Light and Color Perception

<Vision System>

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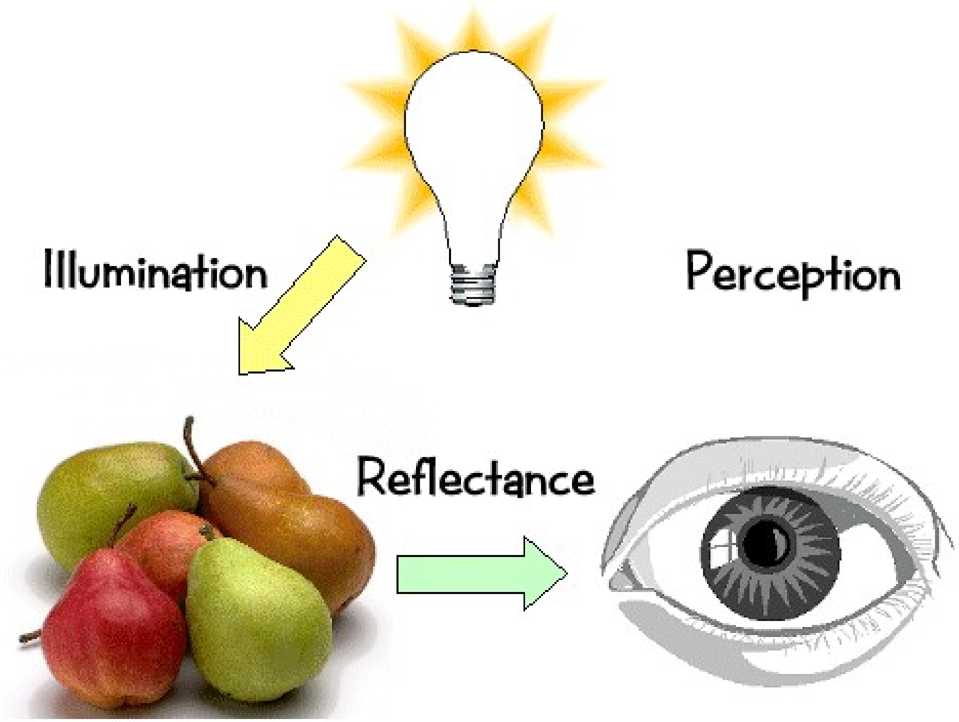
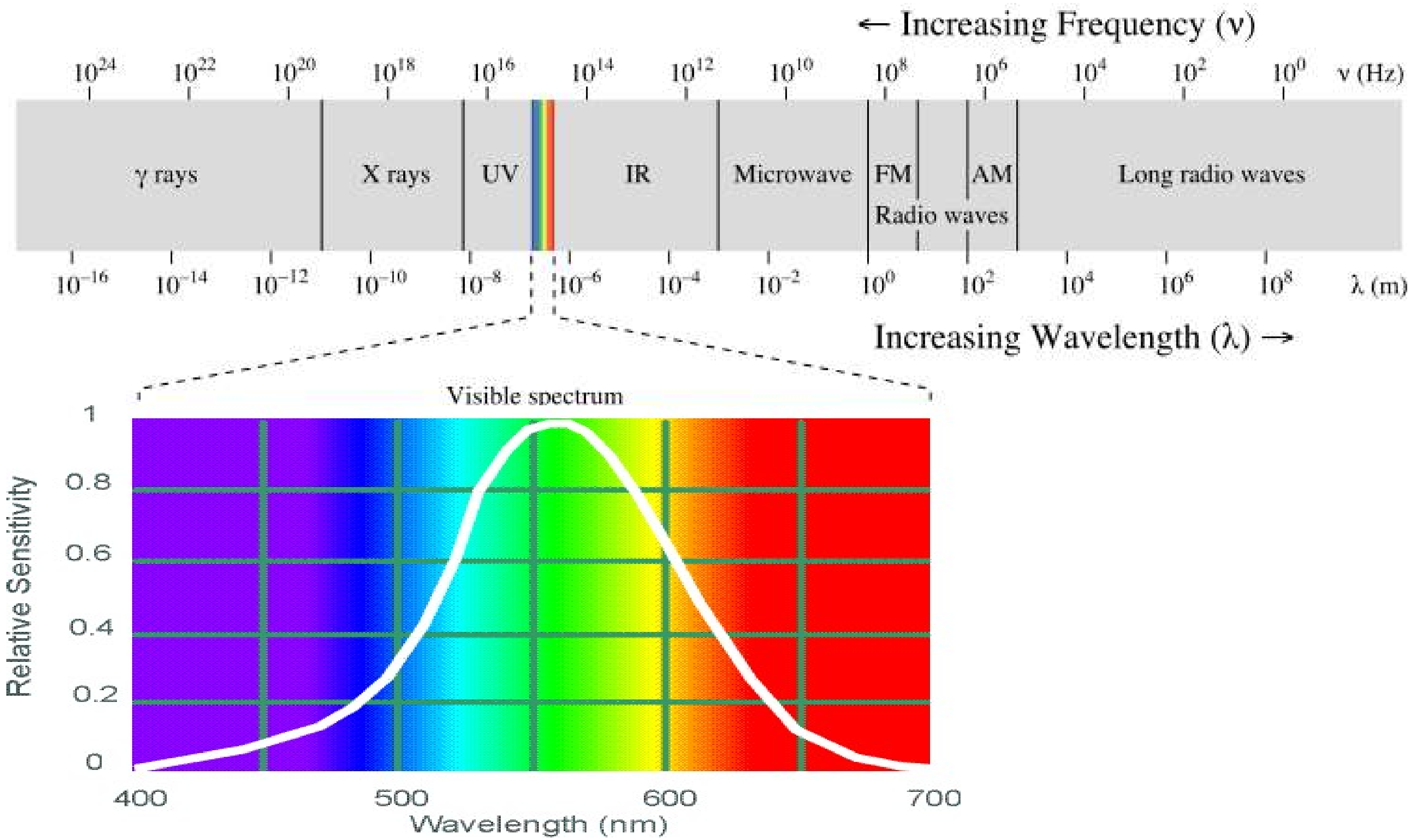
What is color?

Color is a psychological property of our visual experiences when we look at objects and lights, *not* a physical property of those objects or lights (S. Palmer, *Vision Science: Photons to Phenomenology*)

Color is the result of interaction between physical light in the environment and our visual system



Electromagnetic spectrum



Human Luminance Sensitivity Function

Why do we see light at these wavelengths?

Because that's where the sun radiates electromagnetic energy

Achromatic vs. Chromatic

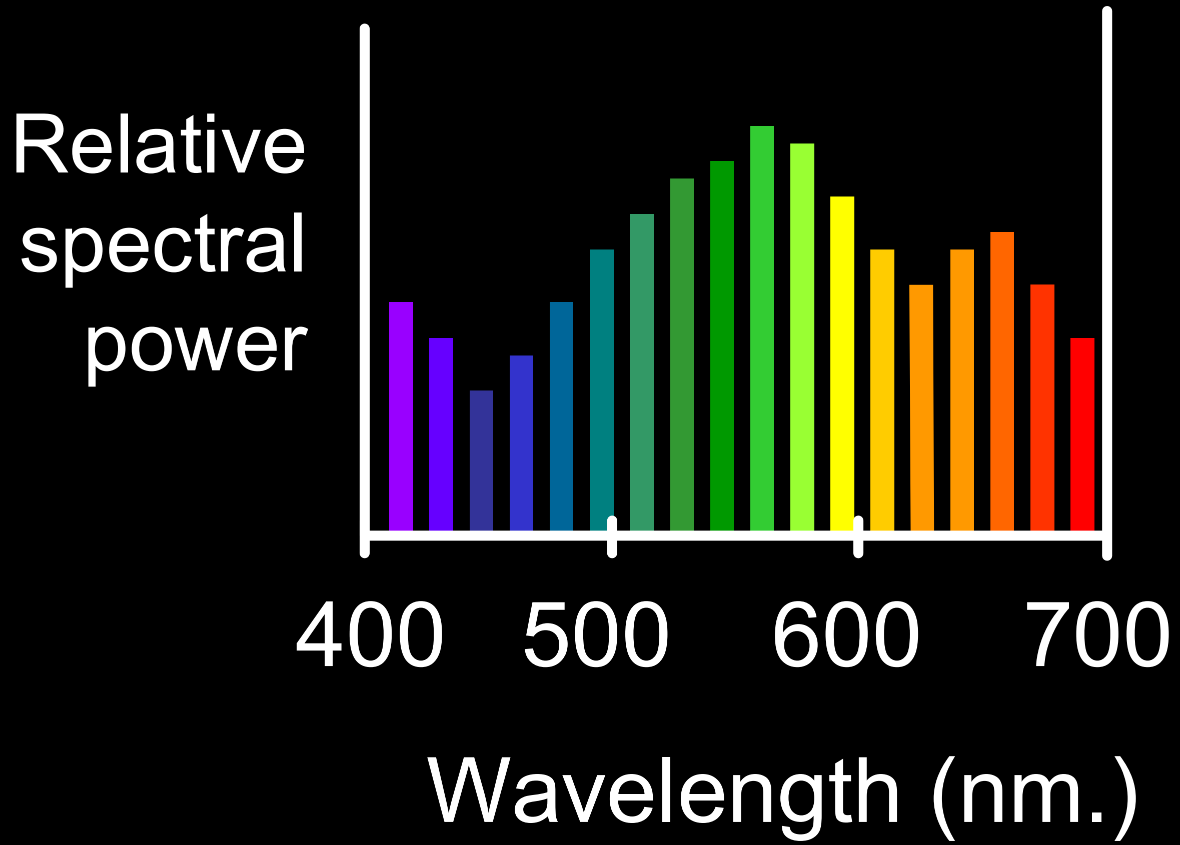
- The colors that humans perceive are determined by the nature of the light reflected from an object! Green objects reflect “green” light!
- Achromatic: Only *intensities* (amount of light). Achromatic information ranges from black to white

Example: Gray levels as seen on black/white TV screens.

- Chromatic: Lightwaves; Visual range: 400nm-700nm

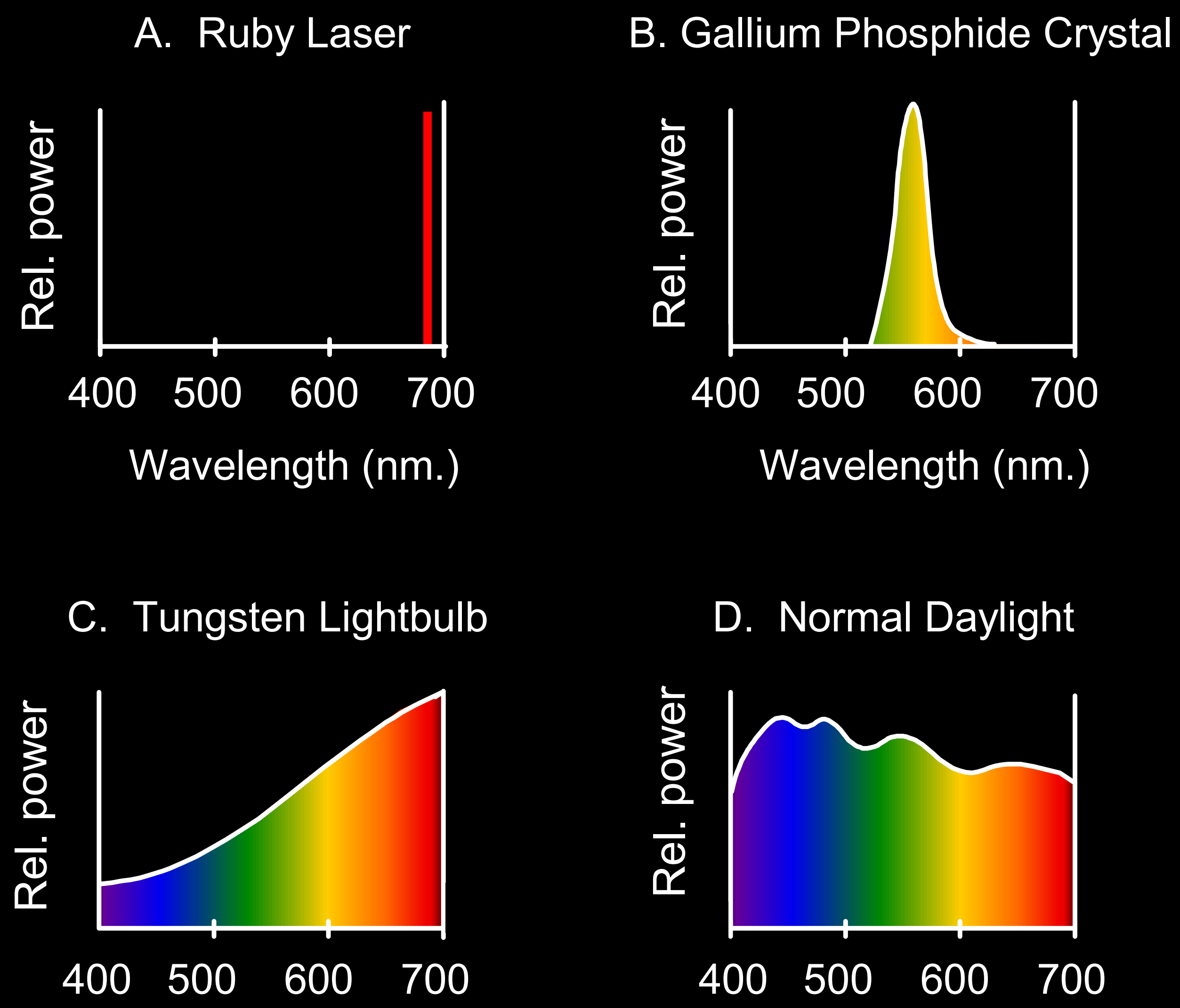
The Physics of Light

Any source of light can be completely described physically by its spectrum: the amount of energy emitted (per time unit) at each wavelength



