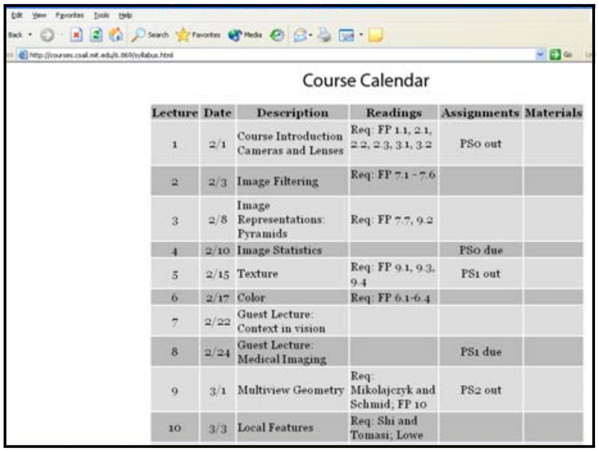
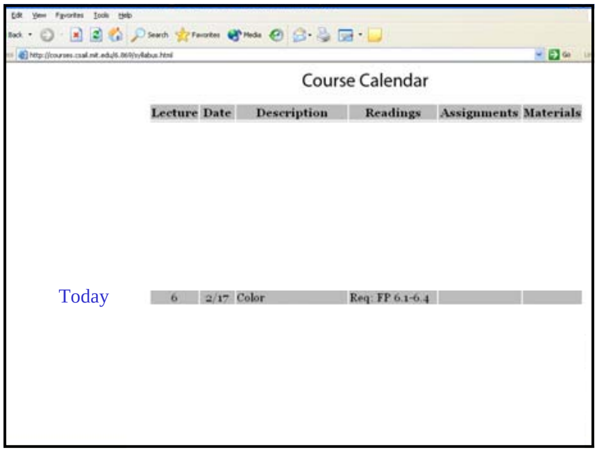


Course Calendar

Lecture	Date	Description	Readings	Assignments	Materials
1	2/1	Course Introduction Cameras and Lenses	Req: FP 1.1, 2.1, 2.2, 2.3, 3.1, 3.2	PS0 out	
2	2/3	Image Filtering	Req: FP 7.1 - 7.6		
3	2/8	Image Representations: Pyramids	Req: FP 7.7, 9.2		
4	2/10	Image Statistics		PS0 due	
5	2/15	Texture	Req: FP 9.1, 9.3, 9.4	PS1 out	
6	2/17	Color	Req: FP 6.1-6.4		
7	2/22	Guest Lecture: Context in vision			
8	2/24	Guest Lecture: Medical Imaging		PS1 due	
9	3/1	Multiview Geometry	Req: Mikolajczyk and Schmid; FP 10	PS2 out	
10	3/3	Local Features	Req: Shi and Tomasi; Lowe		



Course Calendar

Lecture	Date	Description	Readings	Assignments	Materials
6	2/17	Color	Req: FP 6.1-6.4		

Today

Color

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

Feb. 17, 2005
MIT 6.869
Prof. Freeman

Why does a visual system need color?

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

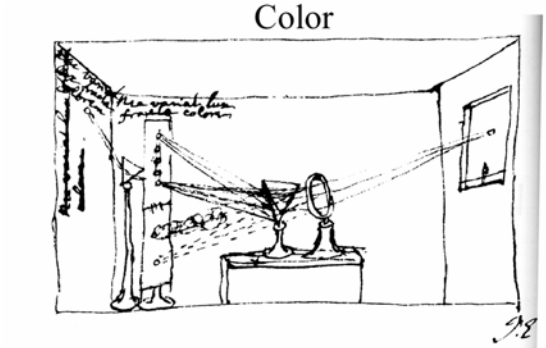
Why does a visual system need color? (an incomplete list…)

- 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.

