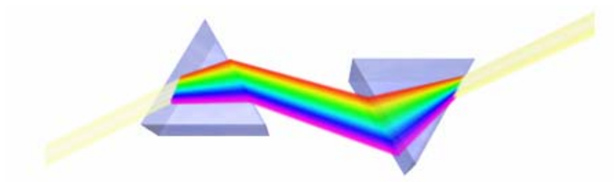
Lecture 2: Color

Tuesday, Sept 4



Why do we need color for visual processing?

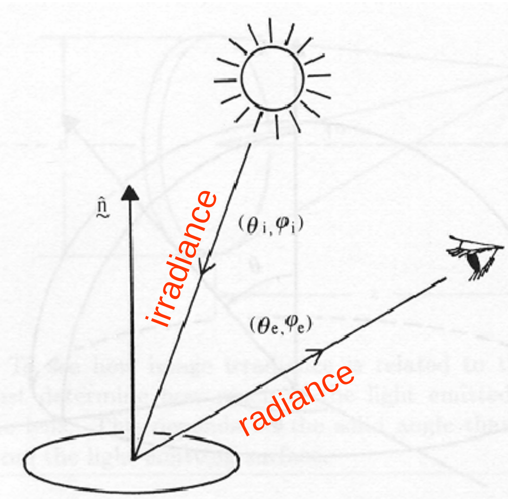
Color

- **Color of light** arriving at camera depends on
  - Spectral reflectance of the surface light is leaving
  - Spectral radiance of light falling on that patch
- **Color perceived** depends on
  - Physics of light
  - Visual system receptors
  - Brain processing, environment

Radiometry: some definitions

- **Radiance**: power emitted per unit area in a direction
- **Irradiance**: total incident power falling on a surface

Directions specified by (polar angle, azimuth)

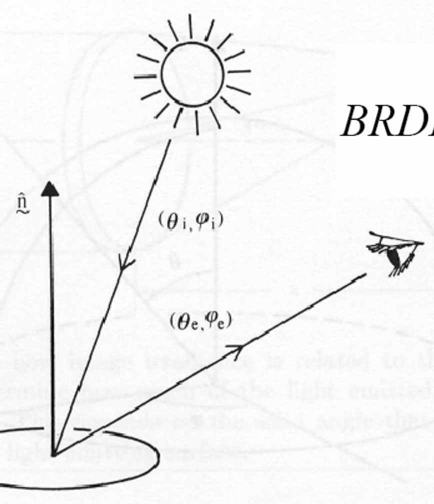


Horn, 1986

Radiometry: BRDF

- **Bidirectional reflectance distribution function**: Model of local reflection that tells how **bright** a surface appears when viewed from one direction when light falls on it from another.

Directions specified by (polar angle, azimuth)



Horn, 1986

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

radiance / irradiance

Radiometry: BRDF

- BRDF is a very general notion
  - some surfaces need it (underside of a CD; tiger eye; etc)
  - very hard to measure
    - illuminate from one direction, view from another, repeat
  - very unstable
    - minor surface damage can change the BRDF
    - e.g. ridges of oil left by contact with the skin can act as lenses
- For many surfaces, light leaving the surface is largely independent of exit angle

Slide from Marc Pollefeys

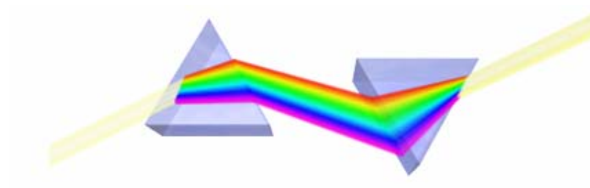
Lambertian surfaces

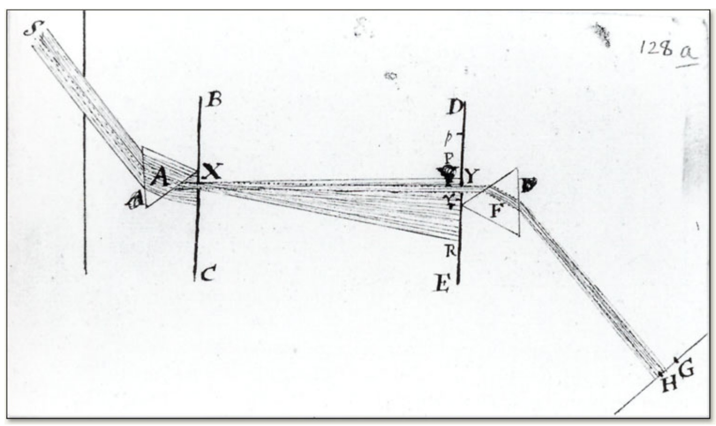
- E.g.: Lambertian / diffuse surfaces: appear equally bright from all viewing directions

$$f(\theta_i, \phi_i, \theta_e, \phi_e) = \text{Constant}$$

Color and light

White light: composed of about equal energy in all wavelengths of the visible spectrum





Newton 1665

Image from http://micro.magnet.fsu.edu/

Since light can arrive in different quantities at different wavelengths…

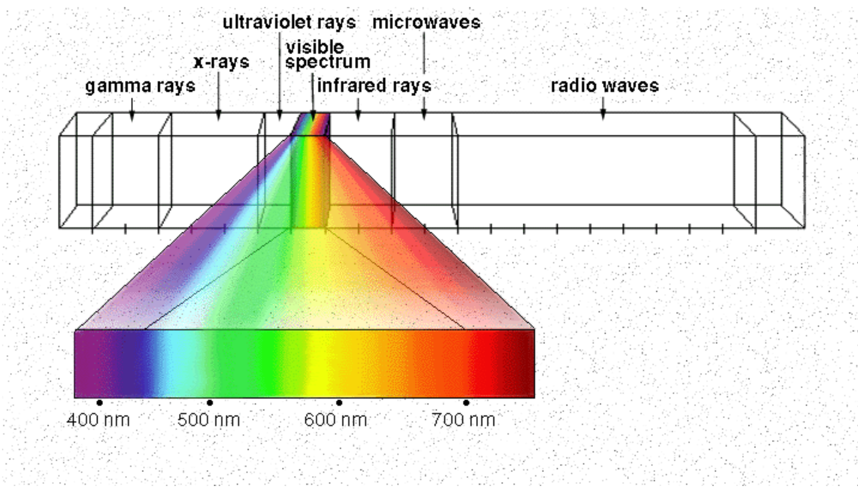


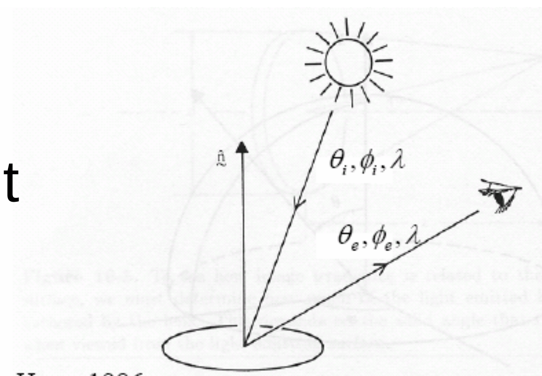
Image credit: nasa.gov

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

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

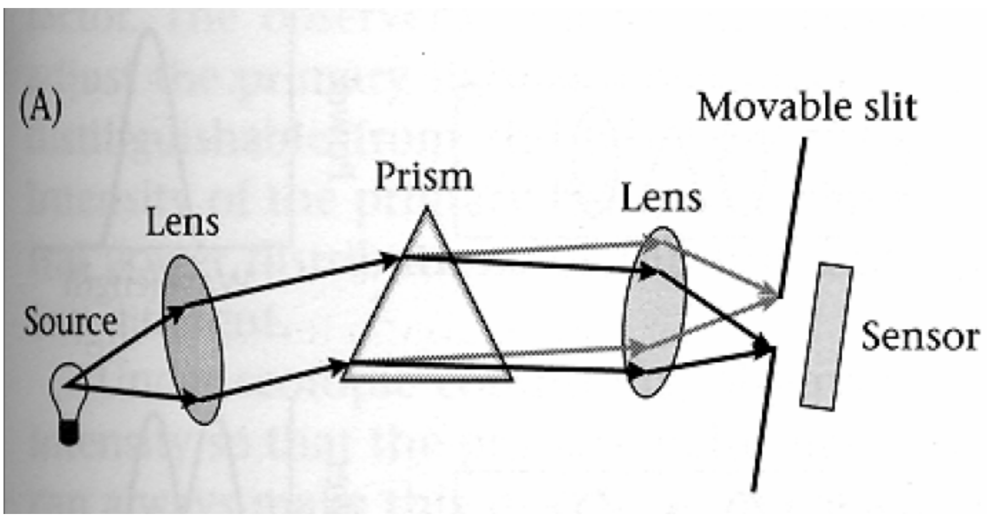
Spectral radiance / spectral irradiance

…extend radiometry terms to incorporate *spectral* units (per unit wavelength)



Horn, 1986

Measuring spectra

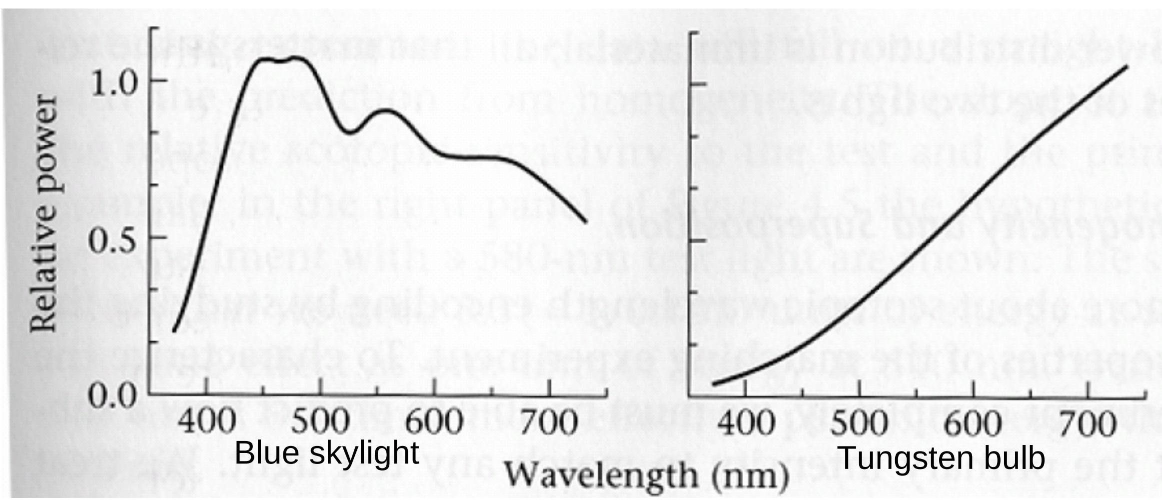


Spectroradiometer: separate input light into its different wavelengths, and measure the energy at each

