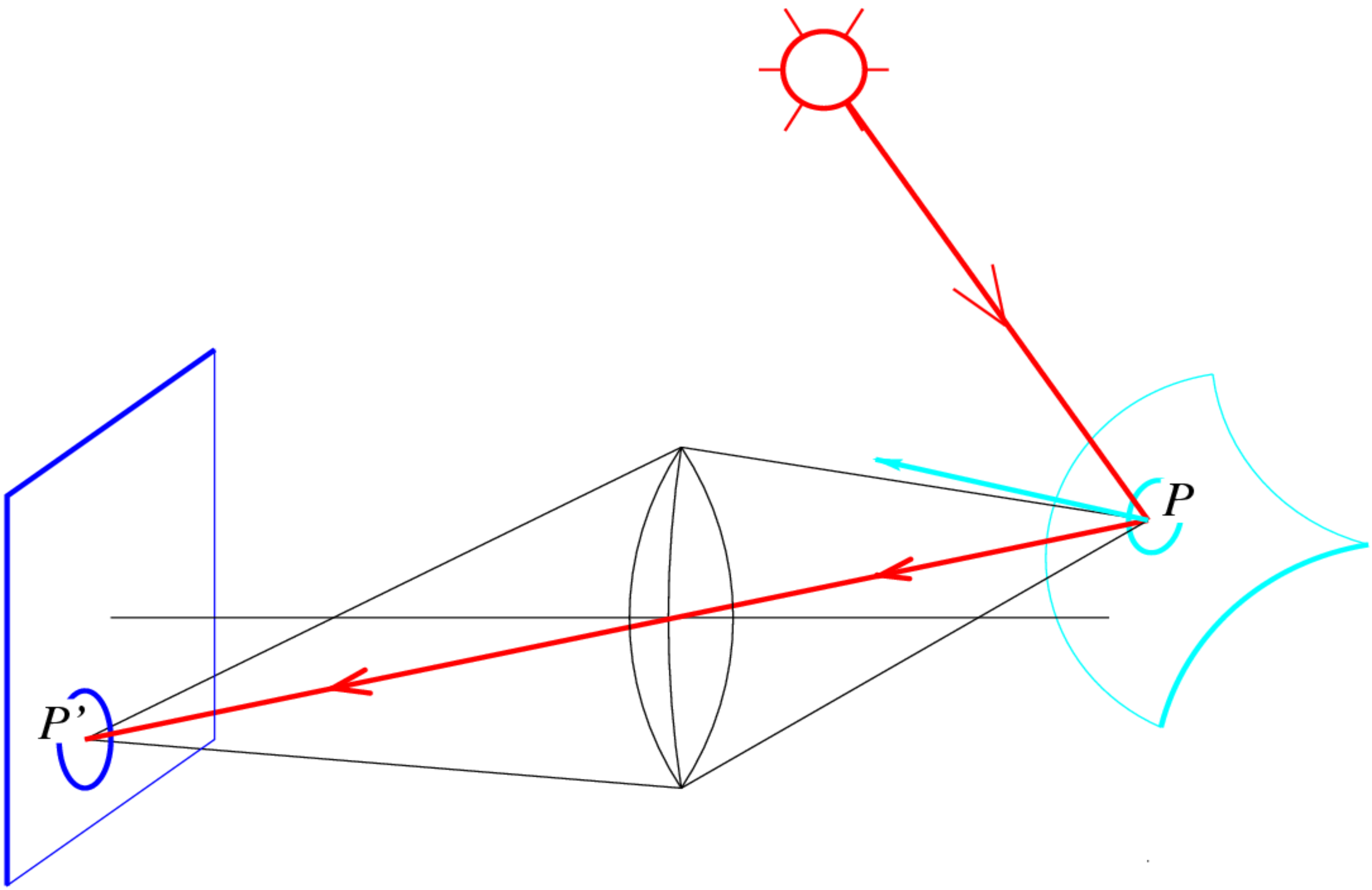
Lecture 4:

Light & Color

Prof. Rob Fergus

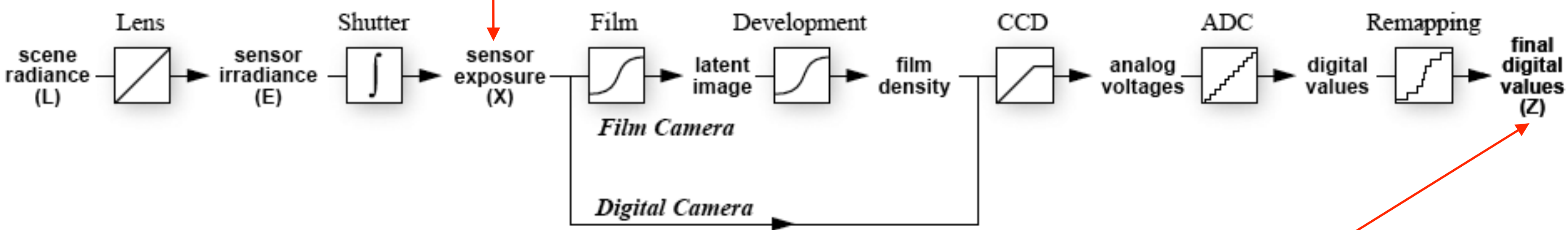
Slides: S. Lazebnik, S. Seitz, W. Freeman, F. Durand, D. Forsyth, D. Lowe, B. Wandell, S.Palmer, K. Grauman

Image formation



From light rays to pixel values

$$X = E \cdot \Delta t$$

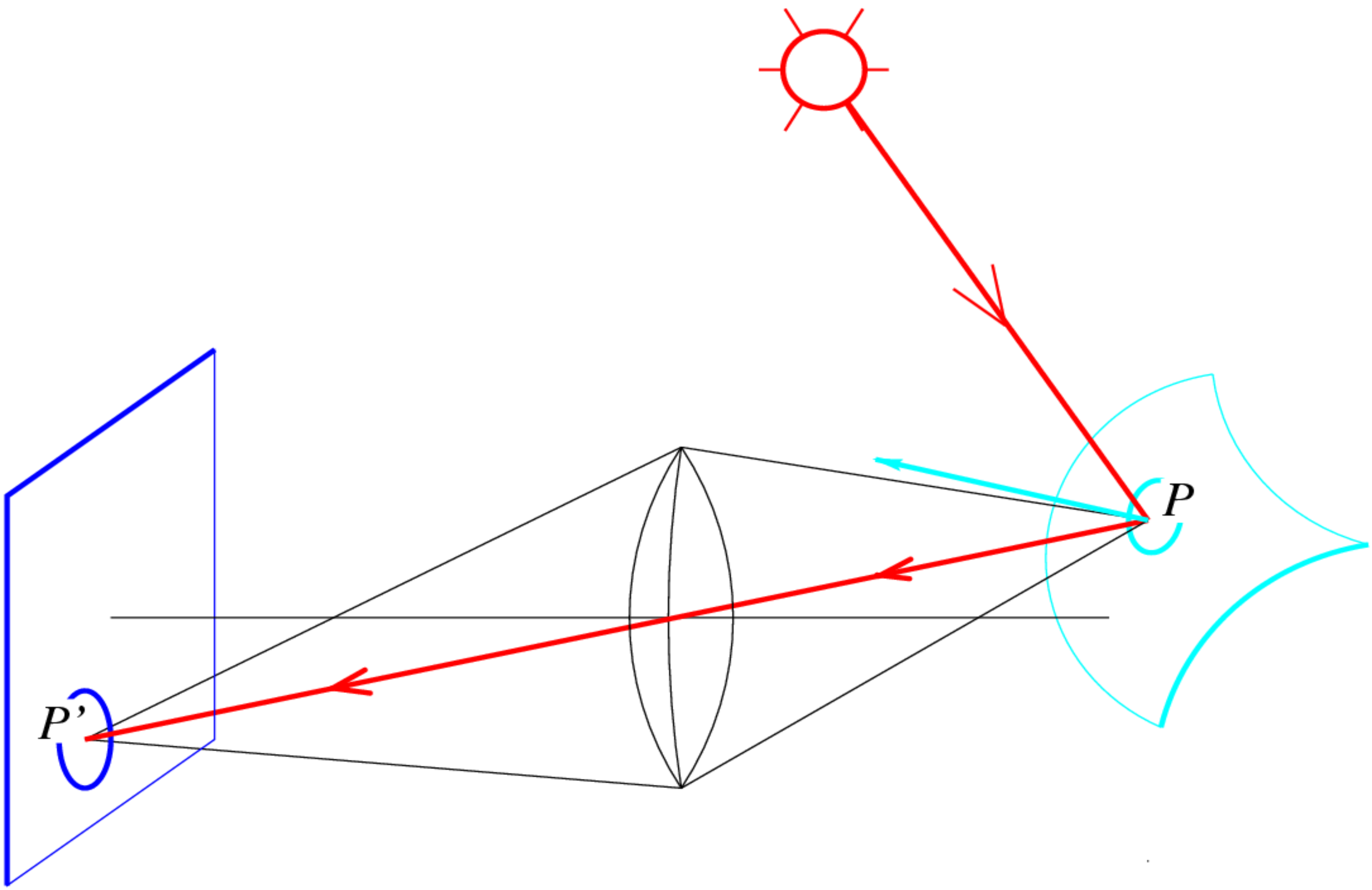


$$Z = f(E \cdot \Delta t)$$

- Camera response function: the mapping f from irradiance to pixel values
  - Useful if we want to estimate material properties
  - Enables us to create high dynamic range images

Source: S. Seitz, P. Debevec

Image formation



The interaction of light and surfaces

- What happens when a light ray hits a point on an object?
  - Some of the light gets **absorbed**
    - converted to other forms of energy (e.g., heat)
  - Some gets **transmitted** through the object
    - possibly bent, through "refraction"
    - Or scattered inside the object (subsurface scattering)
  - Some gets **reflected**
    - possibly in multiple directions at once
  - Really complicated things can happen
    - fluorescence

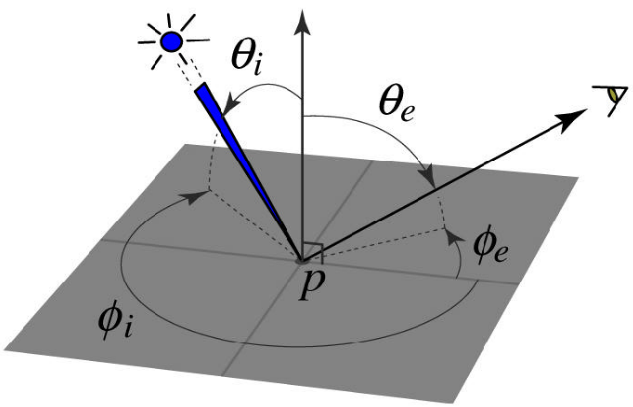
- Let's consider the case of reflection in detail
  - Light coming from a single direction could be reflected in all directions. How can we describe the amount of light reflected in each direction?

Slide by Steve Seitz

Bidirectional reflectance distribution function (BRDF)

- Model of local reflection that tells how bright a surface appears when viewed from one direction when light falls on it from another

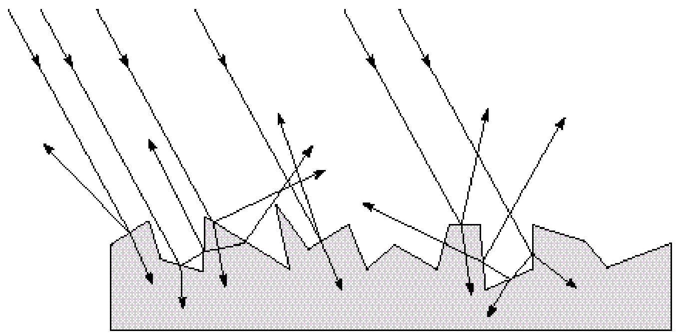
- Definition: ratio of the **radiance L** in the **emitted** direction to **irradiance E** in the **incident** direction



$$\rho(\theta_i,\phi_i,\theta_e,\phi_e) = \frac{L_e(\theta_e,\phi_e)}{E_i(\theta_i,\phi_i)} = \frac{L_e(\theta_e,\phi_e)}{L_i(\theta_i,\phi_i)\cos\theta_i d\omega}$$

BRDFs can be incredibly complicated…

Diffuse reflection

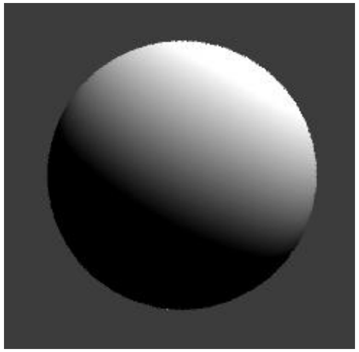


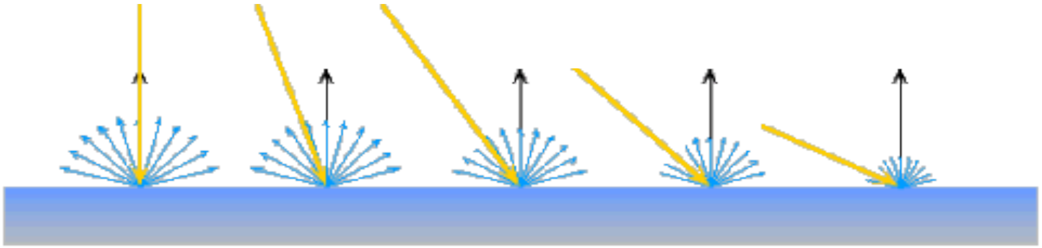
- Light is reflected equally in all directions
  - Dull, matte surfaces like chalk or latex paint
  - Microfacets scatter incoming light randomly

- **BRDF is constant**
  - *Albedo*: fraction of incident irradiance reflected by the surface

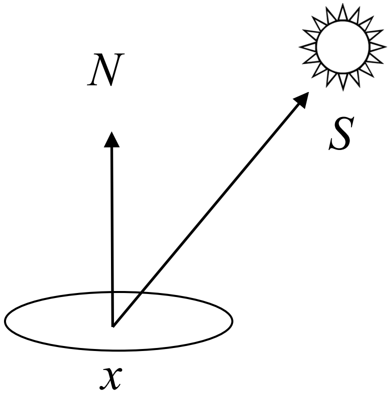
Diffuse reflection: Lambert's law

- Viewed brightness does not depend on viewing direction, but it *does* depend on direction of illumination





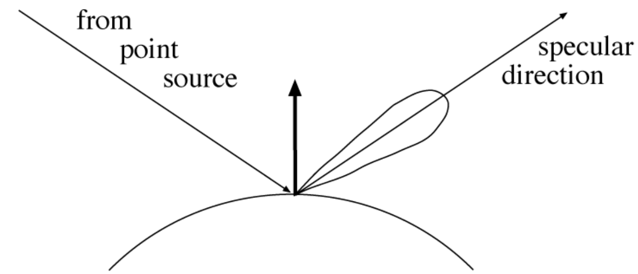
$$B(x) = \rho(x)\big(N(x)\cdot S(x)\big)$$

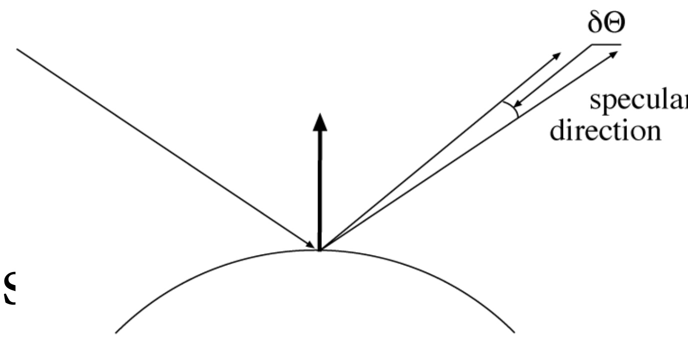


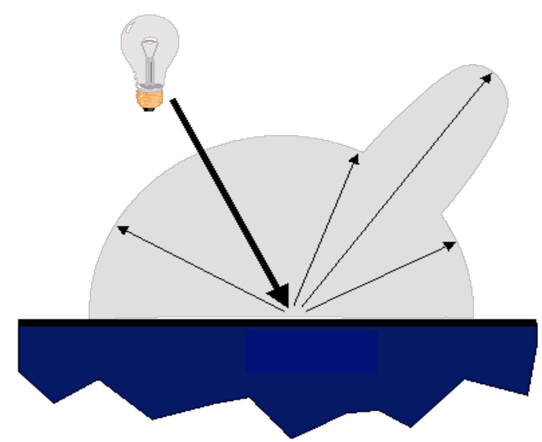
B: radiosity
ρ: albedo
N: unit normal
S: source vector (magnitude proportional to intensity of the source)

Specular reflection

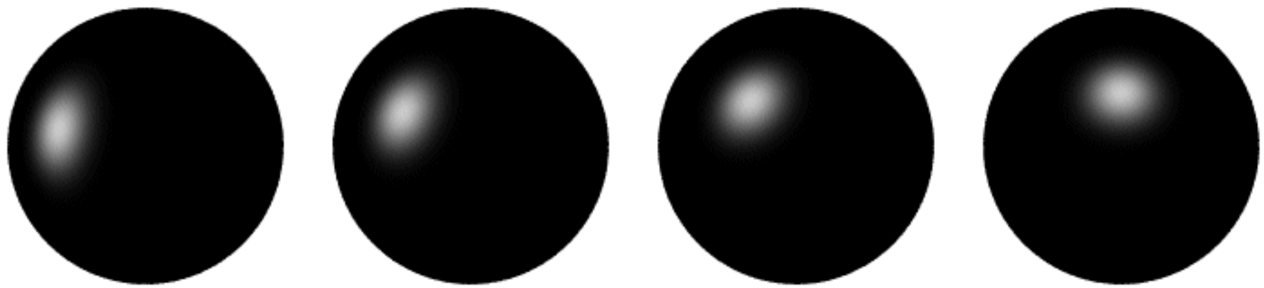
- Radiation arriving along a source direction leaves along the specular direction (source direction reflected about normal)
- Some fraction is absorbed, some reflected
- On real surfaces, energy usually goes into a lobe of directions
- Phong model: reflected energy falls of with $\cos^n(\delta\theta)$
- Lambertian + specular model: sum of diffuse and specular term



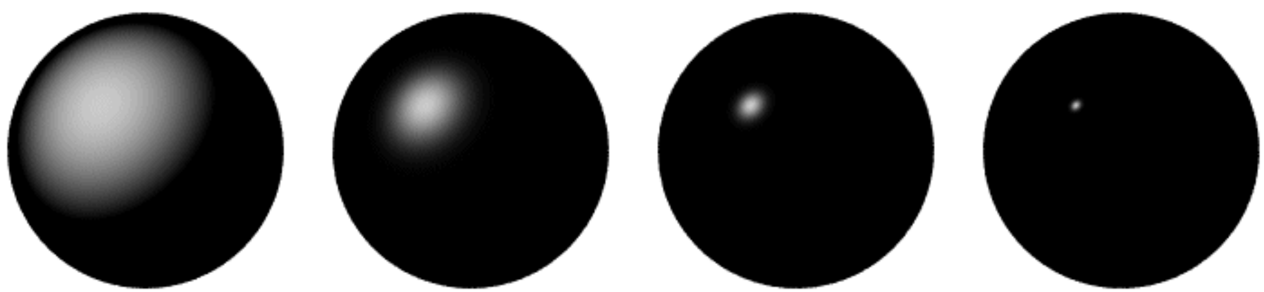




Specular reflection



Moving the light source



Changing the exponent

Color

What is color?