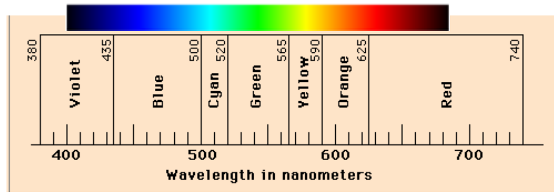
Color



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.

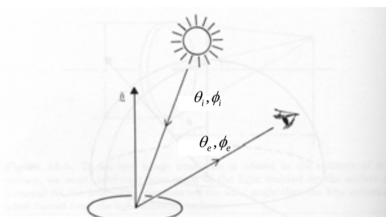
From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Spectral colors



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

Radiometry (review)



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).

radiance

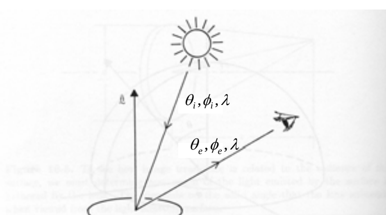
$$BRDF = f(\theta_i, \phi_i, \theta_e, \phi_e) = \frac{L(\theta_e, \phi_e)}{E(\theta_i, \phi_i)}$$

irradiance

Radiometry for colour

- All definitions are now "per unit wavelength"
- All units are now "per unit wavelength"
- All terms are now "spectral"
- Radiance becomes spectral radiance
  - watts per square meter per steradian per unit wavelength
- Irradiance becomes spectral irradiance
  - watts per square meter per unit wavelength

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).

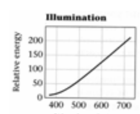
Spectral radiance

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

Spectral irradiance

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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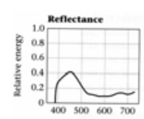

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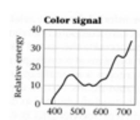
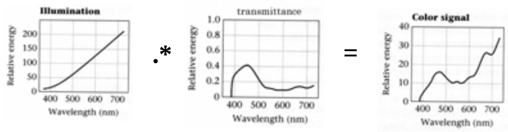


Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

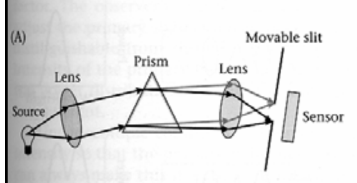
Simplified rendering models: transmittance



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

How measure those spectra: Spectrophotometer

(just like Newton's diagram…)



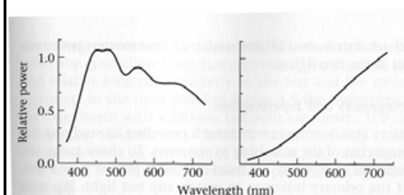
(B)

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

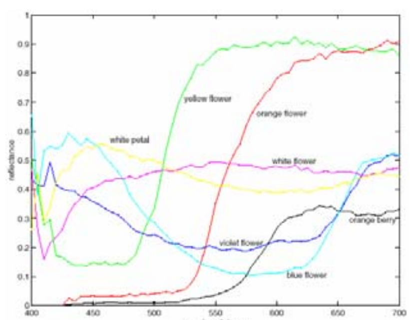


4.4 THE SPECTRAL POWER DISTRIBUTION of two important light sources are shown: (left) blue skylight and (right) a tungsten bulb.

Blue sky   Tungsten light bulb

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

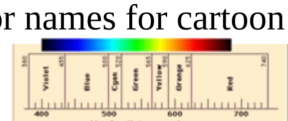
Some reflectance spectra

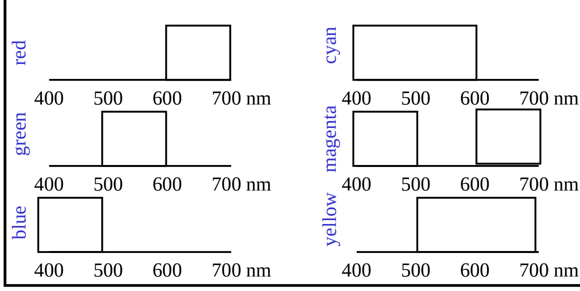


Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions.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