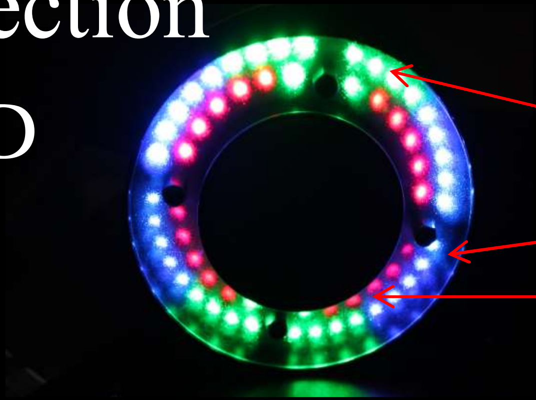
The Physics of Light

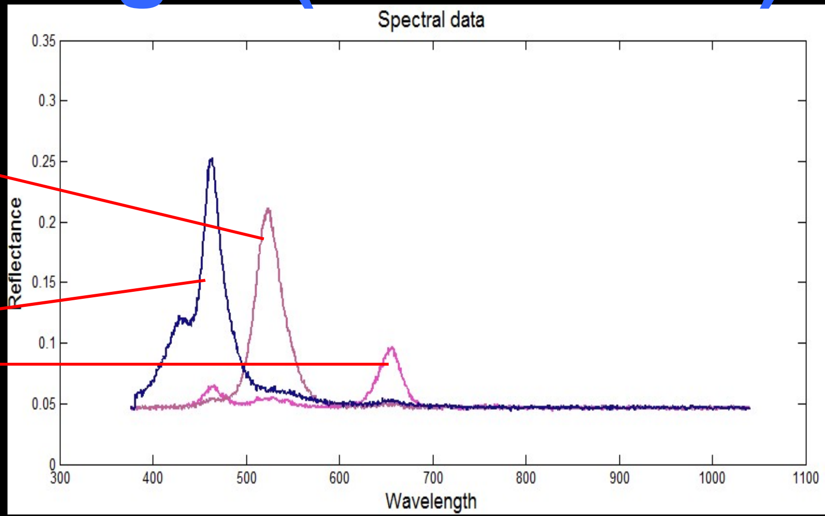
Some examples of the spectra of light sources



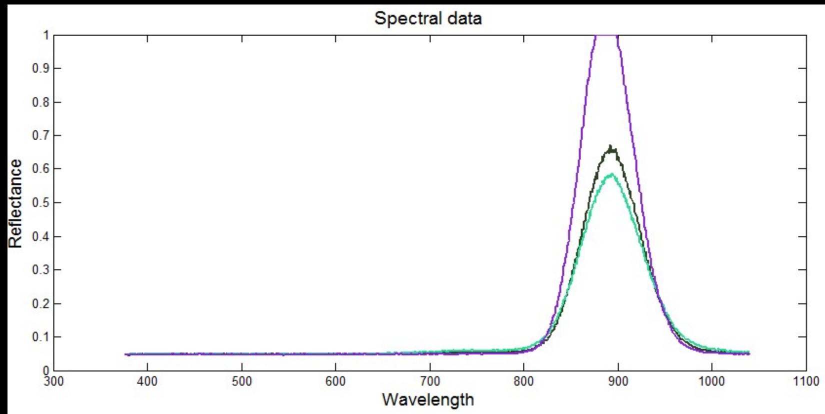
The Physics of Light (Measured)

- Light inspection
  - RGB LED

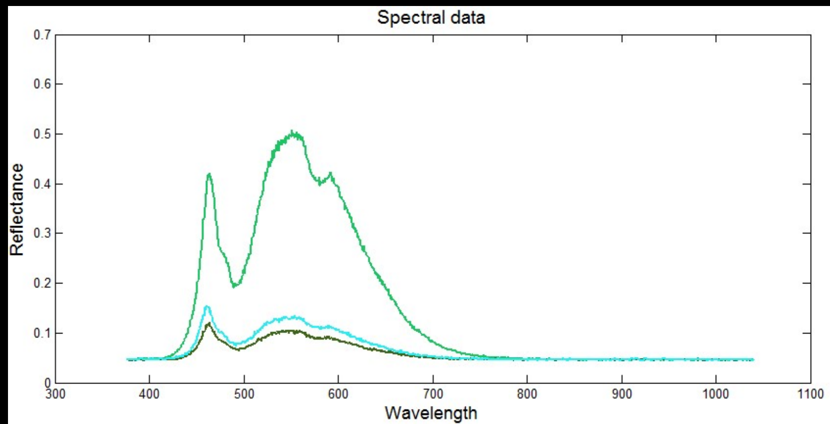




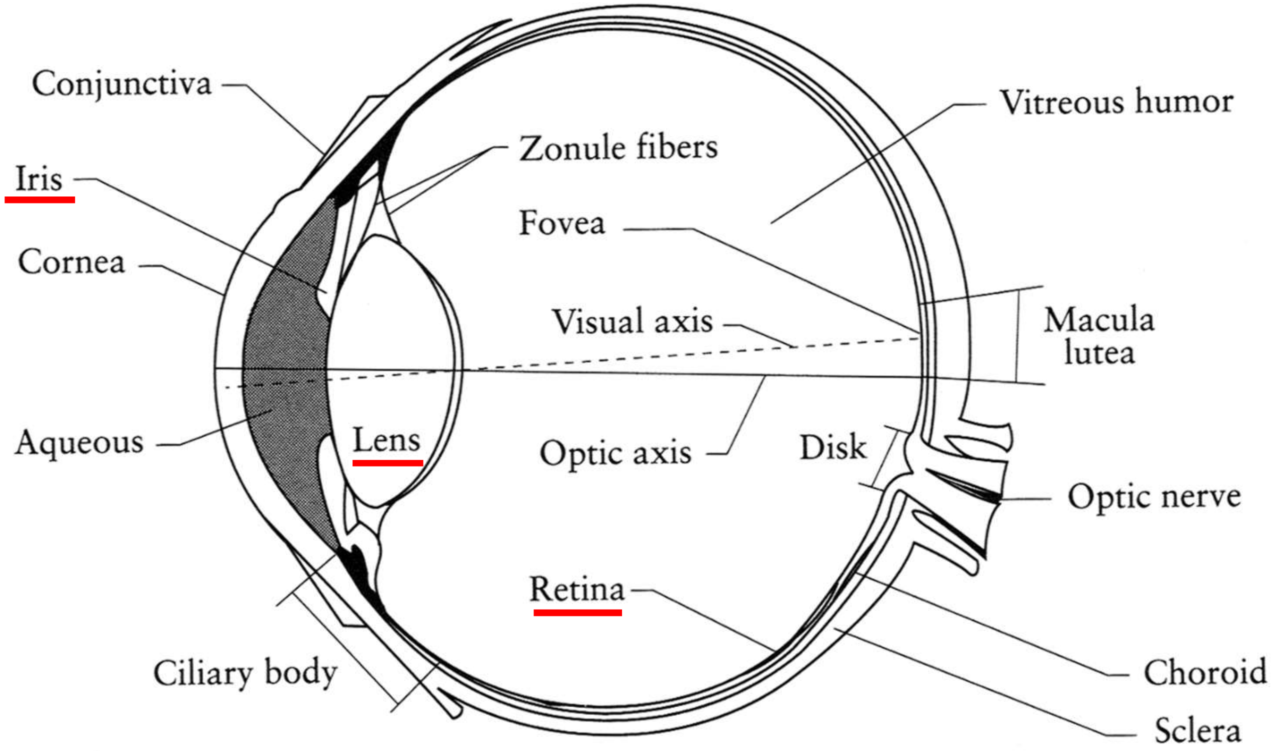
  - IR LED



  - 3M stand



The Eye



The human eye is a camera!

- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- **Lens** - changes shape by using ciliary muscles (to focus on objects at different distances)
- What's the "film"?
  - photoreceptor cells (rods and cones) in the **retina**

Slide by Steve Seitz

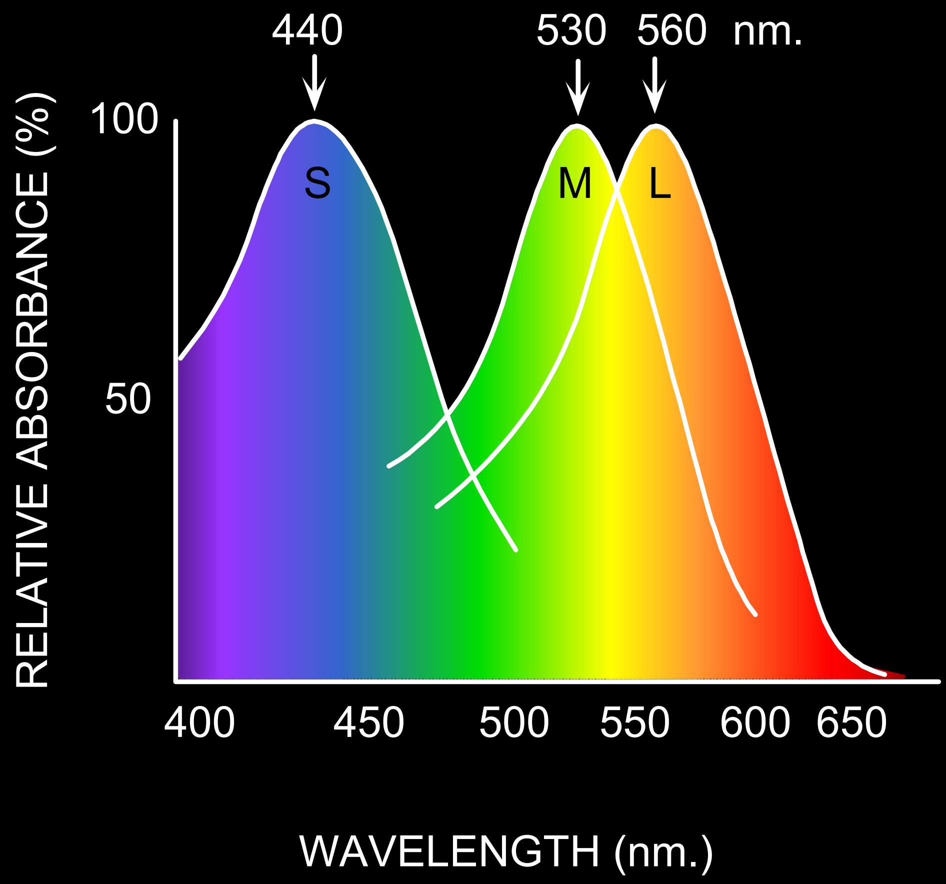
Test Blind Spot

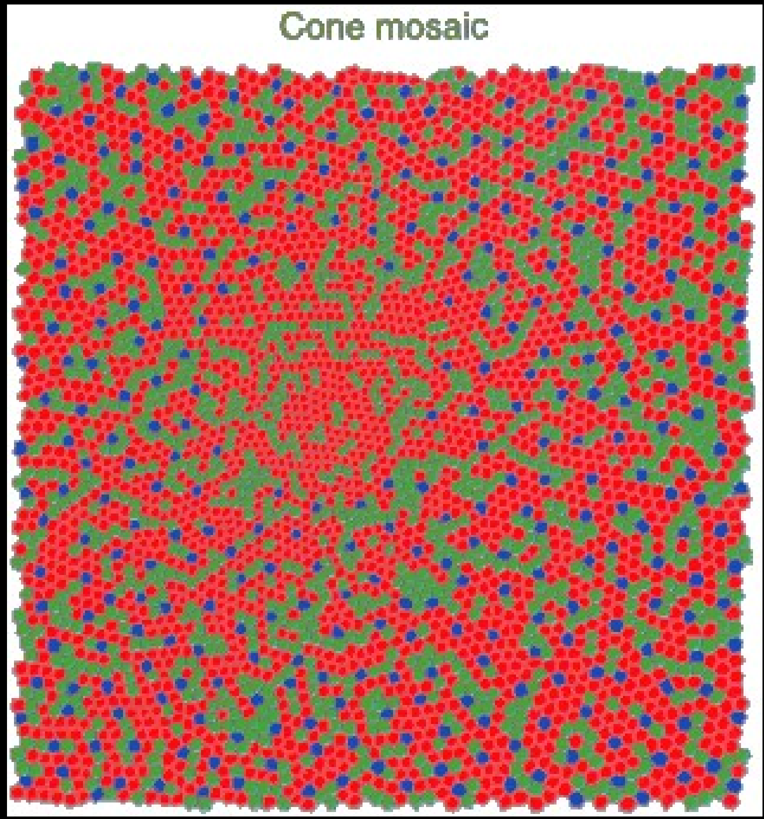
- Cover your **LEFT** eye and stare at the cross with your **RIGH**T eye.
- Now SLOWLY move towards the computer screen while still staring at the cross with your RIGHT eye

http://visionaryeyecare.wordpress.com/2008/08/04/eye-test-find-your-blind-spot-in-each-eye/