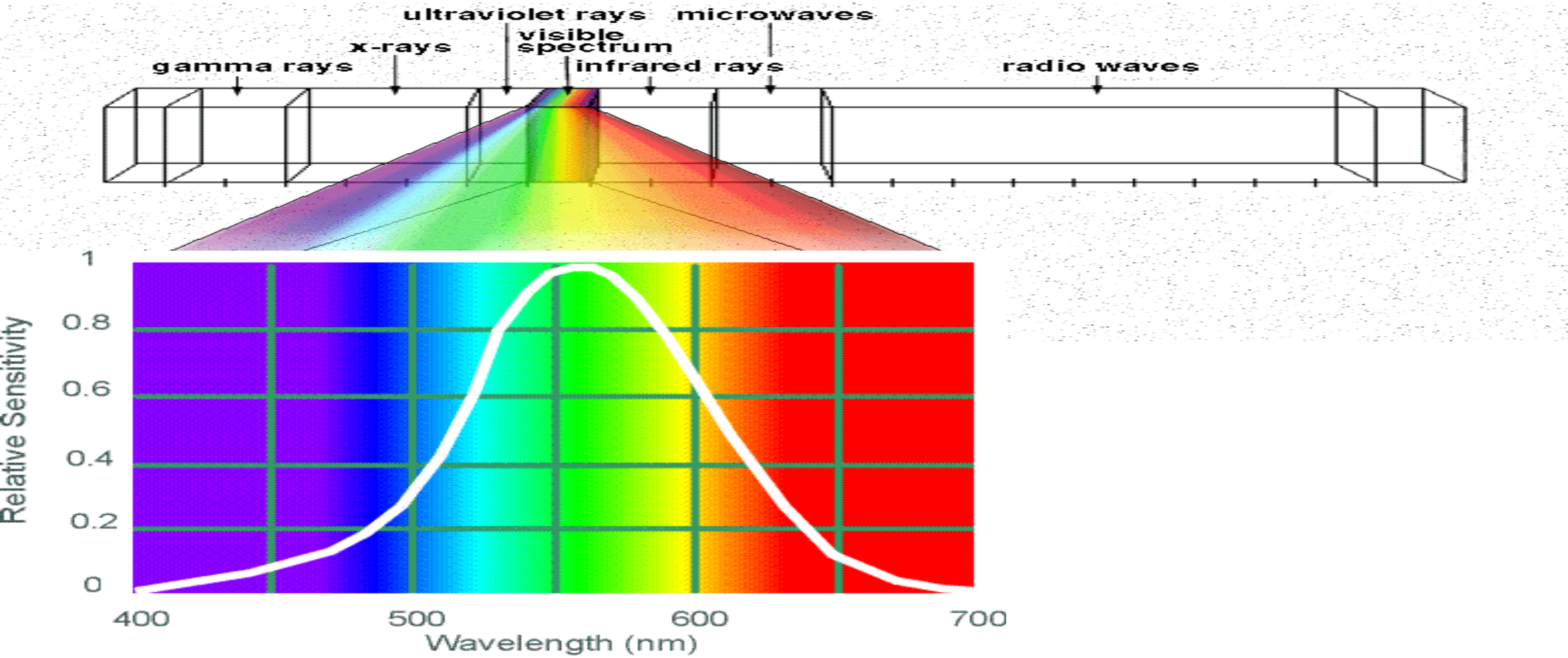
- Color is a psychological property of our visual experiences when we look at objects and lights,
  not a physical property of those objects or lights
  (S. Palmer, *Vision Science: Photons to Phenomenology*)

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

Overview of Color

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

Electromagnetic Spectrum

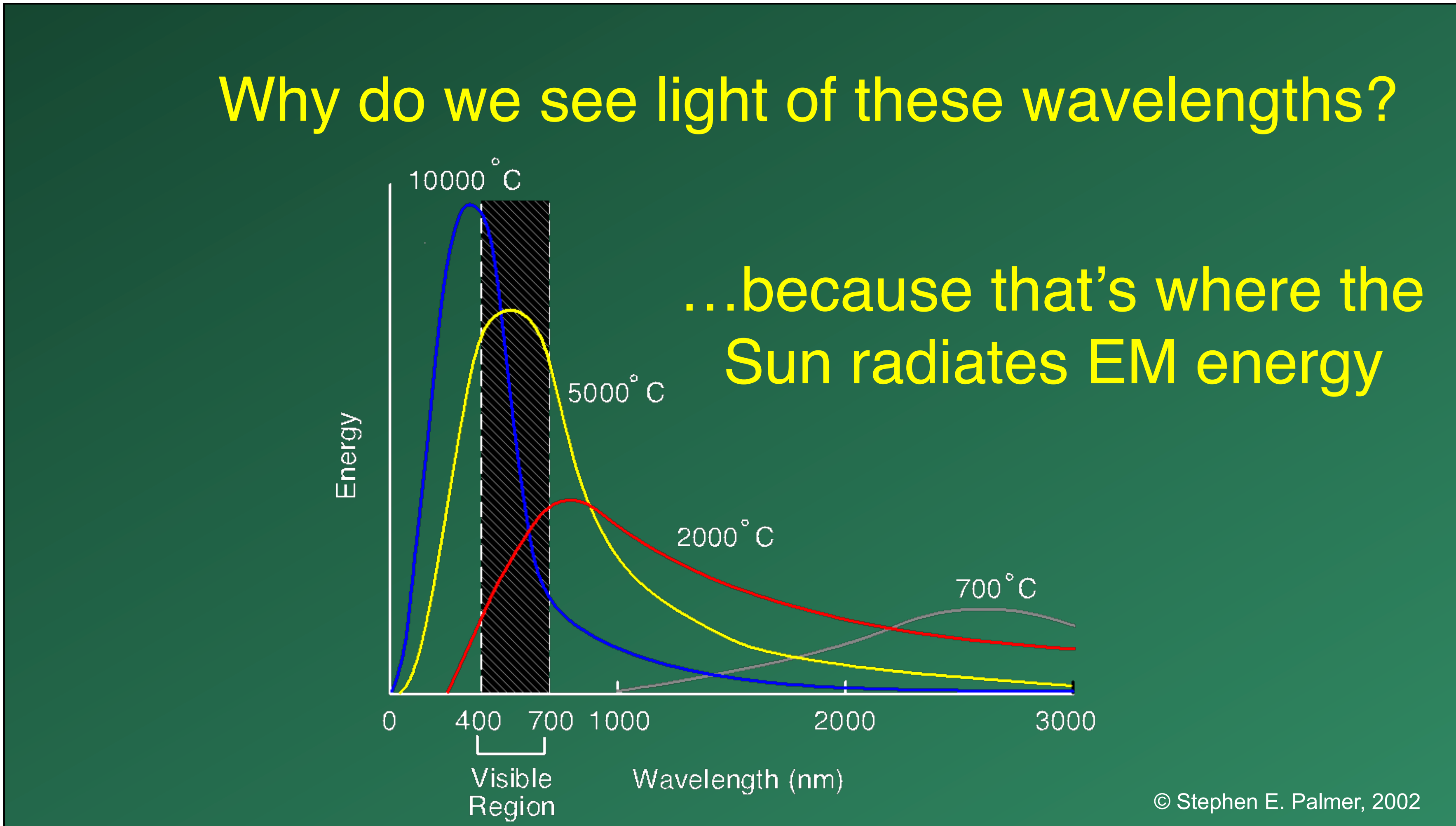


Human Luminance Sensitivity Function

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

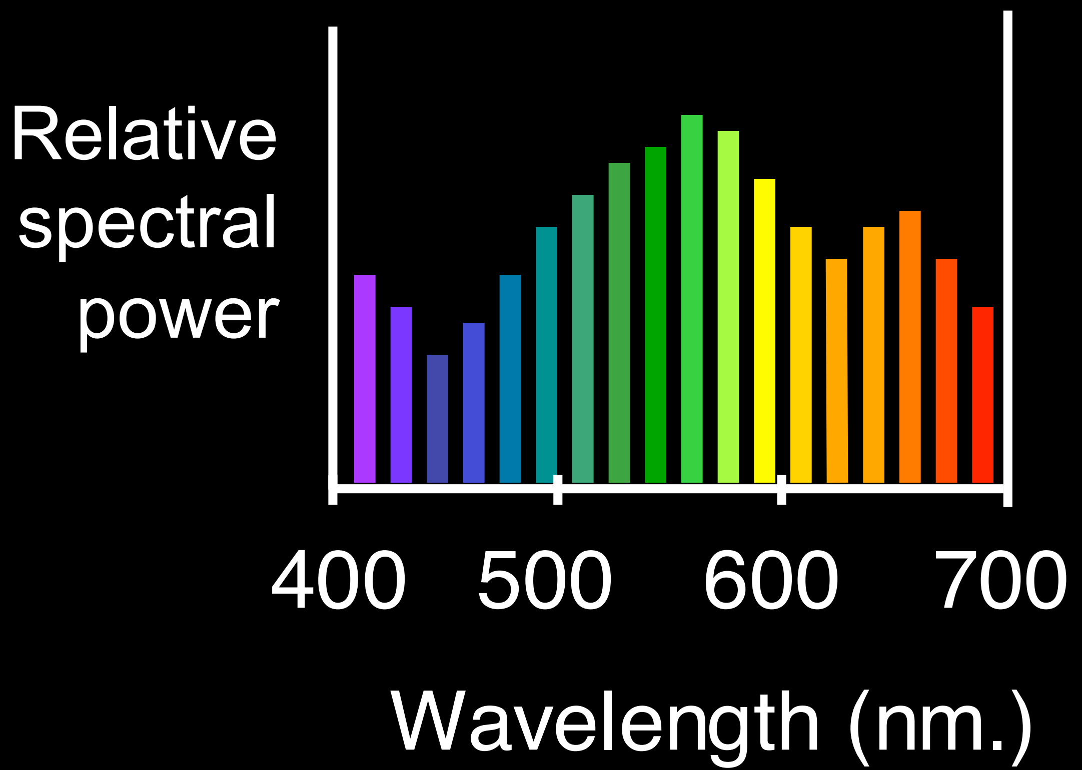
Visible Light

Plank's law for Blackbody radiation
Surface of the sun: ~5800K



The Physics of Light

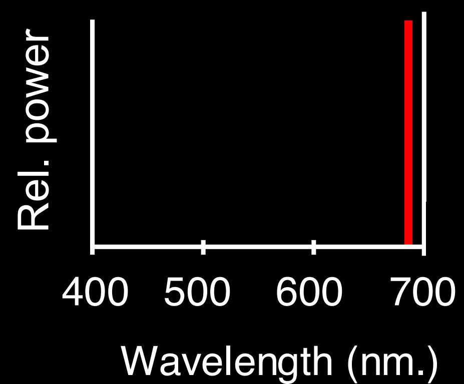
Any source of light can be completely described physically by its spectrum: the amount of energy emitted (per time unit) at each wavelength 400 - 700 nm.



