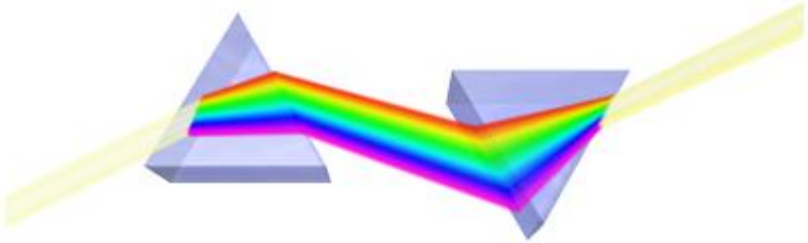
Computer Vision

Lihi Zelnik-Manor

lihi@ee.technion.ac.il

Color



Color

Readings:

- Forsyth and Ponce, Chapter 6
- Szeliski, 2.3.2

Slide Credits

- Trevor Darrell
- Kristen Grauman: 3-48, 50-75, 79-86
- Bob Woodham: 49, 87-90
- and others, indirectly (Steve Palmer, Brian Wandell, etc!)

Today: Color

- Measuring color
  - Spectral power distributions
  - Color mixing
  - Color matching experiments
  - Color spaces
    - Uniform color spaces
- Perception of color
  - Human photoreceptors
  - Environmental effects, adaptation
- Using color in machine vision systems

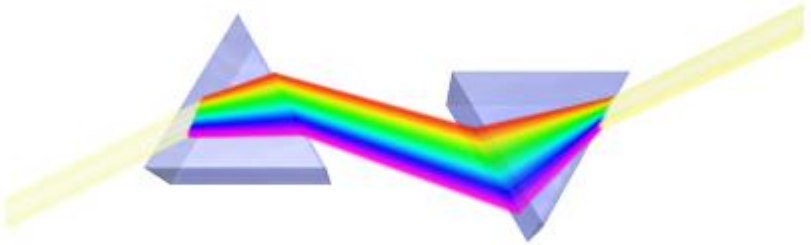
Color and light

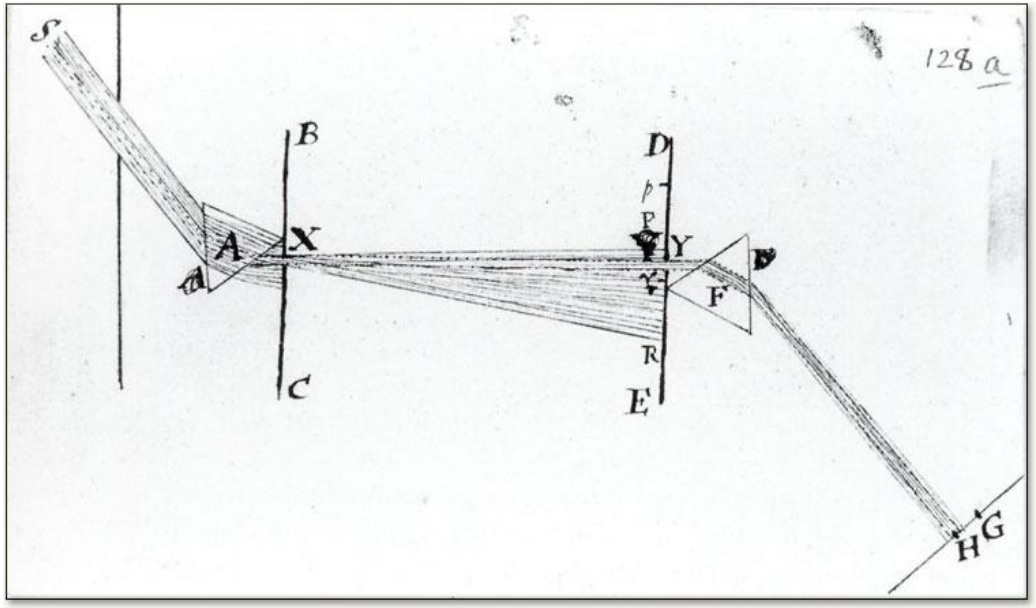
- **Color of light** arriving at camera depends on
  - Spectral reflectance of the surface light is leaving
  - Spectral radiance of light falling on that patch

- **Color perceived** depends on
  - Physics of light
  - Visual system receptors
  - Brain processing, environment