Physiology of Color Vision

Three kinds of cones:

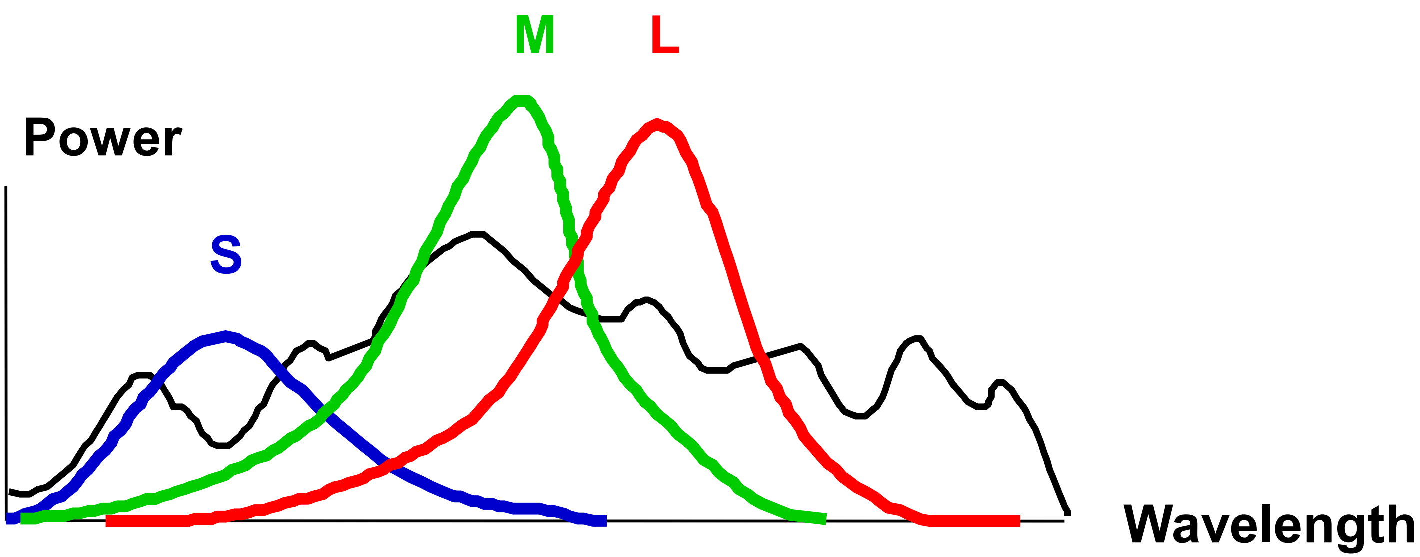




- Ratio of L to M to S cones: approx. 10:5:1
- Almost no S cones in the center of the fovea

Color perception

- R,G,B are called Primary Colors
- R,G,B are used in cameras
- R,G,B were chosen due to the structue of the human eye



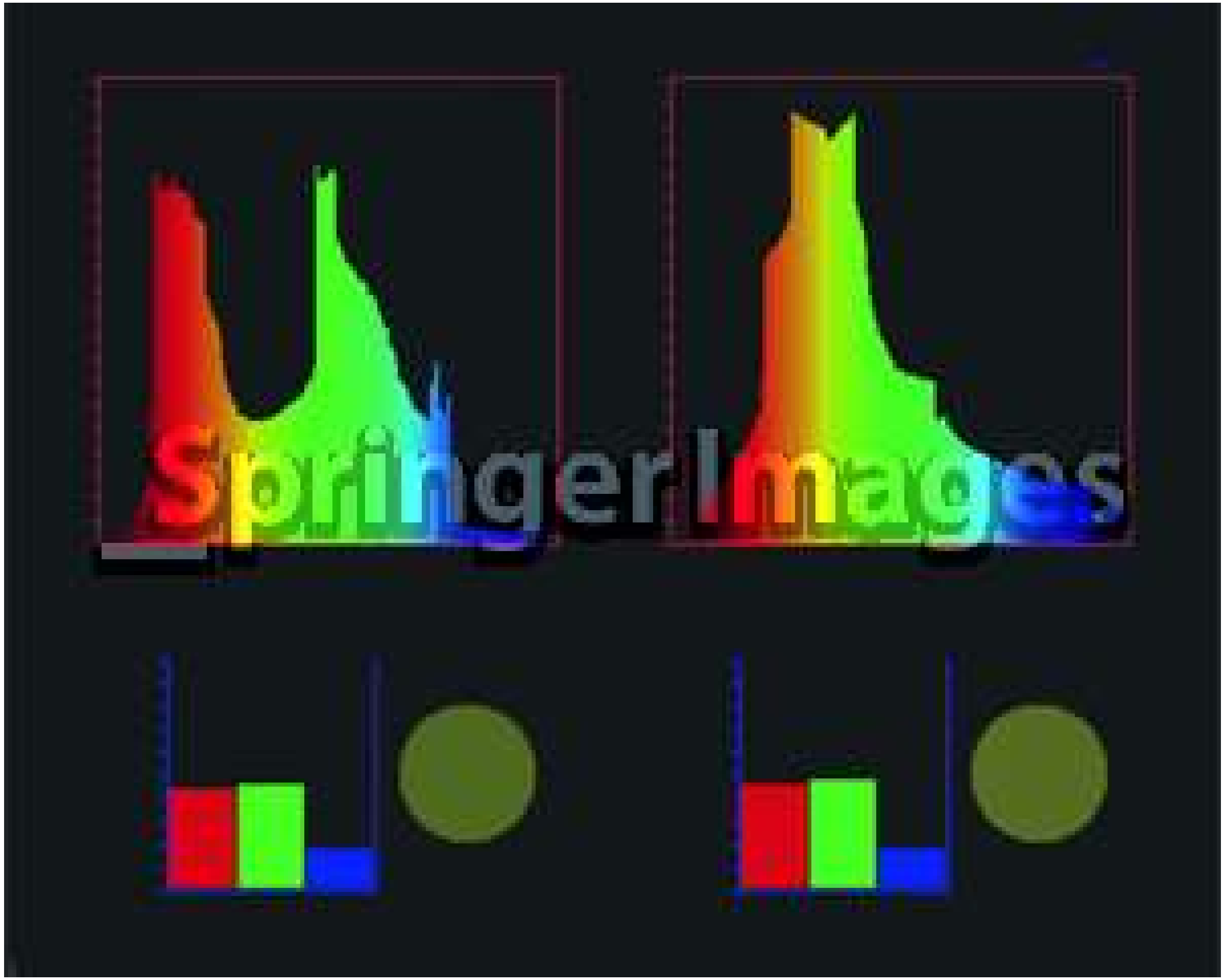
Rods and cones act as filters on the spectrum

- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number
- Q: How can we represent an entire spectrum with 3 numbers?
- A: We can't! Most of the information is lost.
  - As a result, two different spectra may appear indistinguishable
    - » such spectra are known as **metamers**

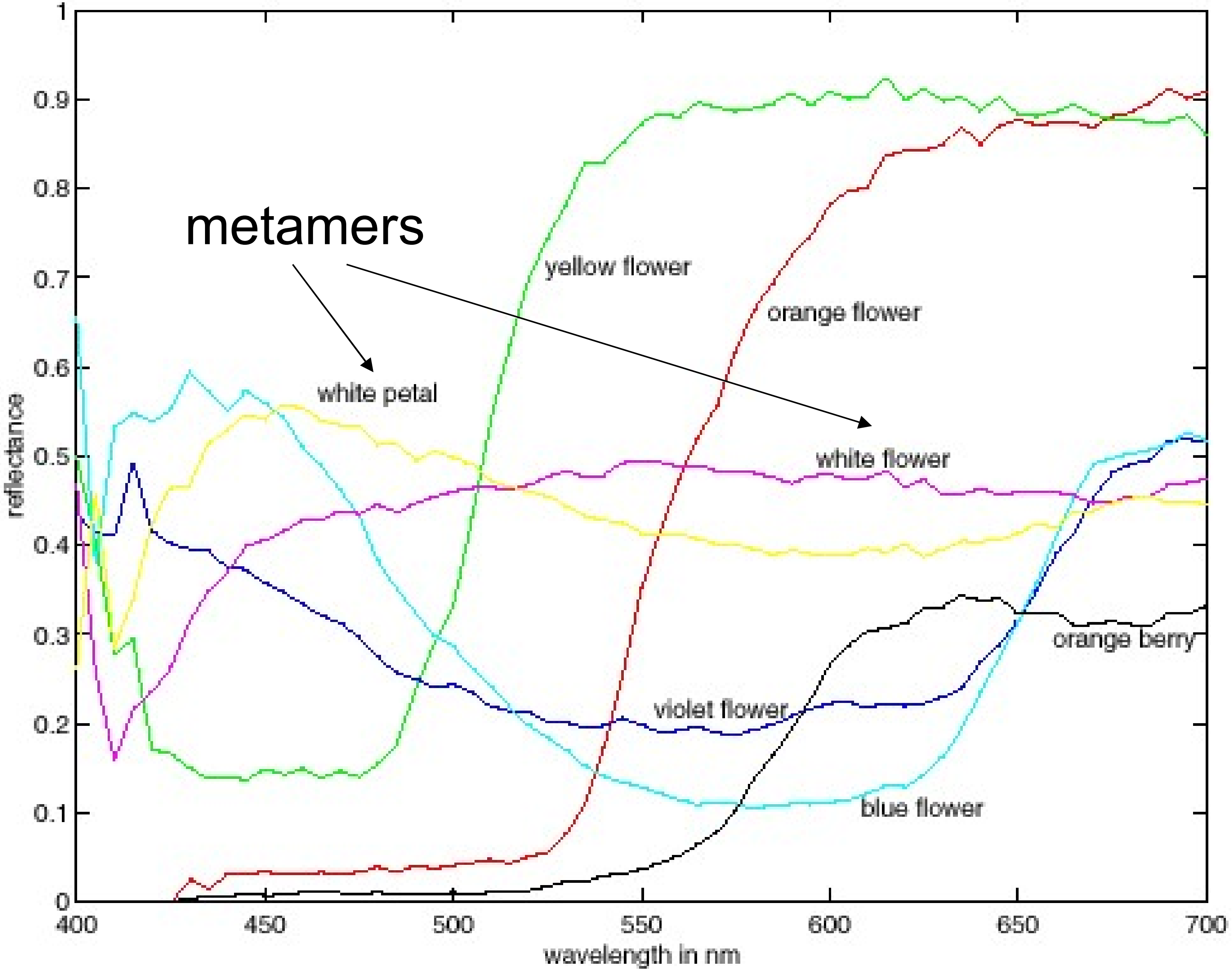
Slide by Steve Seitz

Example of Metamer

- Same color (HVS), different spectrum



Spectra of some real-world surfaces

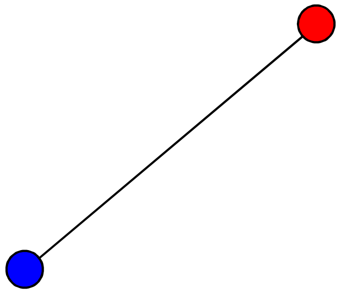


Grassman's Laws

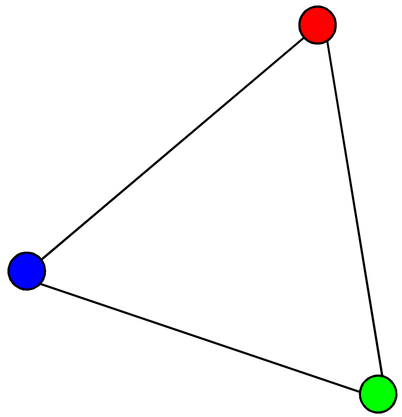
- Color matching appears to be linear
- If two test lights can be matched with the same set of weights, then they match each other:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = u_1 P_1 + u_2 P_2 + u_3 P_3$. Then $A = B$.
- If we mix two test lights, then mixing the matches will match the result:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = v_1 P_1 + v_2 P_2 + v_3 P_3$. Then $A+B = (u_1+v_1) P_1 + (u_2+v_2) P_2 + (u_3+v_3) P_3$.
- If we scale the test light, then the matches get scaled by the same amount:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$. Then $kA = (ku_1) P_1 + (ku_2) P_2 + (ku_3) P_3$.

