Color

CS 543 / ECE 549 – Saurabh Gupta

Many slides adapted from S. Seitz, L. Lazebnik, J. Hayes, S. Palmer

While we wait, what color is the dress?

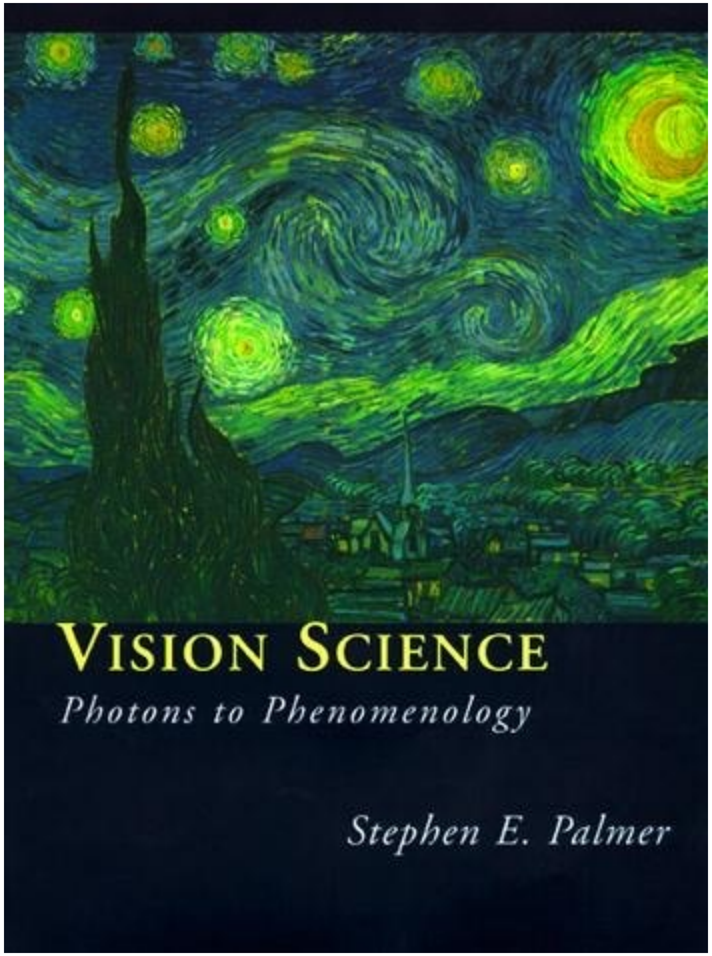
- A. White and gold
- B. Blue and Black

https://www.wired.com/2015/02/science-one-agrees-color-dress/

Slide by L. Lazebnik

What is color?

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

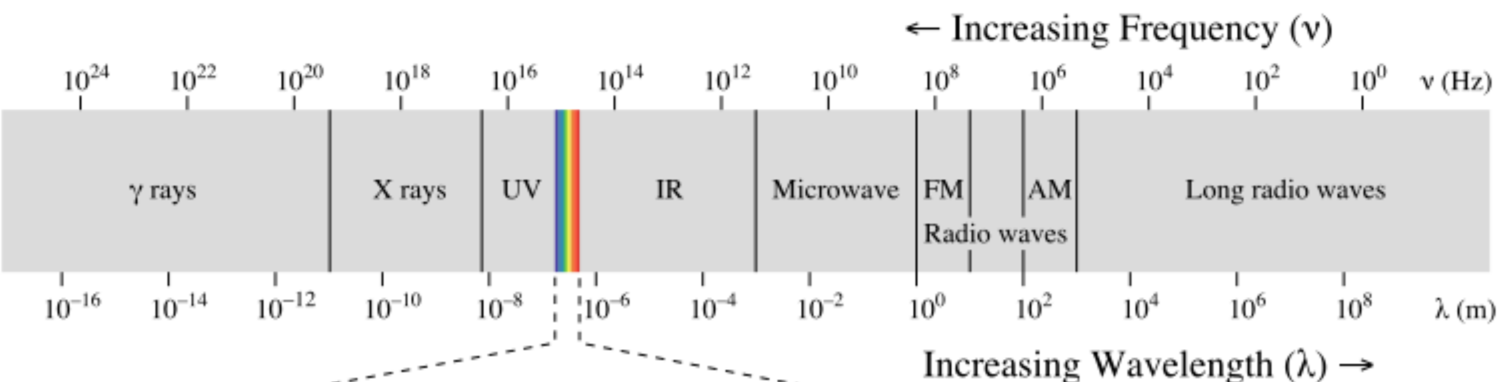


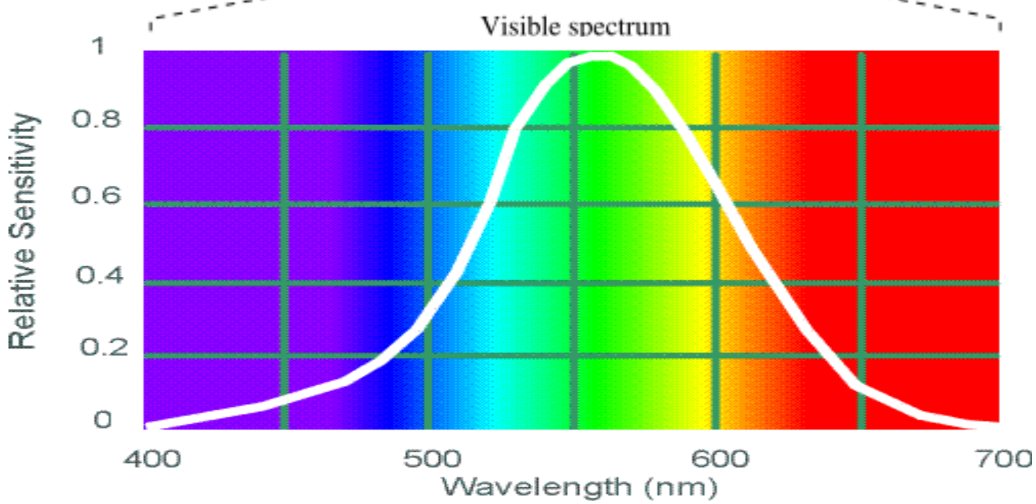
Slide by L. Lazebnik

Outline

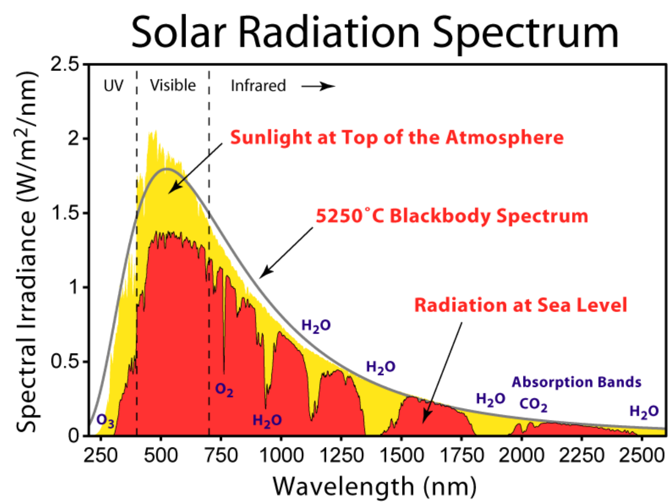
- Physical origin of color
- Spectra of sources and surfaces
- Physiology of color vision
- Trichromatic color theory
- Color spaces
- Color constancy, white balance

Electromagnetic spectrum



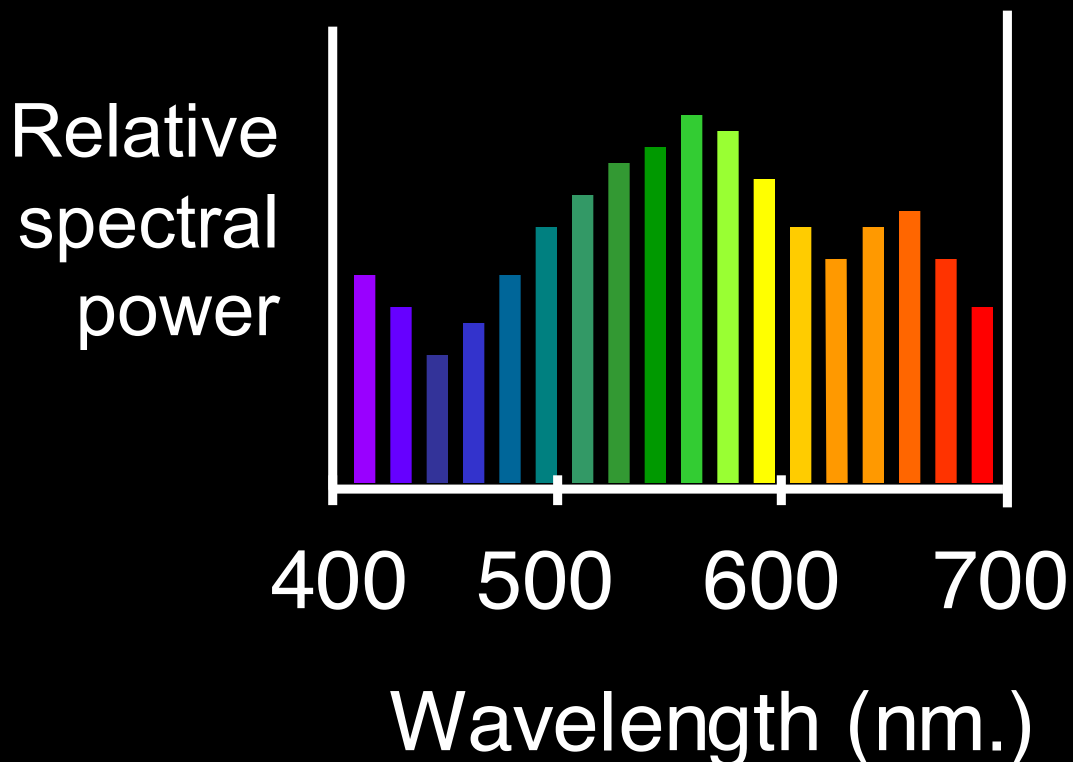


Human Luminance Sensitivity Function



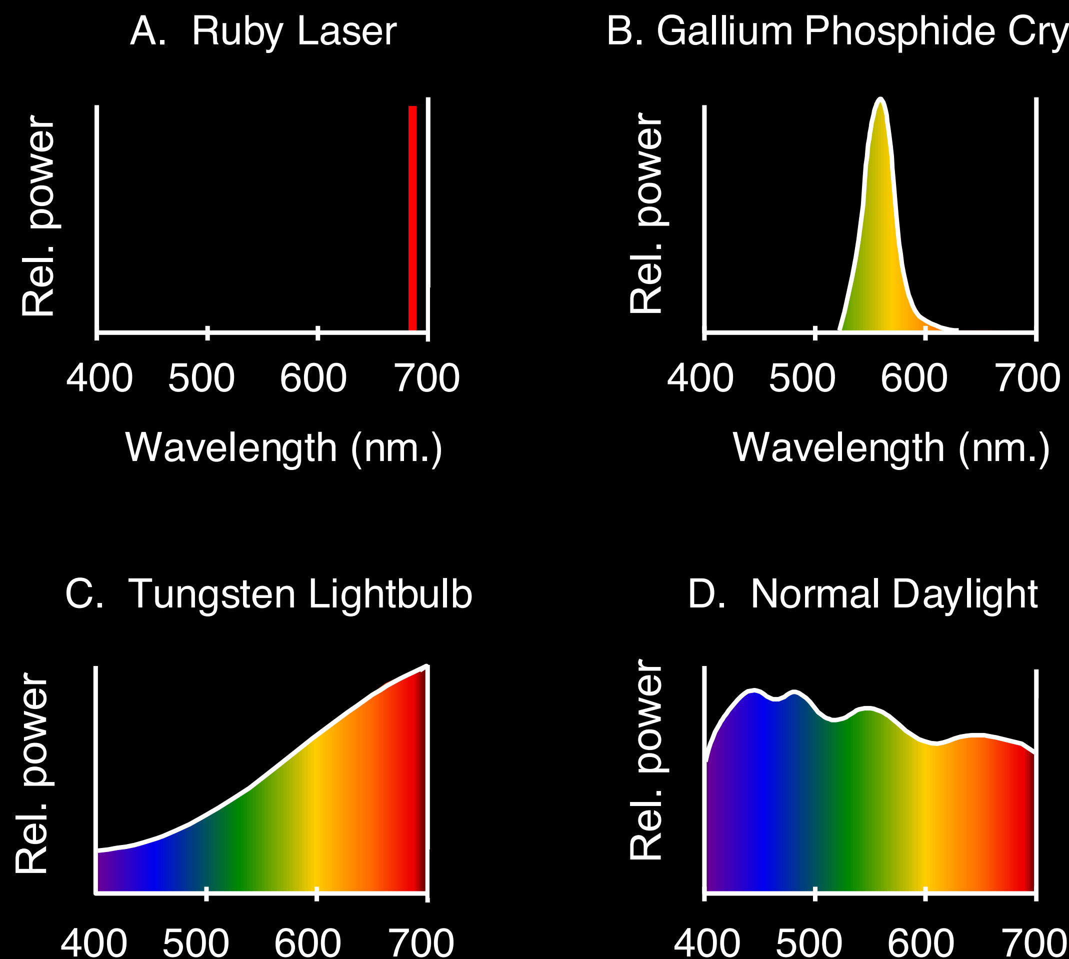
The Physics of Light

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.

