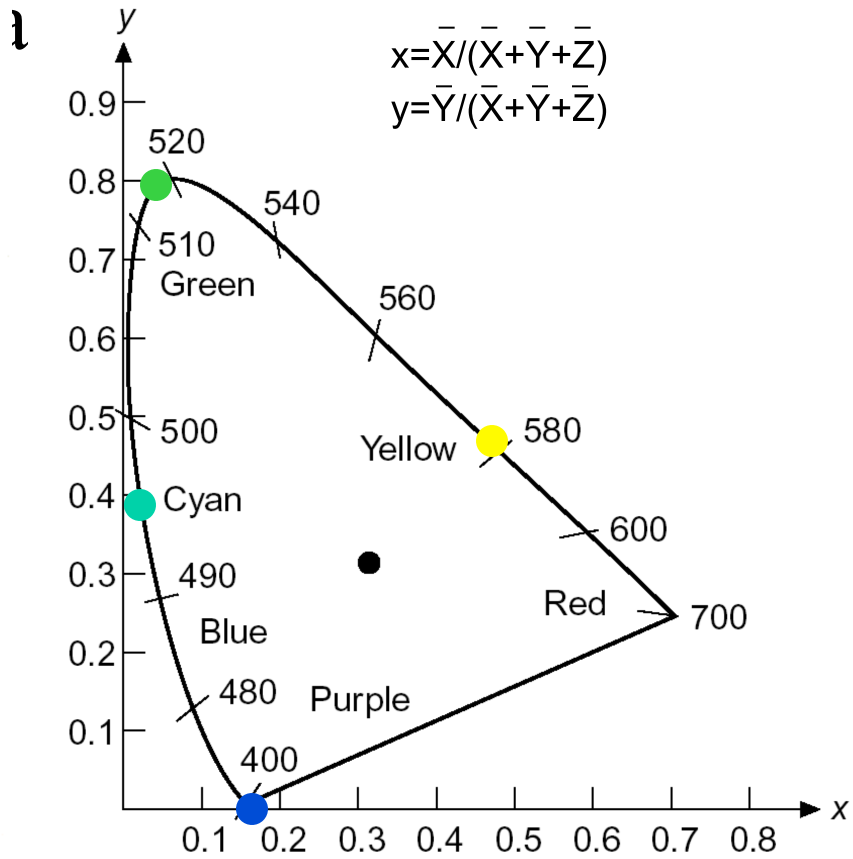
The 1931 standard observer, as it is usually shown.