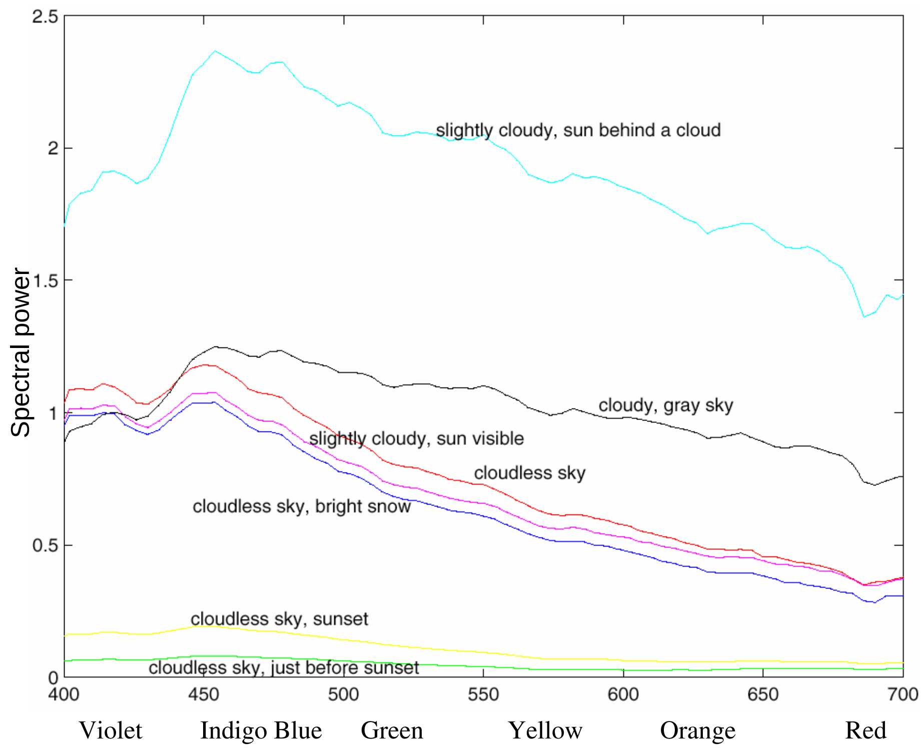
Foundations of Vision, B. Wandell

Spectral power distribution

- the power per unit area per unit wavelength of a radiant object



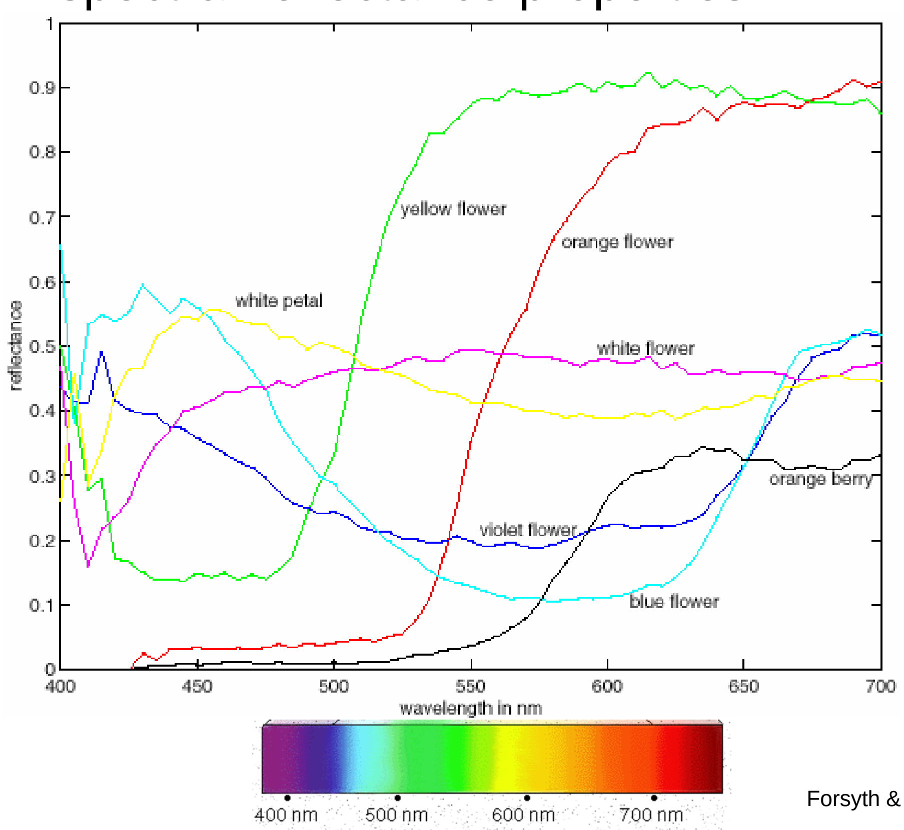
Foundations of Vision, B. Wandell



Spectral power of daylight varies depending on time of day, year, and other conditions.

Measurements by J. Parkkinen and P. Silfsten.

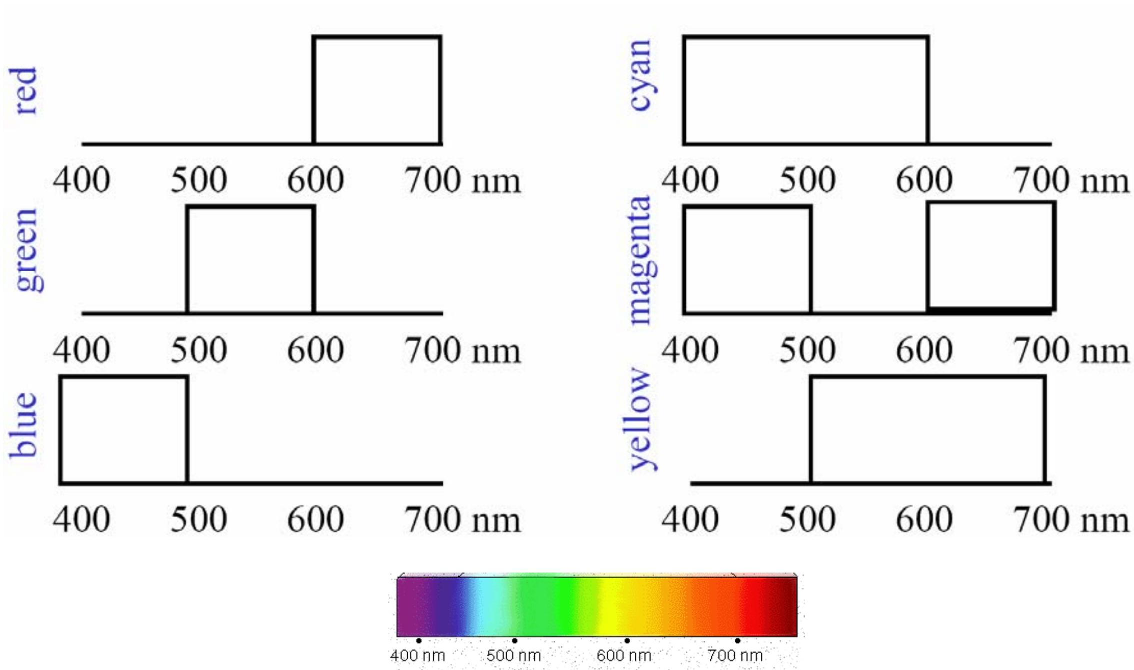
The color viewed is also affected by the surface's spectral reflectance properties.



Spectral reflectances for some natural objects: how much of each wavelength is reflected

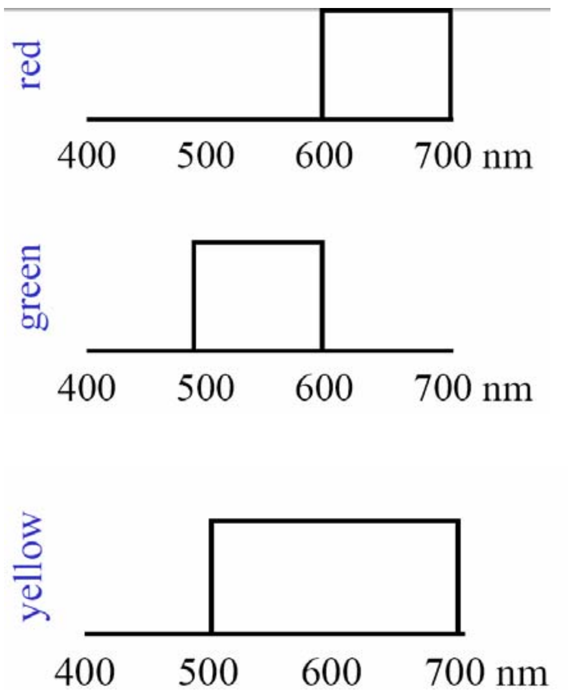
Forsyth & Ponce, measurements by E. Koivisto

Color mixing

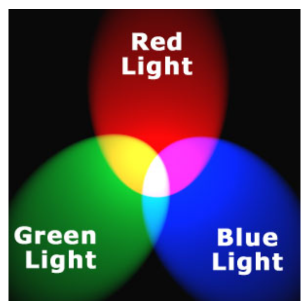


Adapted from W. Freeman

Additive color mixing

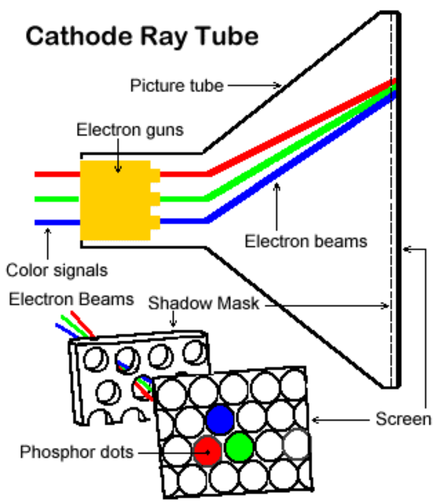


Colors combine by *adding* color spectra



Light *adds* to black.