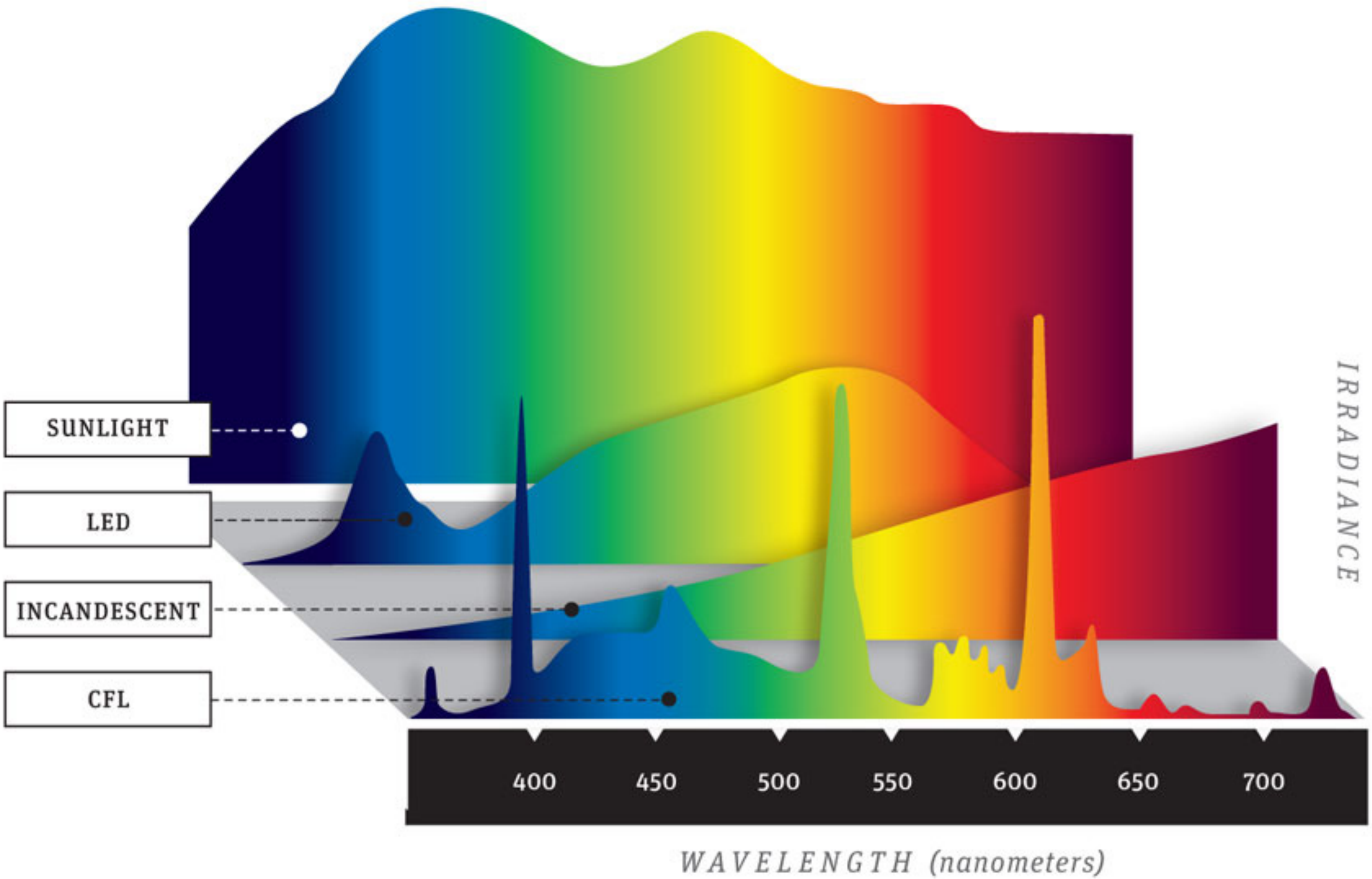


Spectra of Light Sources

Some examples of the spectra of light sources



Spectra of light sources

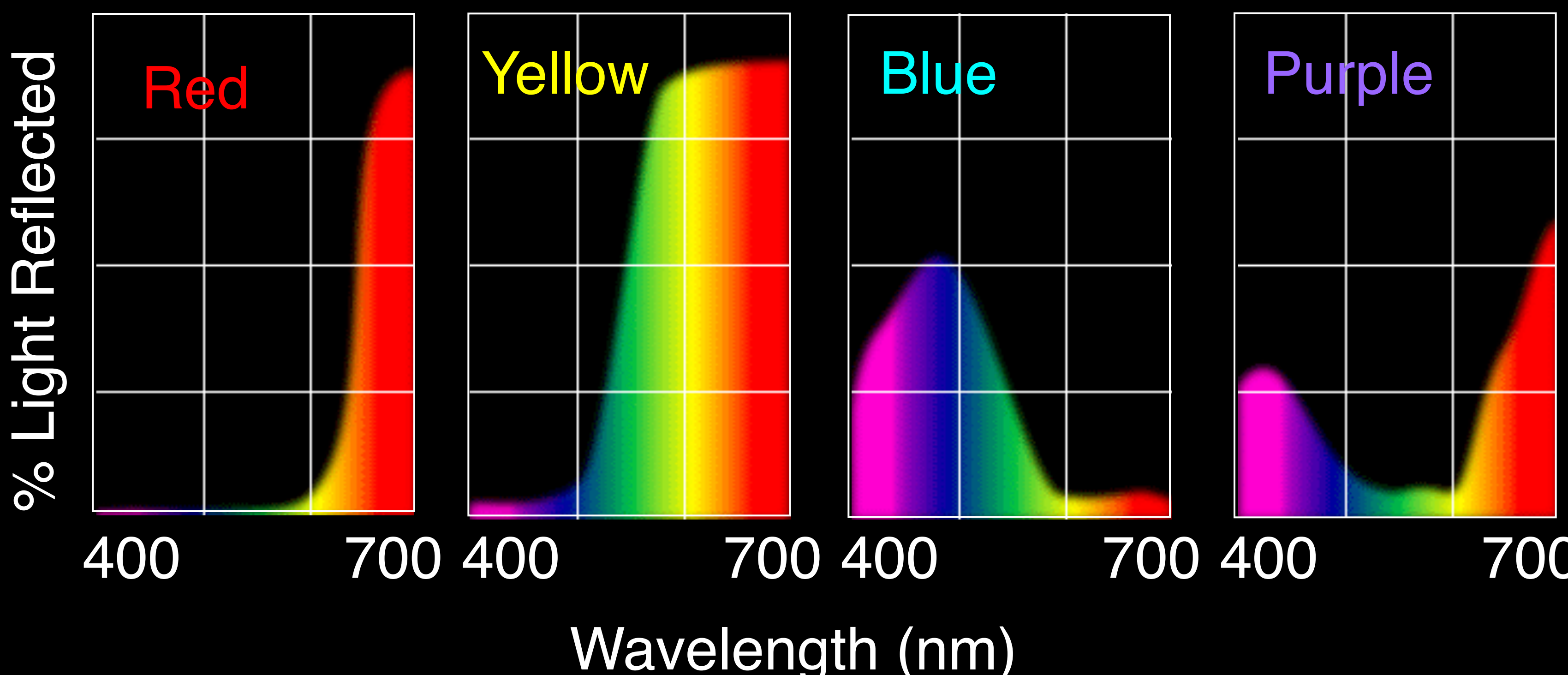


Source: Popular Mechanics

Slide by L. Lazebnik

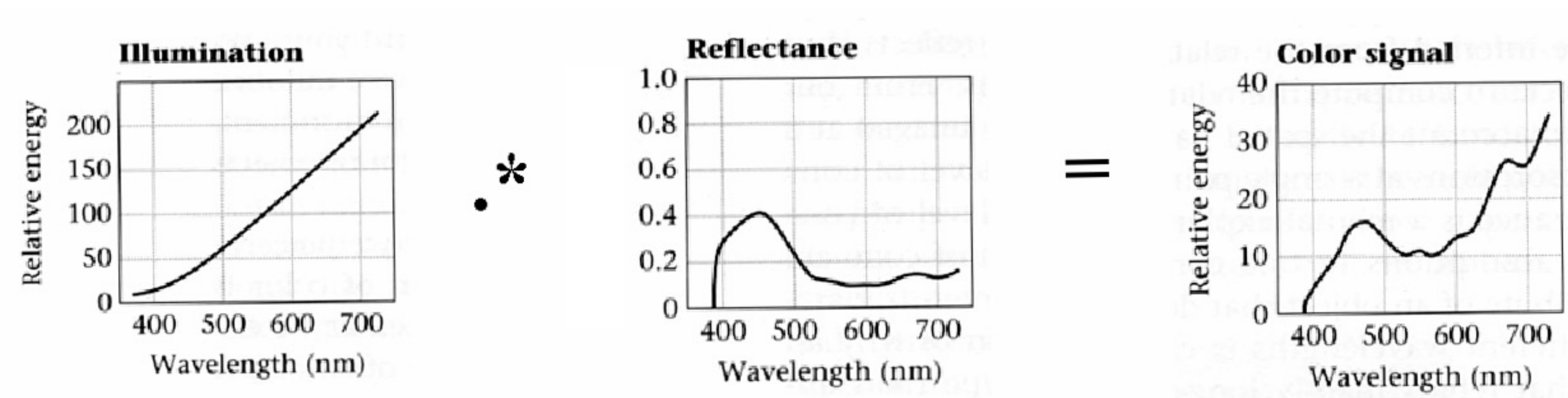
Reflectance Spectra of Surfaces

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



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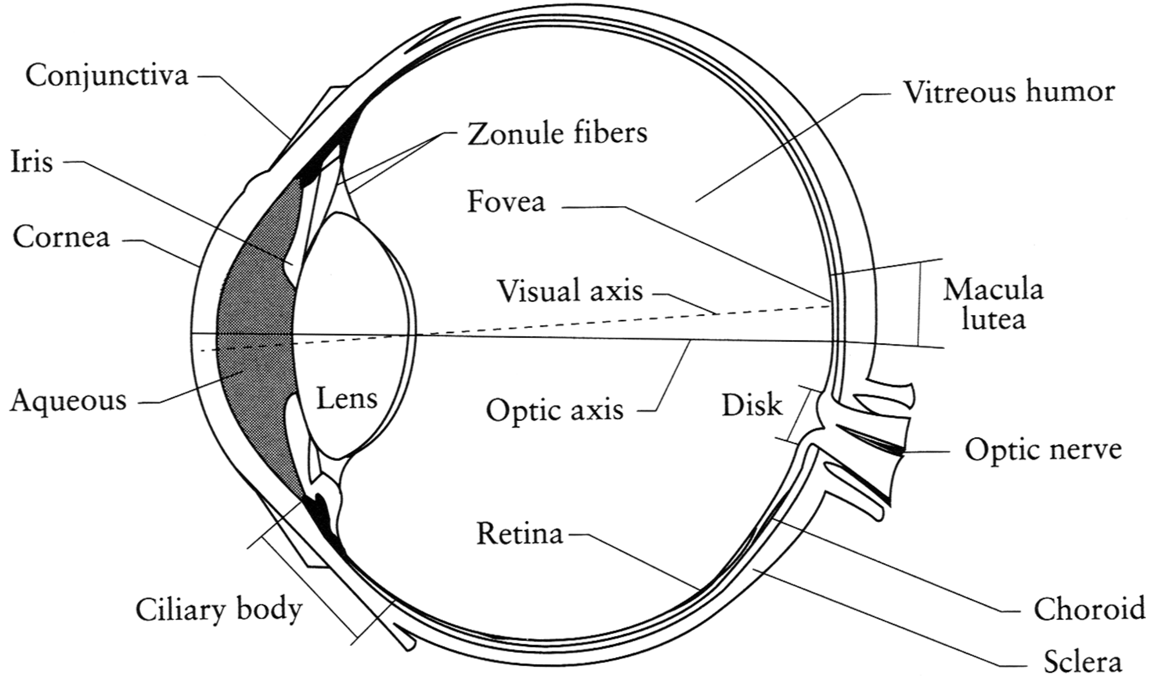
So, what is the dimensionality of color?

