



Lecture:

Color

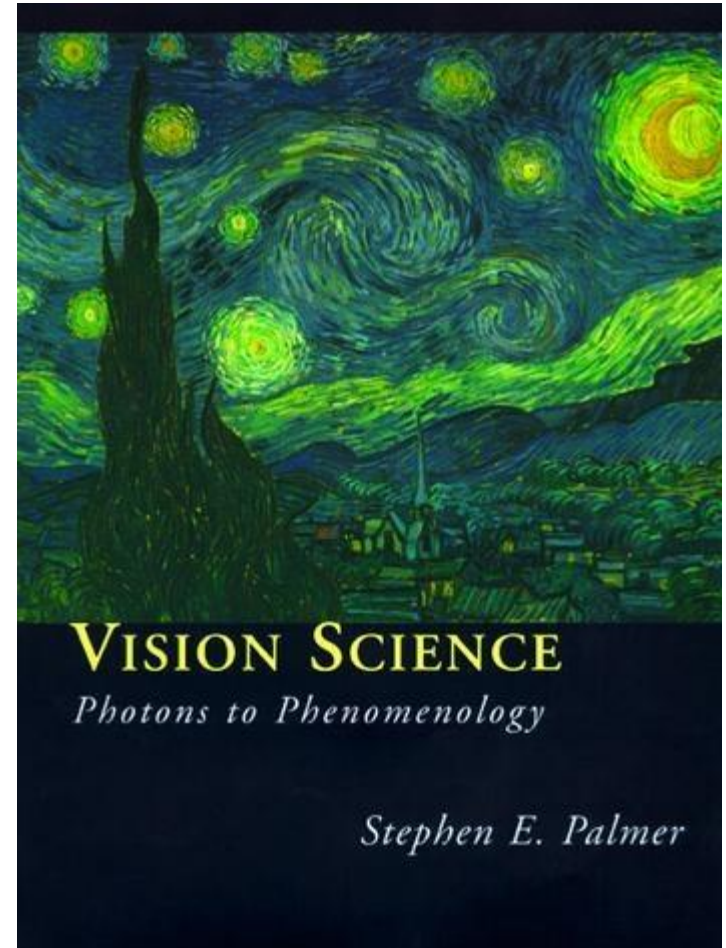
Juan Carlos Niebles and Ranjay Krishna
Stanford AI Lab

Overview of Color

- Physics of color
- Human encoding of color
- Color spaces
- White balancing

What is color?

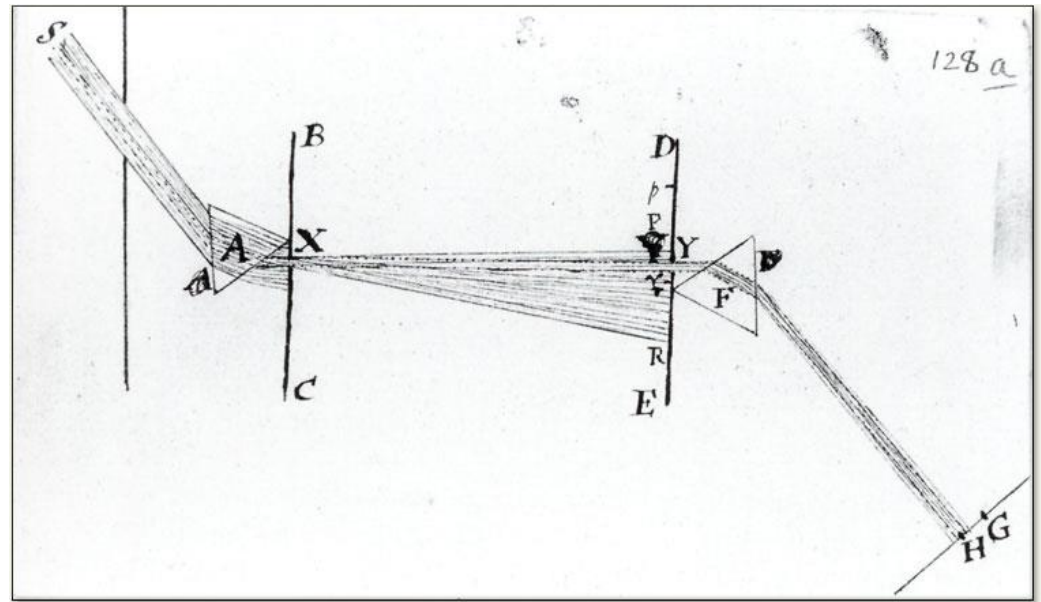
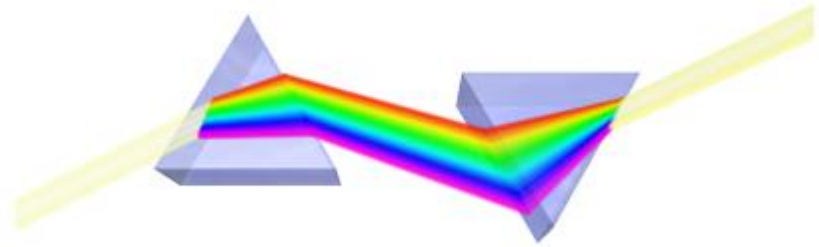
- The result of interaction between physical light in the environment and our visual system.
- A *psychological property* of our visual experiences when we look at objects and lights, *not a physical property* of those objects or lights.



Slide credit: Lana Lazebnik

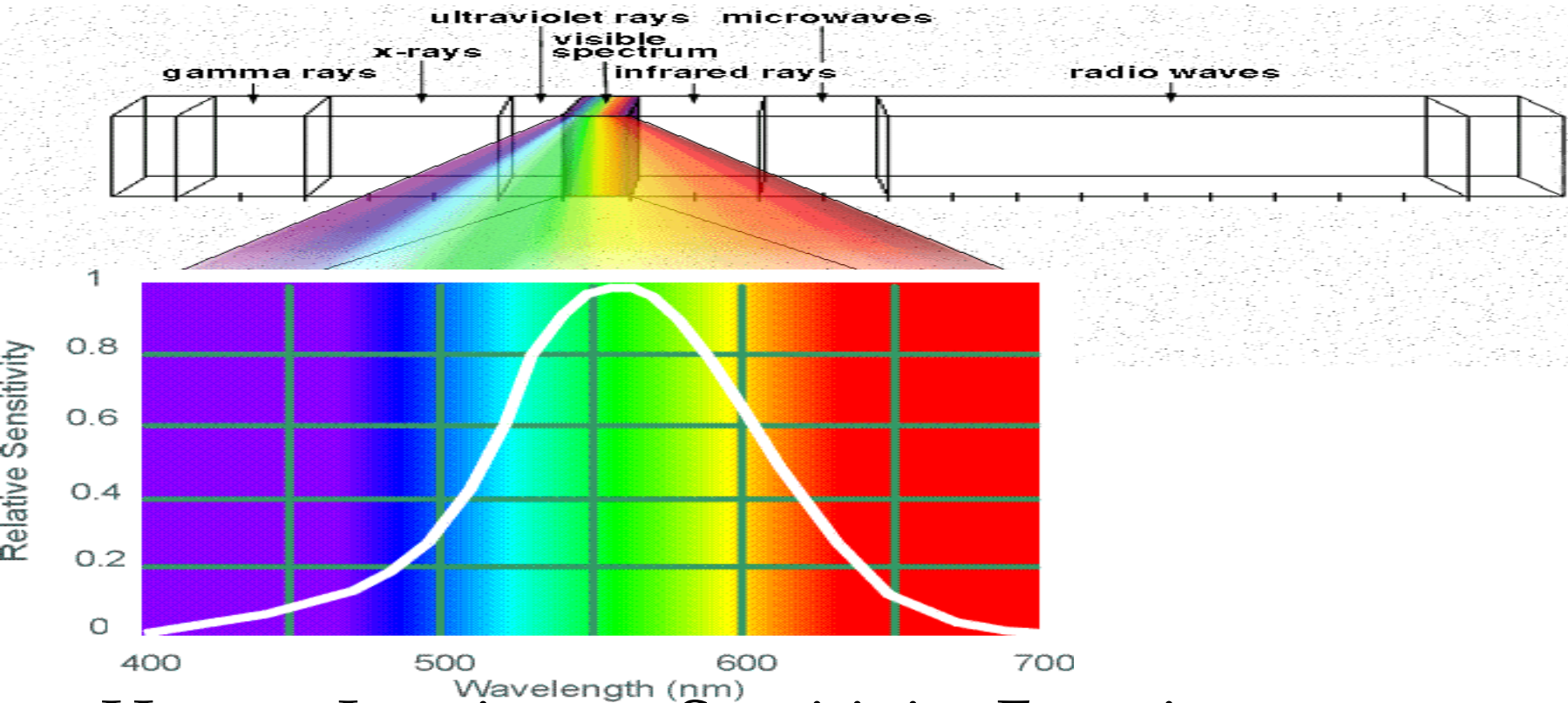
Color and light

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



Newton 1665

Electromagnetic Spectrum



Human Luminance Sensitivity Function

Sun temperature makes it emit yellow light more than any other color.



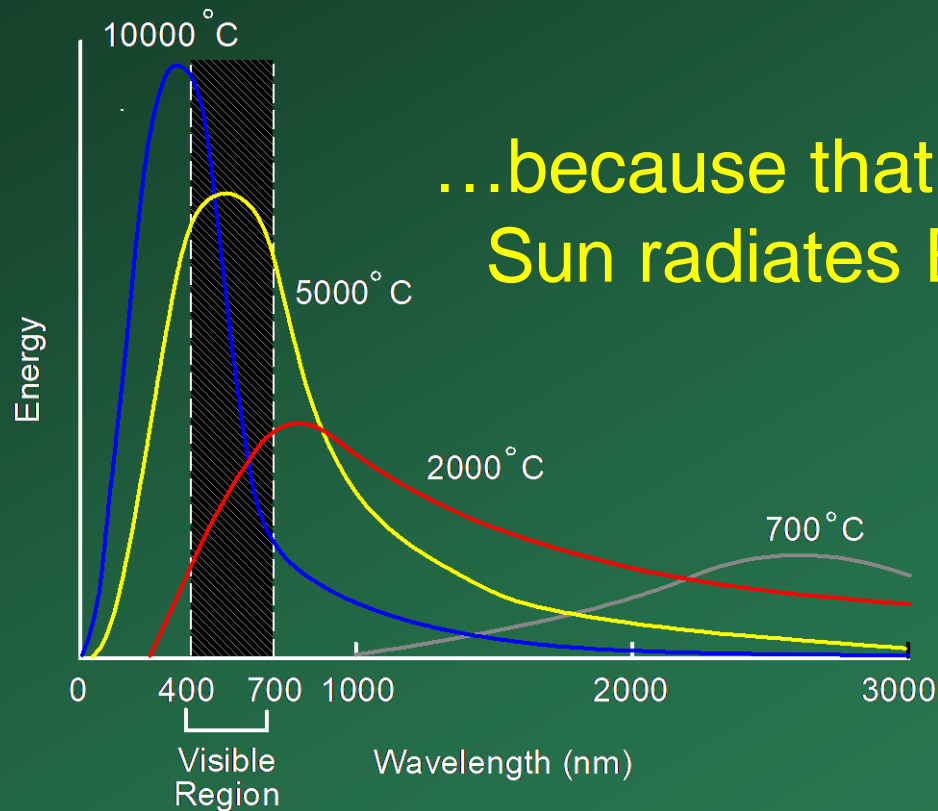
TOTAL SOLAR ECLIPSE

Visible Light

Plank's law for Blackbody radiation

Surface of the sun: $\sim 5800\text{K}$

Why do we see light of these wavelengths?