Examples of additive color systems



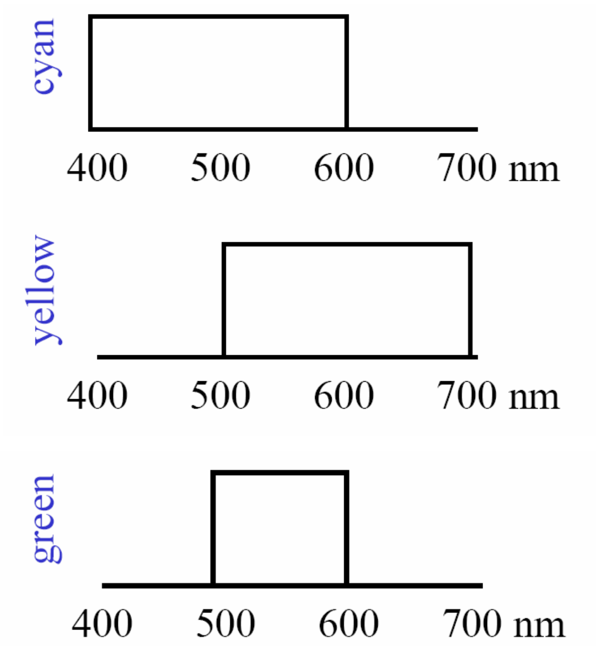
CRT phosphors

multiple projectors

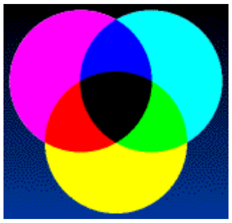
http://www.jegsworks.com

http://www.crtprojectors.co.uk/

Subtractive color mixing



Colors combine by *multiplying* color spectra.



Pigments *remove* color from incident light (white).

Examples of subtractive color systems

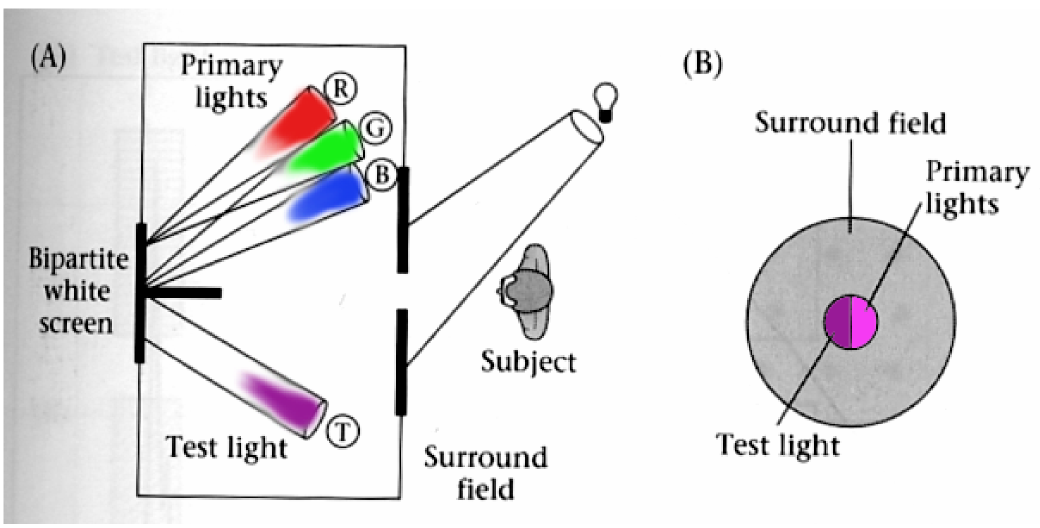
- Printing on paper
- Crayons
- Most photographic film

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.
  - Common to disagree on appropriate color names.
- Color reproduction problems increased by prevalence of digital imaging – e.g. digital libraries of art.
  - How to ensure that everyone perceives the same color?
  - What spectral radiances *produce the same response* from people under simple viewing conditions?

Forsyth & Ponce

Color matching experiment

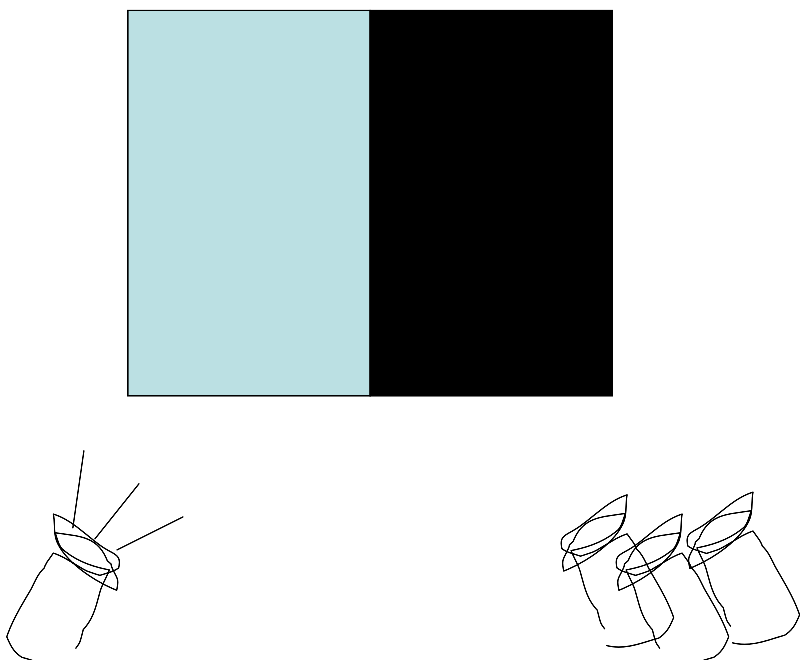


Observer adjusts weight (intensity) for primary lights (fixed SPD's) to match appearance of test light.

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

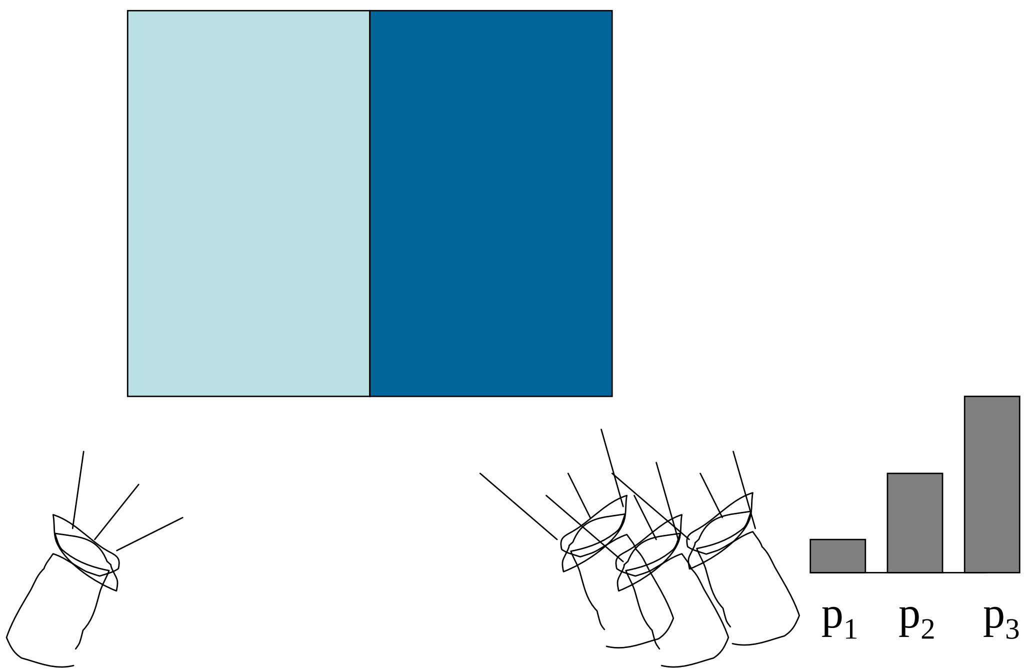
After Judd & Wyszecki.