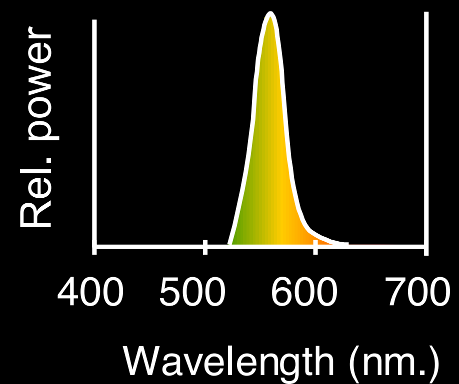
The Physics of Light

Some examples of the spectra of light sources

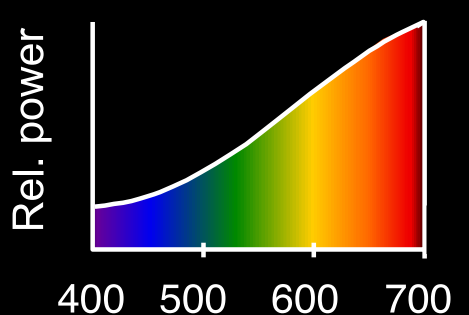
A. Ruby Laser



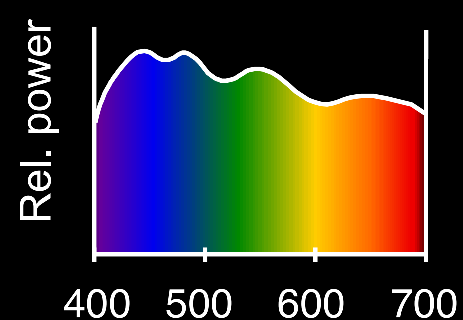
B. Gallium Phosphide Crystal



C. Tungsten Lightbulb

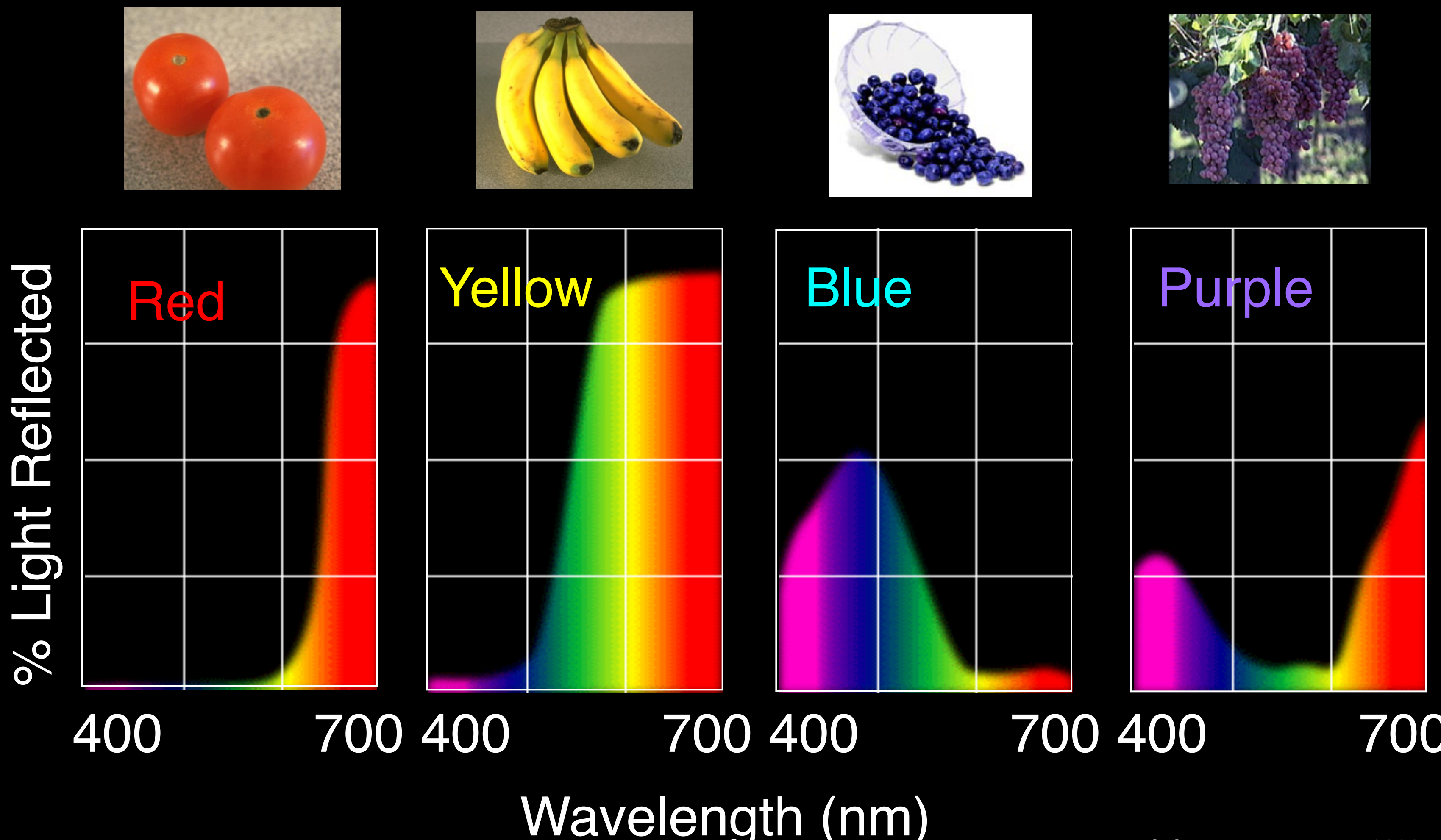


D. Normal Daylight



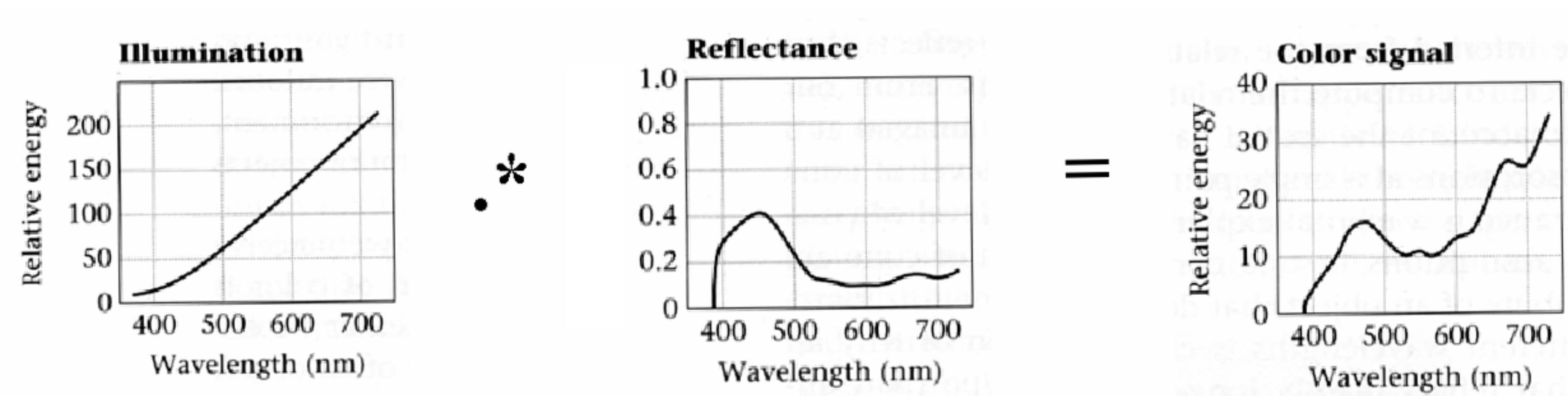
The Physics of Light

Some examples of the reflectance spectra of surfaces



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"



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

Interaction of light and surfaces

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

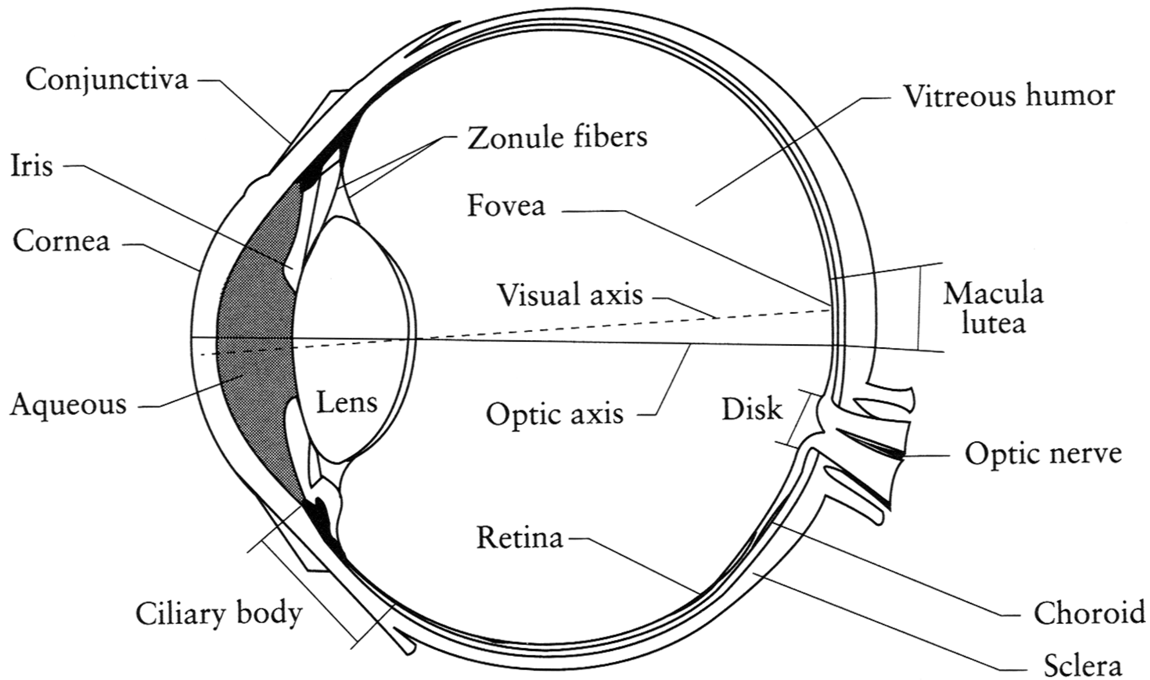
[Olafur Eliasson, *Room for one color*]

Slide by S. Lazebnik

Overview of Color

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

The Eye

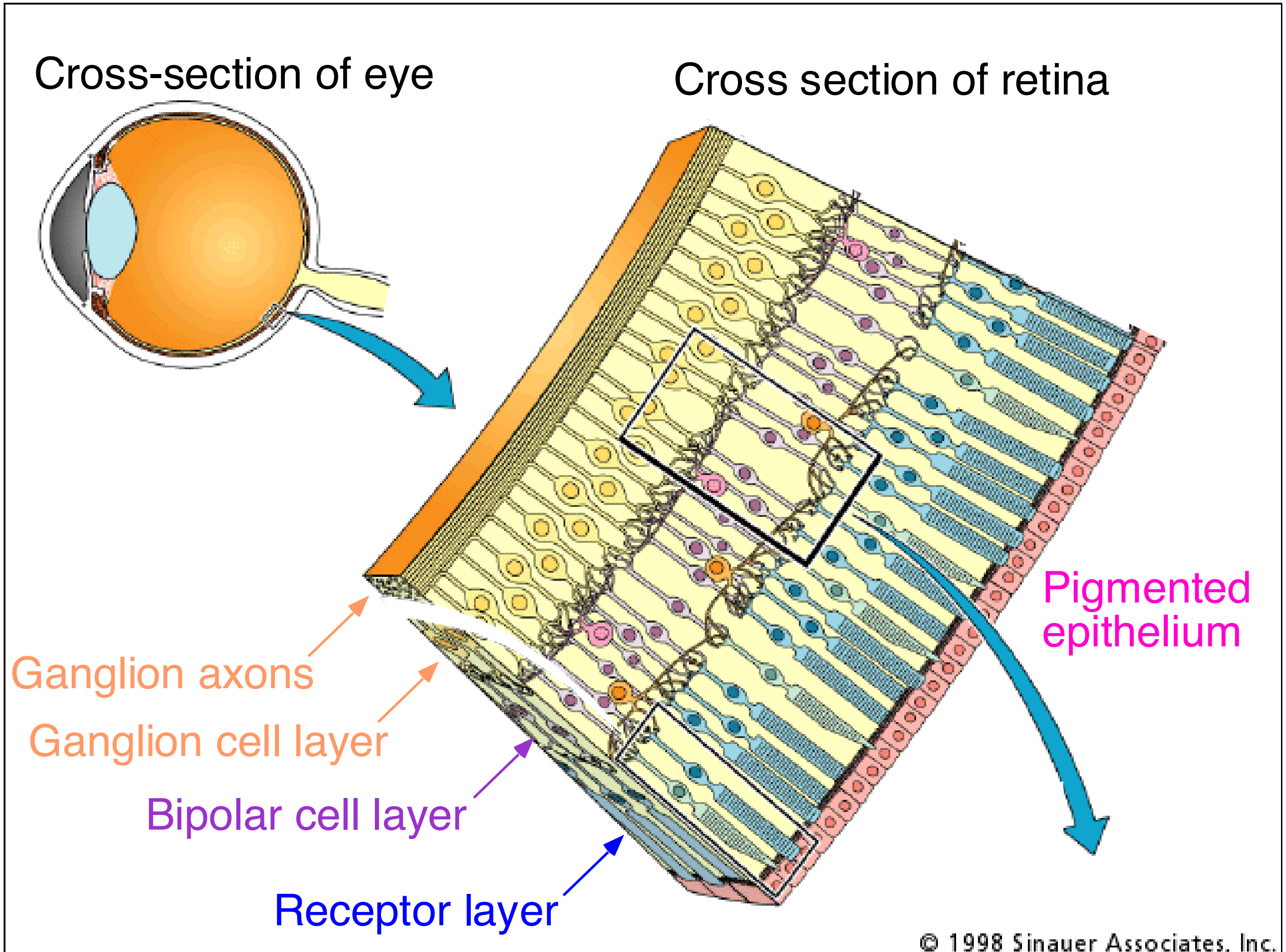


The human eye is a camera!

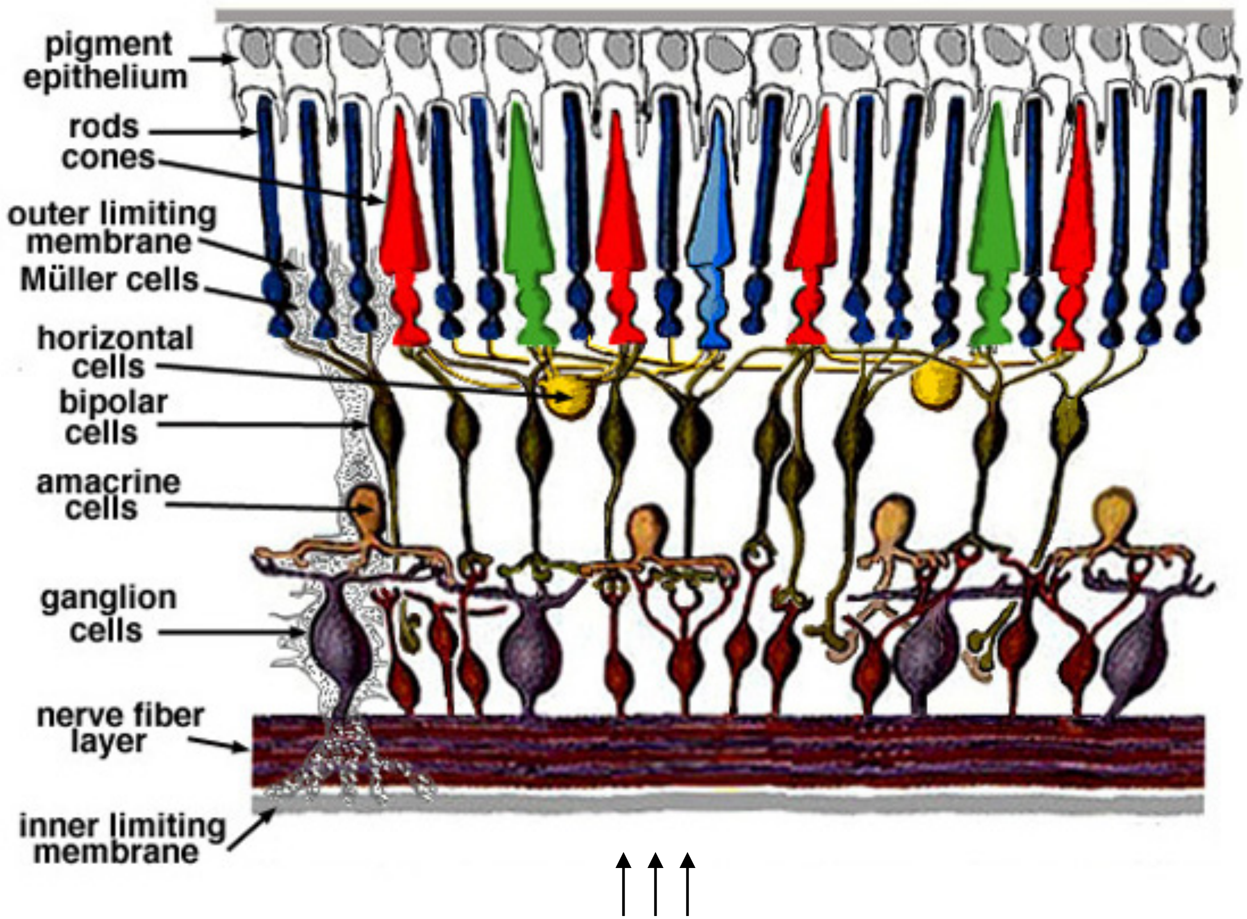
- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- What's the "film"?
  - photoreceptor cells (rods and cones) in the **retina**

Slide by Steve Seitz

The Retina


Cross-section of eye
Cross section of retina
Pigmented epithelium
Ganglion axons
Ganglion cell layer
Bipolar cell layer
Receptor layer
© 1998 Sinauer Associates, Inc.