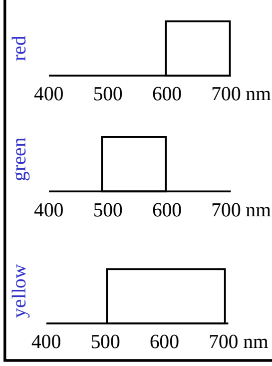
Forsyth, 2002

Color names for cartoon spectra





Additive color mixing

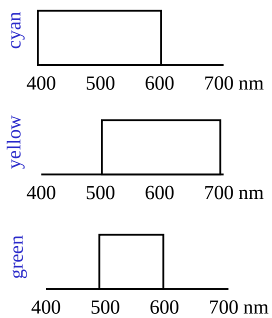


When colors combine by *adding* the color spectra. Examples that follow this mixing rule: CRT phosphors, multiple projectors aimed at a screen, Polachrome slide film.

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

Low-dimensional models for color spectra

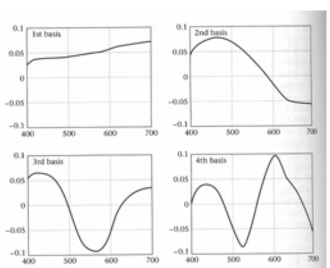
$$\begin{pmatrix} \vdots \\ e(\lambda) \\ \vdots \end{pmatrix} = \begin{pmatrix} \vdots & \vdots & \vdots \\ E_1(\lambda) & E_2(\lambda) & E_3(\lambda) \\ \vdots & \vdots & \vdots \end{pmatrix} \begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix}$$

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:

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

Matlab demonstration

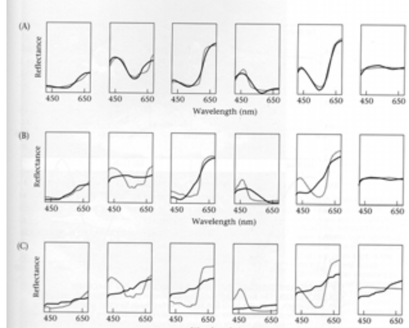
Basis functions for Macbeth color checker



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

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

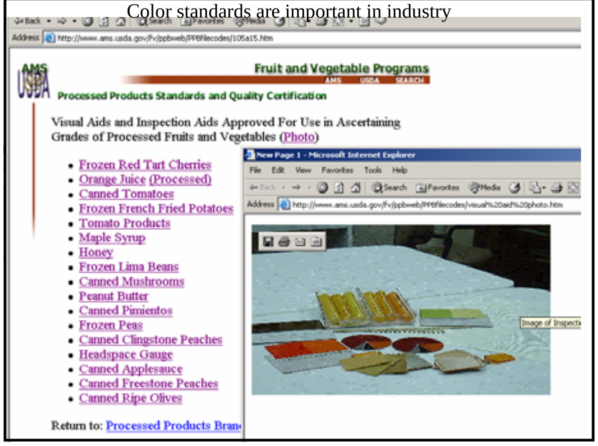
- Color physics.
- Color representation and matching.

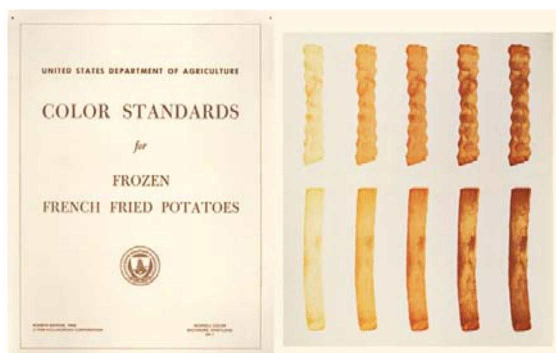
Why specify color numerically?

- 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?