Color matching experiment 1

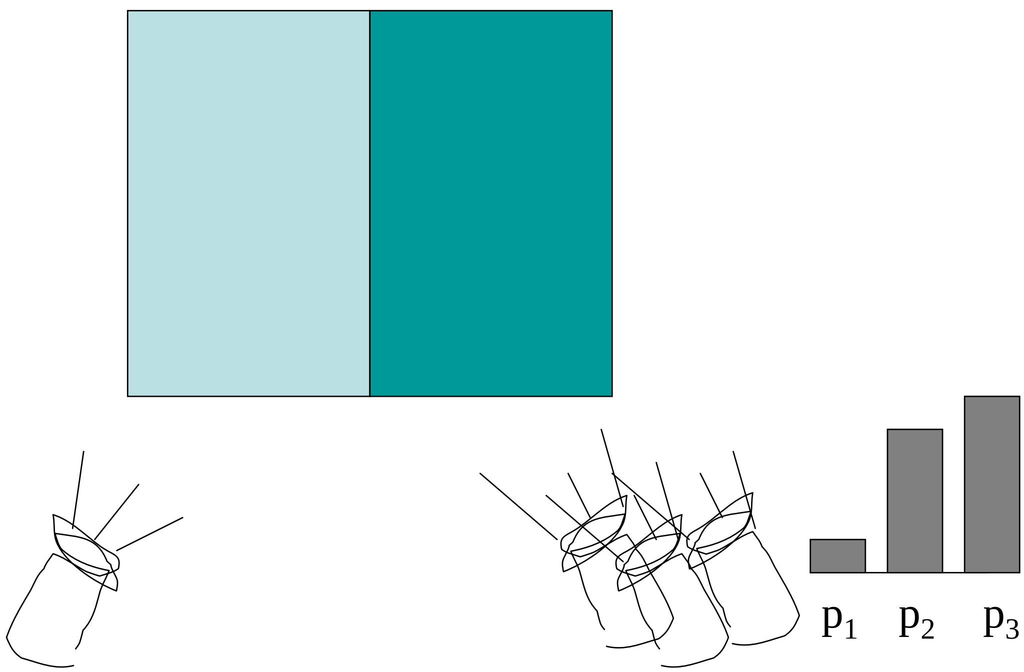


Color matching slides from W. Freeman

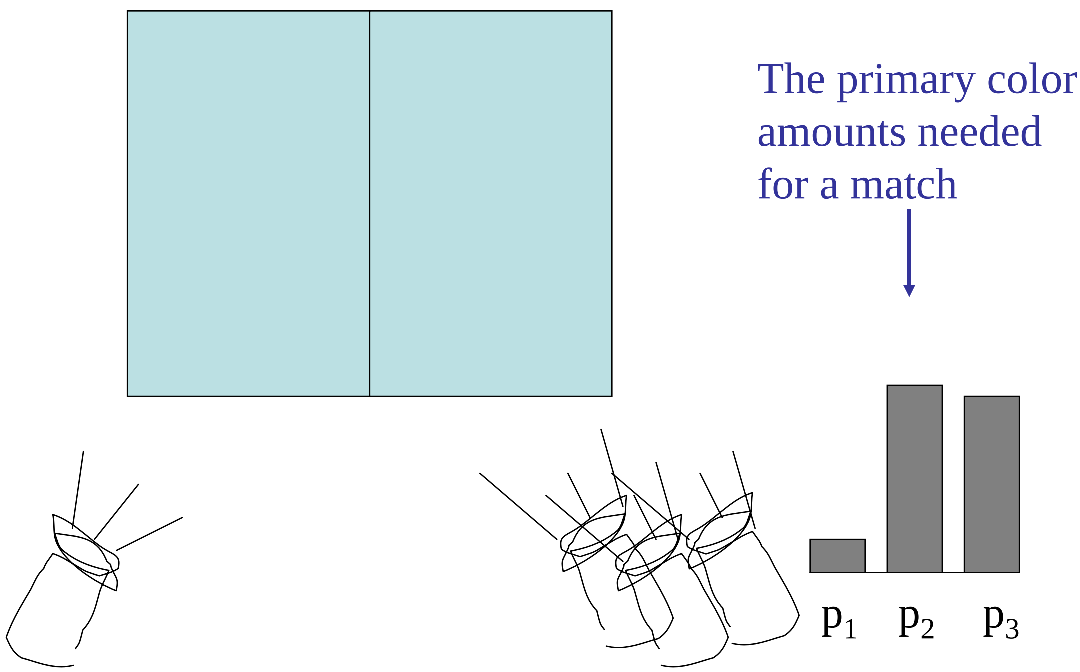
Color matching experiment 1



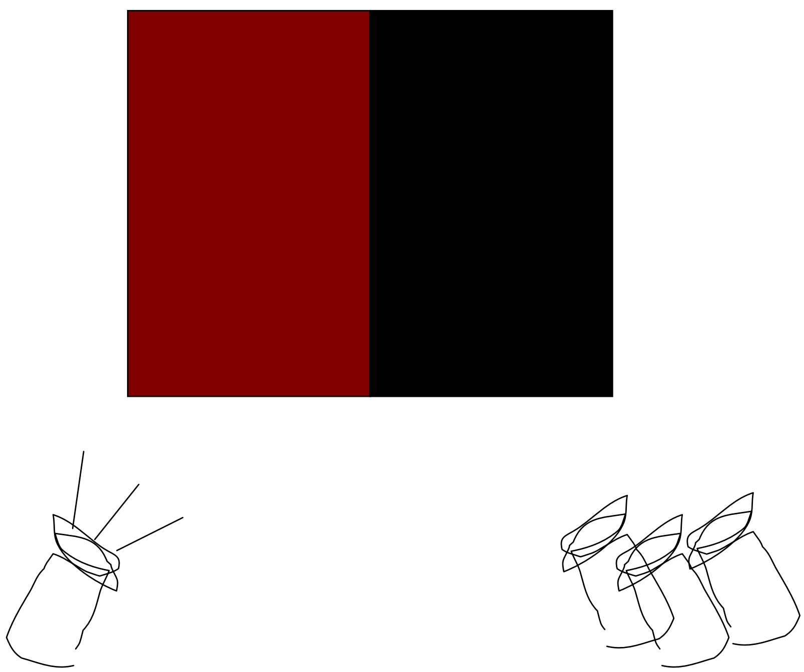
Color matching experiment 1



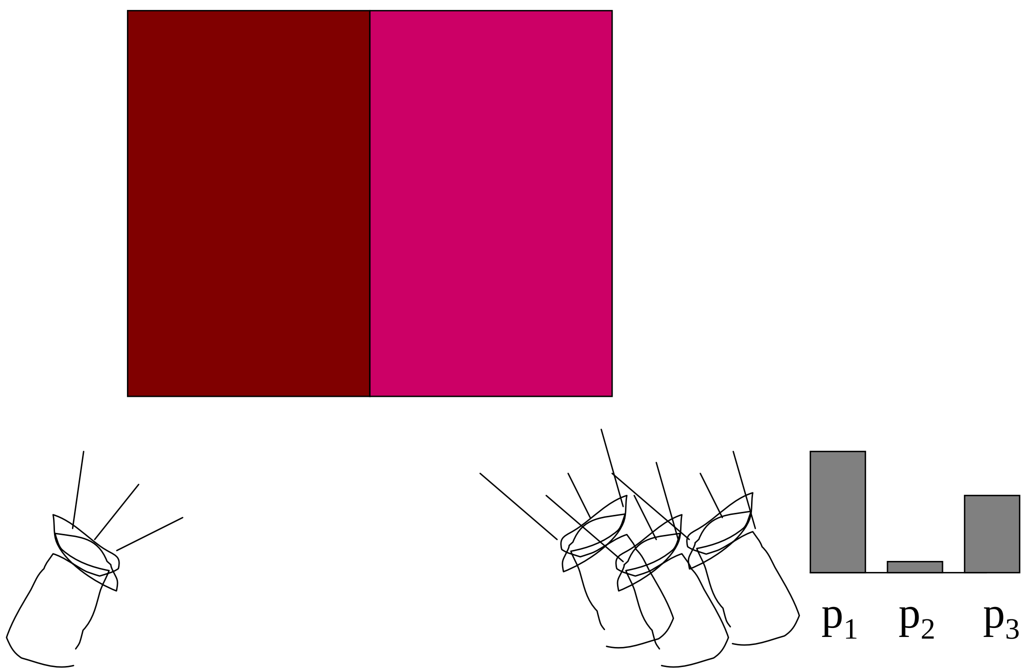
Color matching experiment 1



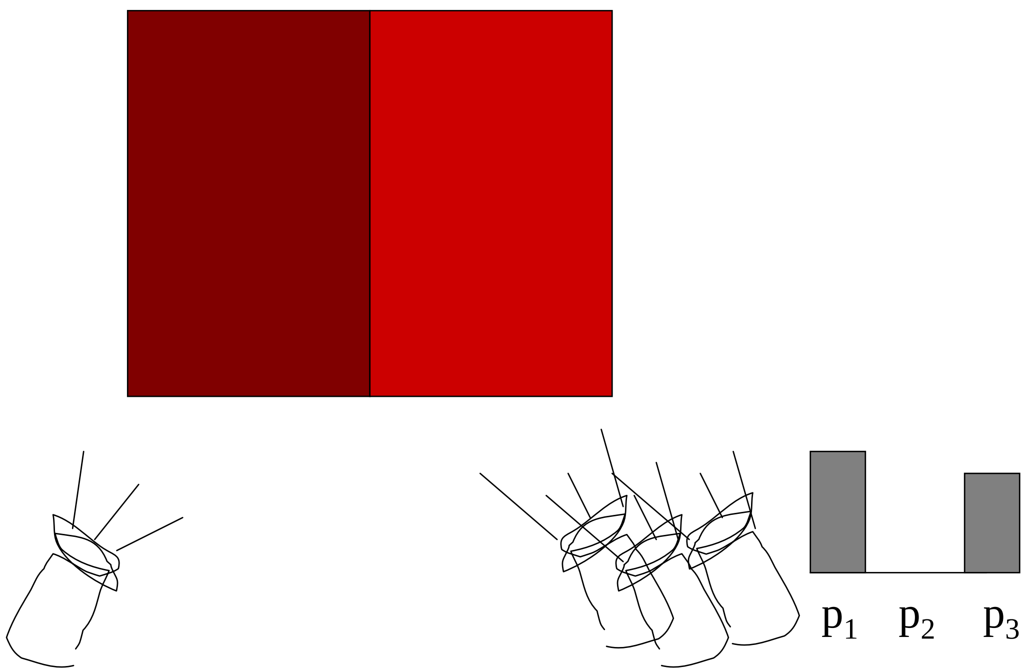
Color matching experiment 2



Color matching experiment 2

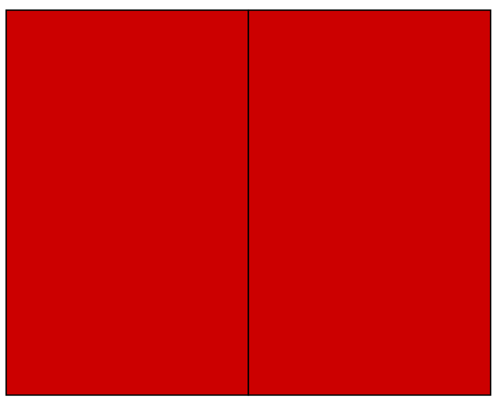


Color matching experiment 2

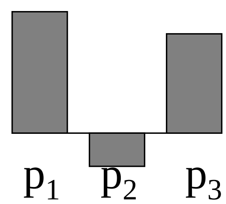


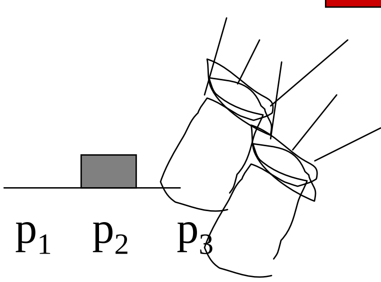
Color matching experiment 2

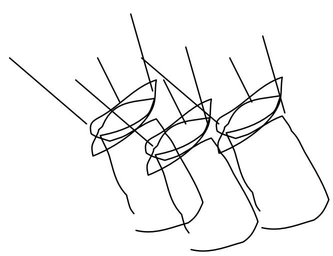
We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.

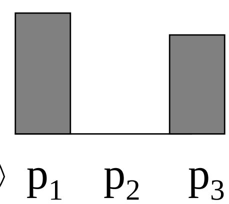


The primary color amounts needed for a match:





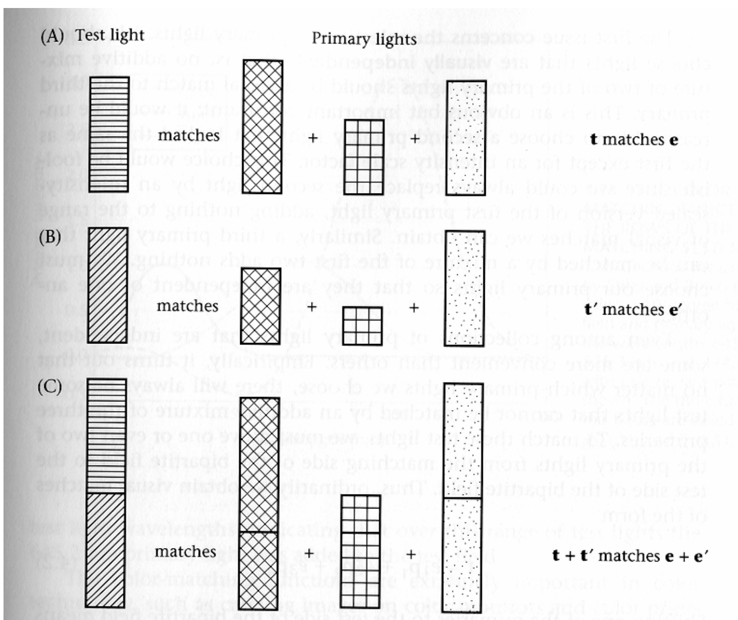




Color matching

- Lights forming a *perceptual* match may be *physically* different
  - Match light: must be combination of primaries
  - Test light: any light
- **Metamers**: pairs of lights that match perceptually but not physically

Grassman's Laws



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

Mixing the matches for two test lights will match the mixture of the two test lights.