- A. 3
- B. (255)^3
- C. 255
- D. Infinite

The Eye

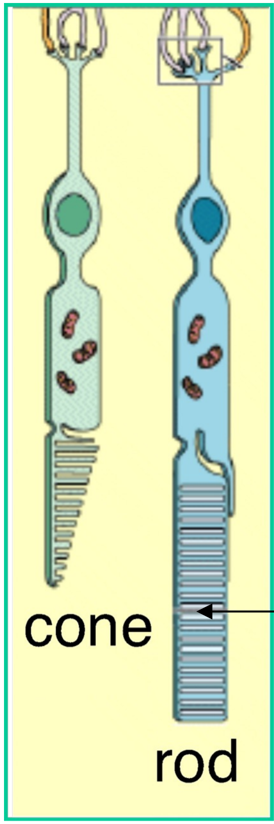


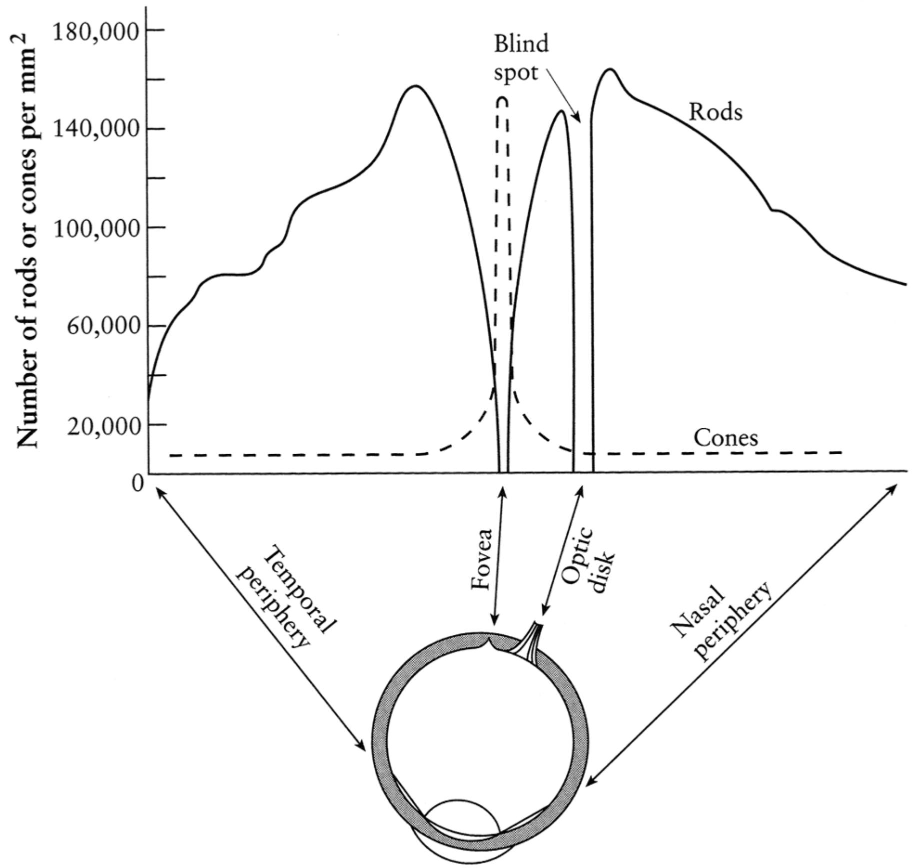
The human eye is a camera!

- **Lens** - changes shape by using ciliary muscles (to focus on objects at different distances)
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- **Iris** - colored annulus with radial muscles
- **Retina** - photoreceptor cells

Slide by Steve Seitz

Rods and cones, fovea





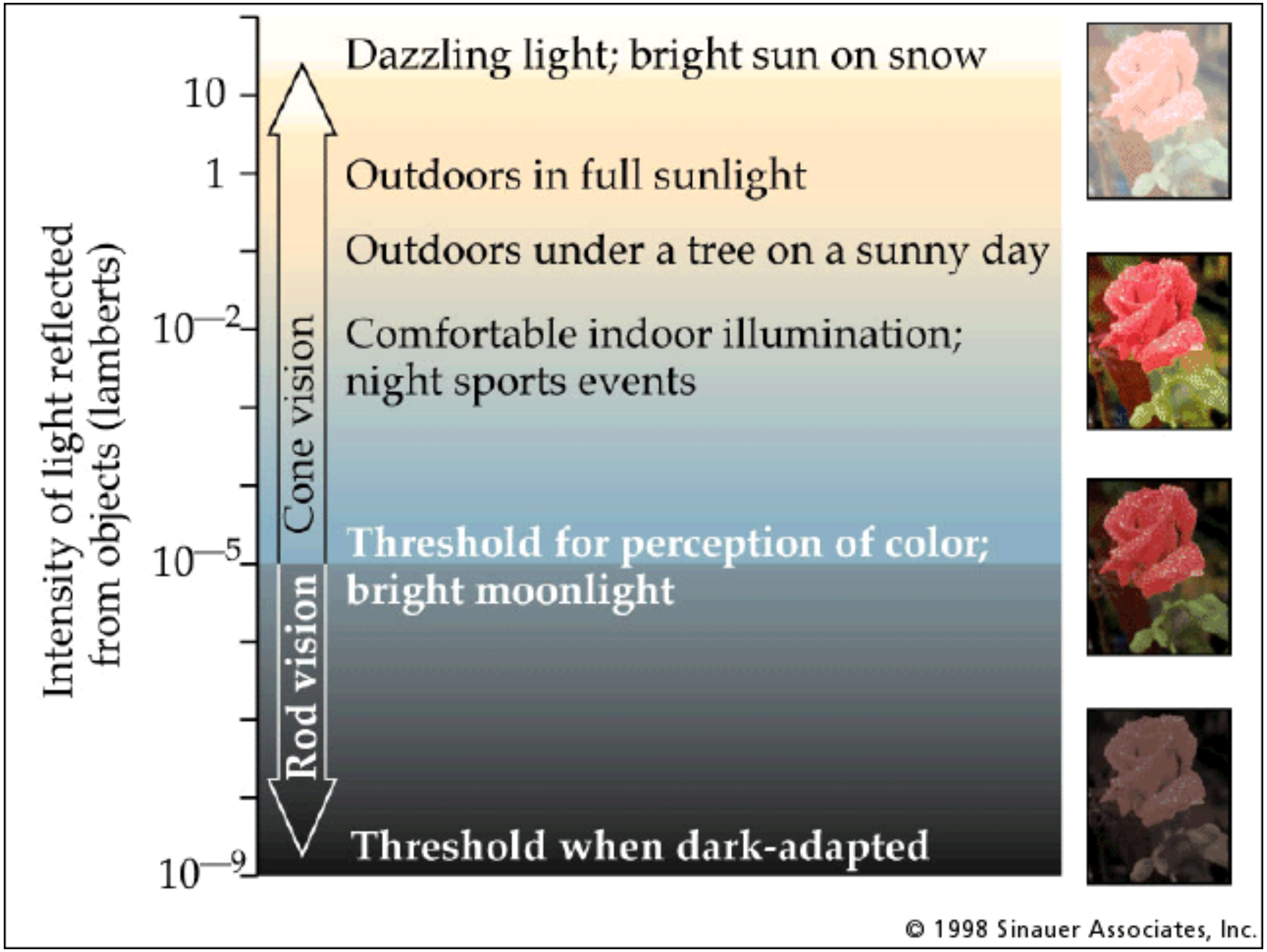
Rods are responsible for intensity, cones for color perception

Rods and cones are *non-uniformly* distributed on the retina

- **Fovea** - Small region (1 or 2°) at the center of the visual field containing the highest density of cones – *and no rods*

Slide by Steve Seitz

Rod / Cone sensitivity

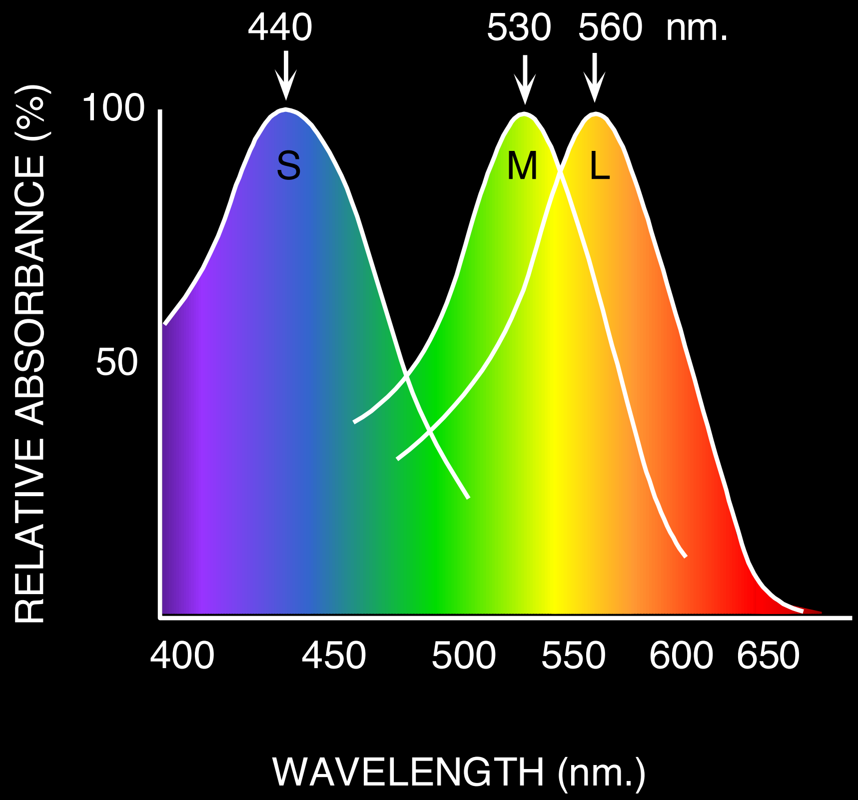


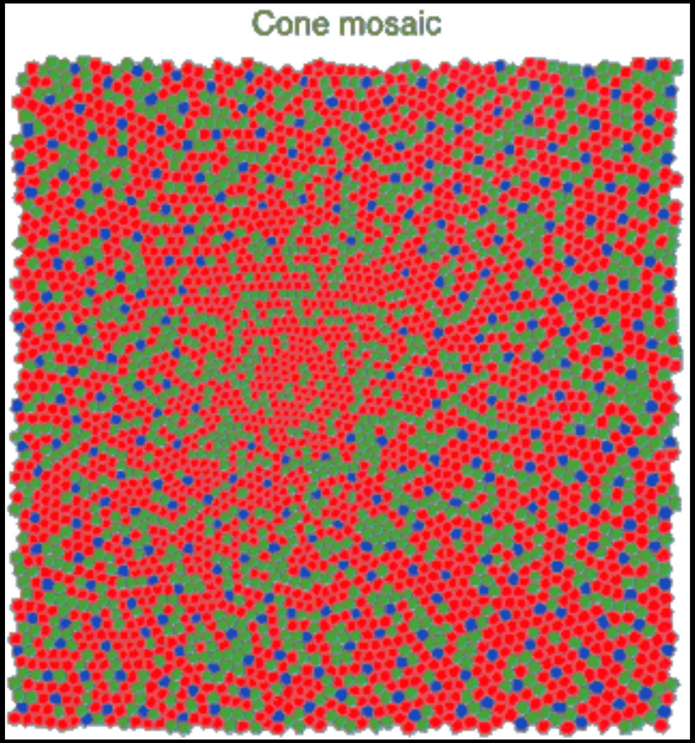
Why can't we read in the dark?

