Lecture:

Color

Adapted from slides by Juan Carlos Niebles, and Ranjay Krishna

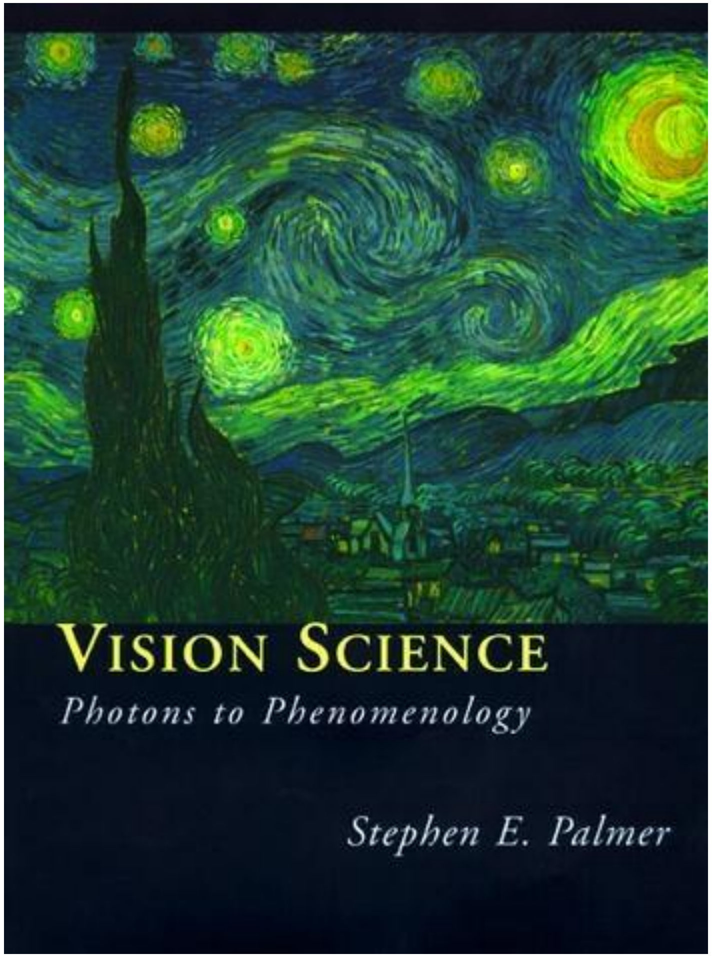
Overview of Color

- 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.

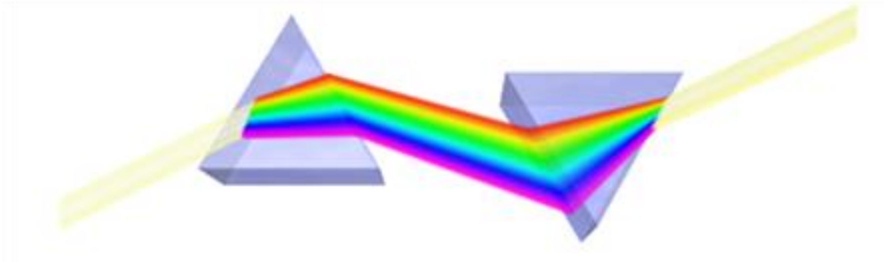
- A ***psychological property* of our visual experiences** when we look at objects and lights, ***not a physical property* of those objects or lights**.

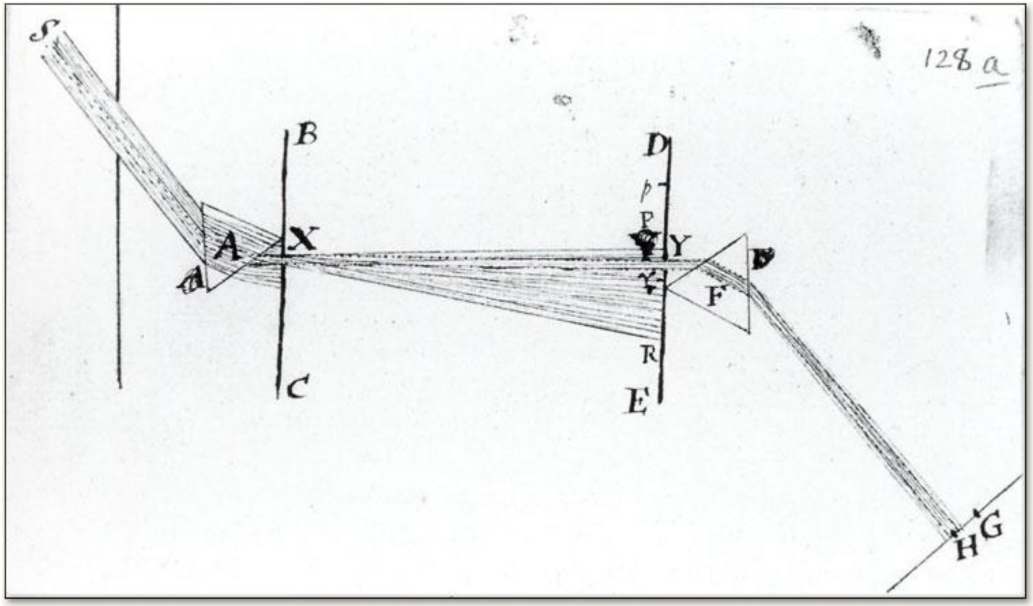


Slide credit: Lana Lazebnik

Color and light

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

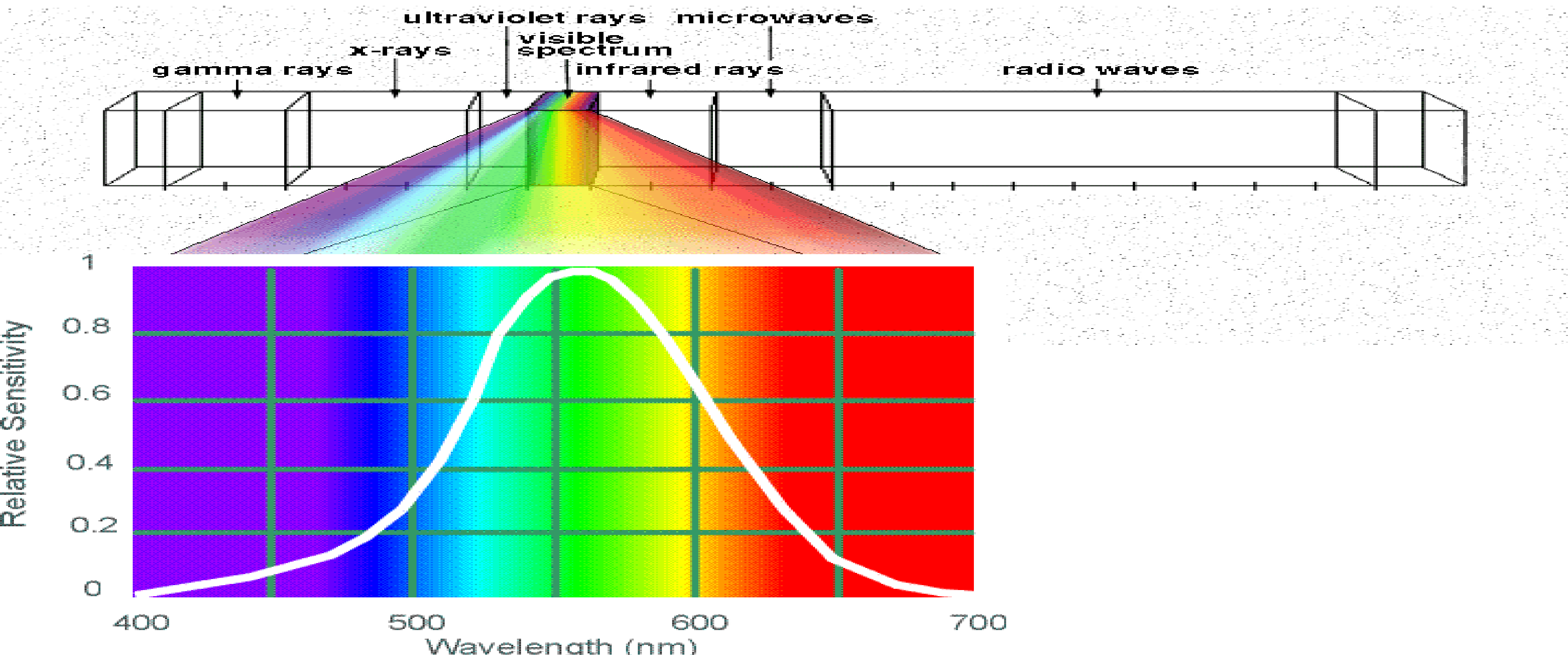




Newton 1665

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

Electromagnetic Spectrum



Human Luminance Sensitivity Function

Adapted from slides by Juan Carlos Niebles, and Ranjay Krishna

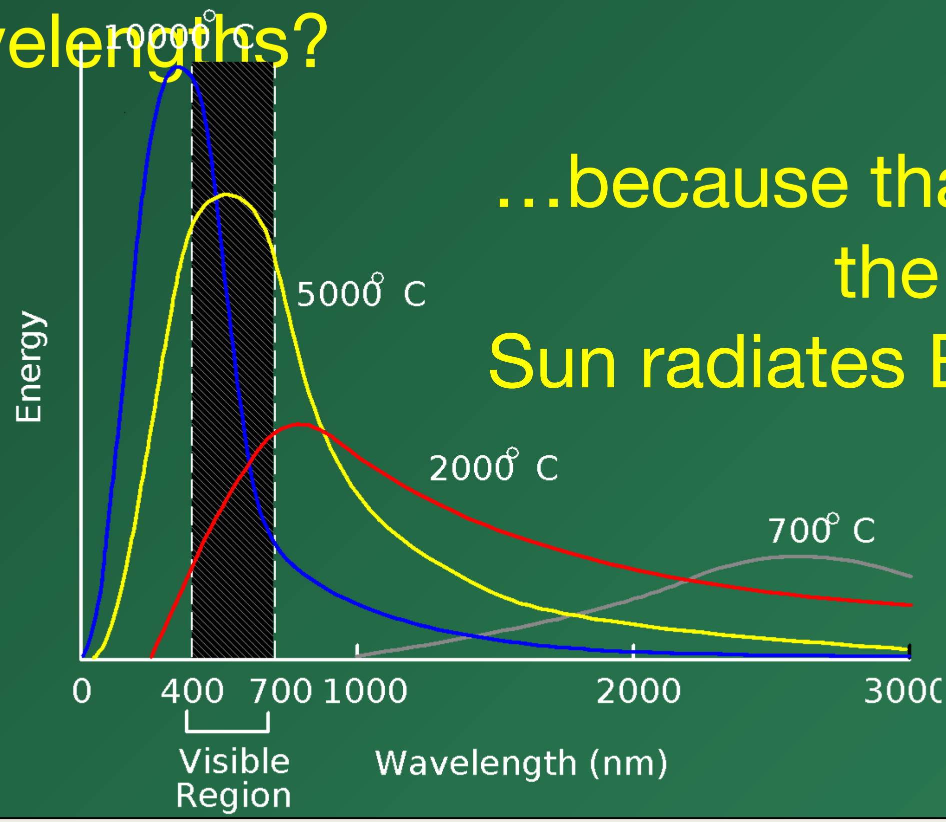
http://www.yorku.ca/eye/photopik.htm

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

Visible Light

Plank's law for Blackbody radiation
Surface of the sun: ~5800K (~5500*C)

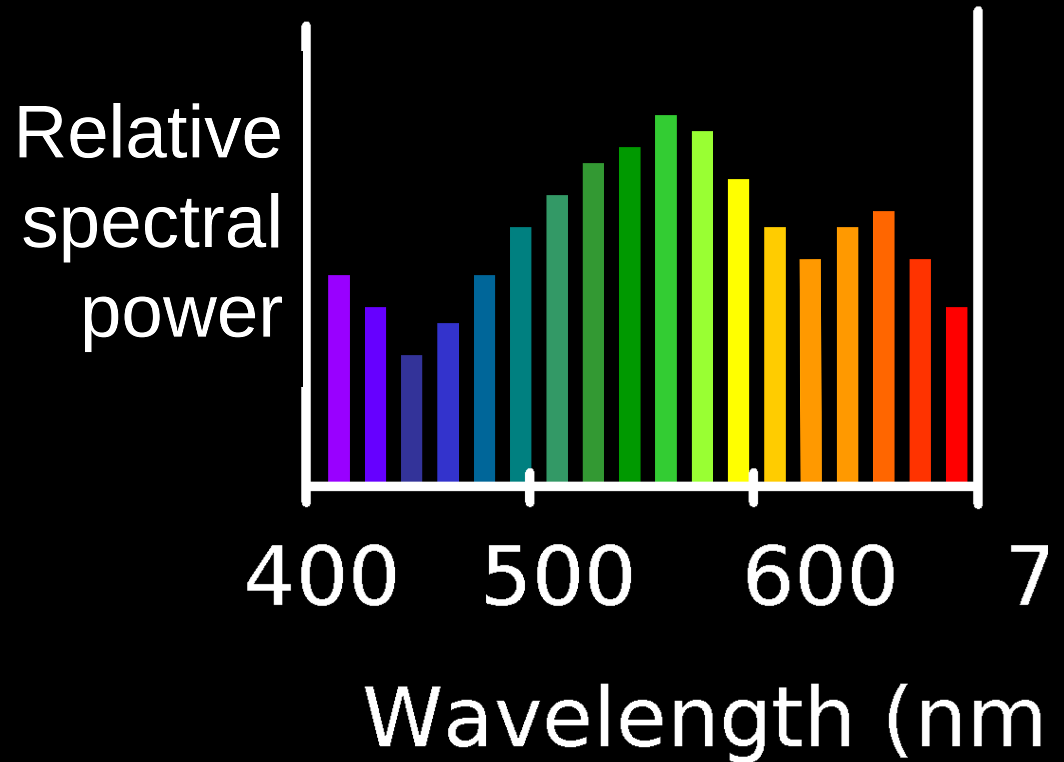
Why do we see light of these wavelengths?