Retina up-close

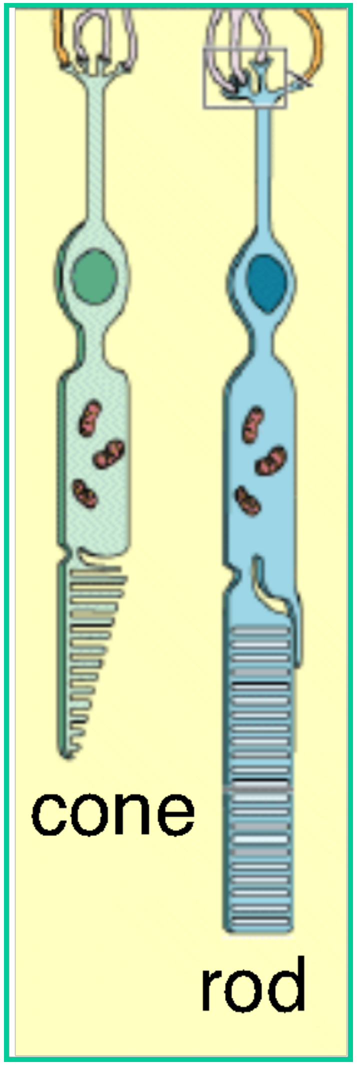


Light

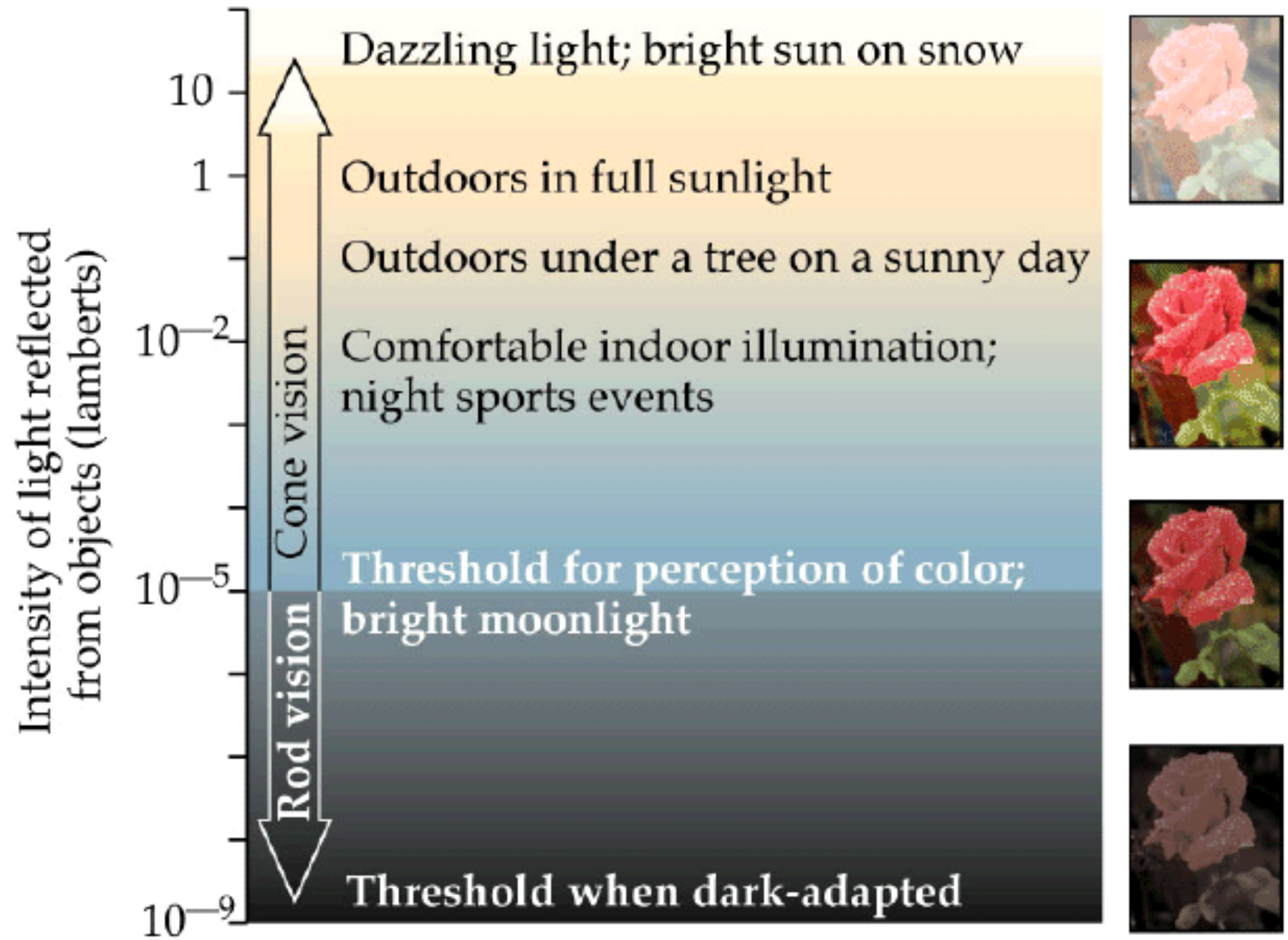
Two types of light-sensitive receptors

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

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



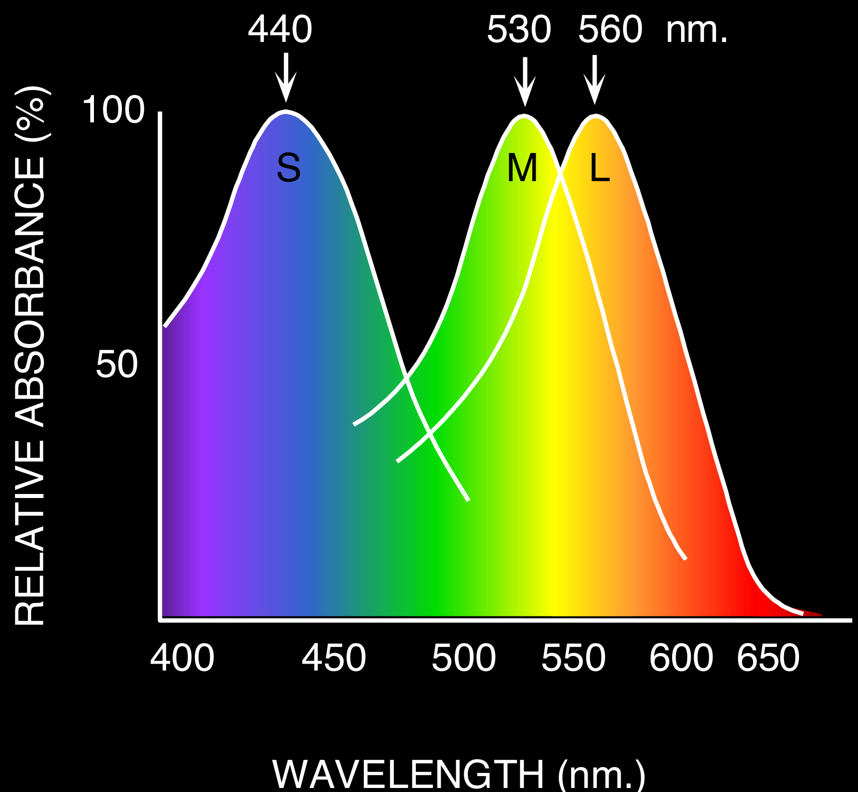
Rod / Cone sensitivity

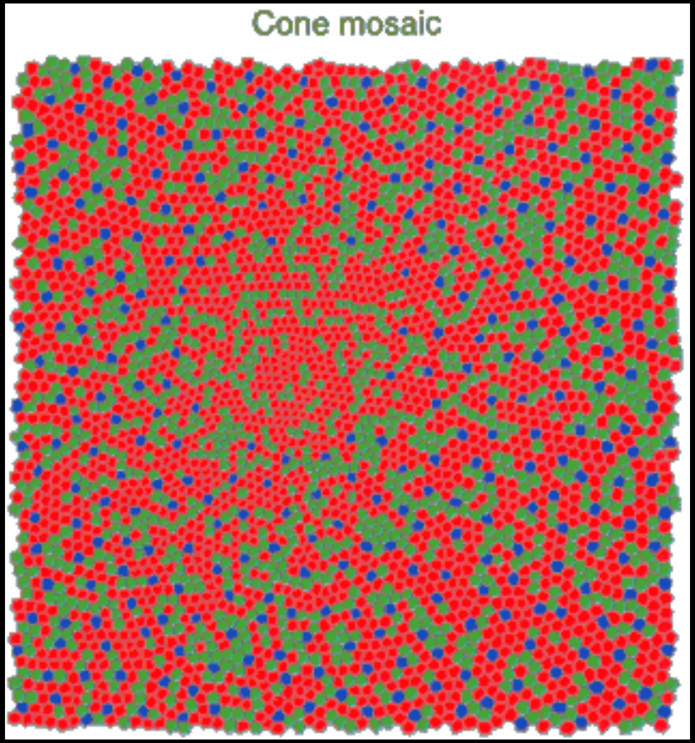


The famous sock-matching problem…

Physiology of Color Vision

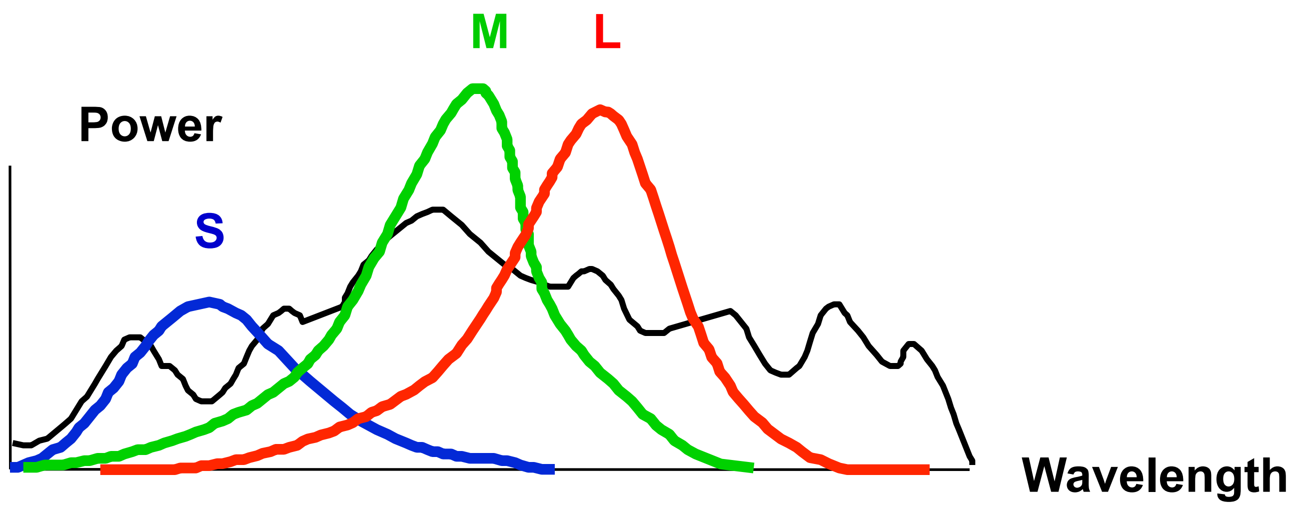
Three kinds of cones:





- Why are M and L cones so close?
- Are are there 3?

Color perception



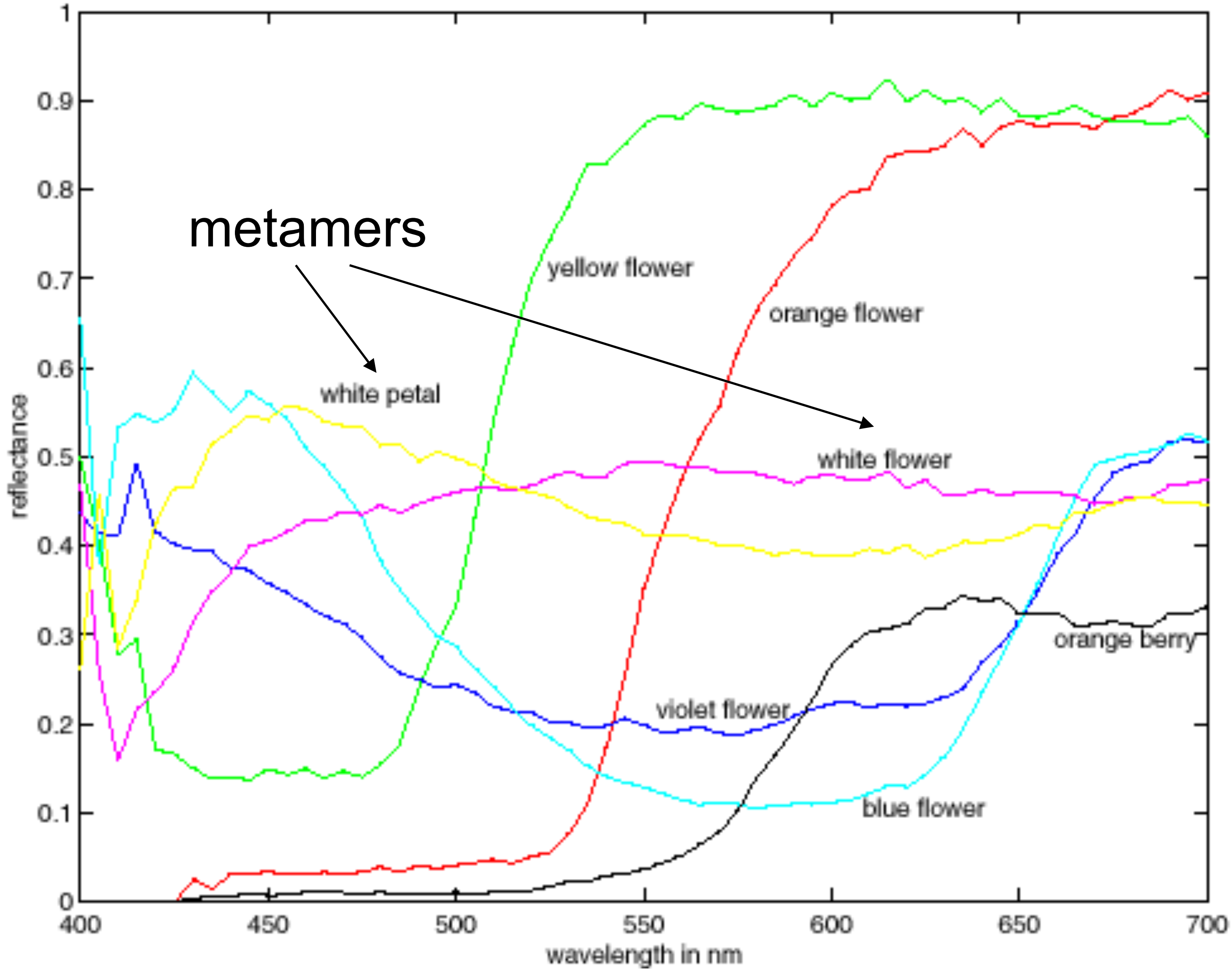
Rods and cones act as filters on the spectrum

