Color

Computational Photography
MIT
Feb. 14, 2006
Bill Freeman and Fredo Durand

Why does a visual system need color?

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

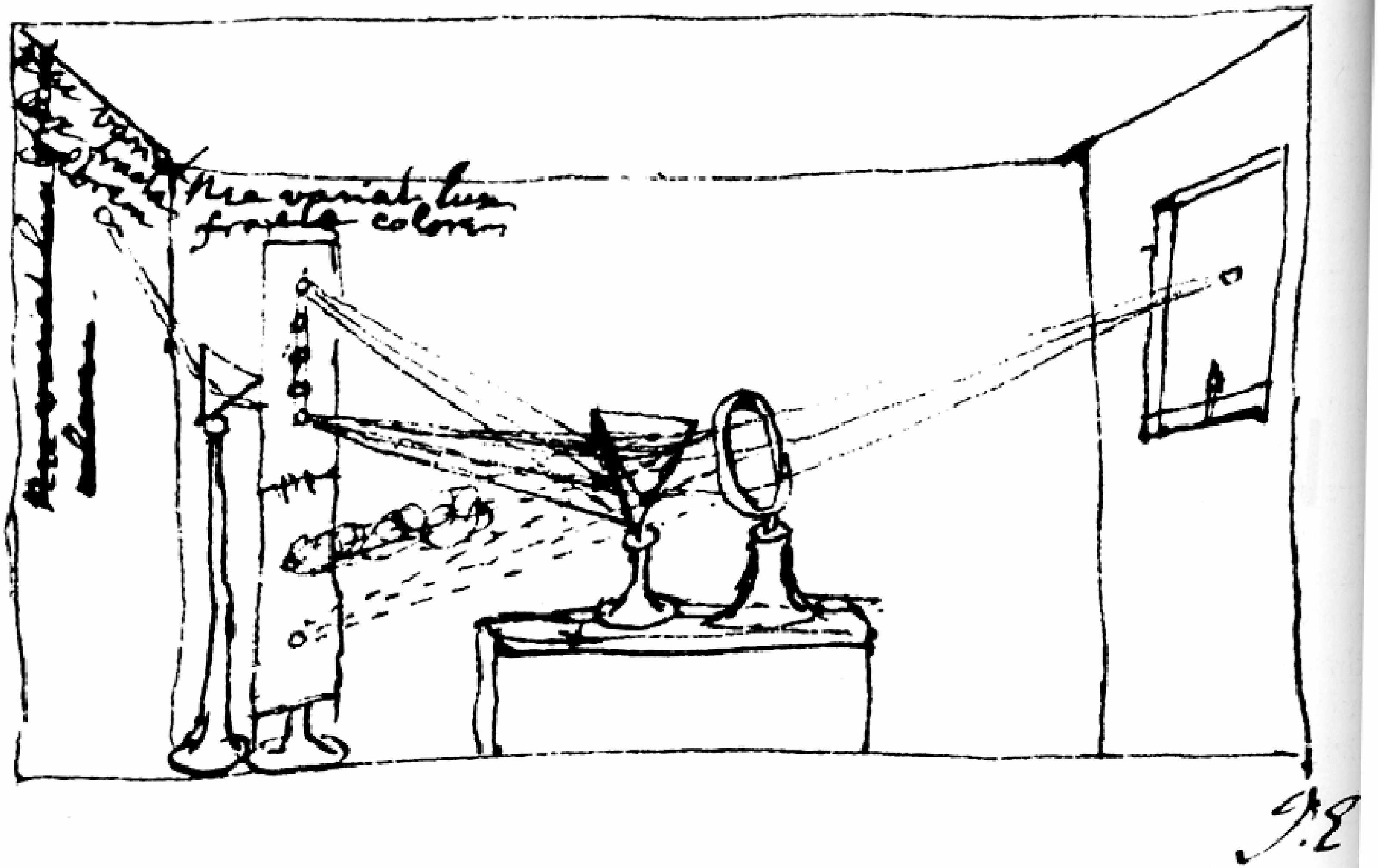
Why does a visual system need color? (an incomplete list…)

- 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.
- To compress images

Lecture outline

- Color physics.
- Color representation and matching.

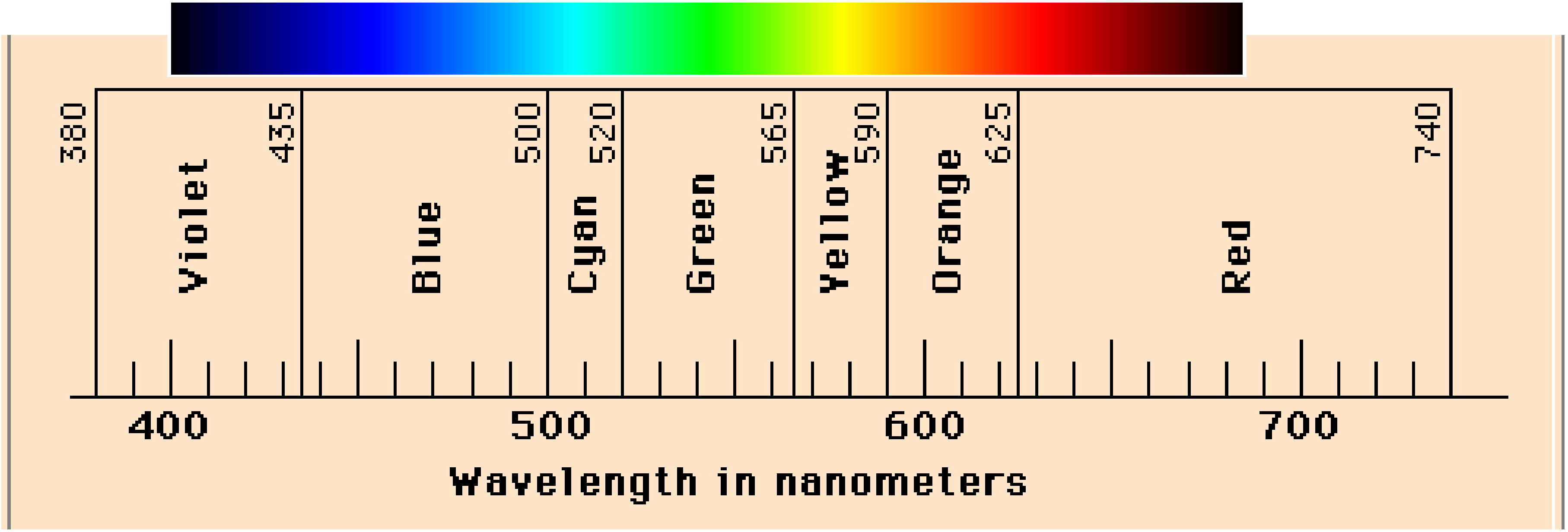
Color



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.

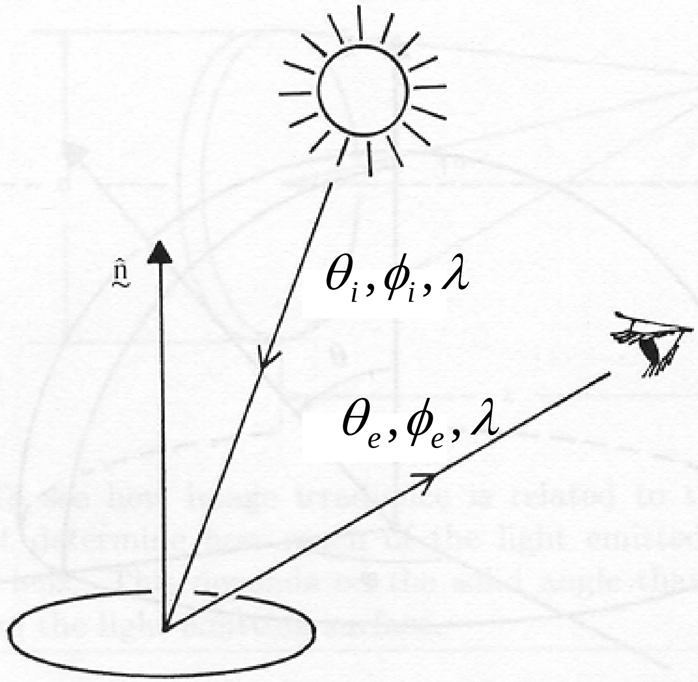
From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Spectral colors



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

Radiometry for color



Horn, 1986

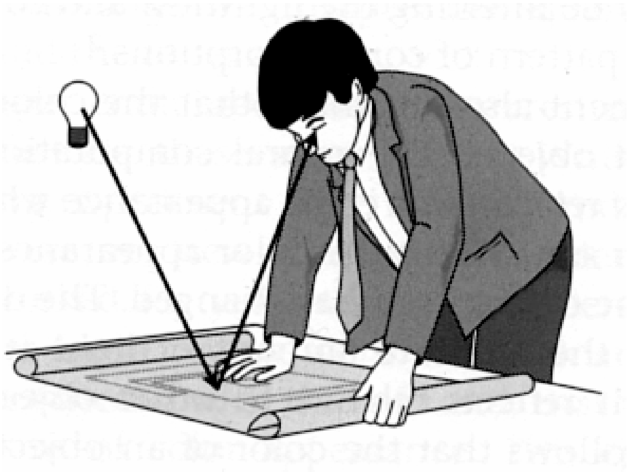
Figure 10-7. The bidirectional reflectance distribution function is the ratio of the radiance of the surface patch as viewed from the direction (θ_e, ϕ_e) to the irradiance resulting from illumination from the direction (θ_i, ϕ_i).

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

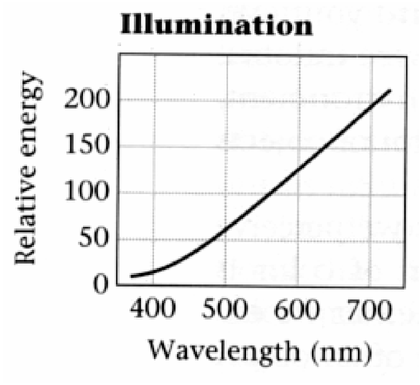
$$BRDF = f(\theta_i, \phi_i, \theta_e, \phi_e, \lambda) = \frac{L(\theta_e, \phi_e, \lambda)}{E(\theta_i, \phi_i, \lambda)}$$

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

Simplified rendering models: reflectance



Often are more interested in relative spectral composition than in overall intensity, so the spectral BRDF computation simplifies a wavelength-by-wavelength multiplication of relative energies.



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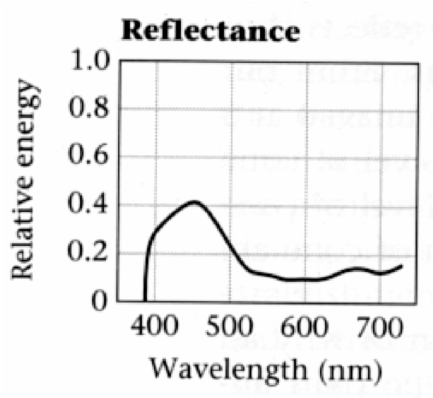

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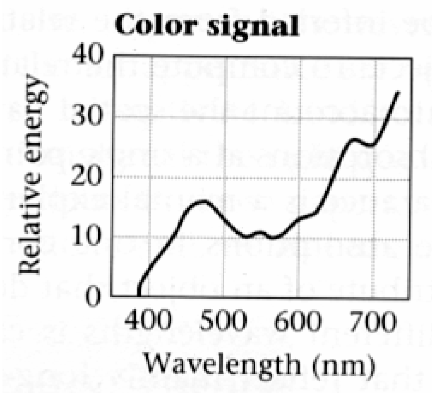
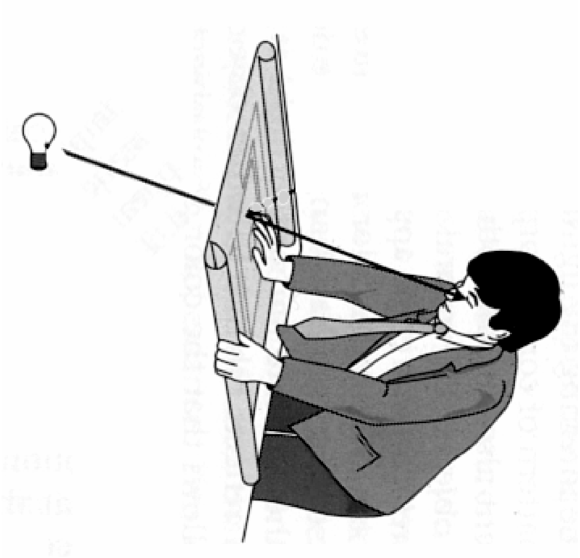
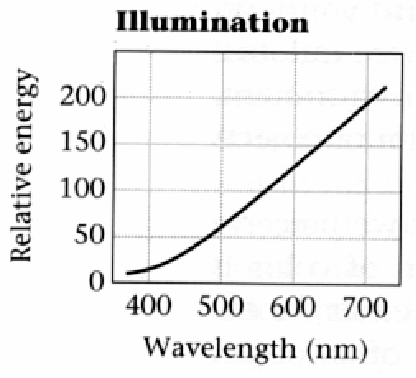


Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Simplified rendering models: transmittance





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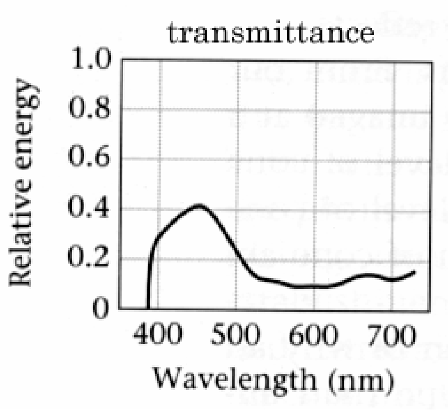

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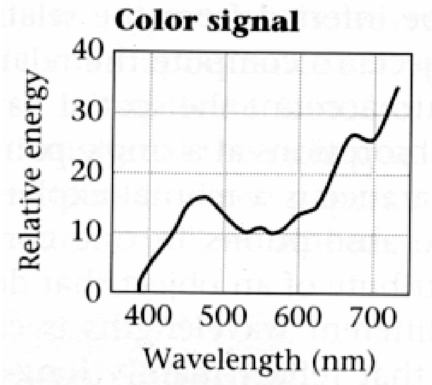
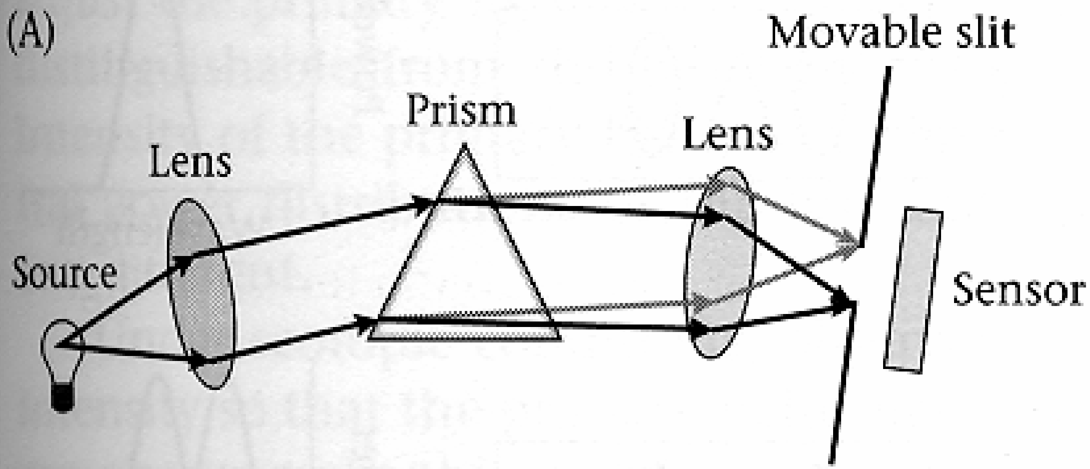


Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

How measure those spectra: Spectrophotometer

(just like Newton's diagram…)



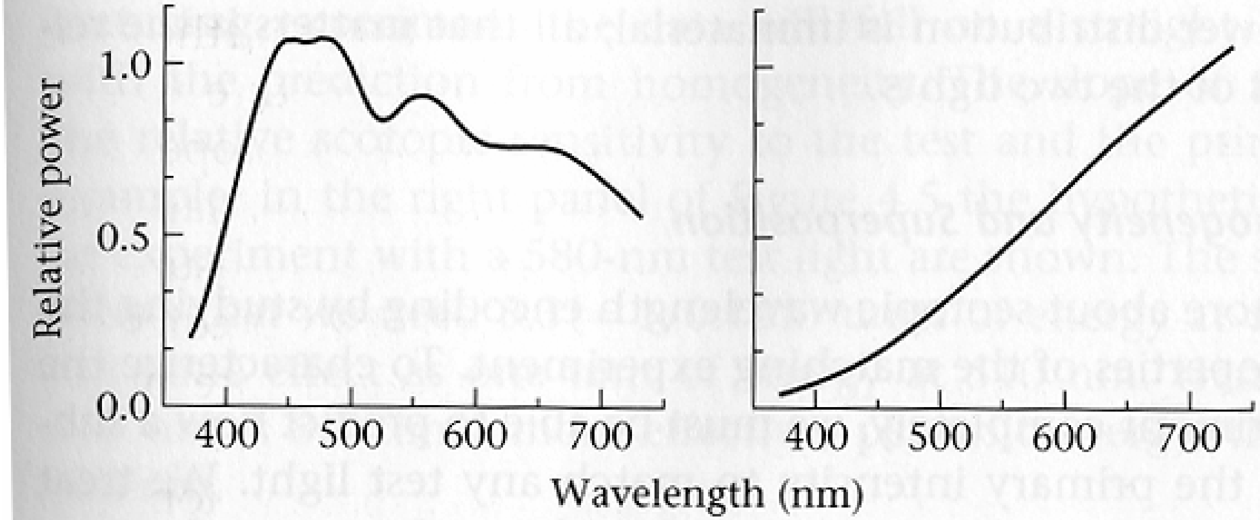
(B)

Wavelength (nm)	Color (viewed in isolation)
700	Red
610	Orange
580	Yellow
540	Green
480	Blue
400	Violet

4.2 A SPECTRORADIOMETER is used to measure the spectral power distribution of light. (A) A schematic design of a spectroradiometer includes a means for separating the input light into its different wavelengths and a detector for measuring the energy at each of the separate wavelengths. (B) The color names associated with the appearance of lights at a variety of wavelengths are shown. After Wyszecki and Stiles, 1982.

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

Two illumination spectra



4.4 THE SPECTRAL POWER DISTRIBUTION of two important light sources are shown: (left) blue skylight and (right) a tungsten bulb.

Blue sky

Tungsten light bulb

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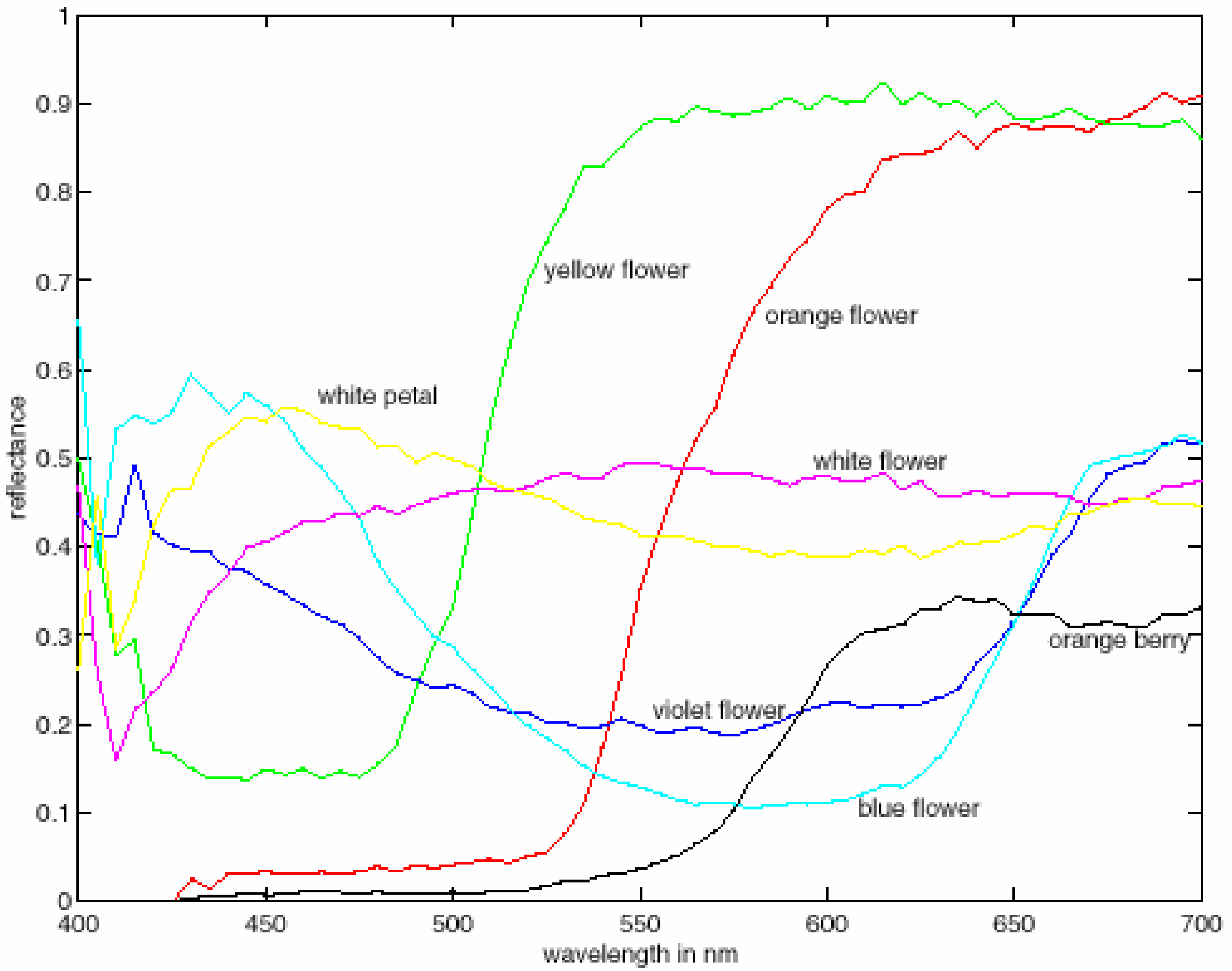
Some reflectance spectra

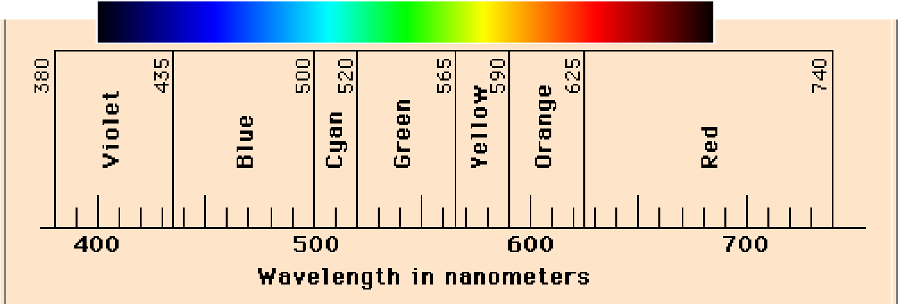


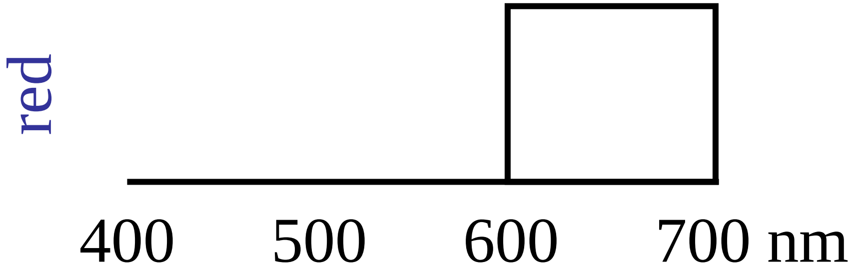
Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions.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

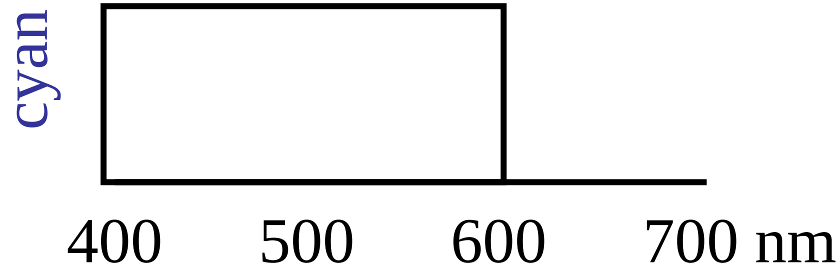
Forsyth, 2002

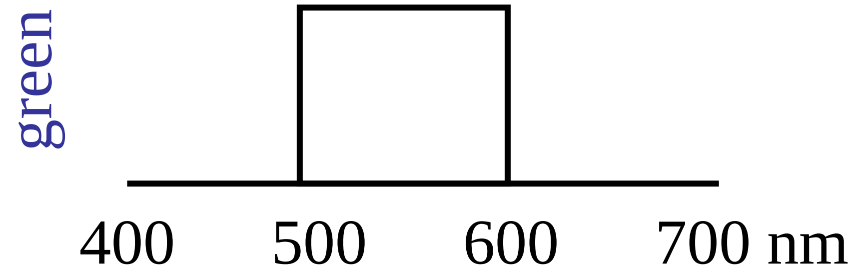
Questions?

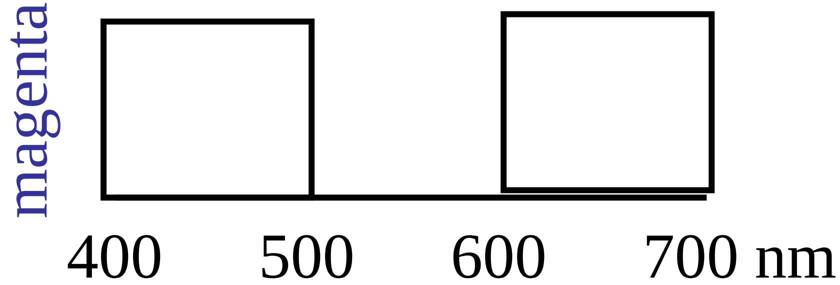
Color names for cartoon spectra

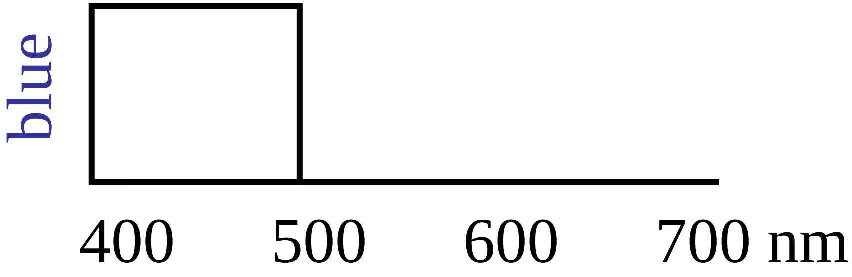


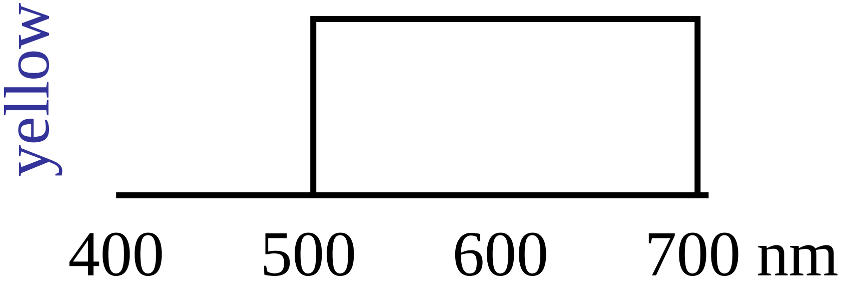




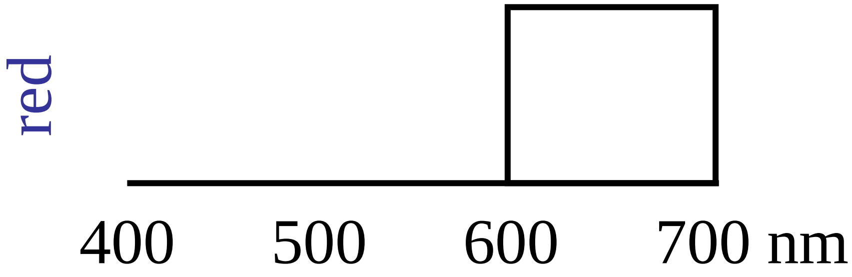


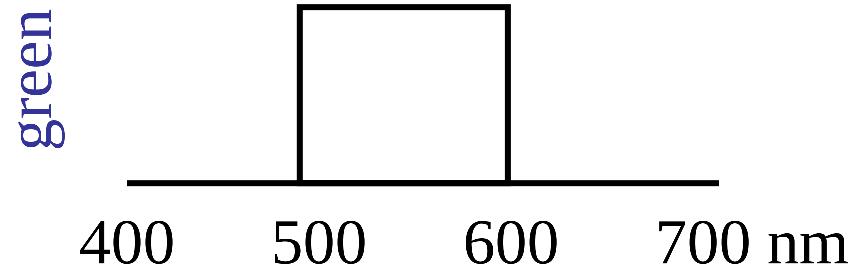


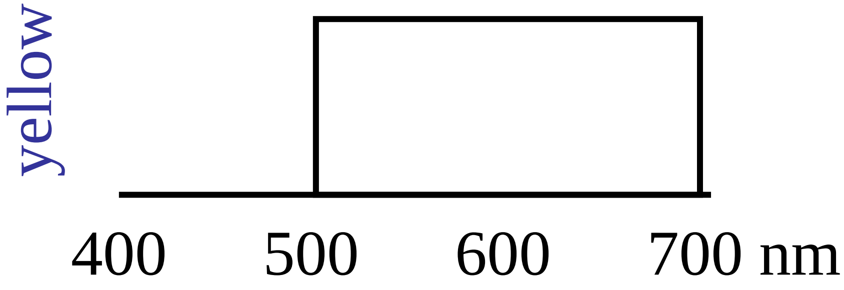




Additive color mixing





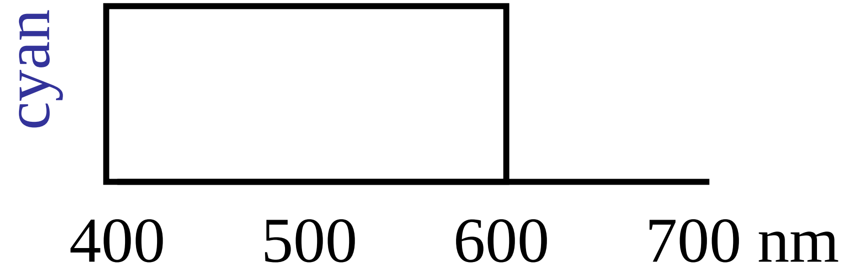


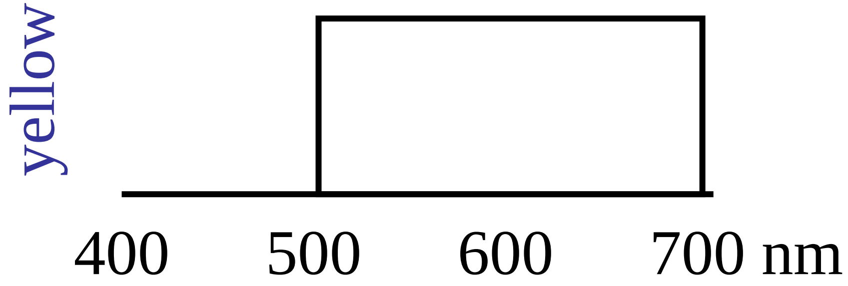
When colors combine by *adding* the color spectra. Example color displays that follow this mixing rule: CRT phosphors, multiple projectors aimed at a screen, Polachrome slide film.