Slide by A. Efros

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

Physiology of Color Vision: Fun facts

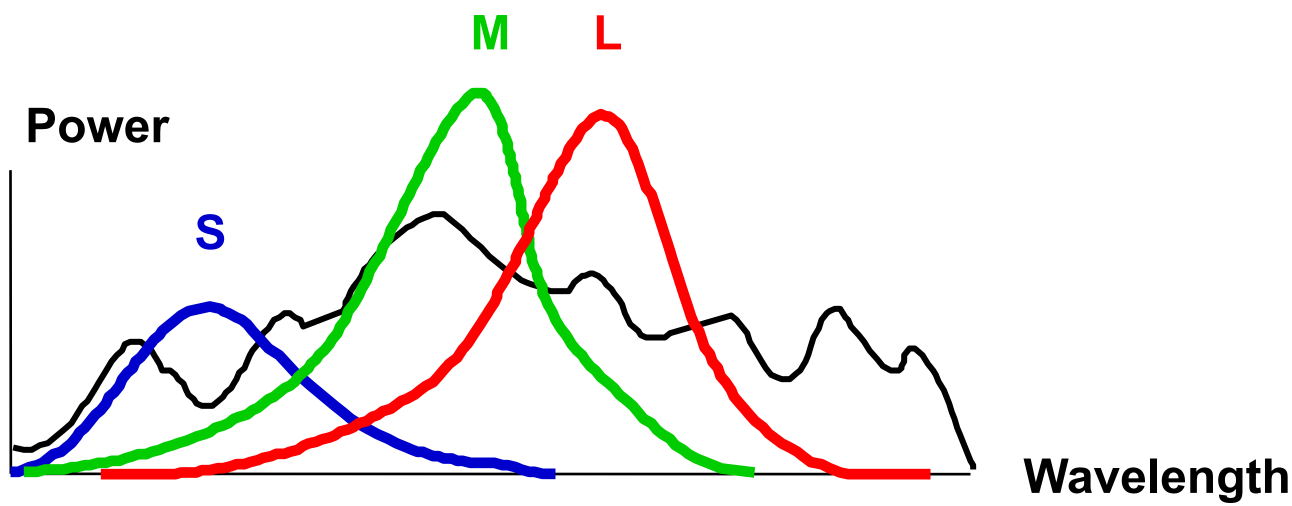
- “M” and “L” pigments are encoded on the X-chromosome
  - That’s why men are more likely to be color blind
  - “L” gene has high variation, so some women may be *tetrachromatic*
- Some animals have one (night animals), two (e.g., dogs), four (fish, birds), five (pigeons, some reptiles/amphibians), or even 12 (mantis shrimp) types of cones

http://ngm.nationalgeographic.com/2016/02/evolution-of-eyes-text

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

Slide by D. Hoiem

Color perception



Rods and cones act as *filters* on the spectrum

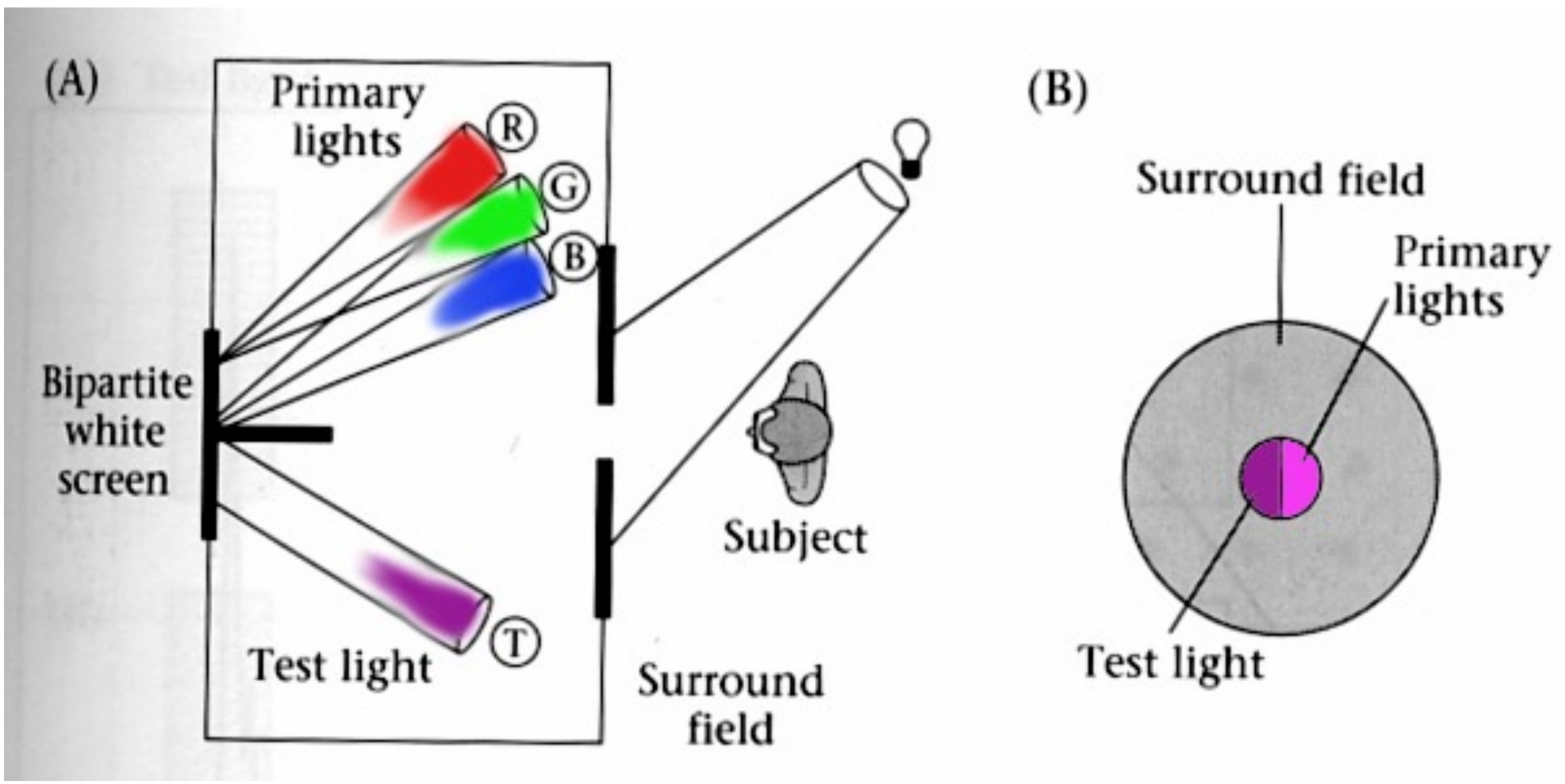
- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number

- How can we represent an entire spectrum with three numbers?
- 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

Color matching experiments

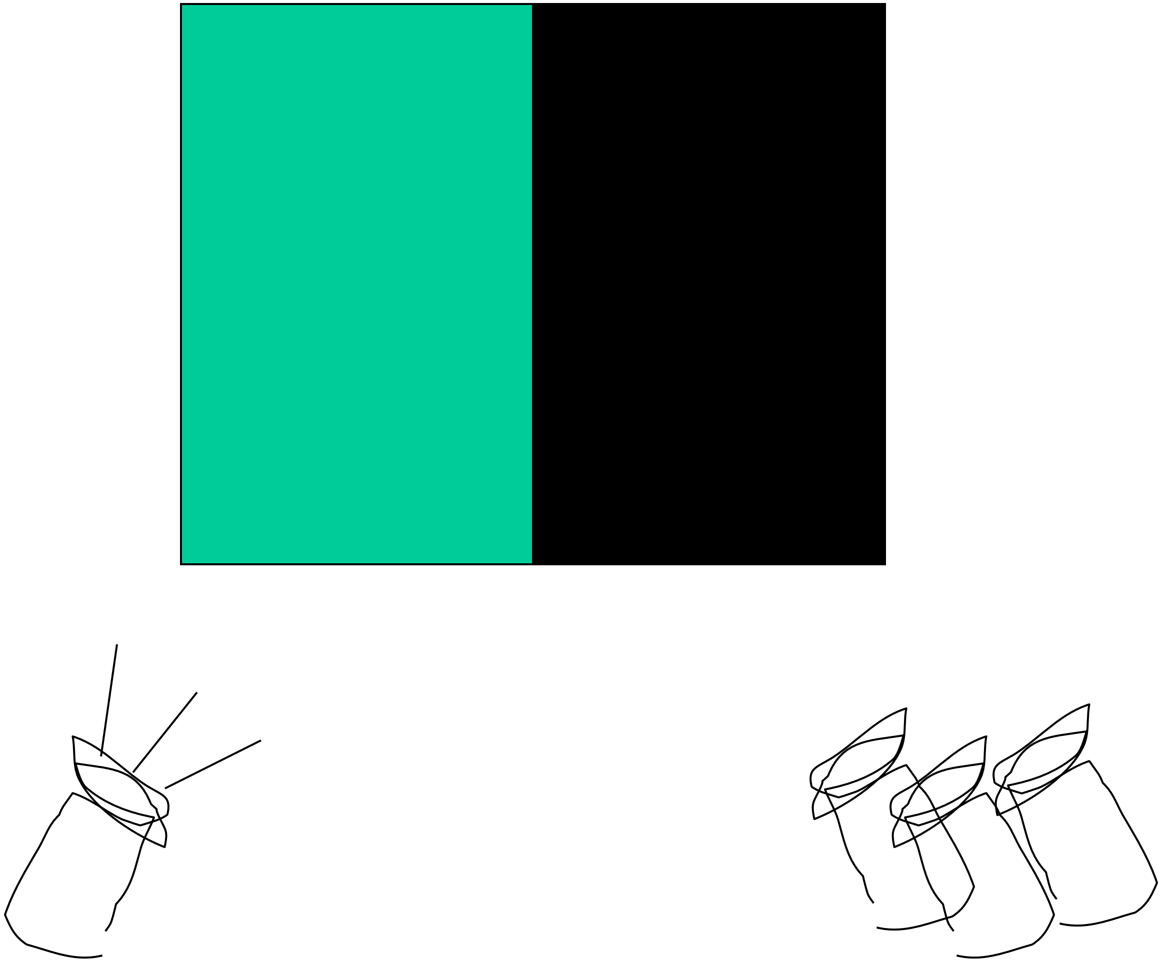
- We would like to understand which spectra produce the same color sensation in people under similar viewing conditions



