EE 584
MACHINE VISION

Color

- Fundamentals
- Color Mixing
- Color Matching
- Trichromacy
- Color Spaces
- Surface Color from Image Color

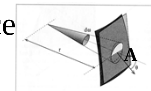
Radiometry : Definitions

Light is a radiant energy by which its action on the organs of vision, enables them to perform their function of sight

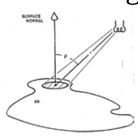
Light typically consists waves of different wavelengths (λ)

The following definitions apply in general for lightwaves:

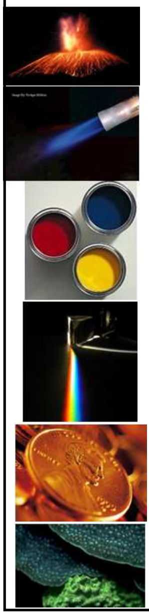
- *Radiant flux:* power propagated as light radiation (W)
- *Irradiance* : amount of light falling on a unit surface (W/m2)
- *Radiance* : amount of light radiating from a unit surface towards a "solid" angle (W/m2 steradian)



- *Radiant exitance (radiosity)* : amount of light radiating from a unit surface (W/m2)
- *Radiant intensity:* amount of light radiating towards a "solid" angle (W/steradian)



Causes of color



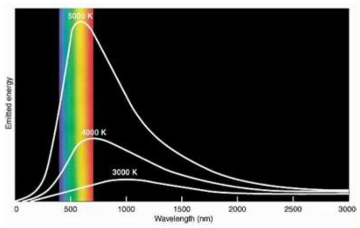
- The sensation of color is caused by the brain.
- Some ways to get this sensation include:
  - Pressure on the eyelids
  - Dreaming, hallucinations, etc.
- Main way to get it is the response of the visual system to the presence/absence of **light at various wavelengths.**

- Light could be produced in different amounts at different wavelengths
- Light could be differentially reflected (e.g. some pigments).
- It could be differentially refracted - (e.g. Newton's prism)
- Wavelength dependent specular reflection - e.g. shiny copper penny (actually most metals).
- Flourescence - light at invisible wavelengths is absorbed and reemitted at visible wavelengths.

Black body radiators

- Construct a hot body with near-zero reflectance (black body)
  - Easiest way to do this is to build a hollow metal object with a tiny hole in it, and look at the hole.
- The spectral power distribution of light leaving this object is a simple function of temperature

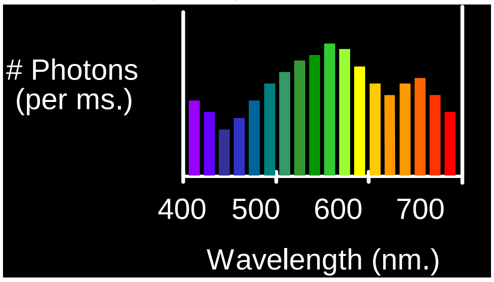
$$E(\lambda) \propto \left(\frac{1}{\lambda^5}\right)\left(\frac{1}{\exp(hc/k\lambda T)-1}\right)$$



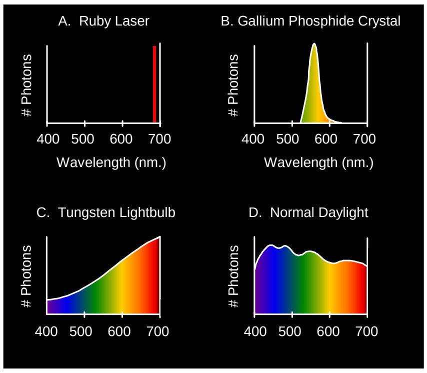
- Incandescent lamps = blackbody radiator at 1500-3000K
- This leads to the notion of color temperature
  - temperature of a black body that would look the same

Spectral power distribution

- The power per unit area at each wavelength of a radiant object



- Some examples of the spectra of light sources



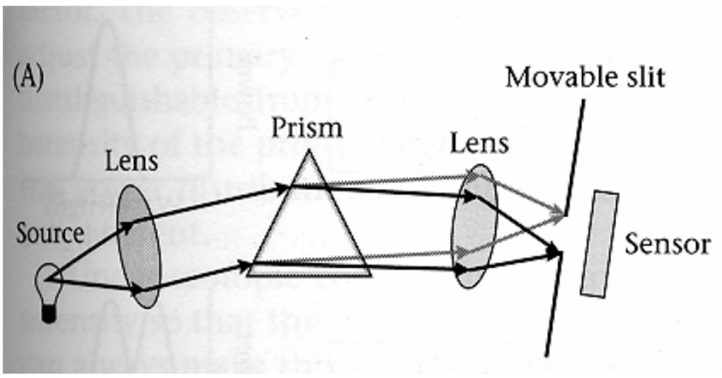
5

Figure © Stephen E. Palmer, 2002

These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

Spectral power distribution Measurement

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

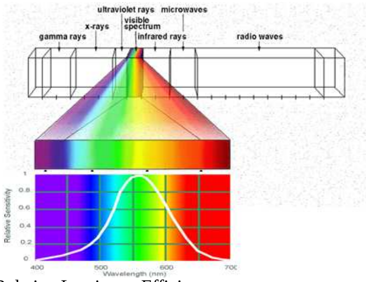


6

Foundations of Vision, B. Wandell

Radiometry vs. Photometry

- **Radiometric measurements**: Quantitative description of <u>physical</u> intensity

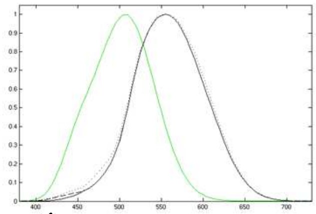


Relative Luminous Efficiency
(Human Luminance Sensitivity Function)

- **Photometric measurements**: Quantitative description of <u>perceptual brightness</u>
- *Luminous flux* (lumen, lm) :

$$F = K_m \int_0^\infty C(\lambda)V(\lambda)d\lambda$$

  - $K_m = 685\ lm/W$
  - Spectral power distribution, $C(\lambda)$
  - <u>Relative luminous efficiency</u>, $V(\lambda)$, describes the average <u>visual sensitivity</u> of the <u>human eye</u> to light of different wavelengths.