Color and light

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

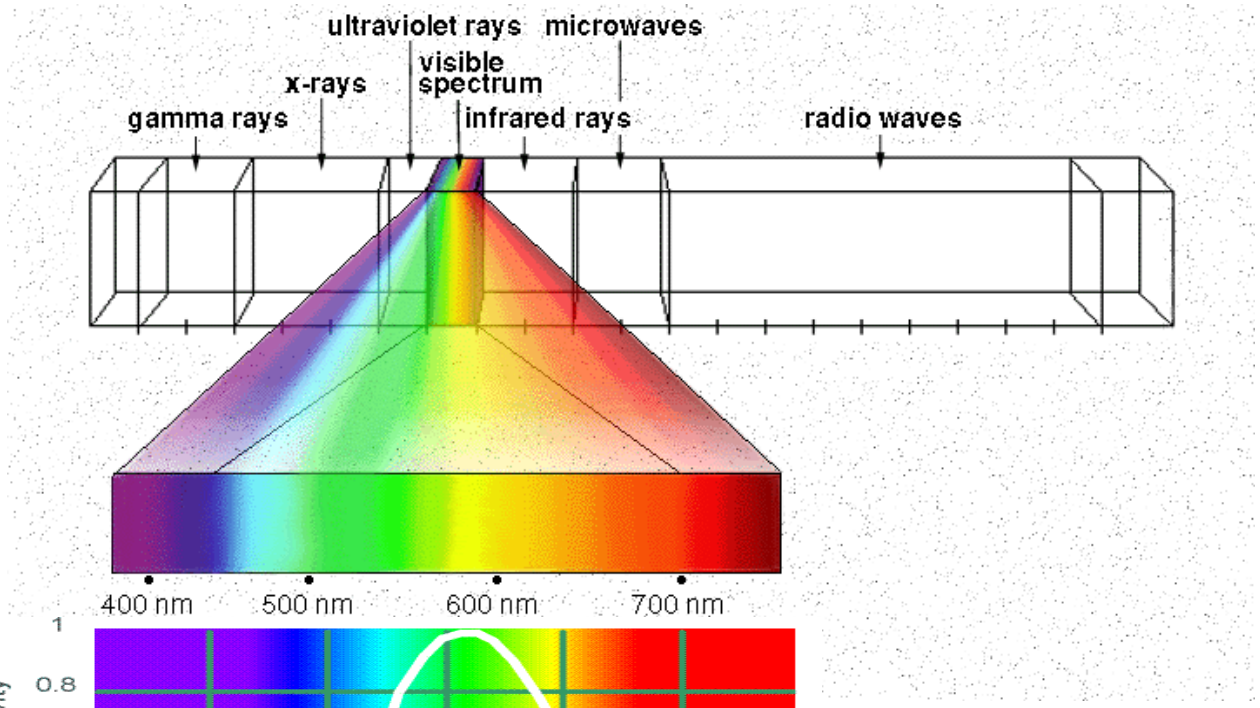


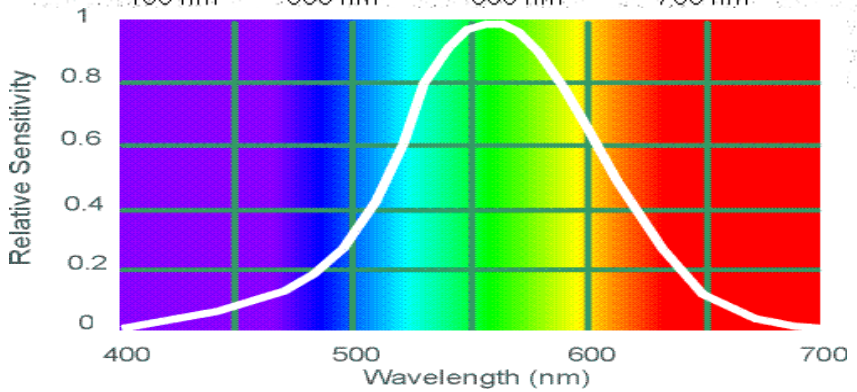


Newton 1665

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

Electromagnetic spectrum

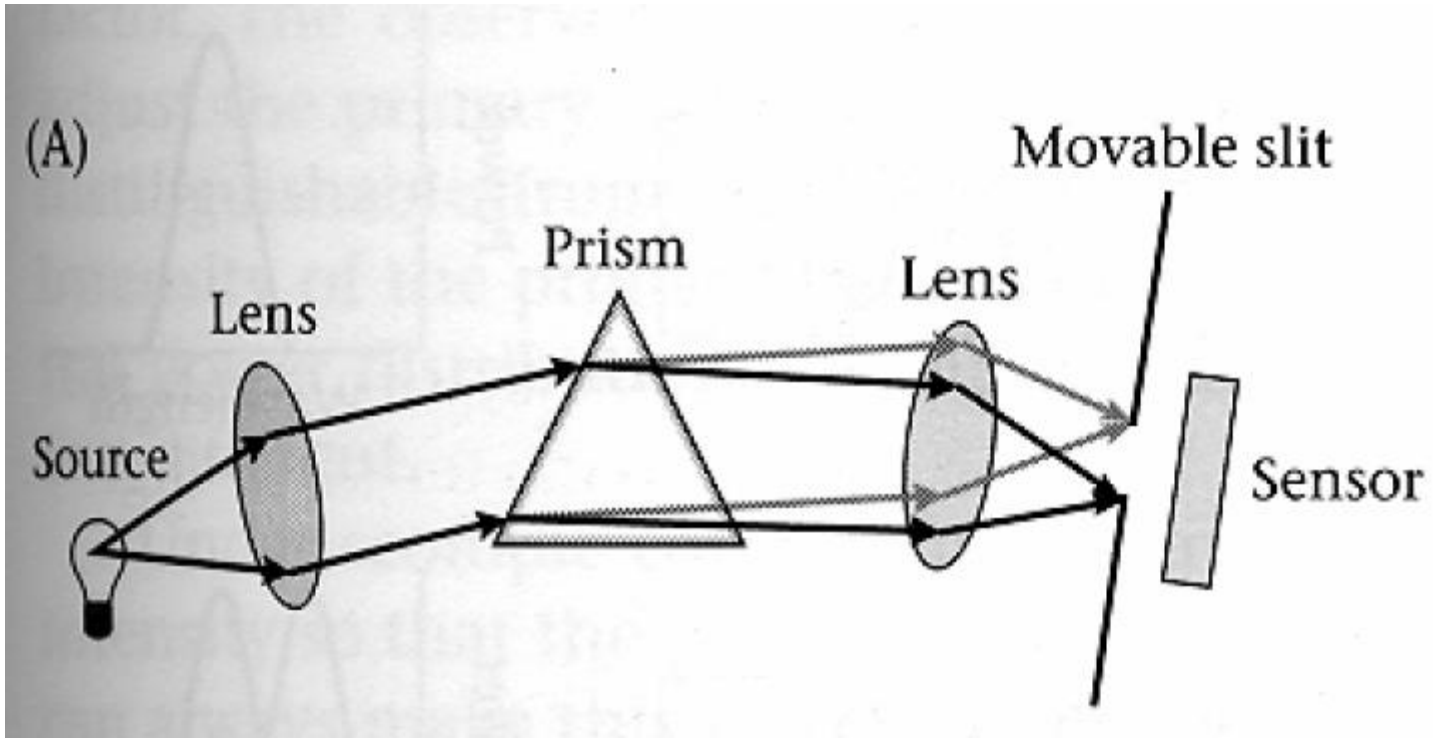




Human Luminance Sensitivity Function

Image credit: nasa.gov

Measuring spectra

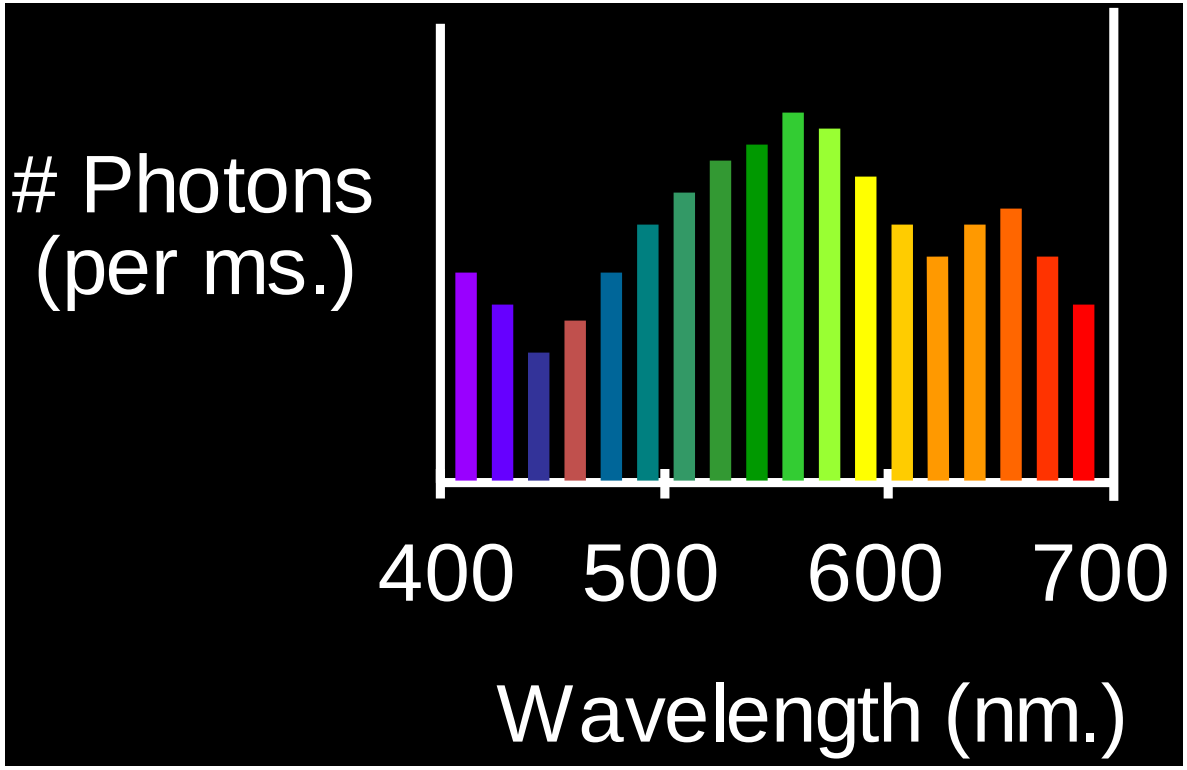


Spectroradiometer: separate input light into its different wavelengths, and measure the energy at each.

Foundations of Vision, B. Wandell

Spectral power distribution

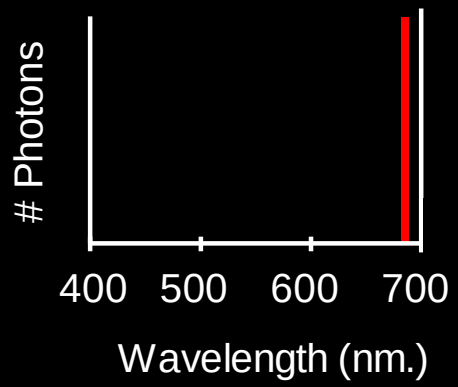
- The power per unit area at each wavelength of a radiant object