Forsyth & Ponce

Color standards are important in industry

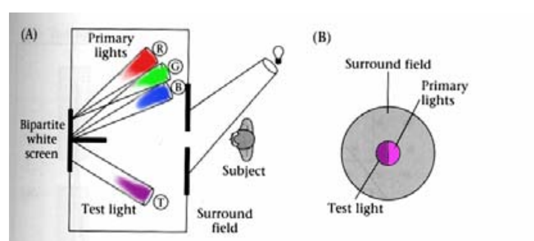




An assumption that sneaks in here

- 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>.

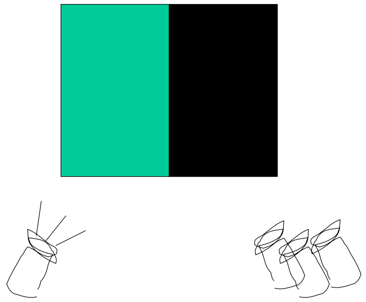
Color matching experiment



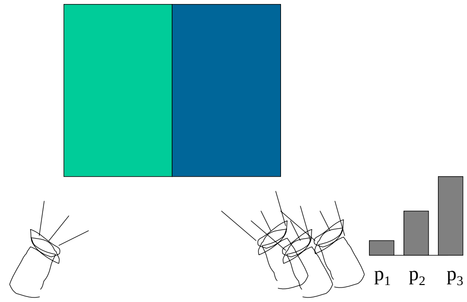
4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