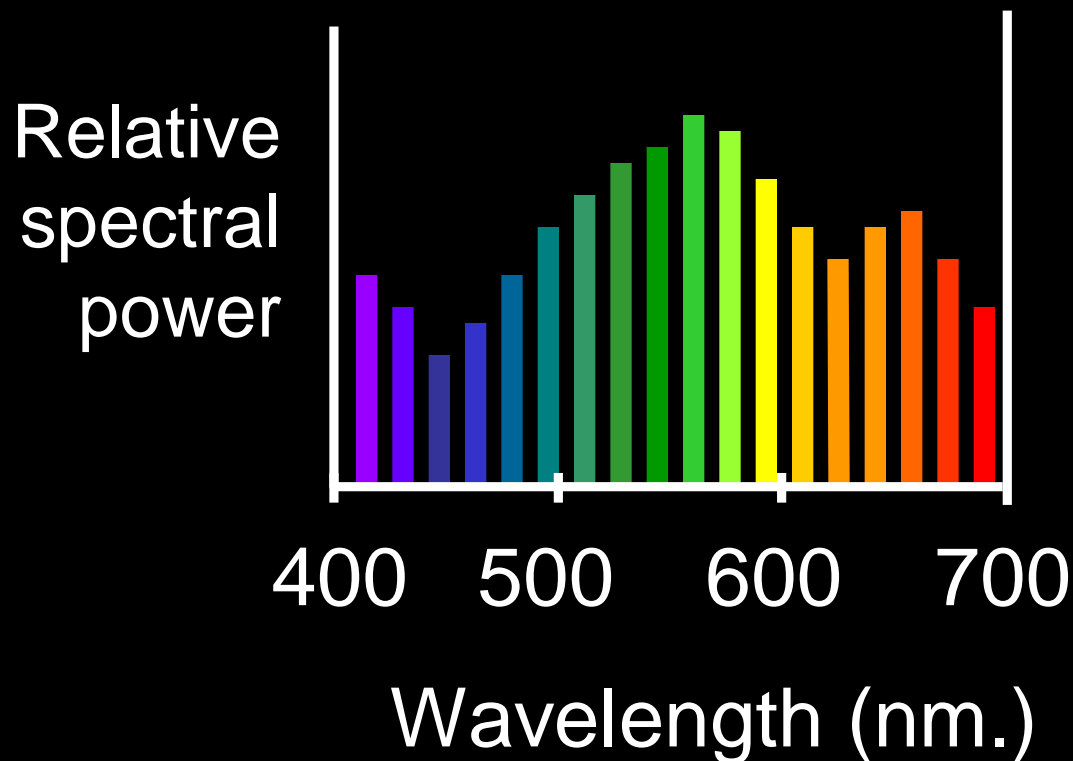


...because that's where the Sun radiates EM energy

© Stephen E. Palmer, 2002

The Physics of Light

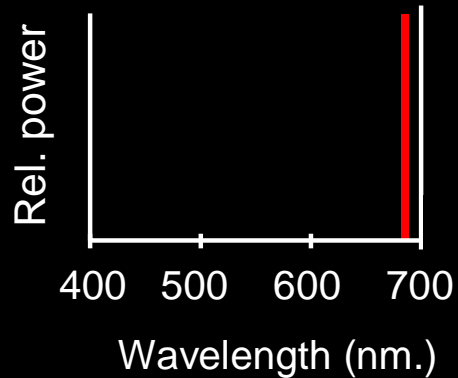
Any source of light can be completely described physically by its spectrum: the amount of energy emitted (per time unit) at each wavelength 400 - 700 nm.



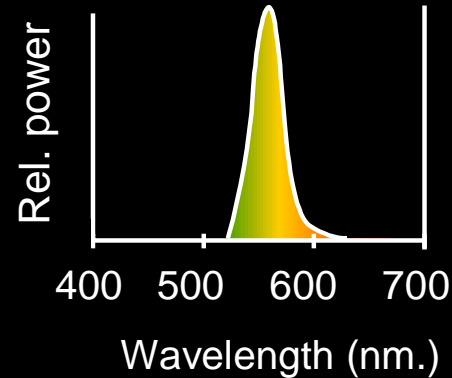
The Physics of Light

Some examples of the spectra of light sources

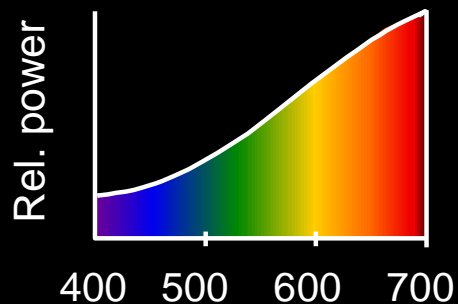
A. Ruby Laser



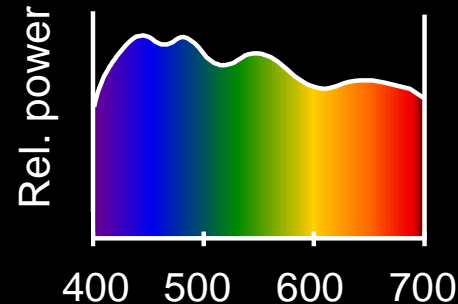
B. Gallium Phosphide Crystal



C. Tungsten Lightbulb

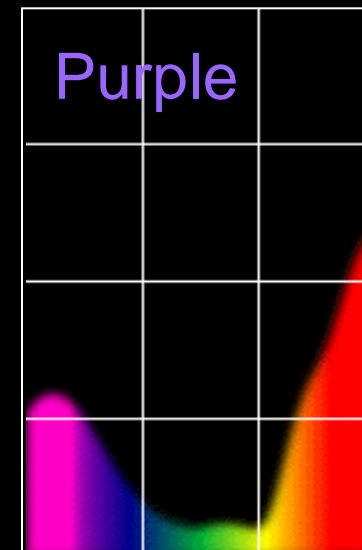
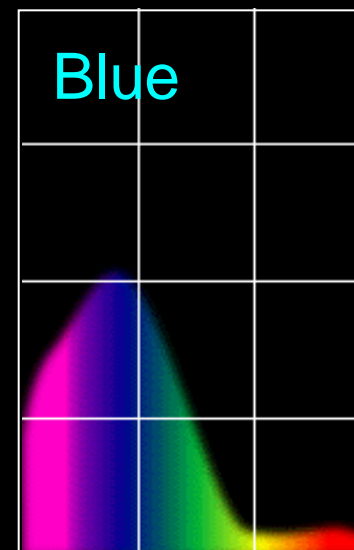
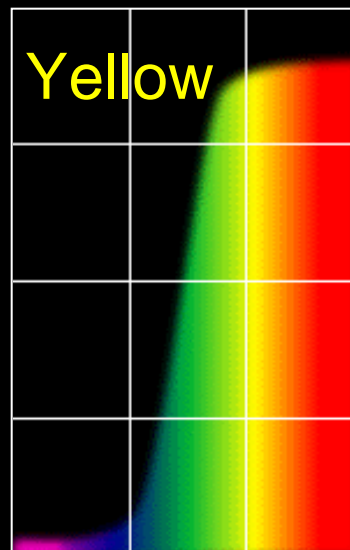
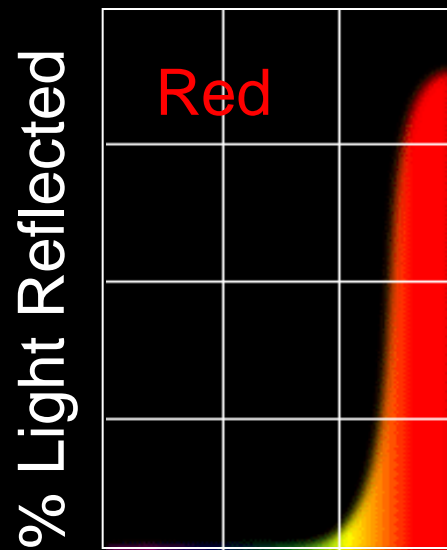


D. Normal Daylight



The Physics of Light

Some examples of the reflectance spectra of surfaces



400

700

400

700

400

700

400

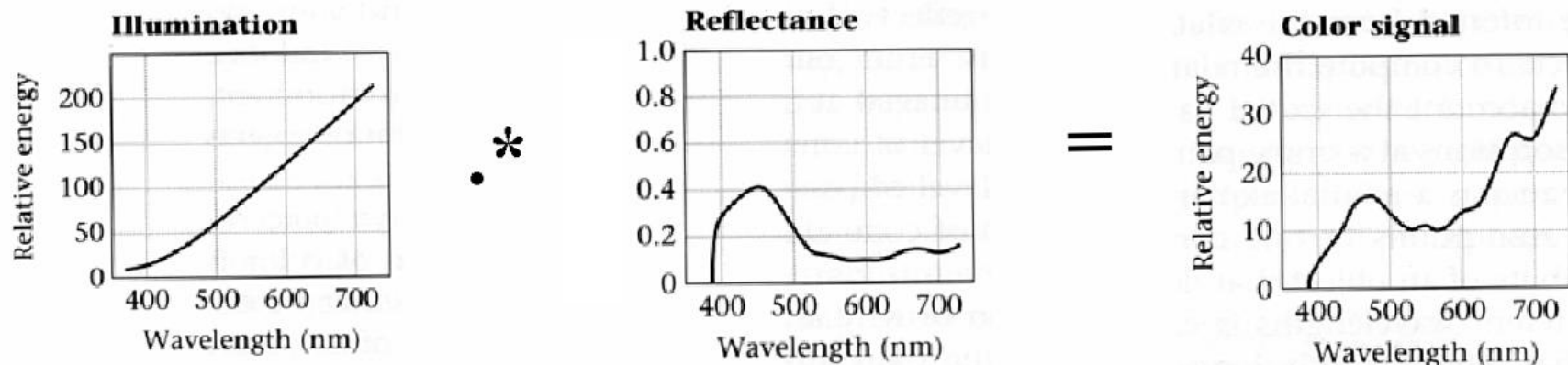
700

Wavelength (nm)

Interaction of light and surfaces



- Reflected color is the result of interaction of light source spectrum with surface reflectance
- Spectral radiometry
 - All definitions and units are now “per unit wavelength”
 - All terms are now “spectral”



Interaction of light and surfaces

- What is the observed color of any surface under monochromatic light?



Olafur Eliasson, *Room for one color*







James Turrell, Breathing Light



Inspired Drake in “Hotline Bling”