…because that's where the Sun radiates EM energy

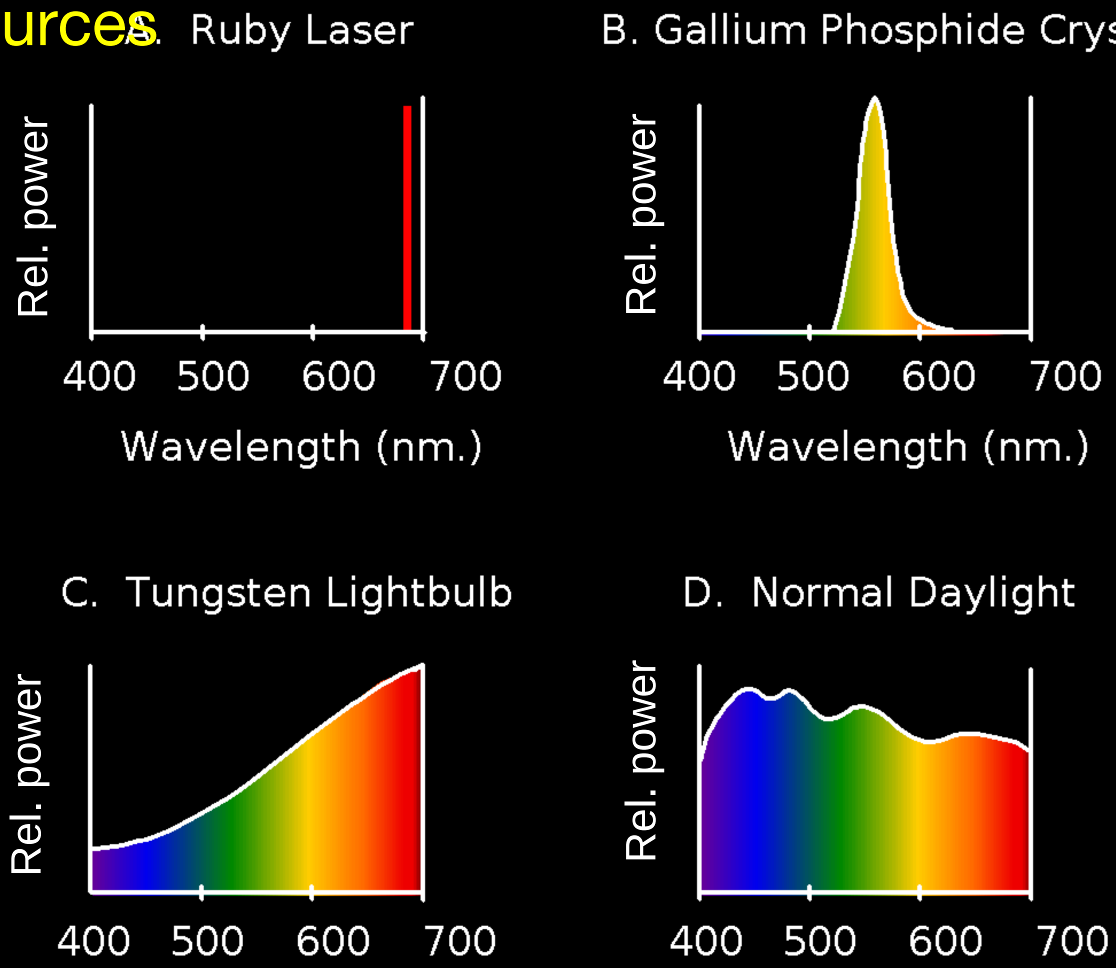
The Physics of Light

Any source of visible 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

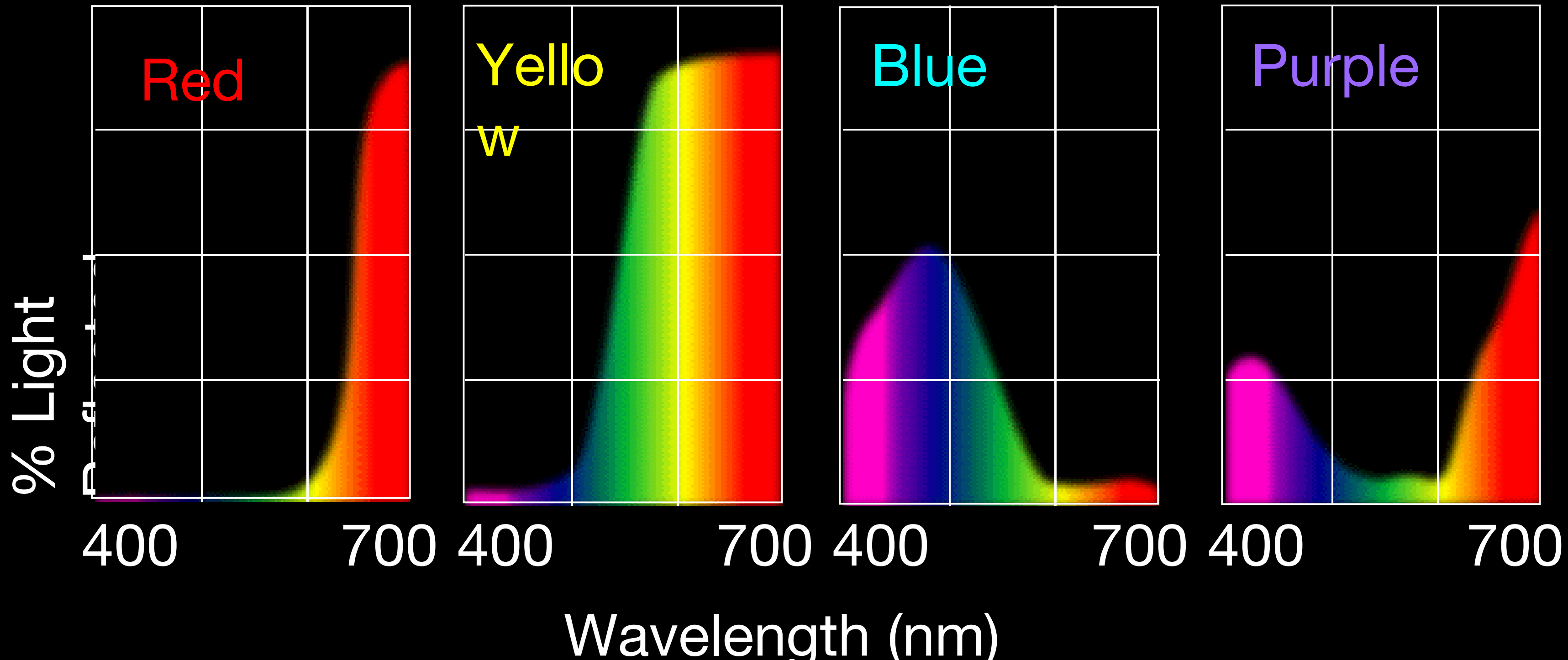
Some examples of the spectra of light sources



The Physics of Light

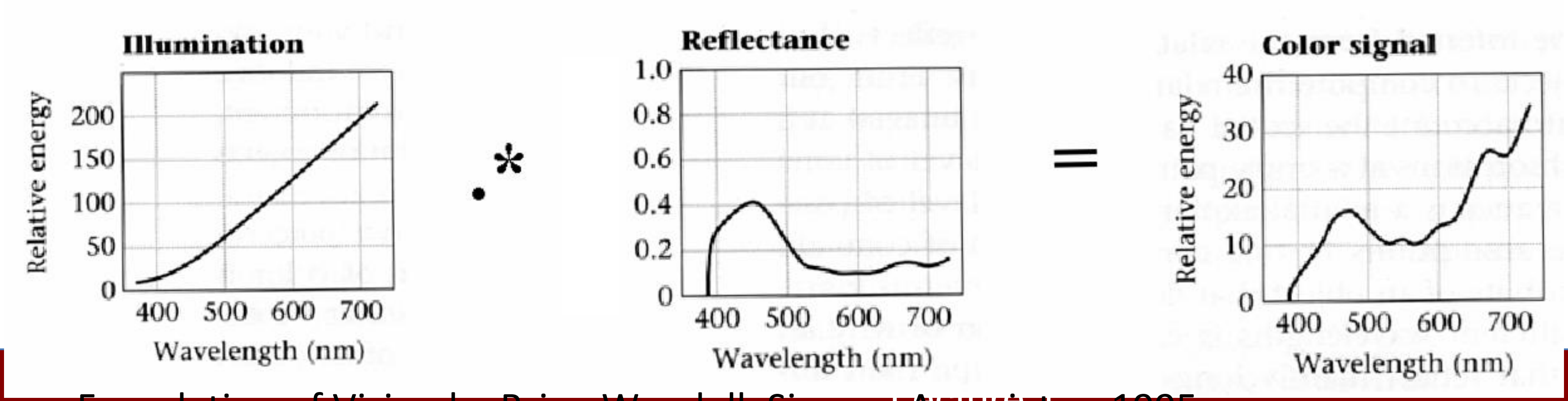
Some examples of the reflectance spectra of surfaces



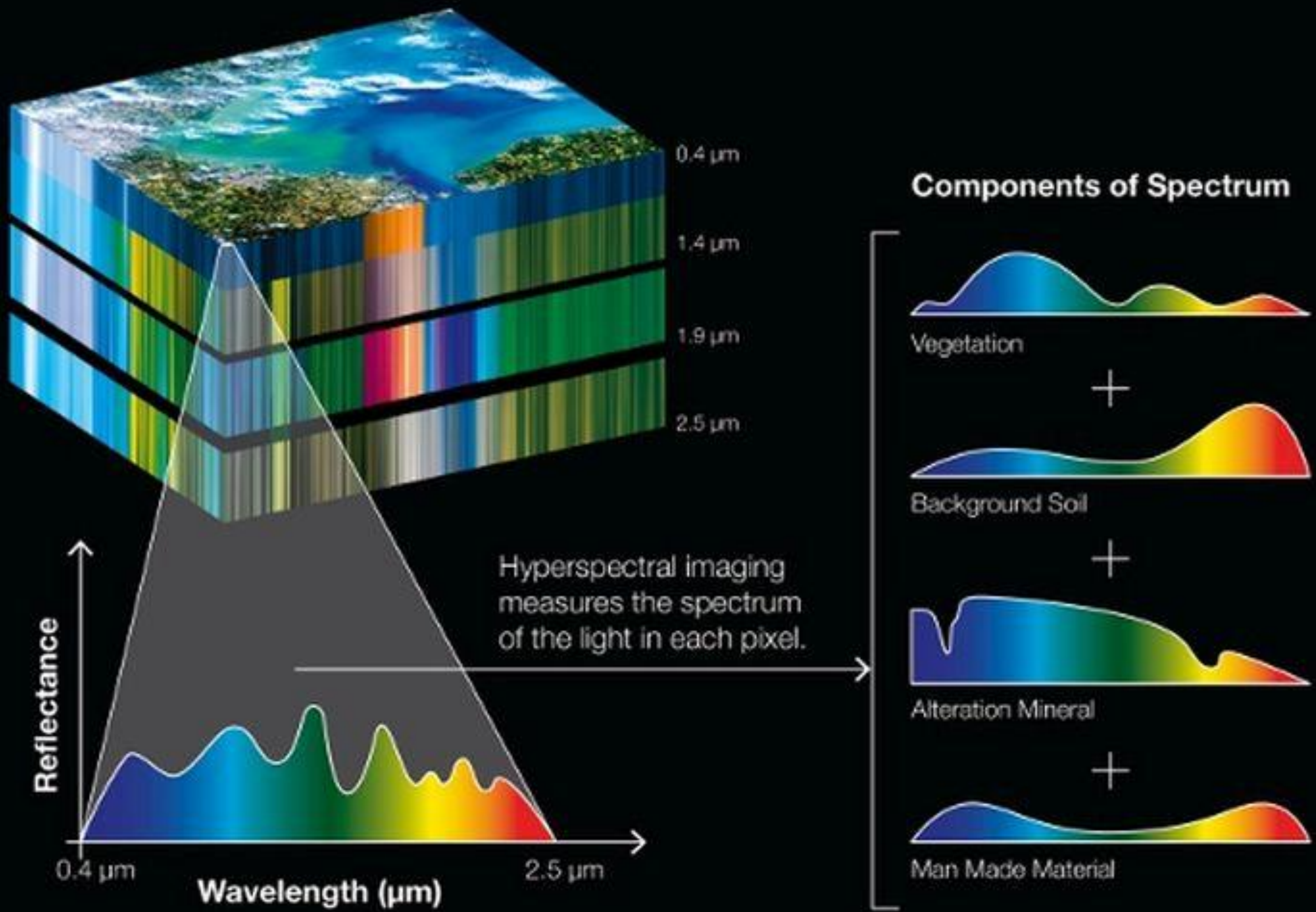
Interaction of light and surfaces

- Reflected color is the result of interaction of light source spectrum with surface reflectance



From Foundation of Vision by Brian Wandell, Sinauer Associates, 1995

Hyperspectral Imaging Technology



Interaction of light and surfaces

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

Adapted from slides by Juan Carlos Niebles, and Ranjay Krishna [Olafur Eliasson, *Room for one color*]

Slide by S. Lazebnik

Interaction of light and surfaces

monochromatic light refers to visible **light** of a narrow band of wavelengths
A blue book under red mono. light looks black
A red book under red mono. light looks red
A white book under red mono. light looks red

Adapted from slides by Juan Carlos Niebles, and Ranjay Krishna [Olafur Eliasson, *Room for one color*]

Slide by S. Lazebnik

James Turrell, a Californian artist, used light and color to completely immerse people in a world where there was no depth perception.