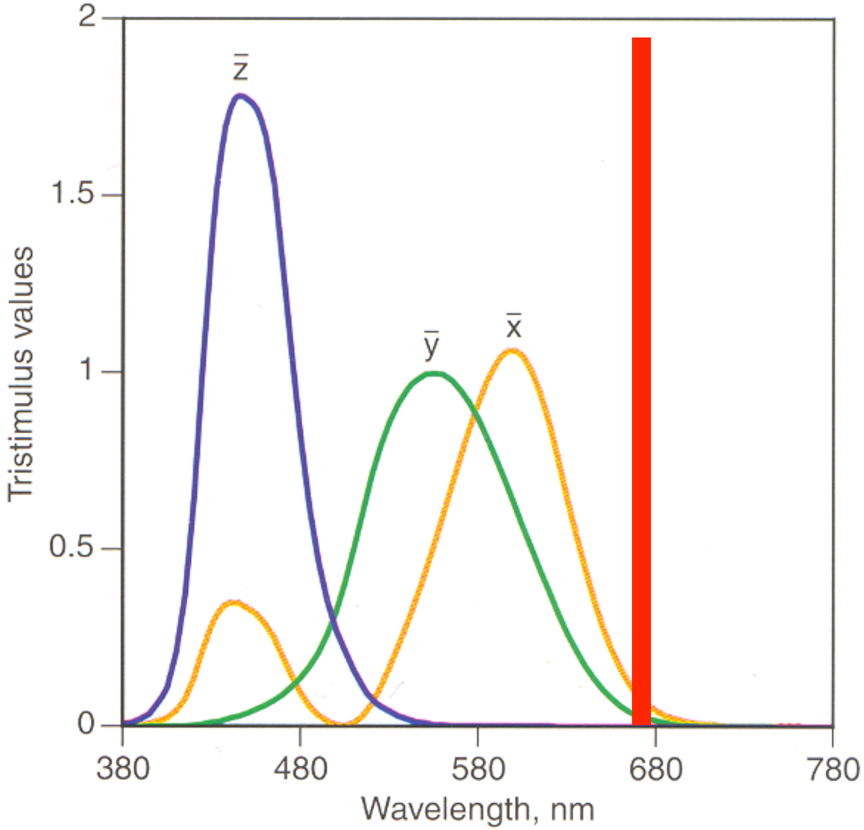
Pure wavelength in chromaticity diagram



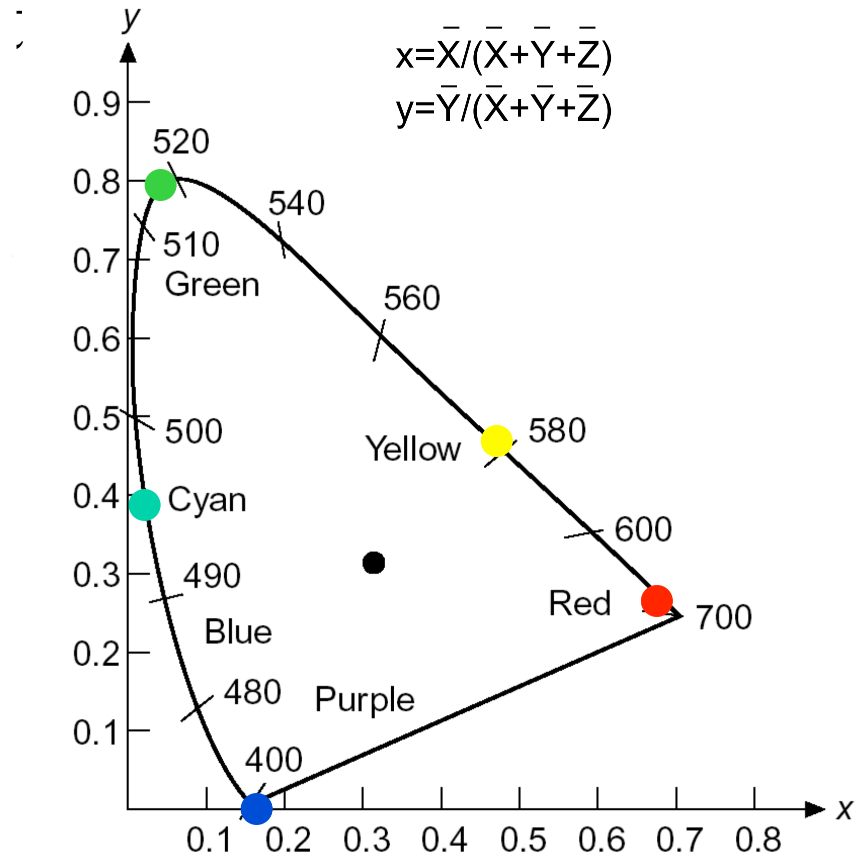
The 1931 standard observer, as it is usually shown.



Pure wavelength in chromaticity diagram



The 1931 standard observer, as it is usually shown.



XYZ vs. RGB