Overview of Color

- Physics of color
- Human encoding of color
- Color spaces
- White balancing

Two types of light-sensitive receptors

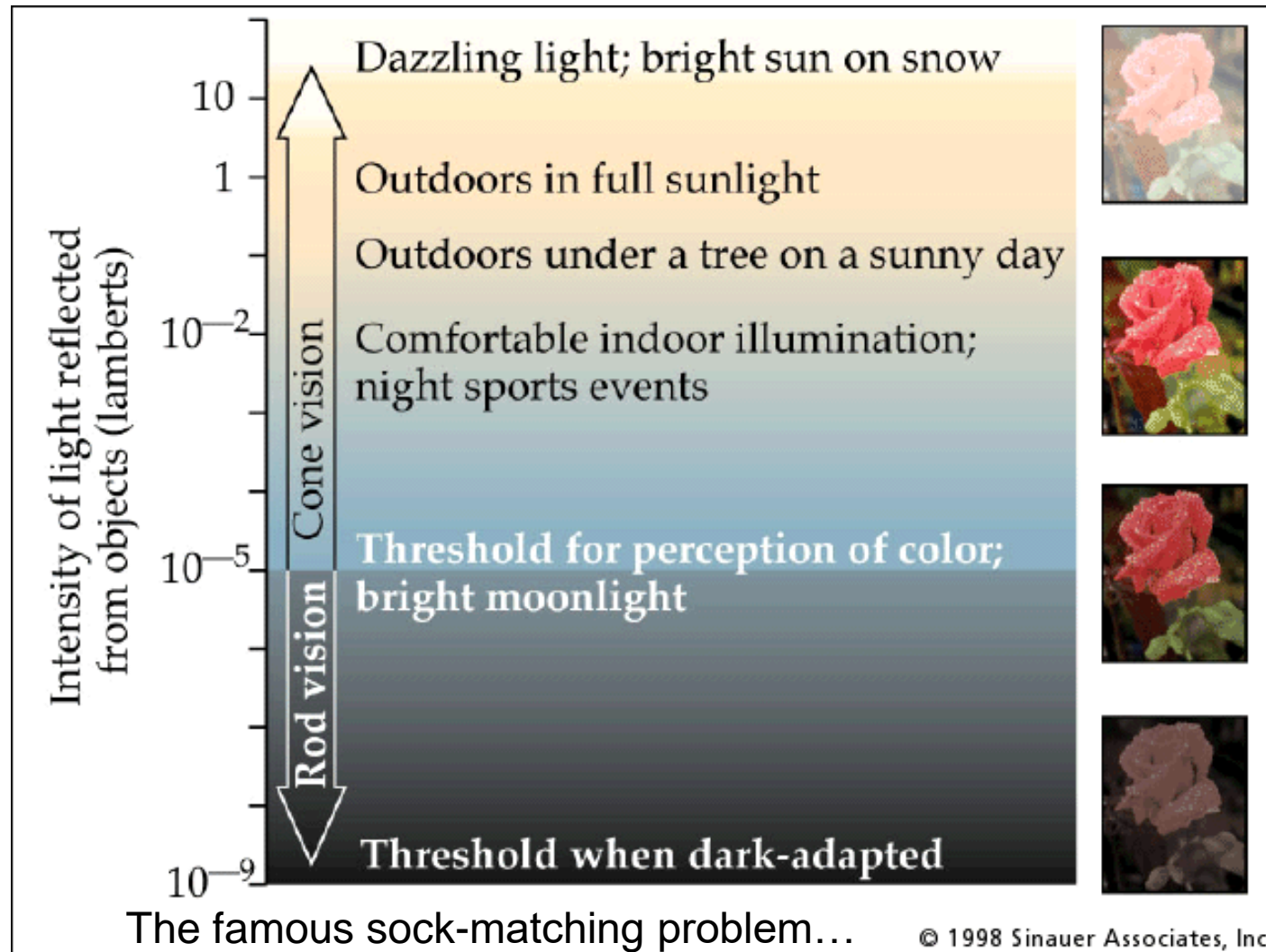
Cones

cone-shaped
less sensitive
operate in high light
color vision

Rods

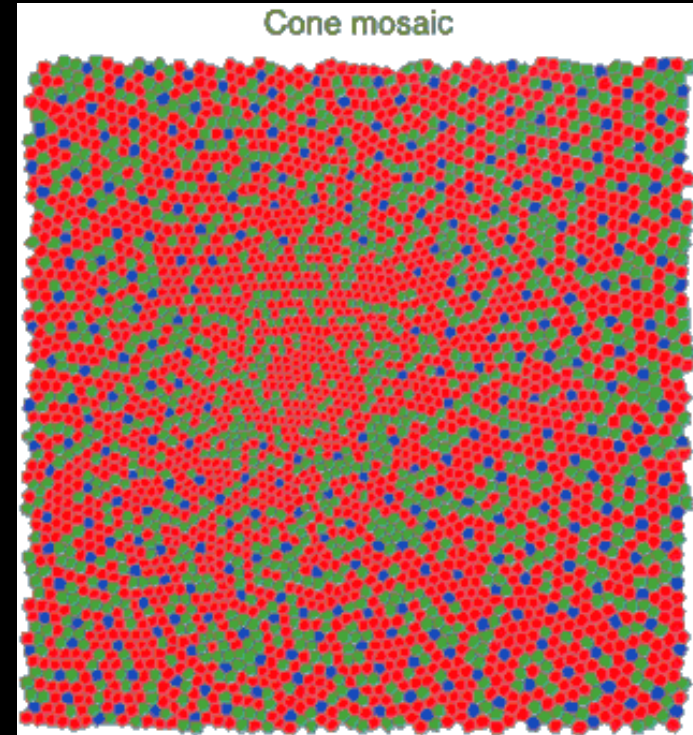
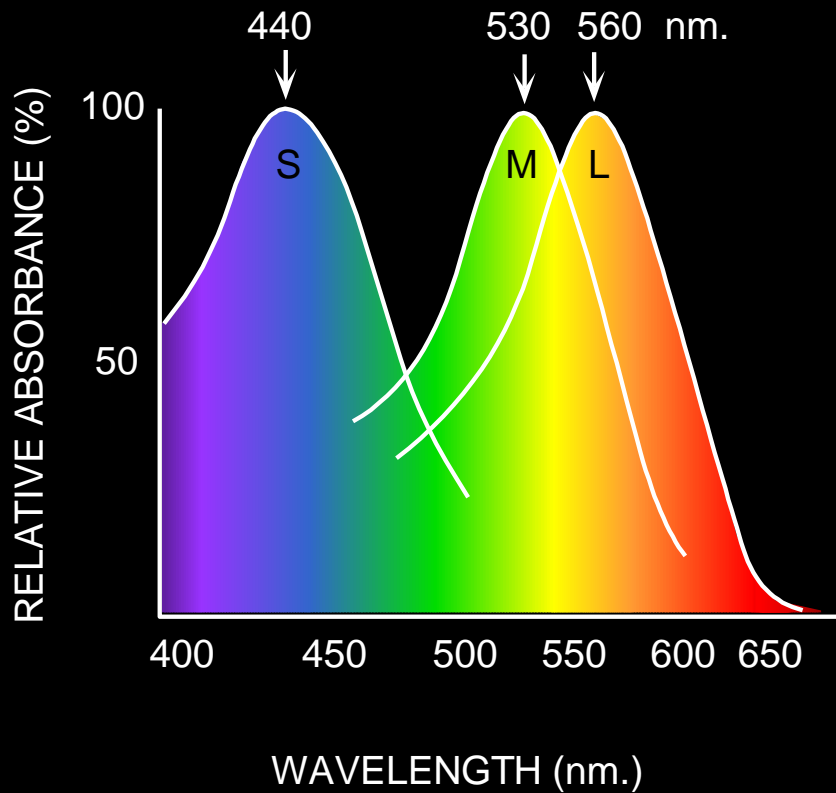
rod-shaped
highly sensitive
operate at night
gray-scale vision

Rod / Cone sensitivity

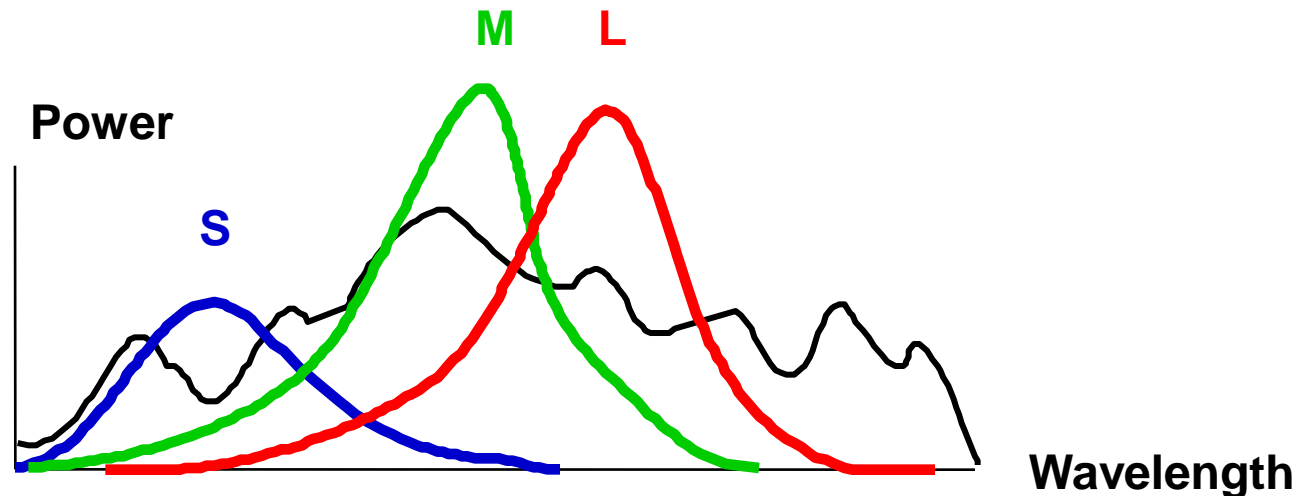


Physiology of Color Vision

Three kinds of cones:



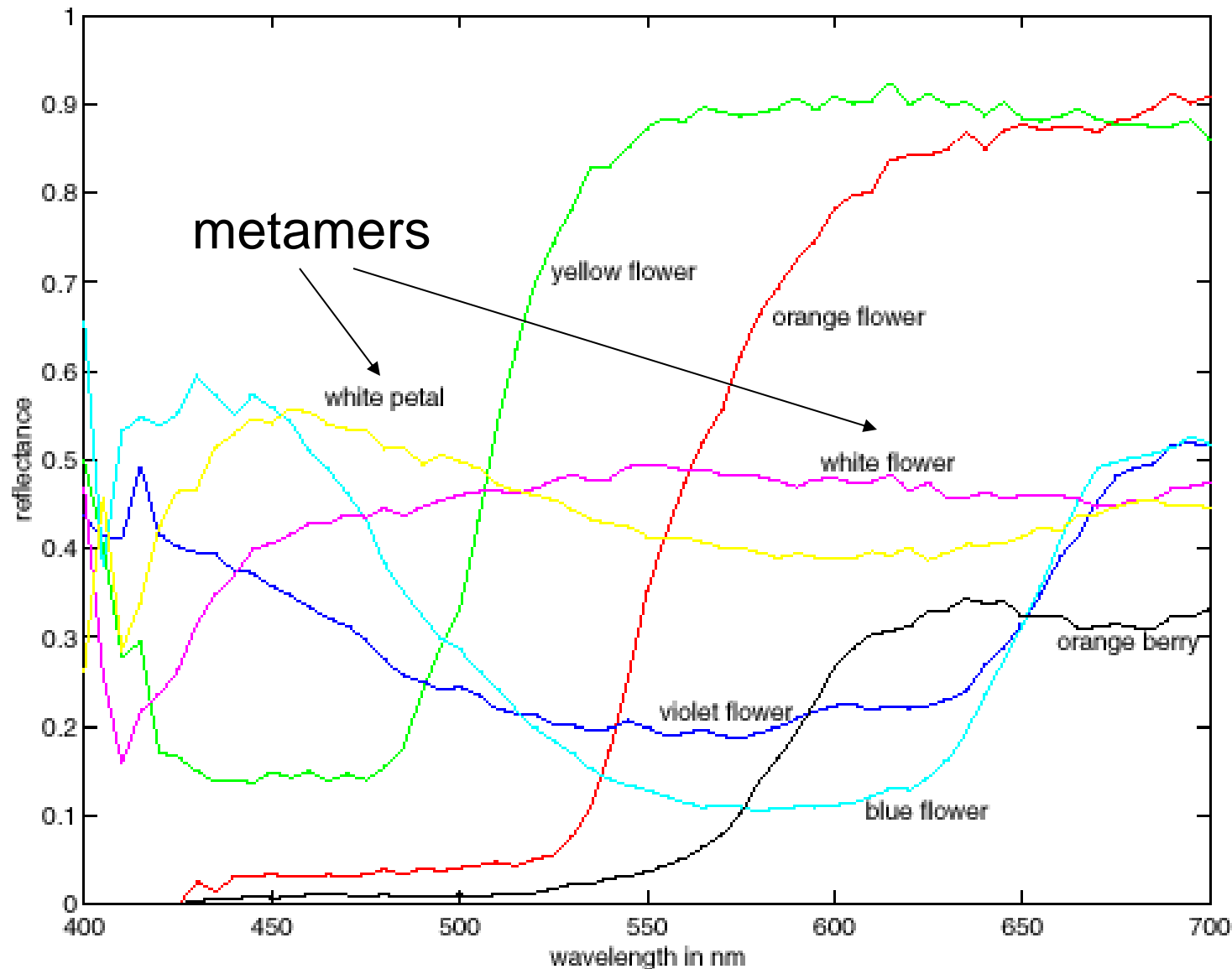
Color perception



Rods and cones act as filters on the spectrum

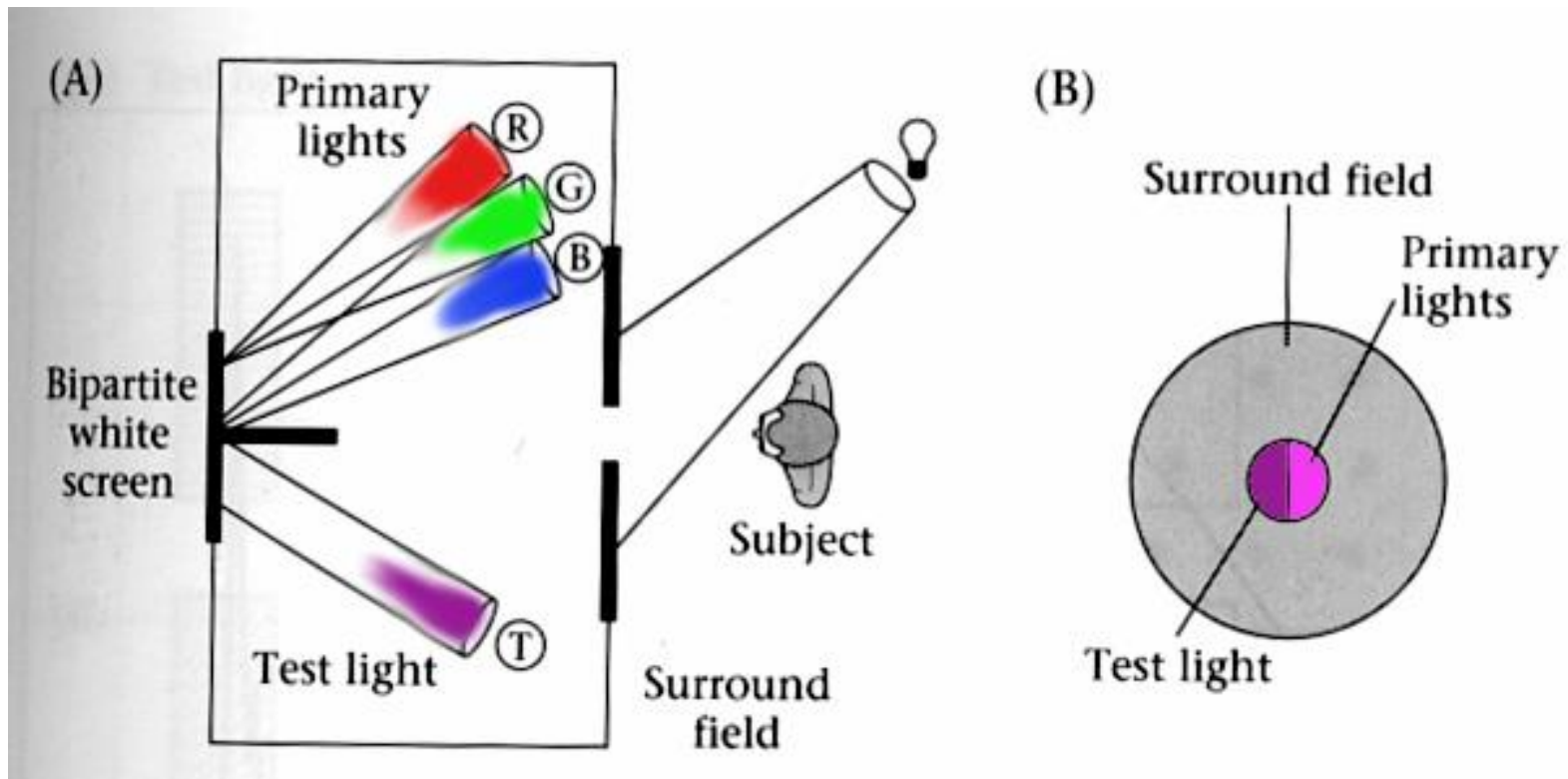
- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
 - Each cone yields one number
- Q: How can we represent an entire spectrum with 3 numbers?
- A: We can't! Most of the information is lost.
 - As a result, two different spectra may appear indistinguishable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

Spectra of some real-world surfaces

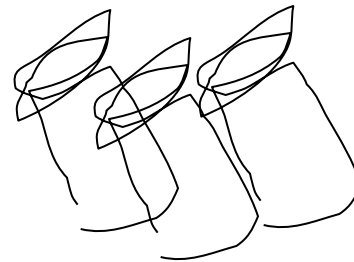
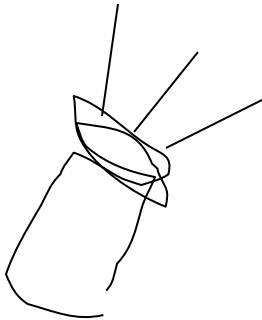
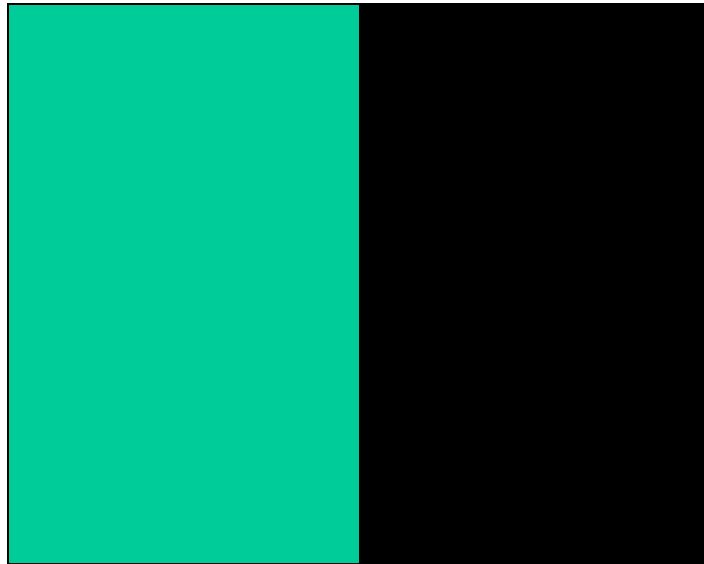


Standardizing color experience

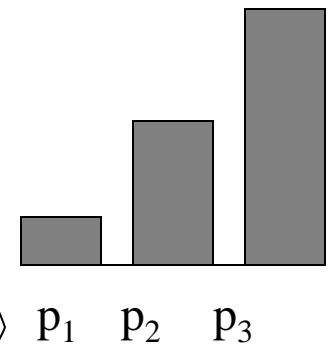
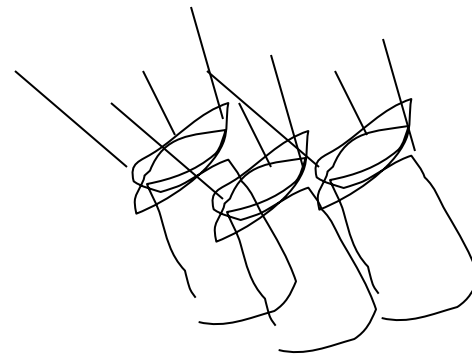
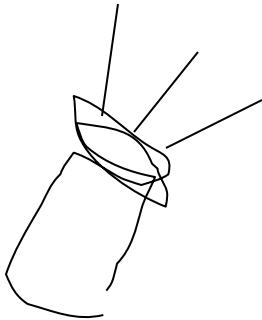
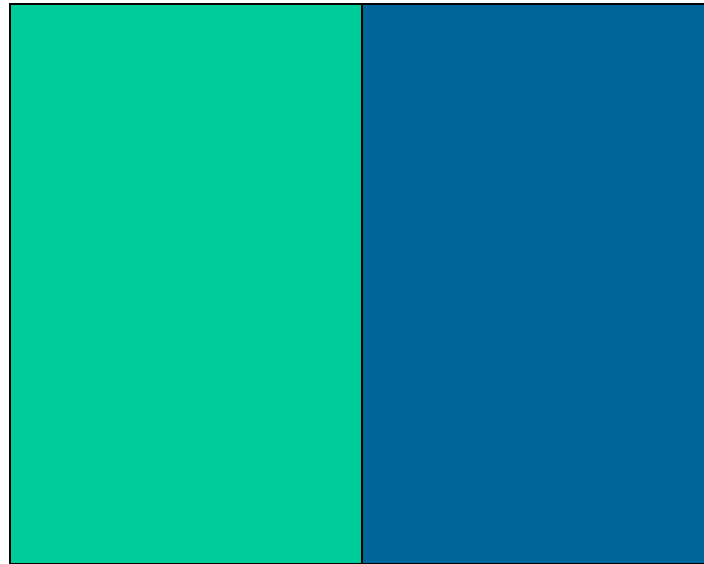
- We would like to understand which spectra produce the same color sensation in people under similar viewing conditions
- Color matching experiments



Color matching experiment 1

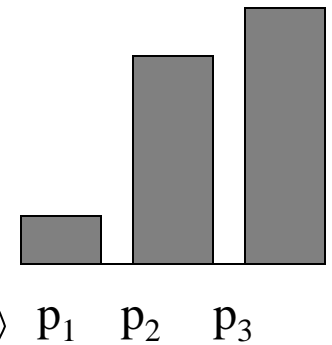
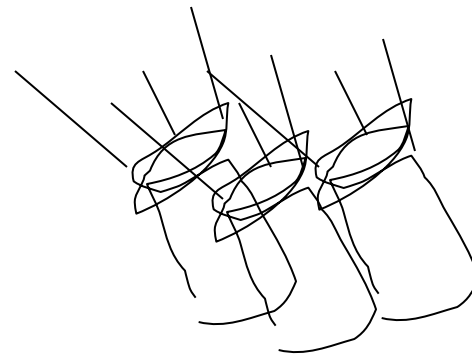
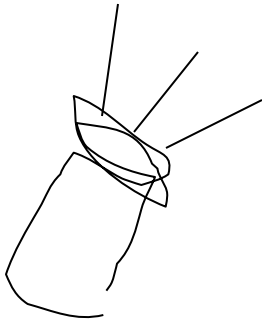
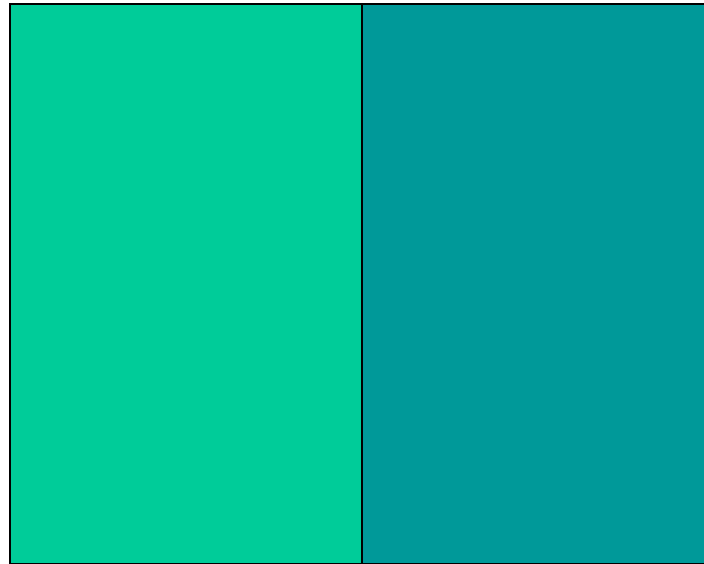


Color matching experiment 1



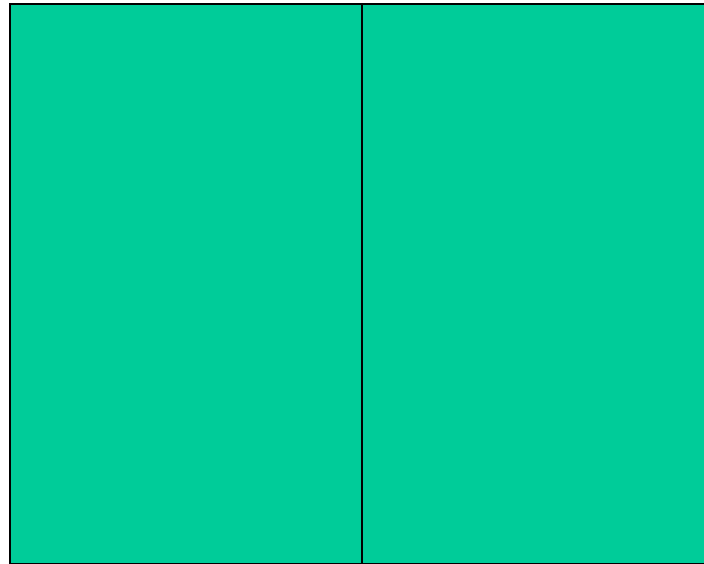
Source: W. Freeman

Color matching experiment 1

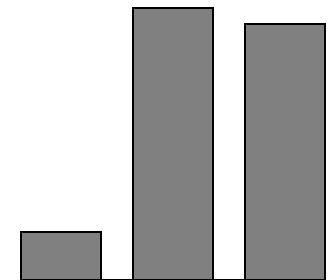
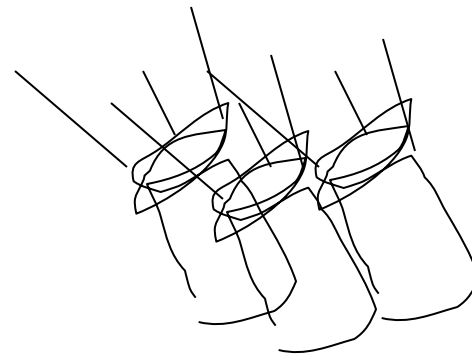
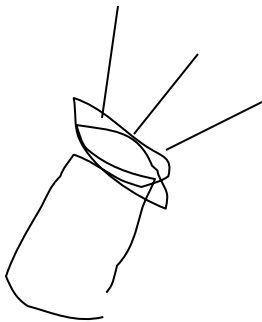