James Turrell, Breathing Light

Overview of Color

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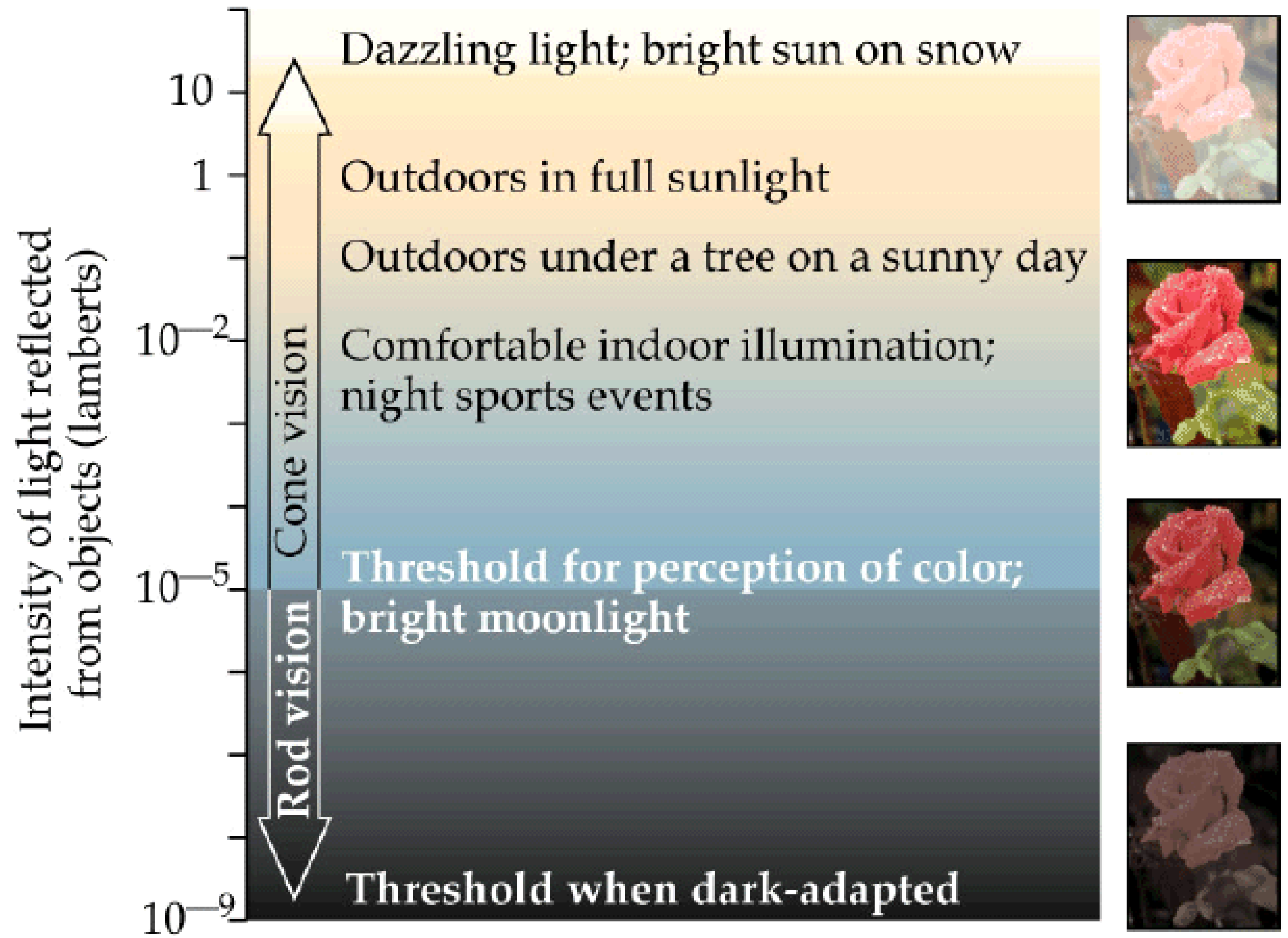
Two types of light-sensitive receptors

Cones
- cone-shaped
- less sensitive
- operate in high light
- color vision

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

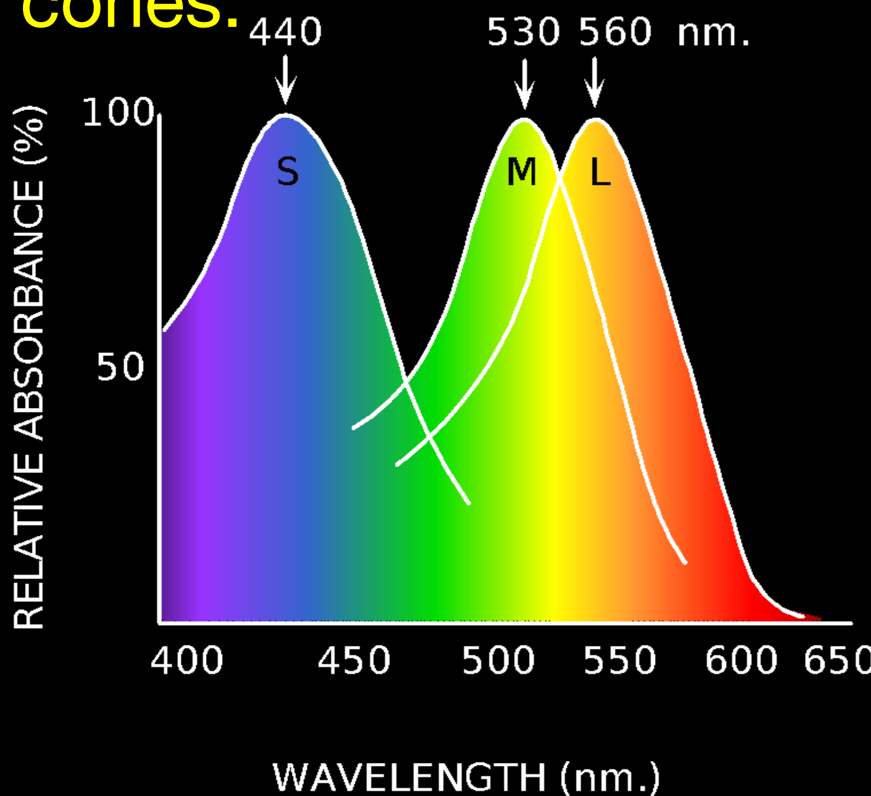
Rod / Cone sensitivity

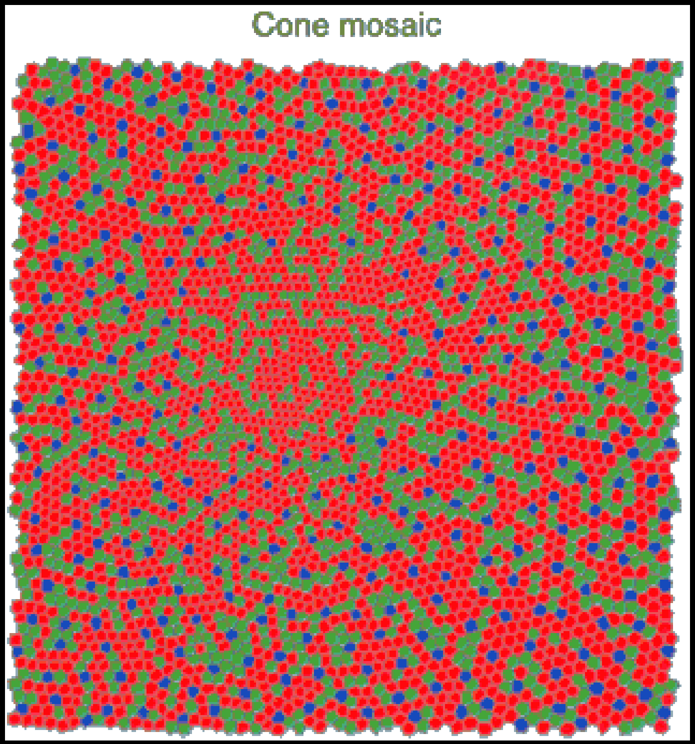


The famous sock-matching problem…

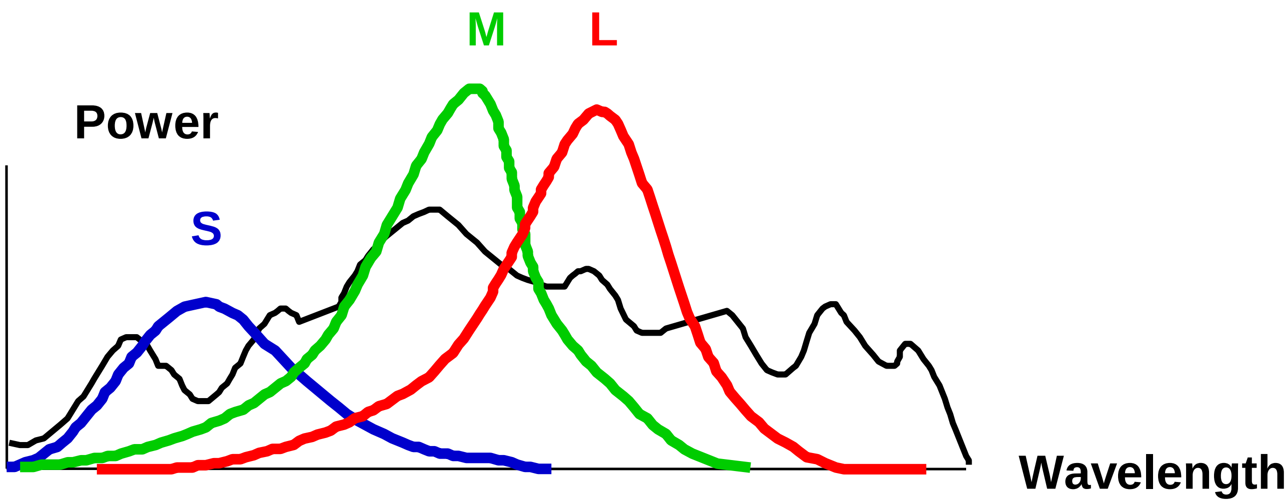
Physiology of Color Vision

Three kinds of cones:





Color perception



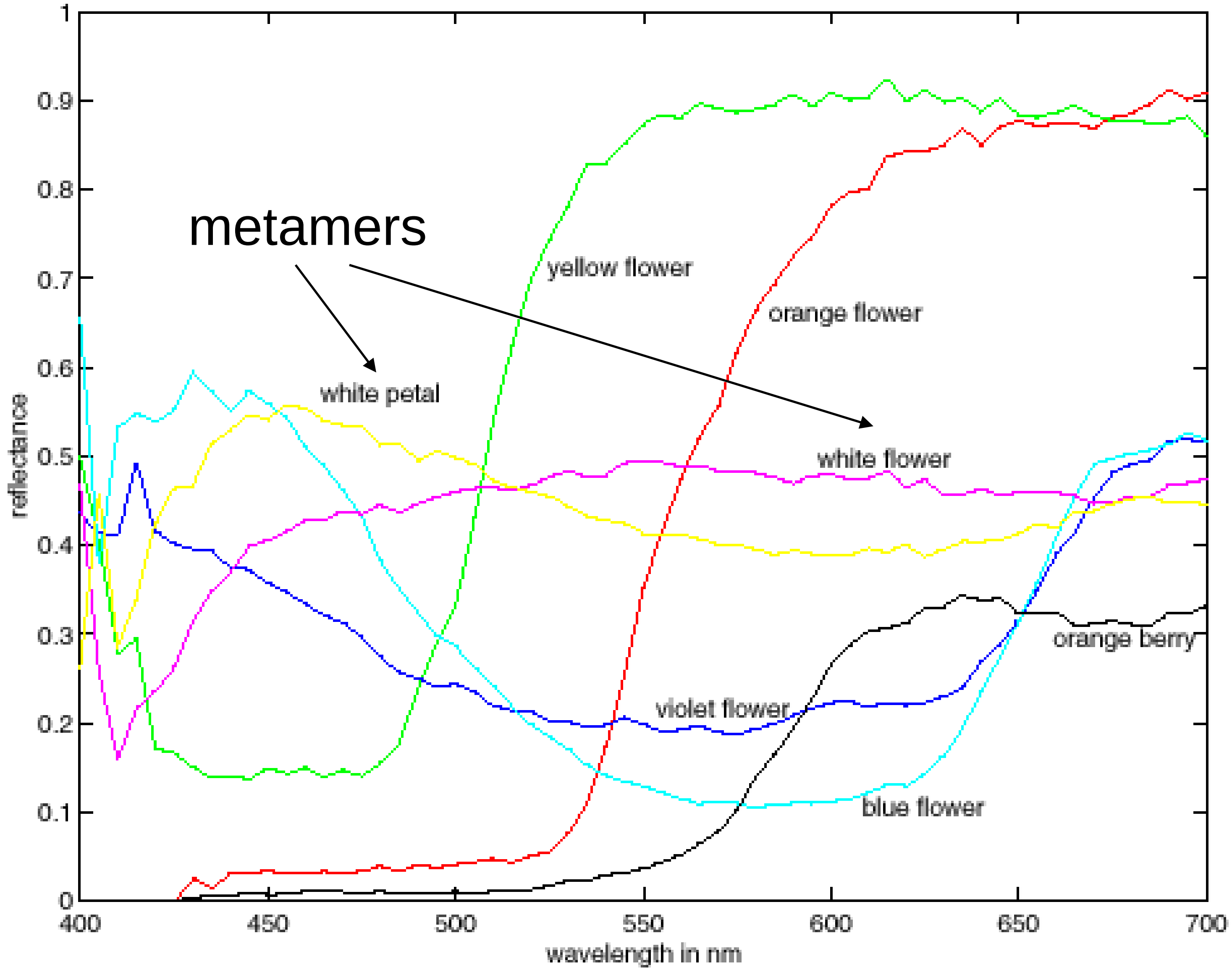
Rods and cones act as filters on the spectrum