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 3.24 & -1.54 & -0.50 \\ -0.97 & 1.88 & 0.04 \\ 0.06 & -0.20 & 1.06 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

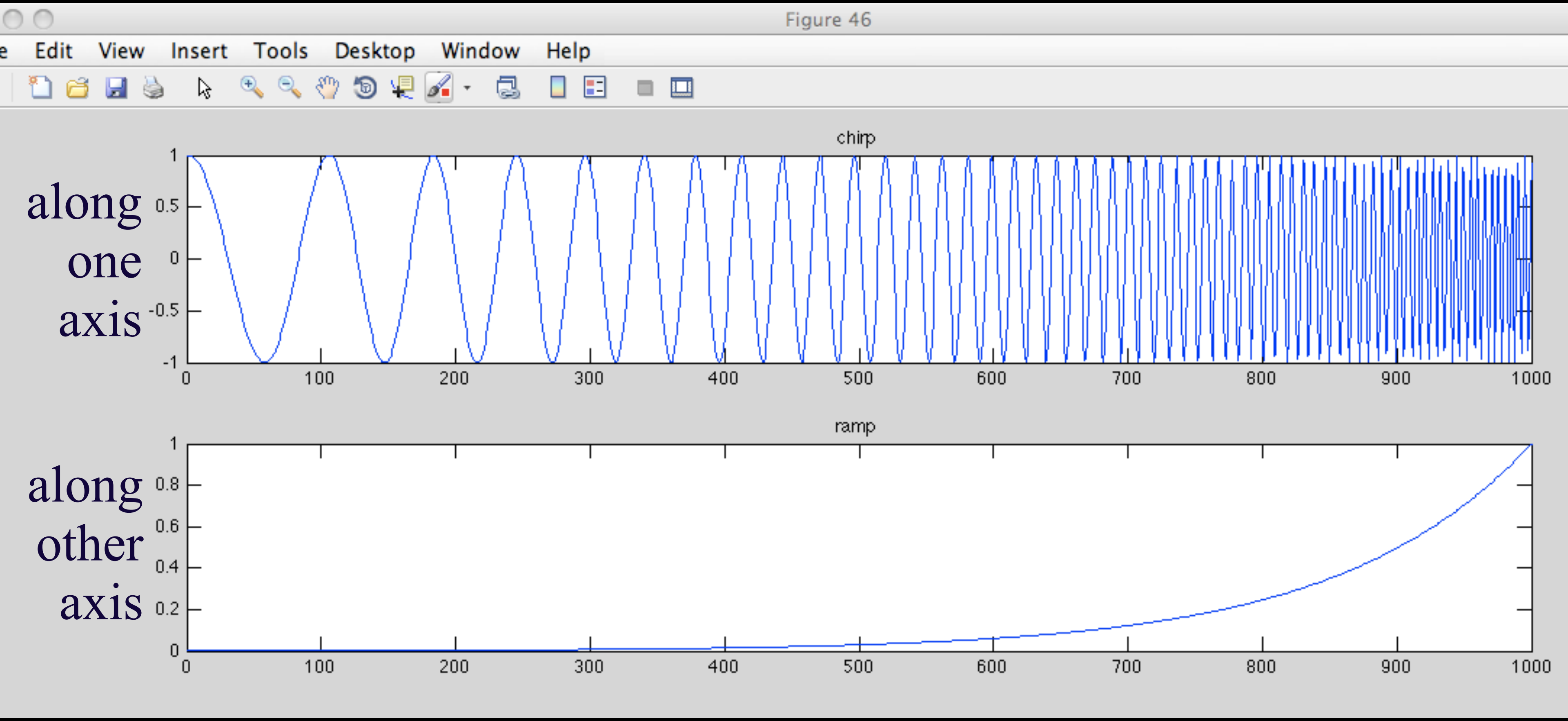
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.41 & 0.36 & 0.18 \\ 0.21 & 0.72 & 0.07 \\ 0.02 & 0.12 & 0.95 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