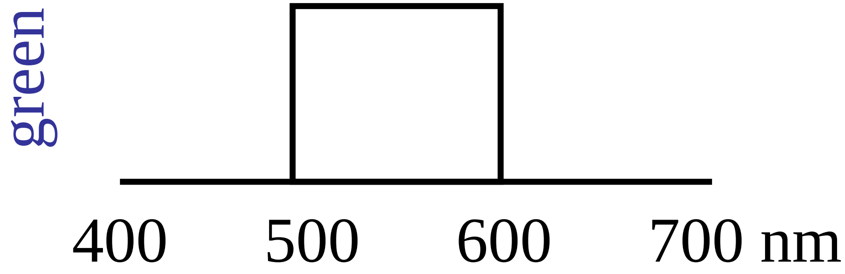
Red and green make…

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!

Overhead projector demo

- Subtractive color mixing

Crayons

Questions?

Low-dimensional models for color spectra

$$\begin{pmatrix} \vdots \\ e(\lambda) \\ \vdots \end{pmatrix} = \begin{pmatrix} \vdots & \vdots & \vdots \\ E_1(\lambda) & E_2(\lambda) & E_3(\lambda) \\ \vdots & \vdots & \vdots \end{pmatrix} \begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix}$$

How to find a linear model for color spectra:

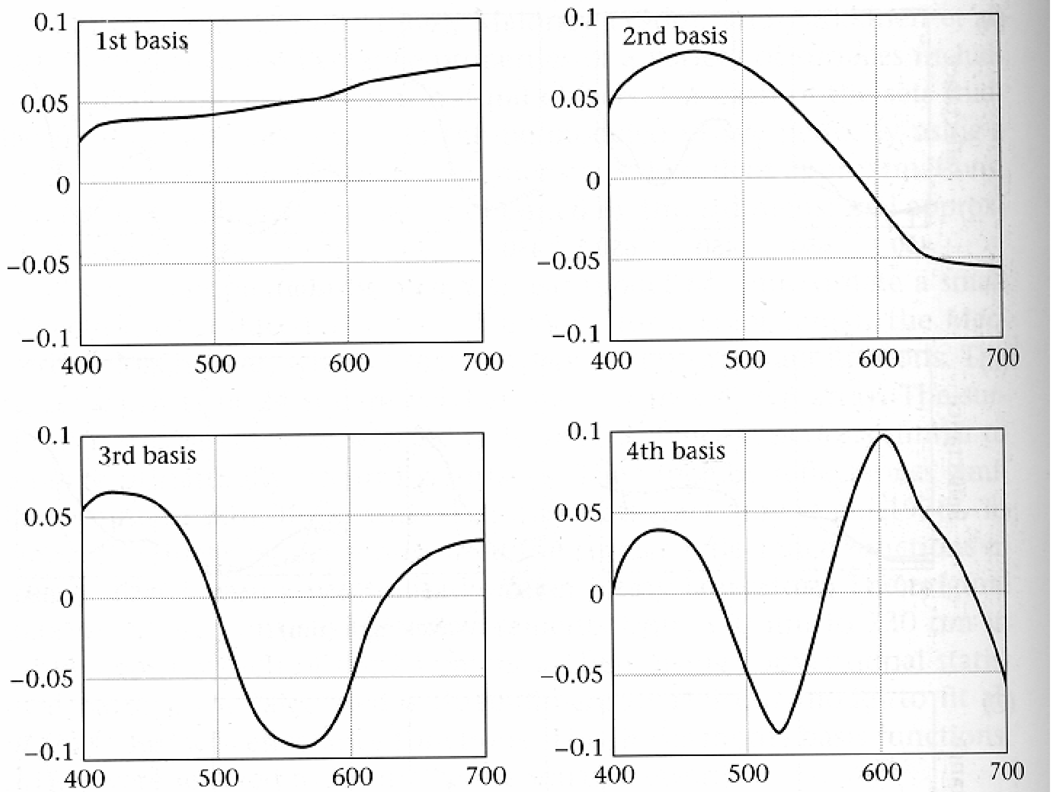
--form a matrix, D, of measured spectra, 1 spectrum per column.

--[u, s, v] = svd(D) satisfies D = u*s*v‘

--the first n columns of u give the best (least-squares optimal) n-dimensional linear bases for the data, D:

$$D \approx u(:,1:n) * s(1:n,1:n) * v(1:n,:)'$$

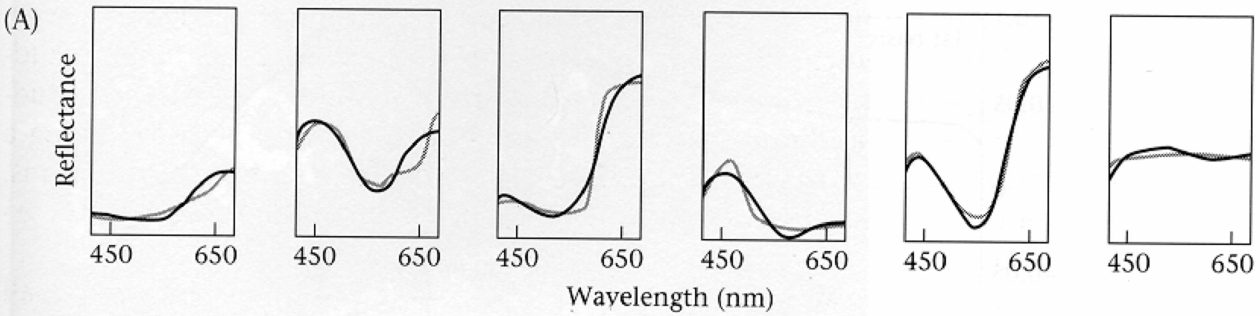
Basis functions for Macbeth color checker



9.9 BASIS FUNCTIONS OF THE LINEAR MODEL FOR THE MACBETH COLORCHECKER. The surface-reflectance functions in the collection vary smoothly with wavelength, as do the basis functions. The first basis function is all positive and explains the most variance in the surface-reflectance functions. The basis functions are ordered in terms of their relative significance for reducing the error in the linear-model approximation to the surfaces.

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

n-dimensional linear models for color spectra

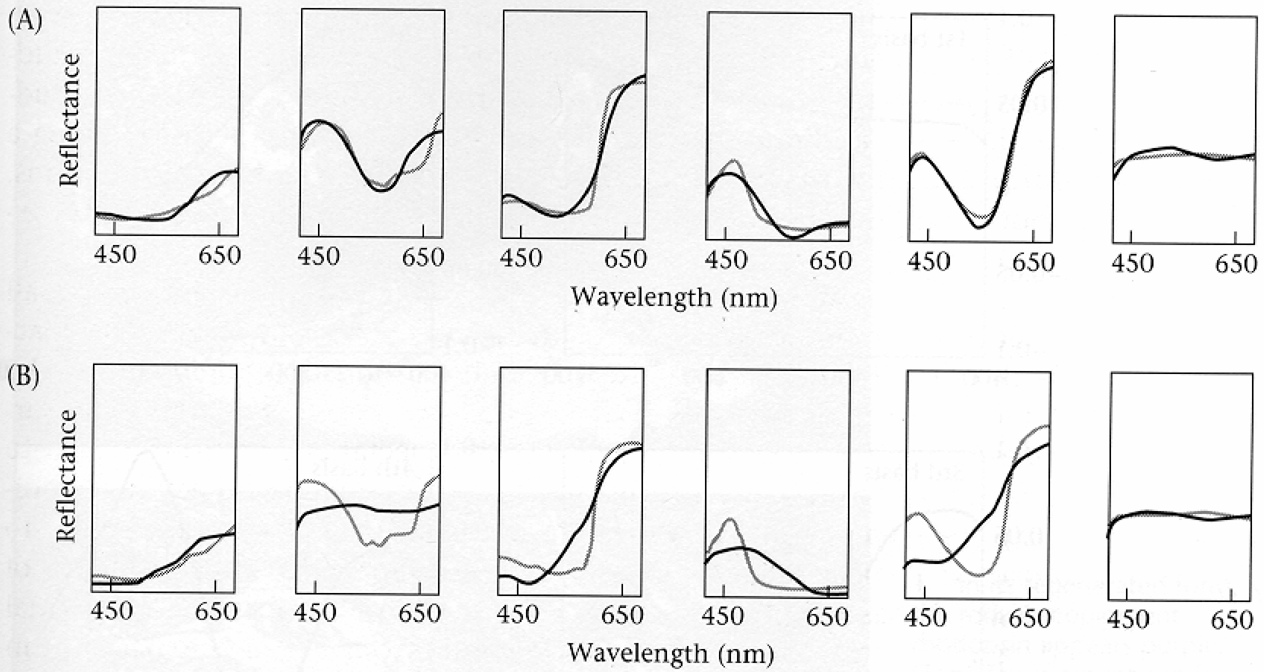


n = 3

9.8 A LINEAR MODEL TO APPROXIMATE THE SURFACE REFLECTANCES IN THE MACBETH COLORCHECKER. The panels in each row of this figure show the surface-reflectance functions of six colored surfaces (shaded lines) and the approximation to these functions using a linear model (solid lines). The approximations using linear models with (A) three, (B) two, and (C) one dimension are shown.

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

n-dimensional linear models for color spectra



n = 3

n = 2

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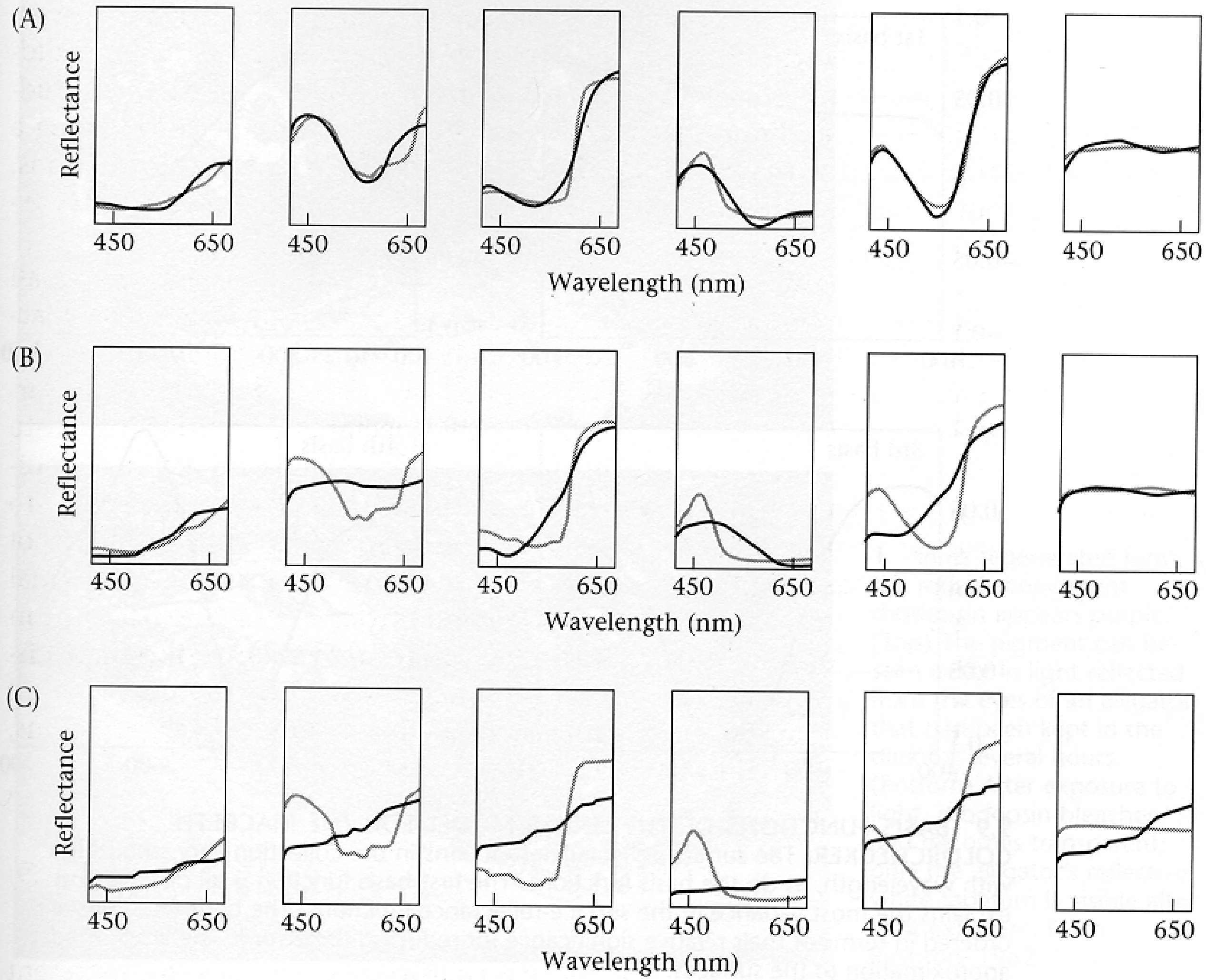
n-dimensional linear models for color spectra



n = 3

n = 2

n = 1

9.8 A LINEAR MODEL TO APPROXIMATE THE SURFACE REFLECTANCES IN THE MACBETH COLORCHECKER. The panels in each row of this figure show the surface-reflectance functions of six colored surfaces (shaded lines) and the approximation to these functions using a linear model (solid lines). The approximations using linear models with (A) three, (B) two, and (C) one dimension are shown.