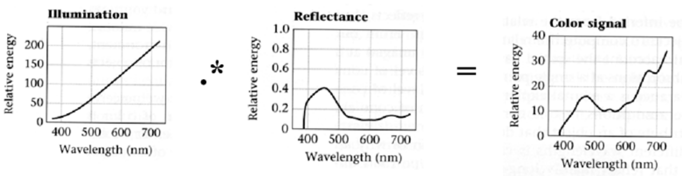
$V(\lambda)$: Low illum. vs High illum.

EE 584 Lecture Notes by A. Aydin Alatan 2013

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.

BRDF(λ) = radiance(λ) / irradiance(λ)
Bidirectional <u>Reflectance</u> Distribution Func.

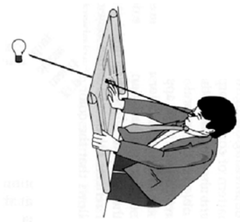


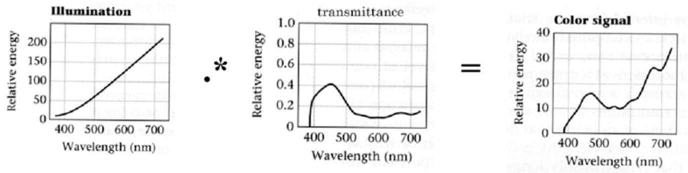
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

slide from T. Darrel

These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

Simplified rendering models: Transmittance



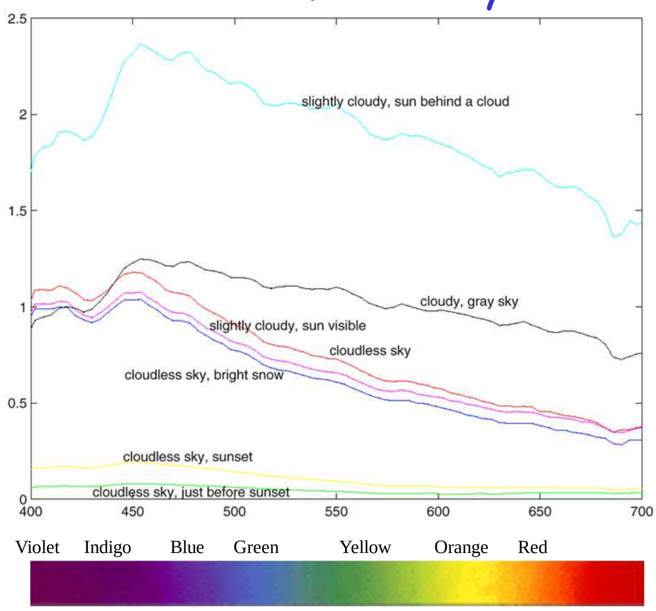


Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

9 slide from T. Darrel

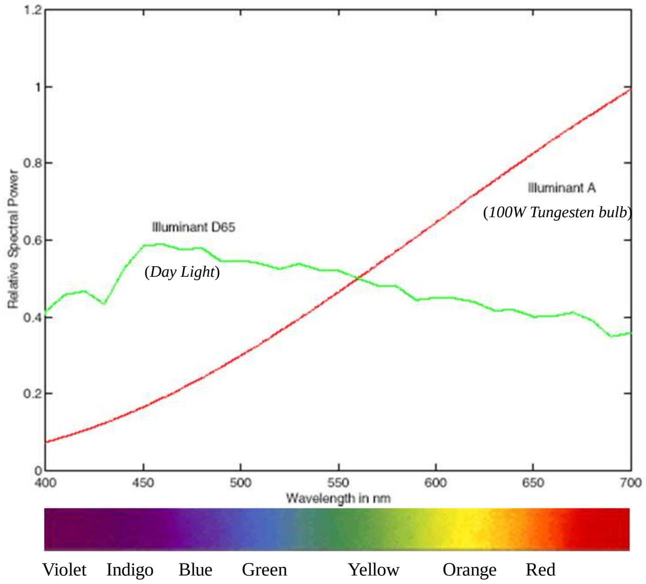
These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

Color of the sky

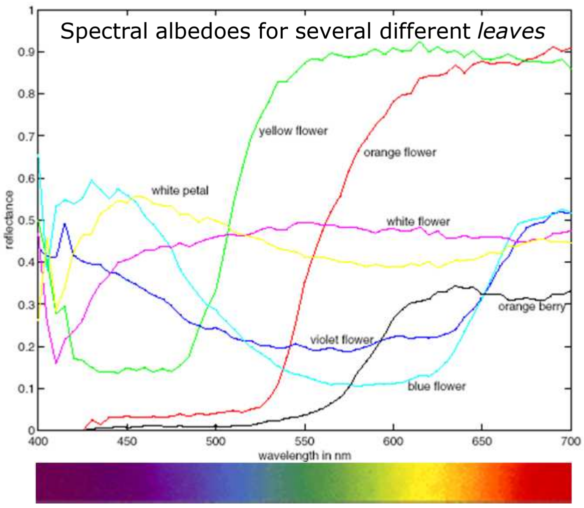


10 J. Parkkinen and P. Silfsten

Color of lightsources



Color of Surfaces



A simplified model for surface color:

$$\underbrace{E(\lambda)}_{\text{spectral radiosity}} = \underbrace{\rho(\lambda)}_{\text{spectral albedo}} \underbrace{S(\lambda)}_{\text{spectral irradiance}}$$

Spectral albedo== Spectral reflectance

Spectral albedos are typically quite smooth functions.

spectral albedo $\Rightarrow$ color
color $\not\Rightarrow$ spectral albedo

Measurements by E.Koivisto.

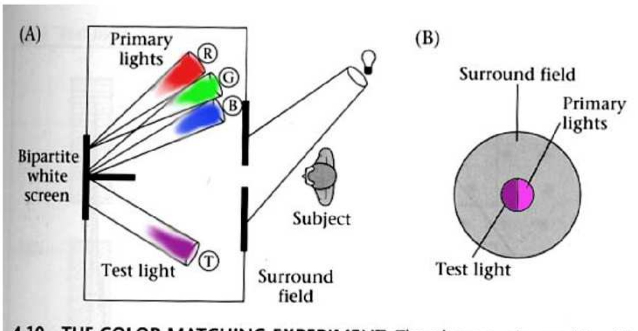
Why specify color numerically?