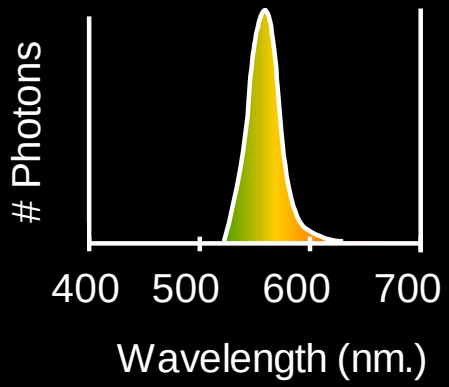
Spectral power distributions

Some examples of the spectra of light sources

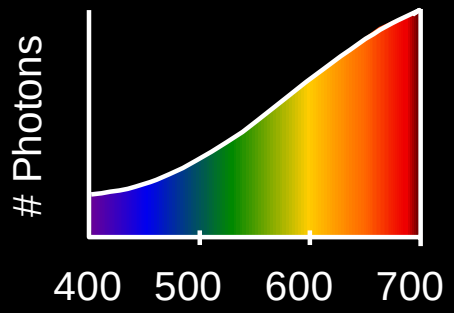
A. Ruby Laser



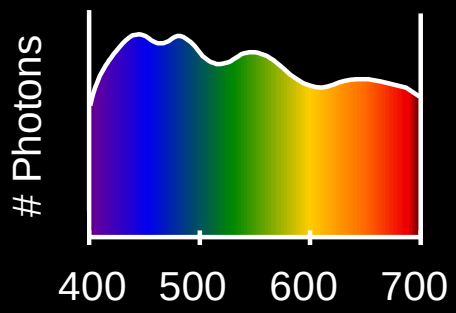
B. Gallium Phosphide Crystal



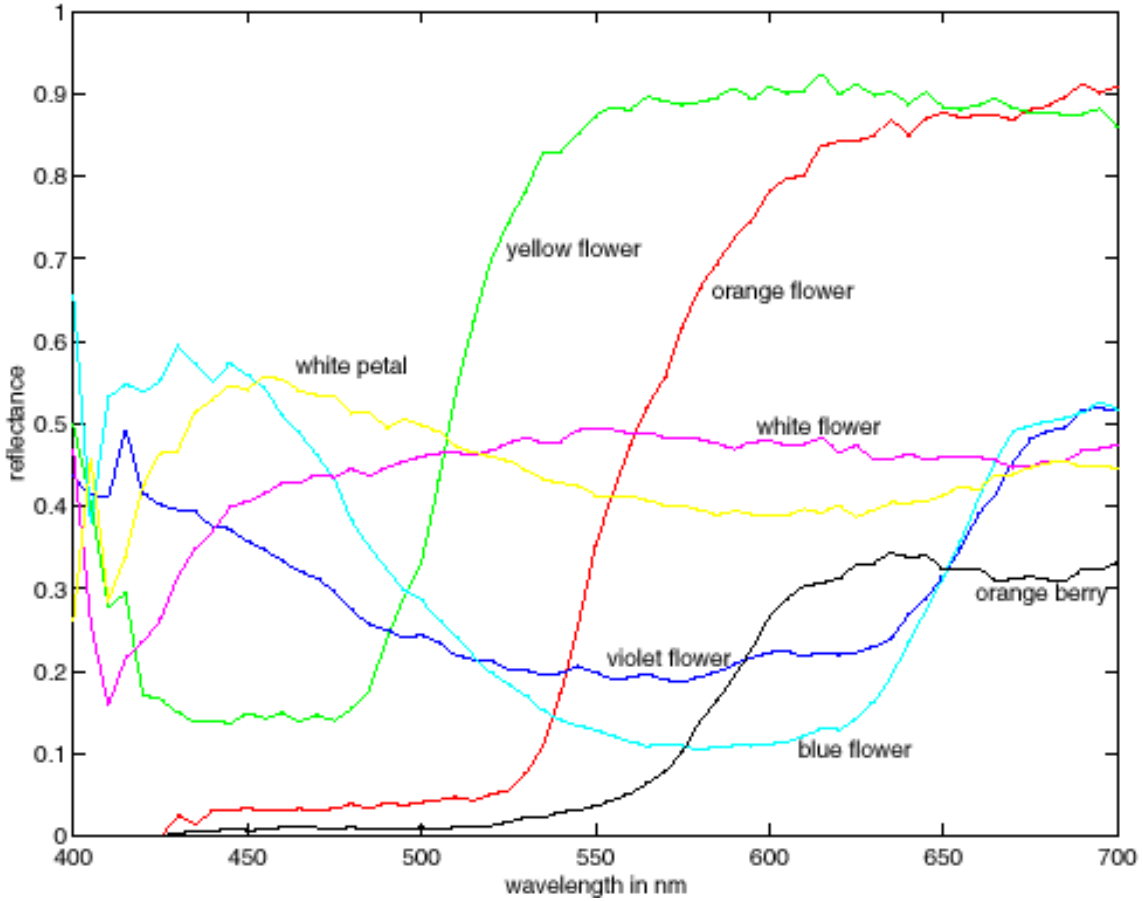
C. Tungsten Lightbulb

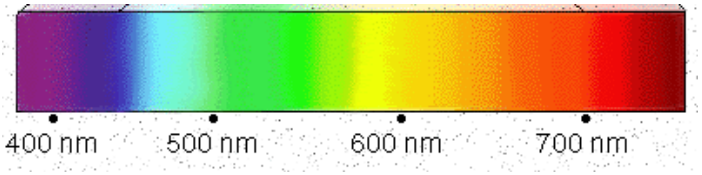


D. Normal Daylight



The color viewed is also affected by the surface's spectral reflectance properties.





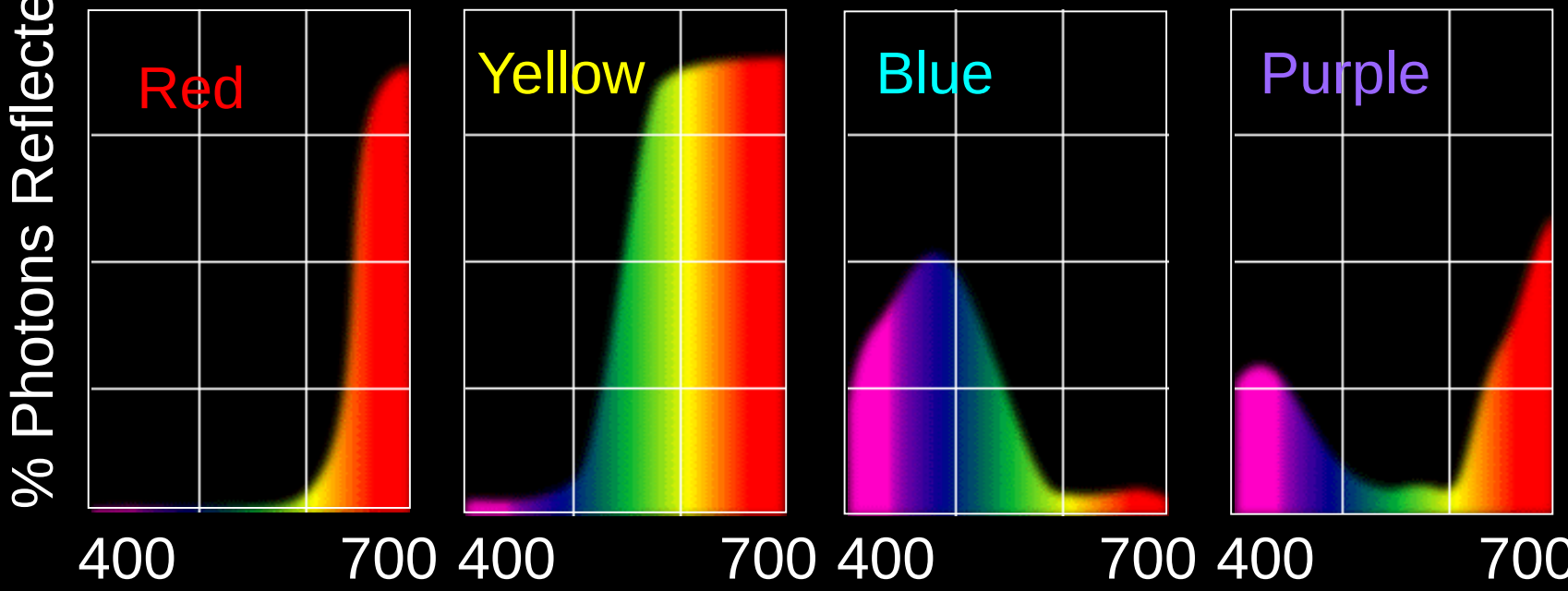
Spectral reflectances for some natural objects: how much of each wavelength is reflected for that surface