Slide by L. Lazebnik

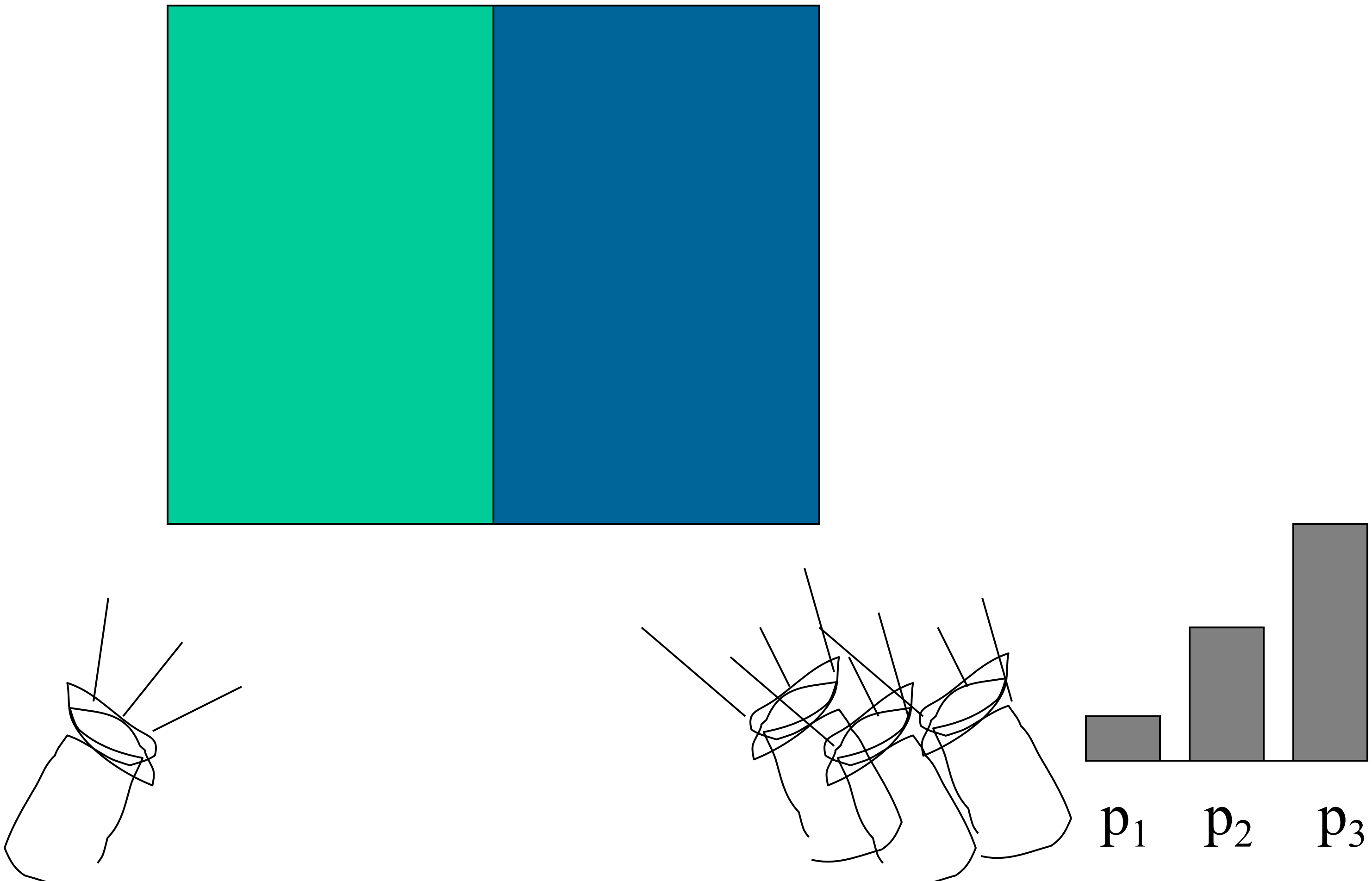
Wandell, Foundations of Vision, 1995

Color matching experiment 1



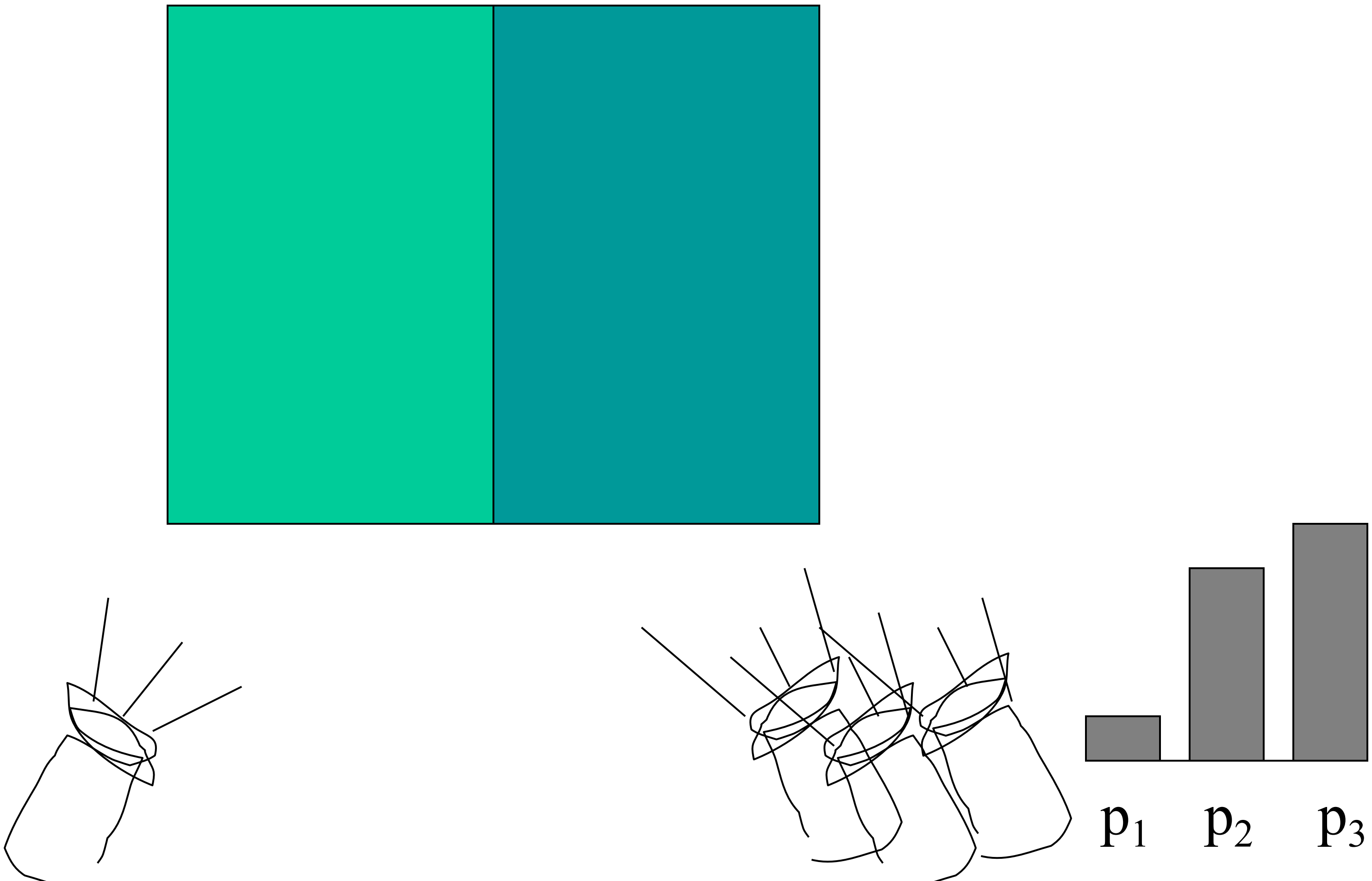
Source: W. Freeman

Color matching experiment 1



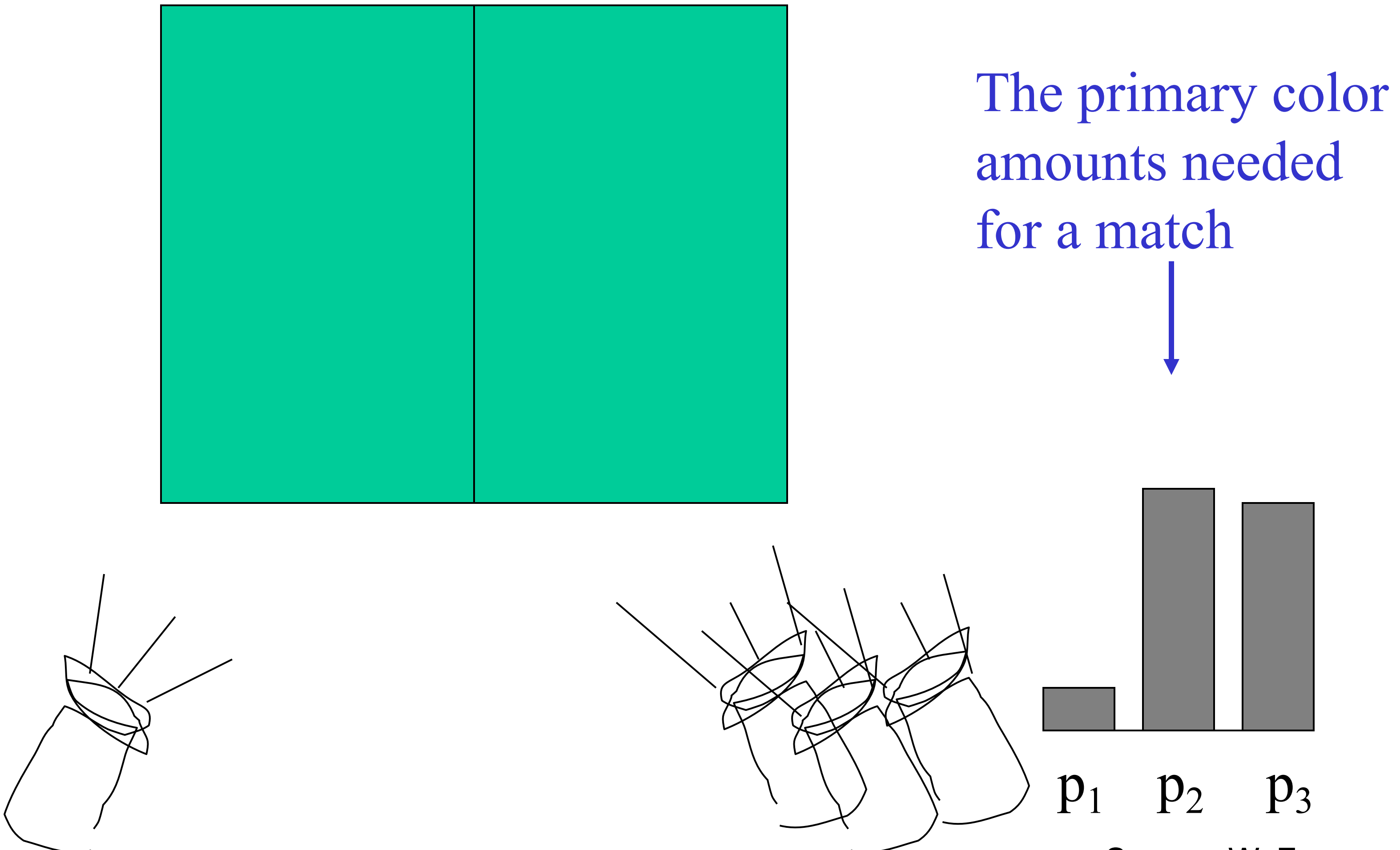
Source: W. Freeman

Color matching experiment 1



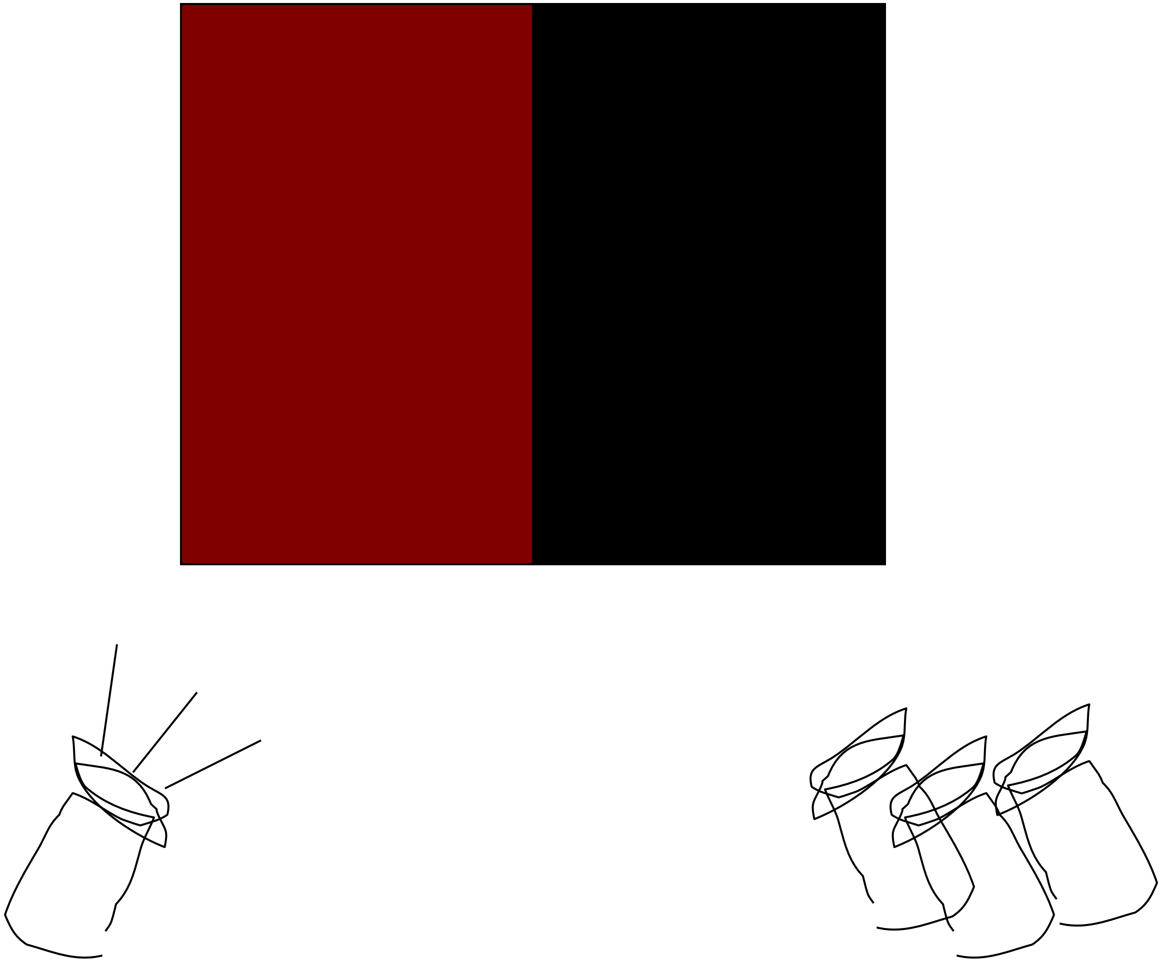
Source: W. Freeman

Color matching experiment 1



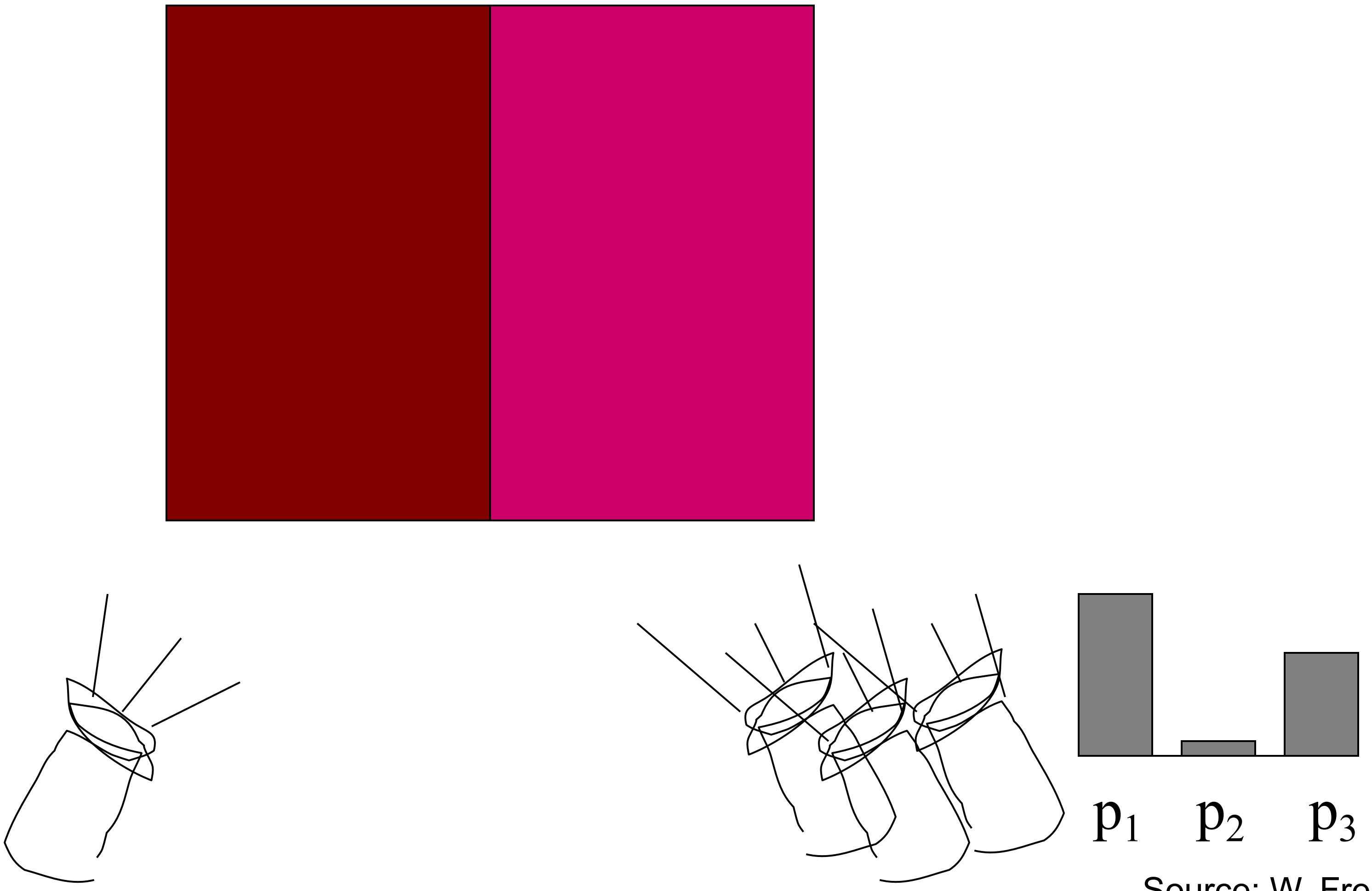
Source: W. Freeman

Color matching experiment 2



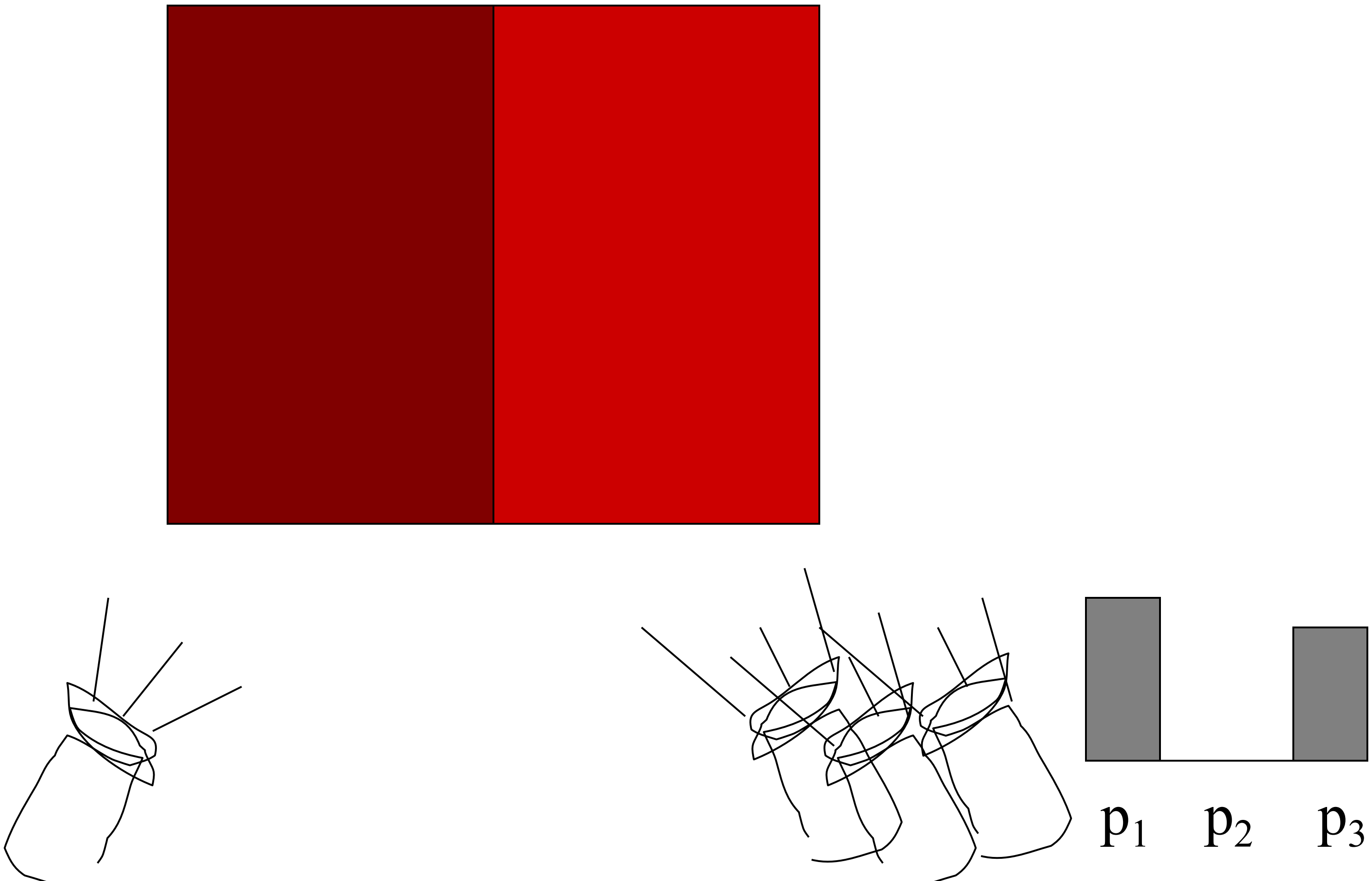