Linear color spaces

- Defined by a choice of three primaries
- The coordinates of a color are given by the weights of the primaries used to match it
- *Matching functions*: weights required to match single-wavelength light sources

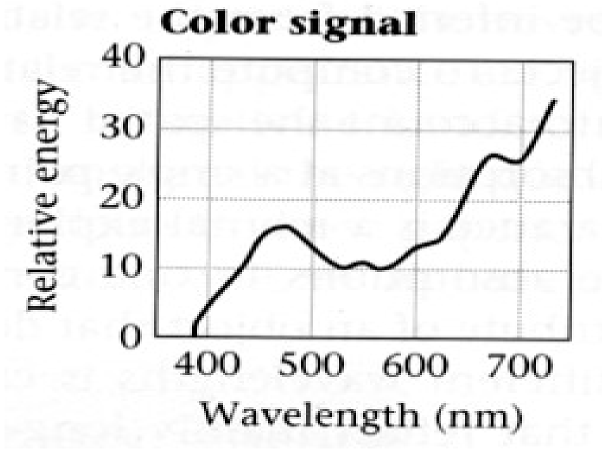


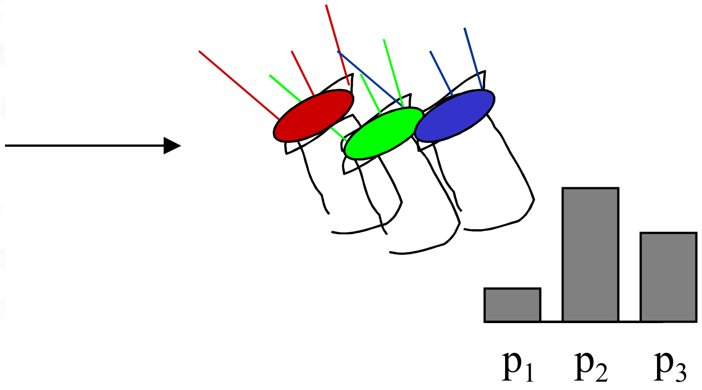
mixing two lights produces colors that lie along a straight line in color space



mixing three lights produces colors that lie within the triangle they define in color space

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



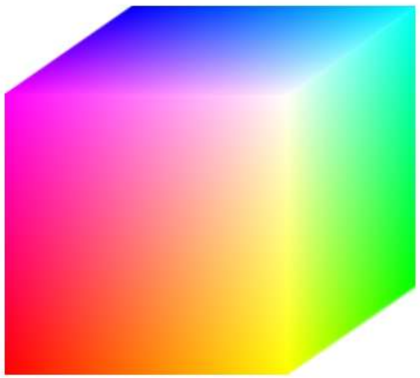


- Pick a set of primaries, $p_1(\lambda), p_2(\lambda), p_3(\lambda)$
- Measure the amount of each primary, $c_1(\lambda_0), c_2(\lambda_0), c_3(\lambda_0)$ needed to match a monochromatic light, $t(\lambda_0)$ at each spectral wavelength λ_0 (pick some spectral step size). These are the color matching functions.

Source: W. Freeman

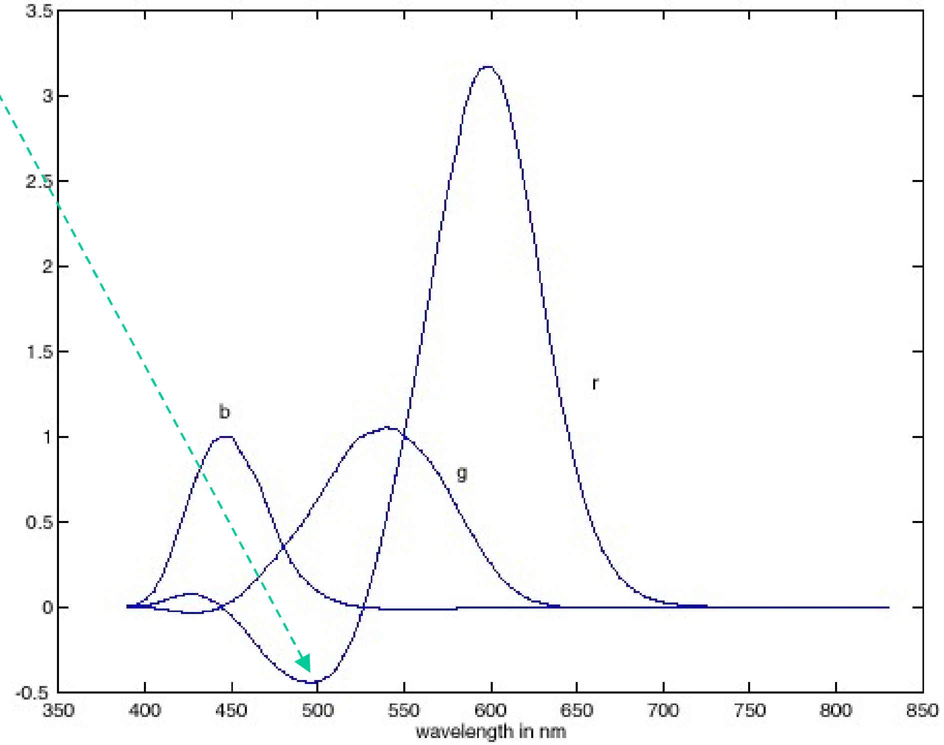
Linear color spaces: RGB

- Primaries are monochromatic lights (for monitors, they correspond to the three types of phosphors)
- *Subtractive matching* required for some wavelengths
- If R,G,B have the same energy we perceive a shade of white (gray, black).

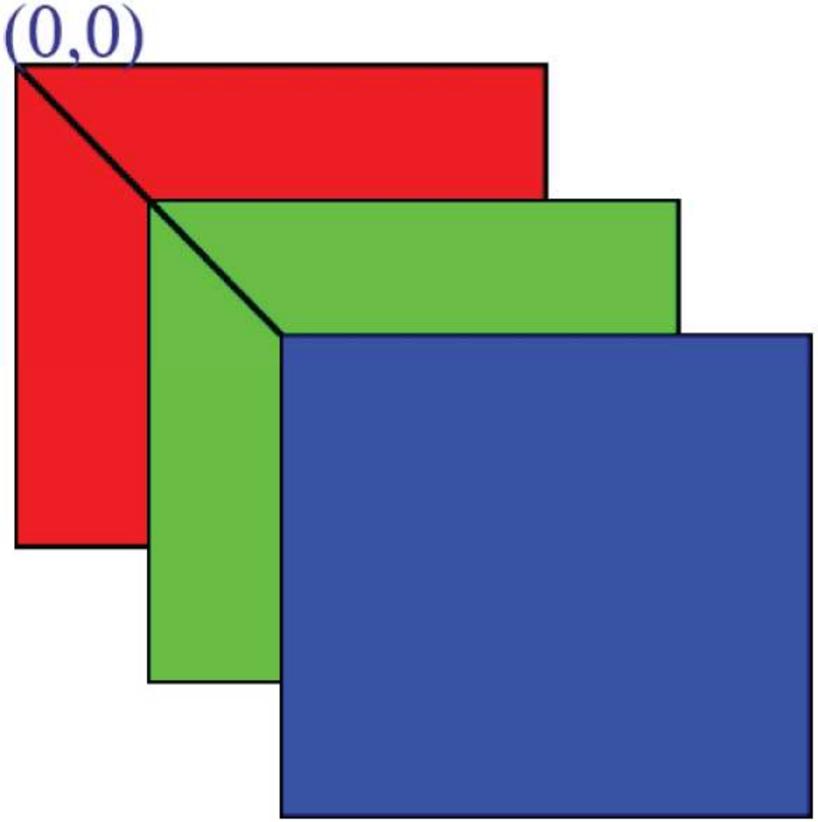


$p_1 = 645.2$ nm
$p_2 = 525.3$ nm
$p_3 = 444.4$ nm

RGB matching functions



RGB Color Space



A single pixel consists of three components: [0, 255]. Each pixel is a vector.

128	251	60

=

Pixel-vector in the computer memory

Final pixel color in the image

Caution

Sometimes pixels are not stored as vectors but in Image Bands. First, the complete red-component is stored, then the complete green, then blue.

Example RGB

Original Image

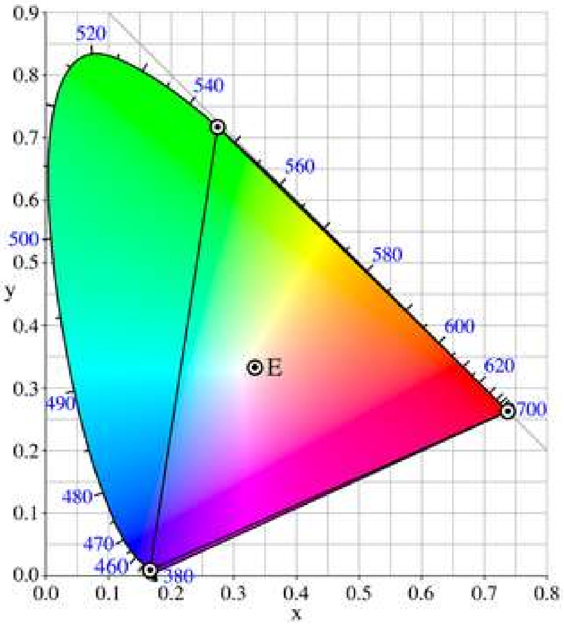
Red Band

Green Band

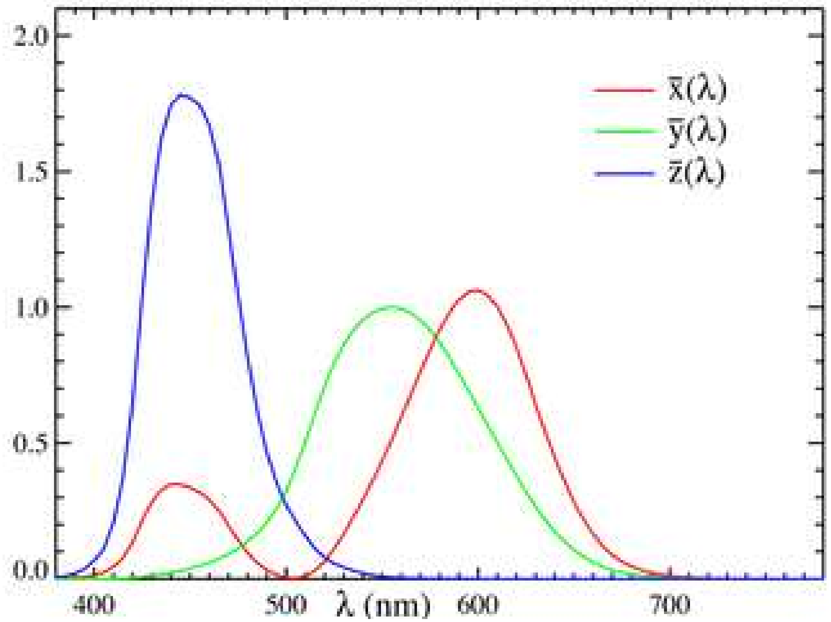
Blue Band

Linear color spaces: CIE XYZ

- Established in 1931 by the [International Commission on Illumination]
- Primaries are imaginary, but matching functions are everywhere positive
- 2D visualization: draw (x,y), where $x = X/(X+Y+Z)$, $y = Y/(X+Y+Z)$