- Accurate color reproduction is commercially valuable
  - Many products are identified by color
- 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?
- Colorimetry is the science of quantitatively measuring color

13

These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

Color matching experiment

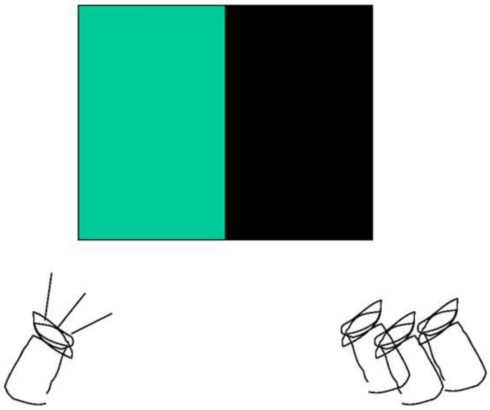


4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

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

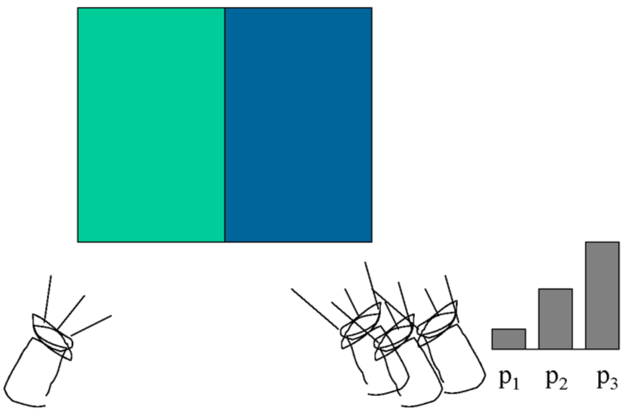
14 slide from T. Darrel

Color matching experiment 1



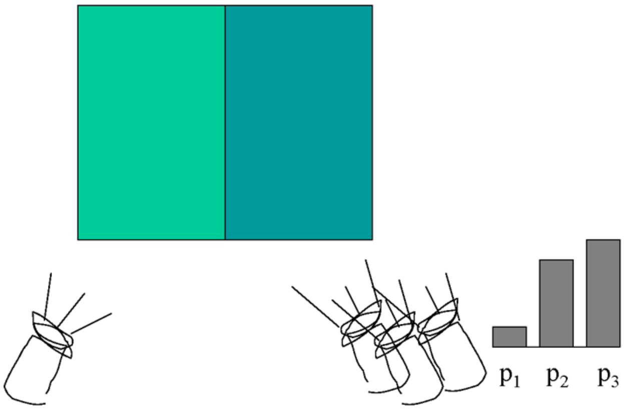
15 slide from T. Darrel

Color matching experiment 1



16 slide from T. Darrel

Color matching experiment 1

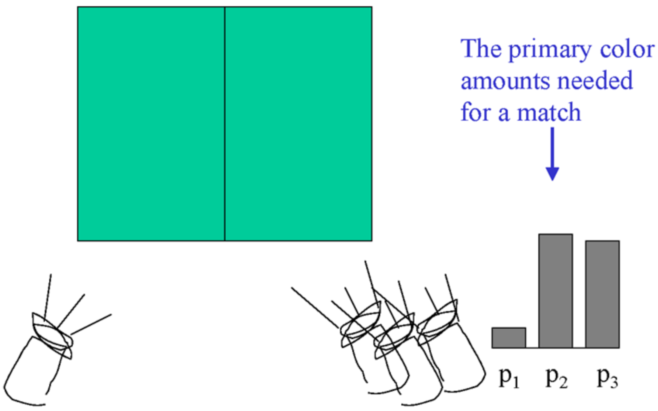


17

slide from T. Darrel

These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

Color matching experiment 1

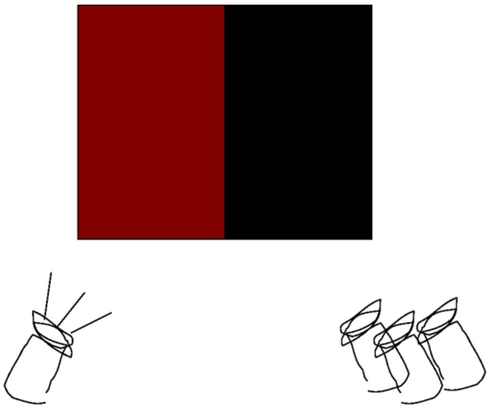


Note that the same experiment should initially be performed for a reference white color to determine its weights