Source: W. Freeman

Color matching experiment 2



Source: W. Freeman

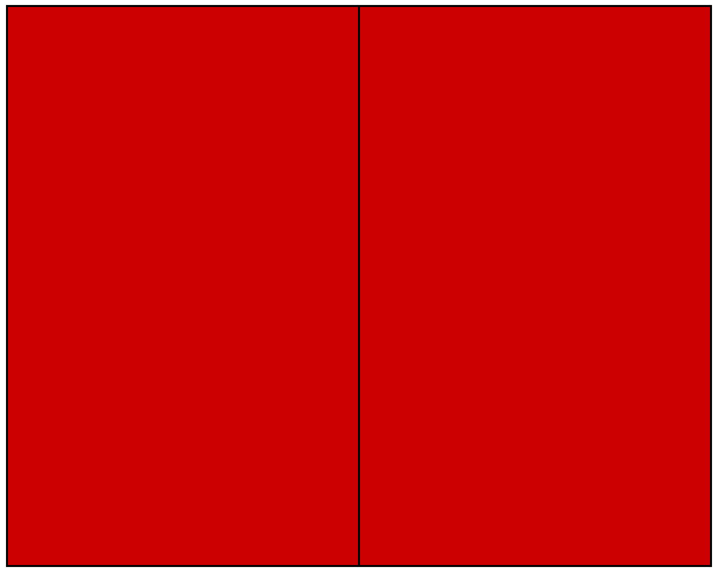
Color matching experiment 2



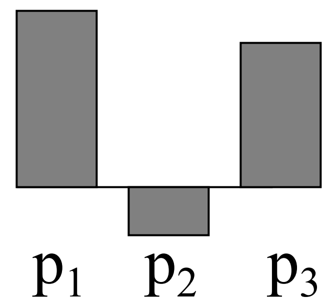
Source: W. Freeman

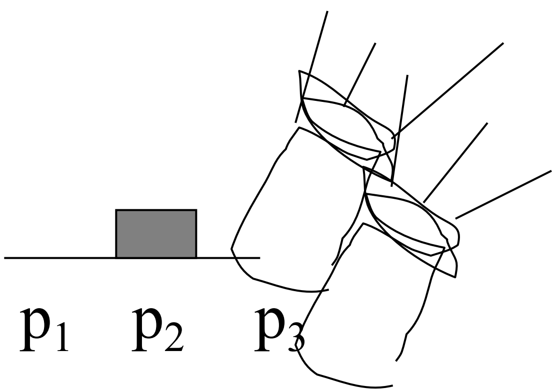
Color matching experiment 2

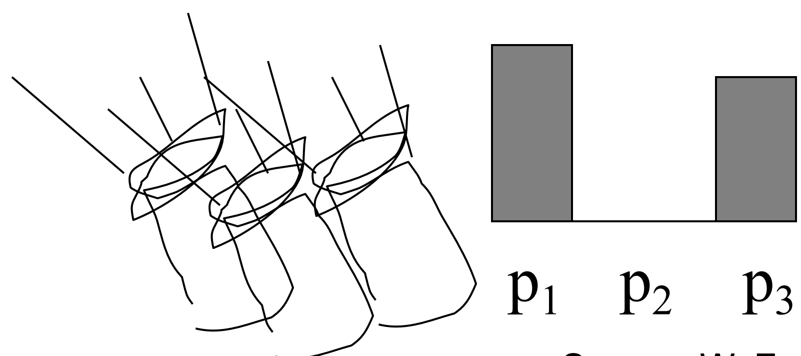
We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.



The primary color amounts needed for a match:







Source: W. Freeman

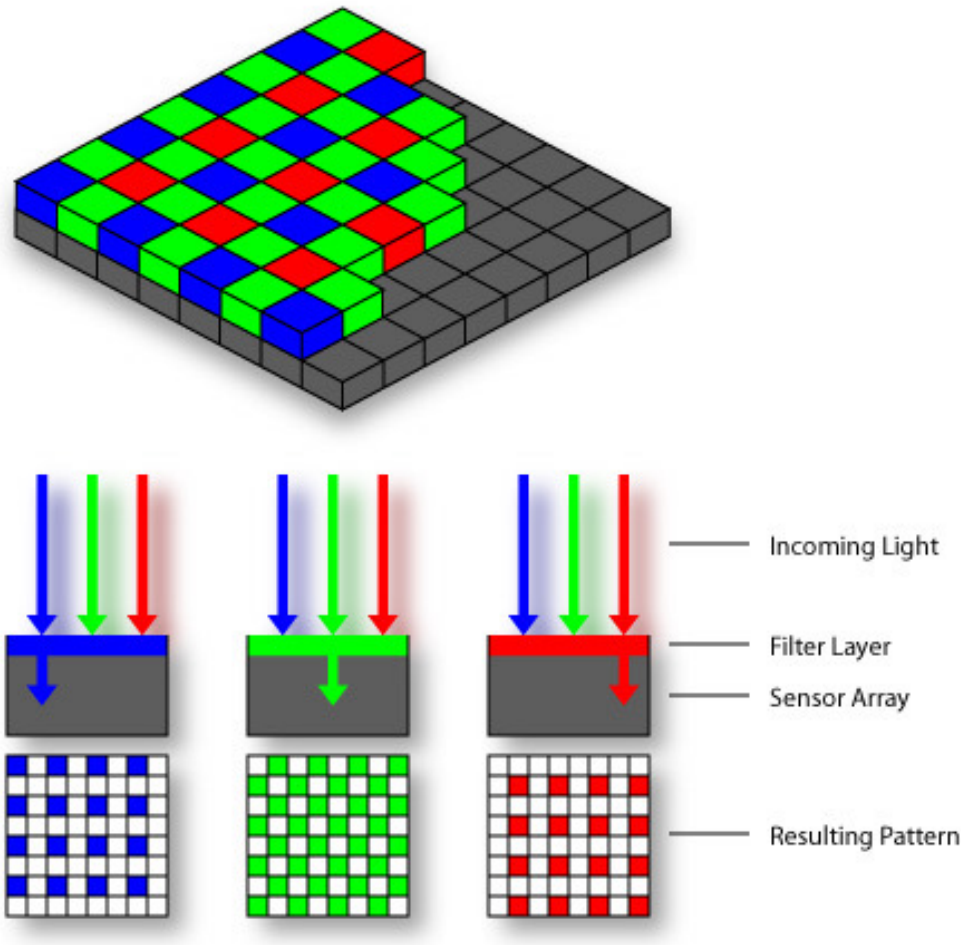
Trichromacy

- 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)