Source: W. Freeman

Color matching experiment 1



The primary color
amounts needed for a
match

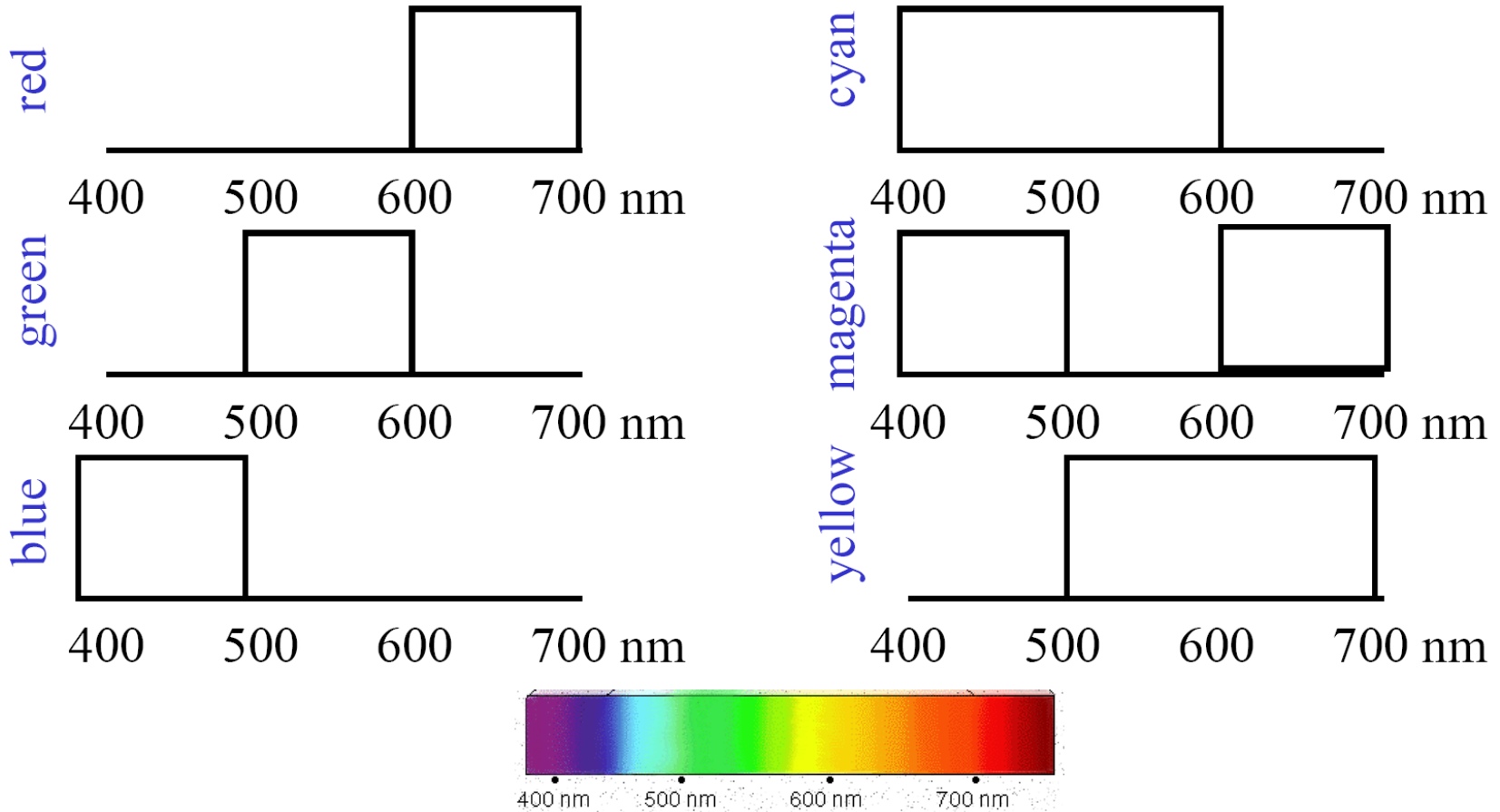


p_1

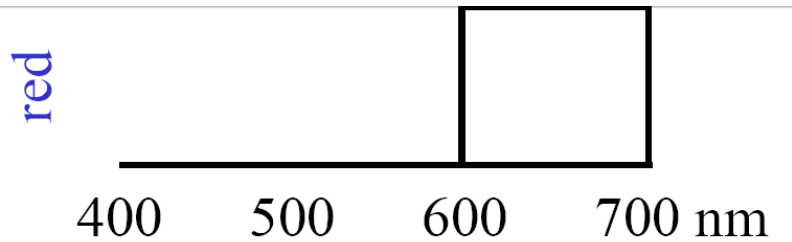
p_2

p_3

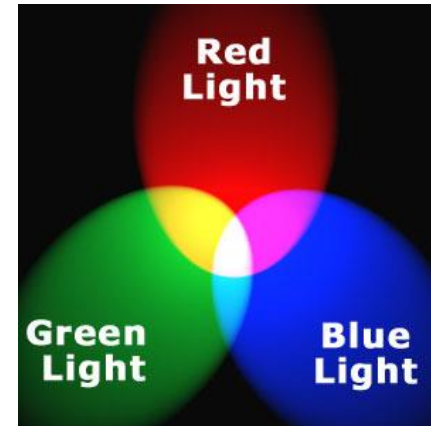
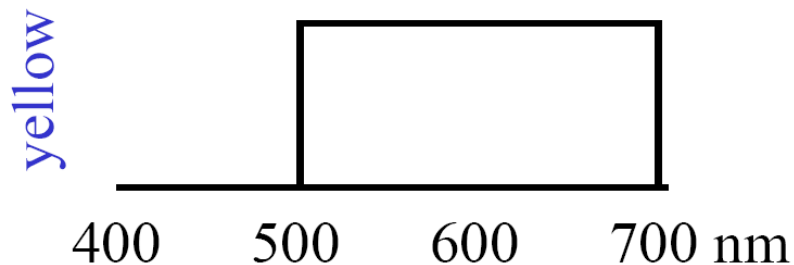
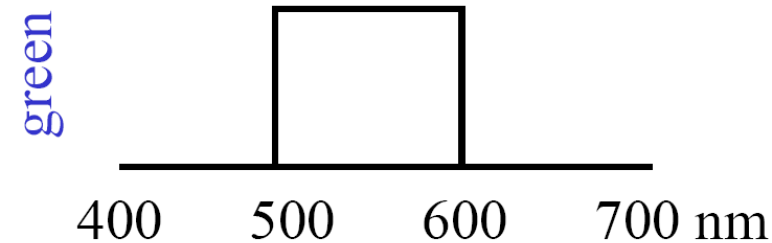
Color mixing



Additive color mixing

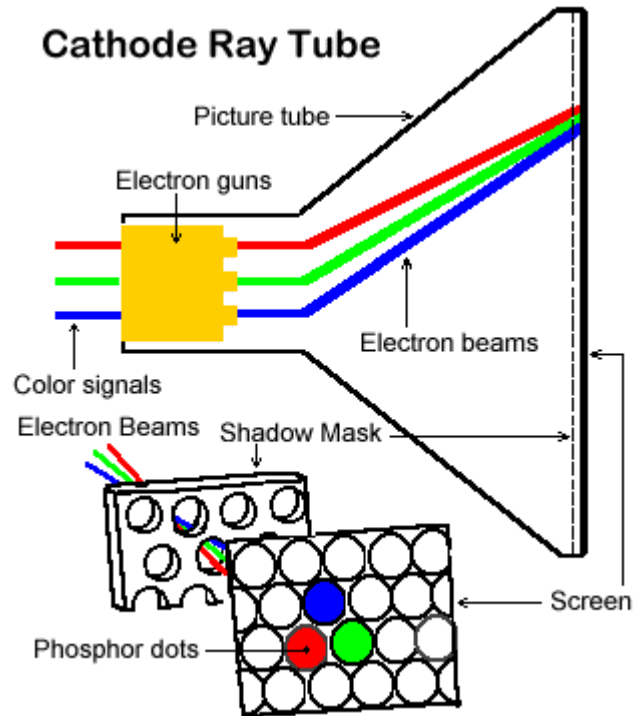


Colors combine by *adding* color spectra

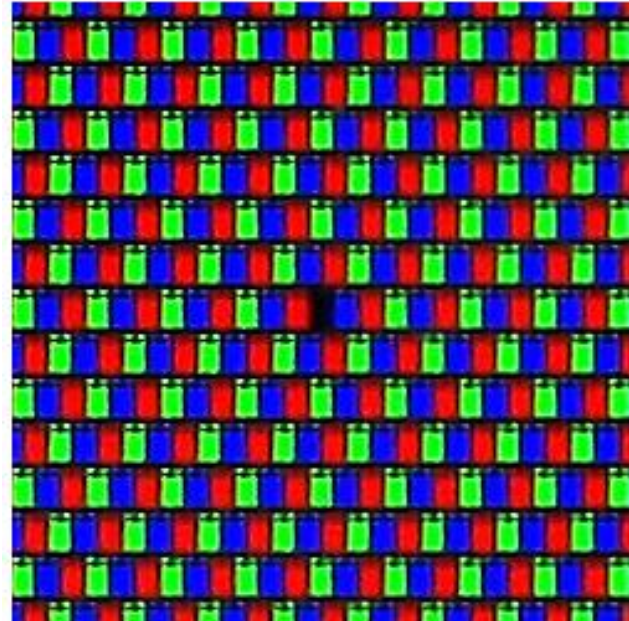


Light *adds* to existing black.

Examples of additive color systems



CRT phosphors

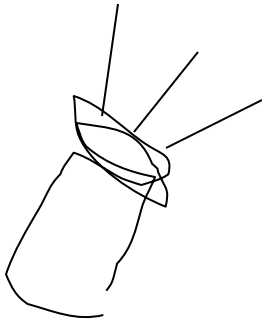
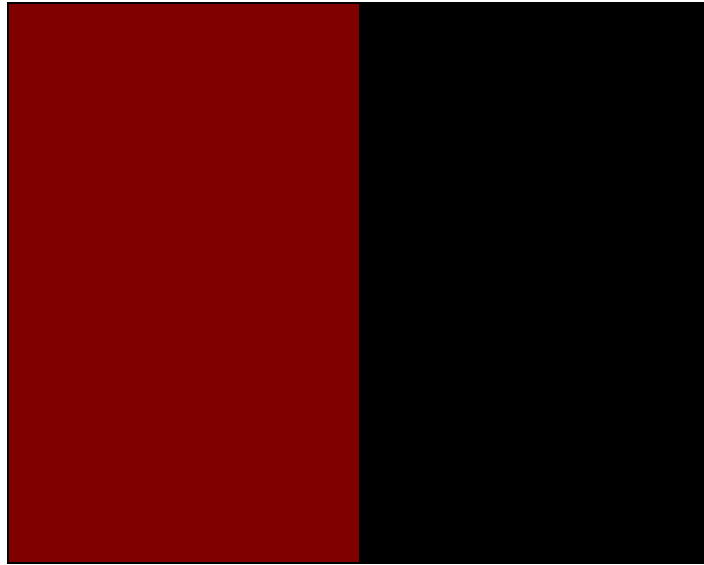


multiple projectors

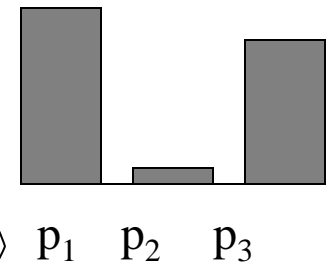
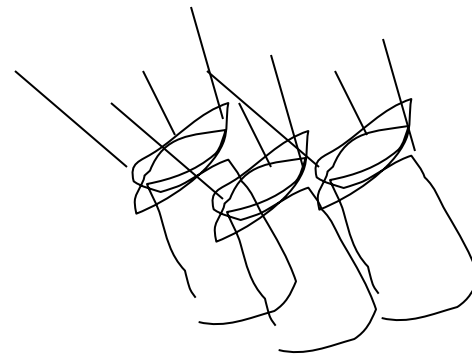
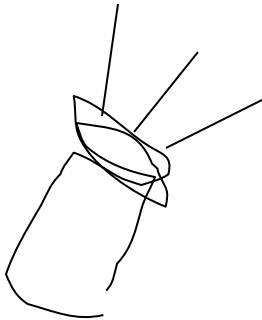
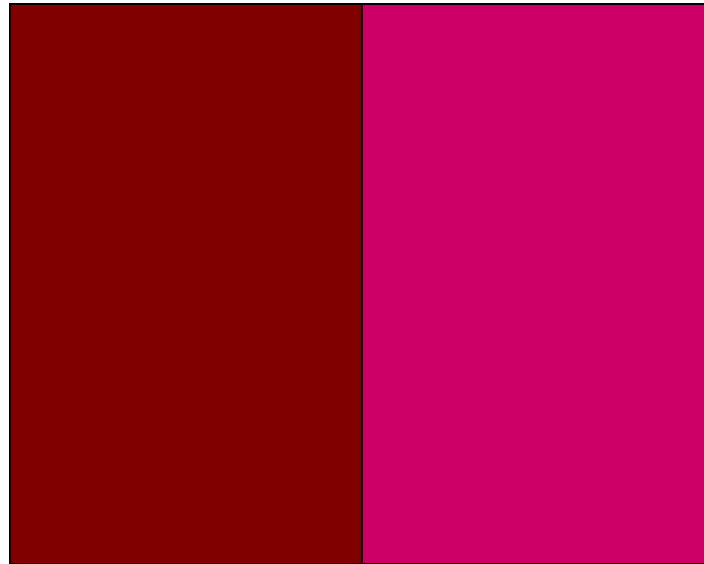
<http://www.jegsworks.com>