Forsyth & Ponce, measurements by E. Koivisto

Surface reflectance spectra

Some examples of the reflectance spectra of surfaces



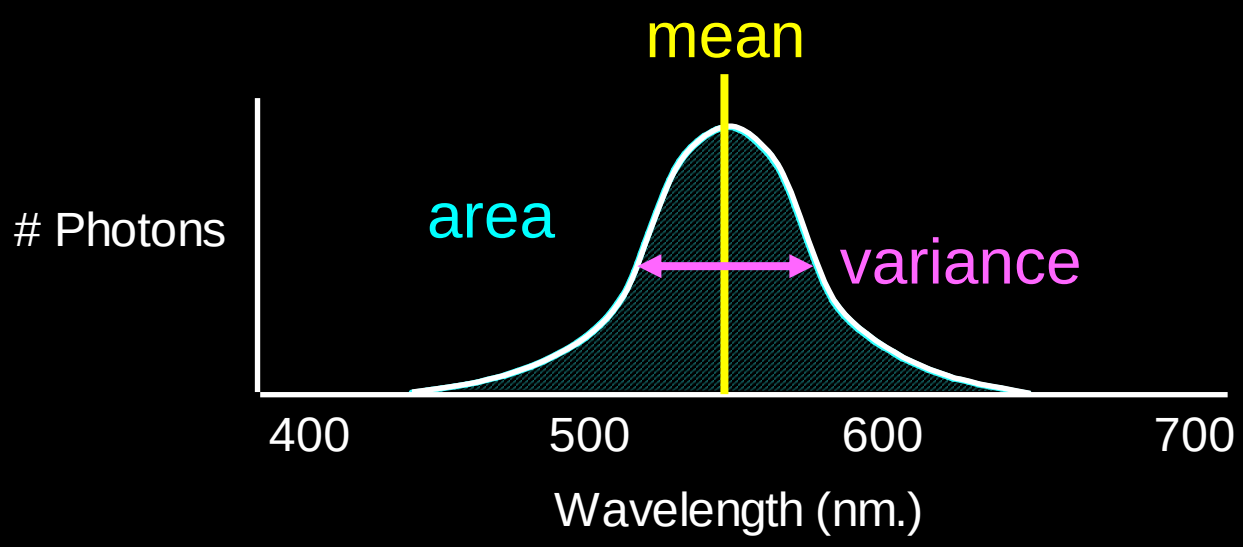



The Psychophysical Correspondence

There is no simple functional description for the perceived color of all lights under all viewing conditions, but ……

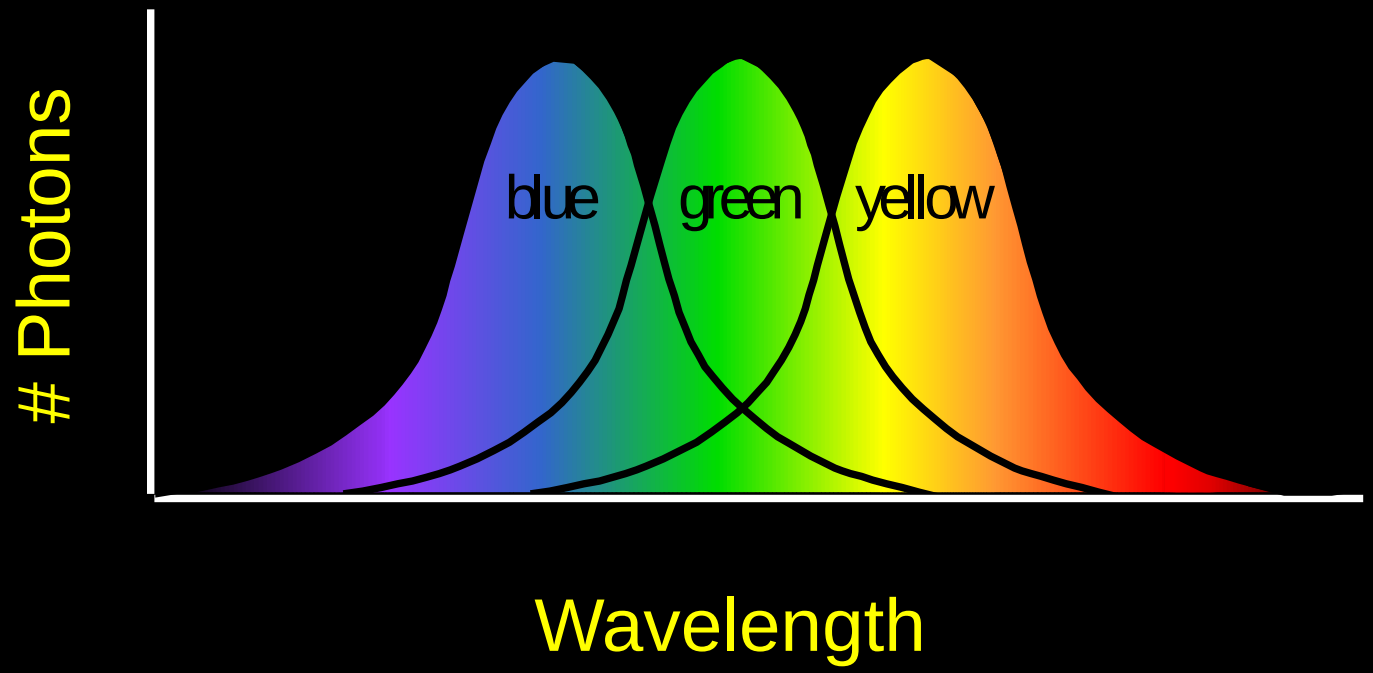
A helpful constraint:

Consider only physical spectra with normal distributions



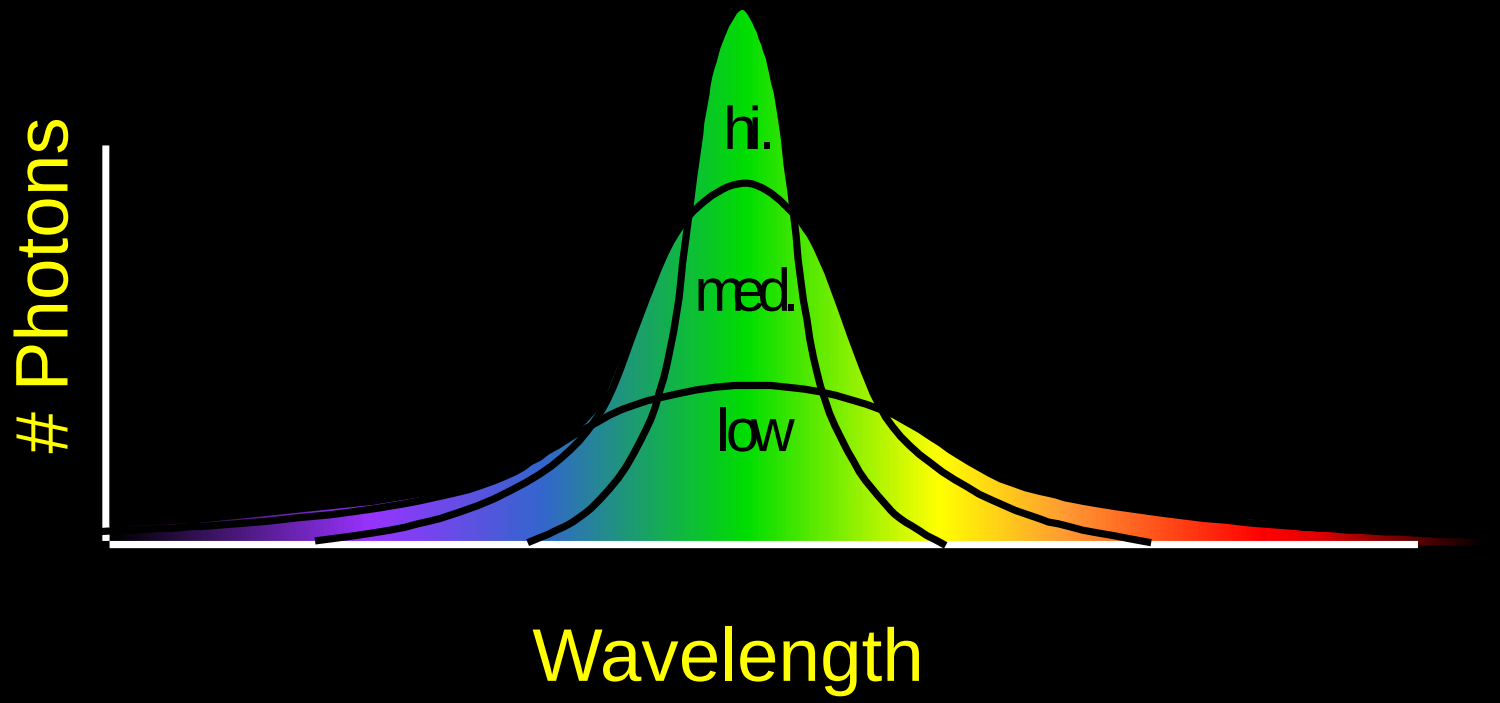
The Psychophysical Correspondence

Mean ⟷ Hue



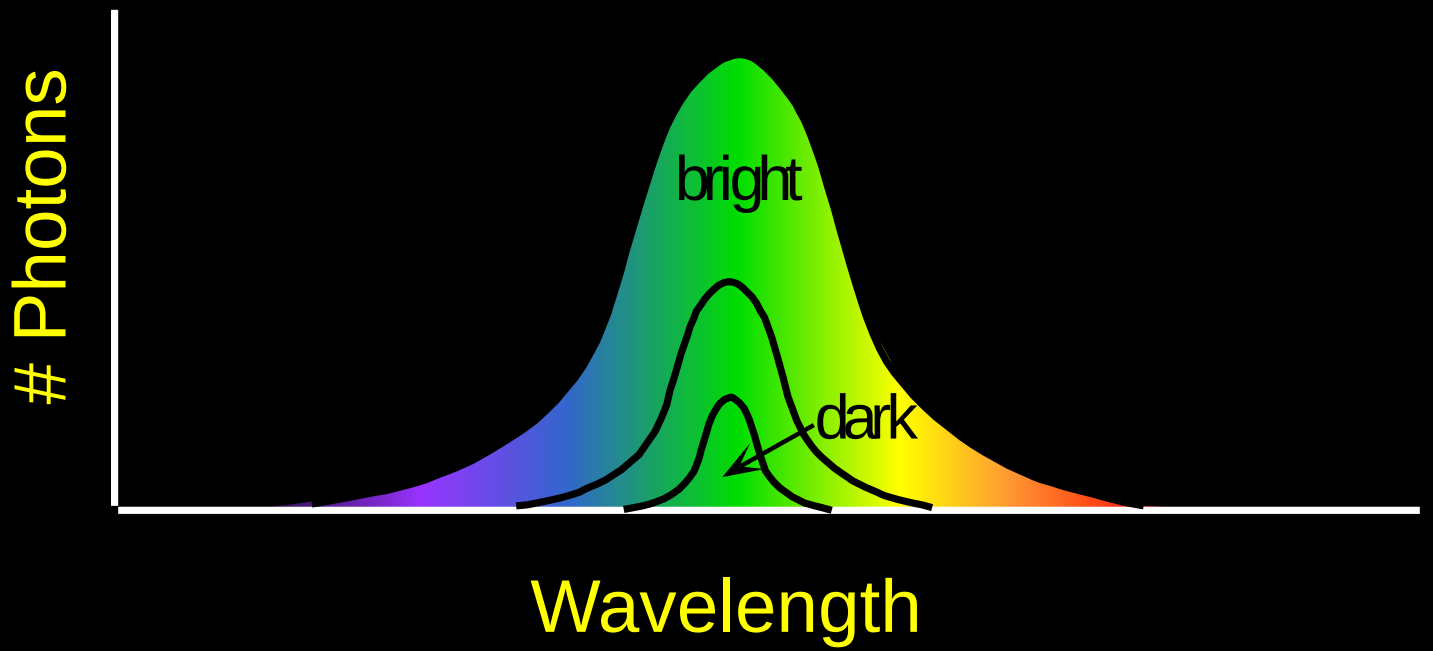
The Psychophysical Correspondence

Variance ⟷ Saturation



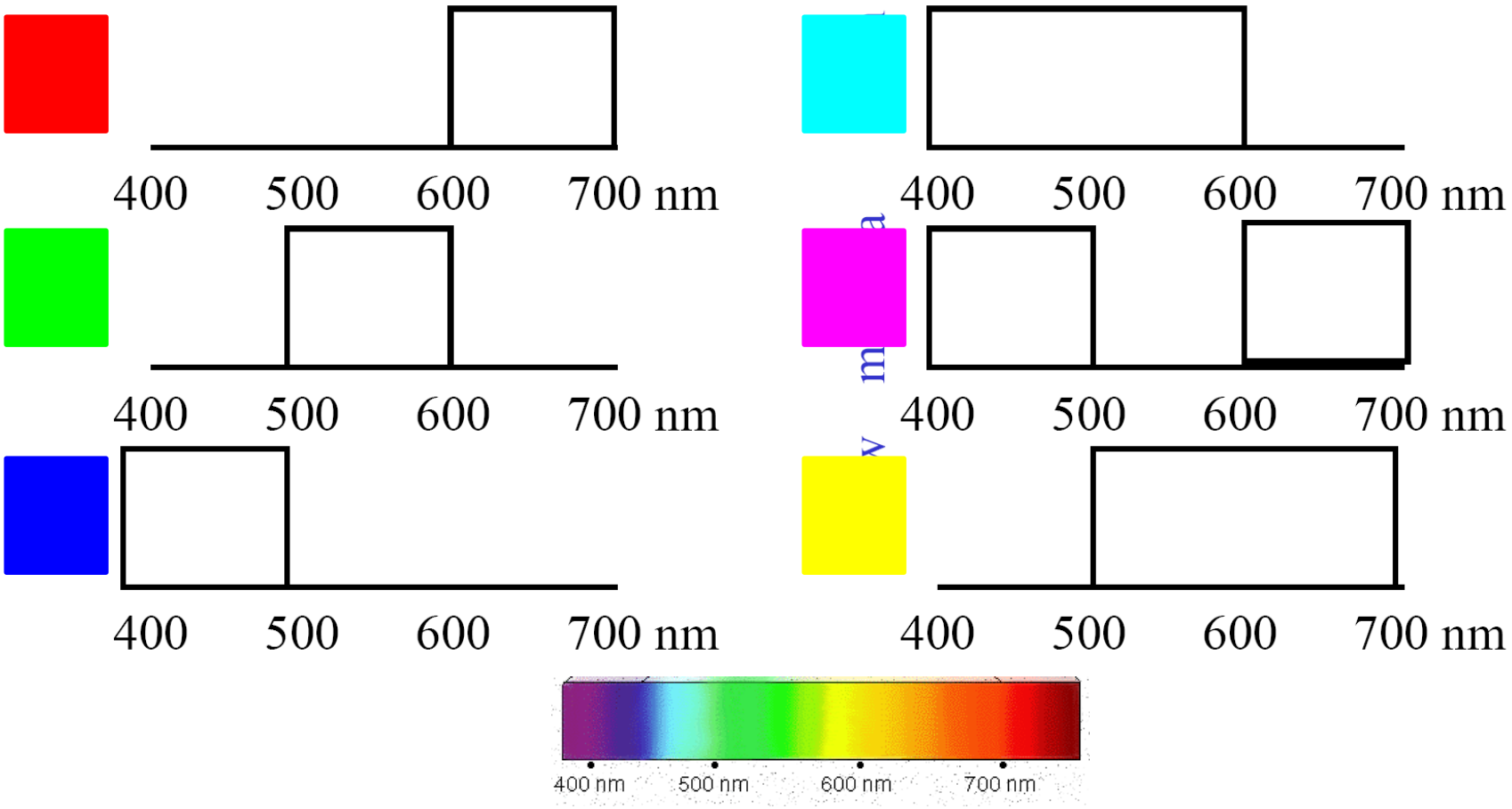
The Psychophysical Correspondence

Area ⟷ Brightness



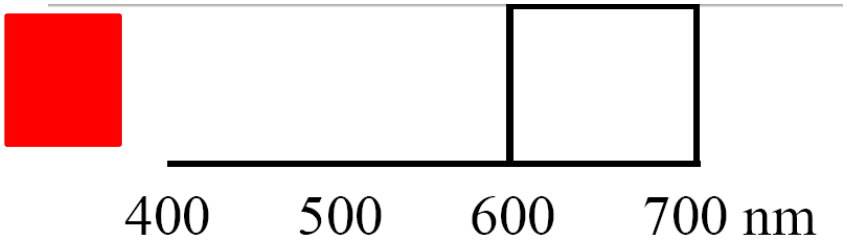
Color mixing

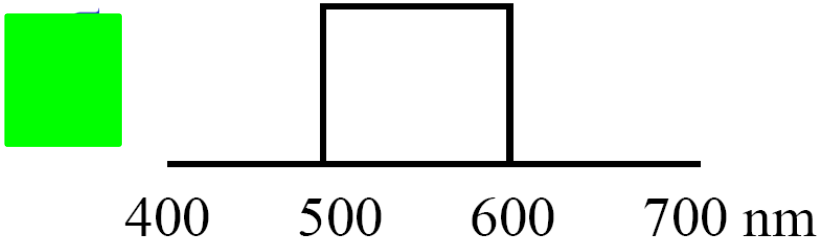
Cartoon spectra for color names:

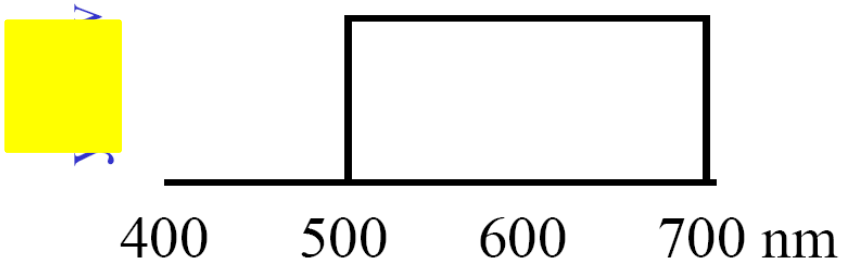


Source: W. Freeman

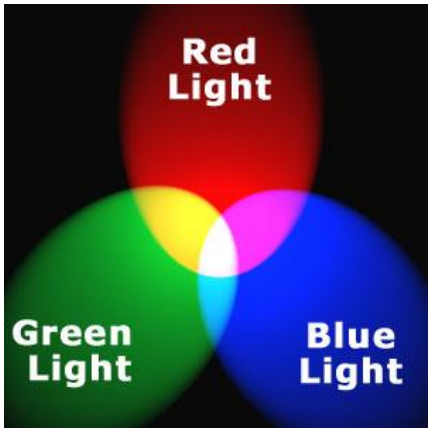
Additive color mixing







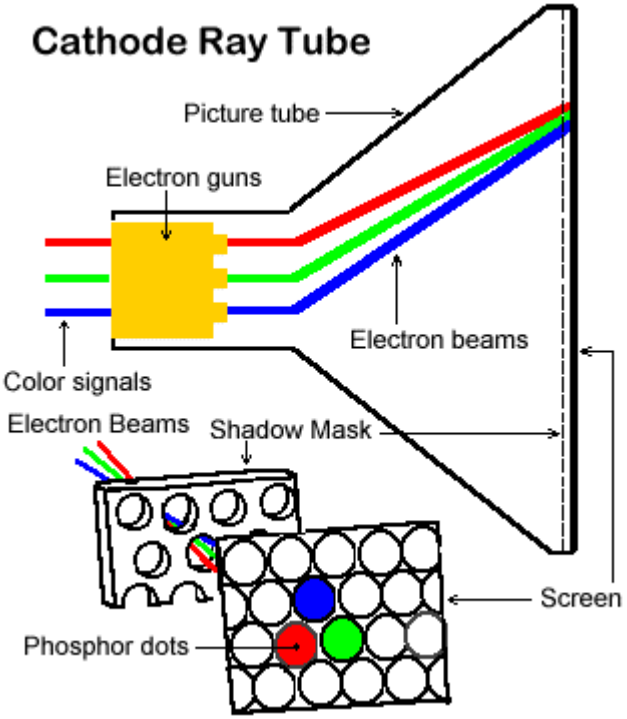
Colors combine by *adding* color spectra



Light *adds* to black.

Source: W. Freeman

Examples of additive color systems



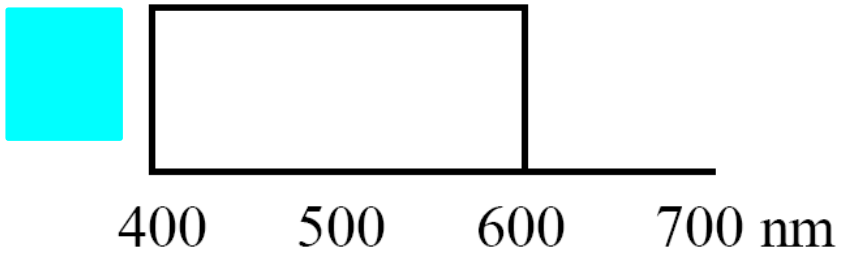