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

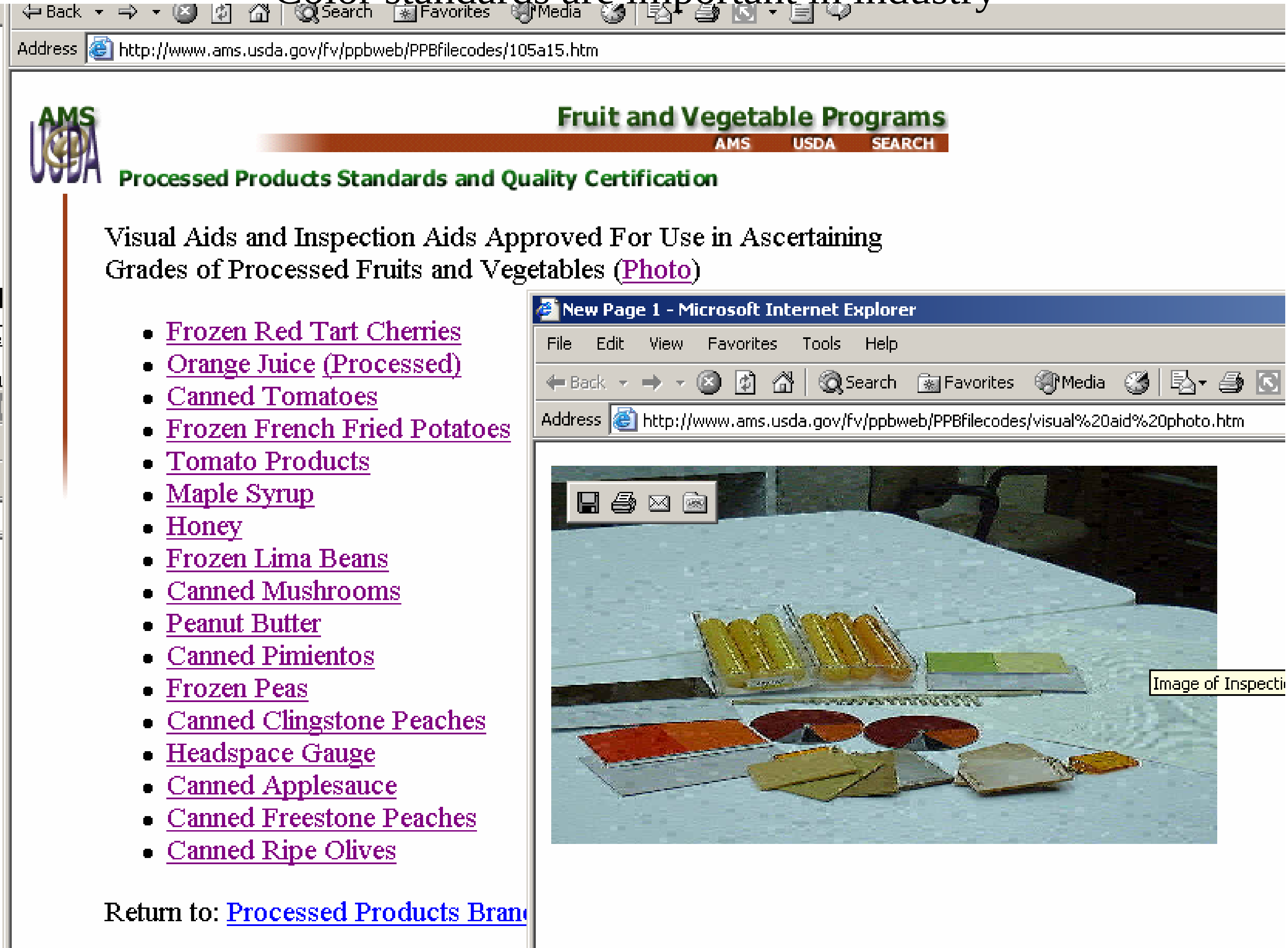
Outline

- Color physics.
- Color representation and matching.

Why specify color numerically?

- Accurate color reproduction is commercially valuable
  - Many products are identified by color (“golden” arches);
- Few color names are widely recognized by English speakers -
  - About 10; other languages have fewer/more, but not many more.
  - It’s common to disagree on appropriate color names.
- Color reproduction problems increased by prevalence of digital imaging - eg. digital libraries of art.
  - How do we ensure that everyone sees the same color?

Color standards are important in industry



Address http://www.ams.usda.gov/fv/ppbweb/PPBfilecodes/105a15.htm

Fruit and Vegetable Programs

Processed Products Standards and Quality Certification

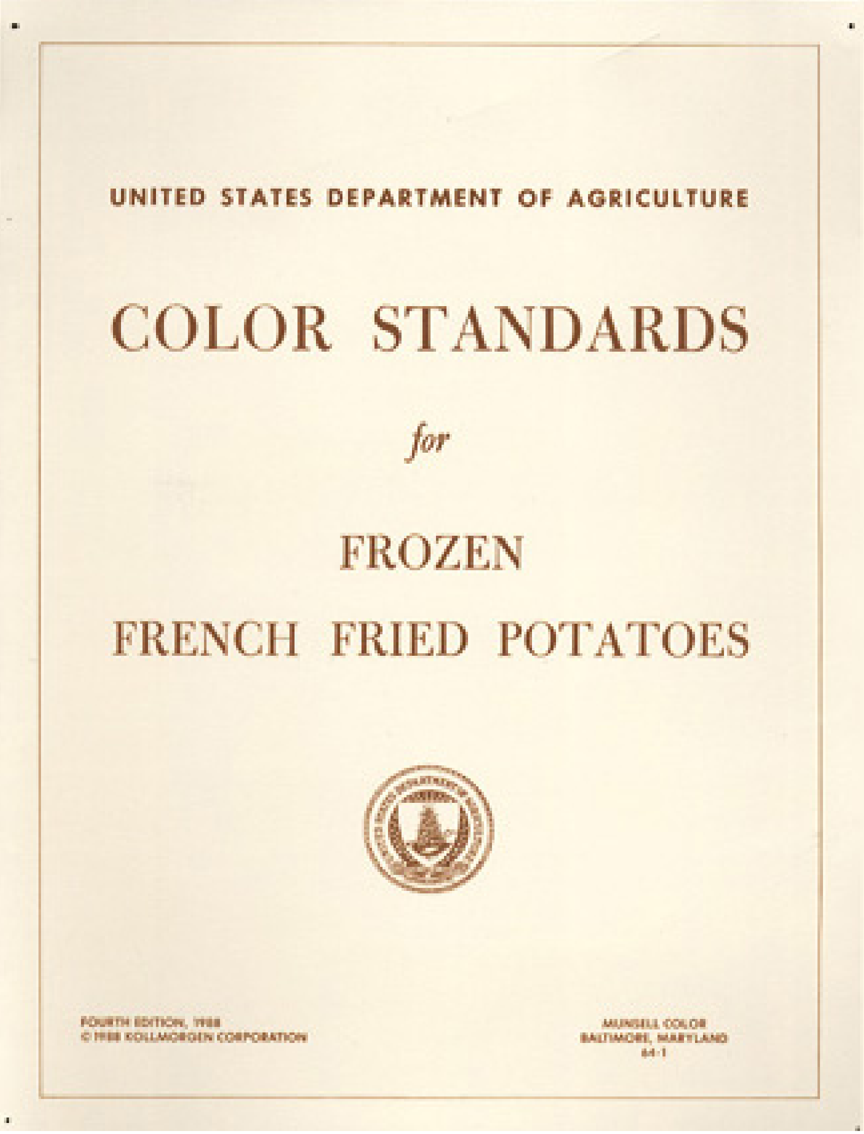
Visual Aids and Inspection Aids Approved For Use in Ascertaining Grades of Processed Fruits and Vegetables (Photo)

- Frozen Red Tart Cherries
- Orange Juice (Processed)
- Canned Tomatoes
- Frozen French Fried Potatoes
- Tomato Products
- Maple Syrup
- Honey
- Frozen Lima Beans
- Canned Mushrooms
- Peanut Butter
- Canned Pimientos
- Frozen Peas
- Canned Clingstone Peaches
- Headspace Gauge
- Canned Applesauce
- Canned Freestone Peaches
- Canned Ripe Olives

Return to: Processed Products Bran

New Page 1 - Microsoft Internet Explorer

Address http://www.ams.usda.gov/fv/ppbweb/PPBfilecodes/visual%20aid%20photo.htm



UNITED STATES DEPARTMENT OF AGRICULTURE

COLOR STANDARDS

for

FROZEN
FRENCH FRIED POTATOES

FOURTH EDITION, 1988
© 1988 KOLLMORGEN CORPORATION

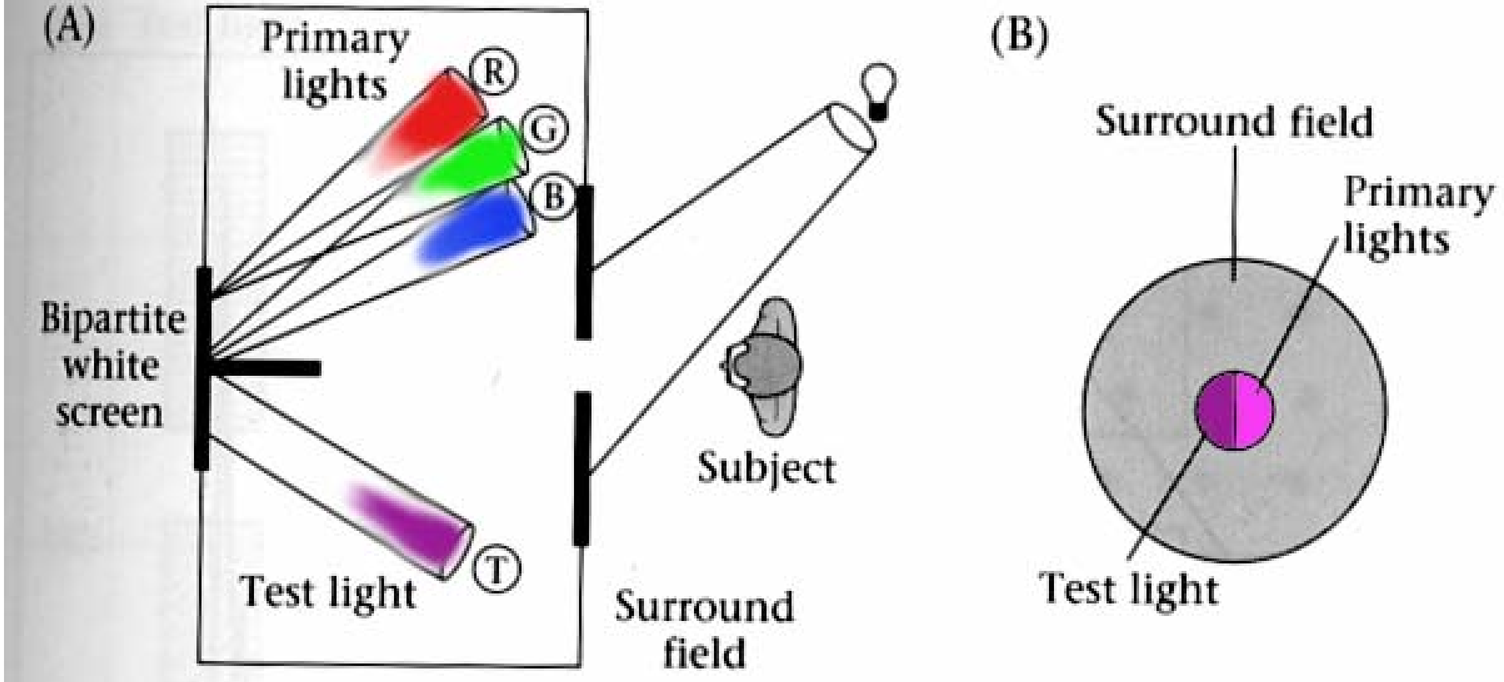
MUNSELL COLOR
BALTIMORE, MARYLAND
64-1

An assumption that sneaks in here

- For now we will assume that the spectrum of the light arriving at your eye completely determines the perceived color.