18

slide from T. Darrel

Color matching experiment 2

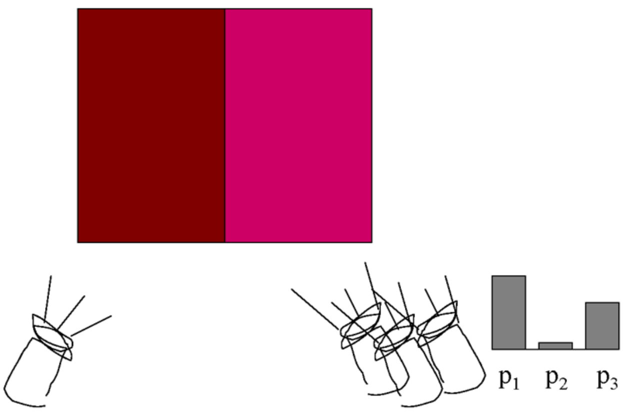


19

slide from T. Darrel

These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

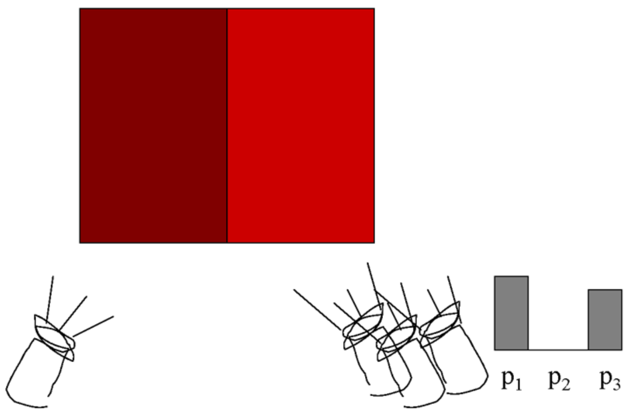
Color matching experiment 2



20

slide from T. Darrel

Color matching experiment 2

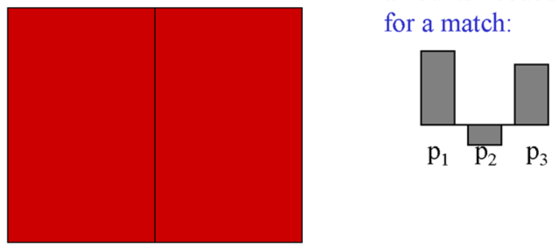


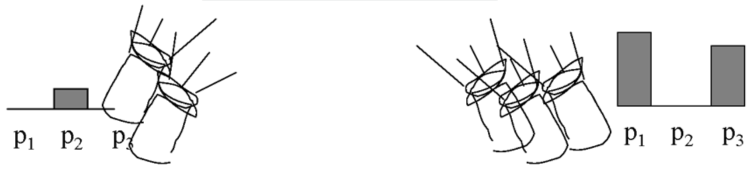
slide from T. Darrel

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.

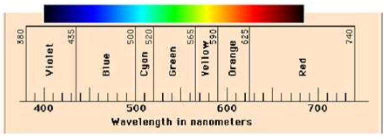
The primary color amounts needed for a match:

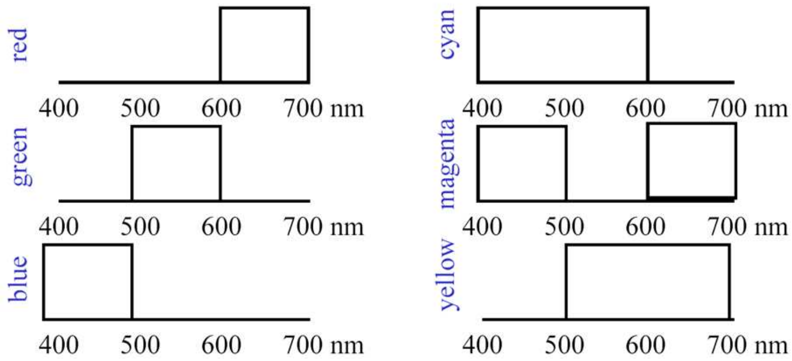




slide from T. Darrel

Color names for cartoon spectra

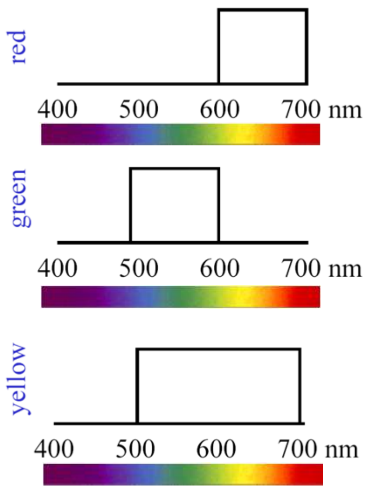




slide from T. Darrel

These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

Additive color mixing



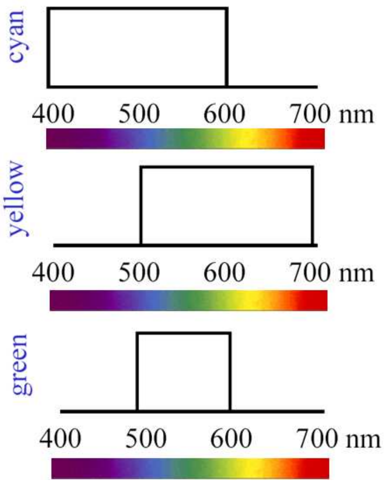
When colors combine by *adding* the color spectra. Examples that follow this mixing rule: CRT phosphors, multiple projectors aimed at a screen, Polachrome slide film.

Red and green make…

Yellow!

slide from T. Darrel

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!

slide from T. Darrel

These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

The principle of trichromacy

- Experimental facts Color Matching :
  - 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.
    - There are some anomalous trichromats, who use three primaries but make different combinations to match.

Grassman's Laws

- Color matching is (approximately) linear
  - 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
  - A color match at one radiance level holds over a wide range of levels
- If we mix 2 test lights, T_a & T_b
  where $T_a = \omega_{a1}P_1 + \omega_{a2}P_2 + \omega_{a3}P_3$ & $T_b = \omega_{b1}P_1 + \omega_{b2}P_2 + \omega_{b3}P_3$
  it has been experimentally shown that
  ➔ $T_a + T_b = (\omega_{a1} + \omega_{b1})P_1 + (\omega_{a2} + \omega_{b2})P_2 + (\omega_{a3} + \omega_{b3})P_3$
  ➔ *Linearity*

27 *Here "=" means "matches".*

These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

Color Matching Functions

- Pick a set of 3 primary color lights, P_1, P_2 & P_3
- For a single wavelength (λ) unit source, $U(\lambda)$ (i.e. monochromatic), find experimentally the weight of each primary to match this source

$$U(\lambda) = \underbrace{c_1(\lambda)}_{color}P_1 + \underbrace{c_2(\lambda)}_{matching}P_2 + \underbrace{c_3(\lambda)}_{functions}P_3$$

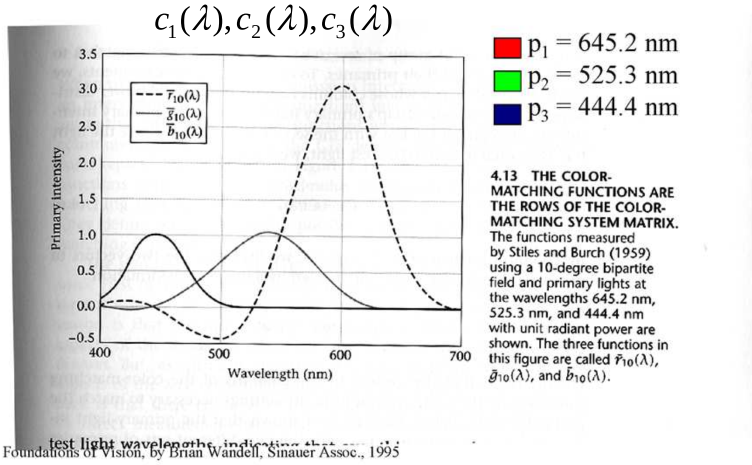
- For an arbitrary source, S, in order to find the corresponding weights for each primary :

$$S = \omega_1 P_1 + \omega_2 P_2 + \omega_3 P_3$$
$$= \left(\int S(\lambda)c_1(\lambda)d\lambda\right)P_1 + \left(\int S(\lambda)c_2(\lambda)d\lambda\right)P_2 + \left(\int S(\lambda)c_3(\lambda)d\lambda\right)P_3$$