- 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**

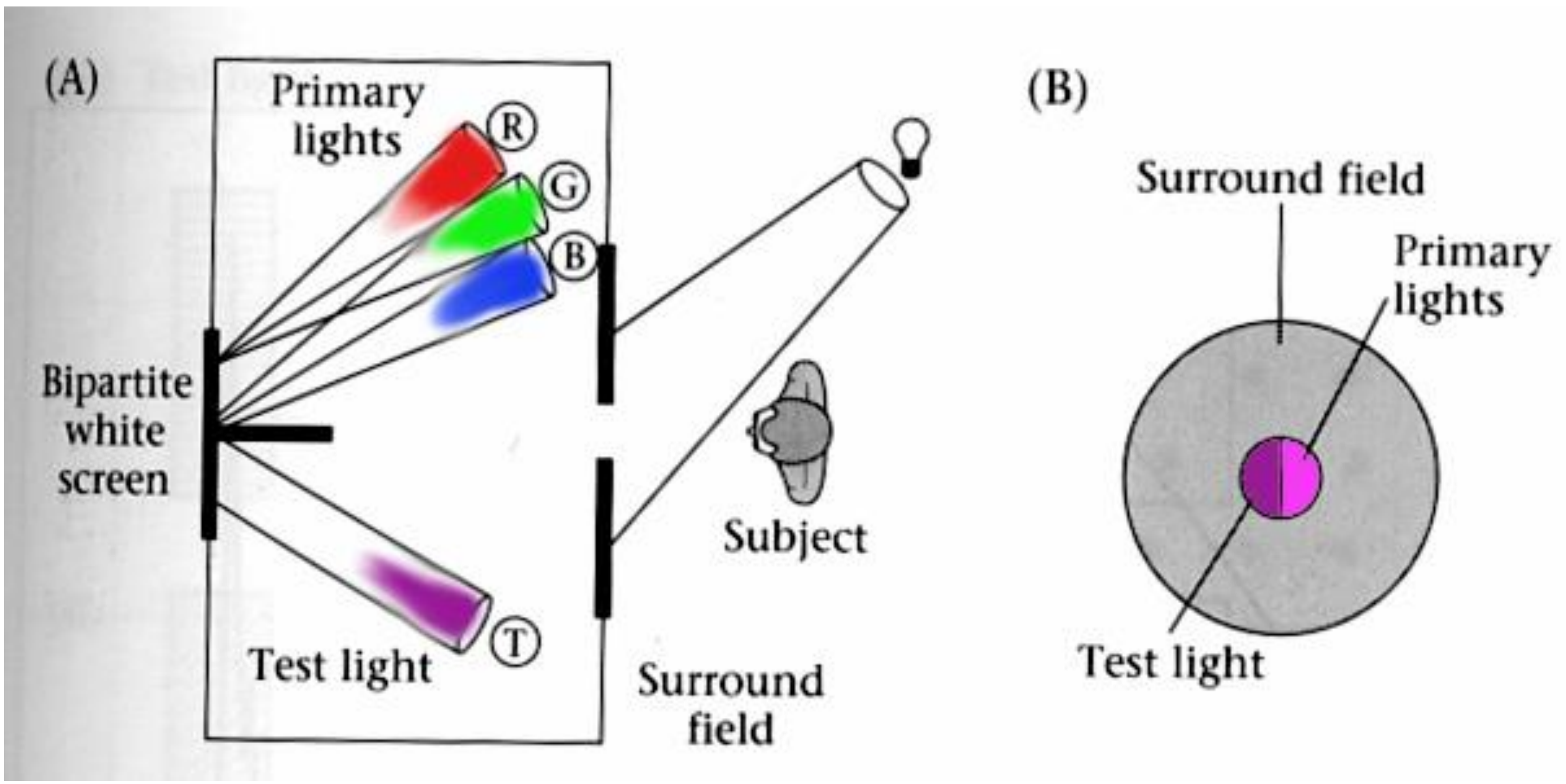
Slide by Steve Seitz

Spectra of some real-world surfaces



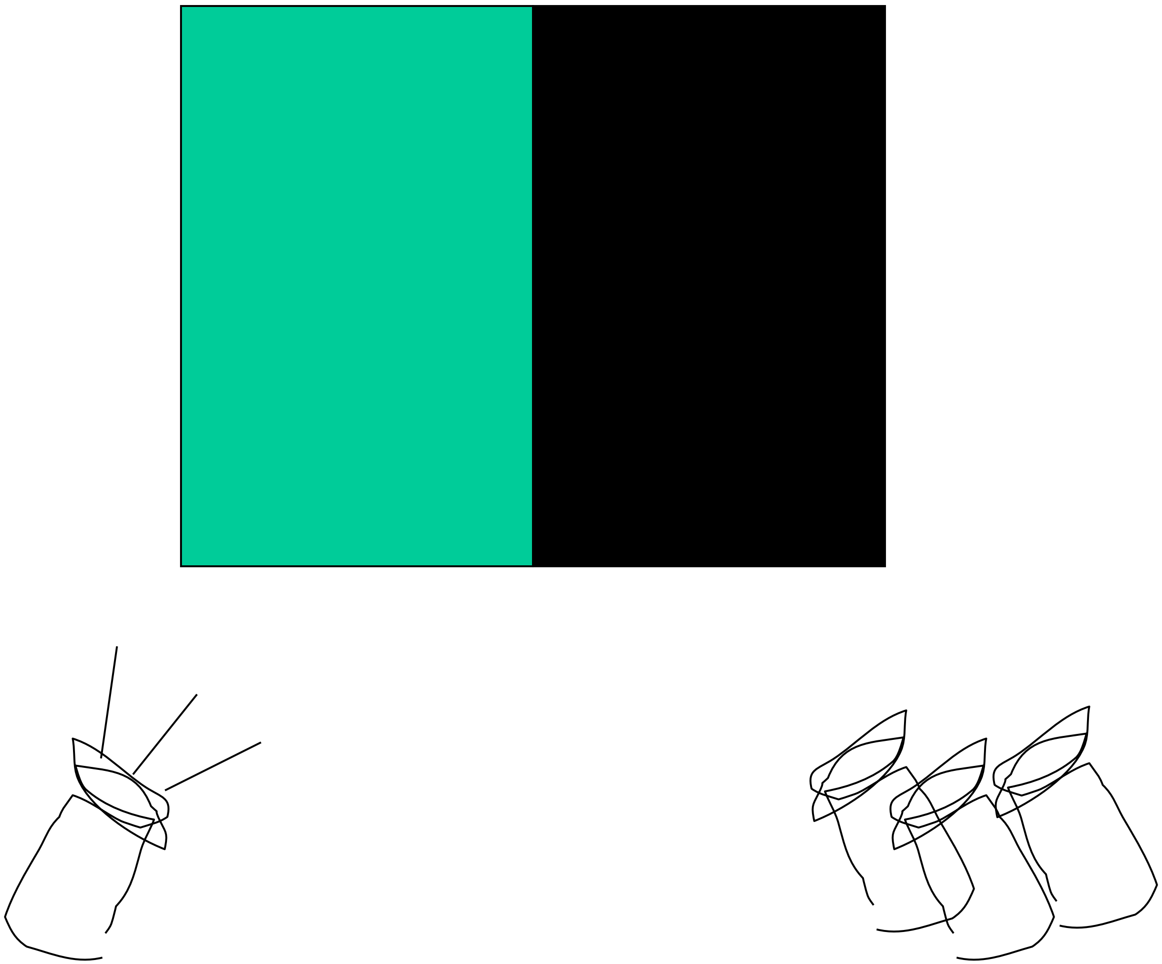
Standardizing color experience

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



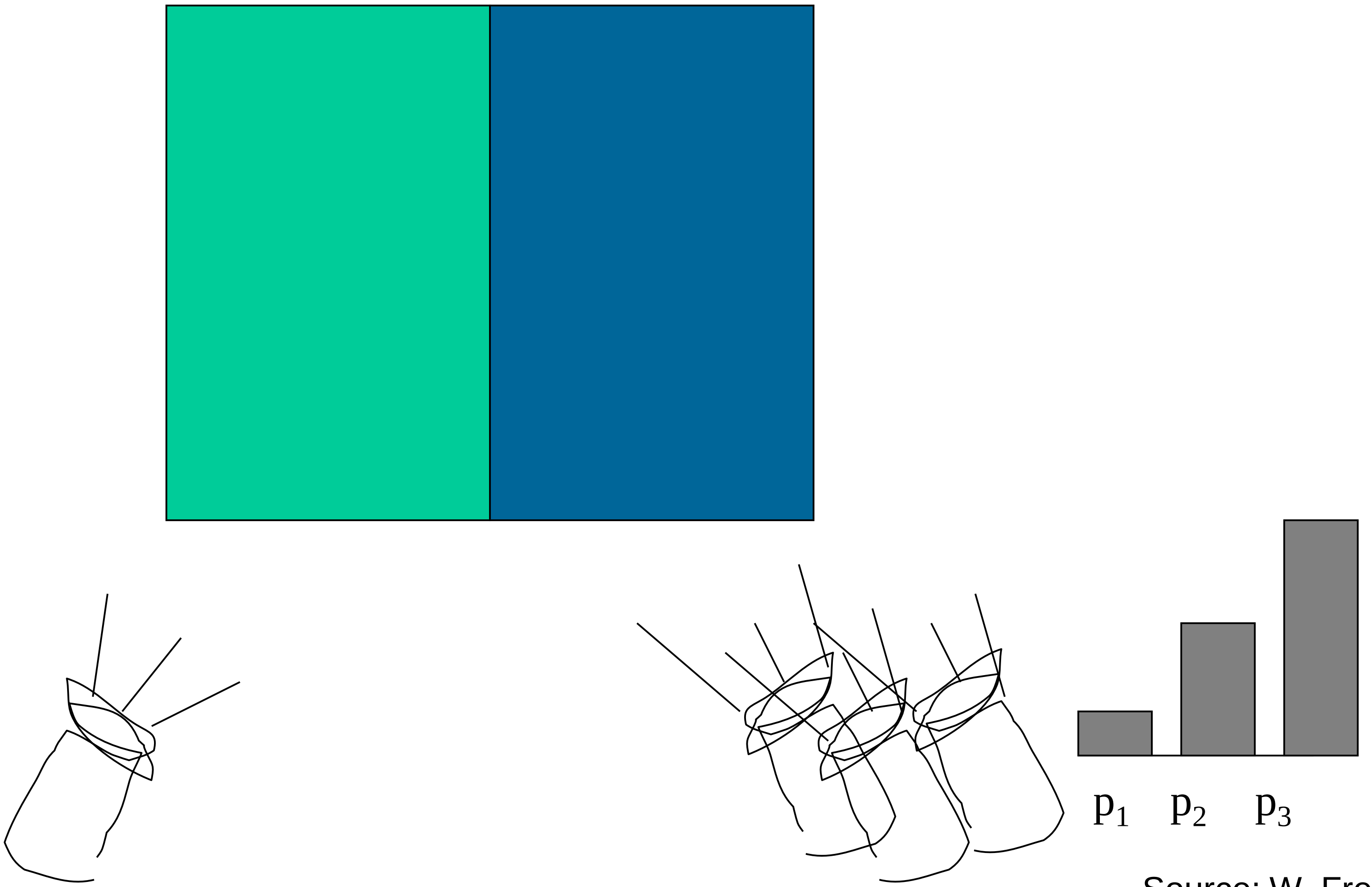
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Color matching experiment 1