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

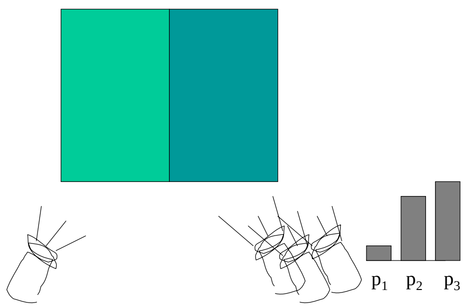
Color matching experiment 1



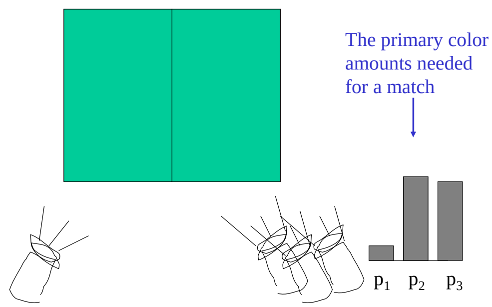
Color matching experiment 1



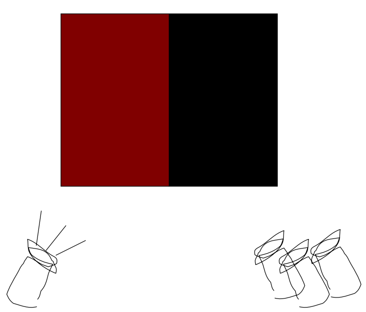
Color matching experiment 1



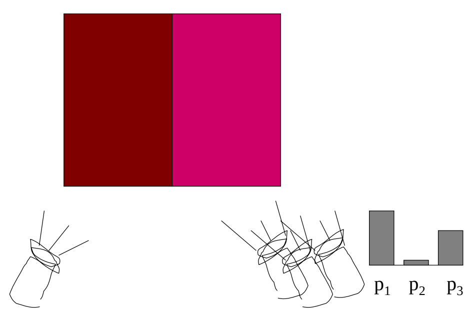
Color matching experiment 1



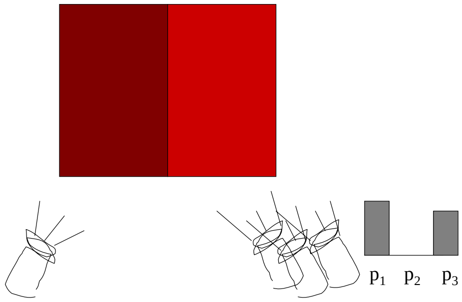
Color matching experiment 2



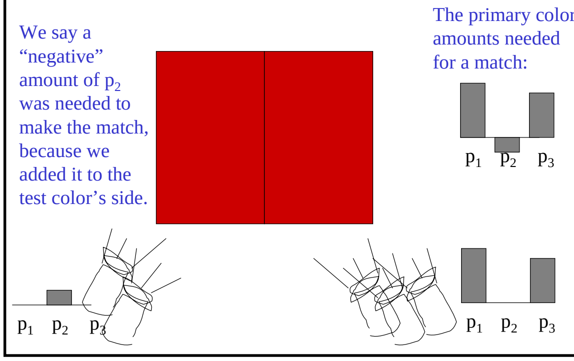
Color matching experiment 2

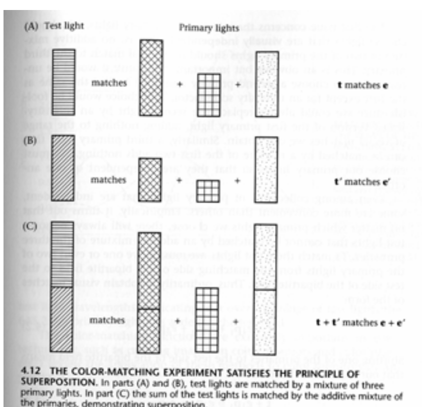


Color matching experiment 2



Color matching experiment 2





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.

Forsyth & Ponce

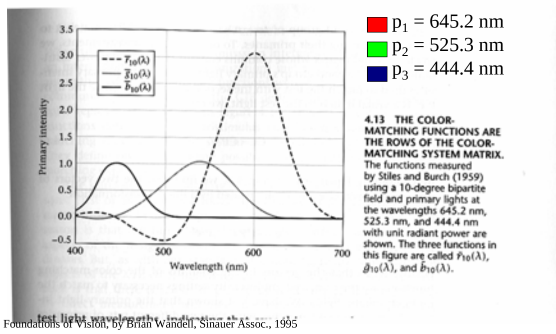
Measure color by color-matching paradigm

- 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.

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

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

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.

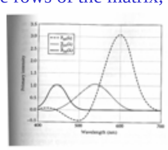
And any spectral signal can be thought of as a linear combination of very many monochromatic lights, with the linear coefficient given by the spectral power at each wavelength.

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

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.

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

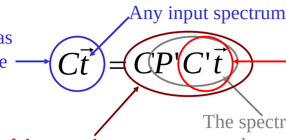
Then the amounts of each primary needed to match t are:

$$C\vec{t}$$

How do you translate colors between different systems of primaries? (and why would you need to?)

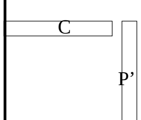
$p_1 = (0\ 0\ 0\ 0\ 0 \ldots\ 0\ 1\ 0)^T$
$p_2 = (0\ 0 \ldots 0\ 1\ 0 \ldots 0\ 0)^T$
$p_3 = (0\ 1\ 0\ 0 \ldots 0\ 0\ 0\ 0)^T$
Primary spectra, P
Color matching functions, C

$p'_1 = (0\ 0.2\ 0.3\ 4.5\ 7 \ldots 2.1)^T$
$p'_2 = (0.1\ 0.44\ 2.1 \ldots\ 0.3\ 0)^T$
$p'_3 = (1.2\ 1.7\ 1.6 \ldots\ 0\ 0)^T$
Primary spectra, P'
Color matching functions, C'



So color matching functions translate like this:

From previous slide $C\vec{t} = CP'C'\vec{t}$ But this holds for any input spectrum, t, so…

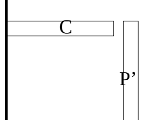


$$C = \underbrace{CP'}_{\text{a 3x3 matrix}}C'$$

P' are the old primaries
C are the new primaries' color matching functions

How do you translate from the color in one set of primaries to that in another?