- 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**

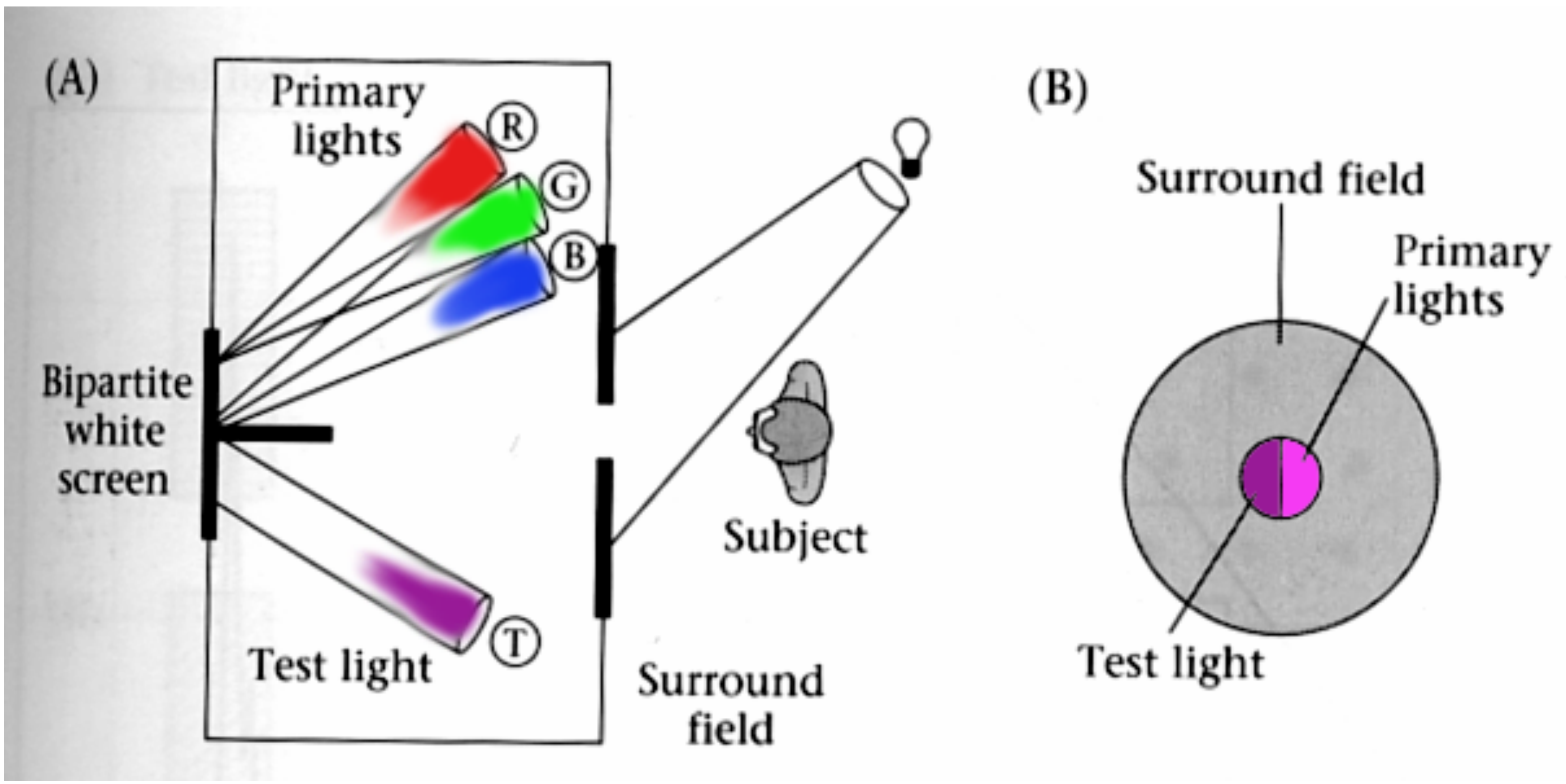
Slide by Steve Seitz

Spectra of some real-world surfaces



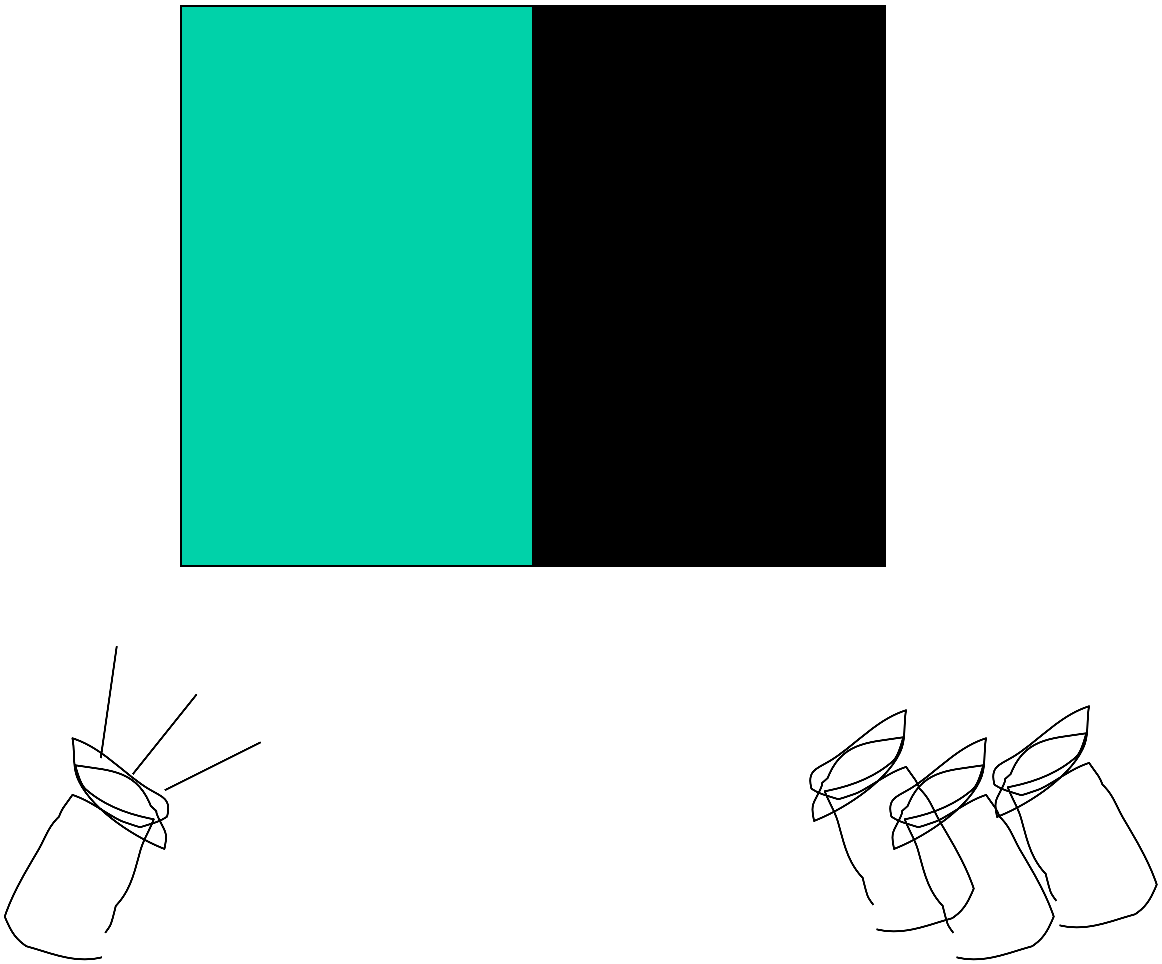
Standardizing color experience

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



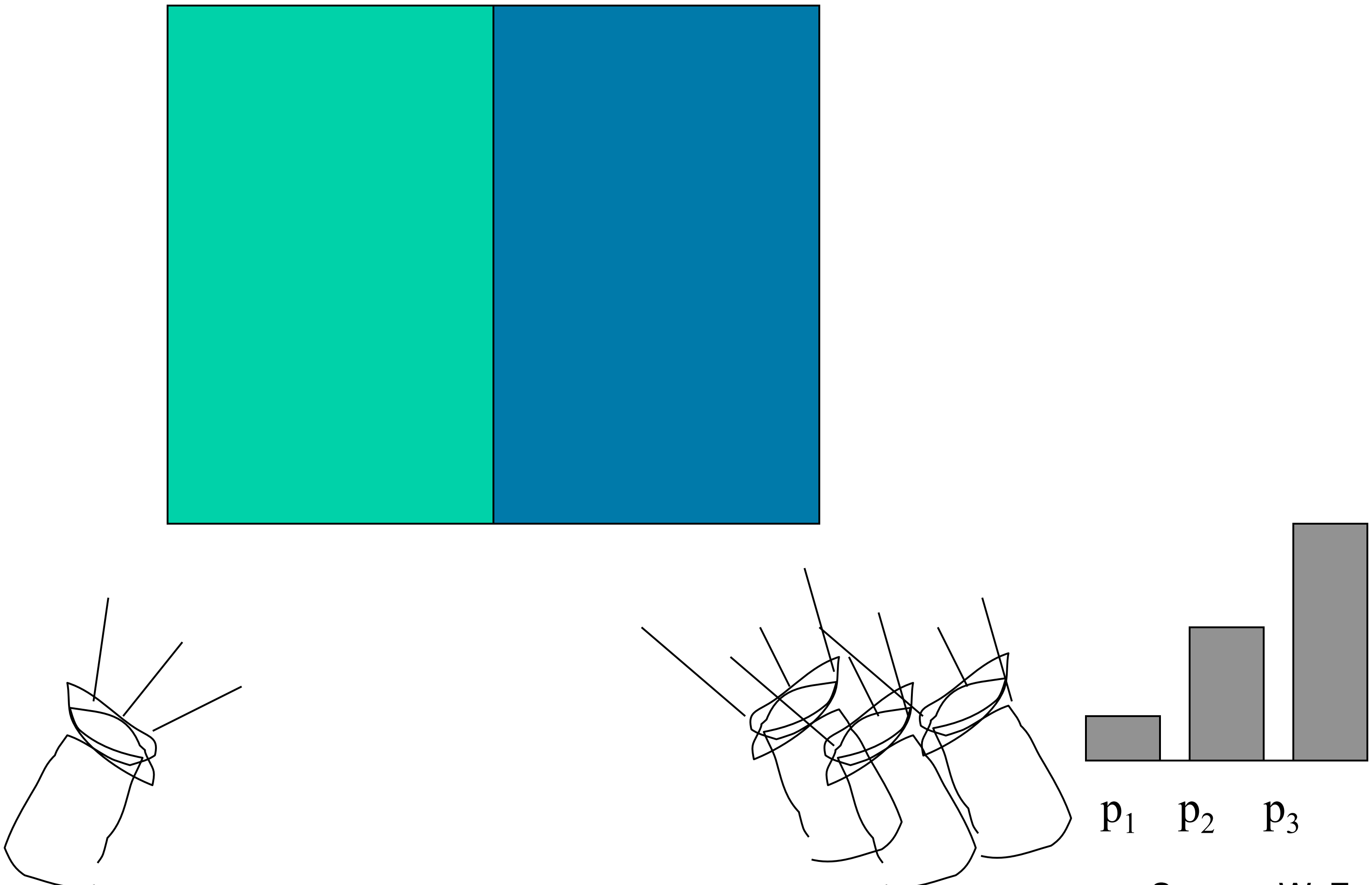
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Color matching experiment 1