If same weights used to match two test lights, then test lights match.

Positive scaling of test light -> scaling of weights (additive matching is linear).

Measuring color by color-matching

- 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.
- If you have some other spectral signal, s, and s matches t perceptually, then e_1, e_2, e_3 will also form a match for s, by Grassman's laws.
- Useful:
  – Predict the color of a new spectral signal
  – Translate to representations using other primary lights.

Adapted from W. Freeman

Measuring color by color-matching

- Why is computing the color match for any color signal for any set of primaries useful?
  - 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.

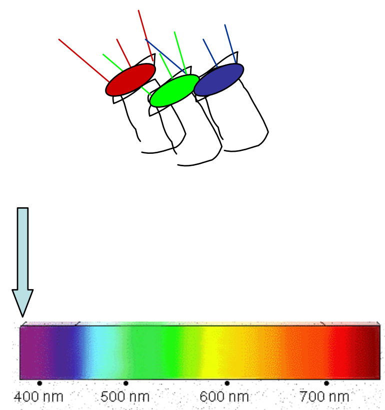
Adapted from W. Freeman

Image credit: pbs.org

Computing color matches

- How to compute the weights that will yield a perceptual match for any test light using any set of primaries:

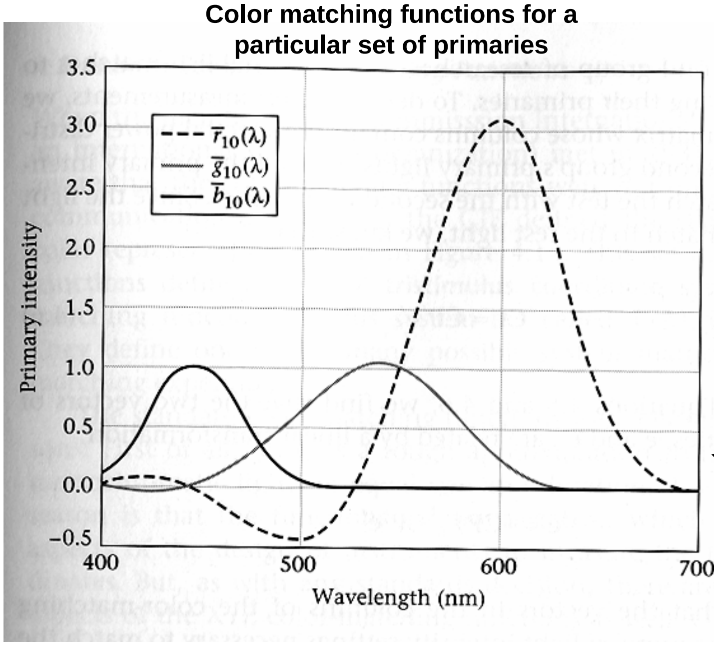
1. Select primaries
2. Estimate their *color matching functions*: observer matches series of monochromatic lights, one at each wavelength



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

Computing color matches

Color matching functions for a particular set of primaries



p_1 = 645.2 nm

p_2 = 525.3 nm

p_3 = 444.4 nm

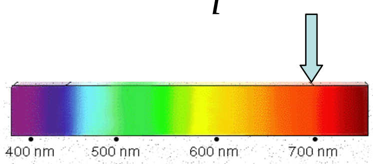
Rows of matrix C

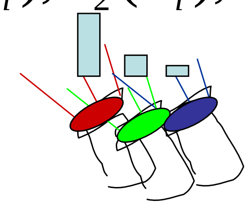
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Adapted from W. Freeman

Computing color matches

λ_i ⟷ matches ⟷ $c_1(\lambda_i), c_2(\lambda_i), c_3(\lambda_i)$

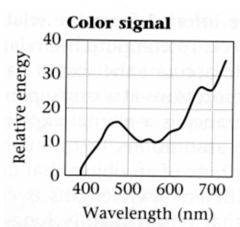




Now have matching functions for all monochromatic light sources

---

Arbitrary new spectral signal is a linear combination of the monochromatic sources



$$\mathbf{t} = \begin{pmatrix} t(\lambda_1) \\ \ldots \\ t(\lambda_N) \end{pmatrix}$$

Computing color matches

Intensities of primary lights needed to obtain match:

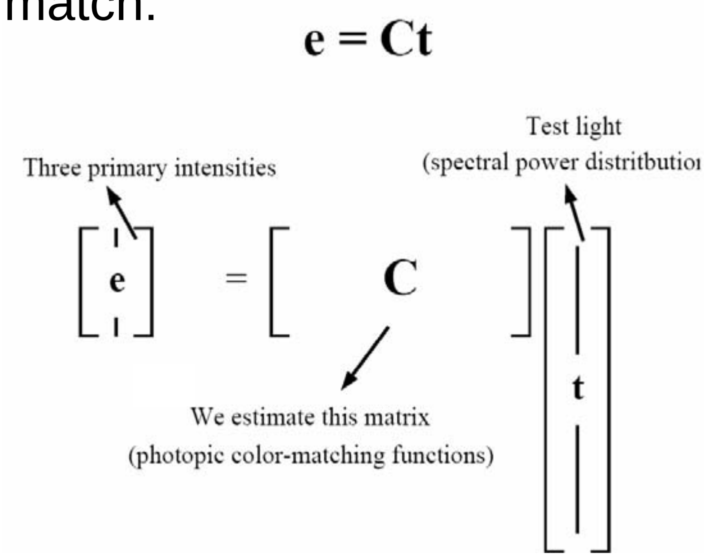


Fig from B. Wandell, 1996

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'

Any input spectrum, t

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

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.

Slide by W. Freeman

How do you translate colors between different systems of primaries?

The values of the 3 primaries, in the unprimed system

The values of the 3 primaries, in the primed system

$$e = CP'e'$$

a 3x3 matrix

- Transforms one set of primaries to another
- Each column is vector of intensities of the original primaries (P) that are needed to match the new primaries (P')

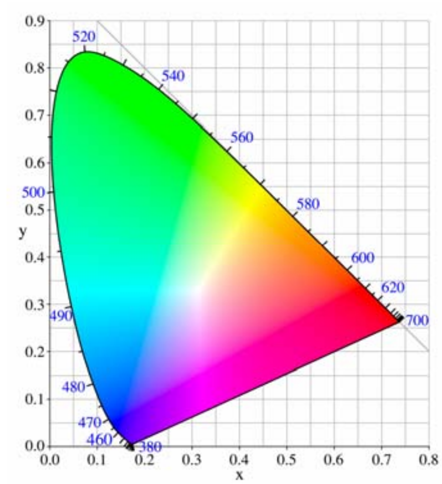
Adapted from W. Freeman

Standard color spaces

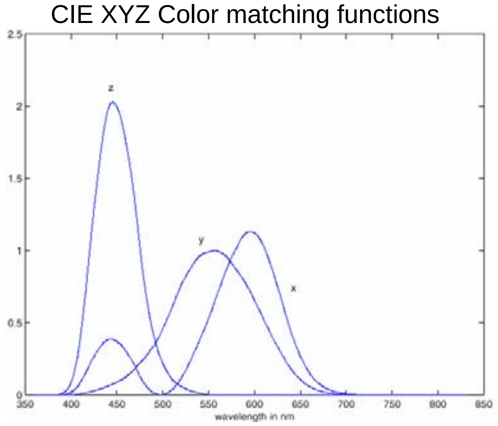
- Use a common set of primaries/color matching functions
- Linear
  - CIE XYZ
  - RGB
  - CMY
- Non-linear
  - HSV

CIE XYZ color space

- Established by the commission international d’eclairage (CIE), 1931
- Usually projected to display:
  (x,y) = (X/(X+Y+Z), Y/(X+Y+Z))