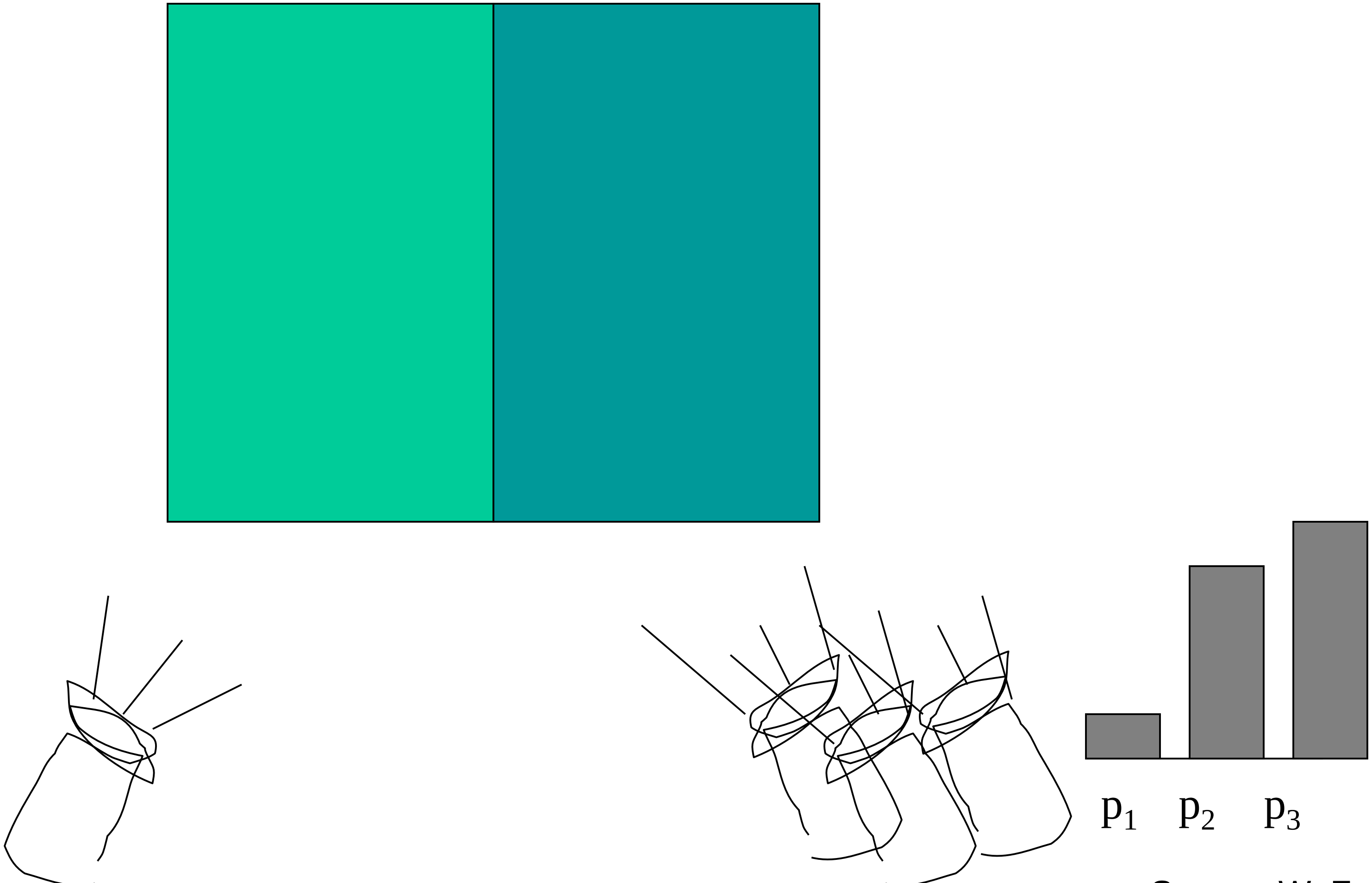
Source: W. Freeman

Color matching experiment 1



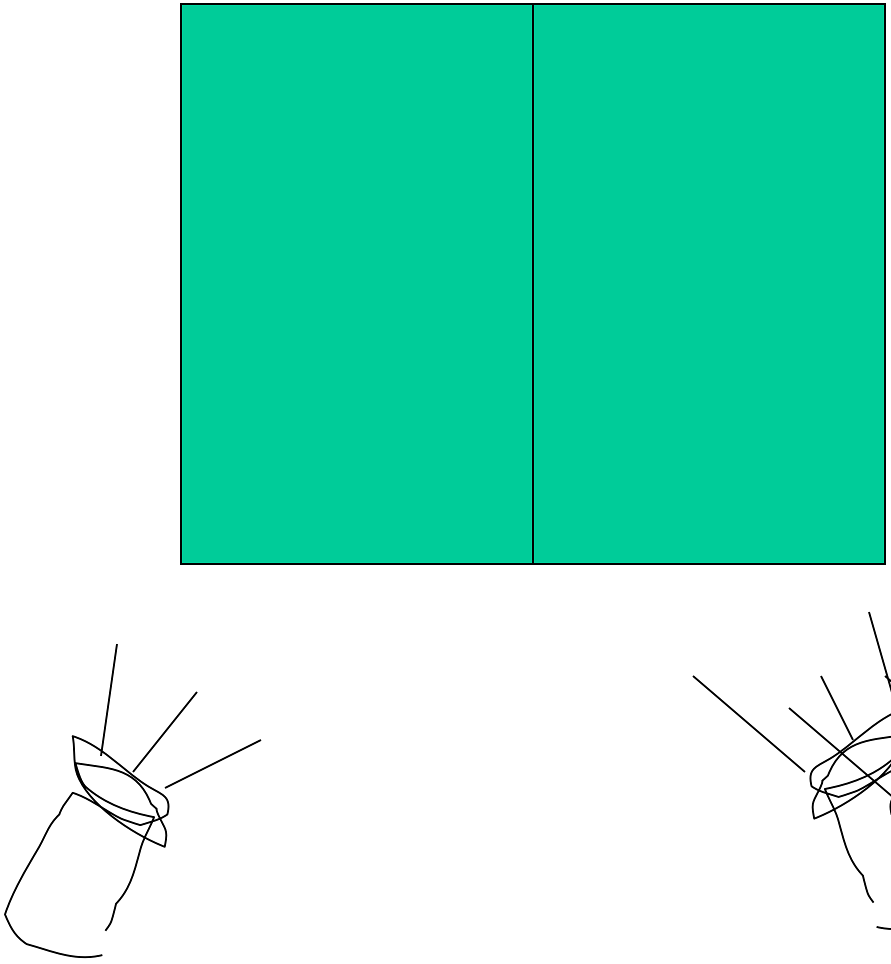
Source: W. Freeman

Color matching experiment 1

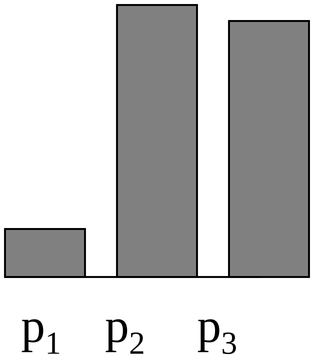


Source: W. Freeman

Color matching experiment 1

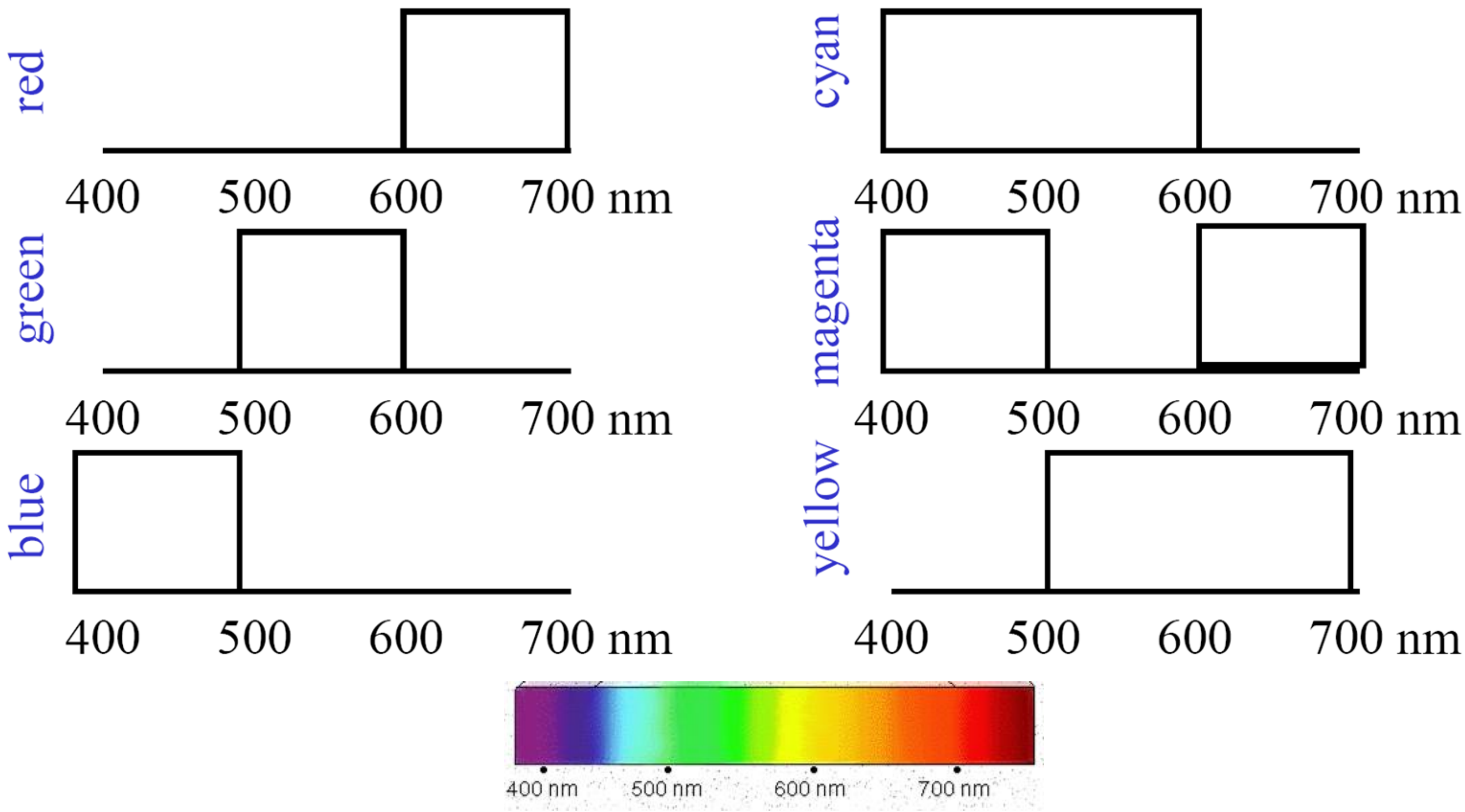


The primary color amounts needed for a match



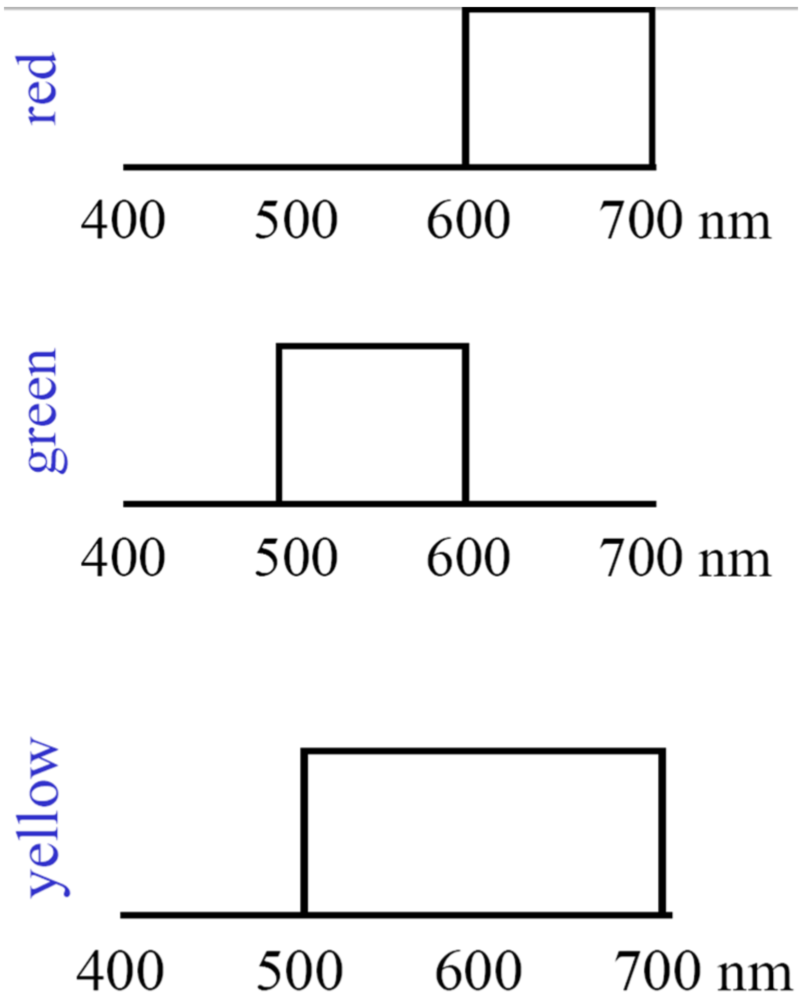
Source: W. Freeman

Color mixing

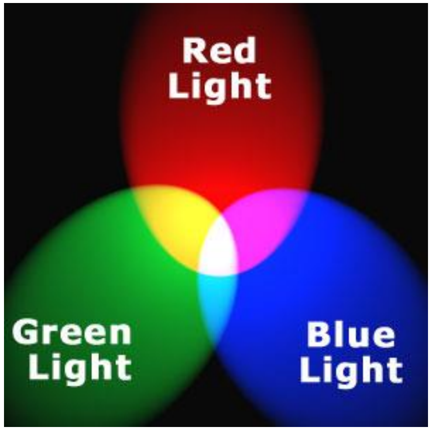


Source: W. Freeman

Additive color mixing



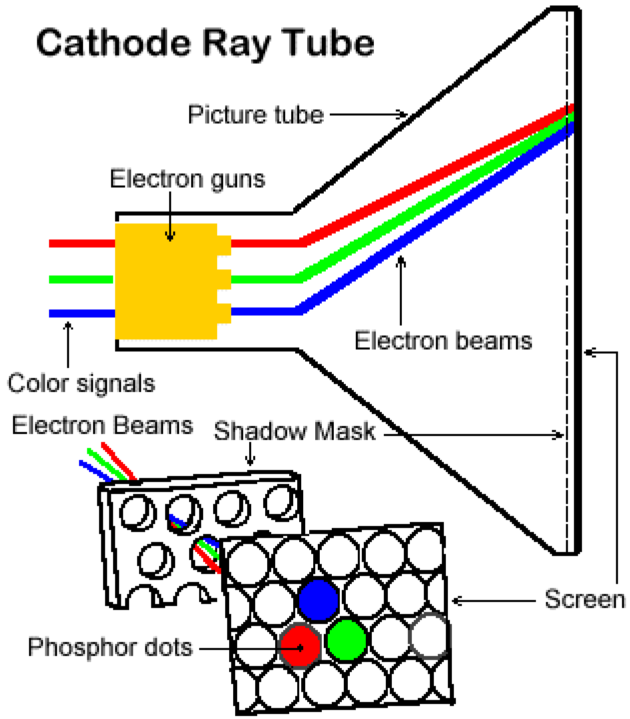
Colors combine by ***adding*** color spectra



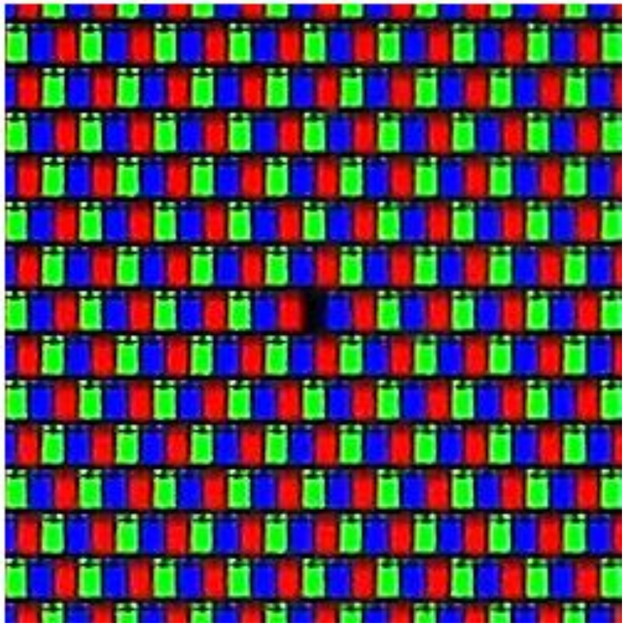
Light *adds* to existing black.