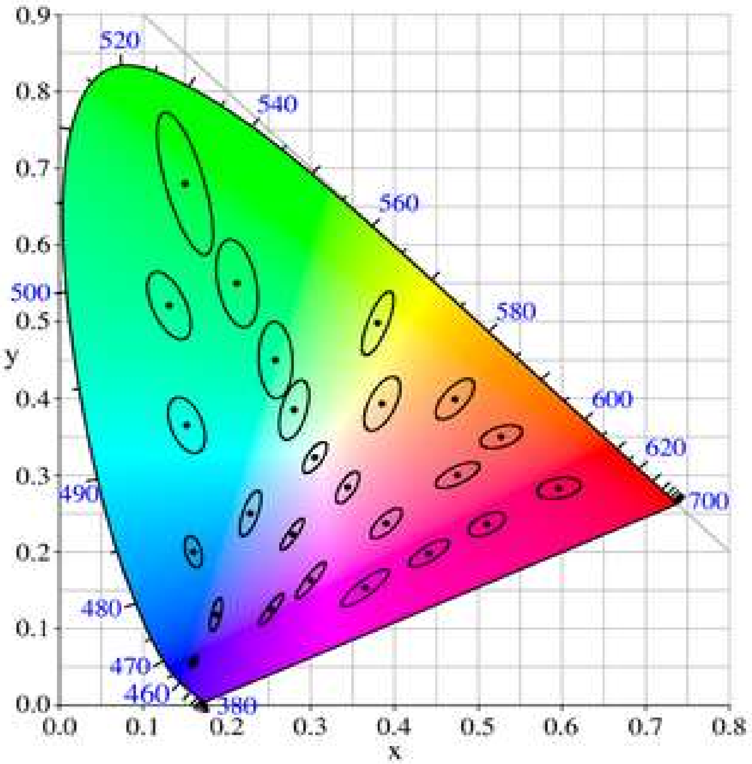
Matching functions



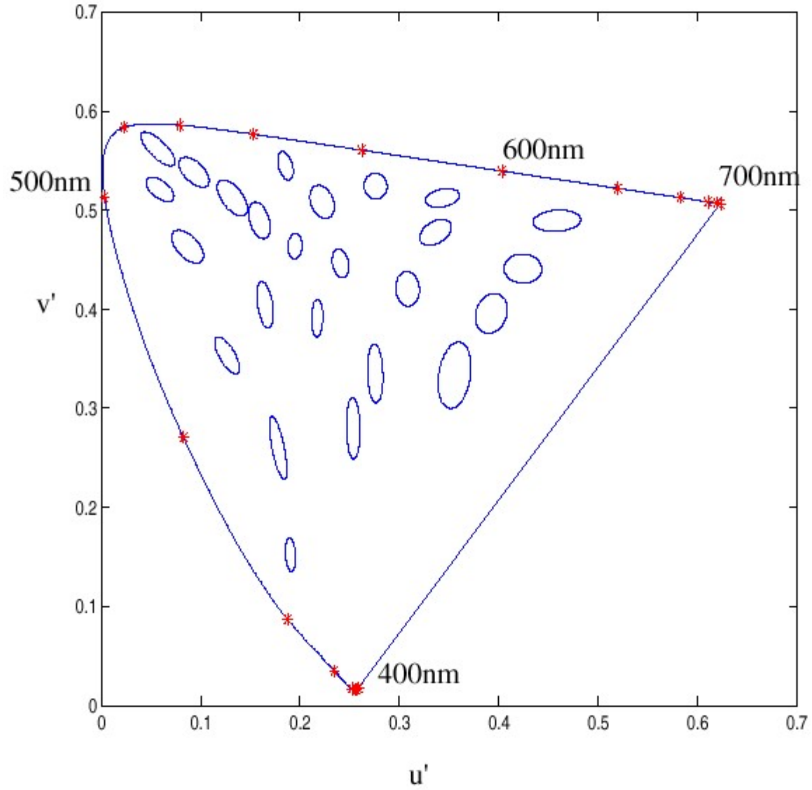
http://en.wikipedia.org/wiki/CIE_1931_color_space

Uniform color spaces

- Unfortunately, differences in x,y coordinates do not reflect perceptual color differences
- CIE u'v' is a projective transform of x,y to make the ellipses more uniform



McAdam ellipses: Just noticeable differences in color



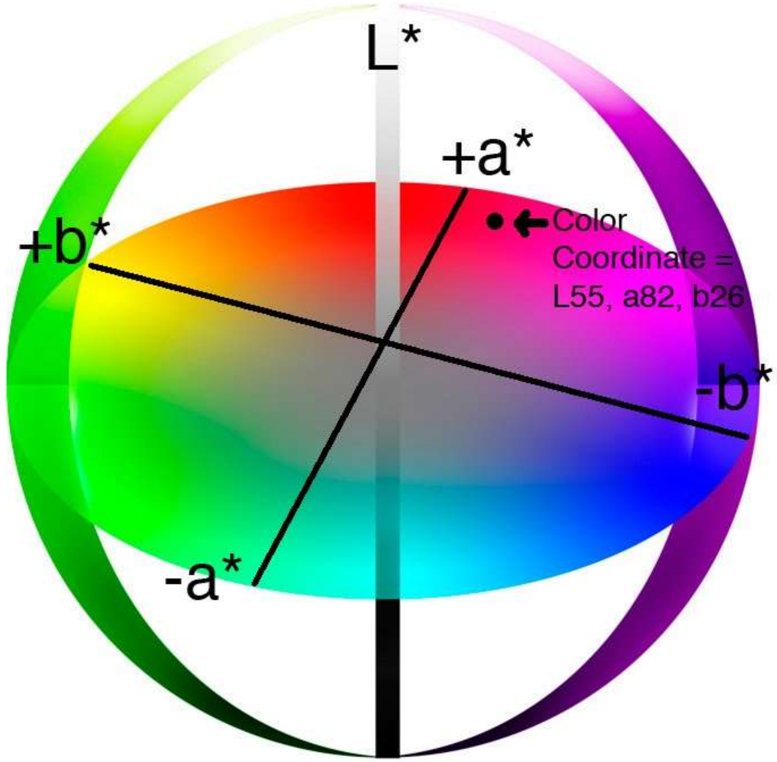
Uniform color spaces

- Unfortunately, differences in x,y coordinates do not reflect perceptual color differences
- CIE u'v' is a projective transform of x,y to make the ellipses more uniform
- Next generation: CIE L*a*b* (Koenderink: "an awful mix of magical numbers and arbitrary functions that somehow 'fit' the eye measure")

$$L^\star = 116 f(Y/Y_n) - 16$$
$$a^\star = 500\left[f(X/X_n) - f(Y/Y_n)\right]$$
$$b^\star = 200\left[f(Y/Y_n) - f(Z/Z_n)\right]$$

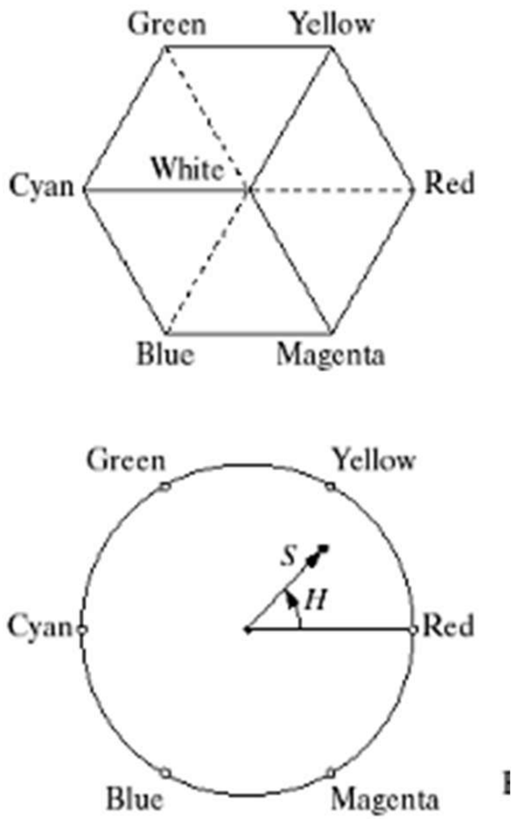
where

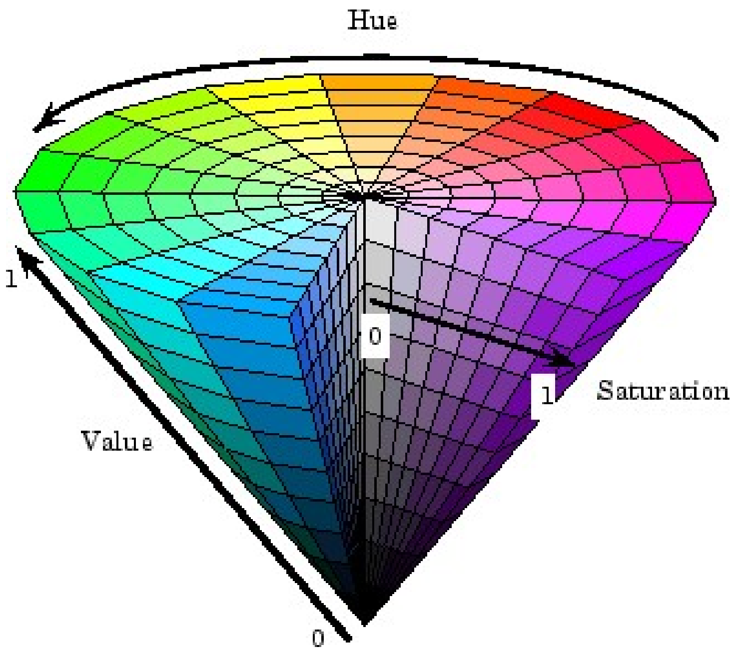
$$f(t) = \begin{cases} t^{1/3} & \text{if } t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29} & \text{otherwise} \end{cases}$$

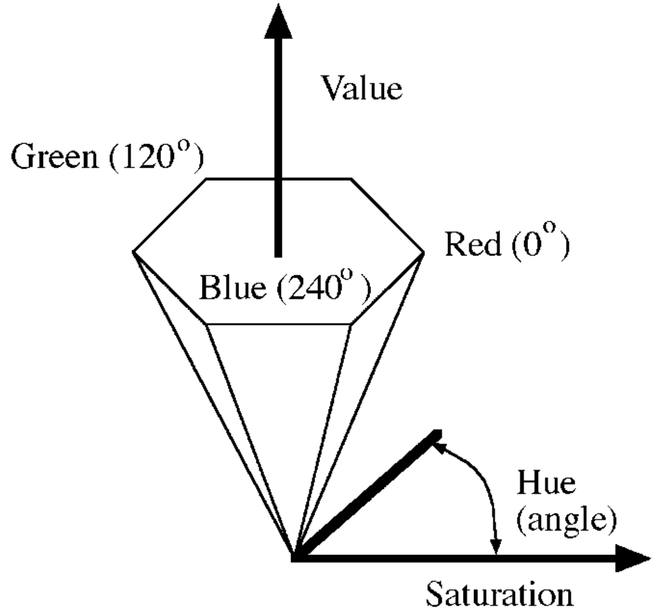


Nonlinear color spaces: HSV

중요

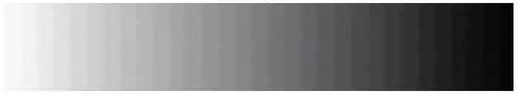






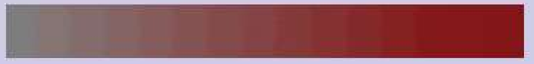
- Perceptually meaningful dimensions:
  Hue (색상), Saturation (채도), Value (Intensity, 명도)
- RGB cube on its vertex

Another way of separating color and intensity: HSI

- H=Hue, S=Saturation, I=intensity
- intensity I: 
- H and S may characterize a color: Chromatics

Hue 

- associated with the dominant wavelength in the mixture of light waves, as perceived by an observer.
- is the color attribute that describes a pure color

Saturation 

- relative purity
- amount of white light in the color
- mixed with hue

Example

Pure colors are fully saturated. Not saturated is, e.g., pink (red+white).