- Linear transform
- XYZ is rarely used for storage
- There are tons of flavors of RGB
  - sRGB, Adobe RGB
  - Different matrices!
- XYZ is more standardized
- XYZ can reproduce all colors with positive values
- XYZ is not realizable physically !!
  - What happens if you go “off” the diagram
  - In fact, the orthogonal (synthesis) basis of XYZ requires negative values.

Concepts in color measurement

- What are colors?
  - Arise from power spectrum of light.
- How represent colors:
  - Pick primaries
  - Measure color matching functions (CMF's)
  - Matrix mult the test color's power spectrum by CMF's to find color in terms of the 3 primary color values which will give a perceptual match to the test color's power spectrum.
- How share color descriptions between people?
  - Standardize on a few sets of primaries.
  - Translate colors between systems of primaries (3x3 matrix multiplications).

Displaying Contrast Sensitivity Function (CSF)



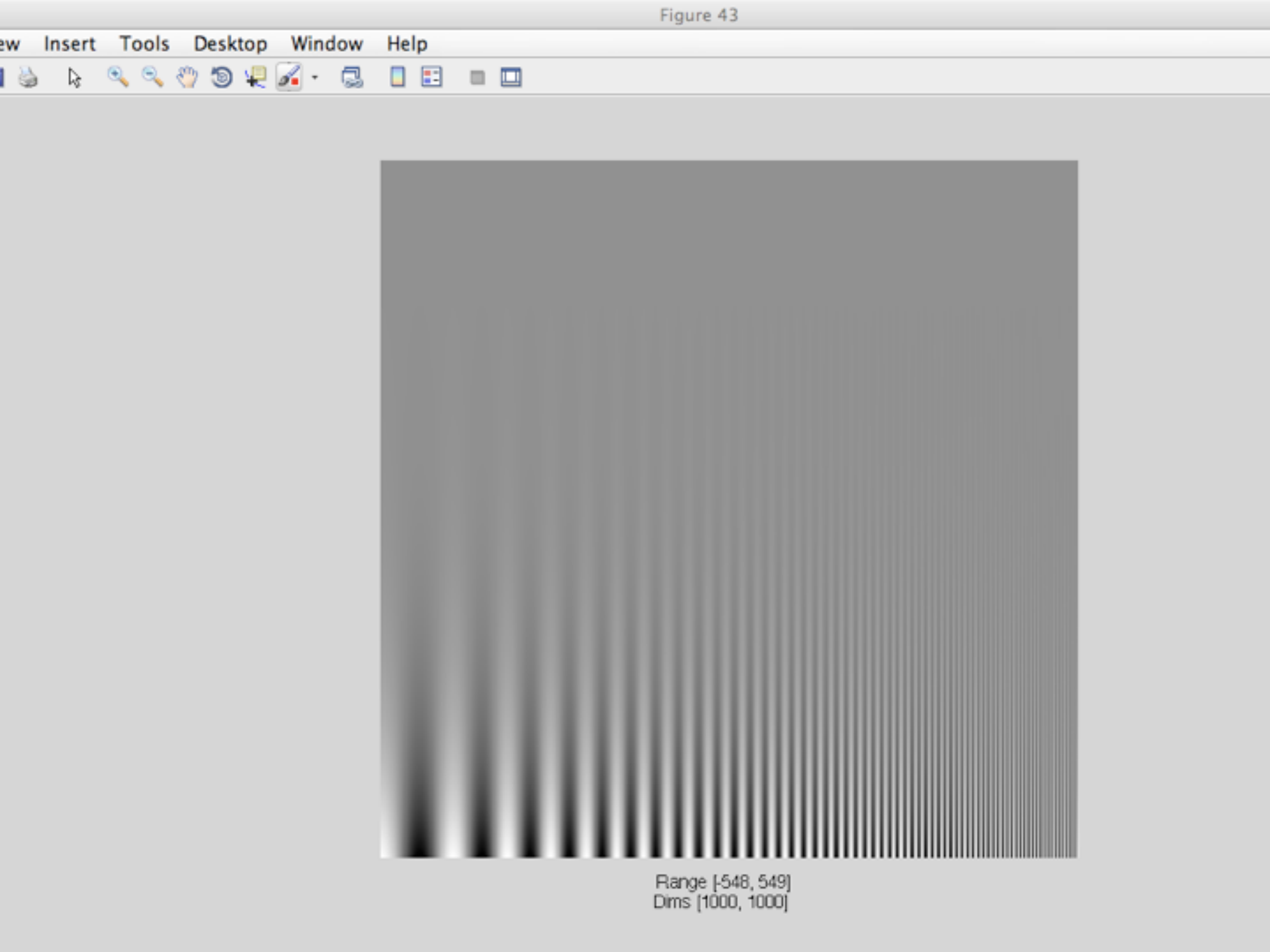
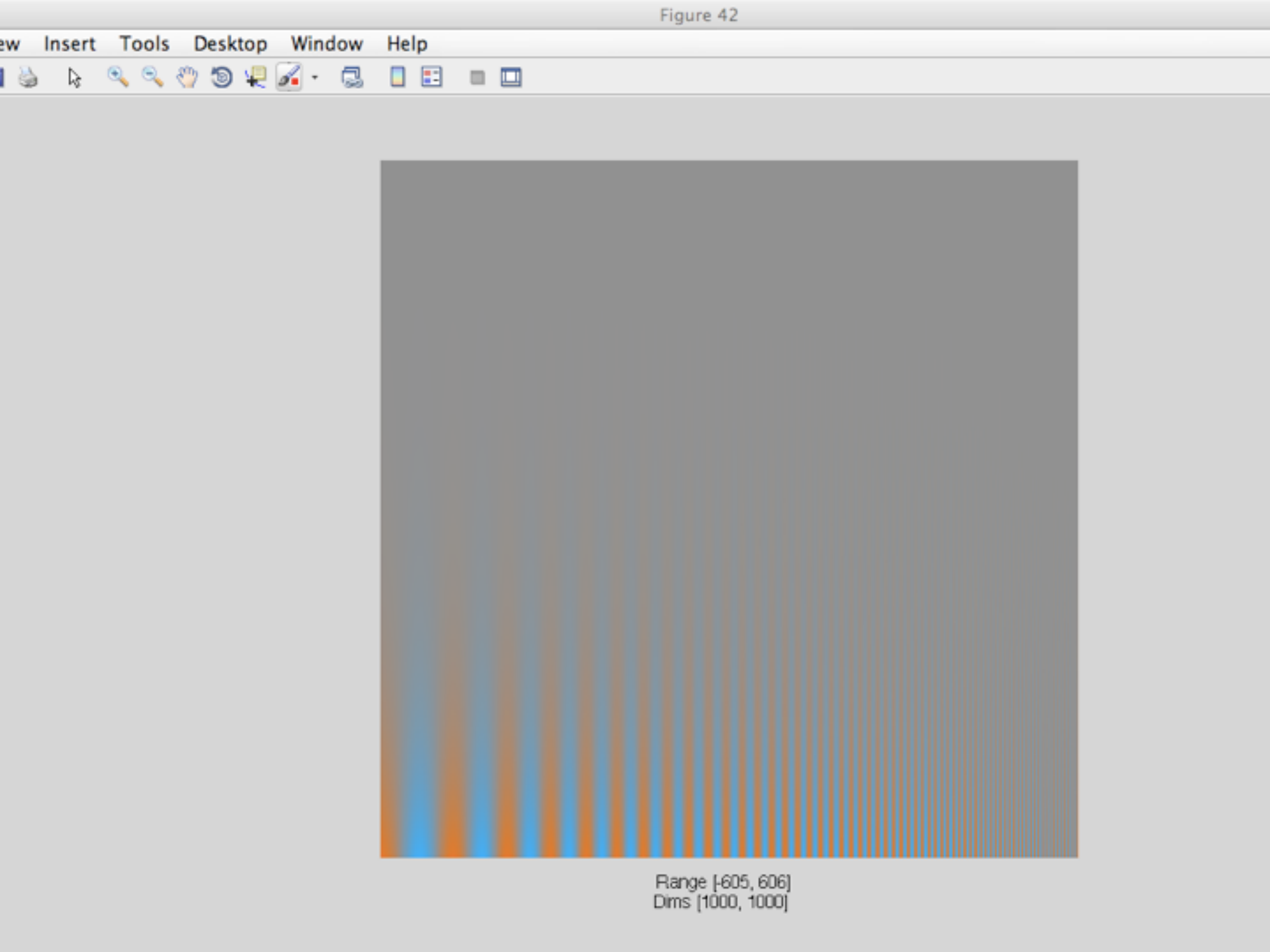