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

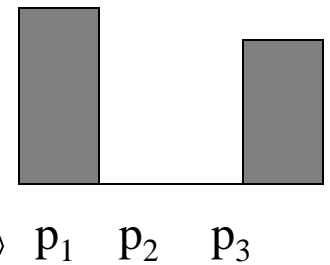
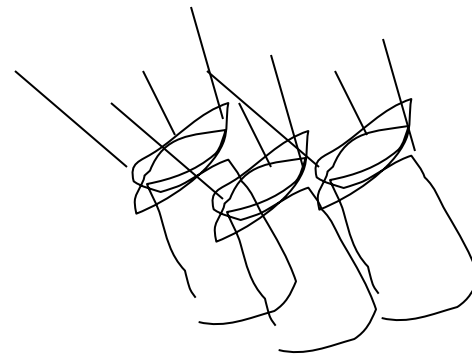
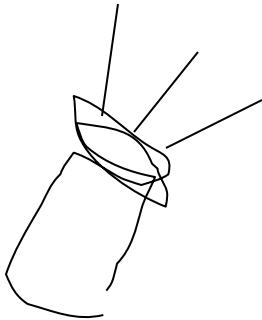
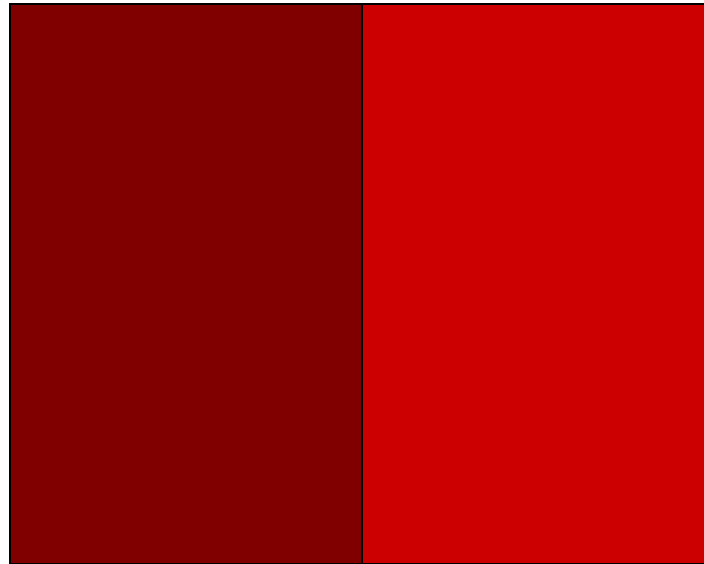
Color matching experiment 2



Color matching experiment 2



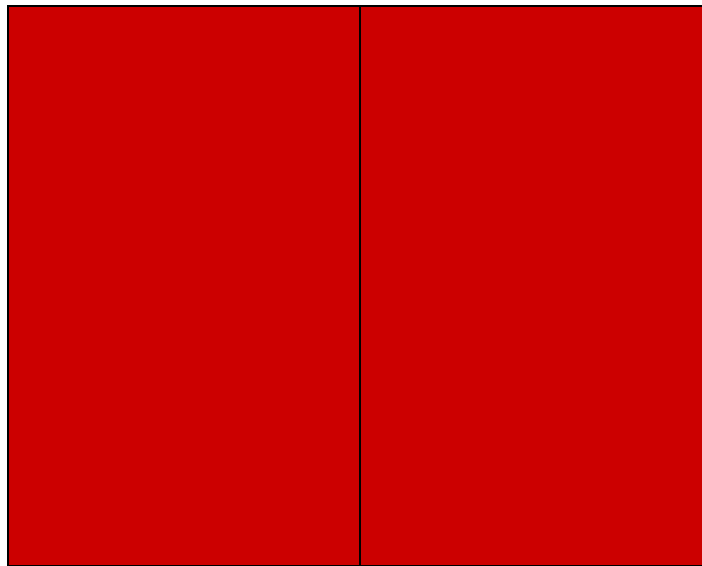
Color matching experiment 2



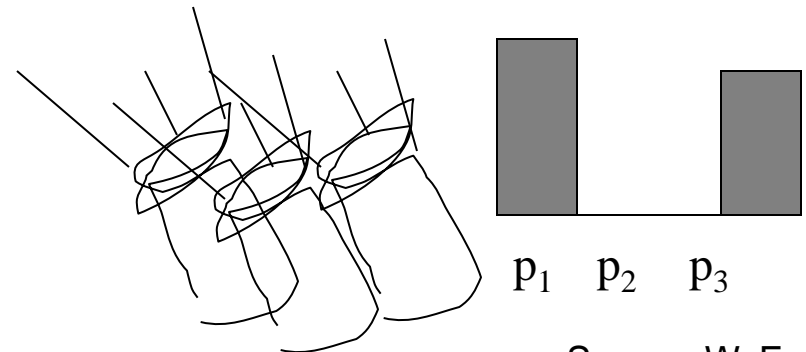
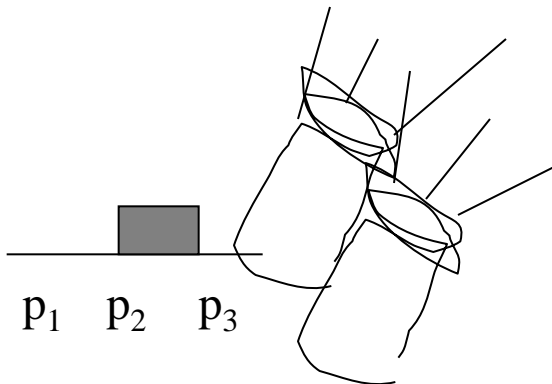
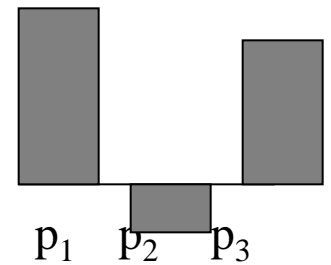
Source: W. Freeman

Color matching experiment 2

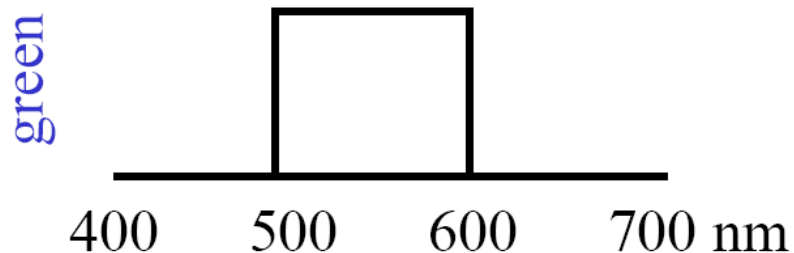
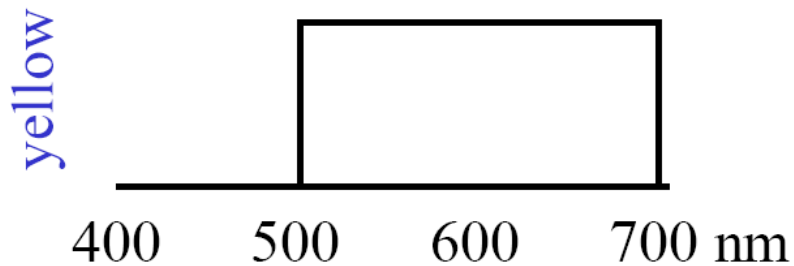
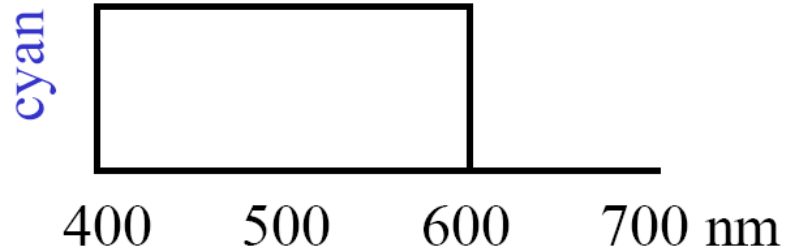
We say a “negative” amount of p_2 was needed to make the match, because we added it to the test color’s side.



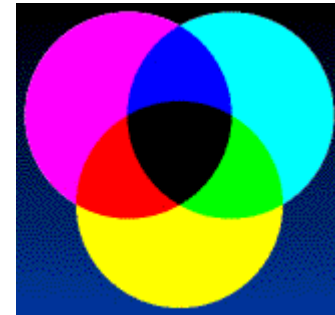
The primary color amounts needed for a match:



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
- Photographic film



Trichromacy

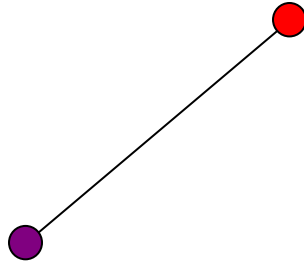
- In color matching experiments, most people can match any given light with three primaries
 - Primaries must be *independent*
- For the same light and same primaries, most people select the same weights
 - Exception: color blindness
- Trichromatic color theory
 - Three numbers seem to be sufficient for encoding color
 - Dates back to 18th century (Thomas Young)

Overview of Color

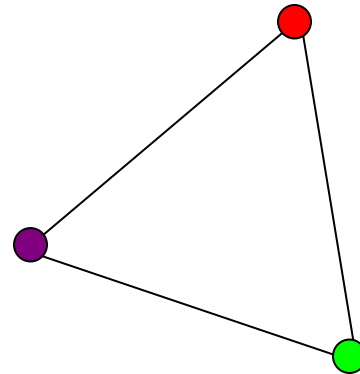
- Physics of color
- Human encoding of color
- Color spaces
- White balancing

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

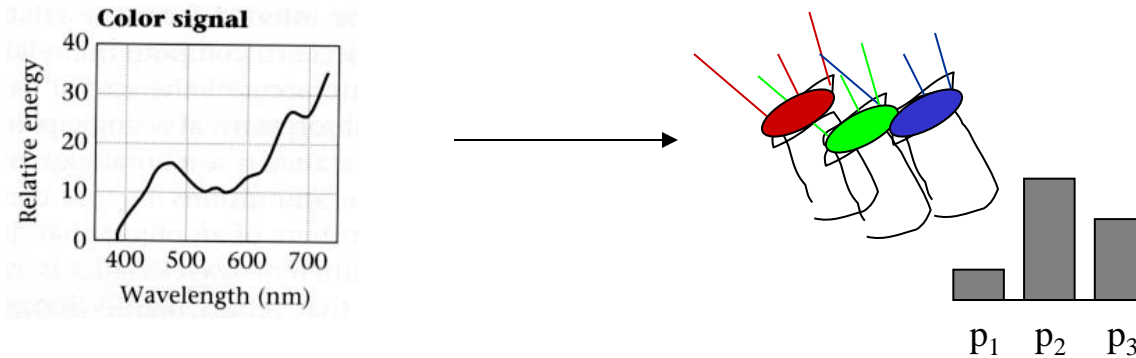


mixing two lights produces
colors that lie along a straight
line in color space



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

How to compute the weights of the primaries to match any spectral signal

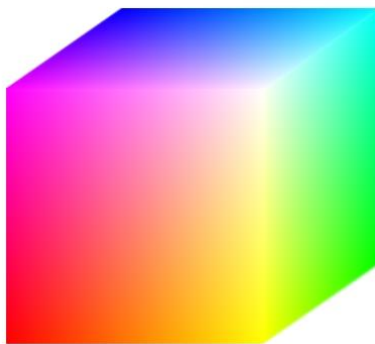





- **Matching functions:** the amount of each primary needed to match a monochromatic light source at each wavelength