Example HSI

Original Image

Hue

Saturation

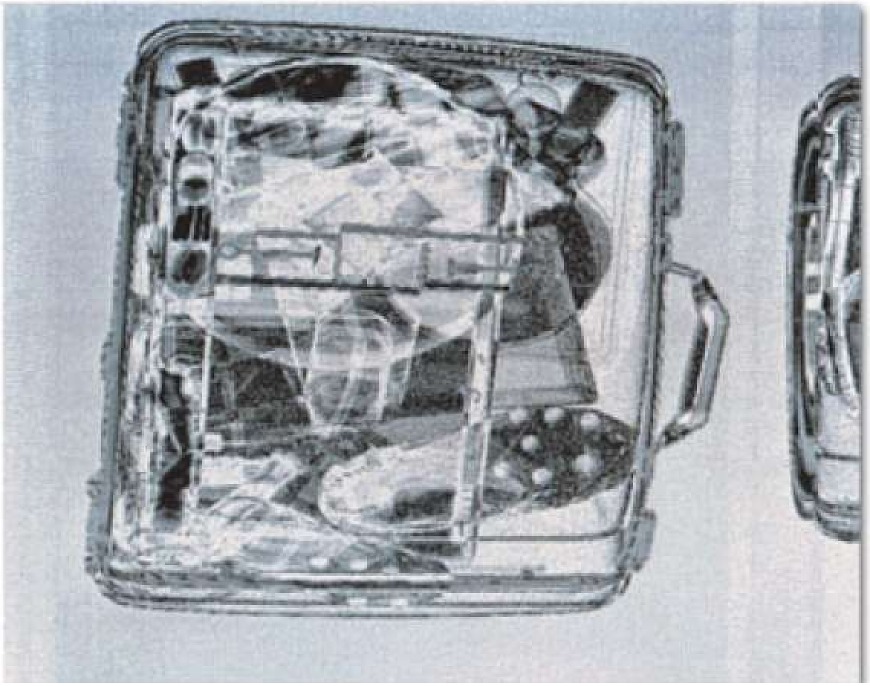
Intensity

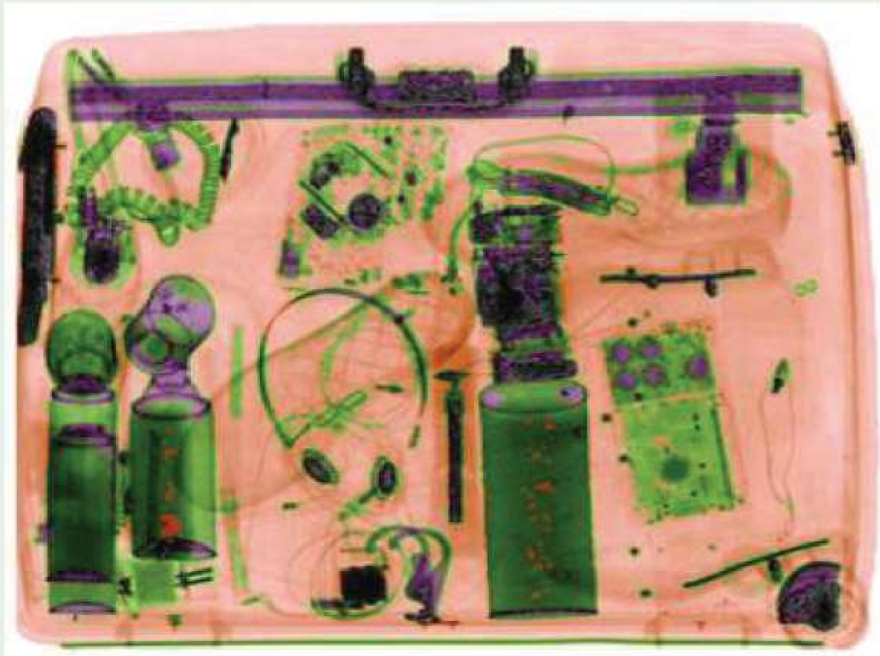
What is Pseudo Color?

Full Color vs. Psedo Color

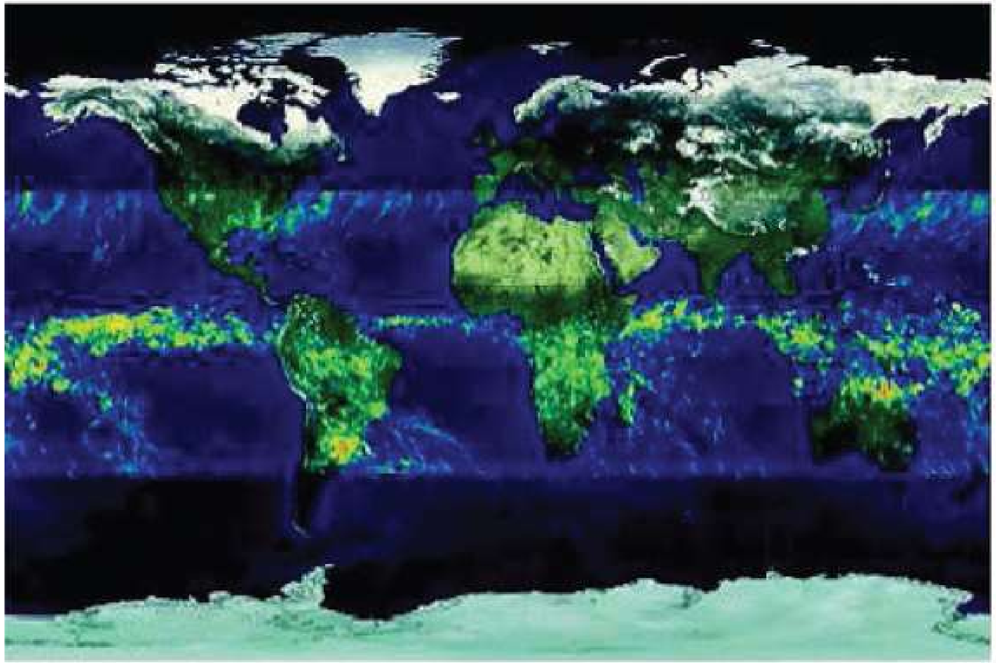
- Full Color Images: Acquired by a (TV/DV) camera, digital camer or scanner
- Pseudo Color Images: Assigned a shade of color to a monochrome intensity or range of intensities