CRT phosphors

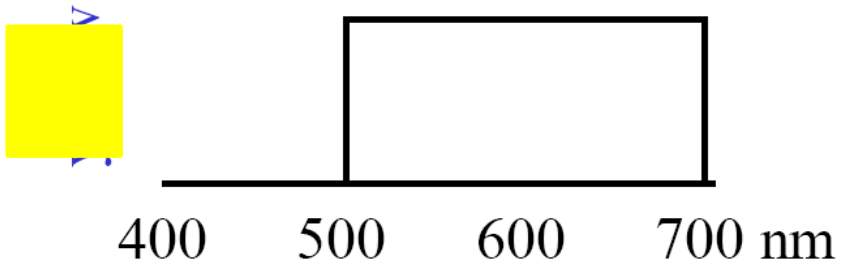
multiple projectors

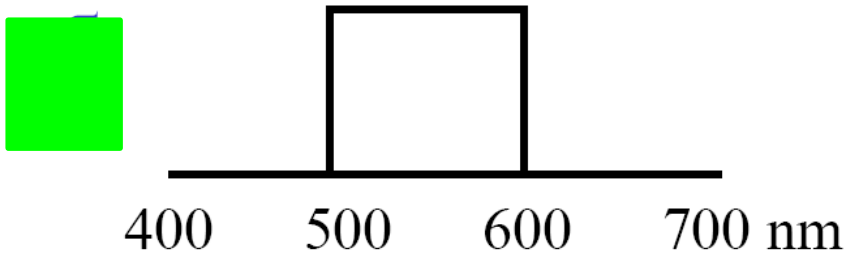
http://www.jegsworks.com

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

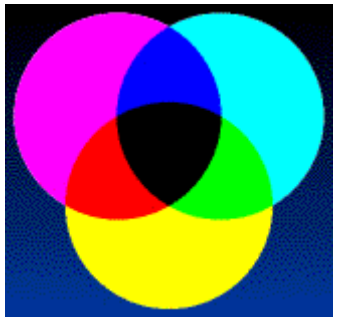
Subtractive color mixing







Colors combine by *multiplying* color spectra.



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

Source: W. Freeman

Examples of subtractive color systems

- Printing on paper
- Most photographic film

Today: Color

- Measuring color
  - Spectral power distributions
  - Color mixing
  - Color matching experiments
  - Color spaces
    - Uniform color spaces
- Perception of color
  - Human photoreceptors
  - Environmental effects, adaptation
- Using color in machine vision systems

Why specify color *numerically*?