Figure 43
ew Insert Tools Desktop Window Help
Range [-548, 549]
Dims [1000, 1000]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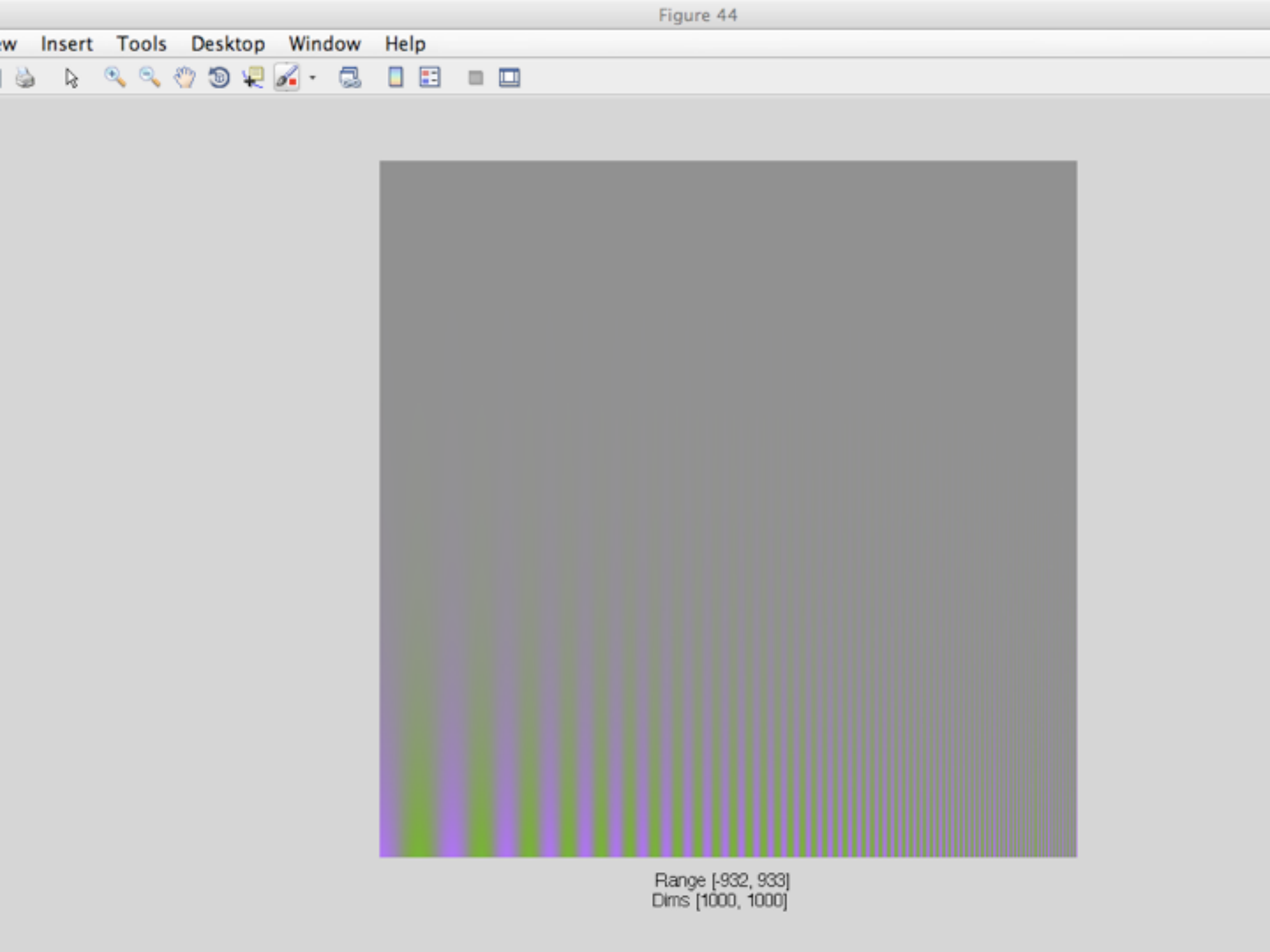
Figure 44
ew Insert Tools Desktop Window Help
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Dims [1000, 1000]

Another psychophysical fact: luminance and chrominance channels in the brain

From W. E. Glenn, in Digital Images and Human Vision, MIT Press, edited by Watson, 1993