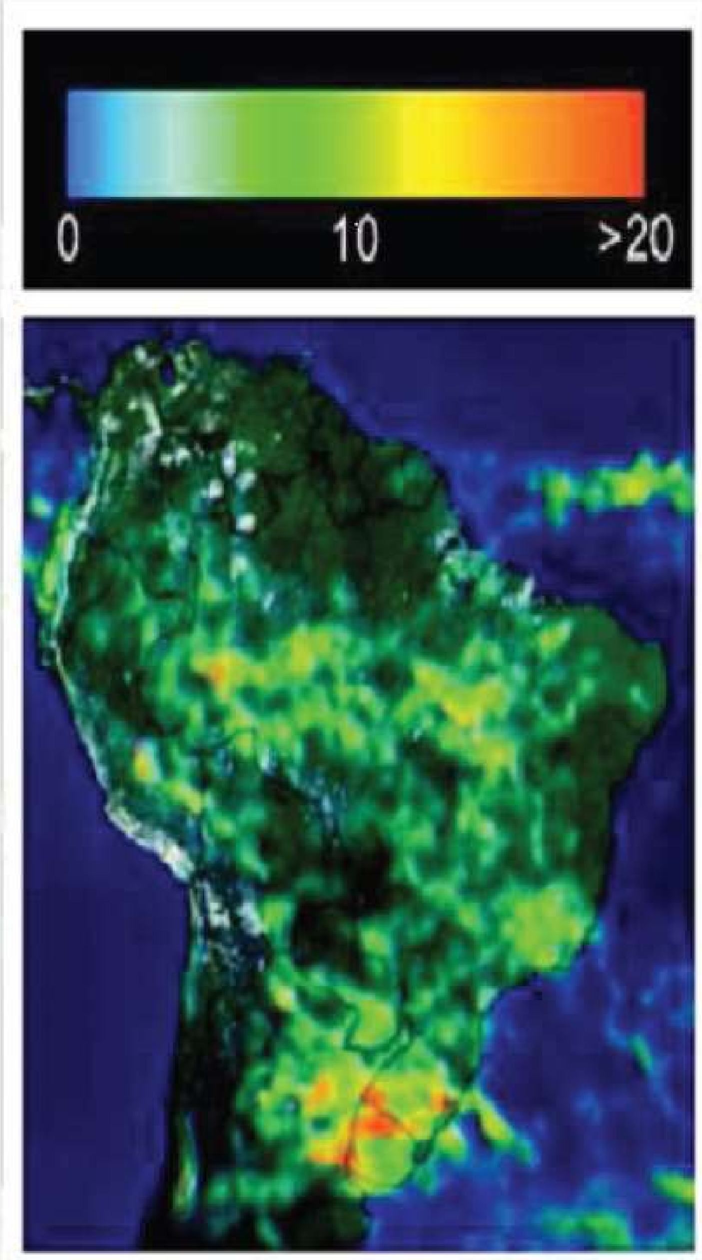
Example





Example





Lightness constancy

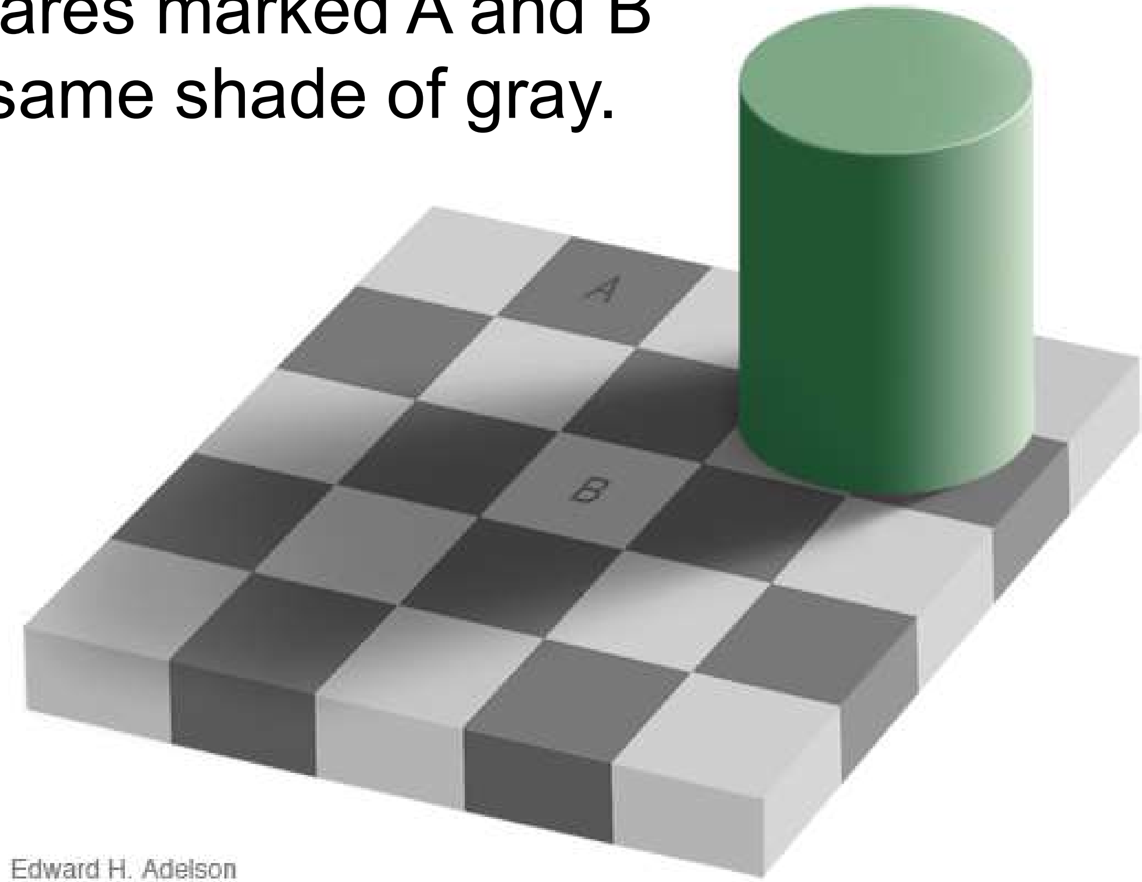
White in light and in shadow

J. S. Sargent, The Daughters of Edward D. Boit, 1882

Slide by F. Durand

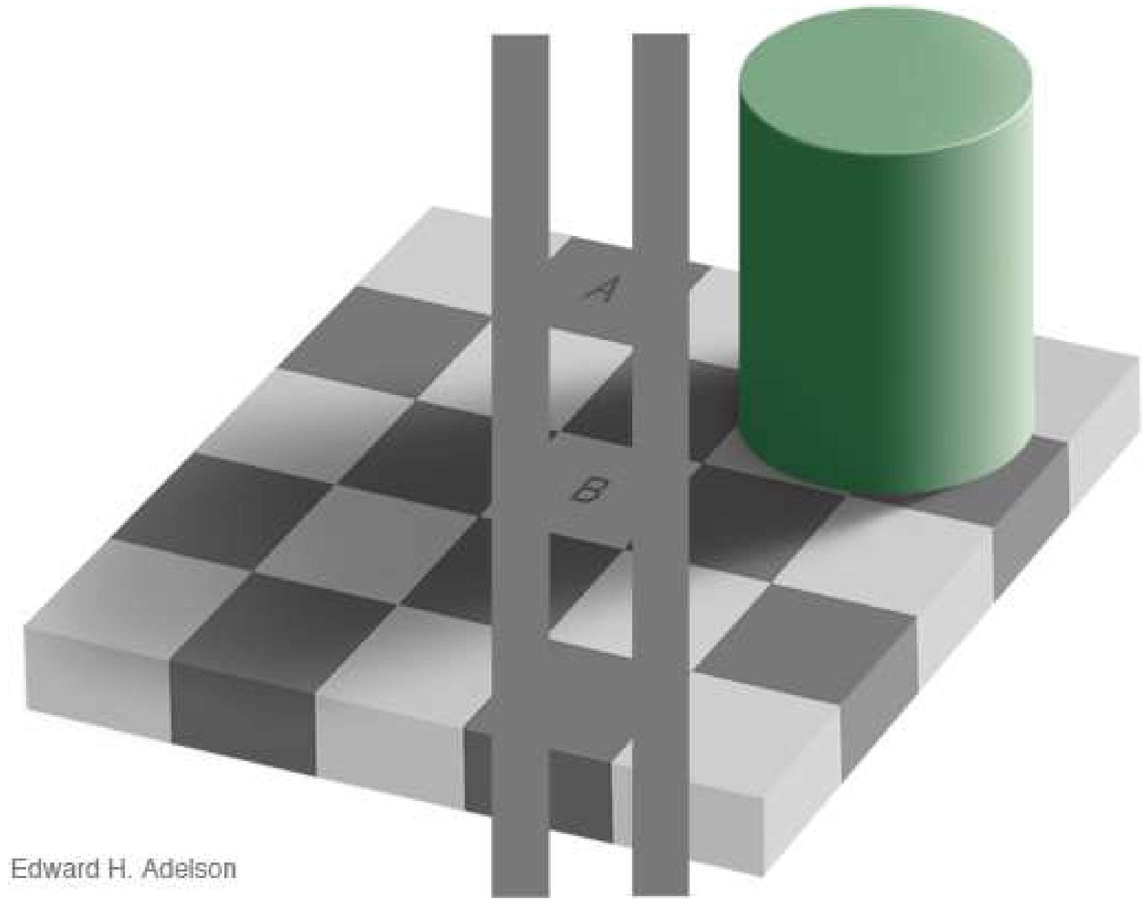
Lightness constancy

The squares marked A and B are the same shade of gray.



http://web.mit.edu/persci/people/adelson/checkershadow_illusion.html

Lightness constancy



- Possible explanations
  - Simultaneous contrast
  - Reflectance edges vs. illumination edges

http://web.mit.edu/persci/people/adelson/checkershadow_illusion.html

White balance

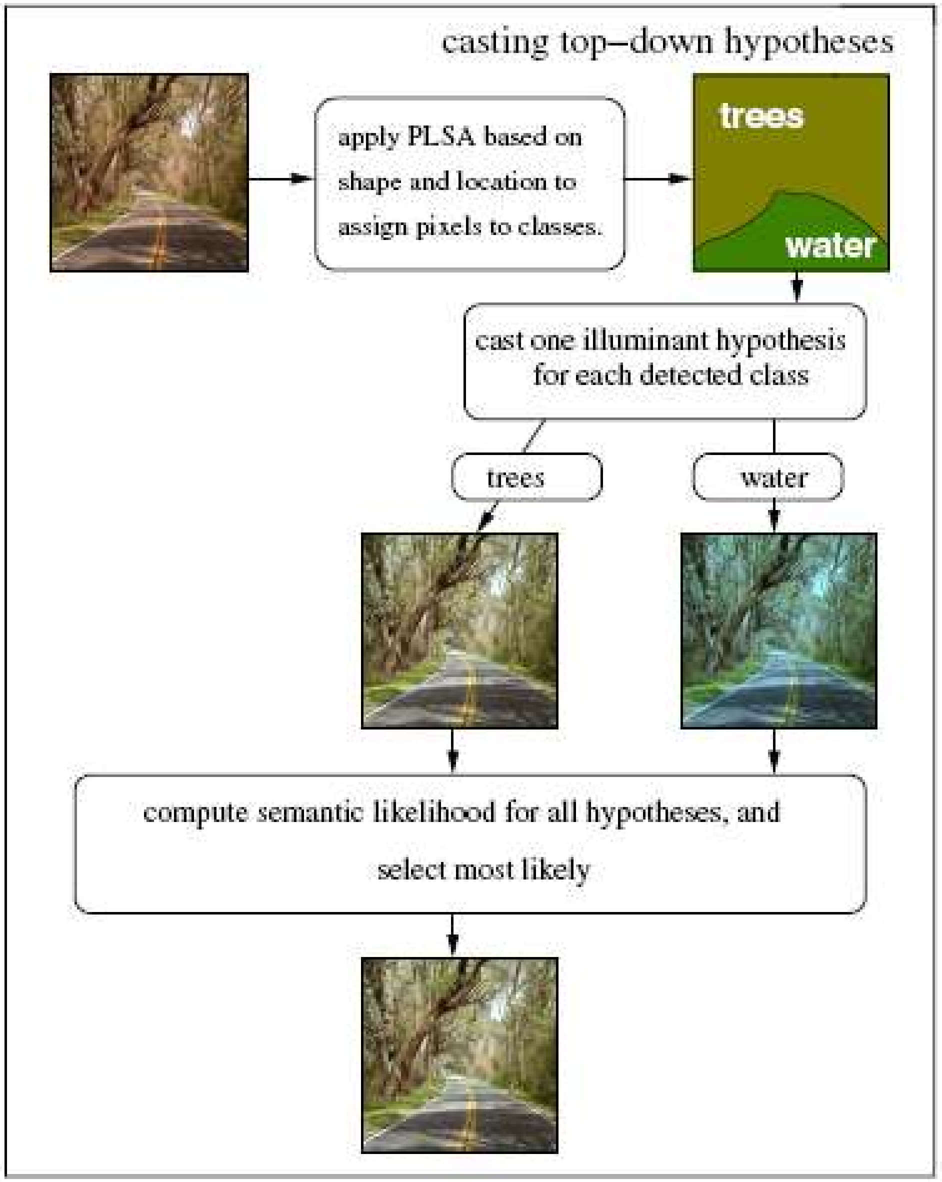
- When looking at a picture on screen or print, we adapt to the illuminant of the room, not to that of the scene in the picture
- When the white balance is not correct, the picture will have an unnatural color "cast"

incorrect white balance

correct white balance

http://www.cambridgeincolour.com/tutorials/white-balance.htm

White balance by recognition



- Key idea: For each of the semantic classes present in the image, compute the illuminant that transforms the pixels assigned to that class so that the average color of that class matches the average color of the same class in a database of “typical” images

J. Van de Weijer, C. Schmid and J. Verbeek, Using High-Level Visual Information for Color Constancy, ICCV 2007.

Mixed illumination

- When there are several types of illuminants in the scene, different reference points will yield different results

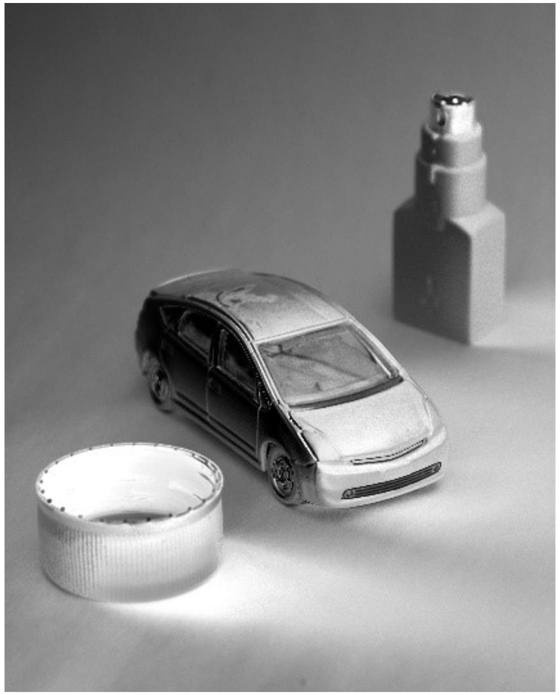
Reference: moon

Reference: stone

http://www.cambridgeincolour.com/tutorials/white-balance.htm

Spatially varying white balance

Input



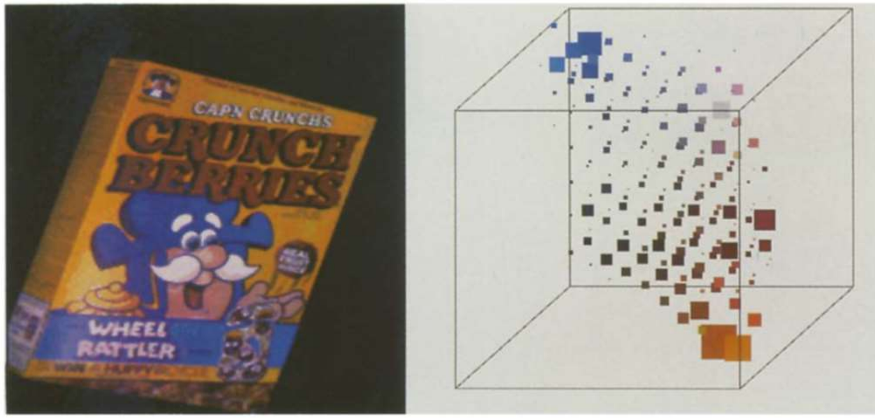
Alpha map

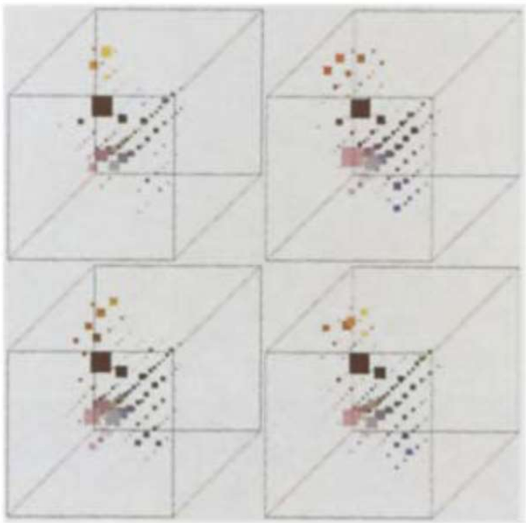
Output

E. Hsu, T. Mertens, S. Paris, S. Avidan, and F. Durand, "Light Mixture Estimation for Spatially Varying White Balance," SIGGRAPH 2008