Source: W. Freeman

Examples of additive color systems



CRT phosphors

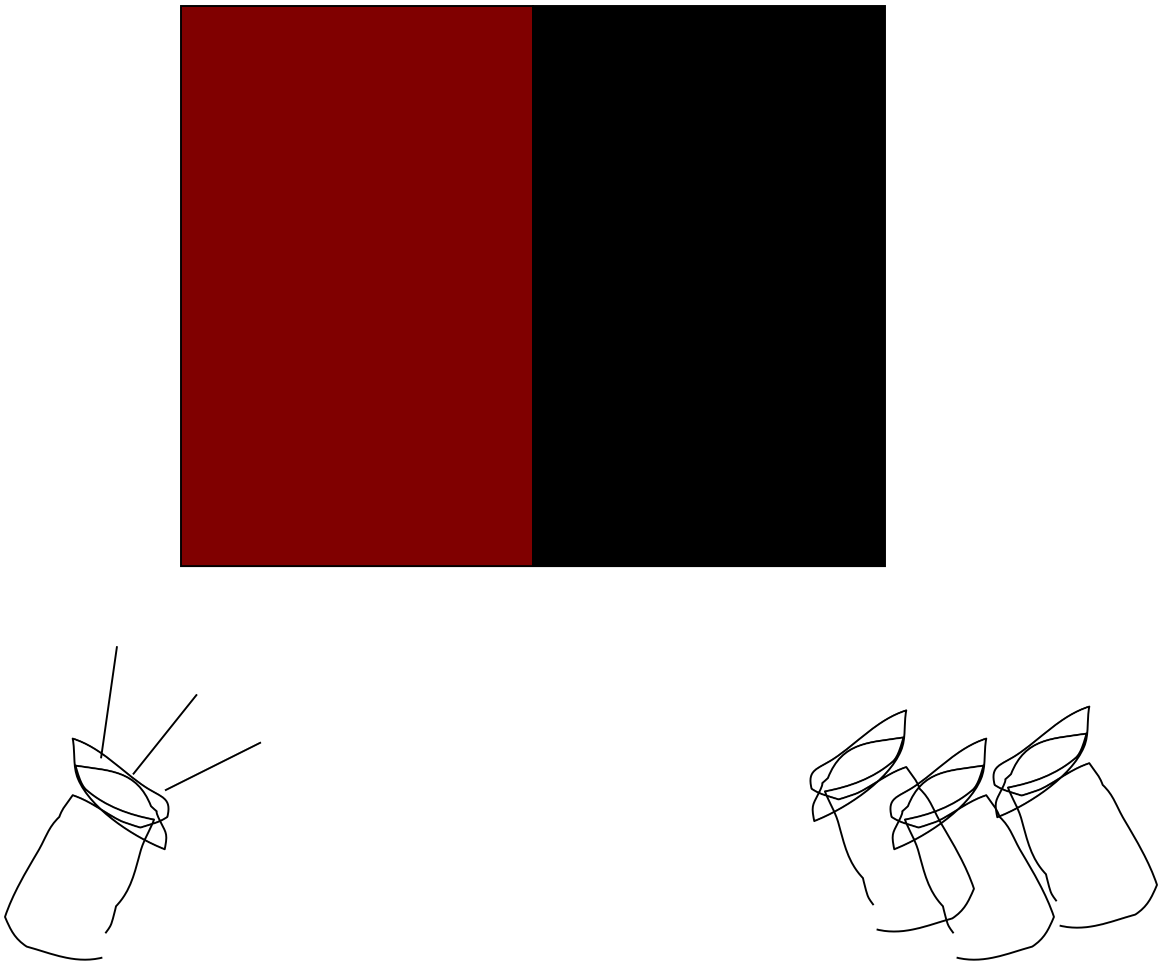


multiple projectors

http://www.jegsworks.com

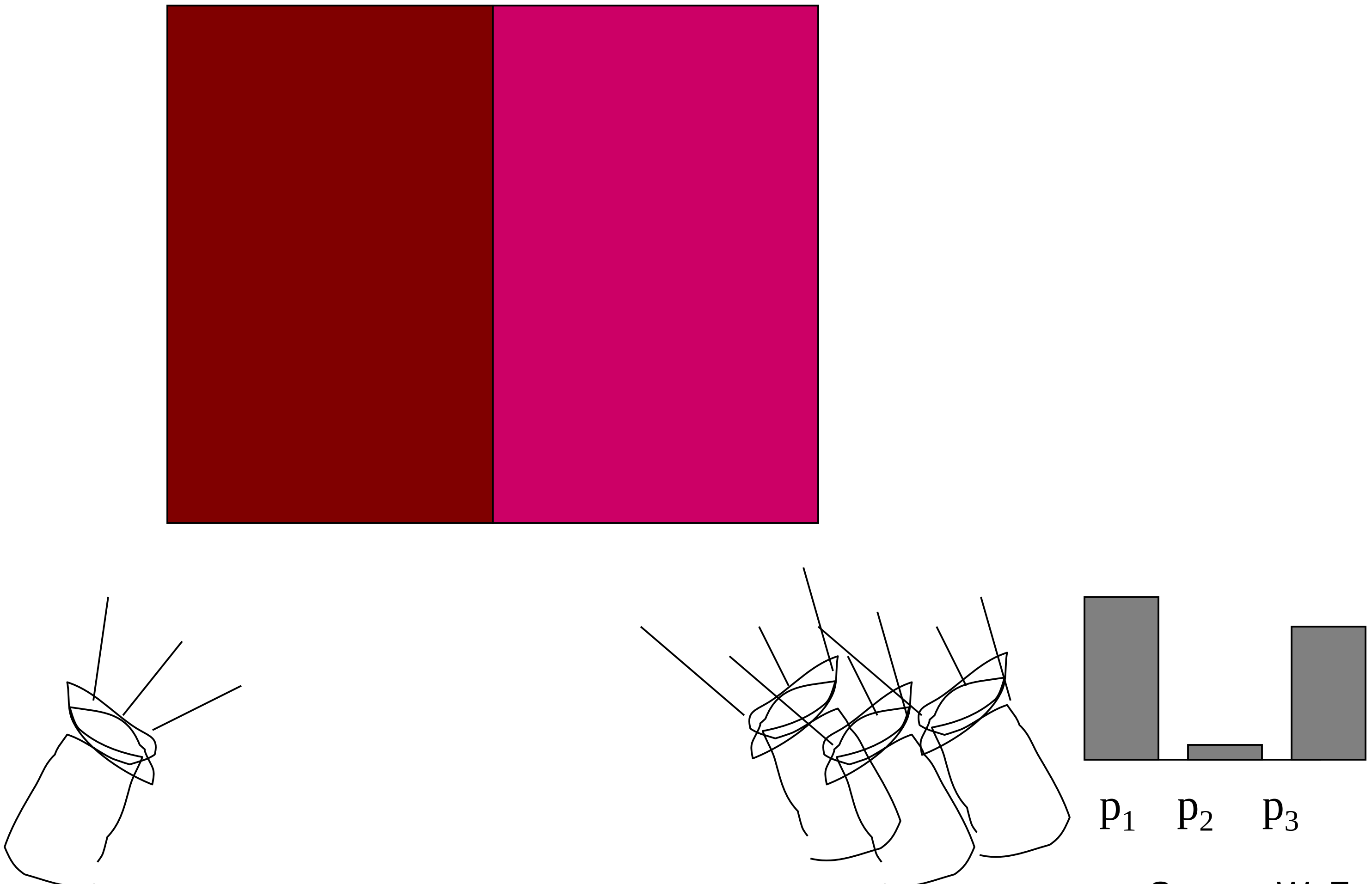
http://www.crtprojectors.co.uk/

Color matching experiment 2



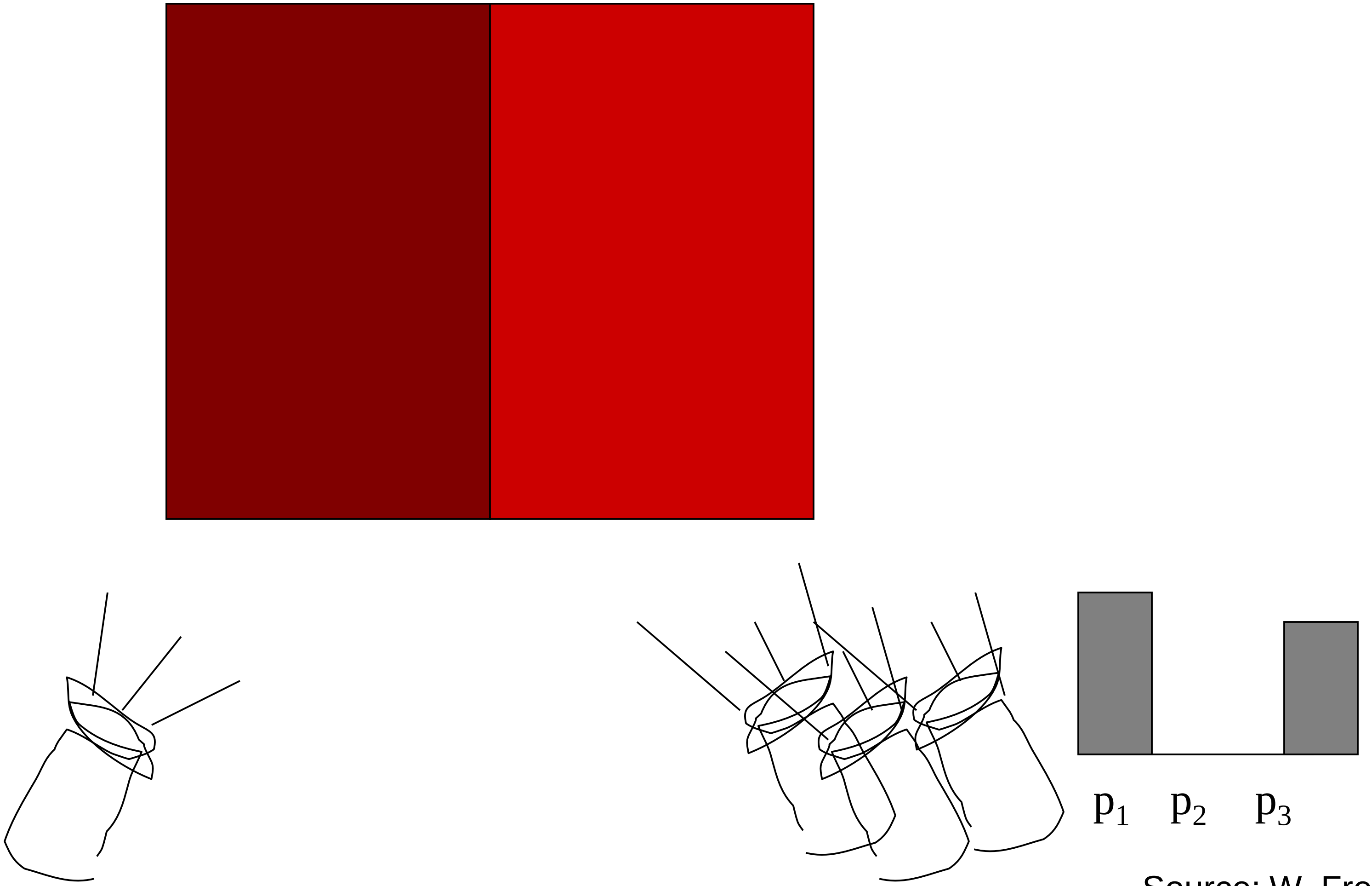
Source: W. Freeman

Color matching experiment 2



Source: W. Freeman

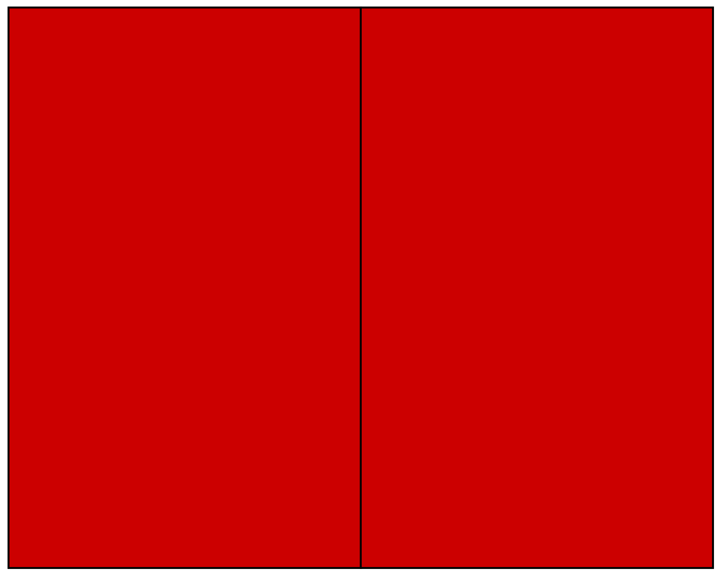
Color matching experiment 2



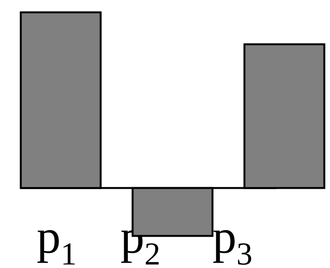
Source: W. Freeman

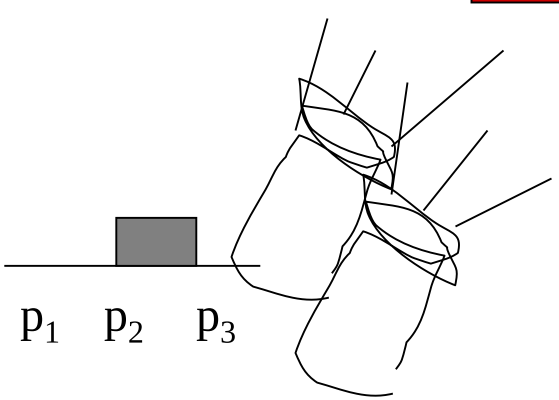
Color matching experiment 2

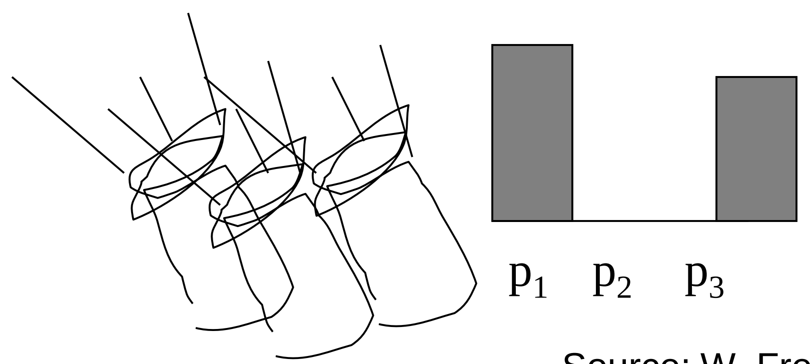
We say a “negative” amount of p_2 was needed to make the match, **because we added it to the test color’s side**.



The primary color amounts needed for a match:

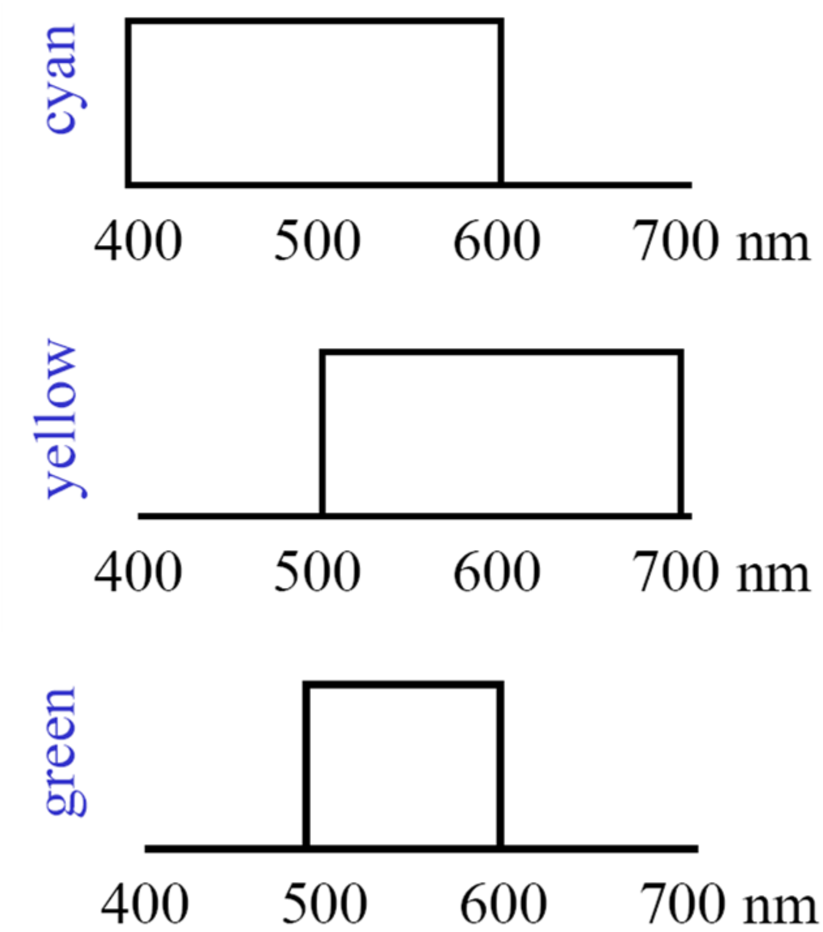




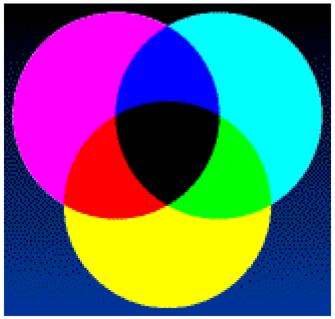


Source: W. Freeman

Subtractive color mixing



Colors combine by ***multiplying*** color spectra.