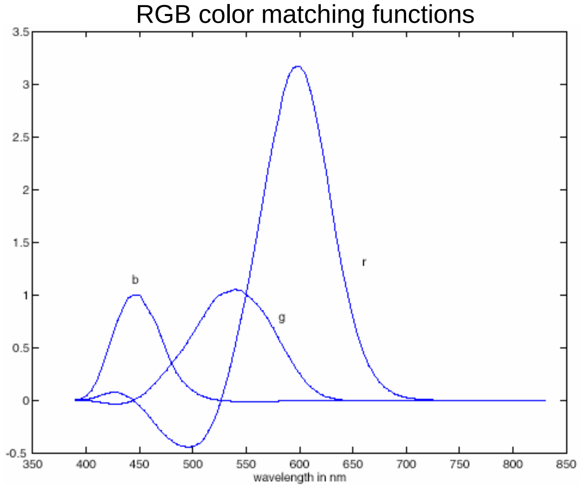
CIE XYZ Color matching functions

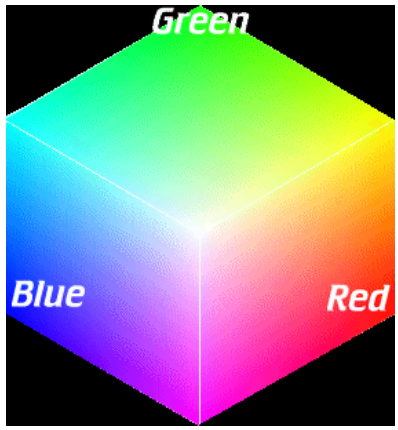


RGB color space

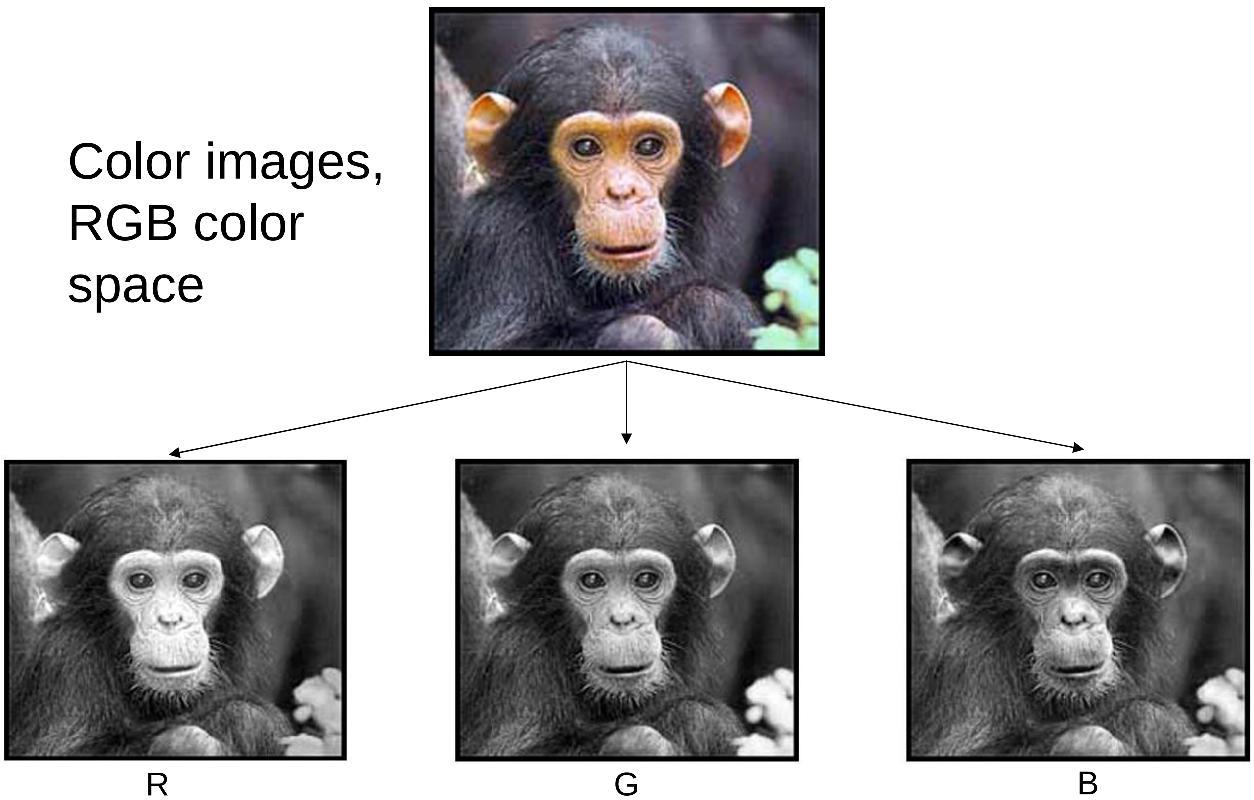
- Single wavelength primaries
- Phosphors for monitor

RGB color matching functions



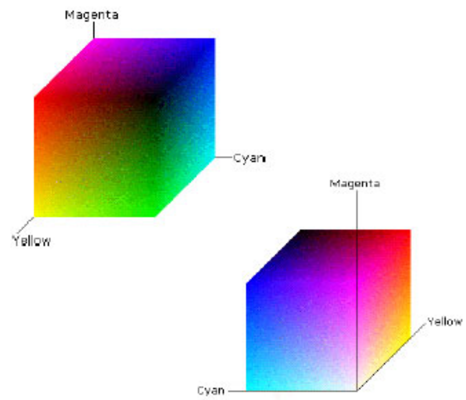


Color images, RGB color space



CMY

- Cyan Magenta Yellow
- Subtractive mixing (inks, pigment)



http://www.tech-writer.net/images/CMYKcolorcube.jpg

HSV

- Hue, Saturation, Value (Brightness)
- Nonlinear – reflects topology of colors by coding **hue** as an angle

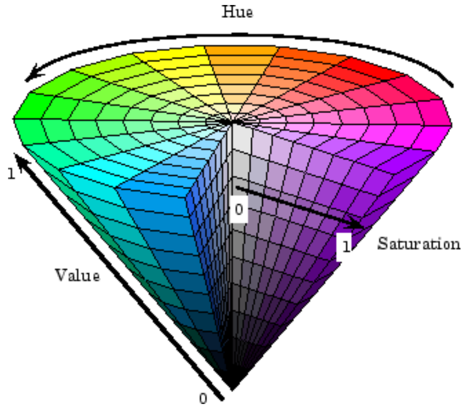
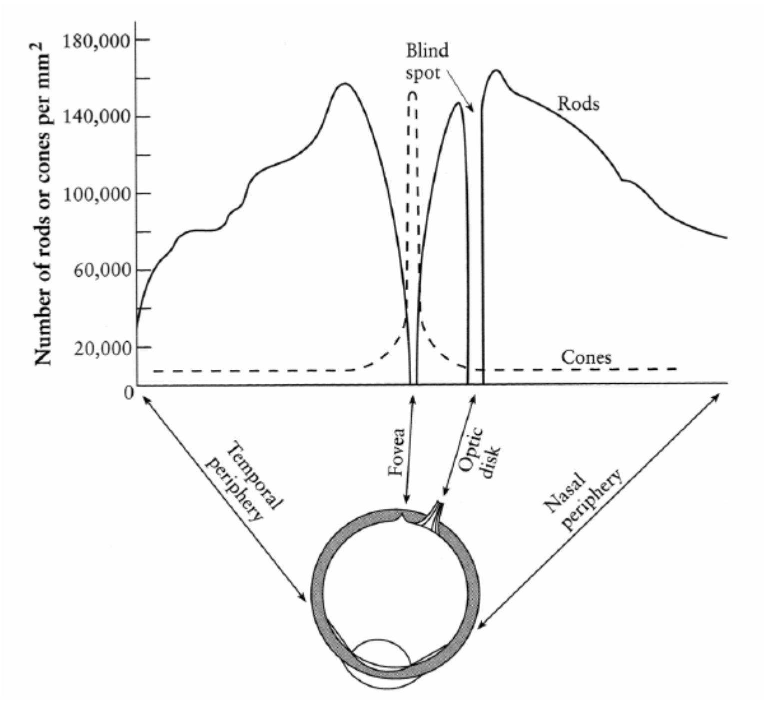


Image from mathworks.com

Color

- **Color of light** arriving at camera depends on
  - Spectral reflectance of the surface light is leaving
  - Spectral radiance of light falling on that patch
- **Color perceived** depends on
  - Physics of light
  - Visual system receptors
  - Brain processing, environment

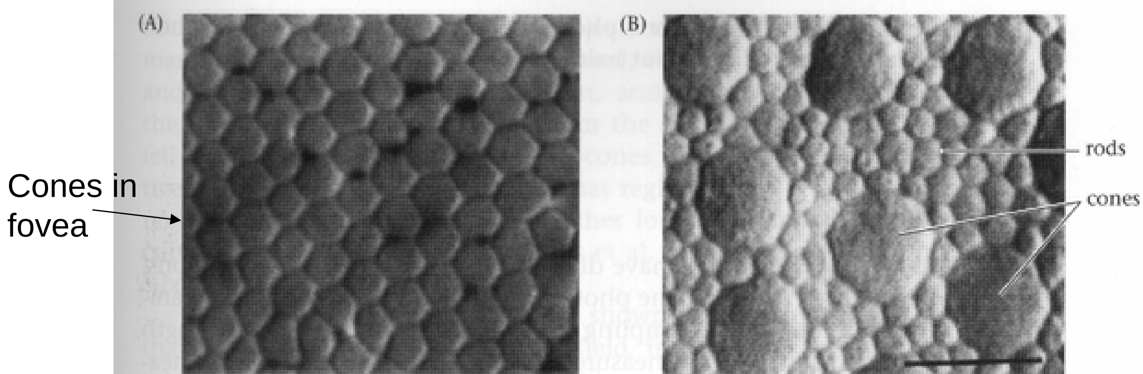
Human photoreceptors

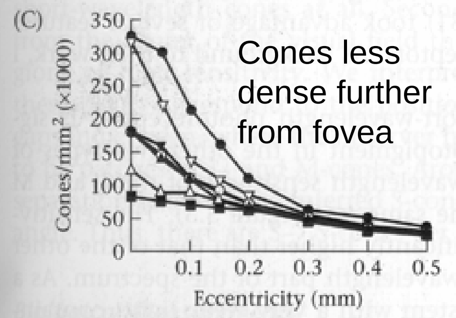


-**Rods** responsible for intensity
-**Cones** responsible for color
-**Fovea:** small region (1 or 2°) at the center of the visual field containing the highest density of cones (and no rods).
– Less visual acuity in the periphery

Adapted from Seitz, Duygulu

Human photoreceptors



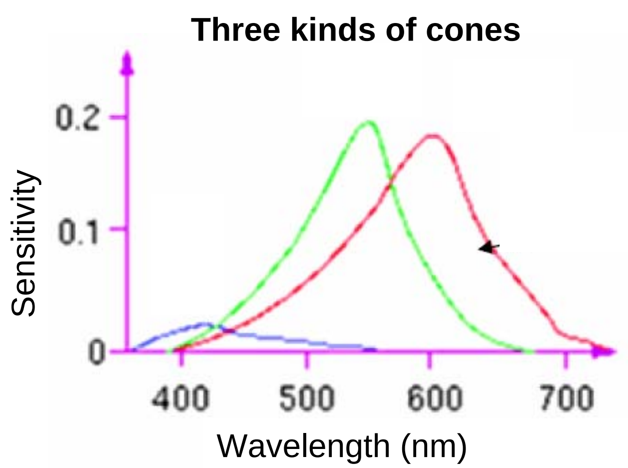


3.4 THE SPATIAL MOSAIC OF THE HUMAN CONES. Cross sections of the human retina at the level of the inner segments showing (A) cones in the fovea, and (B) cones in the periphery. Note the size difference (scale bar = 10 μm), and that, as the separation between cones grows, the rod receptors fill in the 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 photoreceptors

- React only to some wavelengths, with different sensitivities
- Brain fuses responses from local neighborhood of several cones for perceived color
- Sensitivities vary from person to person, and with age
- Color blindness: deficiency in at least one type of cone



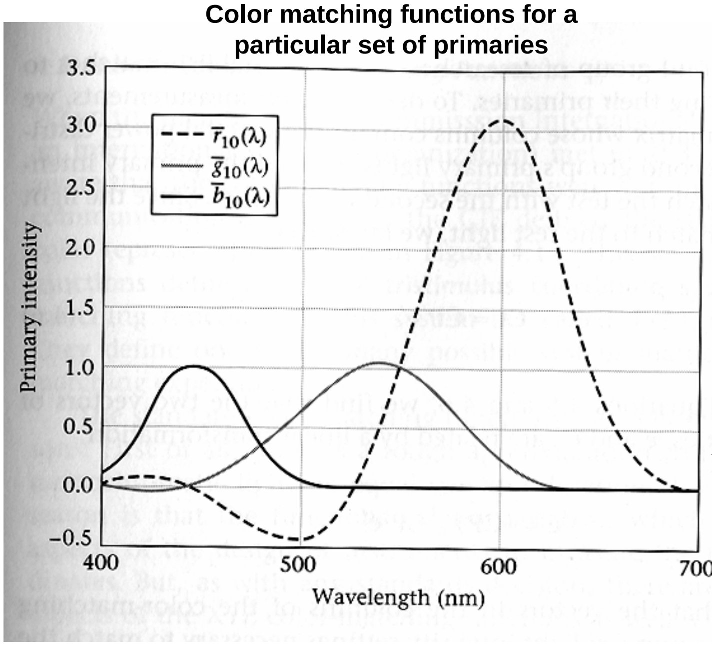
Trichromacy

- Experimental facts:
  - **Three primaries** will work for most people if we allow subtractive matching
    - Exceptional people can match with two or only one primary.
    - This could be caused by a variety of deficiencies.
  - Most people make the *same* matches (i.e., select the same mixtures)
    - Suggests three common types of receptors
    - …observed color matching functions obtainable from some 3x3 matrix transformation of the human photopigment response curves?