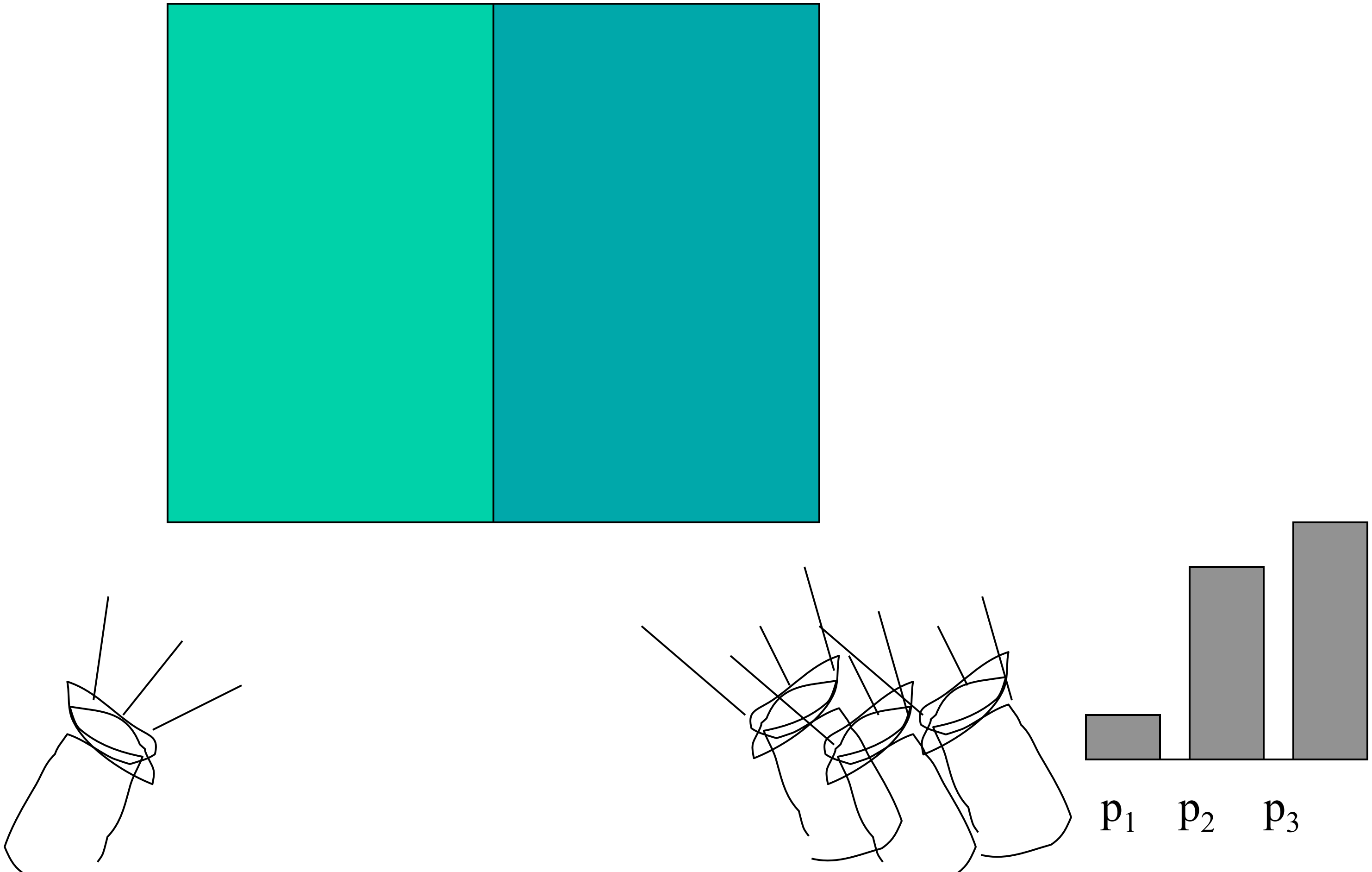
Source: W. Freeman

Color matching experiment 1



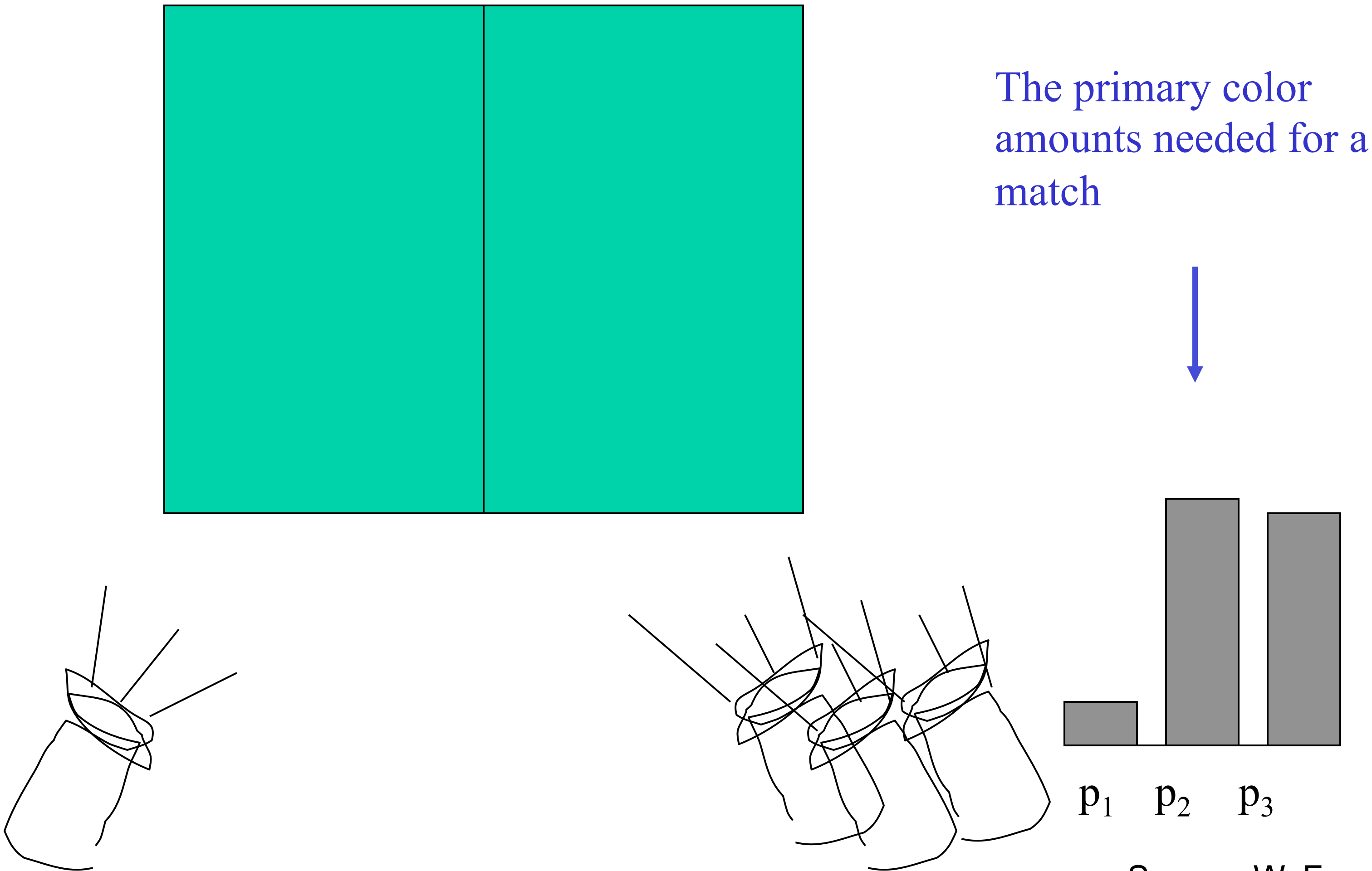
Source: W. Freeman

Color matching experiment 1



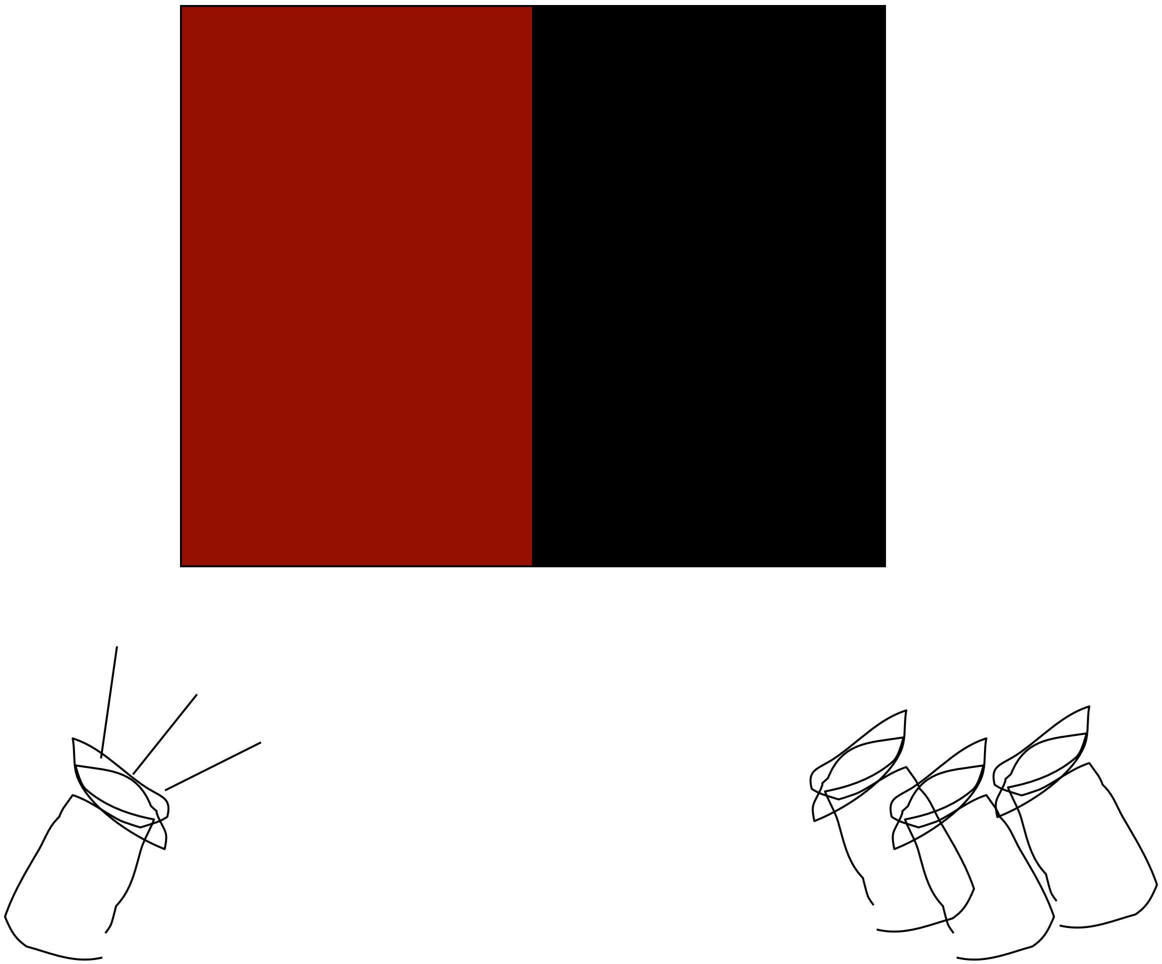
Source: W. Freeman

Color matching experiment 1



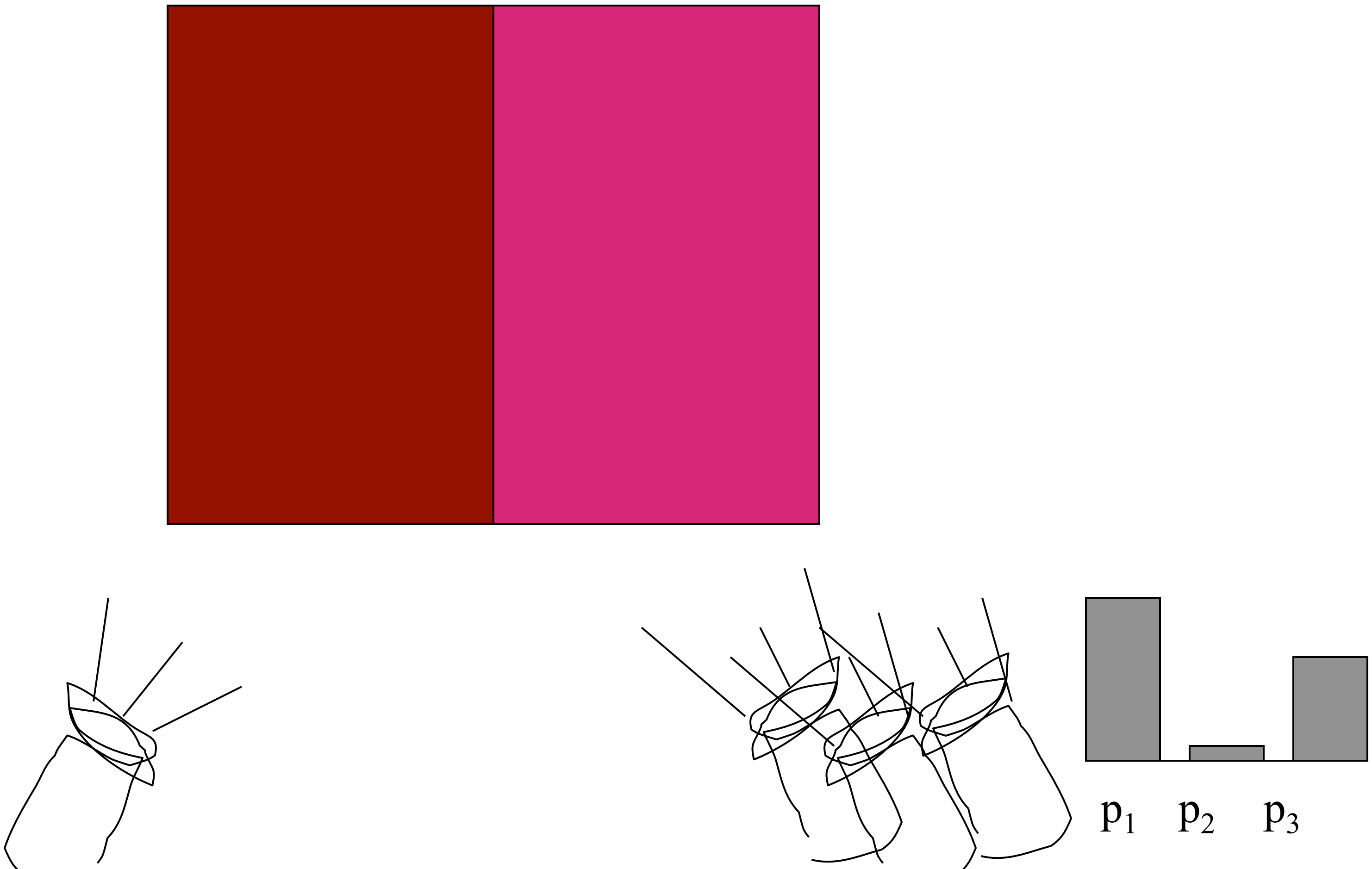
Source: W. Freeman

Color matching experiment 2



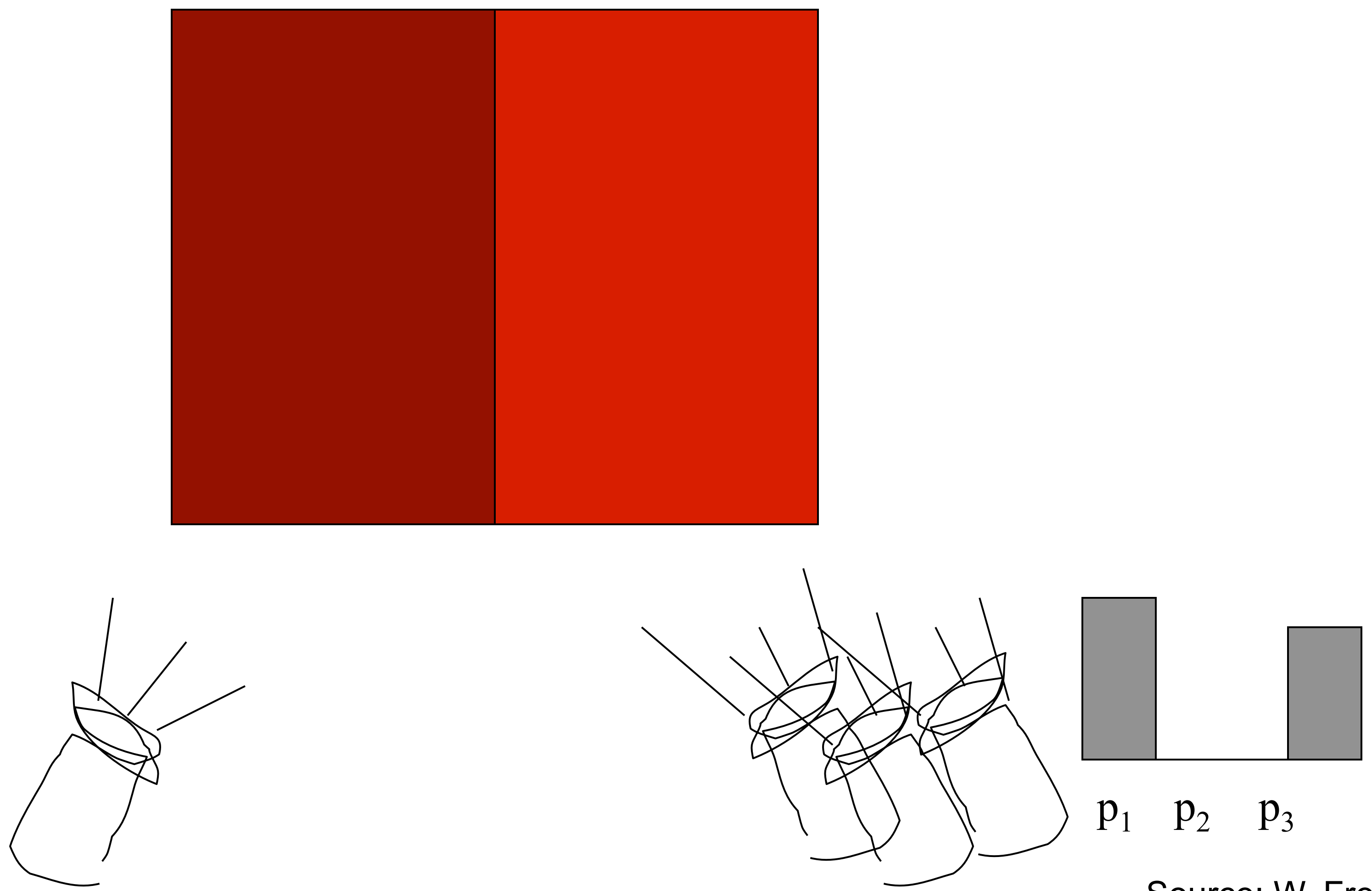
Source: W. Freeman

Color matching experiment 2



Source: W. Freeman

Color matching experiment 2

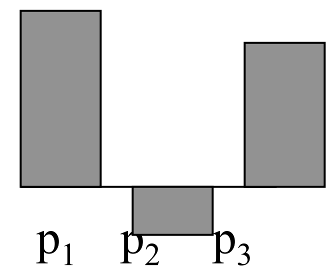


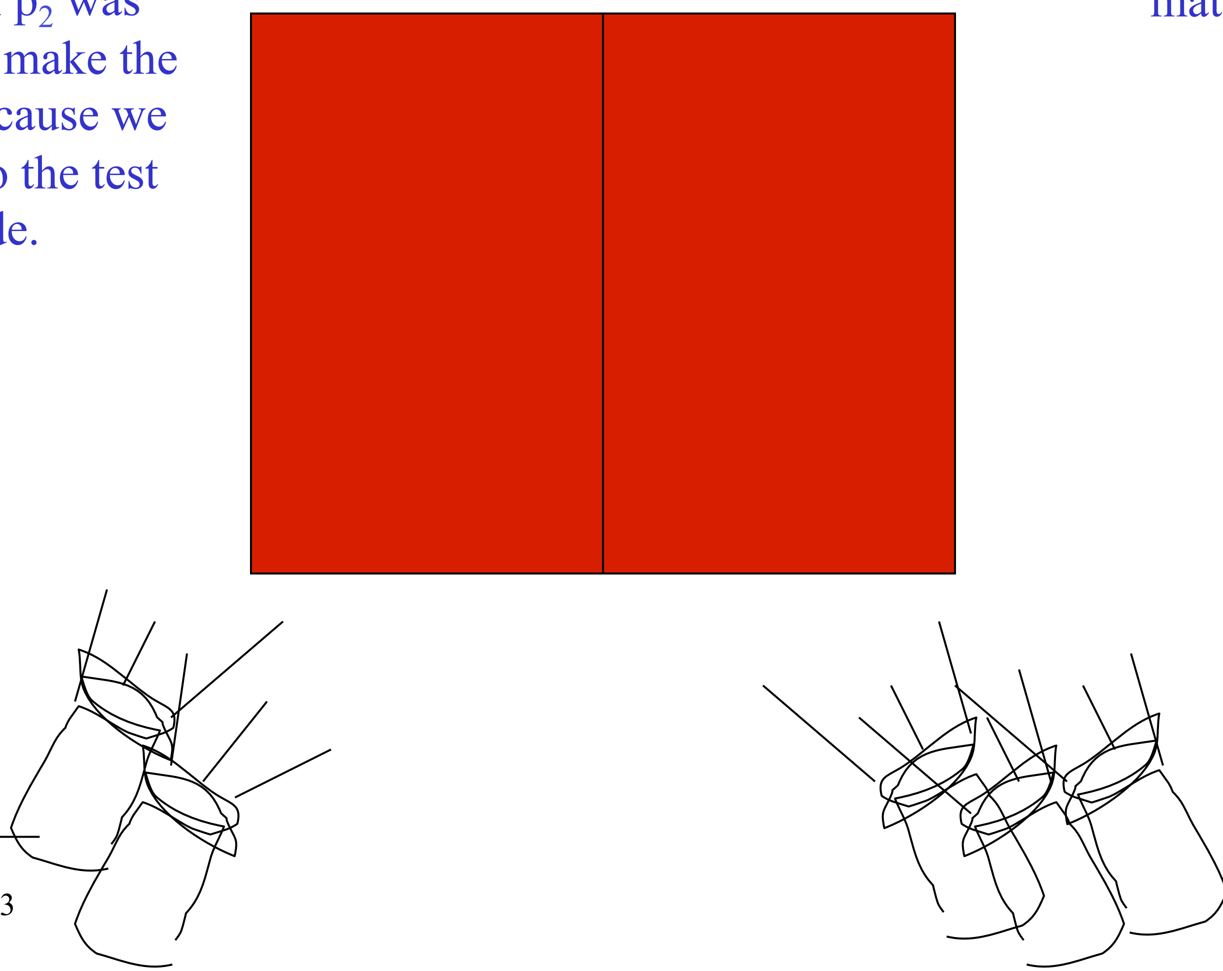
Source: W. Freeman

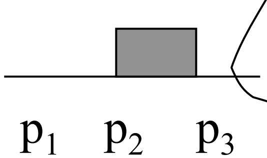
Color matching experiment 2

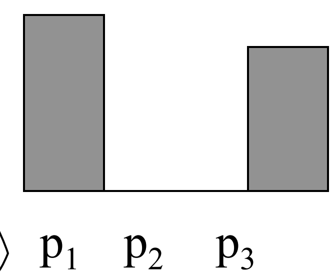
We say a “negative” amount of p_2 was needed to make the match, because we added it to the test color’s side.

The primary color amounts needed for a match:







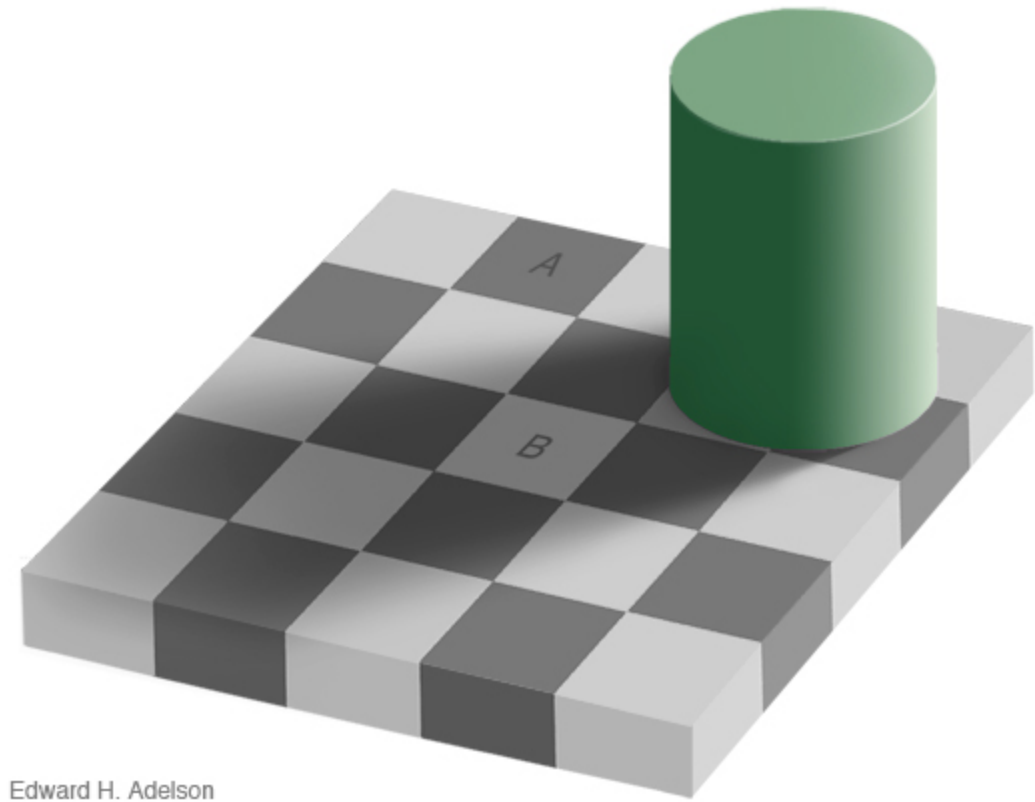


Source: W. Freeman

Trichromacy

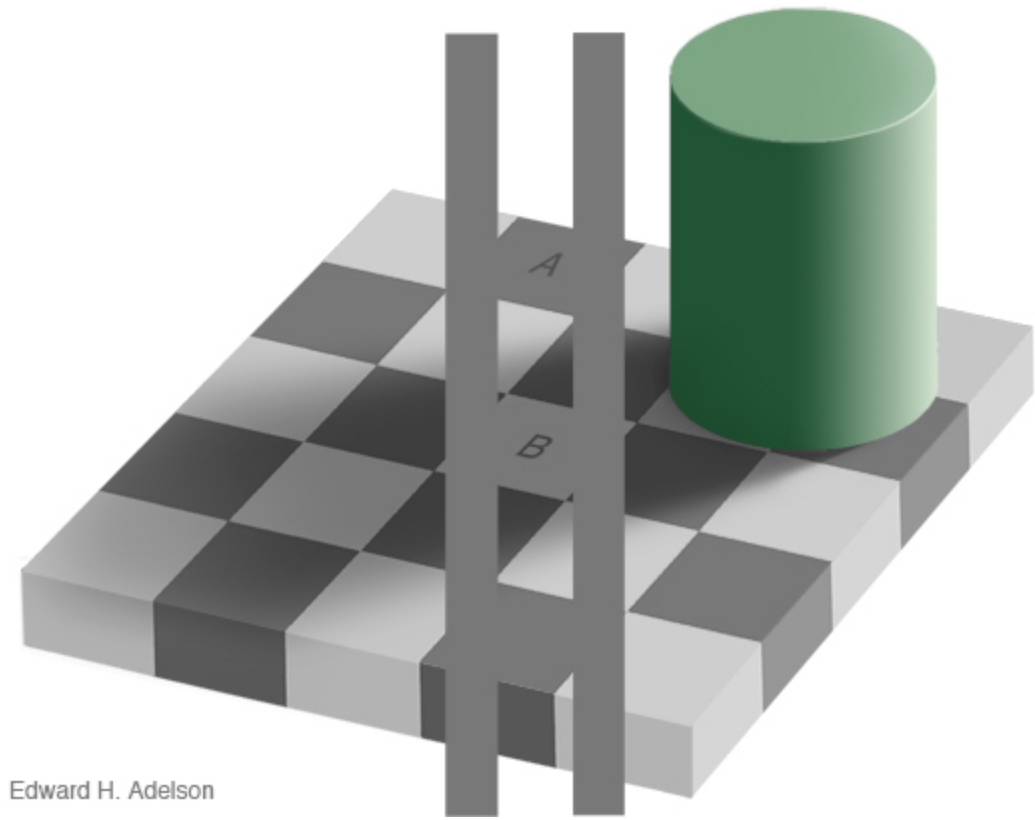
- In color matching experiments, most people can match any given light with three primaries
  - Primaries must be *independent*
- For the same light and same primaries, most people select the same weights
  - Exception: color blindness
- Trichromatic color theory
  - Three numbers seem to be sufficient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