RGB space

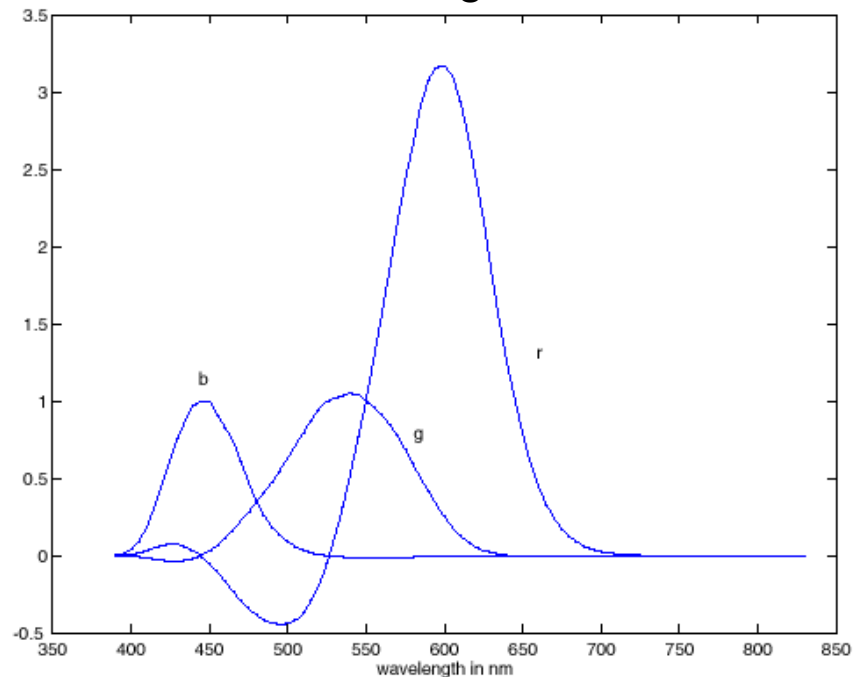
- Primaries are monochromatic lights (for monitors, they correspond to the three types of phosphors)
- *Subtractive matching* required for some wavelengths

RGB primaries



 $p_1 = 645.2 \text{ nm}$
 $p_2 = 525.3 \text{ nm}$
 $p_3 = 444.4 \text{ nm}$

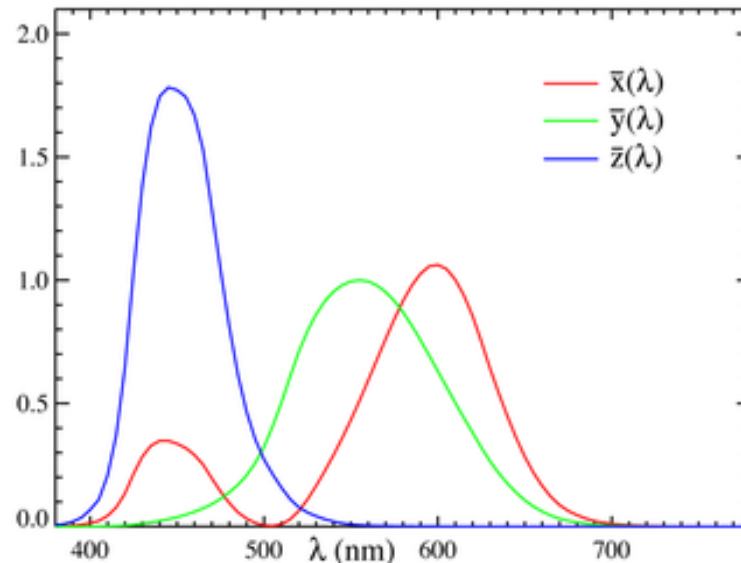
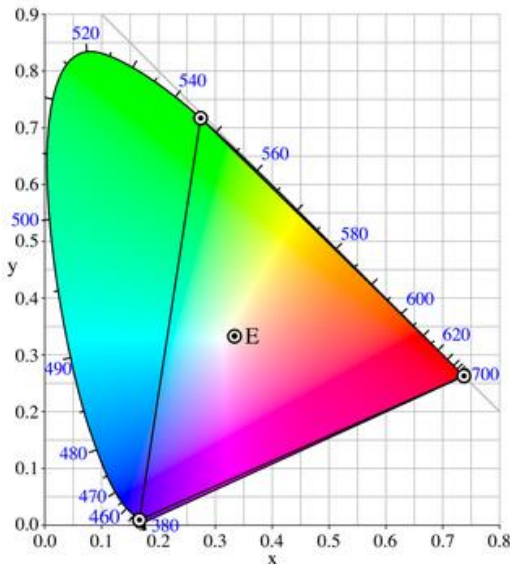
RGB matching functions



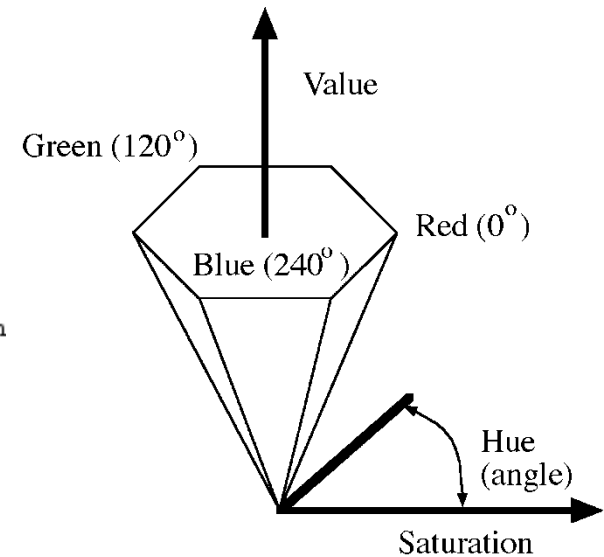
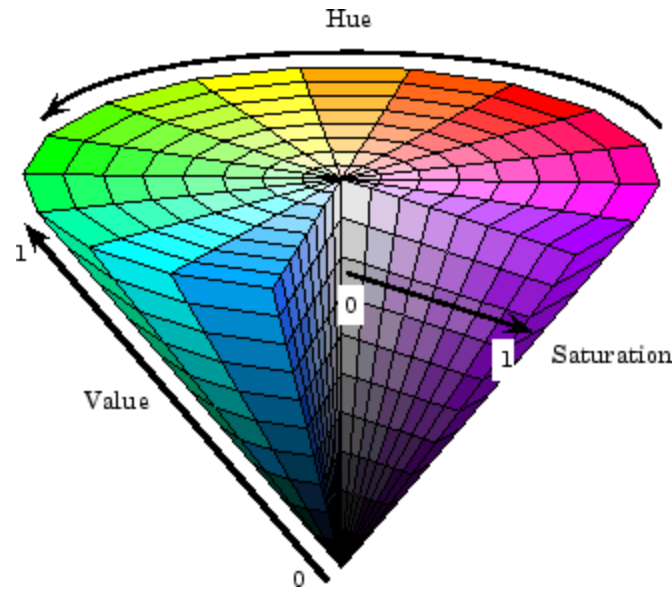
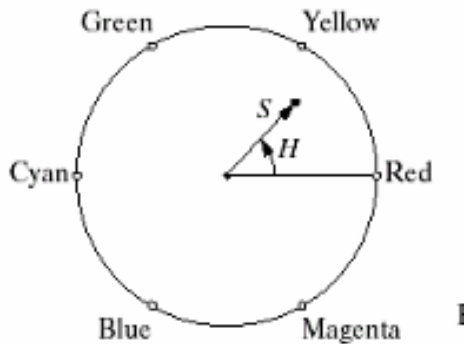
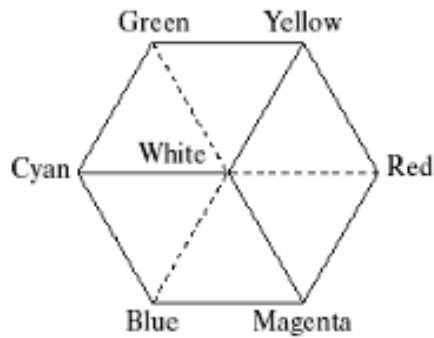
Linear color spaces: CIE XYZ

- Primaries are imaginary, but matching functions are everywhere positive
- The Y parameter corresponds to brightness or *luminance* of a color
- 2D visualization: draw (x,y) , where $x = X/(X+Y+Z)$, $y = Y/(X+Y+Z)$

Matching functions



Nonlinear color spaces: HSV



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

Overview of Color

- Physics of color
- Human encoding of color
- Color spaces
- White balancing

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

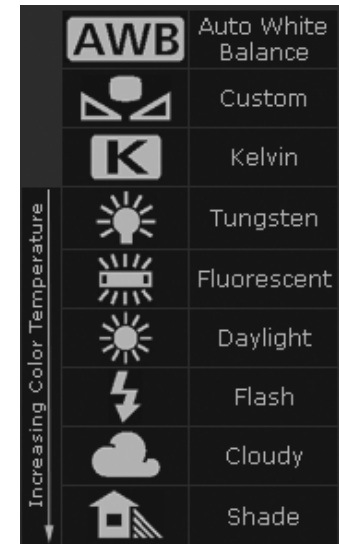


correct white balance



White balance

- Film cameras:
 - Different types of film or different filters for different illumination conditions
- Digital cameras:
 - Automatic white balance
 - White balance settings corresponding to several common illuminants
 - Custom white balance using a reference object



White balance

- Von Kries adaptation
 - Multiply each channel by a gain factor
 - A more general transformation would correspond to an arbitrary 3x3 matrix

White balance

- Von Kries adaptation
 - Multiply each channel by a gain factor
 - A more general transformation would correspond to an arbitrary 3x3 matrix
- Best way: gray card
 - Take a picture of a neutral object (white or gray)
 - Deduce the weight of each channel
 - If the object is recoded as r_w , g_w , b_w
use weights $1/r_w$, $1/g_w$, $1/b_w$

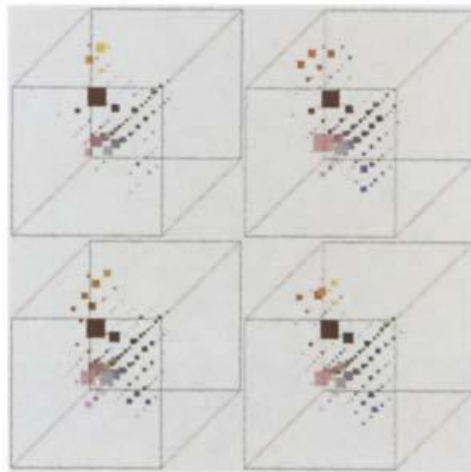
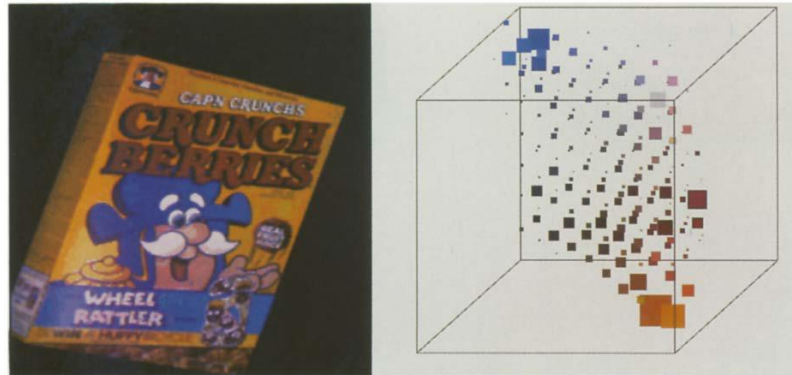


White balance

- Without gray cards: we need to “guess” which pixels correspond to white objects
- Gray world assumption
 - The image average r_{ave} , g_{ave} , b_{ave} is gray
 - Use weights $1/r_{ave}$, $1/g_{ave}$, $1/b_{ave}$
- Brightest pixel assumption (non-saturated)
 - Highlights usually have the color of the light source
 - Use weights inversely proportional to the values of the brightest pixels
- Gamut mapping
 - Gamut: convex hull of all pixel colors in an image
 - Find the transformation that matches the gamut of the image to the gamut of a “typical” image under white light
- Use image statistics, learning techniques