Uses of color in computer vision

Color histograms for indexing and retrieval

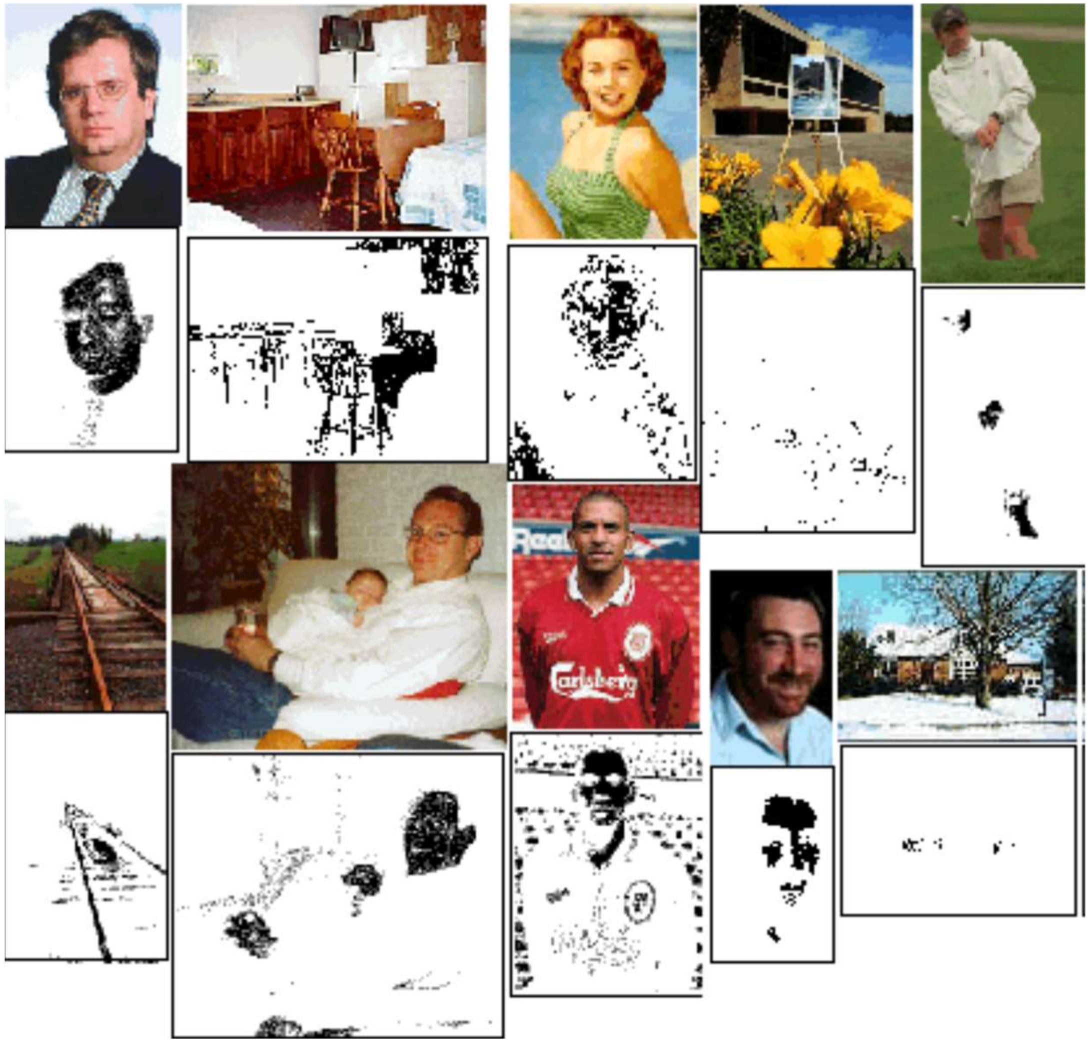




Swain and Ballard, [Color Indexing](), IJCV 1991.

Uses of color in computer vision

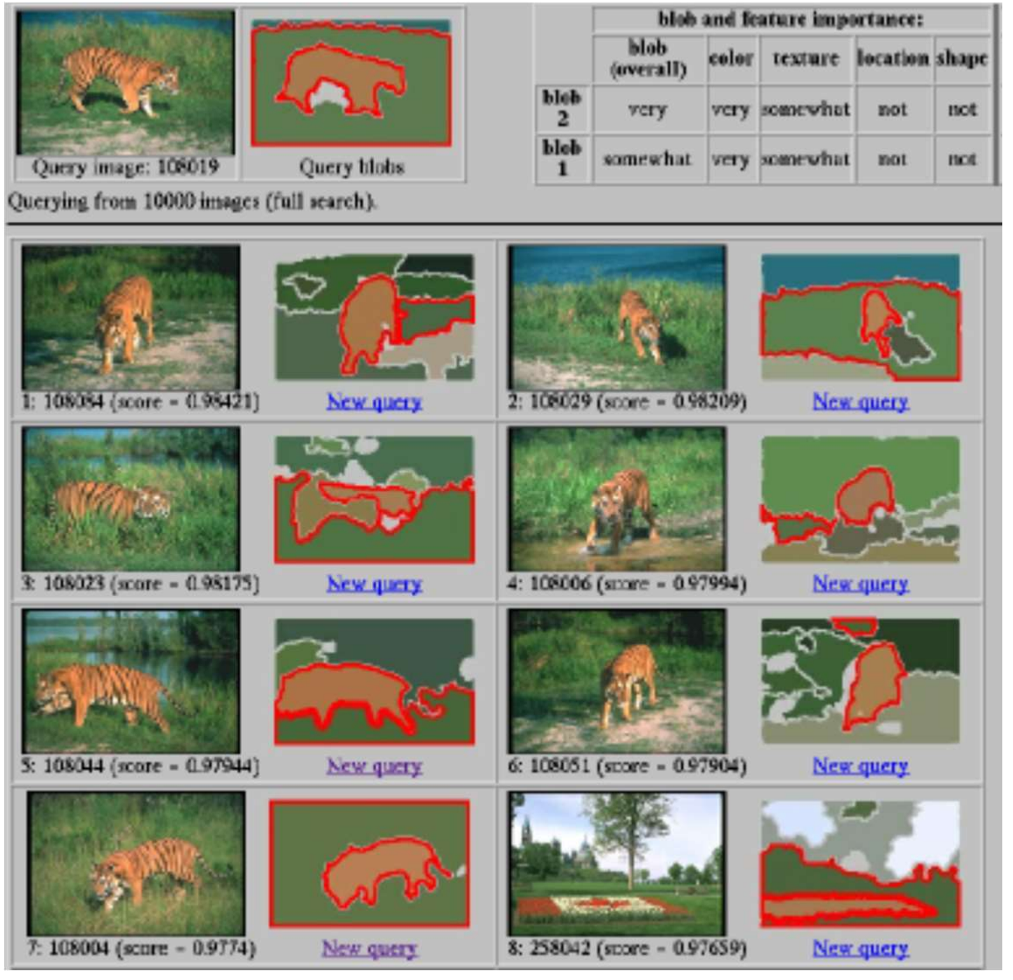
Skin detection



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

Uses of color in computer vision

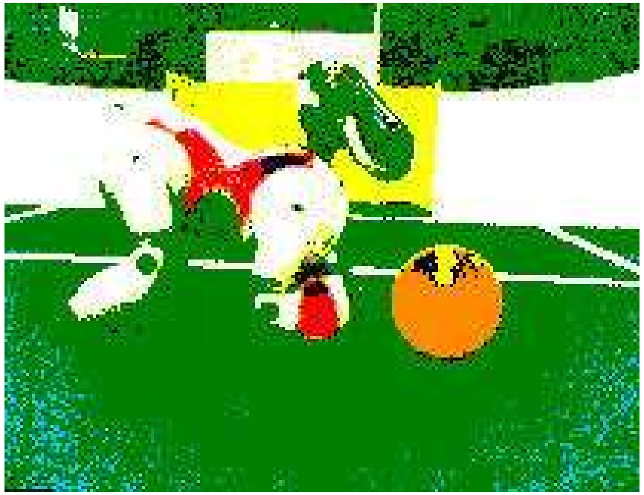
Image segmentation and retrieval



C. Carson, S. Belongie, H. Greenspan, and Ji. Malik, Blobworld: Image segmentation using Expectation-Maximization and its application to image querying, ICVIS 1999.

Uses of color in computer vision

Robot soccer

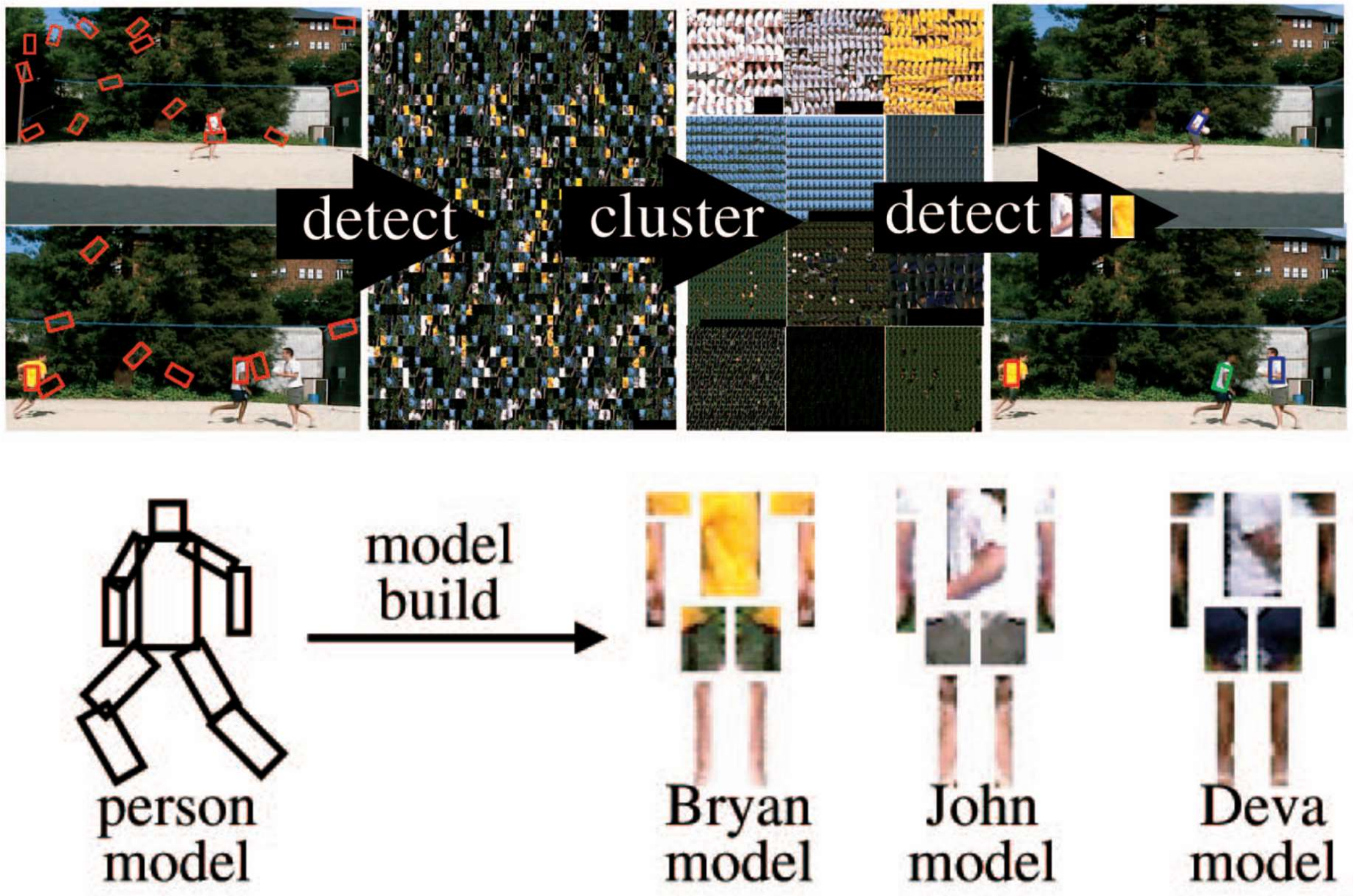
 

M. Sridharan and P. Stone, [Towards Eliminating Manual Color Calibration at RoboCup](). RoboCup-2005: Robot Soccer World Cup IX, Springer Verlag, 2006

Source: K. Grauman

Uses of color in computer vision

Building appearance models for tracking



D. Ramanan, D. Forsyth, and A. Zisserman. [Tracking People by Learning their Appearance](). PAMI 2007.

Uses of color in computer vision

Judging visual realism

J.-F. Lalonde and A. Efros. [Using Color Compatibility for Assessing Image Realism](). ICCV 2007.

Lab. Color space conversion

- https://docs.opencv.org/2.4/modules/imgproc/doc/miscellaneous_transformations.html#cvtcolor

```python
import cv2
import matplotlib.pyplot as plt

imgRGB = cv2.imread('cube.jpg')
cv2.imshow('input',imgRGB)

# rgb color split
b,g,r= cv2.split(imgRGB)

cv2.imshow("b", b)
cv2.imshow("g", g)
cv2.imshow("r", r)

# rgb to hsv
imgHSV = cv2.cvtColor(imgRGB, cv2.COLOR_BGR2HSV)

# hsv color split
h,s,v= cv2.split(imgHSV)

cv2.imshow("h", h)
cv2.imshow("s", s)
cv2.imshow("v", v)

# lab assignment: detect red, green, blue, yellow cell
```