Lightness constancy



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

Lightness constancy



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

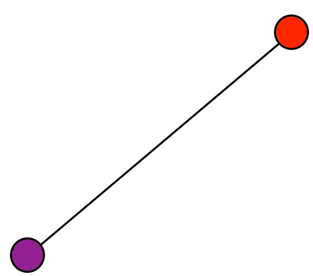
http://web.mit.edu/persci/people/adelson/checkershadow_illusion.html

Overview of Color

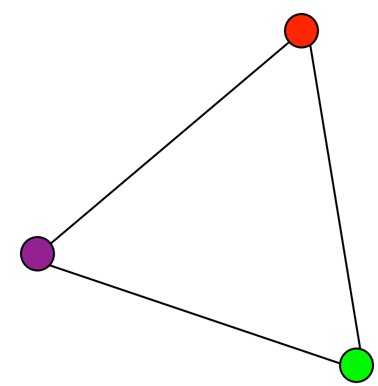
- Physics of color
- Human encoding of color
- Color spaces
- White balancing

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

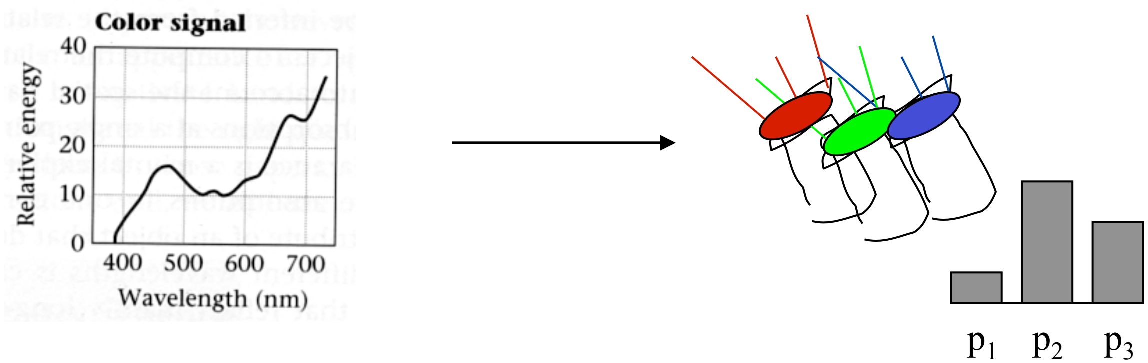


mixing two lights produces colors that lie along a straight line in color space



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

Source: W. Freeman

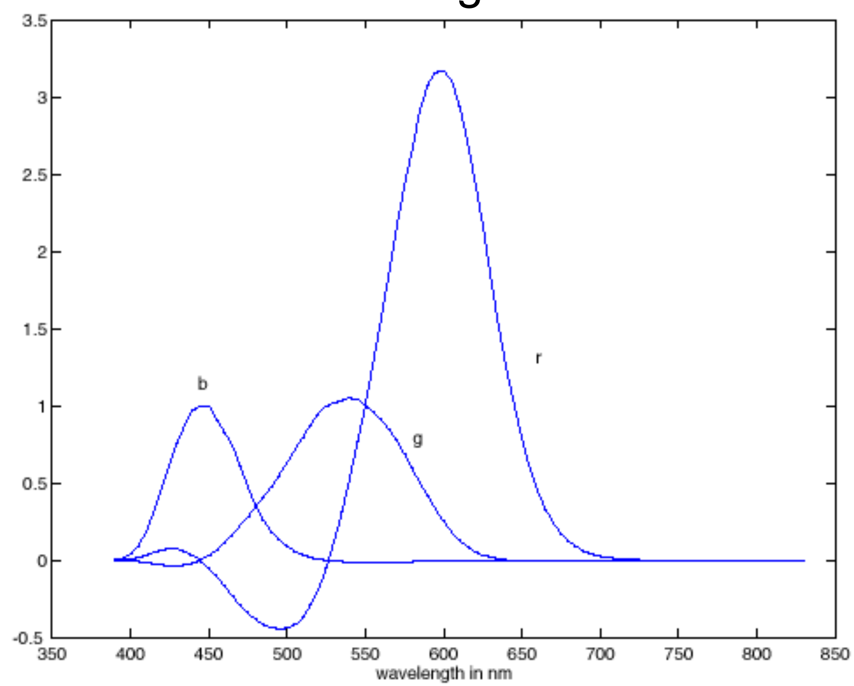
RGB space

- 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

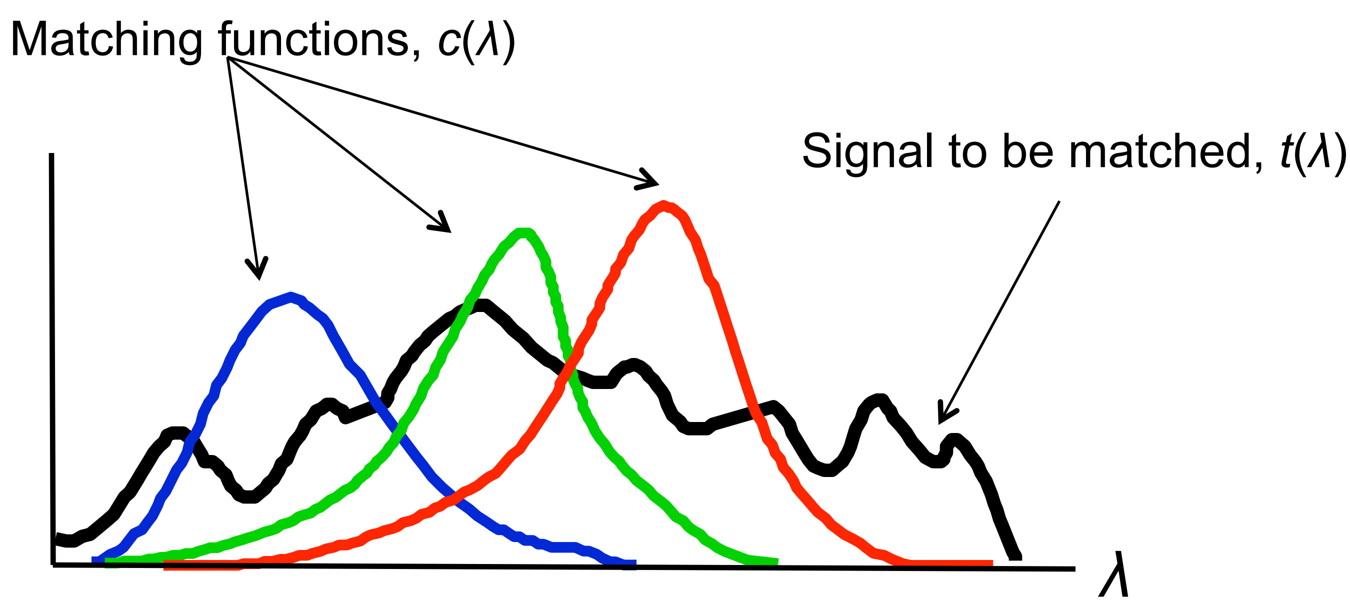
RGB matching functions



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

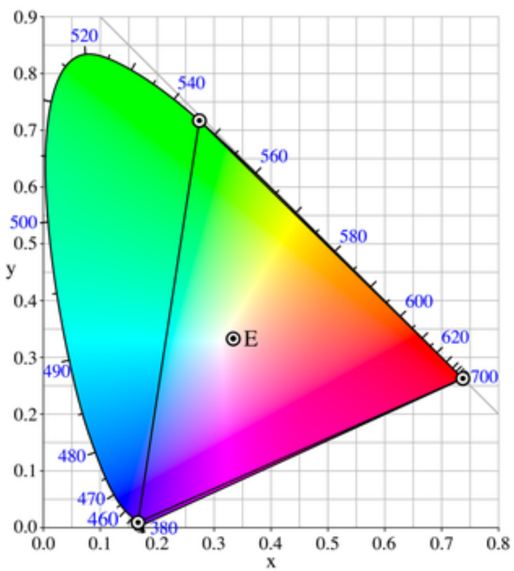
- Let $c(\lambda)$ be one of the matching functions, and let $t(\lambda)$ be the spectrum of the signal. Then the weight of the corresponding primary needed to match t is

$$w = \int_{\lambda} c(\lambda) t(\lambda) d\lambda$$

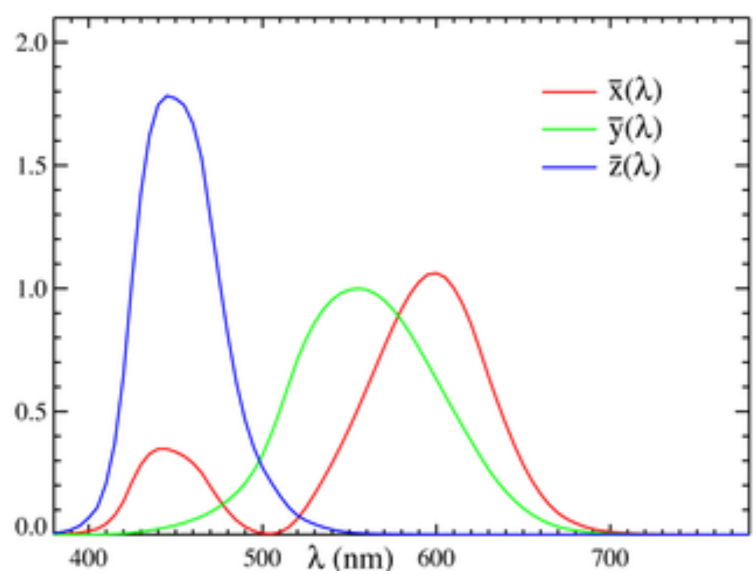


Linear color spaces: CIE XYZ

- 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 $x = X/(X+Y+Z)$, $y = Y/(X+Y+Z)$

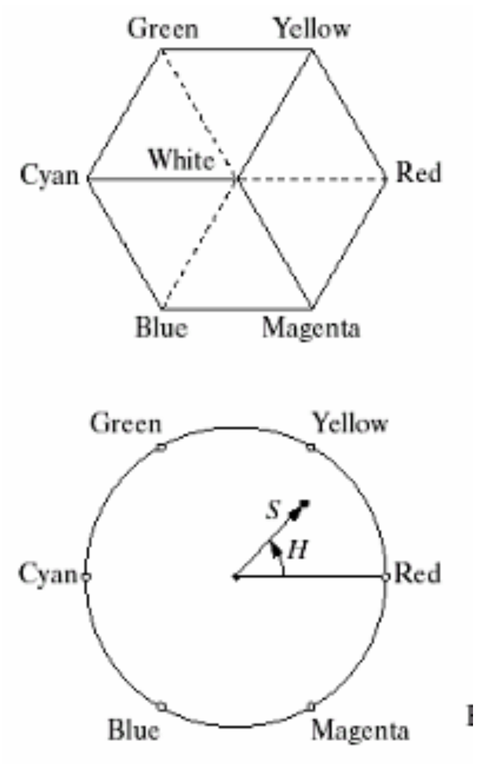


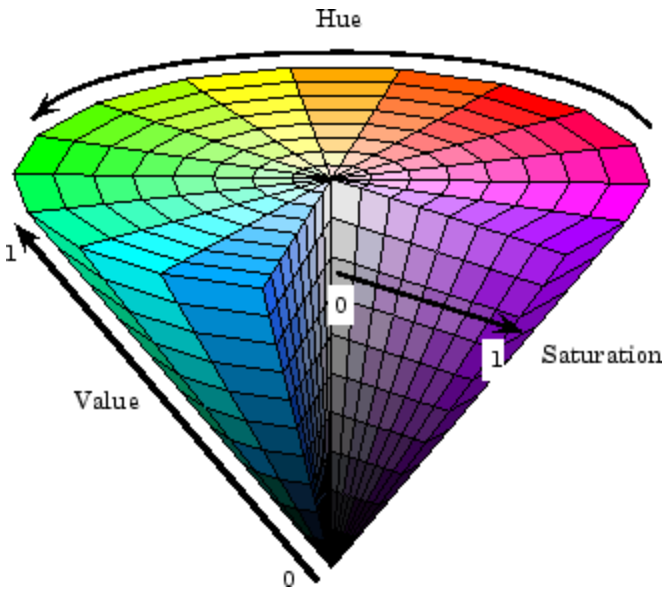
Matching functions

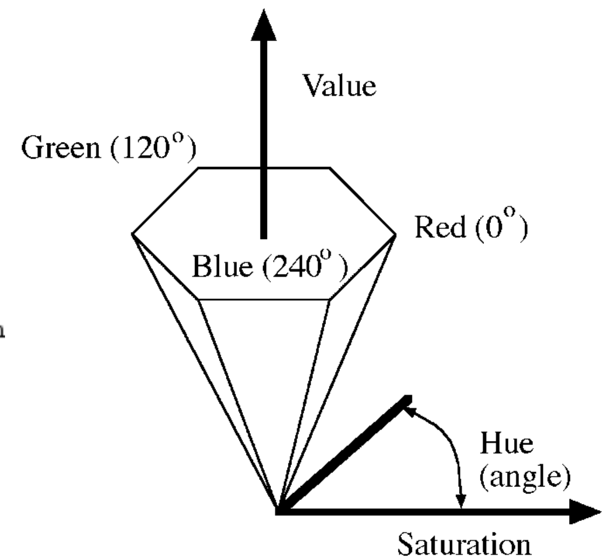


http://en.wikipedia.org/wiki/CIE_1931_color_space

Nonlinear color spaces: HSV



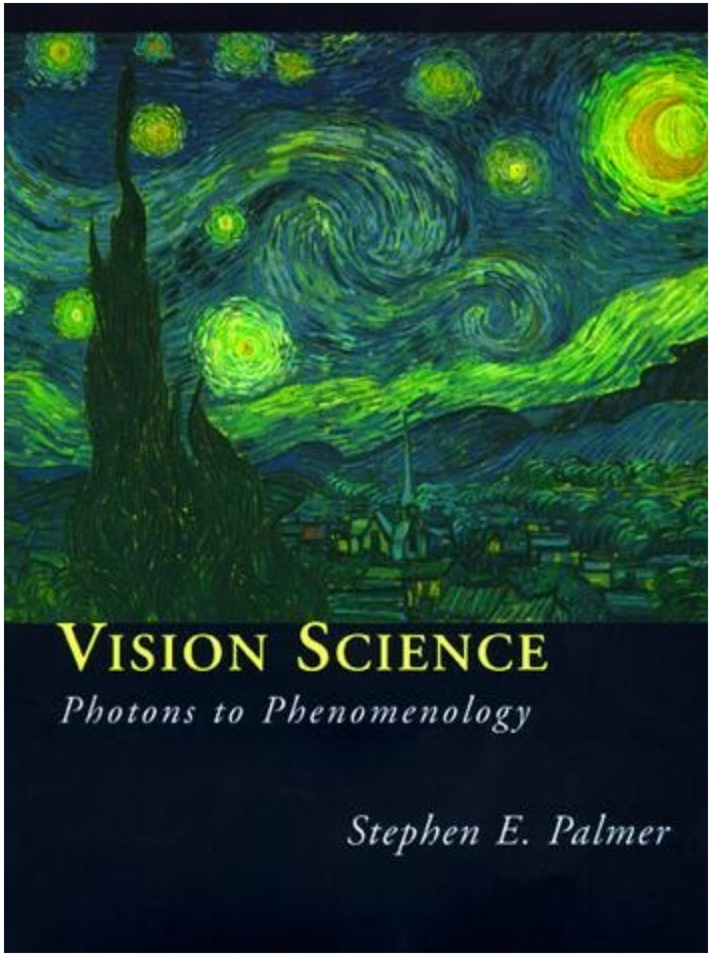




- Perceptually meaningful dimensions: Hue, Saturation, Value (Intensity)
- RGB cube on its vertex