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



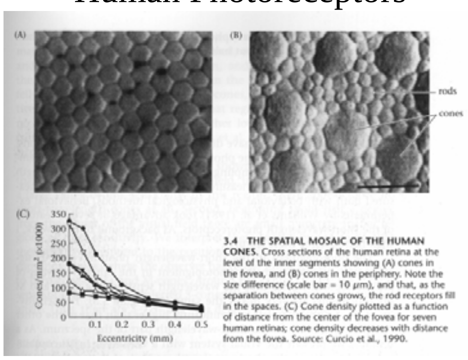
P' are the old primaries
C are the new primaries' color matching functions

What's the machinery in the eye?

Eye Photoreceptor responses

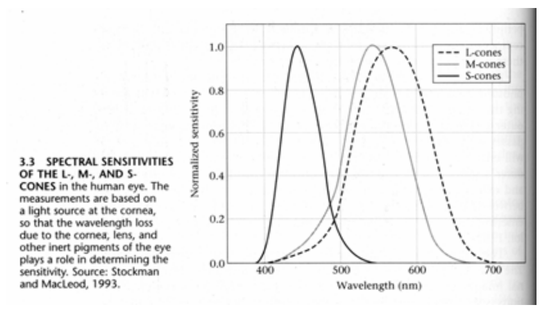
(Where do you think the light comes in?)

Human Photoreceptors



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

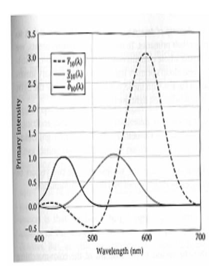
Human eye photoreceptor spectral sensitivities



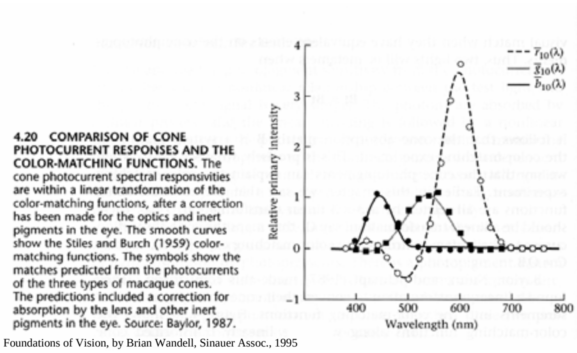
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Are the color matching functions we observe obtainable from some 3x3 matrix transformation of the human photopigment response curves?

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.

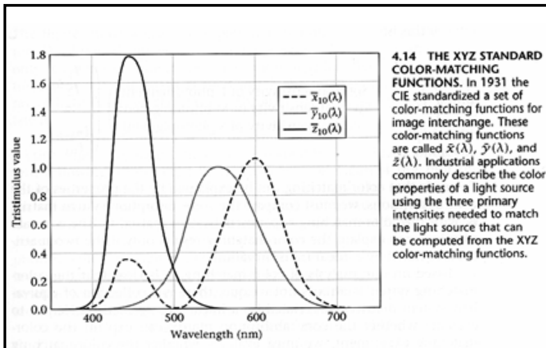
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Since we can define colors using almost any set of primary colors, let's agree on a set of primaries and color matching functions for the world to use…

CIE XYZ color space

- Commission Internationale d'Eclairage, 1931
- "…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."

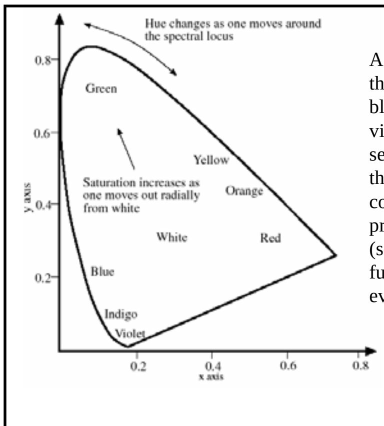
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995



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.