https://en.wikipedia.org/wiki/Young_Helmholtz_theory

Slide by L. Lazebnik

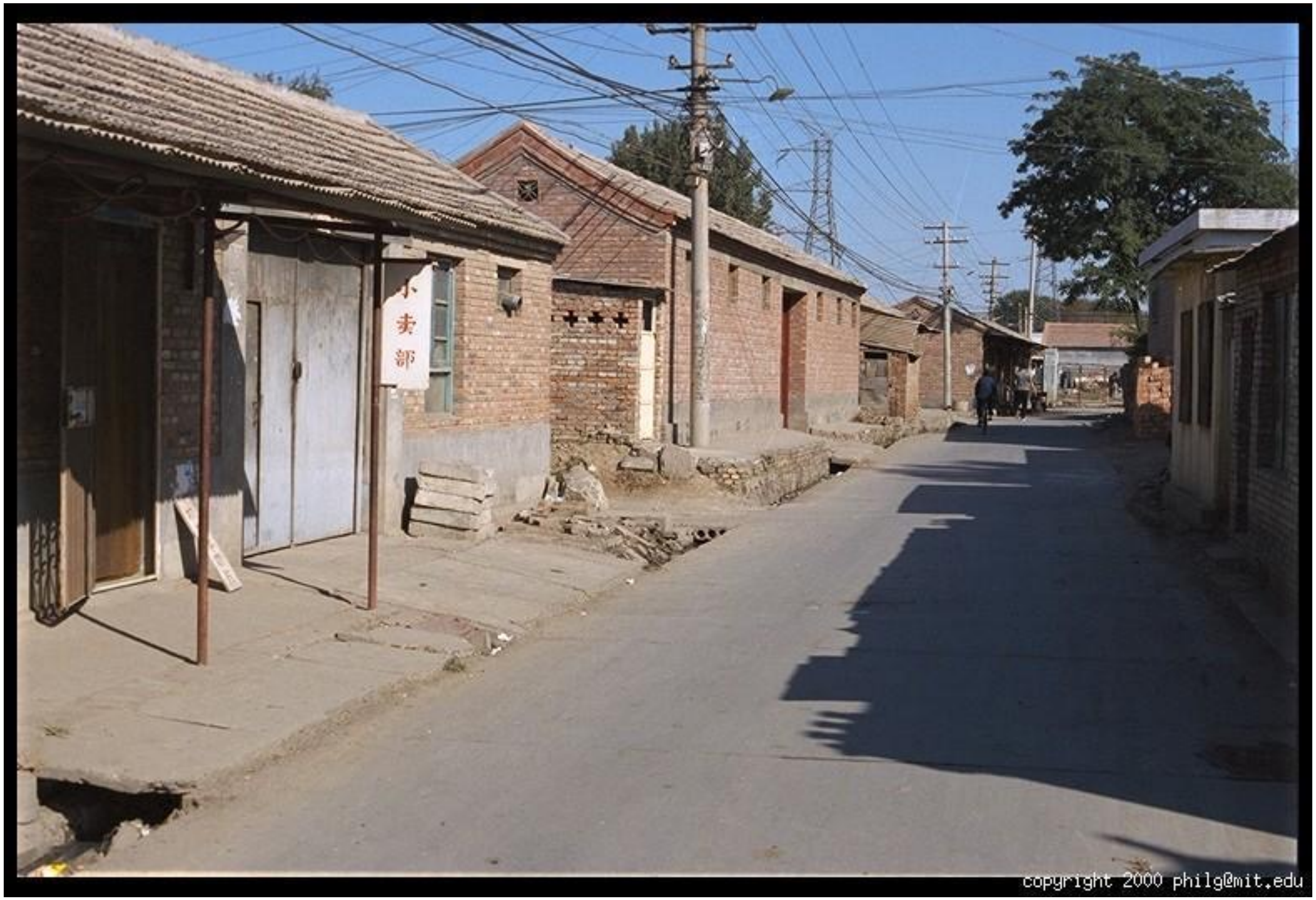
Artificial Cones



Estimate RGB at ‘G’ cells from neighboring values.