Uses of color in computer vision

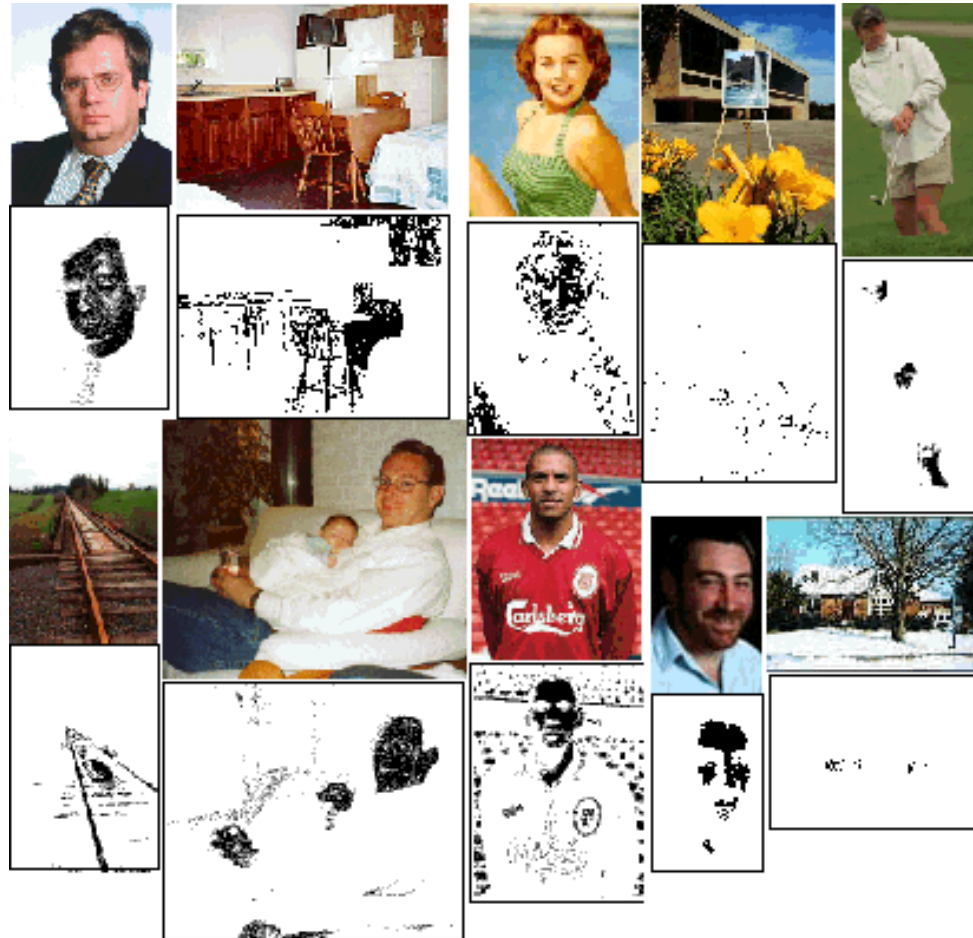
Color histograms for indexing and retrieval



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

Uses of color in computer vision

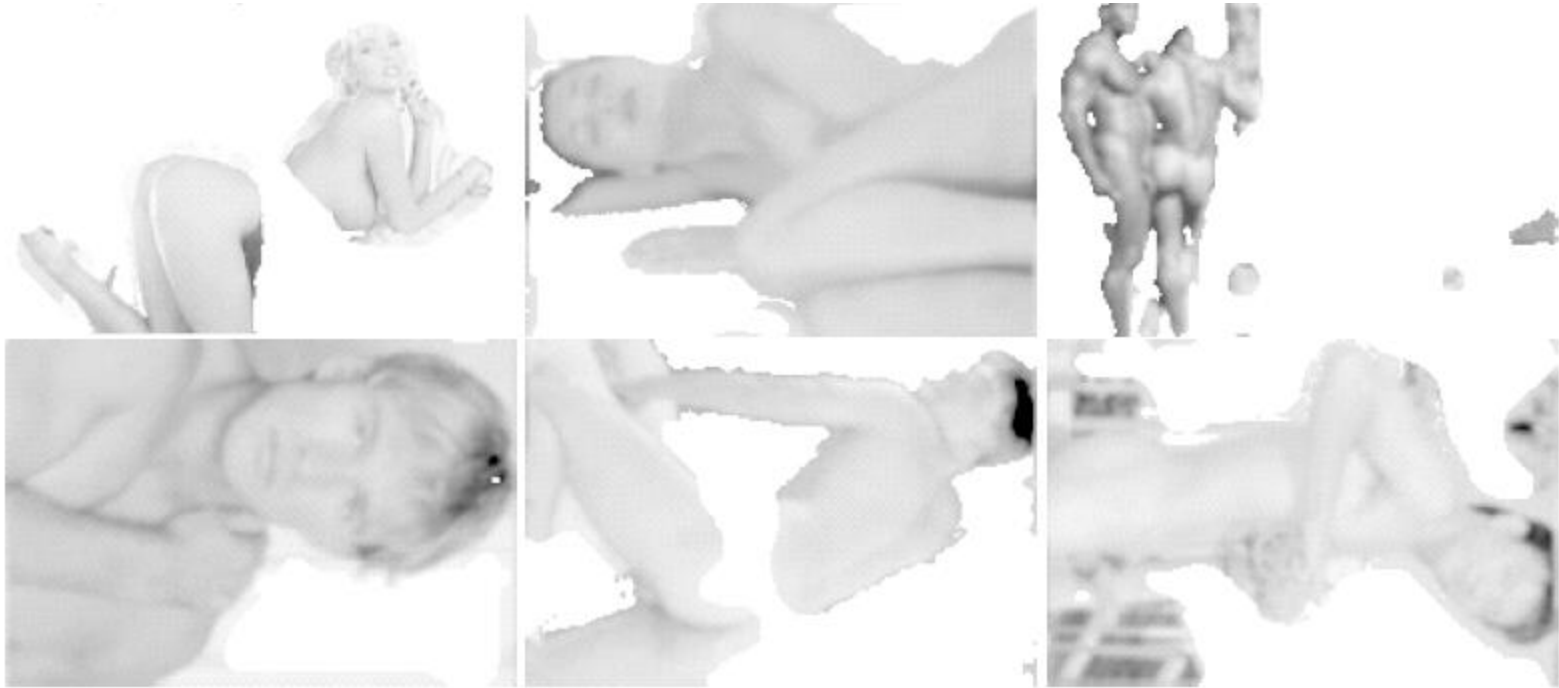
Skin detection



M. Jones and J. Rehg, [Statistical Color Models with Application to Skin Detection](#), IJCV 2002.

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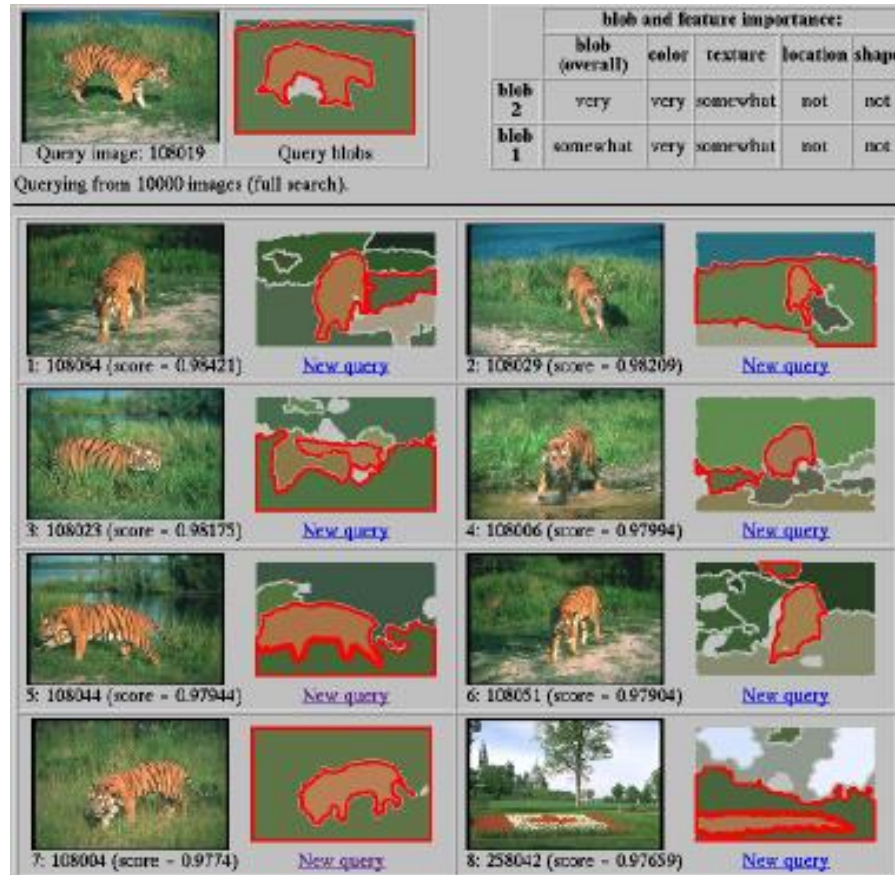
Nude people detection



Forsyth, D.A. and Fleck, M. M., ["Automatic Detection of Human Nudes,"](#) *International Journal of Computer Vision* , **32** , 1, 63-77, August, 1999

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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.

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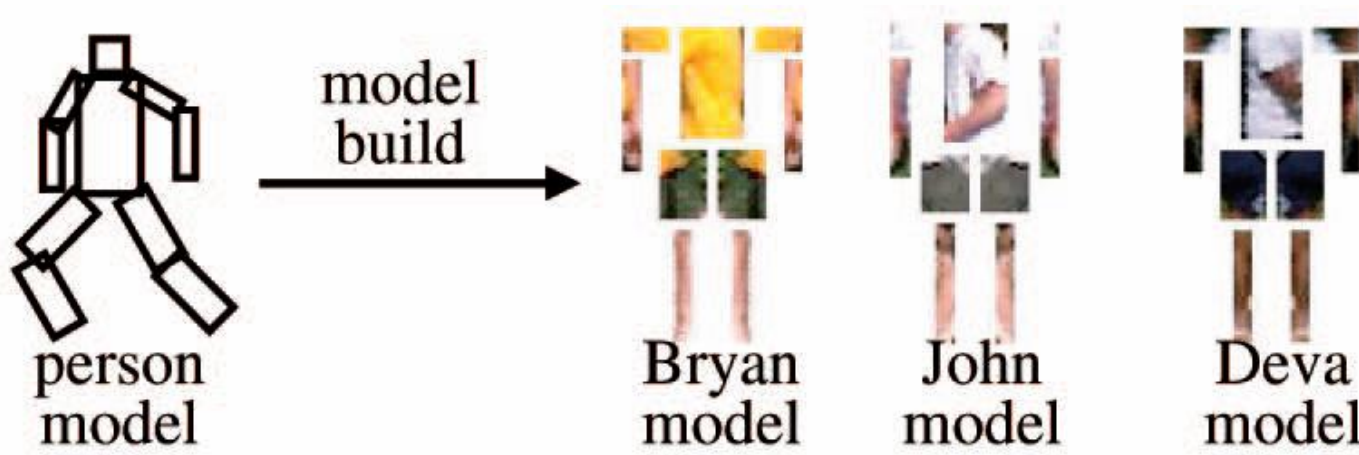
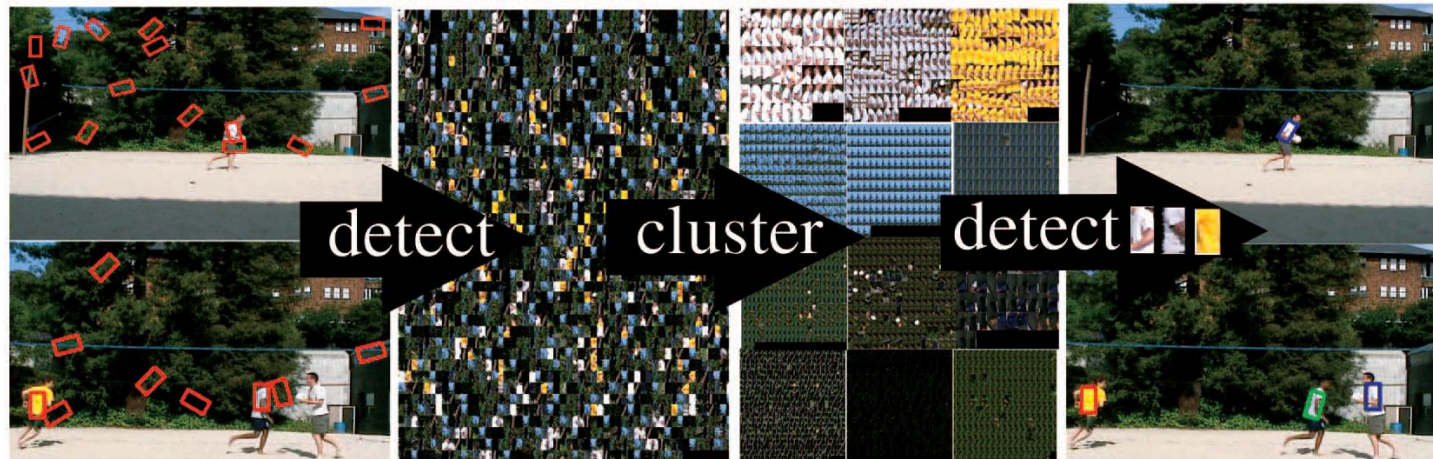
Robot soccer



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

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Building appearance models for tracking



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

Source: S. Lazebnik