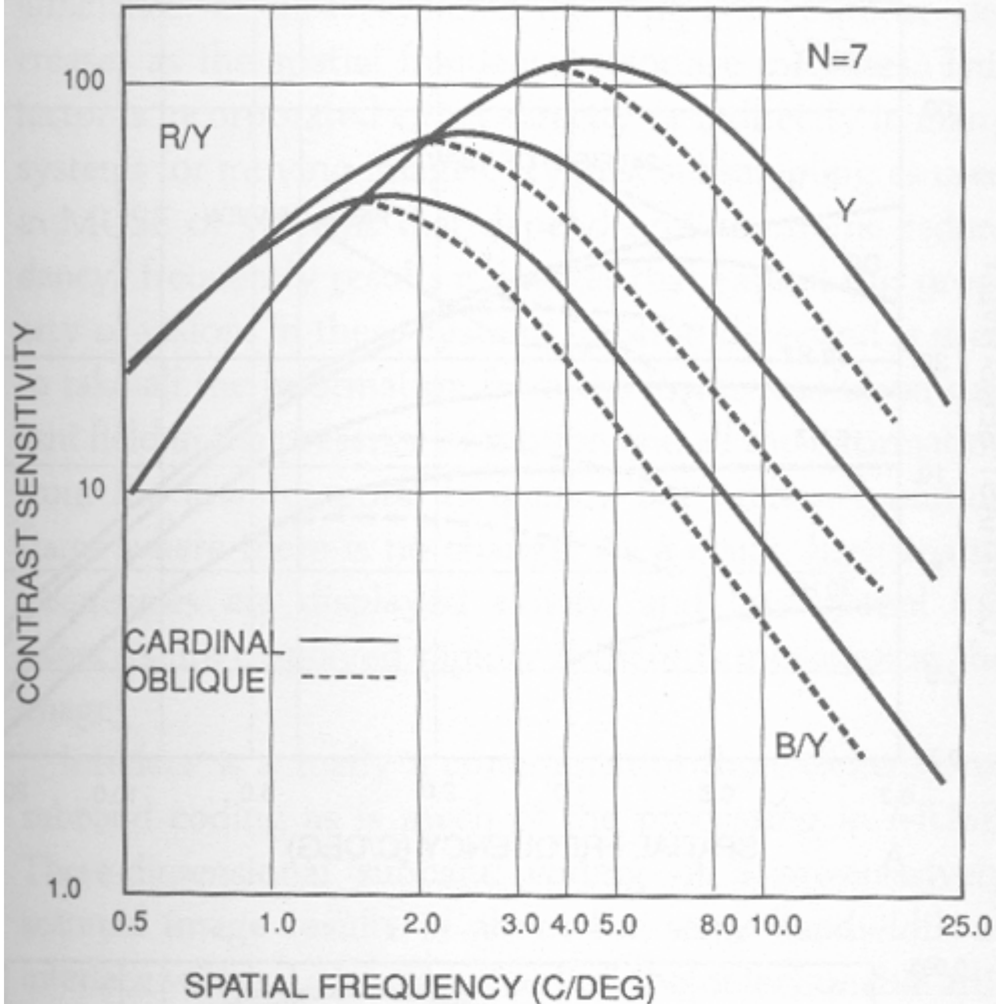


Figure 6.1
Contrast sensitivity threshold functions for static luminance gratings (Y) and isoluminance chromaticity gratings (R/Y,B/Y) averaged over seven observers.

luminance, chrominance color components: Y, I, Q

$$\begin{pmatrix} Y \\ I \\ Q \end{pmatrix} = \begin{pmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.274 & -0.322 \\ 0.211 & -0.523 & 0.312 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

YIQ - RGB

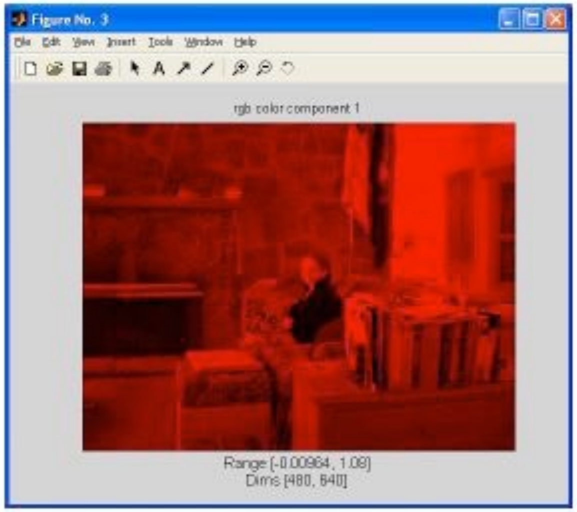


Figure No. 3
rgb color component 1
Range [-0.00964, 1.08]
Dims [480, 640]

R

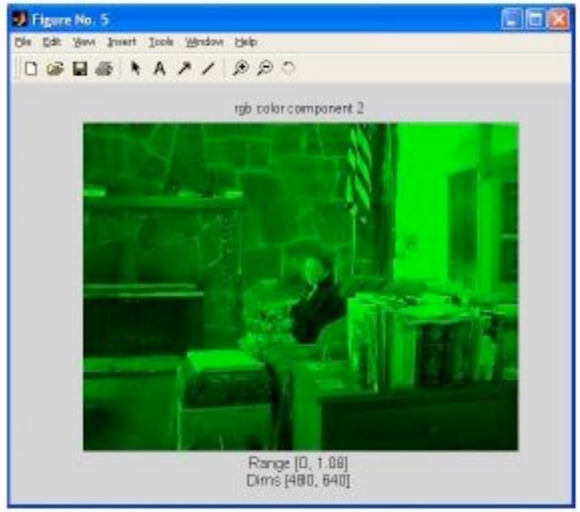


Figure No. 5
rgb color component 2
Range [0, 1.08]
Dims [480, 640]

G

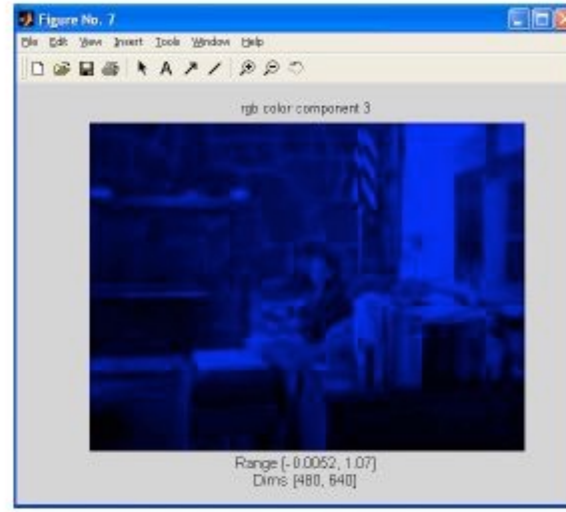


Figure No. 7
rgb color component 3
Range [-0.0052, 1.07]
Dims [480, 640]