28 *Here "=" means "matches".*

Color matching functions for a particular set of monochromatic primaries

$$c_1(\lambda), c_2(\lambda), c_3(\lambda)$$



p_1 = 645.2 nm
p_2 = 525.3 nm
p_3 = 444.4 nm

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

$$U(\lambda) = c_1(\lambda)P_1 + c_2(\lambda)P_2 + c_3(\lambda)P_3$$

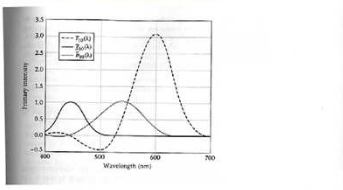
29 slide from T. Darrel

These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

Using the color matching functions to predict the primary match for 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 to be characterized be 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:

$$C\vec{t}$$

$$C\vec{t} = \begin{bmatrix} \sum_i c_1(\lambda_i)t(\lambda_i) \\ \sum_i c_2(\lambda_i)t(\lambda_i) \\ \sum_i c_3(\lambda_i)t(\lambda_i) \end{bmatrix}$$

30 slide from T. Darrel

How to translate between different primaries?

For primaries, P_1, P_2, P_3

For unit & single wavelent spectral signal $U(\lambda)$

$$\Rightarrow U(\lambda) = c_1(\lambda)P_1 + c_2(\lambda)P_2 + c_3(\lambda)P_3$$

For arbitrary spectral signal, $\vec{t} = [t(\lambda_i)]$

$$\Rightarrow \sum_i c_1(\lambda_i)t(\lambda_i)P_1 + \sum_i c_2(\lambda_i)t(\lambda_i)P_2 + \sum_i c_3(\lambda_i)t(\lambda_i)P_3$$

$$\Rightarrow \vec{t} = \omega_1 P_1 + \omega_1 P_2 + \omega_3 P_3$$

For another set of primaries, P_1', P_2', P_3', match $\vec{t} = [t(\lambda_i)]$

$$\Rightarrow \vec{t} = \omega_1' P_1' + \omega_2' P_2' + \omega_3' P_3'$$

What is the relation between $(\omega_1, \omega_2, \omega_3)$ and $(\omega_1', \omega_2', \omega_3')$?

Here "=" means "matches".

How to translate between different primaries?

Write P_1' in terms of the primaries P_1, P_2, P_3

$$P_1' = \omega_{11} P_1 + \omega_{12} P_2 + \omega_3 P_{13} \quad \text{where} \quad \omega_{kj} = \sum_i c_k(\lambda_i) P_j'(\lambda_i)$$

Here "=" means "matches".

Similarly write for P_2' and P_3' to obtain

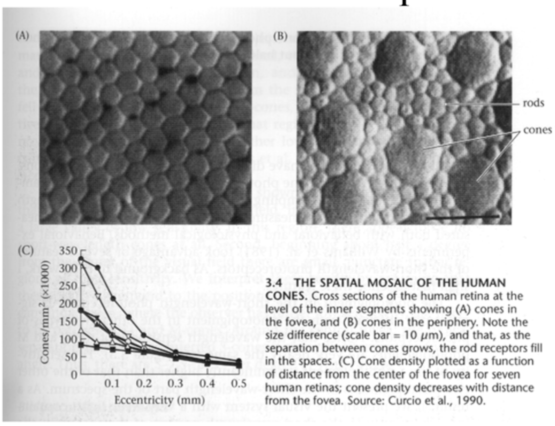
$$\Rightarrow \begin{bmatrix} P_1' \\ P_2' \\ P_3' \end{bmatrix} = \begin{bmatrix} \omega_{11} & \omega_{12} & \omega_{13} \\ \omega_{21} & \omega_{22} & \omega_{23} \\ \omega_{31} & \omega_{32} & \omega_{33} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix}$$

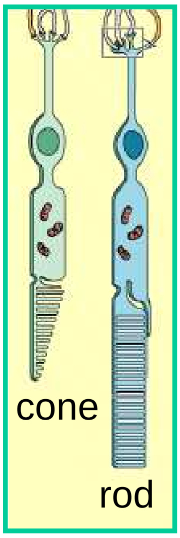
$$\Rightarrow \vec{t} = [\omega_1' \quad \omega_2' \quad \omega_3'] \begin{bmatrix} P_1' \\ P_2' \\ P_3' \end{bmatrix} = [\omega_1' \quad \omega_2' \quad \omega_3'] \begin{bmatrix} \omega_{11} & \omega_{12} & \omega_{13} \\ \omega_{21} & \omega_{22} & \omega_{23} \\ \omega_{31} & \omega_{32} & \omega_{33} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix}$$

Since $\vec{t} = \omega_1 P_1 + \omega_2 P_2 + \omega_3 P_3 \quad \Rightarrow \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} = \begin{bmatrix} \omega_{11} & \omega_{21} & \omega_{31} \\ \omega_{12} & \omega_{22} & \omega_{32} \\ \omega_{13} & \omega_{23} & \omega_{33} \end{bmatrix} \begin{bmatrix} \omega_1' \\ \omega_2' \\ \omega_3' \end{bmatrix}$

How does it work in the eye?

Human Photoreceptors





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

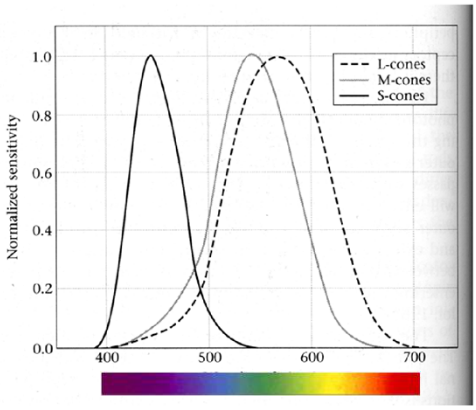
These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

How does it work in the eye?