Useful reference

Stephen E. Palmer, **Vision Science: Photons to Phenomenology**, MIT Press, 1999



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

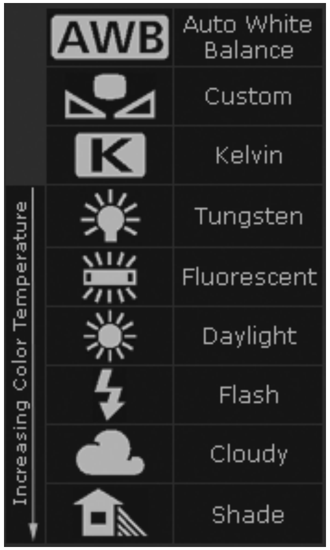
correct white balance

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

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

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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

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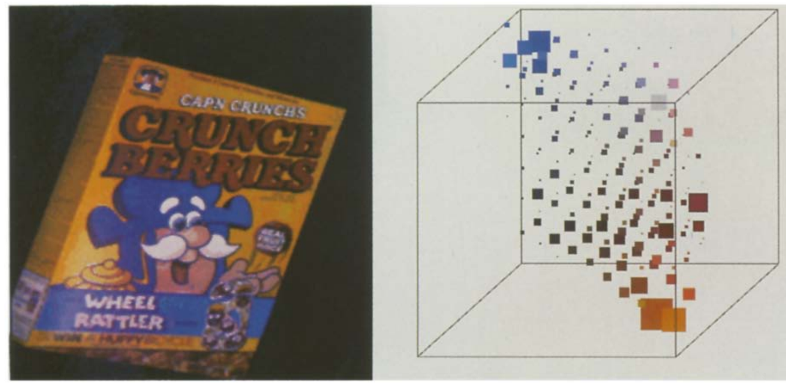
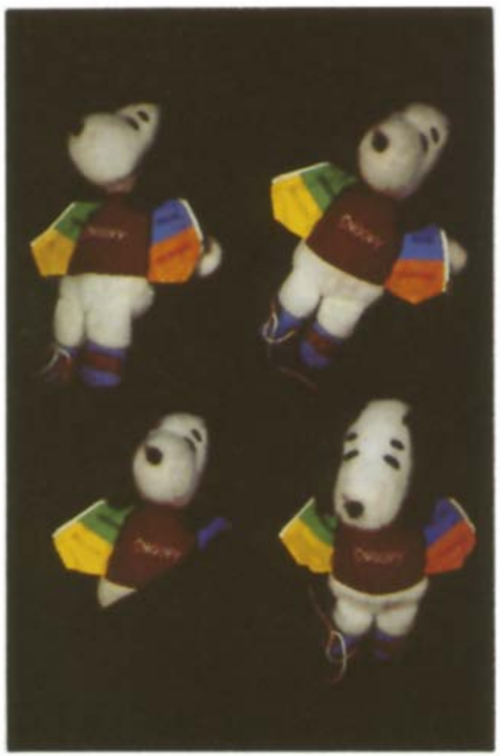
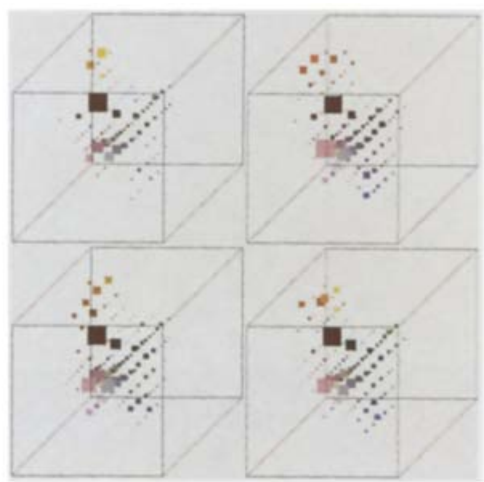
Uses of color in computer vision

Color histograms for indexing and retrieval



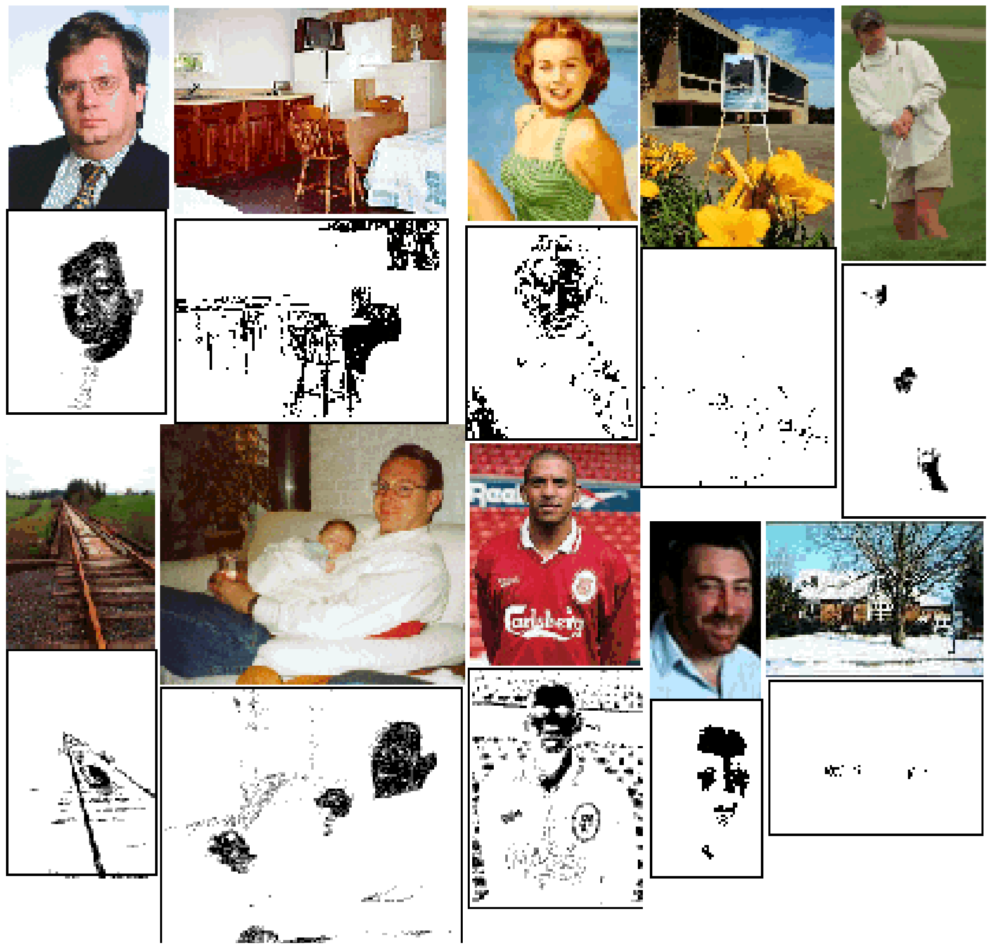




Swain and Ballard, Color Indexing, IJCV 1991.

Uses of color in computer vision

Skin detection

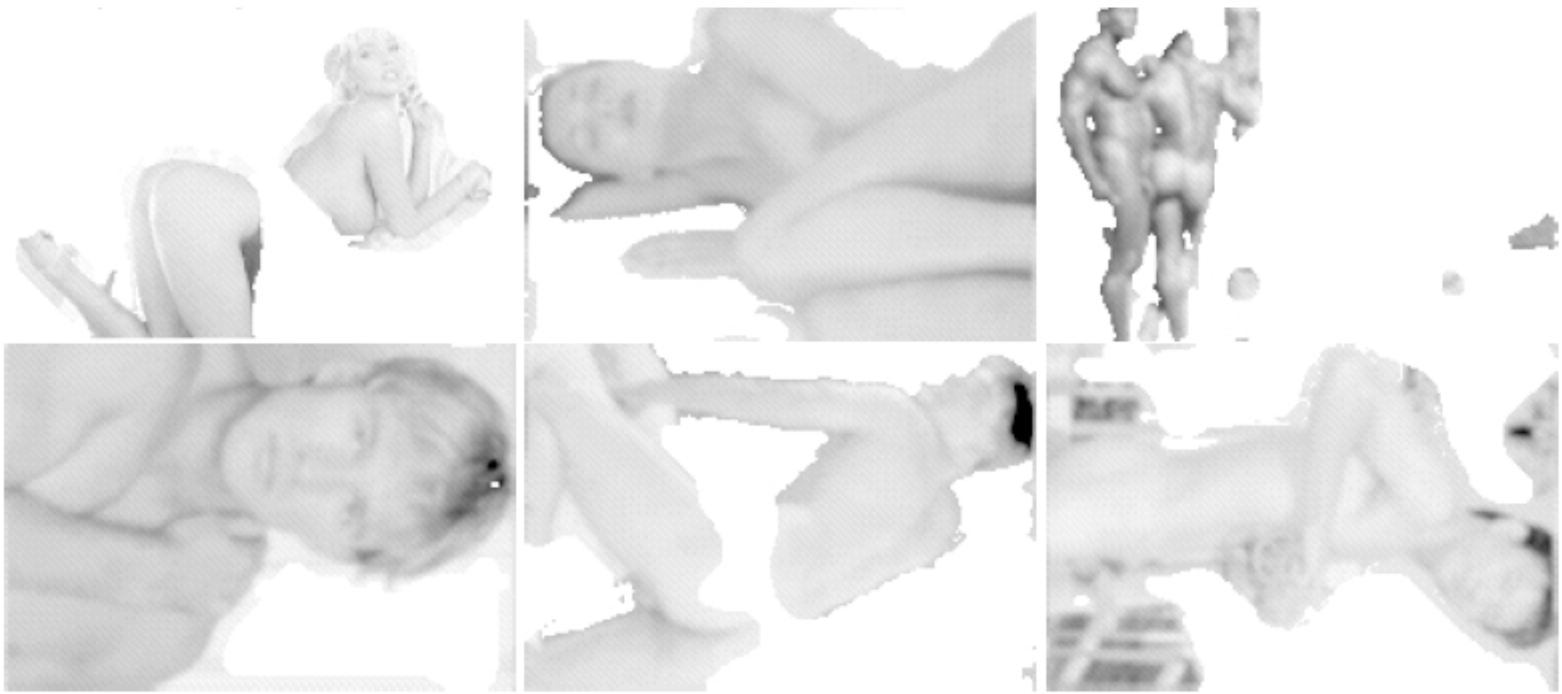


M. Jones and J. Rehg,
Statistical Color Models with Application to Skin

Source: S. Lazebnik

Uses of color in computer vision

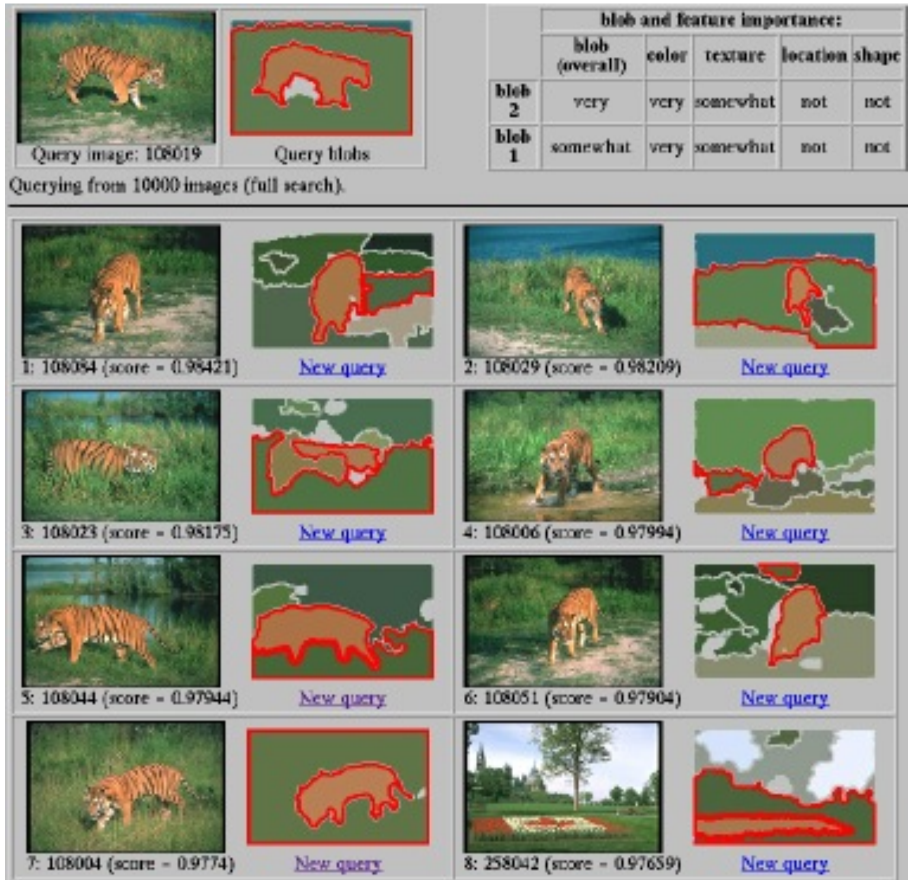
Nude people detection



Forsyth, D.A. and Fleck, M. M., ``Automatic Detection of Human Nudes,'' *International Journal of Computer Vision* , **32** , 1, 63-77, August, 1999

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

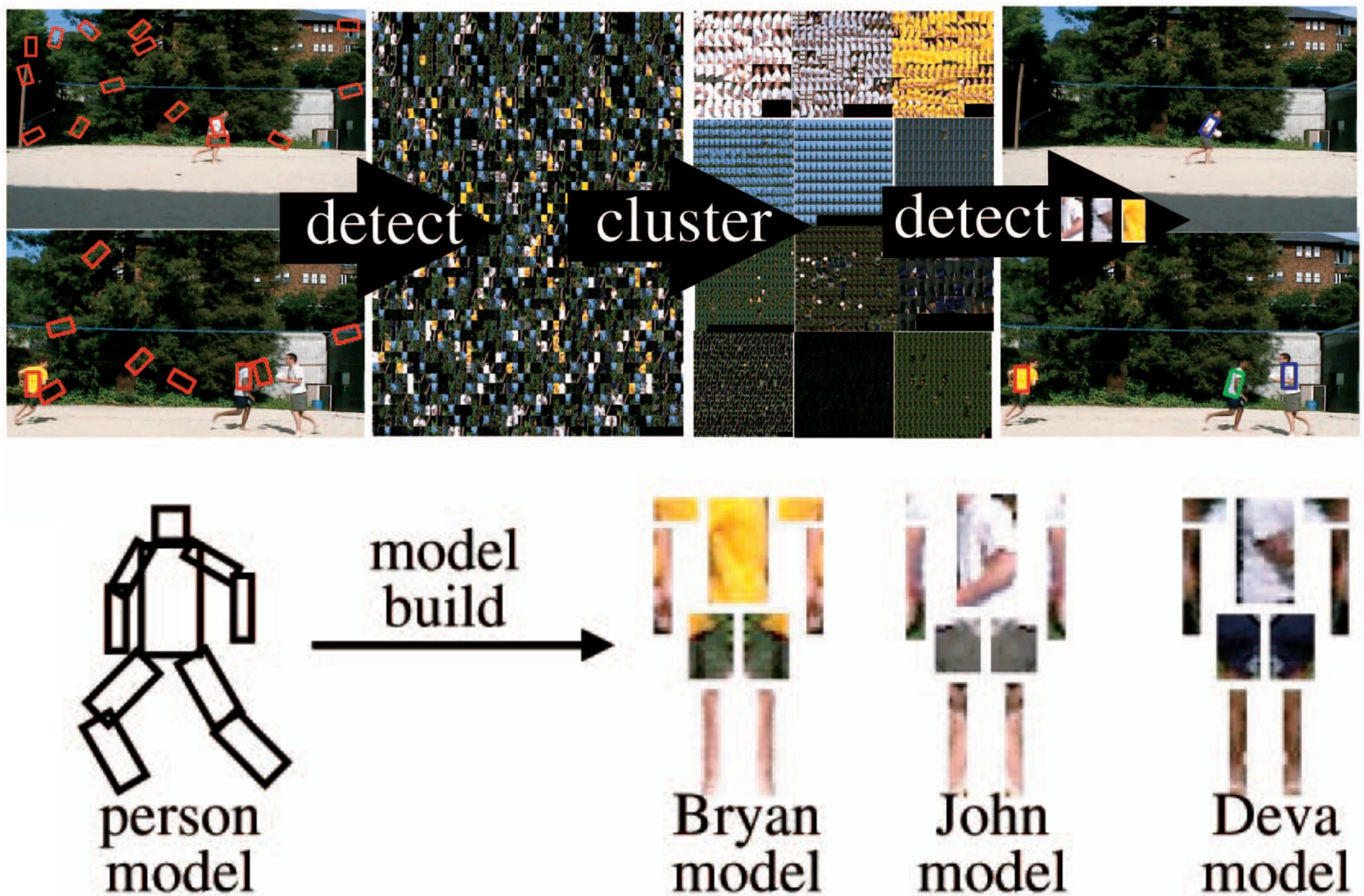
Robot soccer

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