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

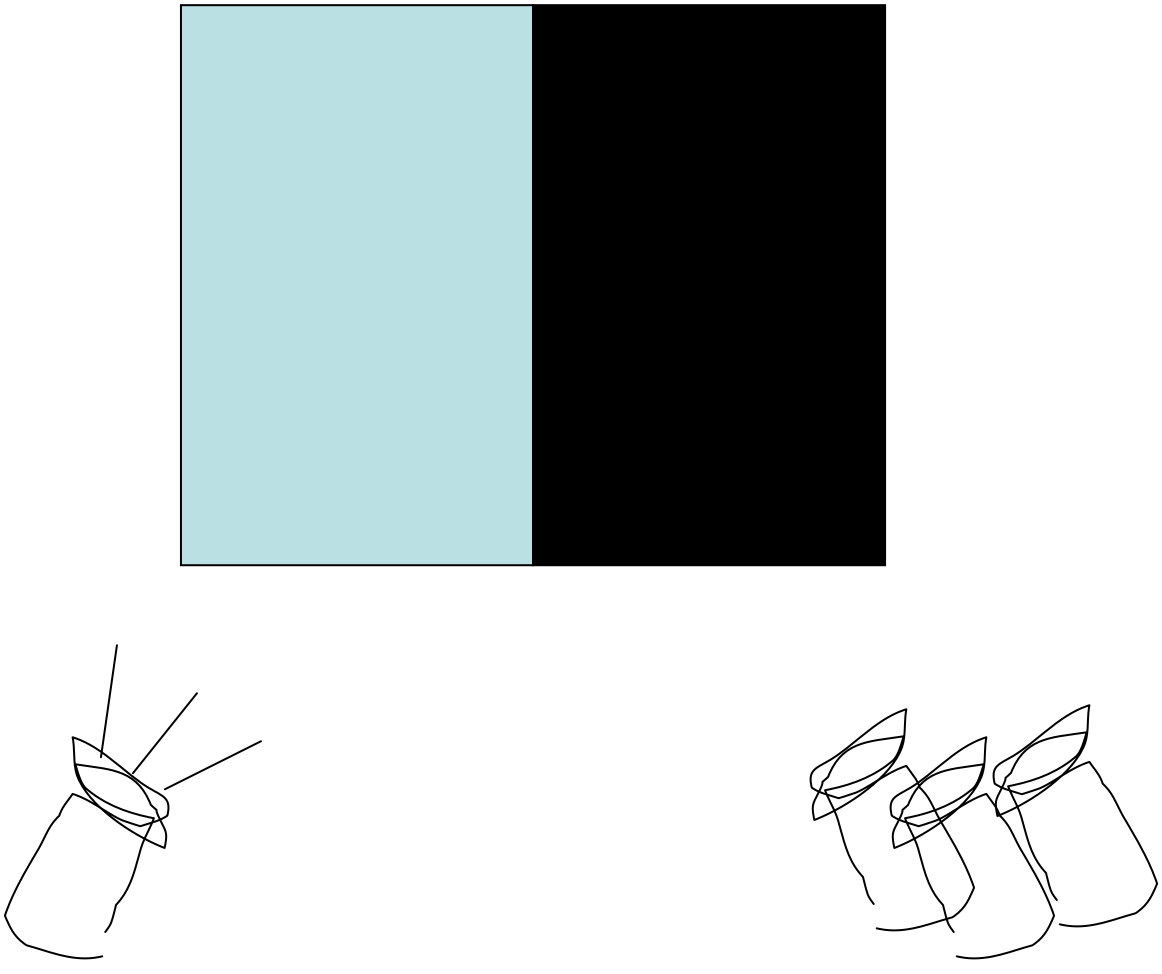
Color matching experiment



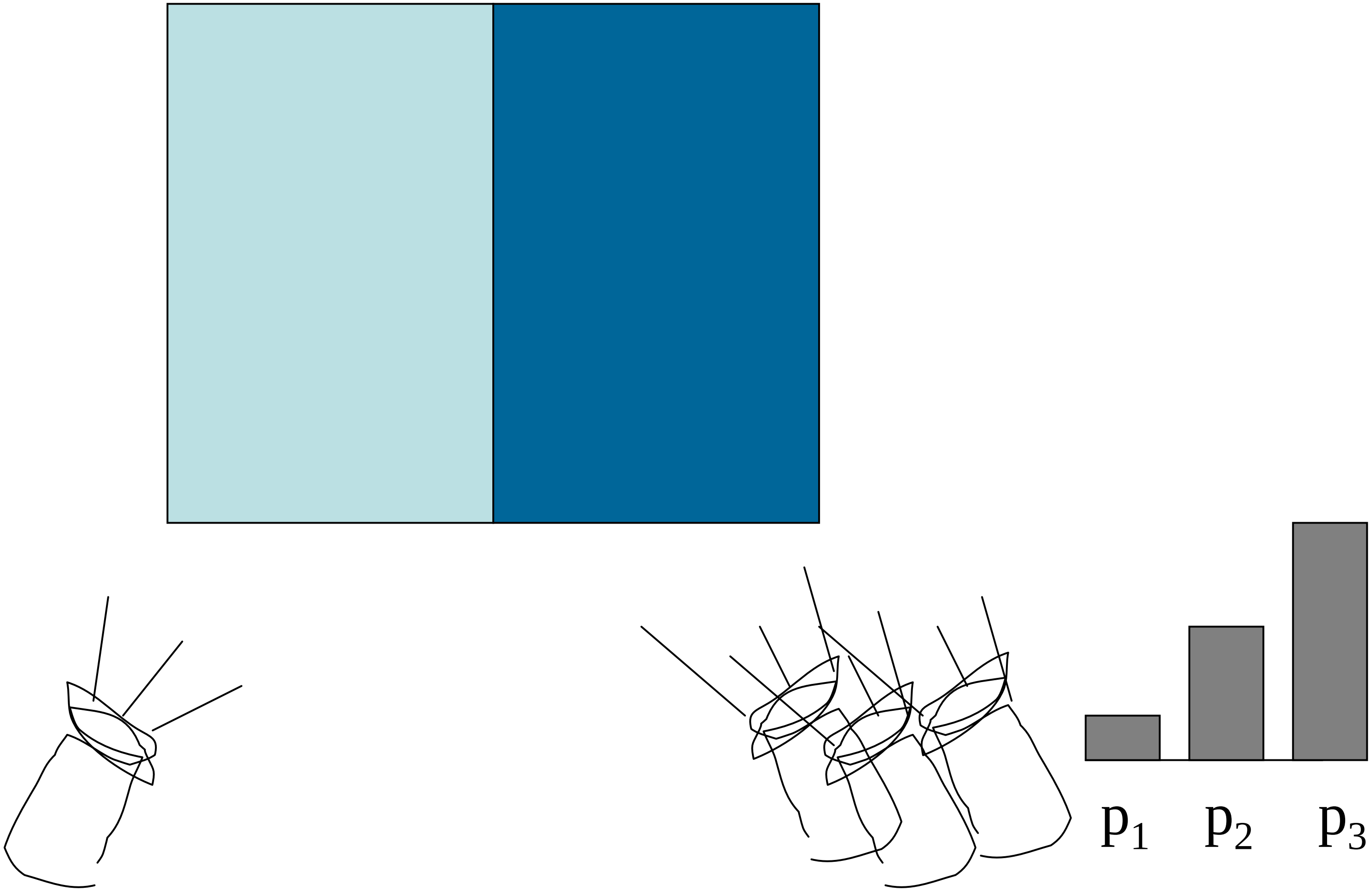
4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