Human eye photoreceptor spectral sensitivities

$$p_k = \int \sigma_k(\lambda) S(\lambda) d\lambda$$

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.



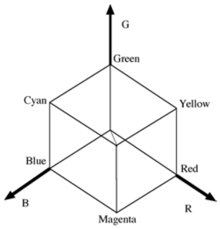
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

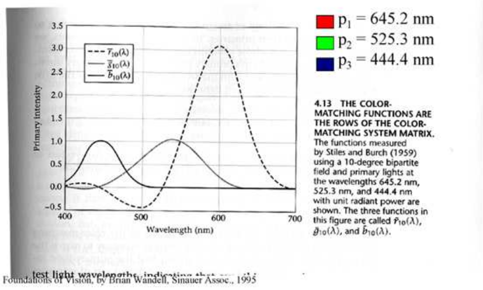
slide from T. Darrel

Color

Color matching functions for a particular set of monochromatic primaries

- Three primaries are Red, Green and Blue which have single wavelengths





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

$$S = \omega_1 P_1 + \omega_2 P_2 + \omega_3 P_3$$
$$= \left(\int S(\lambda) c_1(\lambda) d\lambda\right) P_1 + \left(\int S(\lambda) c_2(\lambda) d\lambda\right) P_2 + \left(\int S(\lambda) c_3(\lambda) d\lambda\right) P_3$$

Since some of the color matching functions are negative, some colors could only be obtained by subtractive color matching

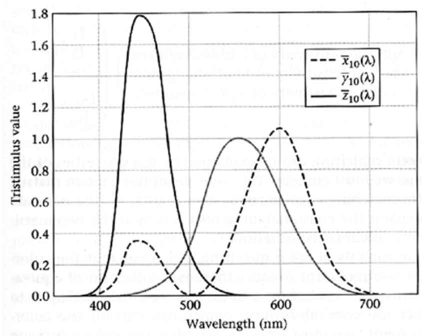
Note the similarity between weights and response in human eye $p_k = \int \sigma_k(\lambda) S(\lambda) d\lambda$

35

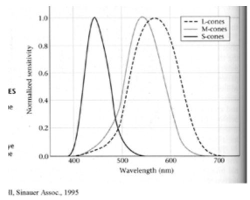
Color Spaces : *CIE XYZ*

Derived from CIE RGB by defining its color matching functions

- Based on imaginary primary colors
- Color matching function for Y is similar to spectral sensitivity of cone-M



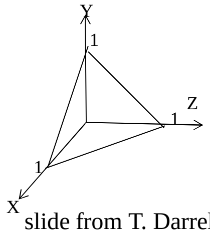
4.14 THE XYZ STANDARD COLOR-MATCHING FUNCTIONS. In 1931 the CIE standardized a set of color-matching functions for image interchange. These color-matching functions are called $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$. Industrial applications commonly describe the color properties 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.



ll, Sinauer Assoc., 1995

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)

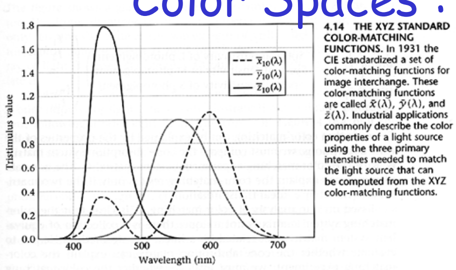
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

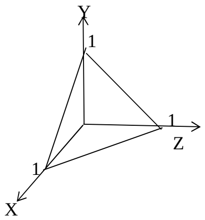


36 Y is the "luminance", perceived relative brightness

slide from T. Darrel

Color Spaces : *CIE XYZ*





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)

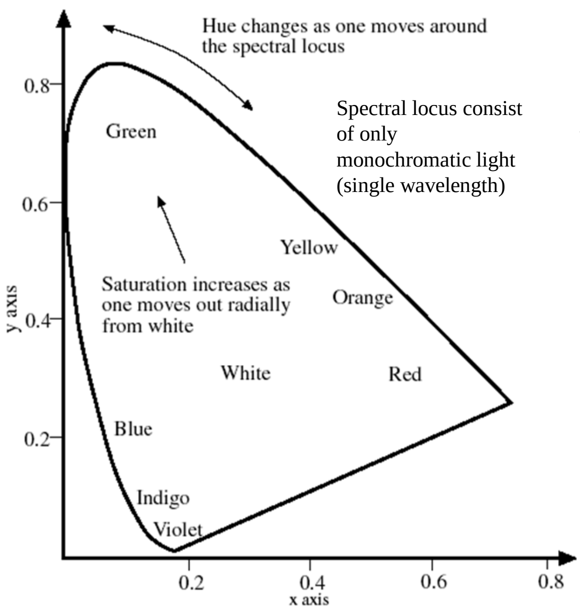
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad z = \frac{Z}{X+Y+Z} = 1 - x - y \qquad X = \frac{Y}{y}x \quad Z = \frac{Y}{y}(1-x-y)$$

This normalized color space is called CIE xyY

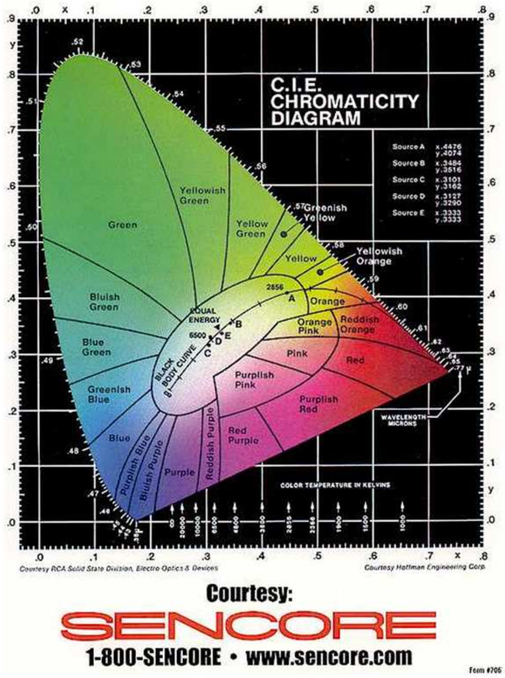
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