Slide by Steve Seitz

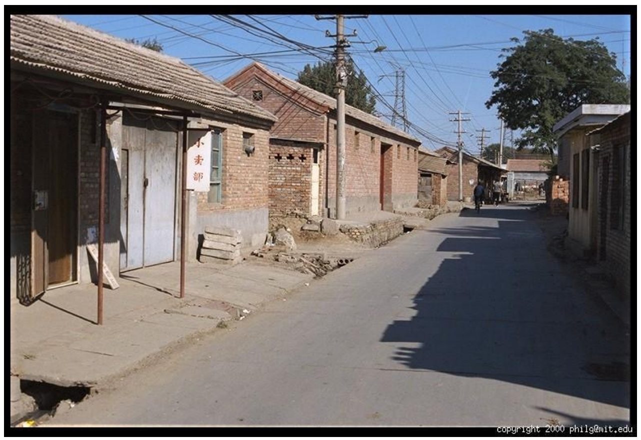
Color Image



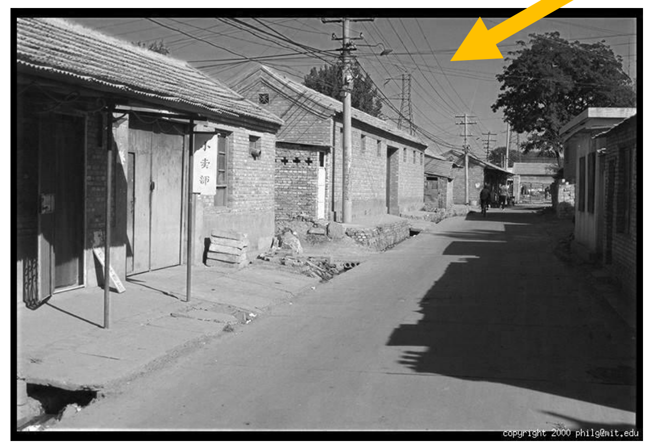
Slide Credit: J. Hays

Color Image

Combined



Red



Green

Blue

Slide Credit: J. Hays

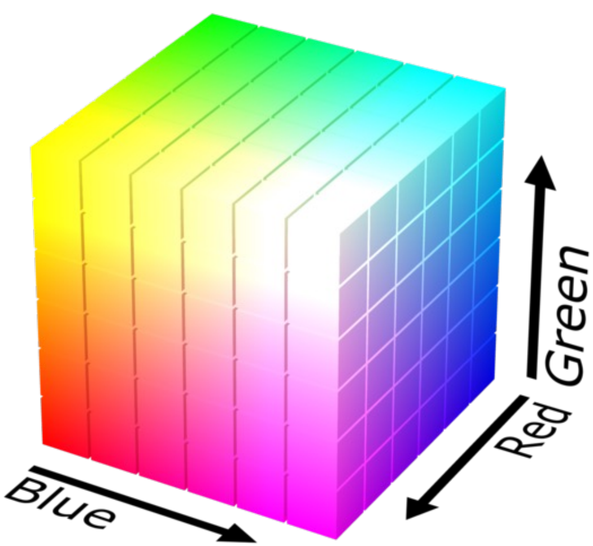
One Option: RGB

<u>Pros</u>

1. Simple
2. Common

<u>Cons</u>

1. Distances don't make sense
2. Correlated



Slide Credit: J. Hays, RGB cube: https://en.wikipedia.org/wiki/RGB_color_model

RGB

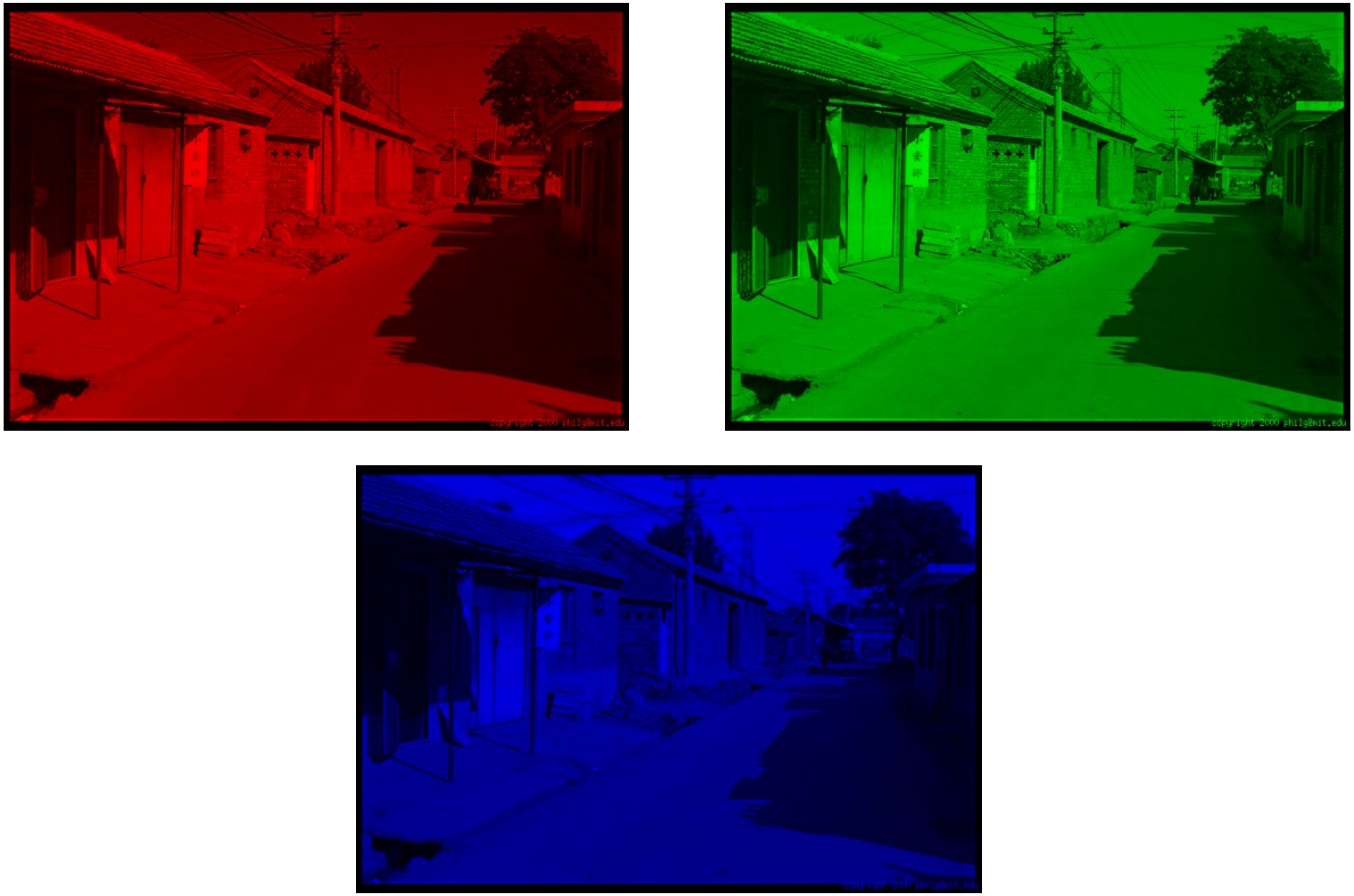


Photo credit: J. Hays

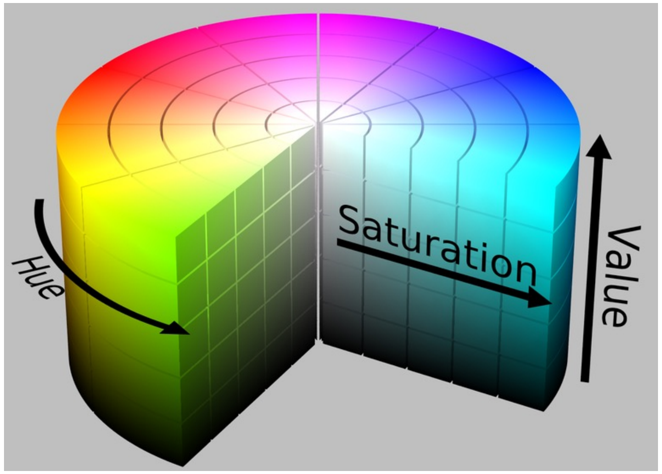
Another Option: HSV

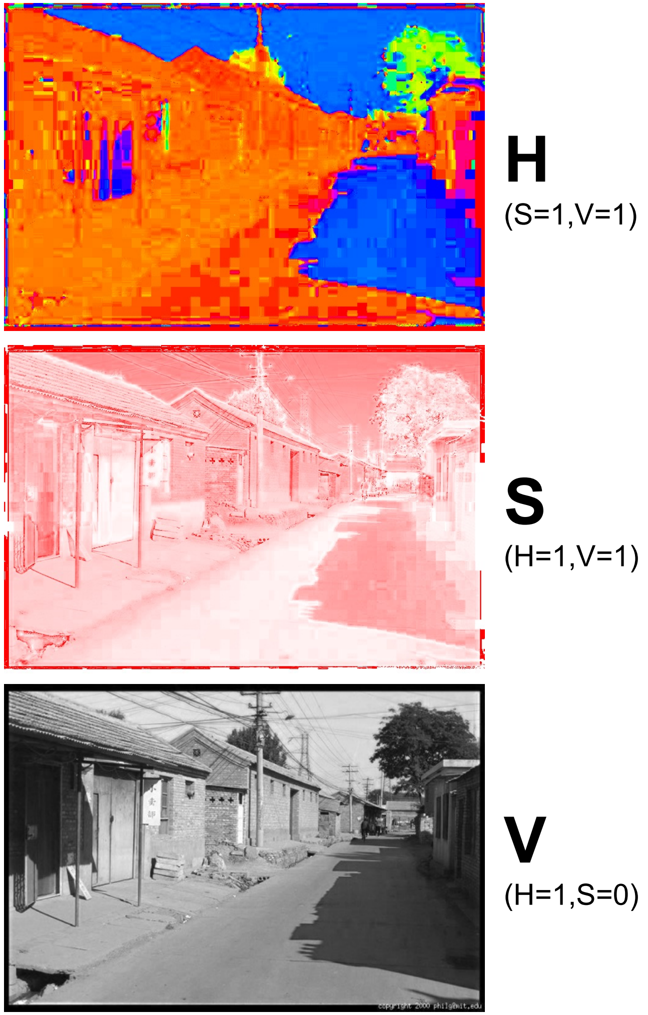
Pros

1. Intuitive for picking colors
2. Sort of common
3. Fast to convert

Cons

1. Not as perceptual





Slide Credit: J. Hays, HSV cylinder: https://en.wikipedia.org/wiki/HSL_and_HSV

HSV

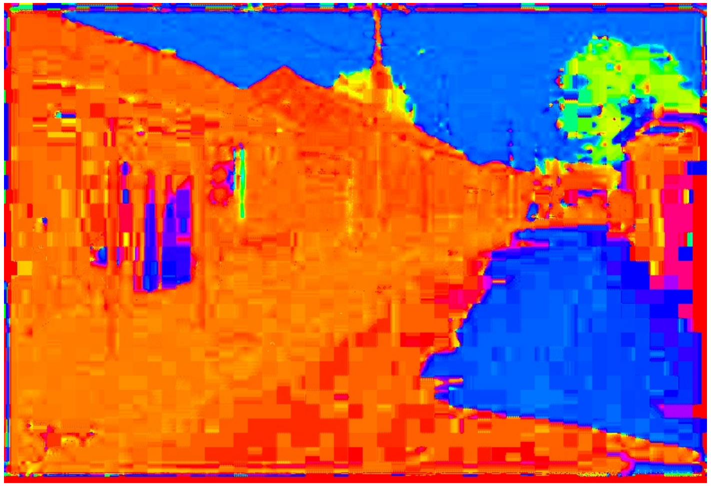


Photo credit: J. Hays

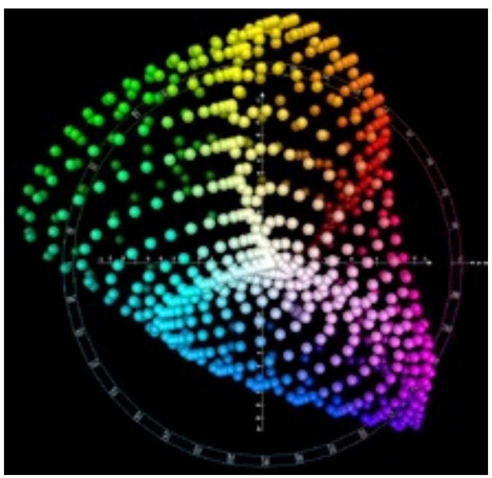
Another Option: Lab

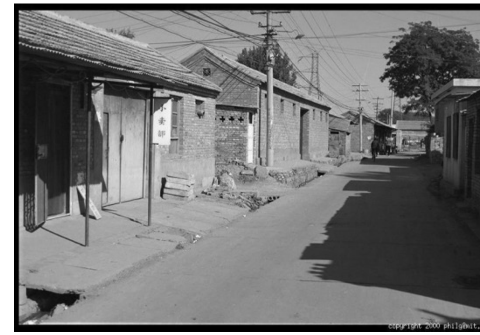
<u>Pros</u>

1. Distances correspond with human judgment

<u>Cons</u>

1. Complex to calculate





L
(a=0,b=0)

a
(L=65,b=0)

b
(L=65,a=0)

Slide Credit: J. Hays, Lab diagram cube: https://en.wikipedia.org/wiki/CIELAB_color_space

Lab

Photo credit: J. Hays

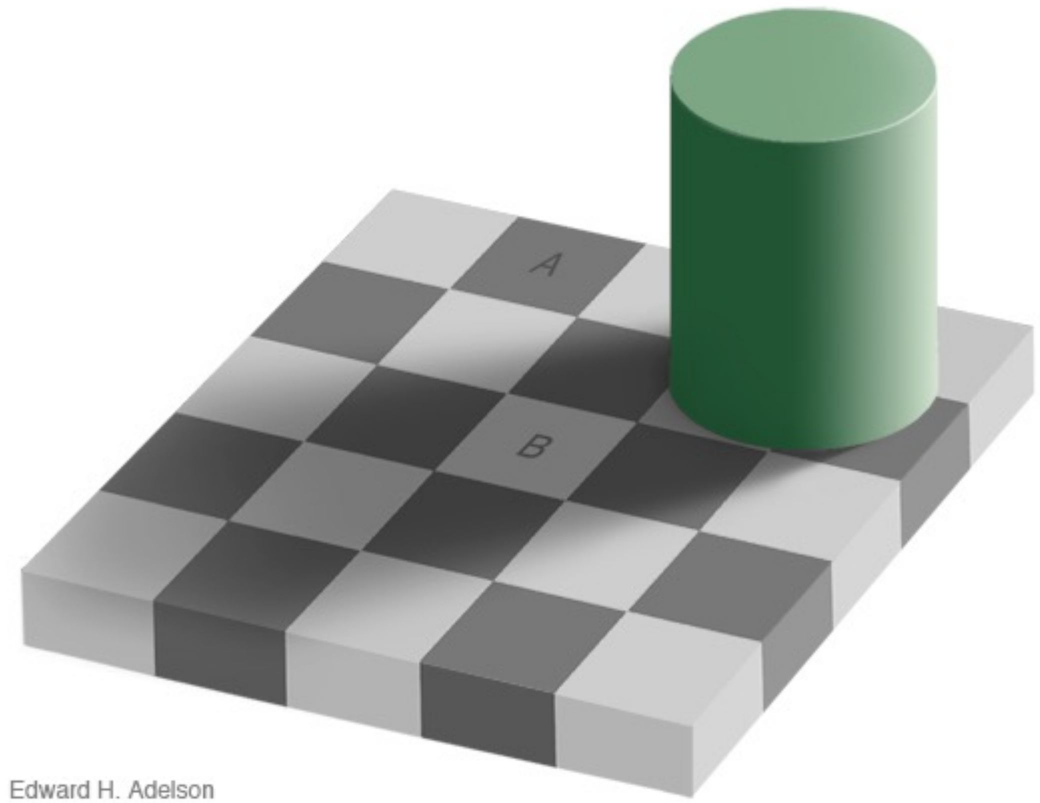
Why Are There So Many?

- Each serves different functions
  - RGB: sort of intuitive, standard, everywhere
  - HSV: good for picking, fast to compute
  - YCbCr/YUV: fast to compute, compresses well
  - Lab: the right(?) thing to do, but “slow” to compute
- Pick based on what you need and don’t sweat it: color really isn’t crucial

Color perception

- Color/lightness constancy
  - The ability of the human visual system to perceive the intrinsic reflectance properties of the surfaces despite changes in illumination conditions

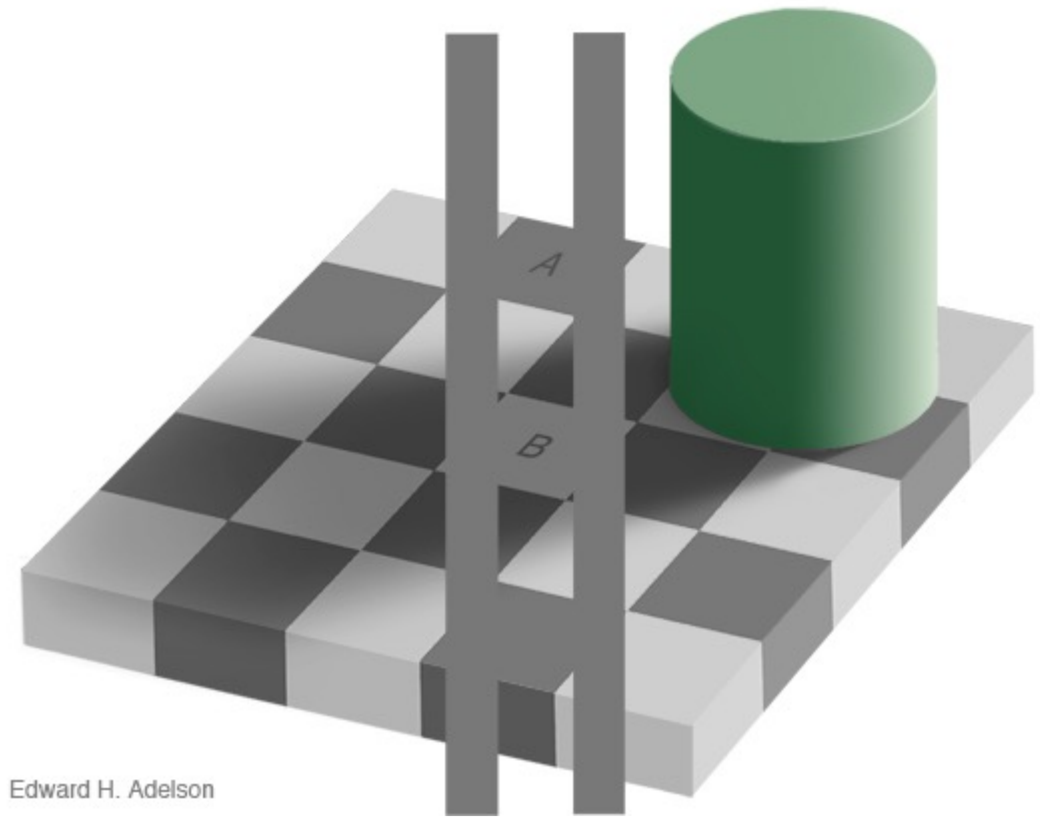
Checker shadow illusion



https://en.wikipedia.org/wiki/Checker_shadow_illusion

Slide by L. Lazebnik

Checker shadow illusion



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

https://en.wikipedia.org/wiki/Checker_shadow_illusion

Slide by L. Lazebnik

What color is the dress?

https://www.wired.com/2015/02/science-one-agrees-color-dress/

Slide by L. Lazebnik

This strawberry cake has no red pixels!

https://www.digitaltrends.com/photography/non-red-strawberries/

White balance

- Analogous to color constancy mechanisms in human vision, cameras have mechanisms to adapt to the illumination in the environment so that neutral (white or gray) objects look neutral

Incorrect white balance

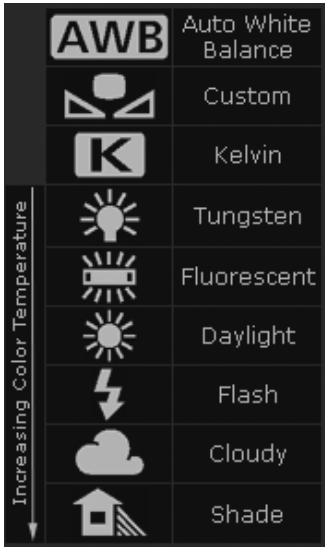
Correct white balance

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

Slide by L. Lazebnik

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 by L. Lazebnik

White balance

- Von Kries adaptation: Multiply each channel by a *gain factor*

- Best way: gray card
  - Take a picture of a neutral object (white or gray)
  - If the object is recorded as r_w, g_w, b_w use weights $1/r_w$, $1/g_w$, $1/b_w$

Slide by L. Lazebnik

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
  - 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 by L. Lazebnik

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

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