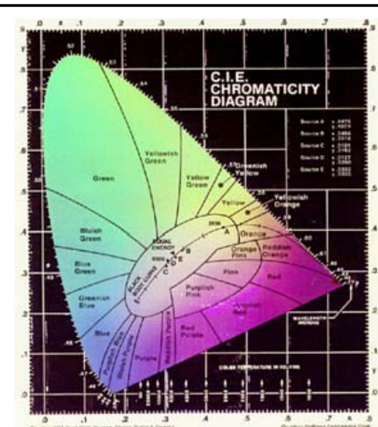
CIE XYZ: Color matching functions are positive everywhere, but primaries are imaginary. Usually draw x, y, where $x=X/(X+Y+Z)$
$y=Y/(X+Y+Z)$

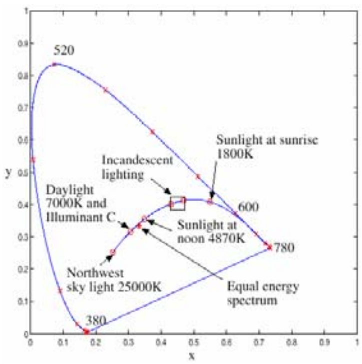
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995



A qualitative rendering of the CIE (x,y) space. The blobby region represents visible colors. There are sets of (x, y) coordinates that don't represent real colors, because the primaries are not real lights (so that the color matching functions could be positive everywhere).

Forsyth & Ponce





A plot of the CIE (x,y) space. We show the spectral locus (the colors of monochromatic lights) and the black-body locus (the colors of heated black-bodies). I have also plotted the range of typical incandescent lighting.

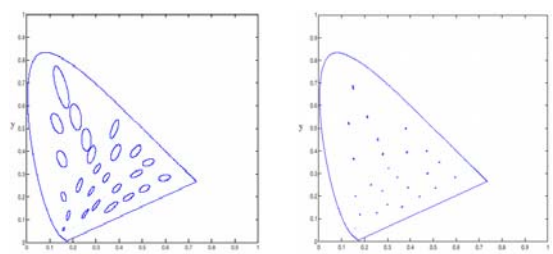
Forsyth & Ponce

Some other color spaces…

Uniform color spaces

- McAdam ellipses (next slide) demonstrate that differences in x,y are a poor guide to differences in color
- Construct color spaces so that differences in coordinates are a good guide to differences in color.

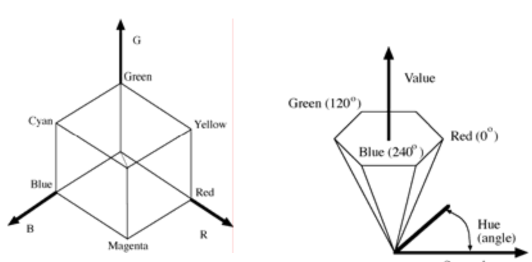
Forsyth & Ponce



Variations in color matches on a CIE x, y space. At the center of the ellipse is the color of a test light; the size of the ellipse represents the scatter of lights that the human observers tested would match to the test color; the boundary shows where the just noticeable difference is. The ellipses on the left have been magnified 10x for clarity; on the right they are plotted to scale. The ellipses are known as MacAdam ellipses after their inventor. The ellipses at the top are larger than those at the bottom of the figure, and that they rotate as they move up. This means that the magnitude of the difference in x, y coordinates is a poor guide to the difference in color.

Forsyth & Ponce

HSV hexcone



Forsyth & Ponce

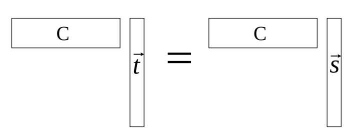
Color metamerism

Two spectra, t and s, perceptually match when

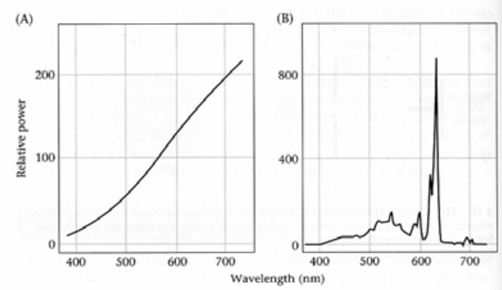
$$C\vec{t} = C\vec{s}$$

where C are the color matching functions for some set of primaries.

Graphically,



Metameric lights



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.

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

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…