B

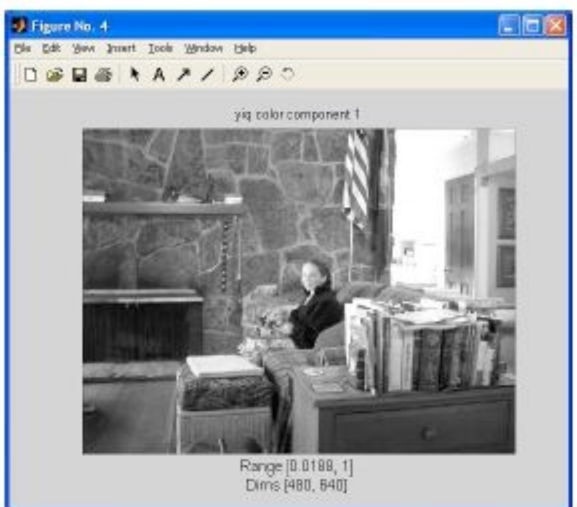


Figure No. 4
yiq color component 1
Range [0.0188, 1]
Dims [480, 640]

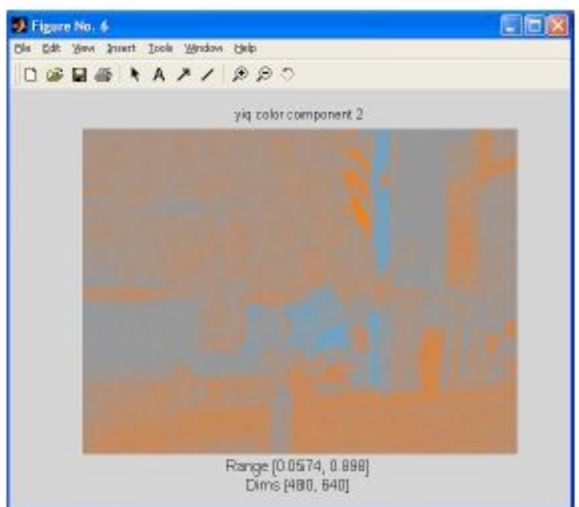


Figure No. 6
yiq color component 2
Range [0.0574, 0.898]
Dims [480, 640]

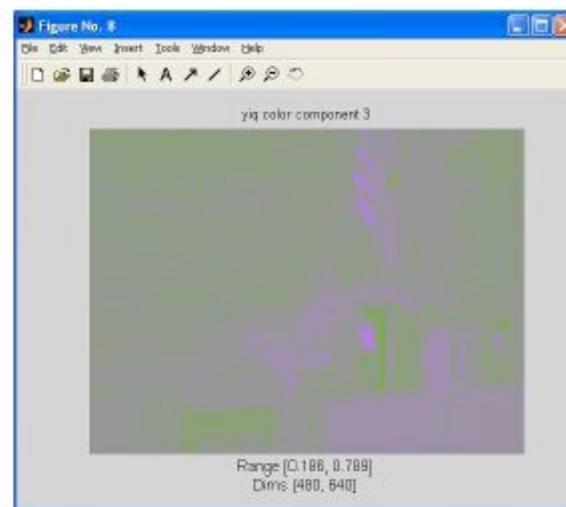


Figure No. 8
yiq color component 3
Range [0.186, 0.789]
Dims [480, 640]

Spatial resolution and color

original

R

G

B

Blurring the R component

original

processed

R

G

B

Blurring the G component

original

processed

R

G

B

Blurring the B component

original

processed

R

G

B

From W. E. Glenn, in Digital Images and Human Vision, MIT Press, edited by Watson, 1993