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

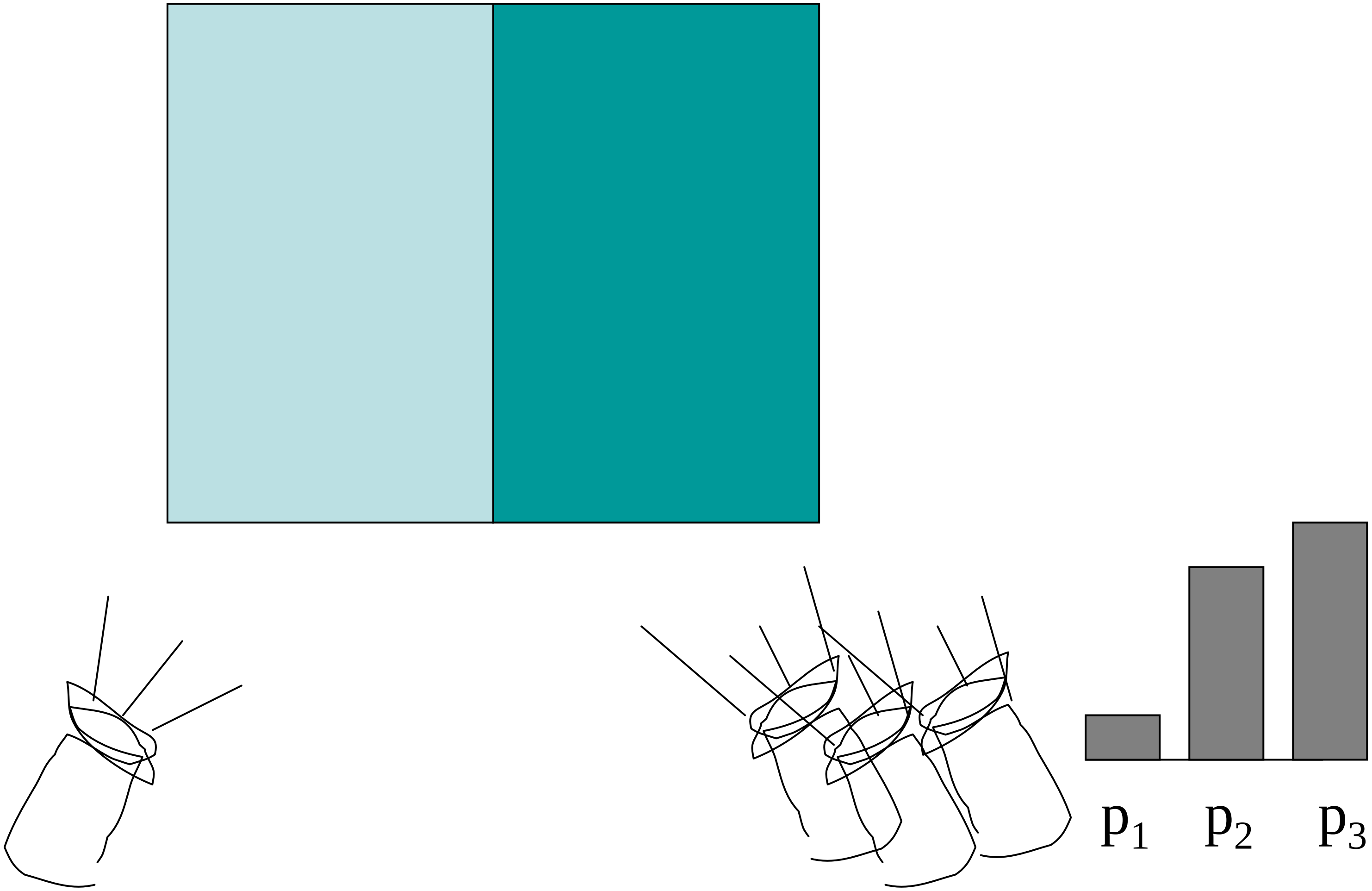
Color matching experiment 1



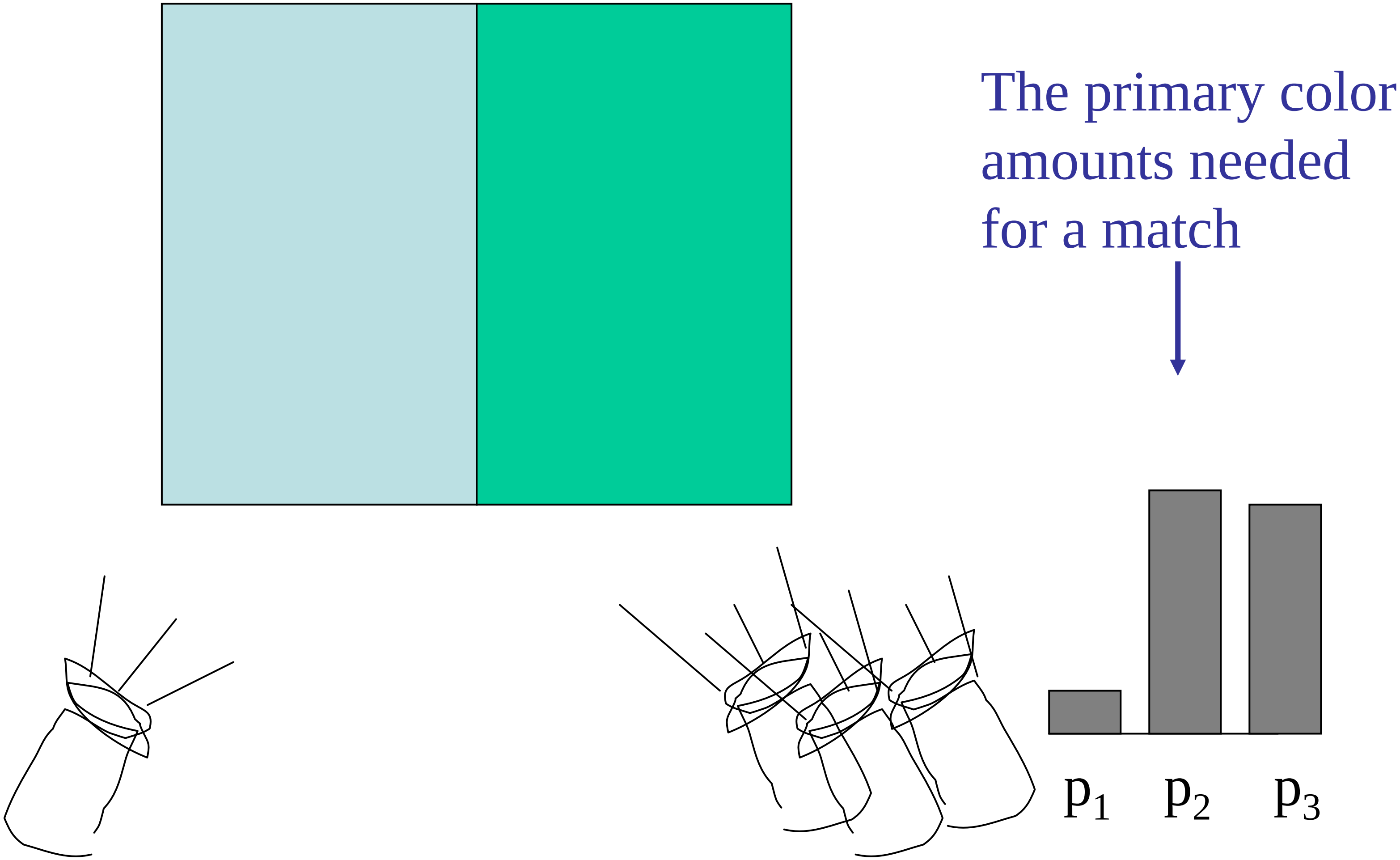
Color matching experiment 1



Color matching experiment 1

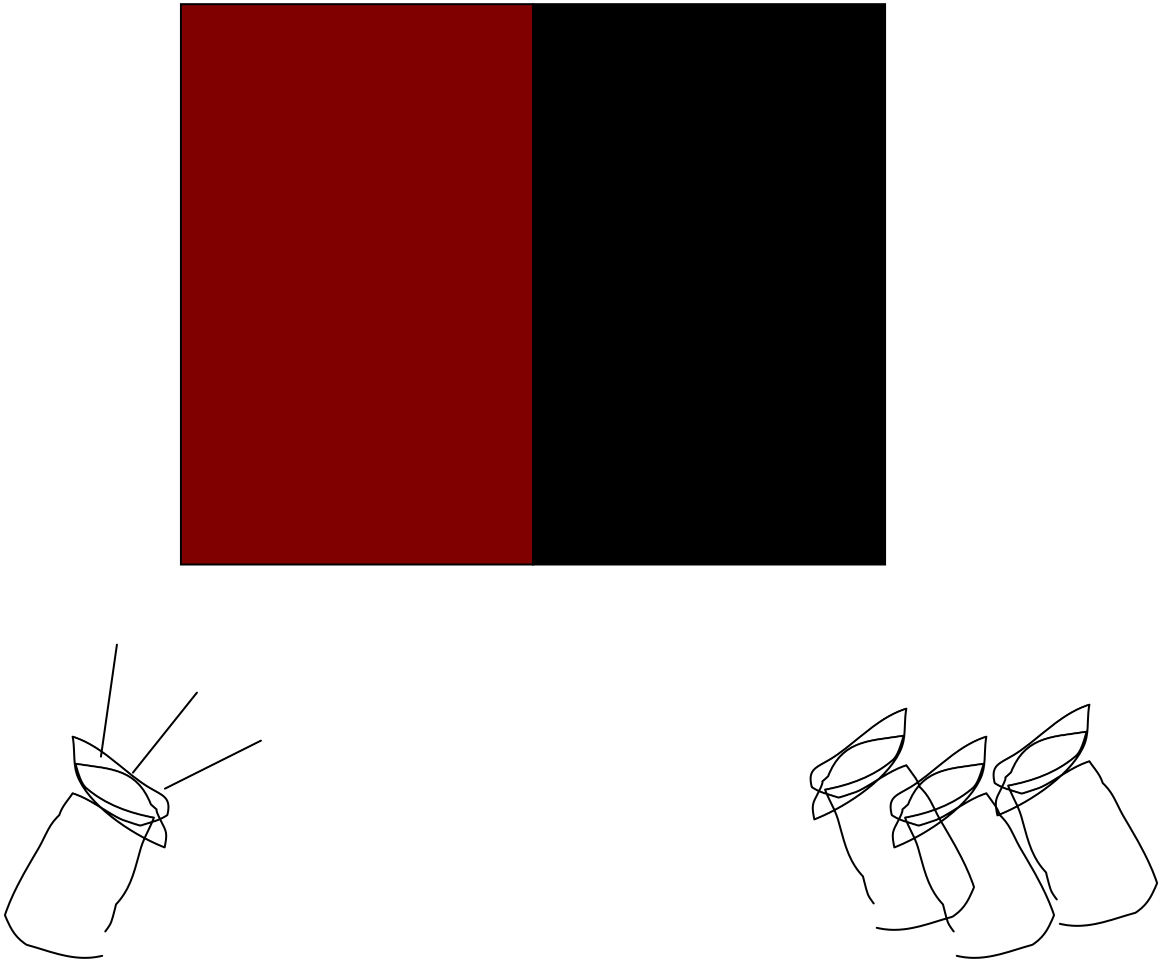


Color matching experiment 1

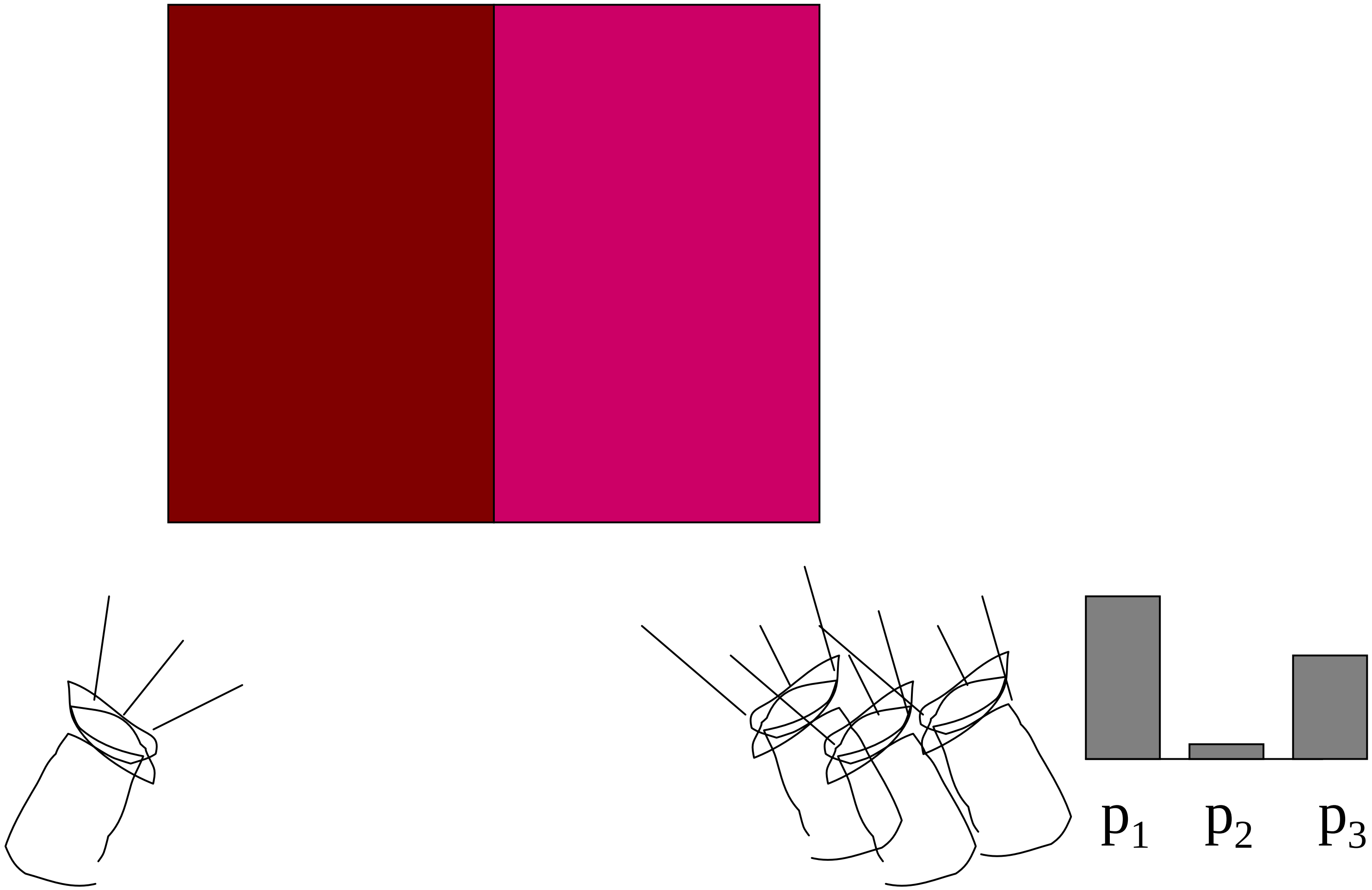


The primary color amounts needed for a match

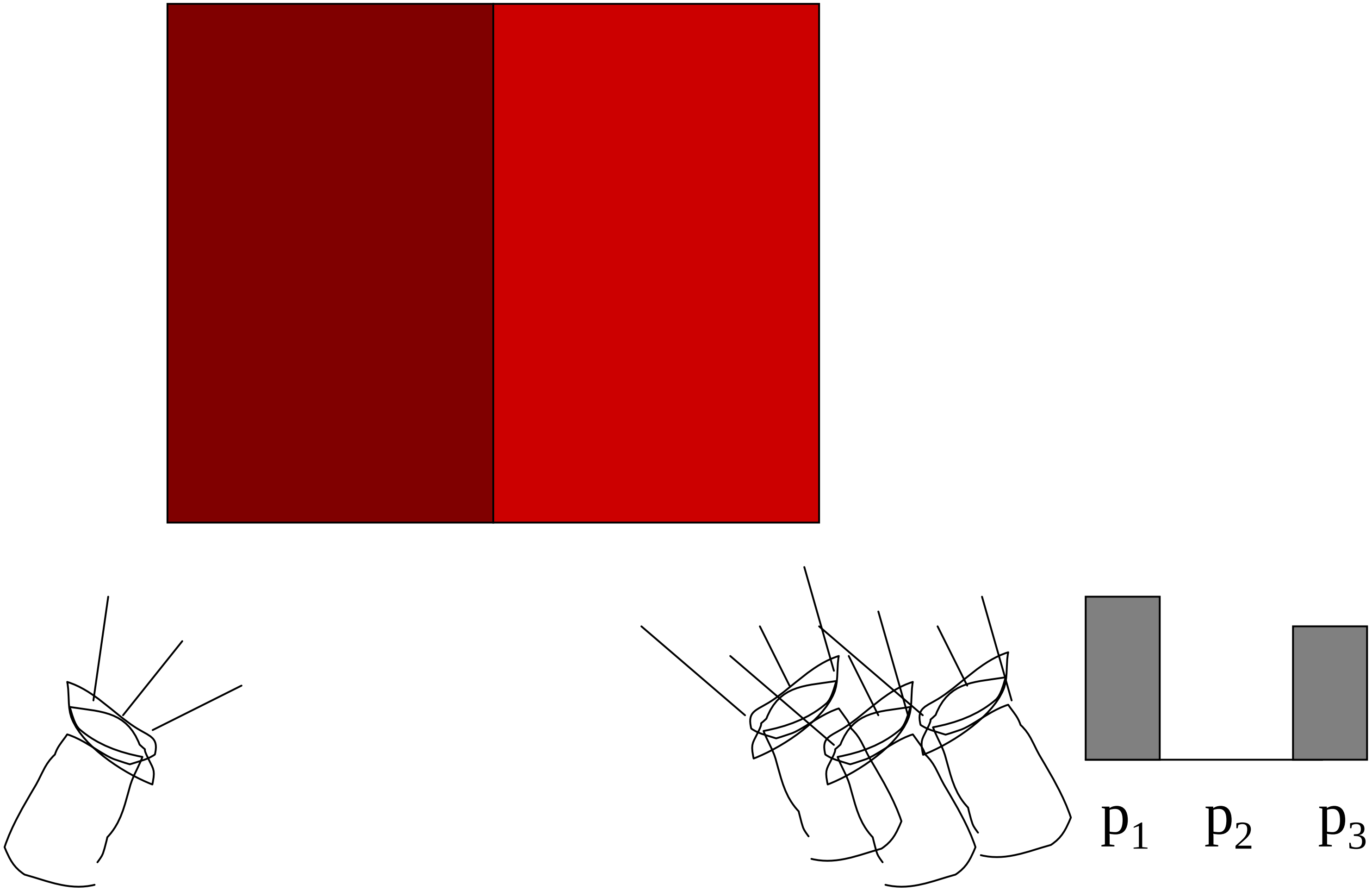
Color matching experiment 2



Color matching experiment 2

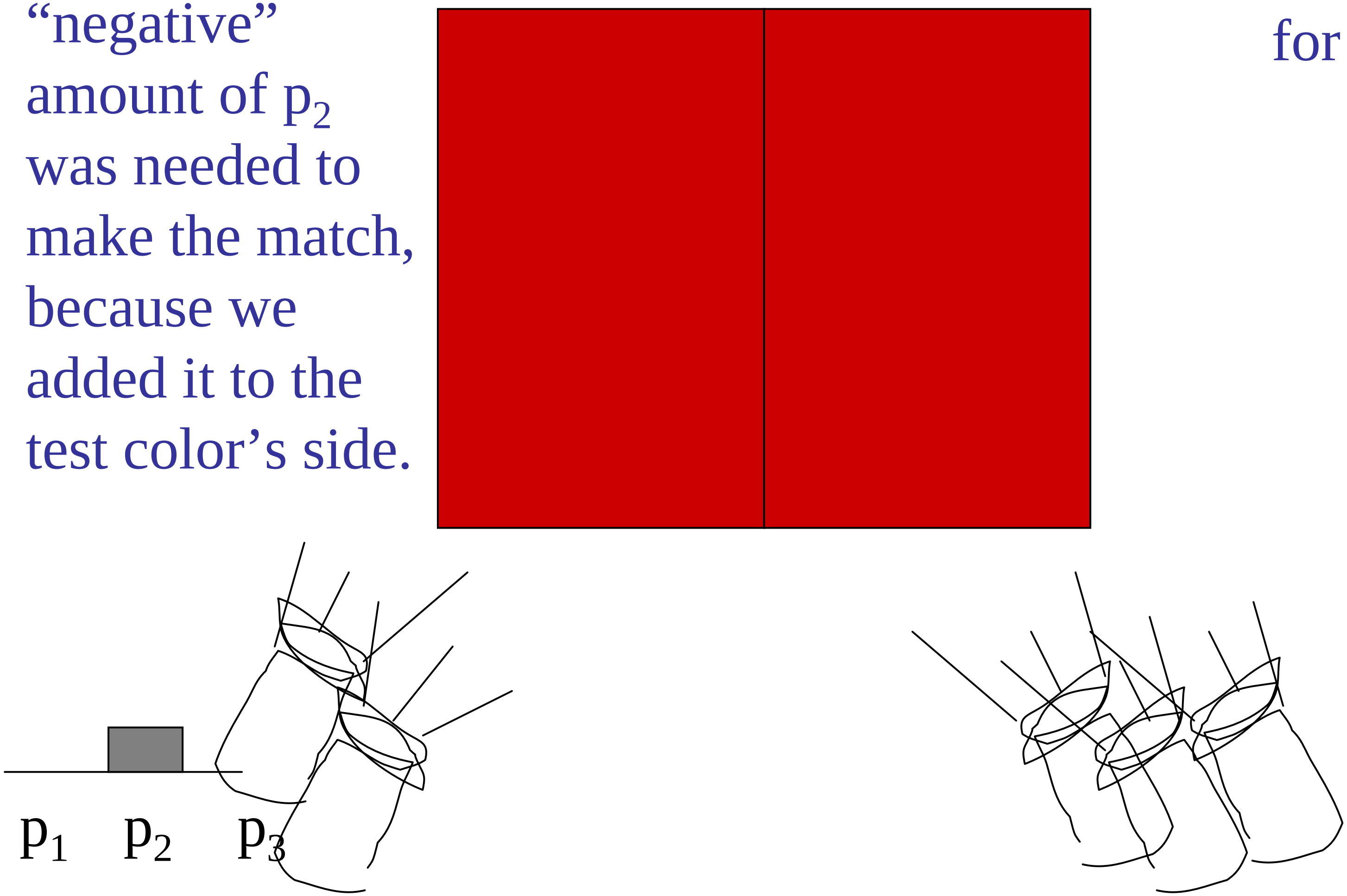


Color matching experiment 2

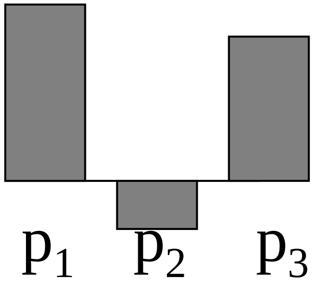


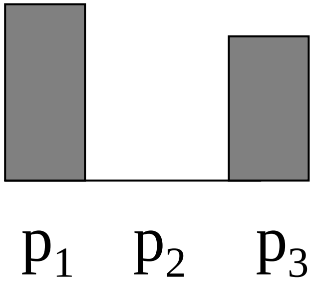
Color matching experiment 2

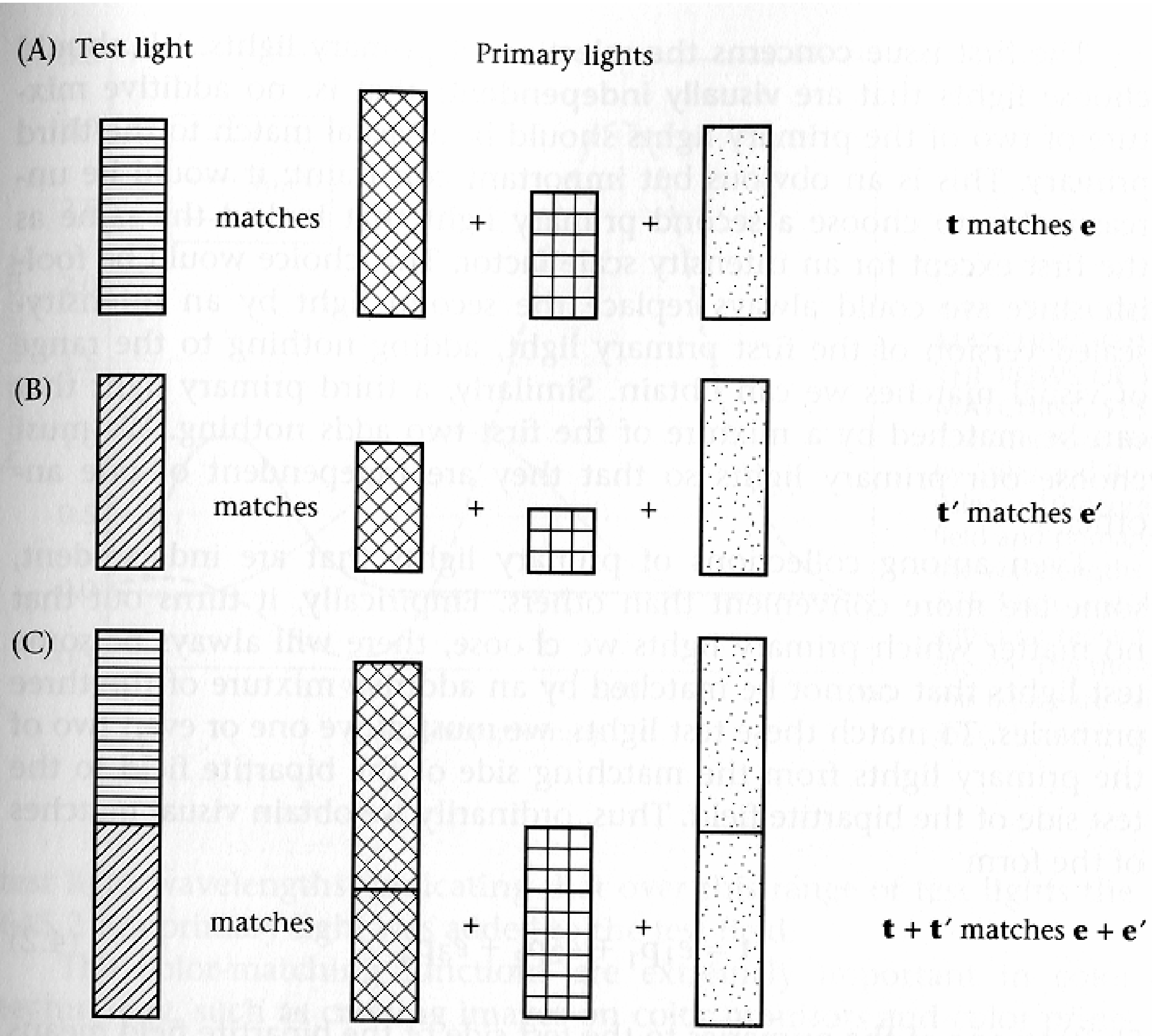
We say a “negative” amount of p_2 was needed to make the match, because we added it to the test color’s side.