Adapted from D. Forsyth

Computing color matches

Color matching functions for a particular set of primaries



p_1 = 645.2 nm

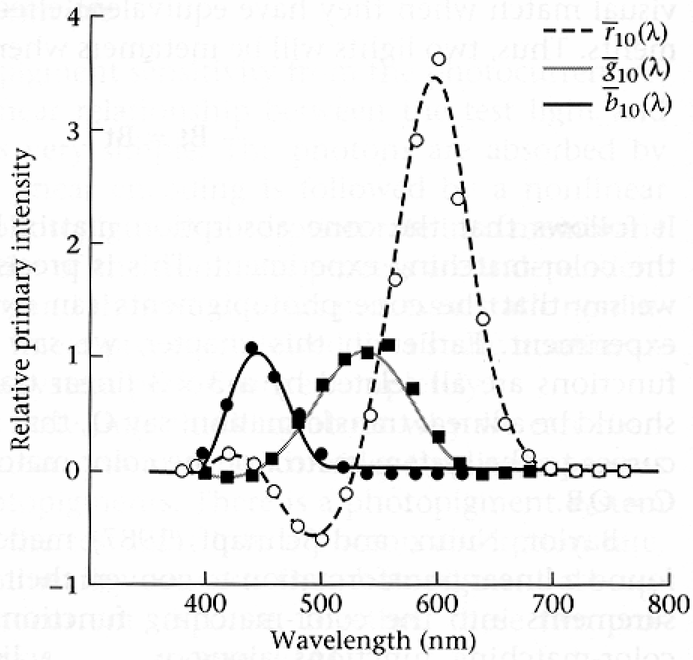
p_2 = 525.3 nm

p_3 = 444.4 nm

Rows of matrix C

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

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

Color

- **Color of light** arriving at camera depends on
  - Spectral reflectance of the surface light is leaving
  - Spectral radiance of light falling on that patch
- **Color perceived** depends on
  - Physics of light
  - Visual system receptors
  - Brain processing, environment

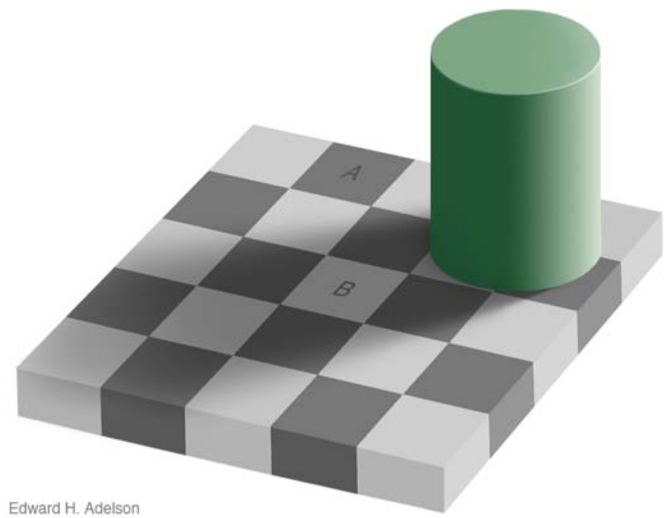
Color, shading perception

- *Chromatic adaptation*: we adapt to a particular illuminant
- *Assimilation & contrast effects*: nearby colors affect what is perceived

Color matching ~= color appearance

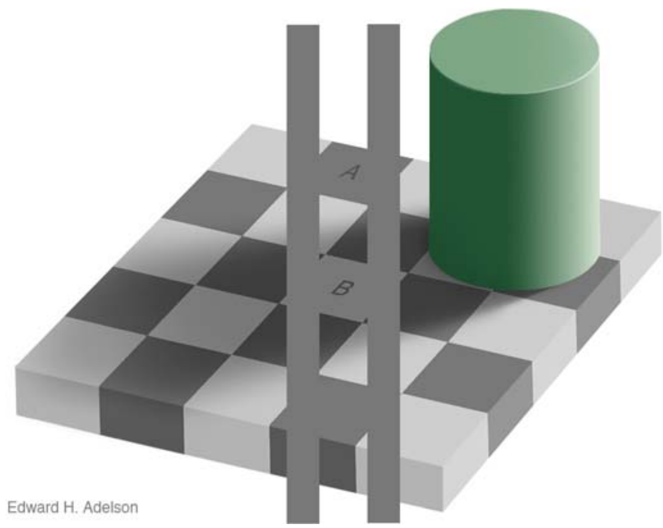
Physics of light ~= perception of light

Color/shading perception



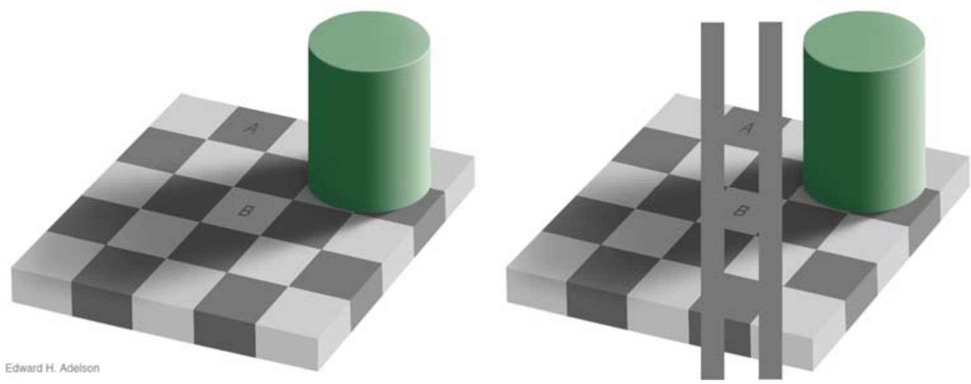
Edward Adelson

Color/shading perception

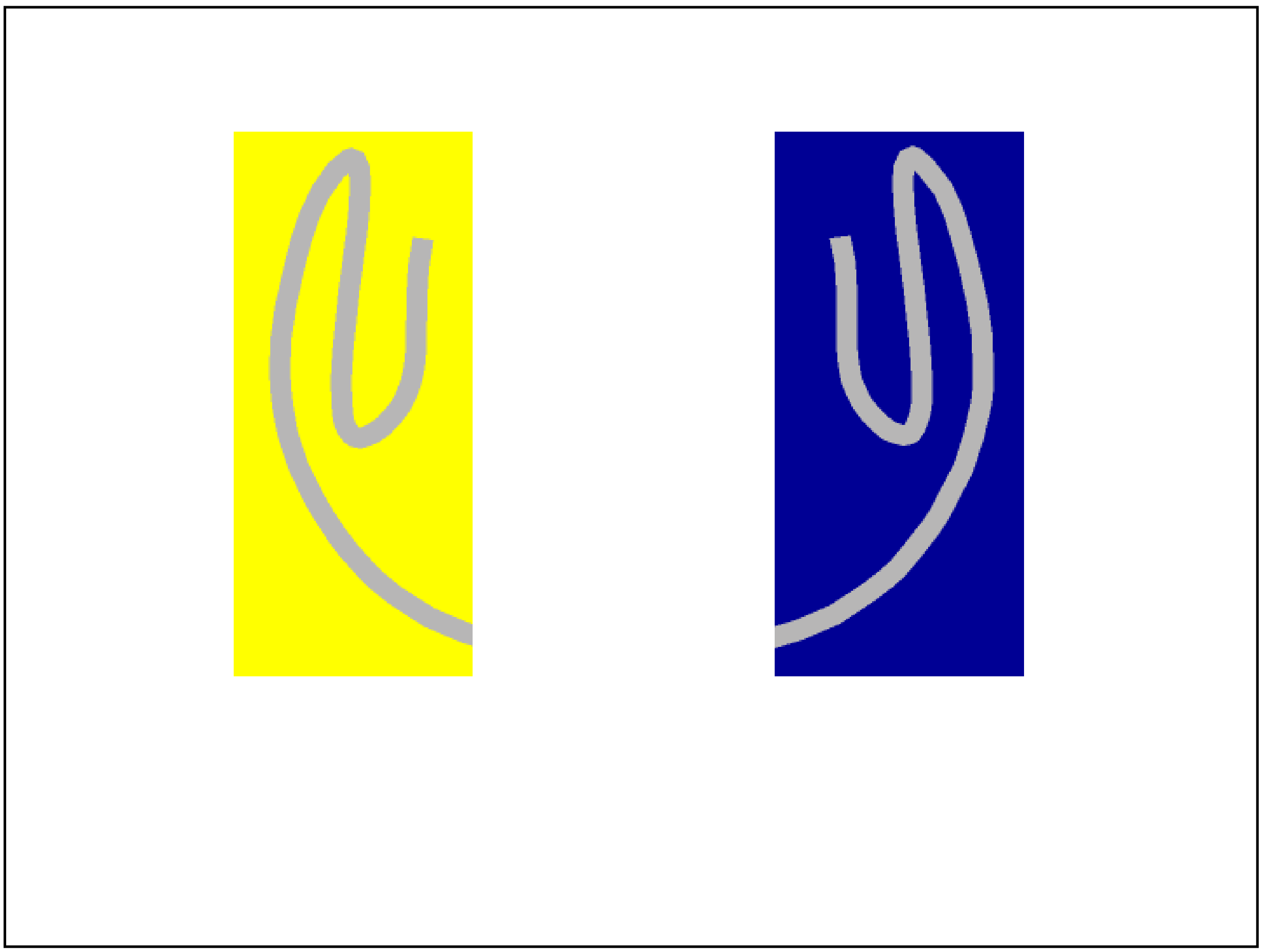


Edward Adelson

Color/shading perception



Edward Adelson



Name that color

Perceptual color matching

- Recall: lights forming a *perceptual* match may be *physically* different
  - Match light: must be combination of primaries
  - Test light: any light
- Metamers: pairs of lights that match perceptually but not physically