37 slide from T. Darrel



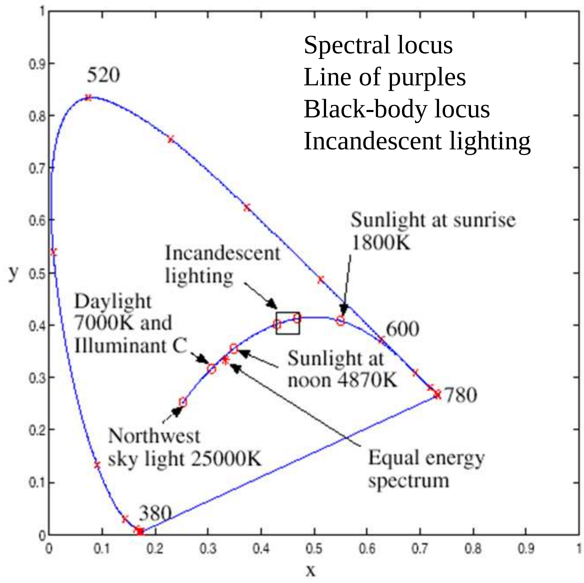
- Note that brightness is assumed to constant (normalized) in CIE (x,y) space.
- A qualitative rendering of the CIE (x,y) space.
- The blobby region represents visible colors.
- There are sets of (x,y) coordinates that do not represent real colors,
  - the primaries are not real lights
  - the color matching functions could be positive everywhere

38



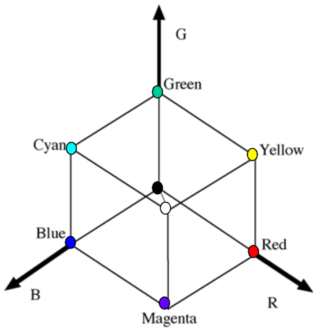
These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

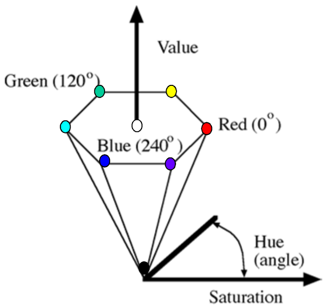
CIE x,y color space

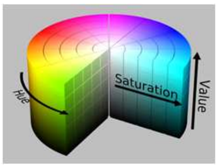


Non-linear color spaces: *HSV*

- *HSV*: Hue, Saturation, Value are non-linear functions of *XYZ*.
  - hue relations are naturally expressed in a circle





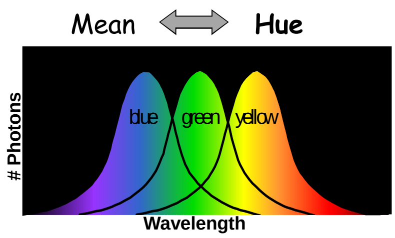


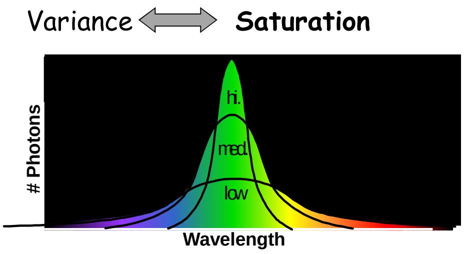
41

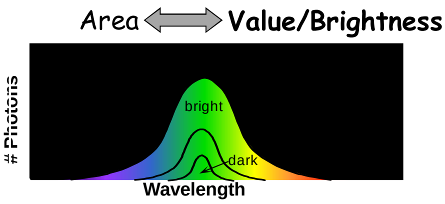
These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

Non-linear color spaces: *HSV*

- The Psychophysical Correspondence
  - Consider physical spectra as normal distributions





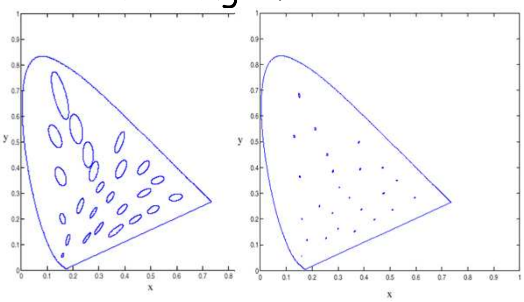


42

Non-linear color spaces: Uniform

- Uniform: equal (small!) steps give the same perceived color changes.

size of the ellipse represents the scatter of lights that the human observers tested would match to the test color;



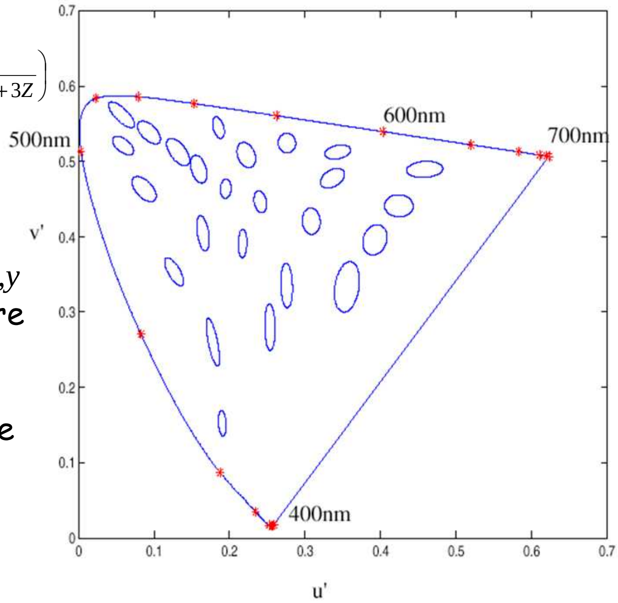
Ellipses on the left have been magnified 10x for clarity.

- *McAdam ellipses* 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 changes in color.