The primary color amounts needed for a match:







4.12 THE COLOR-MATCHING EXPERIMENT SATISFIES THE PRINCIPLE OF SUPERPOSITION. In parts (A) and (B), test lights are matched by a mixture of three primary lights. In part (C) the sum of the test lights is matched by the additive mixture of the primaries, demonstrating superposition.

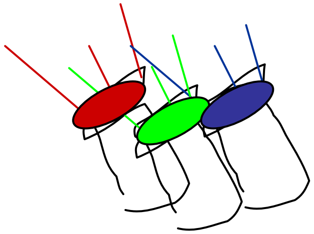
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Grassman's Laws

- For color matches:
  - symmetry: U=V <=>V=U
  - transitivity: U=V and V=W => U=W
  - proportionality: U=V <=> tU=tV
  - additivity: if any two (or more) of the statements

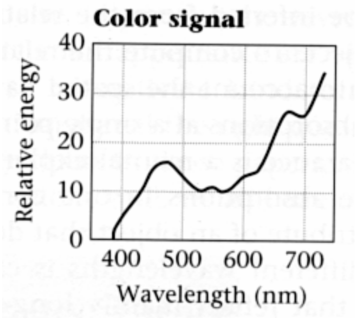
    U=V,
    W=X,
    (U+W)=(V+X) are true, then so is the third
- These statements are as true as any biological law. They mean that additive color matching is linear.

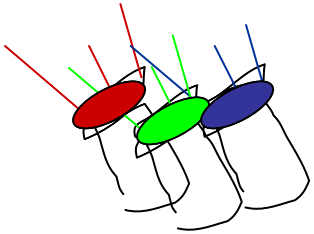
Measure color by color-matching paradigm



- Pick a set of 3 primary color lights.
- Find the amounts of each primary, e_1, e_2, e_3, needed to match some spectral signal, t.
- Those amounts, e_1, e_2, e_3, describe the color of t. If you have some other spectral signal, s, and s matches t perceptually, then e_1, e_2, e_3 will also match s, by Grassman’s laws.
- Why this is useful—it lets us:
  - Predict the color of a new spectral signal
  - Translate to representations using other primary lights.

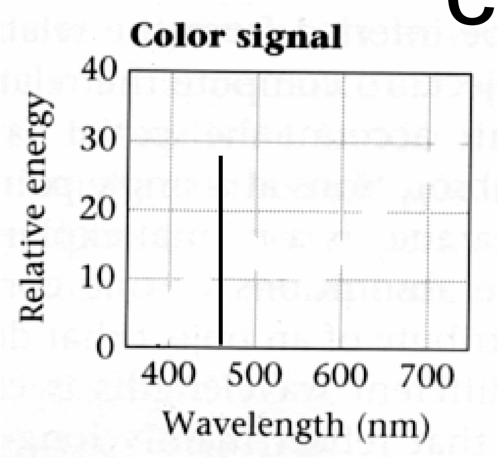
Goal: compute the color match for any color signal for any set of primary colors

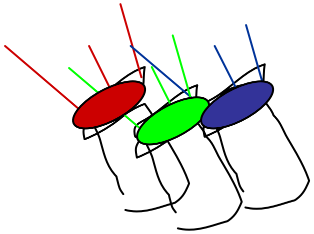




- Examples of why you'd want to do that:
  - Want to paint a carton of Kodak film with the Kodak yellow color.
  - Want to match skin color of a person in a photograph printed on an ink jet printer to their true skin color.
  - Want the colors in the world, on a monitor, and in a print format to all look the same.

How to compute the color match for any color signal for any set of primary colors





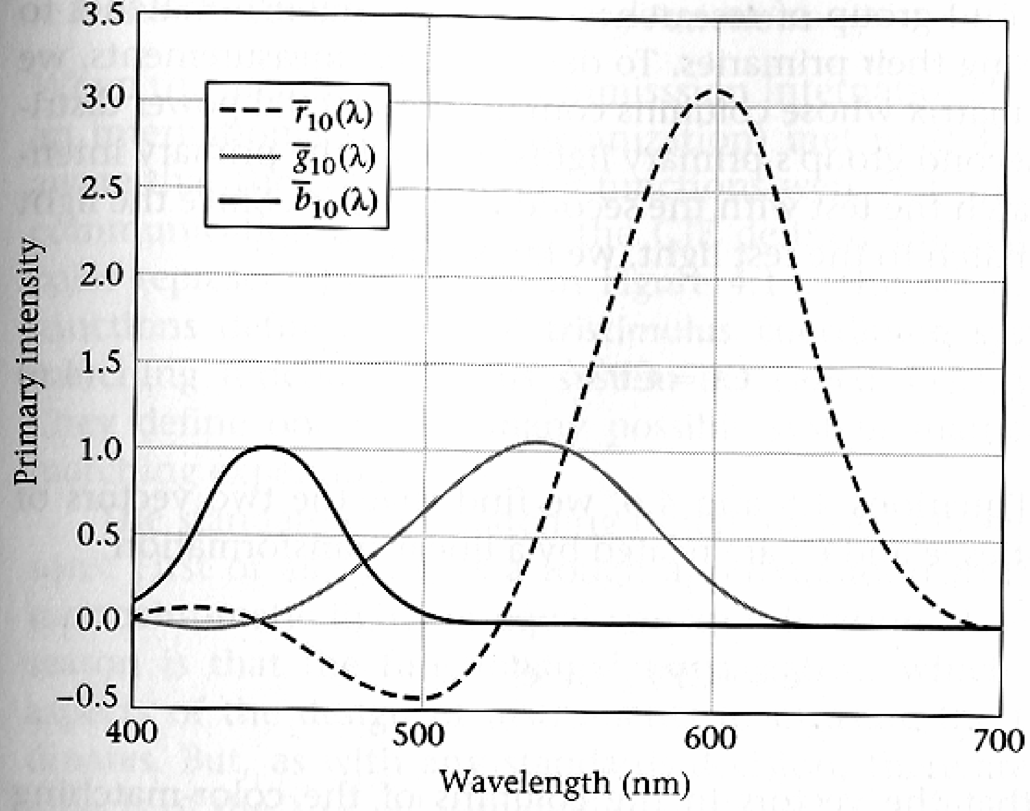
- Pick a set of primaries, $p_1(\lambda\ ), p_2(\lambda\ ), p_3(\lambda\ )$
- Measure the amount of each primary, $c_1(\lambda), c_2(\lambda), c_3(\lambda)$ needed to match a monochromatic light, $t(\lambda\ )$ at each spectral wavelength λ (pick some spectral step size). These are called the color matching functions.

Color matching functions for a particular set of monochromatic primaries

🟥 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 $\bar{b}_{10}(\lambda)$.

test light wavelengths, indicating that

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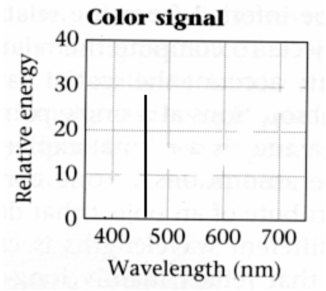
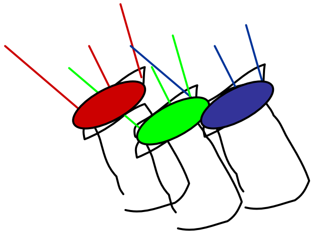
Using the color matching functions to predict the primary match to a new spectral signal



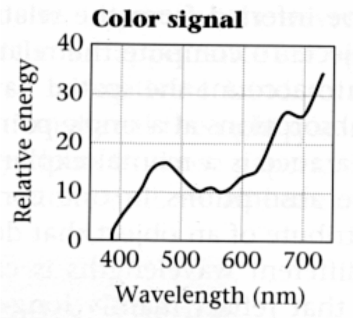
We know that a monochromatic light of λ_i wavelength will be matched by the amounts $c_1(\lambda_i), c_2(\lambda_i), c_3(\lambda_i)$

of each primary.



And any spectral signal can be thought of as a linear combination of very many monochromatic lights, with the linear coefficient given by the spectral power at each wavelength.

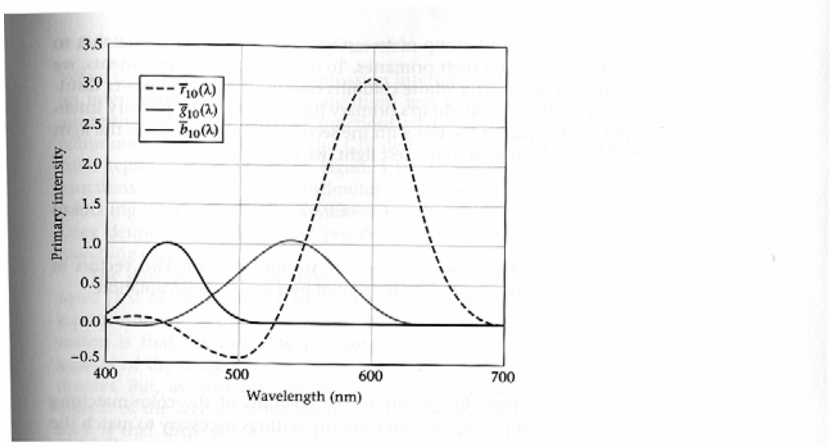
$$\vec{t} = \begin{pmatrix} t(\lambda_1) \\ \vdots \\ t(\lambda_N) \end{pmatrix}$$



Using the color matching functions to predict the primary match to a new spectral signal

Store the color matching functions in the rows of the matrix, C

$$C = \begin{pmatrix} c_1(\lambda_1) & \cdots & c_1(\lambda_N) \\ c_2(\lambda_1) & \cdots & c_2(\lambda_N) \\ c_3(\lambda_1) & \cdots & c_3(\lambda_N) \end{pmatrix}$$



Let the new spectral signal be described by the vector t.

$$\vec{t} = \begin{pmatrix} t(\lambda_1) \\ \vdots \\ t(\lambda_N) \end{pmatrix}$$

Then the amounts of each primary needed to match t are: $C\vec{t}$

Internal review

- So, for any set of primary colors, if we are given the spectral color matching functions for a set of primary lights
- We can calculate the amounts of each primary needed to give a perceptual match to any spectral signal.

Suppose you use one set of primaries and I use another?

- We address this in 2 ways:
  - Learn how to translate between primaries
  - Standardize on a few sets of favored primaries.

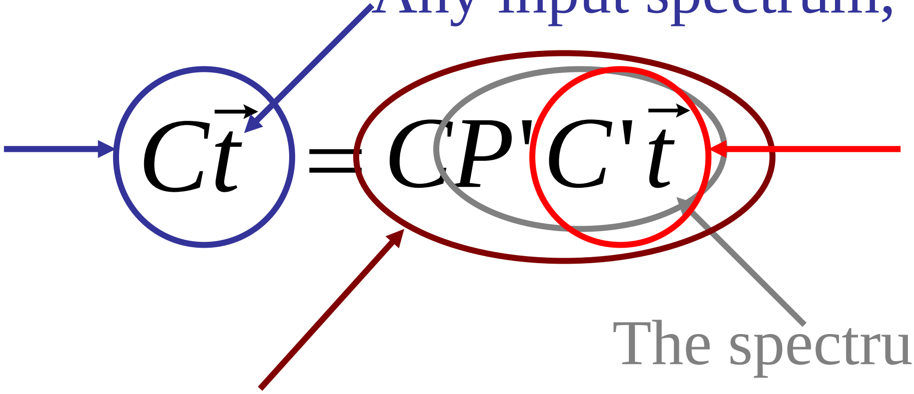
How do you translate colors between different systems of primaries?

🟥 $p_1 = (0\ 0\ 0\ 0\ 0 \ldots\ \ 0\ 1\ 0)^T$
🟩 $p_2 = (0\ 0\ \ldots\ 0\ 1\ 0\ \ldots 0\ 0)^T$
🟦 $p_3 = (0\ 1\ 0\ 0\ \ldots\ 0\ 0\ 0\ 0)^T$

Primary spectra, P
Color matching functions, C

🟧 $p'_1 = (0\ 0.2\ 0.3\ 4.5\ 7\ \ldots.\ 2.1)^T$
🟨 $p'_2 = (0.1\ 0.44\ 2.1\ \ldots\ \ 0.3\ 0)^T$
🟪 $p'_3 = (1.2\ 1.7\ 1.6\ \ldots.\ \ \ 0\ 0)^T$

Primary spectra, P’
Color matching functions, C’



$$C\vec{t} = C P' C' \vec{t}$$

Any input spectrum, t

The amount of each primary in P needed to match the color with spectrum t.

The amount of each P’ primary needed to match t

The spectrum of a perceptual match to t, made using the primaries P’

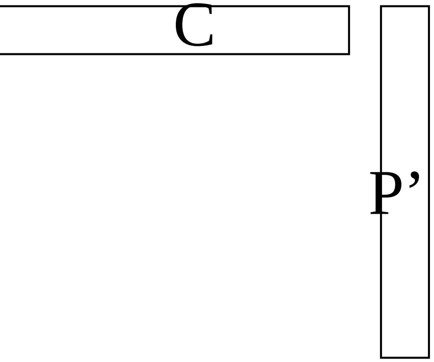
The color of that match to t, described by the primaries, P.