- Accurate color reproduction is commercially valuable
  - Many products are identified by color

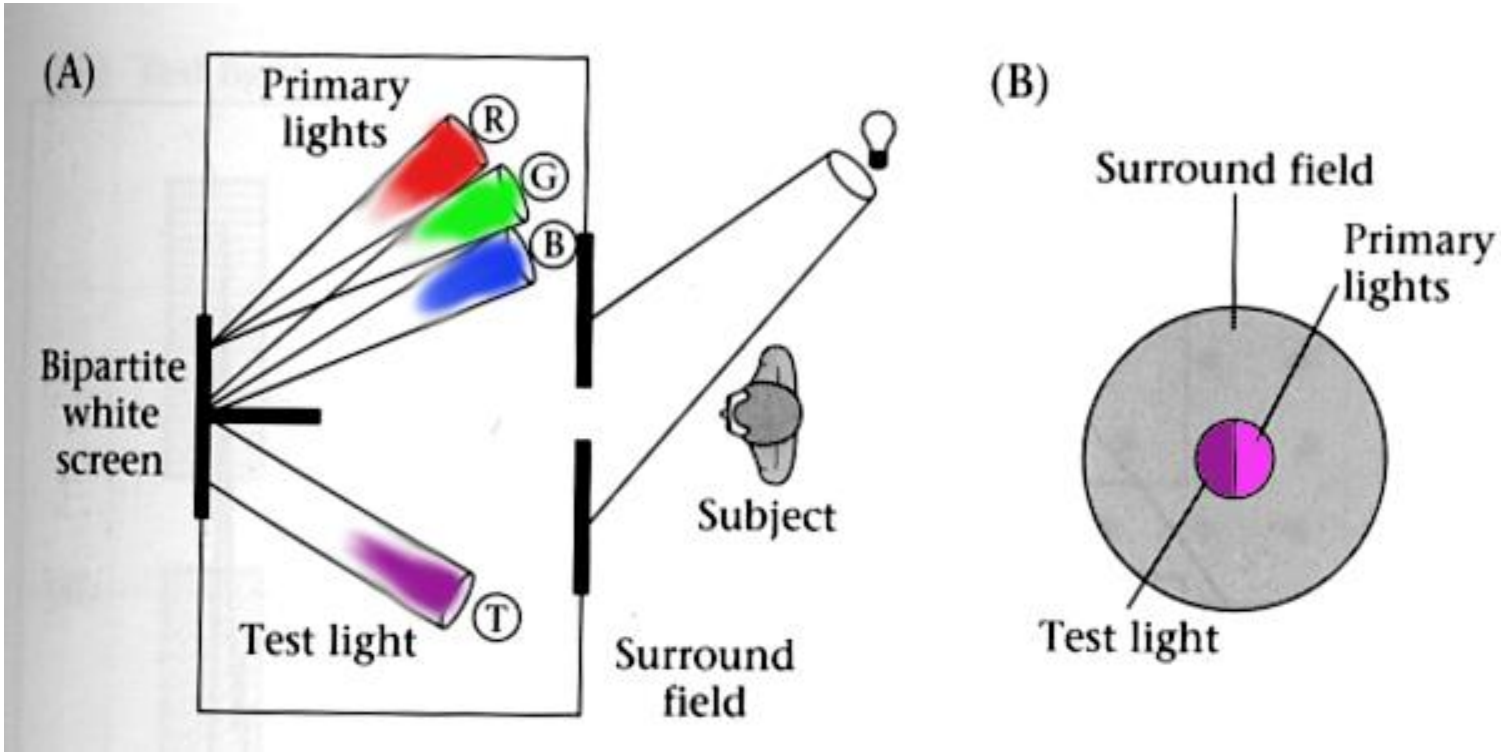
- Few color *names* are widely recognized by English speakers
  - 11: black, blue, brown, grey, green, orange, pink, purple, red, white, and yellow.
  - Other languages have fewer/more.
  - Common to disagree on appropriate color names.

- Color reproduction problems increased by prevalence of digital imaging – e.g. digital libraries of art.
  - How to ensure that everyone perceives the same color?
  - **What spectral radiances *produce the same response* from people under simple viewing conditions?**

Color matching experiments

- Goal:
  What spectral radiances produce same response in human observers?

Color matching experiments



Observer adjusts weight (intensity) for primary lights (fixed SPD's) to match appearance of test light.

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

After Judd & Wyszecki.

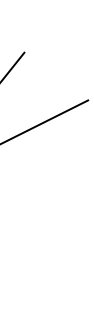
Color matching experiments

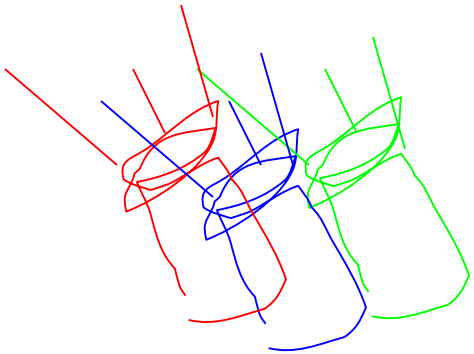
- Goal:
  What spectral radiances produce same response in human observers?

- Assumption:
  Under simple viewing conditions only “test light” affects perception
  - Ignoring additional factors for now like adaptation, complex surrounding scenes, etc.