Non-linear color spaces: *CIE u'v'*

$$(u',v') = \left(\frac{4X}{X+15Y+3Z}, \frac{9Y}{X+15Y+3Z}\right)$$

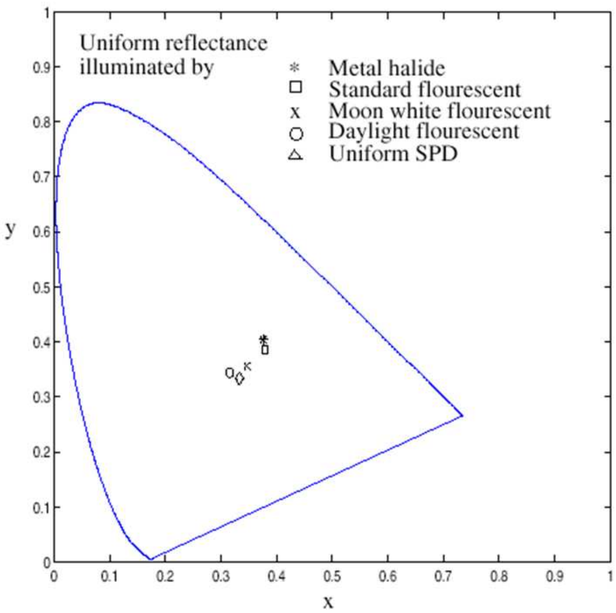
- CIE ($u'v'$) is a projective transform of x, y.
- We transform x,y so that ellipses are most like one another.
- Figure shows the transformed ellipses.



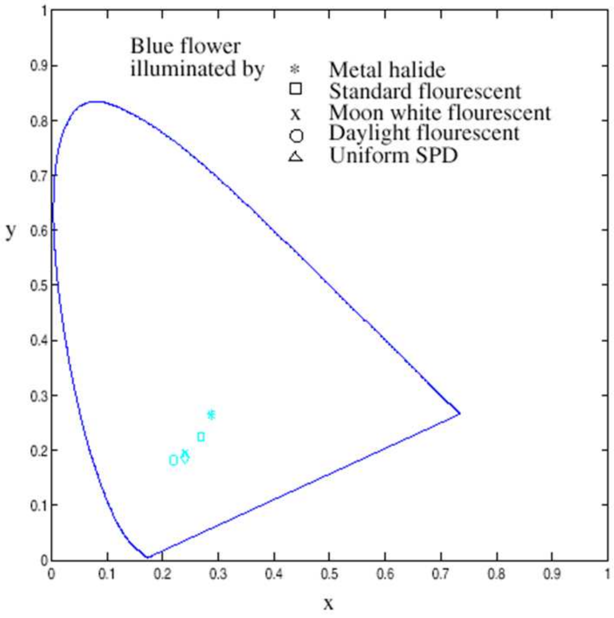
Color constancy

- The spectral radiance (received light power) at the camera depends on two terms
  - surface albedo
  - illuminant spectral radiance

  the effect is much more pronounced than most people think (see following slides)
- We would like an illuminant invariant description of the surface
  - e.g. some measurements of surface albedo
  - need a model of the interactions



- The color of light at the camera varies with the illuminant color
- A uniform reflectance illuminated by five different lights, and the result plotted on CIE x,y



- The <u>color of light at the camera varies</u> with the illuminant color
- A uniform reflectance illuminated by <u>five different lights</u>, and the result plotted on CIE x,y

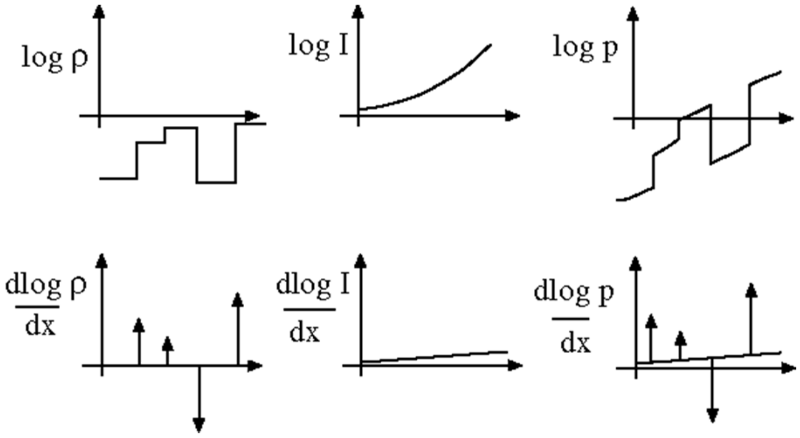
These slides are modified from COMP 256 (UNC) Lecture Notes by Prof. Marc Pollefeys EE 584 Lecture Notes by A. Aydin Alatan 2013

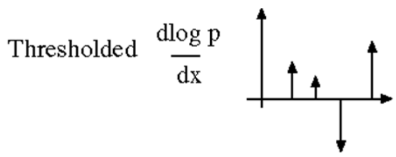
Lightness Constancy

- Lightness is defined as the <u>estimate of a surface reflectance</u> obtained from visual data
- Lightness constancy
  - how "light" is the surface, independent of the brightness of the illuminant
  - issues
    - spatial variation in illumination
    - absolute standard
  - Human lightness constancy is very good
- Assume
  - frontal 1D "surface"
  - <u>slowly varying illumination</u>
  - <u>quickly varying surface reflectance</u>

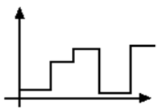
The received light power, C, on a camera from an illuminated surface that has a piecewise constant reflectance (albedo), ρ. (k_c is the camera gain)

$$C(x) = k_c I(x)\rho(x) \quad \Rightarrow \quad \log C(x) = \log k_c + \log I(x) + \log \rho(x)$$





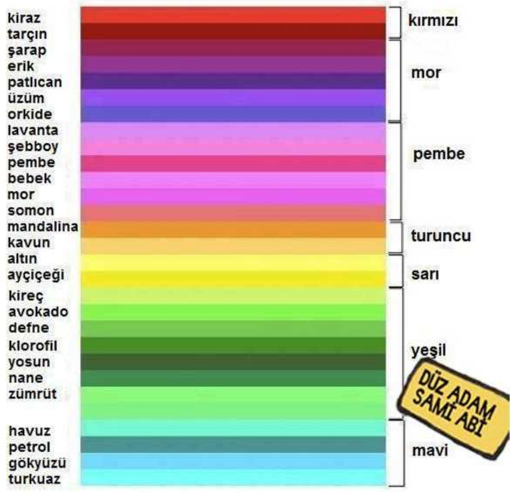
Integrate
This to get



- How do we choose the constant of integration?
  - average lightness is grey
  - lightest object is white

Names for colors by gender (in Turkish) ☺

FEMALE **MALE**



51