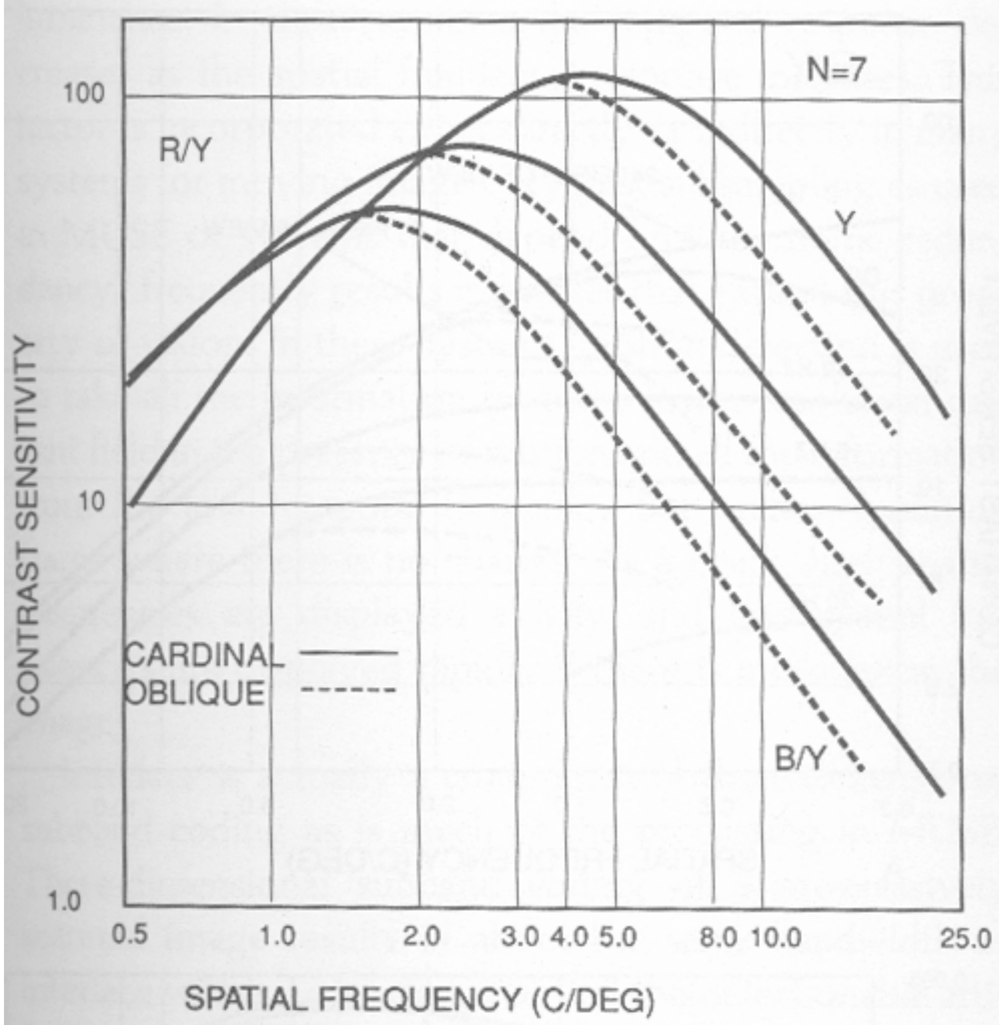


Figure 6.1
Contrast sensitivity threshold functions for static luminance gratings (Y) and isoluminance chromaticity gratings (R/Y,B/Y) averaged over seven observers.

Lab color components

L

a

b

A rotation of the color coordinates into directions that are more perceptually meaningful:
L: luminance,
a: red-green,
b: blue-yellow

Blurring the L Lab component

original

processed

L

a

b

Blurring the a Lab component

original

processed

L

a

b

Blurring the b Lab component

original

processed

L

a

b

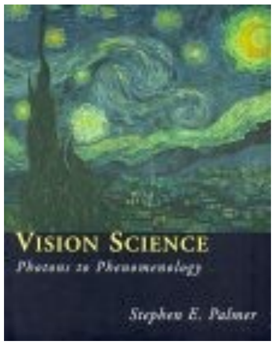
Lecture outline

- Color physics.
- Color perception
  - part 1: assume perceived color only depends on light spectrum.
  - part 2: the more general case.

Color constancy demo

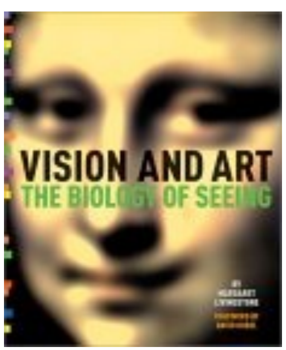
- We assumed that the spectrum impinging on your eye determines the object color. That’s often true, but not always.   Here’s a counter-example…

Selected Bibliography



Vision Science
by Stephen E. Palmer
MIT Press; ISBN: 0262161834
760 pages (May 7, 1999)

Billmeyer and Saltzman's Principles of Color Technology, 3rd Edition
by Roy S. Berns, Fred W. Billmeyer, Max Saltzman
Wiley-Interscience; ISBN: 047119459X
304 pages 3 edition (March 31, 2000)



Vision and Art : The Biology of Seeing
by Margaret Livingstone, David H. Hubel
Harry N Abrams; ISBN: 0810904063
208 pages (May 2002)

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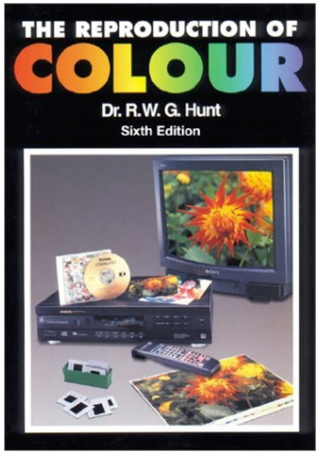
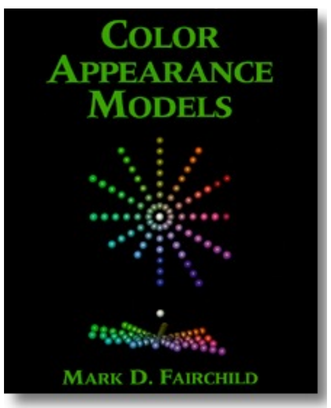


The Reproduction of Color
by R. W. G. Hunt
Fountain Press, 1995



Color Appearance Models
by Mark Fairchild
Addison Wesley, 1998

Other color references

- Reading:
  - Chapter 6, Forsyth & Ponce
  - Chapter 4 of Wandell, Foundations of Vision, Sinauer, 1995 has a good treatment of this.