So, how to translate from the color in one set of primaries to that in another:

The values of the 3 primaries, in the unprimed system

The values of the 3 primaries, in the primed system

$$e = \underbrace{CP'}_{\text{a 3x3 matrix}} e'$$



P’ are the old primaries

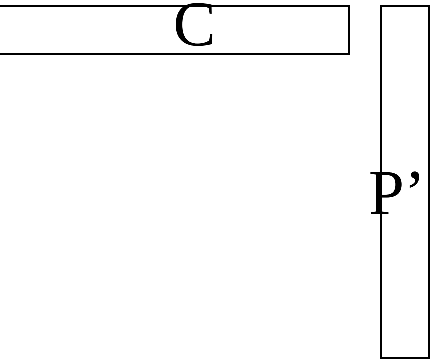
C are the new primaries’ color matching functions

And, by the way, color matching functions translate like this:

From earlier slide

$$C\vec{t} = CP'C'\vec{t}$$

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



$$C = \underbrace{CP'}C'$$

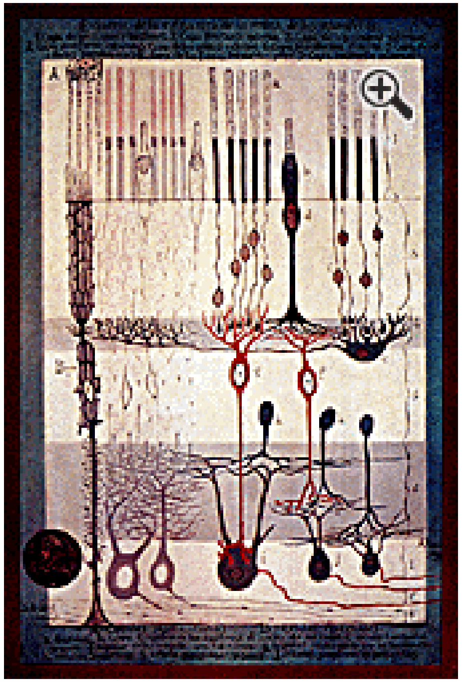
a 3x3 matrix that transforms from the color representation in one set of primaries to that of another.

P’ are the old primaries

C are the new primaries’ color matching functions

What’s the machinery in the eye?

Eye Photoreceptor responses

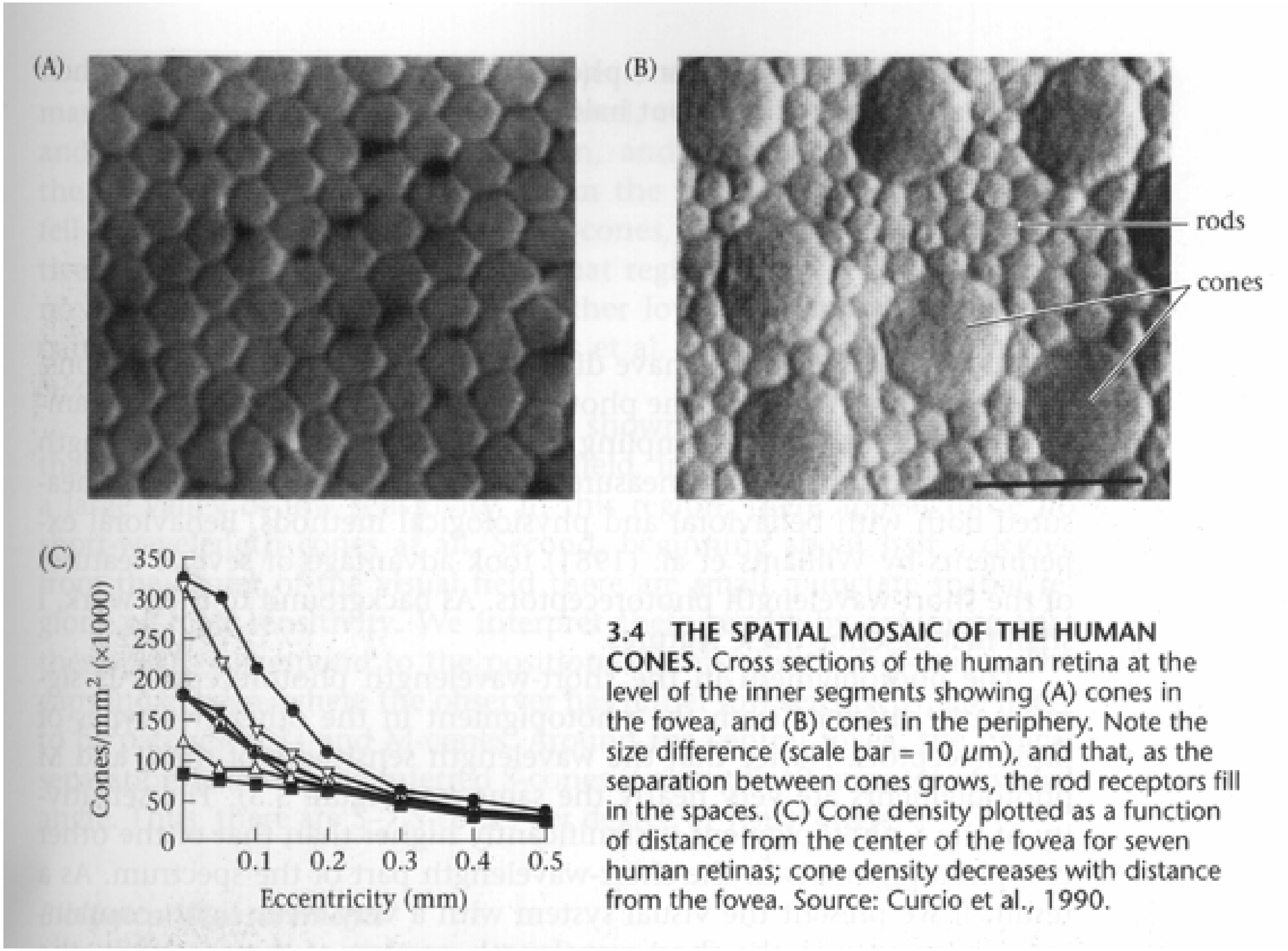


The intricate layers and connections of nerve cells in the retina were drawn by the famed Spanish anatomist Santiago Ramón y Cajal around 1900. Rod and cone cells are at the top. Optic nerve fibers leading to the brain may be seen at bottom right.

Instituto Cajal. CSIC. Madrid.

(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.

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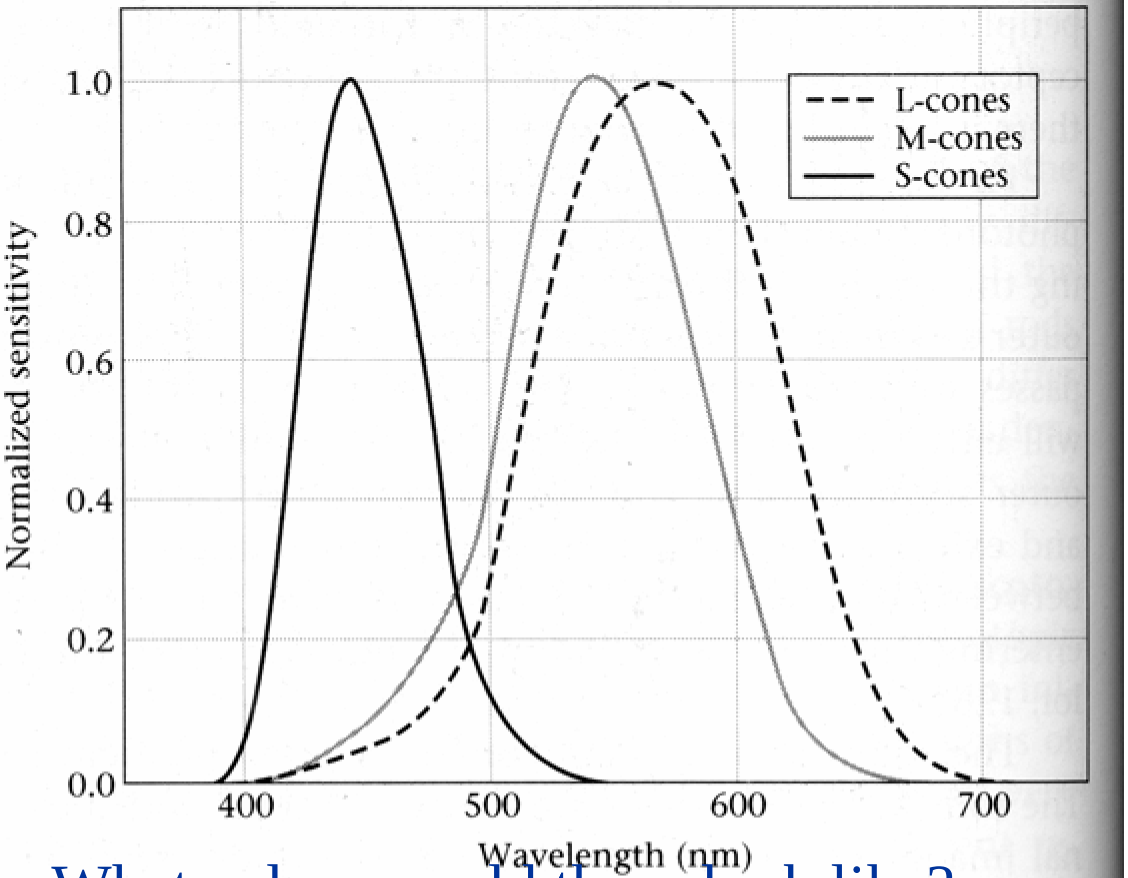
Human eye photoreceptor spectral sensitivities



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.

What colors would these look like?

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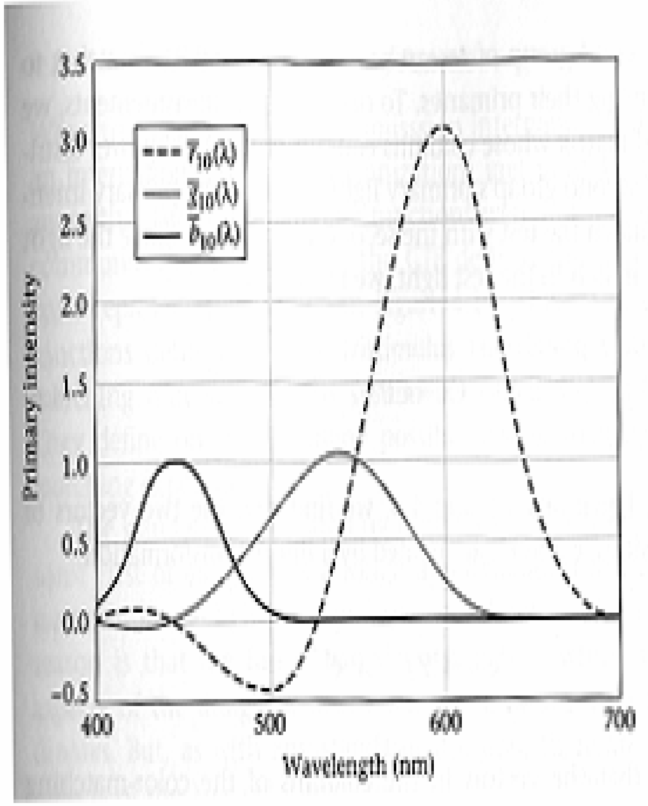
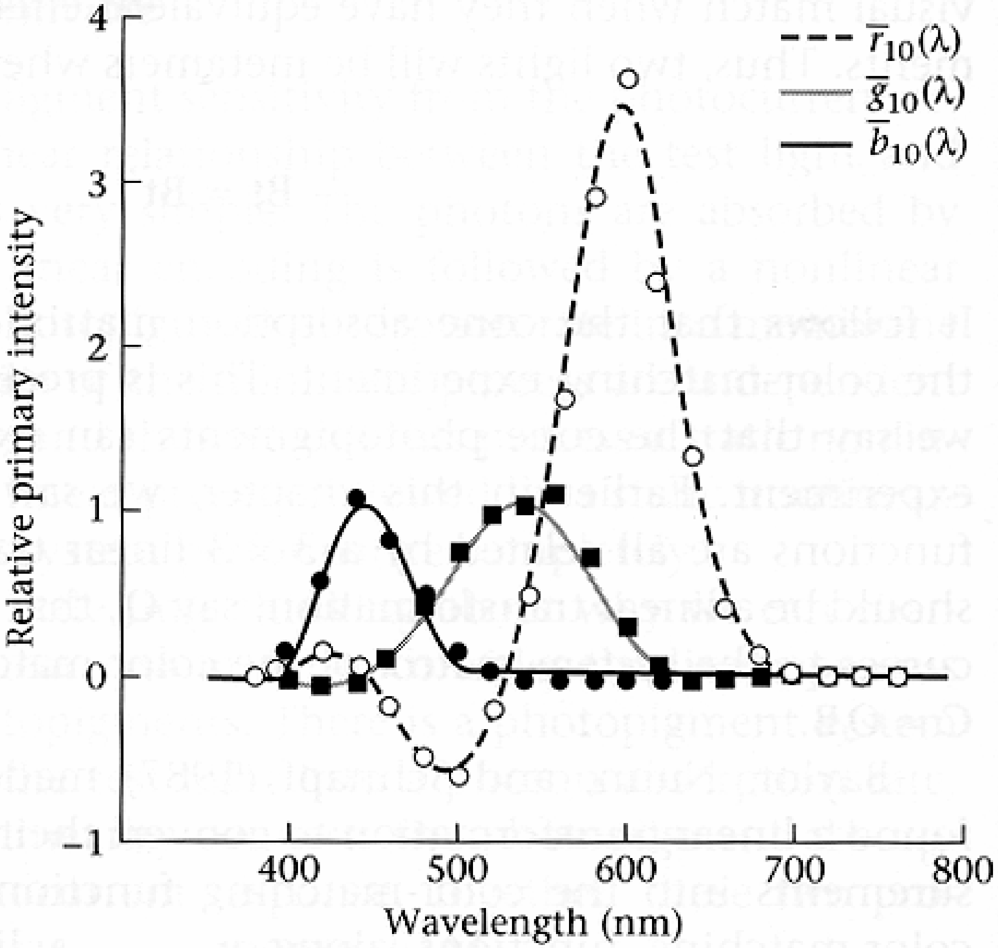
Are the color matching functions we observe obtainable from some 3x3 matrix transformation of the human photopigment response curves? (Because that’s how color matching functions translate).

Color matching functions (for a particular set of spectral primaries



Comparison of color matching functions with best 3x3 transformation of cone responses

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

Internal summary

- What are colors?
  - – Arise from power spectrum of light.
- How represent colors:
  - – Pick primaries
  - – Measure color matching functions (CMF’s)
  - – Matrix mult power spectrum by CMF’s to find color as the 3 primary color values.
- How share color descriptions between people?
  - – Translate colors between systems of primaries
  - – Standardize on a few sets of primaries.