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

Source: W. Freeman

Examples of subtractive color systems

- Printing on paper
- Crayons
- Photographic film

Trichromacy

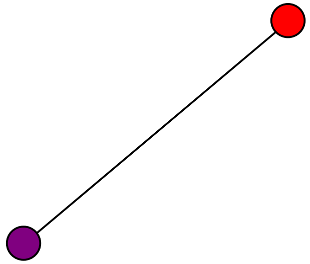
- In color matching experiments, most people can match any given light with three primaries
  - Primaries must be *independent*
- For the same light and same primaries, most people select the same weights
  - Exception: color blindness
- Trichromatic color theory
  - Three numbers seem to be sufficient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

Overview of Color

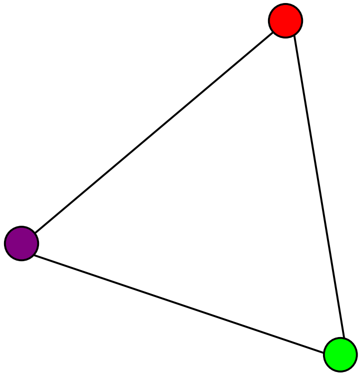
- Physics of color
- Human encoding of color
- Color spaces
- White balancing

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



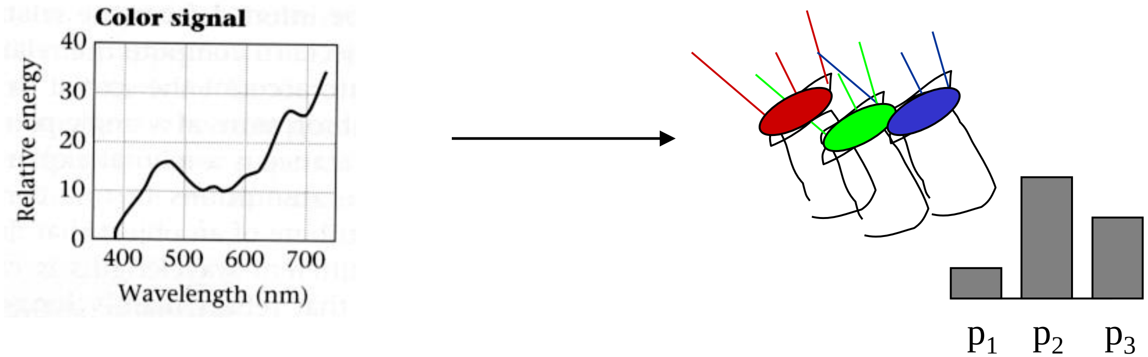
mixing two lights produces colors that lie along a straight line in color space



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

Adapted from slides by Juan Carlos Niebles, and Ranjay Krishna

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



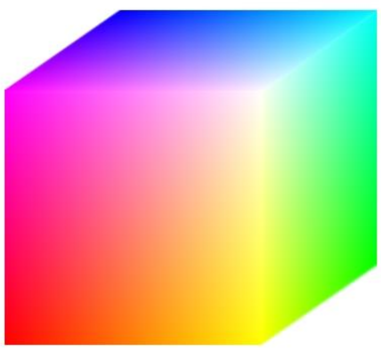
- **Matching functions:** the amount of each primary needed to match a monochromatic light source at each wavelength

Source: W. Freeman

RGB space

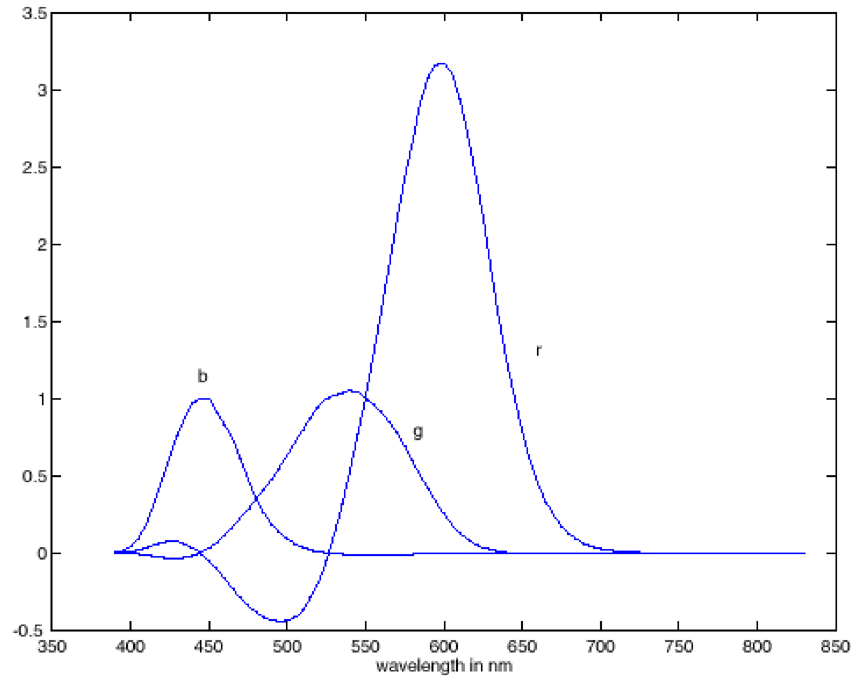
- Primaries are monochromatic lights (for monitors, they correspond to the three types of phosphors)
- *Subtractive matching* required for some wavelengths

RGB primaries



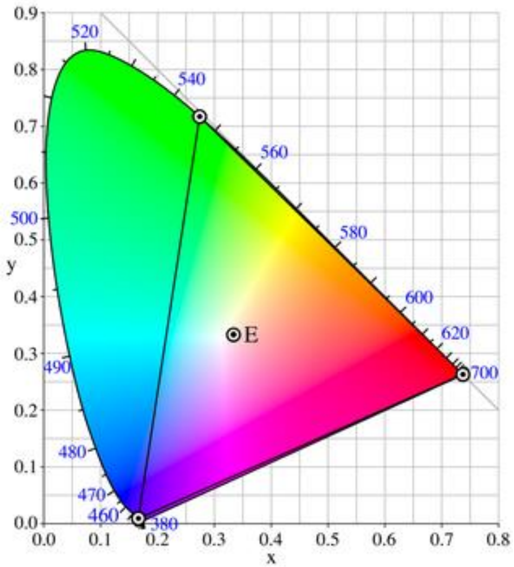
$p_1 = 645.2$ nm
$p_2 = 525.3$ nm
$p_3 = 444.4$ nm

RGB matching functions

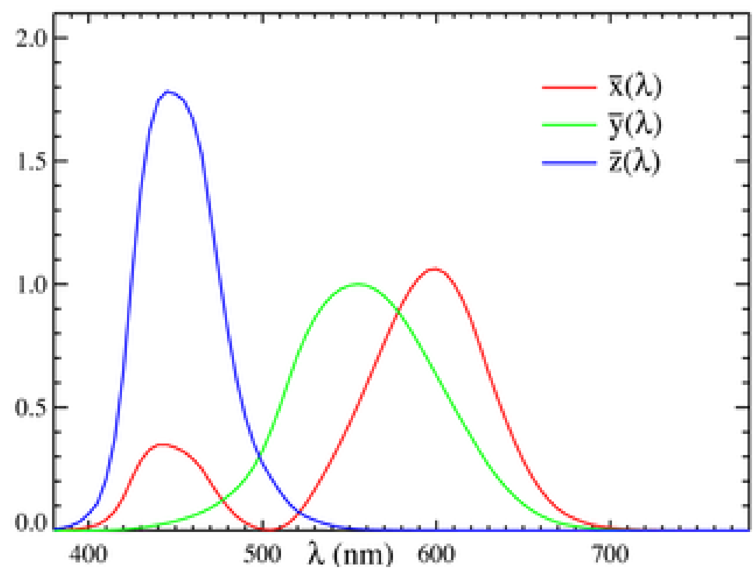


Linear color spaces: CIE XYZ

- Primaries are *imaginary*, but matching functions are everywhere positive
- The Y parameter corresponds to brightness or *luminance* of a color

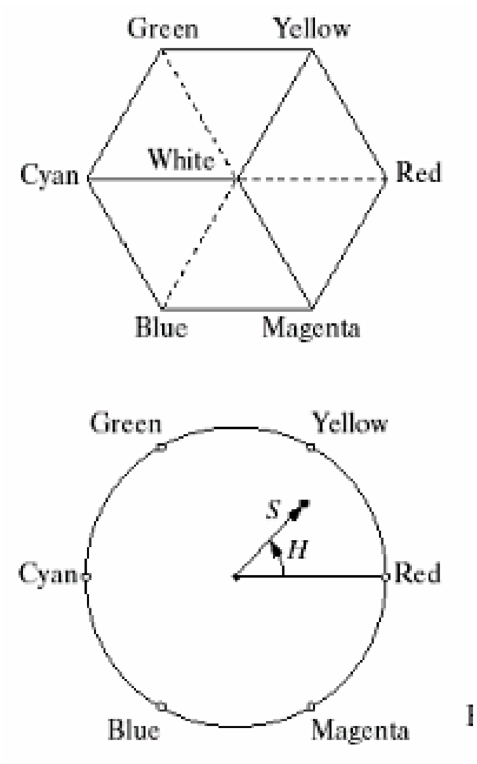


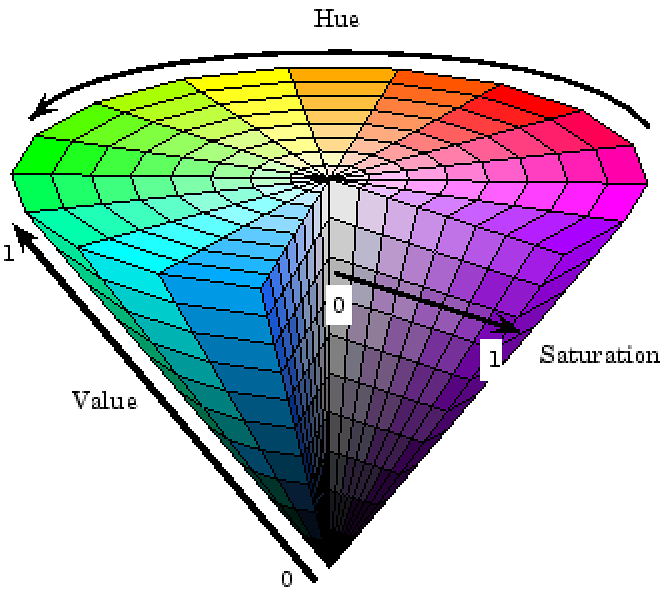
Matching functions

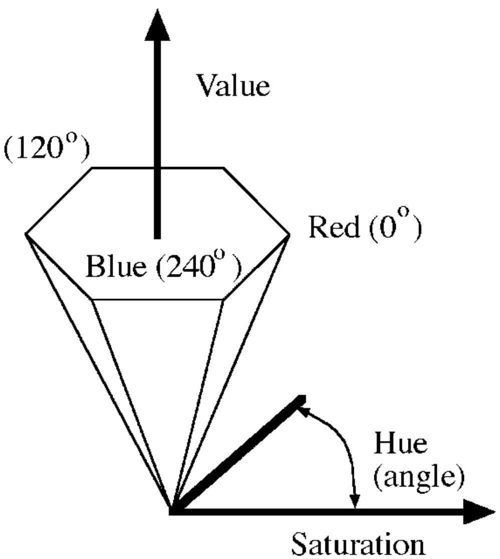


http://en.wikipedia.org/wiki/CIE_1931_color_space

Nonlinear color spaces: HSV







- Perceptually meaningful dimensions: Hue, Saturation, Value (Intensity)

Overview of Color

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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

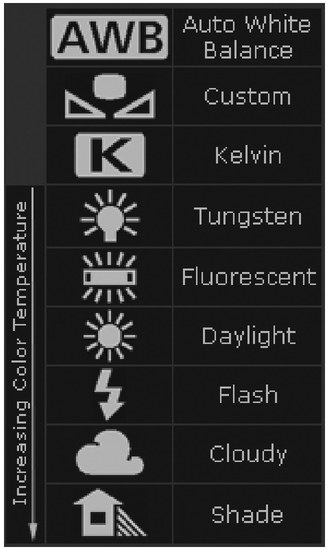
correct white balance

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

White balance

- 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



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

Slide: F. Durand

White balance

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

Slide: F. Durand

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 $1/r_w$, $1/g_w$, $1/b_w$

Slide: F. Durand

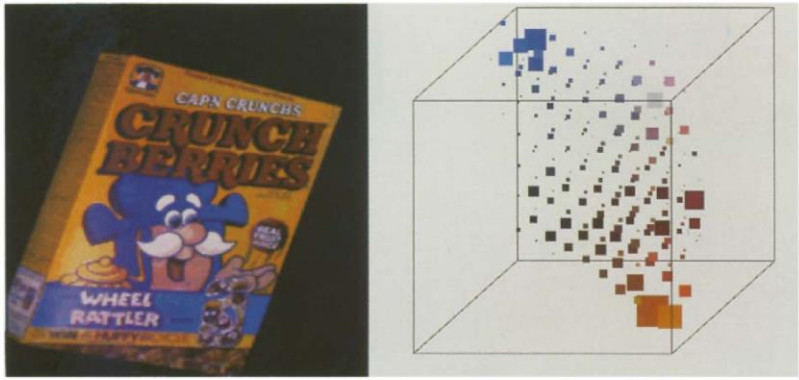
White balance

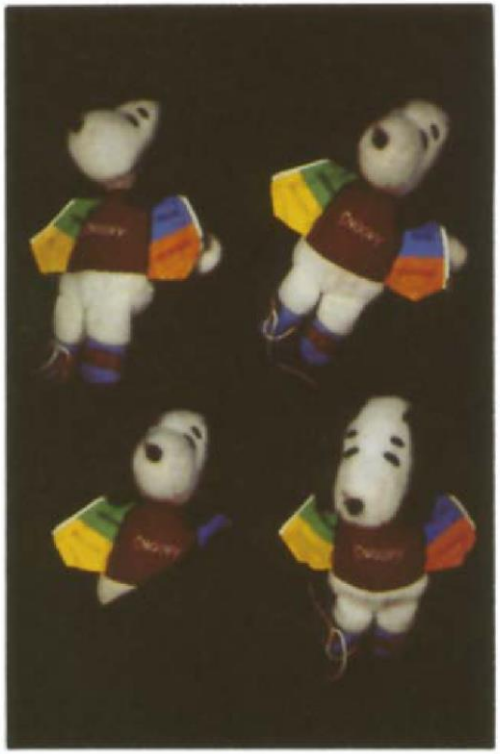
- Without gray cards: we need to “guess” which pixels correspond to white objects
- Gray world assumption
  - The image average r_{ave}, g_{ave}, b_{ave} is gray
  - Use weights $1/r_{ave}$, $1/g_{ave}$, $1/b_{ave}$
- Brightest pixel assumption (non-staurated)
  - Highlights usually have the color of 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