Metameric spectral power distributions

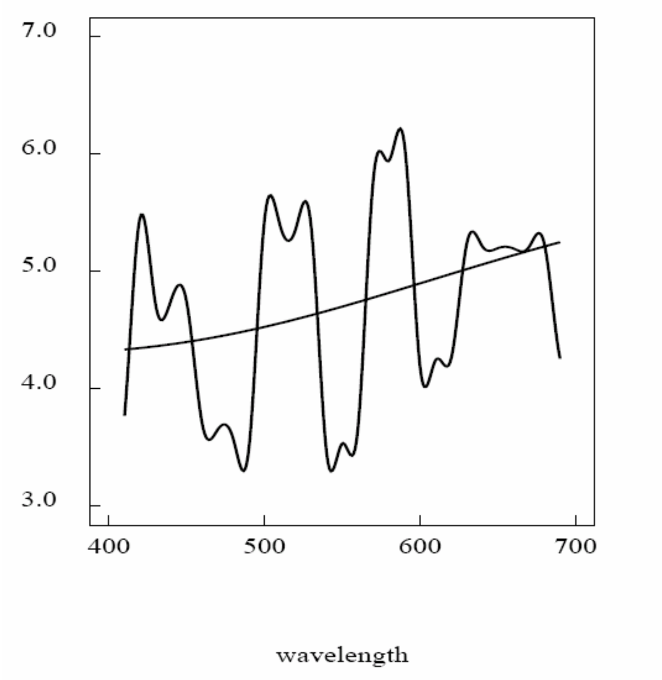
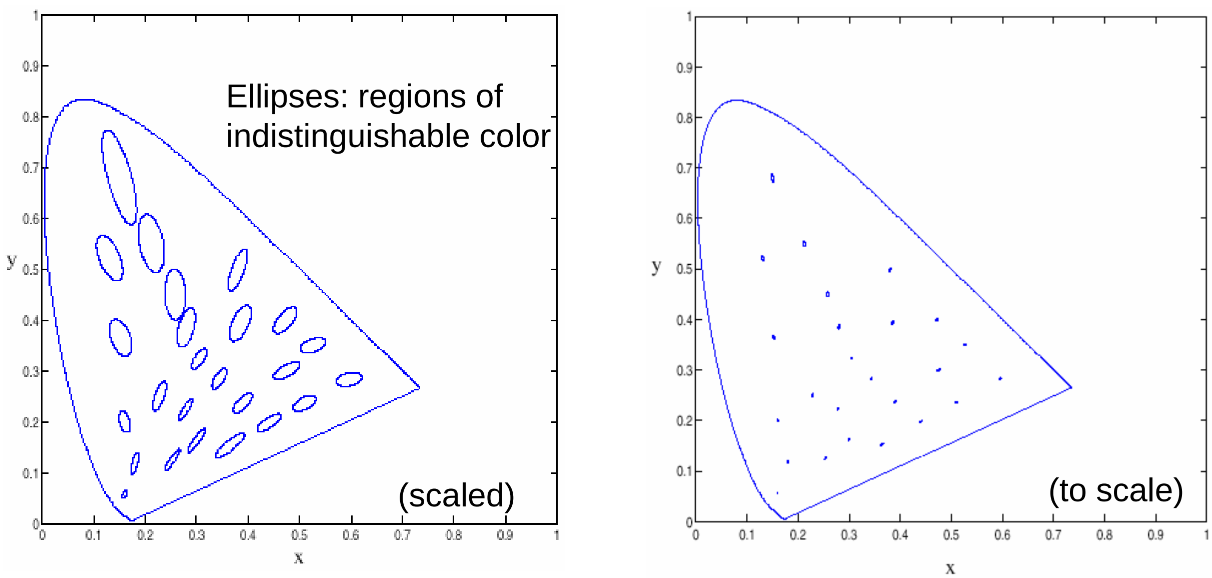


Fig from B. Wandell, 1996

MacAdam ellipses



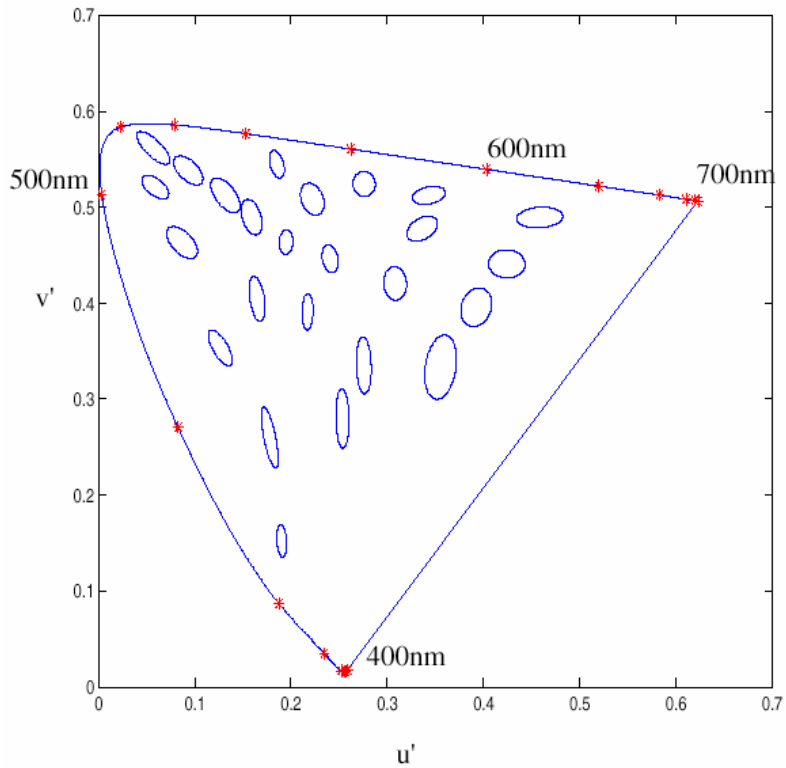
Variations in color matches in CIE x,y space

Euclidean distance in x,y not a good metric for perceptual similarity.

Figs from Forsyth & Ponce

CIE u'v'

- Projective transform of CIE x, y
- Closer to uniform color space (want MacAdam ellipses to be circles)

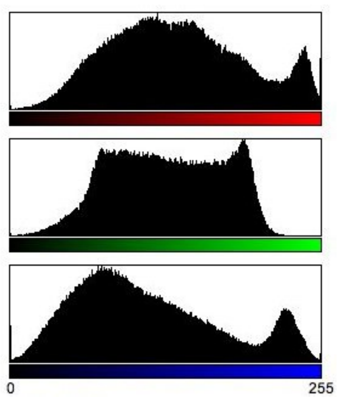


See also: CIE Lab

Forsyth & Ponce

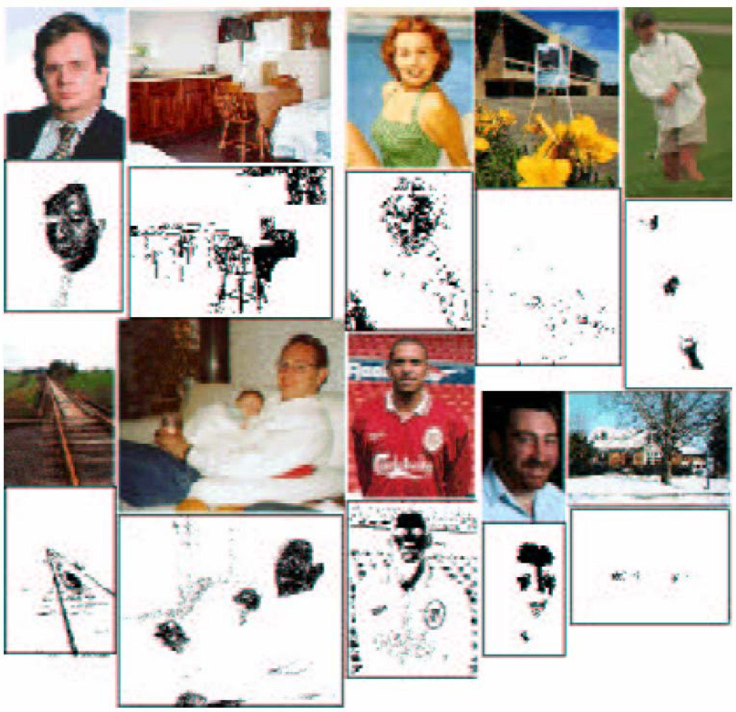
Color histograms

- A simple cue: use distribution of colors to describe image (region)
- No spatial info - invariant to translation, rotation, scale.



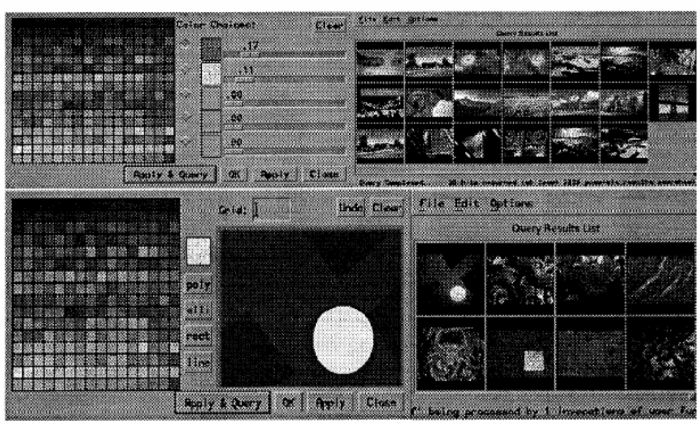
See Swain and Ballard, Color Indexing, IJCV 1991.

Skin detection



M. Jones and J. Rehg, Statistical Color Models with Application to Skin Detection, IJCV 2002.

Color as a low-level cue for CBIR



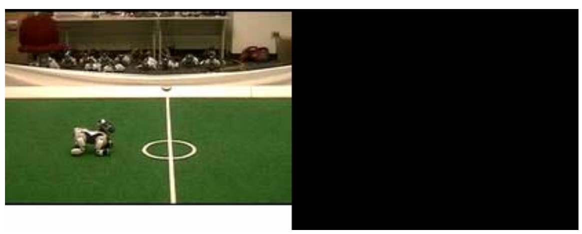
ıre 1: Top: Query by color histogram: Query specification on left. Best 20 results on right. Bottom:
nting". User painting on the left. Best 8 results on right.

IBM's Query by image content (QBIC) system
From Ashley et al., SIGMOD 1995

Blobworld system
Carson et al, 1999

When is color not a good indicator?

Color-based segmentation for robot soccer



Towards Eliminating Manual Color Calibration at RoboCup. Mohan Sridharan and Peter Stone. RoboCup-2005: Robot Soccer World Cup IX, Springer Verlag, 2006

http://www.cs.utexas.edu/users/AustinVilla/?p=research/auto_vis

Next

- Pset0 due Thursday before class – turn in hardcopy
- Read Chapter 7 for Tuesday

Matlab