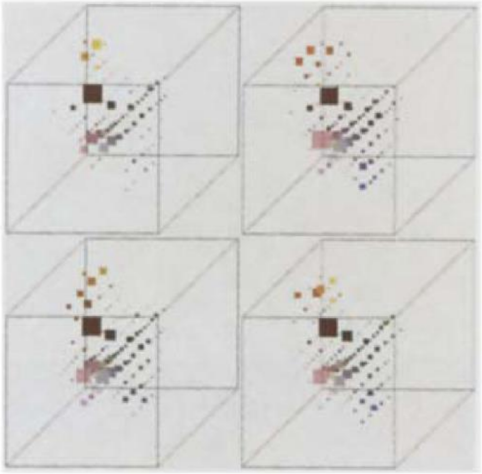
Slide: F. Durand

Uses of color in (old-school) computer vision

Color histograms for indexing and retrieval



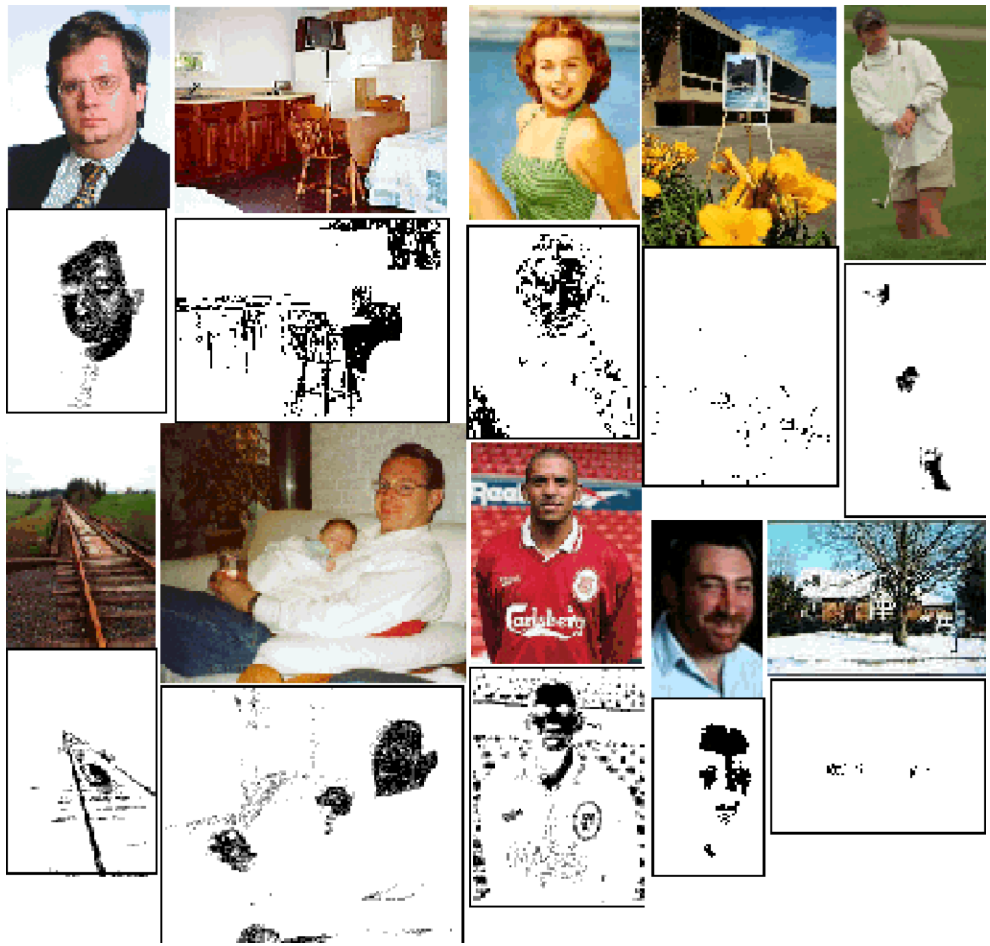




Swain and Ballard, [Color Indexing](), IJCV 1991.

Uses of color in computer vision

Skin detection

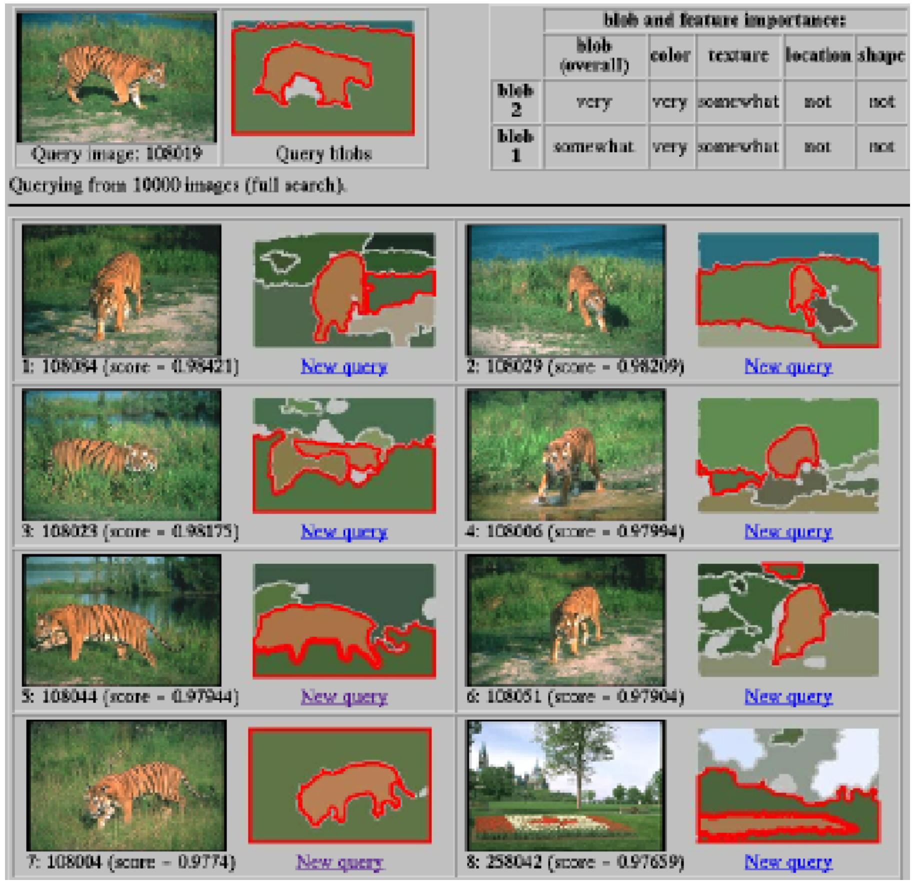


M. Jones and J. Rehg, [Statistical Color Models with Application to Skin Detection](), IJCV 2002.

Source: S. Lazebnik

Uses of color in computer vision

Image segmentation and retrieval

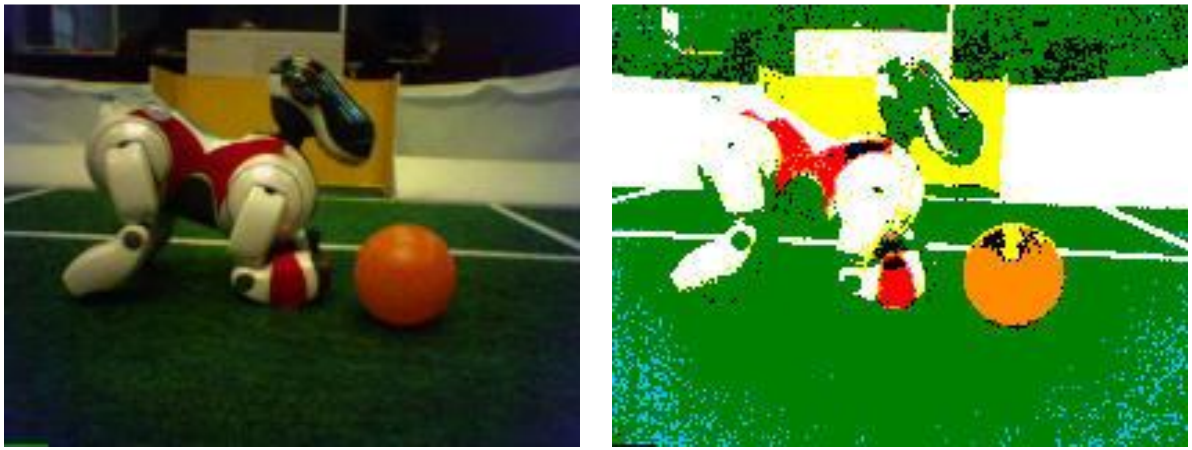


C. Carson, S. Belongie, H. Greenspan, and Ji. Malik, Blobworld: Image segmentation using Expectation-Maximization and its application to image querying, ICVIS 1999.

Source: S. Lazebnik

Uses of color in computer vision

Robot soccer

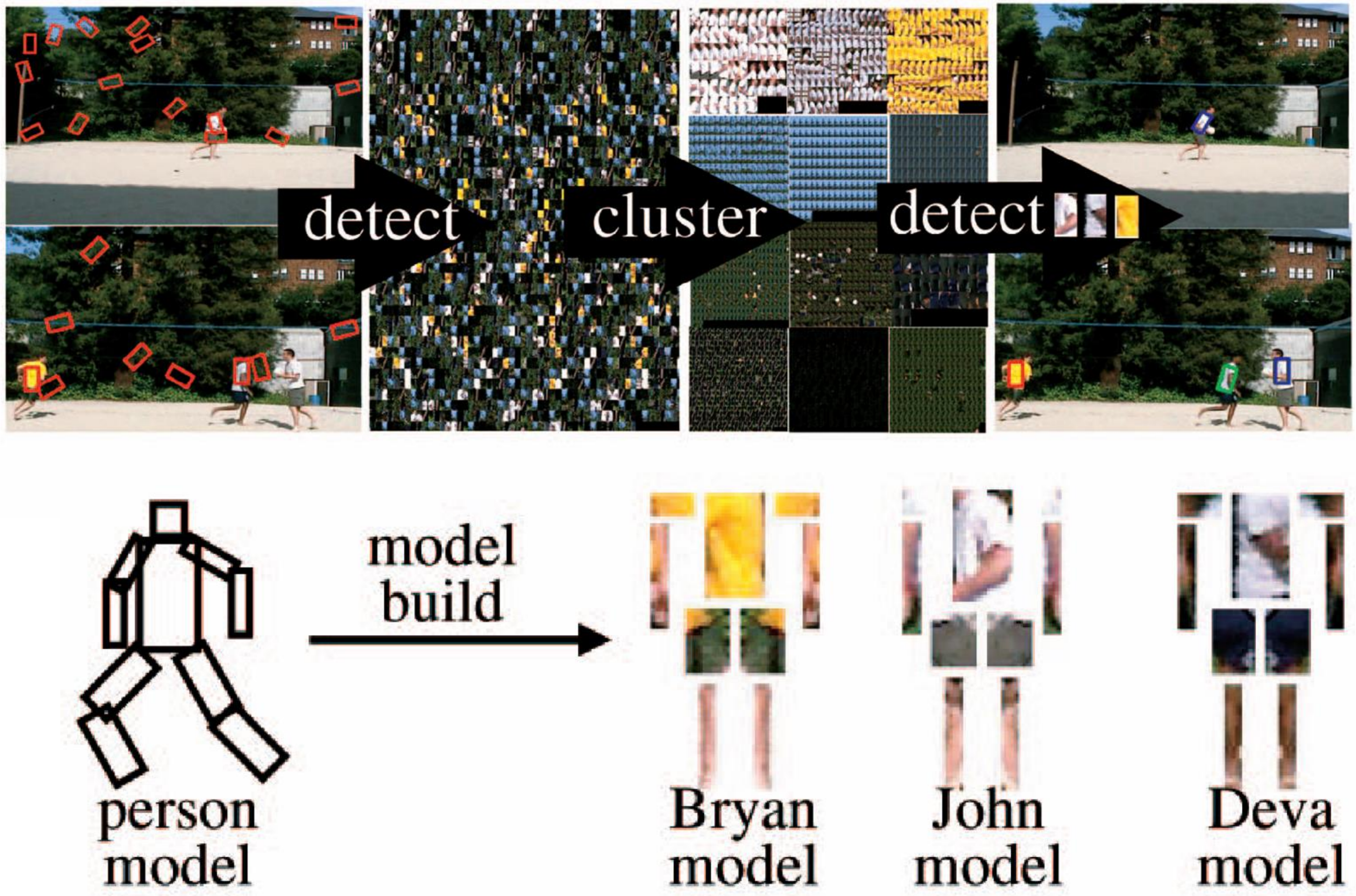


M. Sridharan and P. Stone, Towards Eliminating Manual Color Calibration at RoboCup. RoboCup-2005: Robot Soccer World Cup IX, Springer Verlag, 2006

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.

Source: S. Lazebnik

Credits

- Most slides are mainly by Juan Carlos Niebles and Ranjay Krishna from Stanford AI Lab