Color matching experiment 1

Test light Primary lights

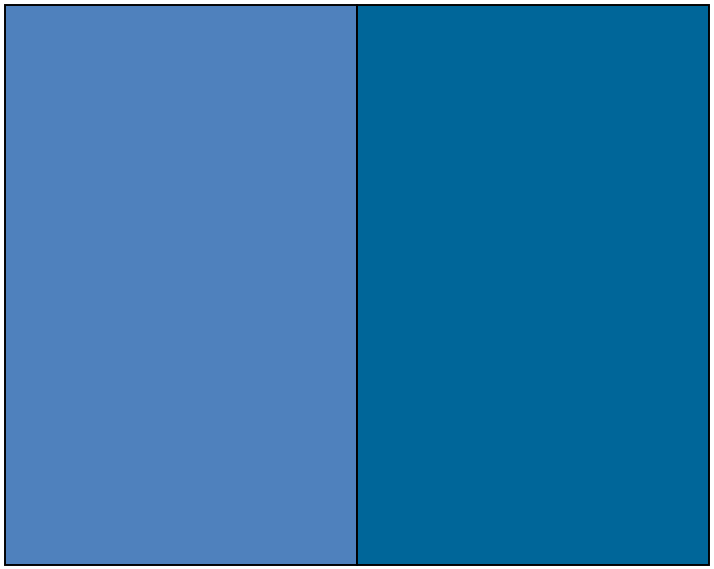


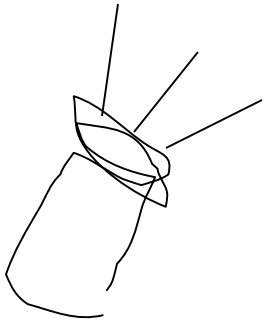


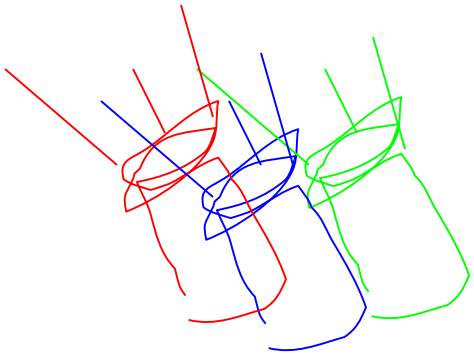
Slide credit: W. Freeman

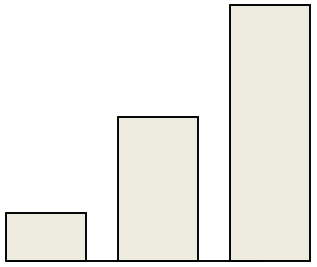
Color matching experiment 1

Test light Primary lights





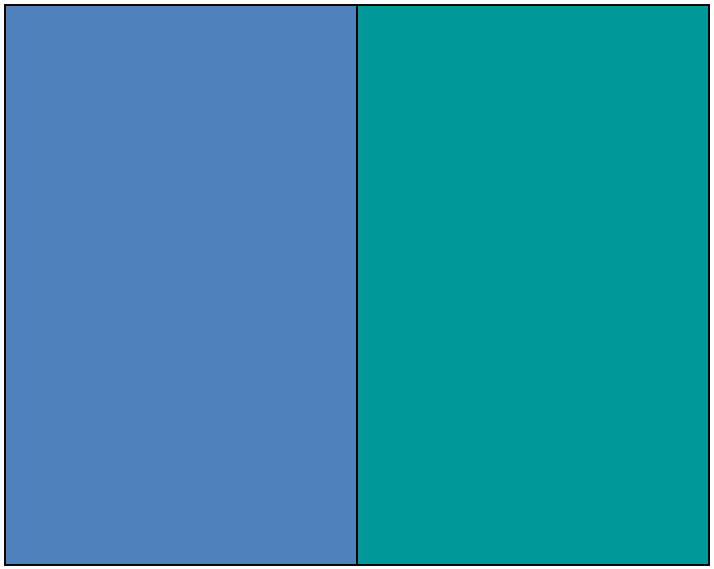


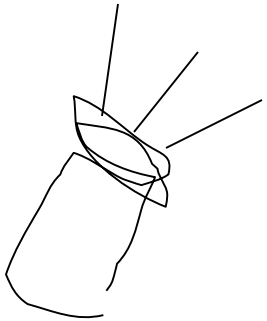


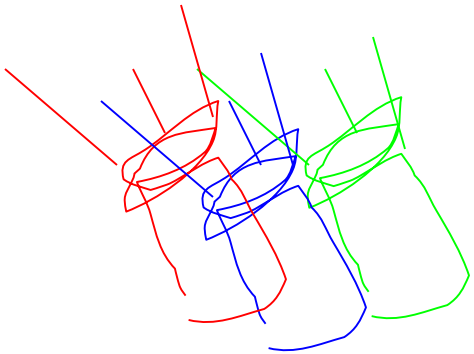
Slide credit: W. Freeman

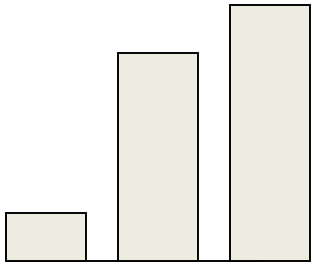
Color matching experiment 1

Test light Primary lights





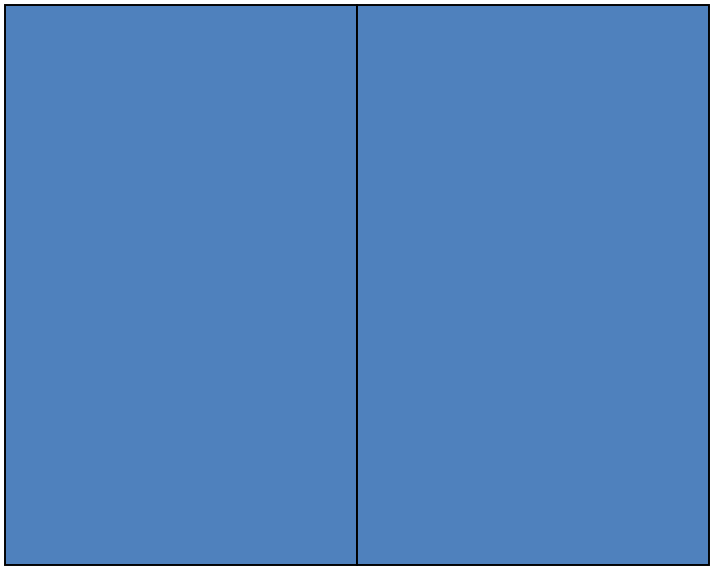




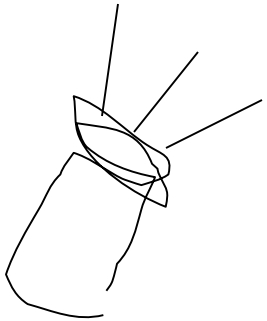
Slide credit: W. Freeman

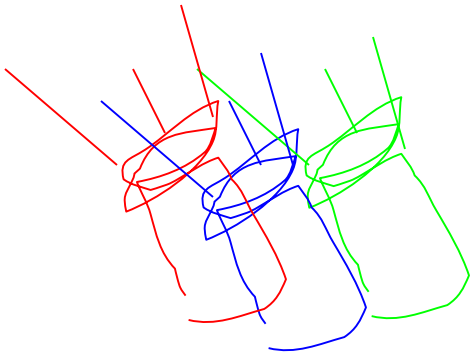
Color matching experiment 1

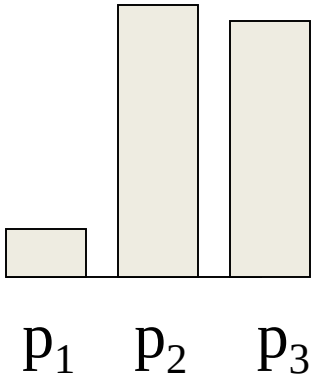
Test light Primary lights



The primary color amounts needed for a match



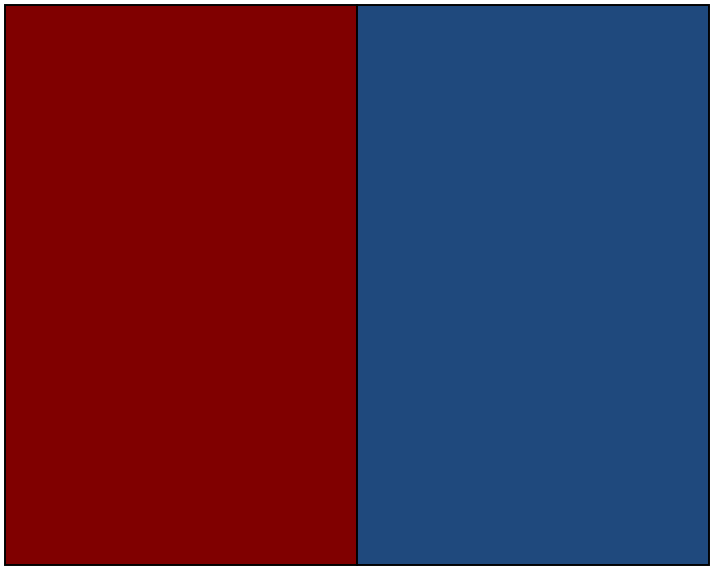


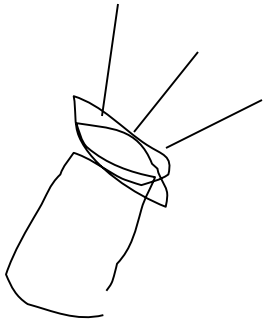


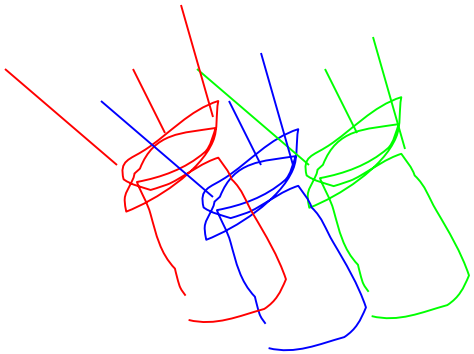
Slide credit: W. Freeman

Color matching experiment 2

Test light Primary lights



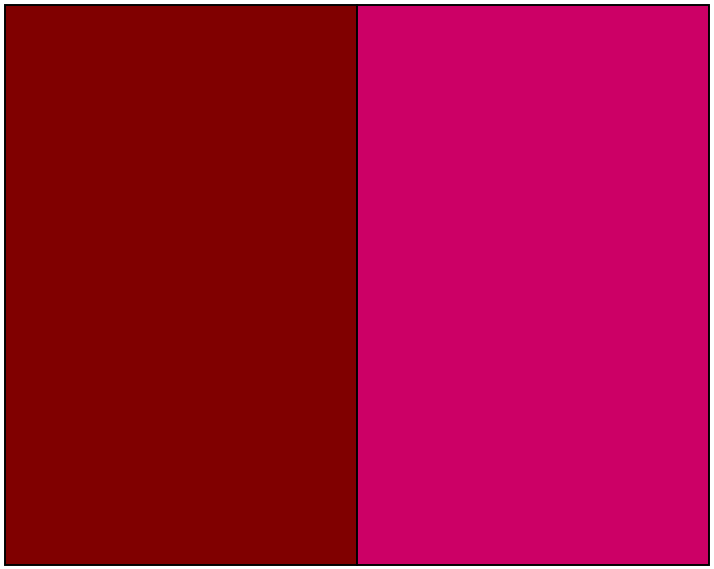


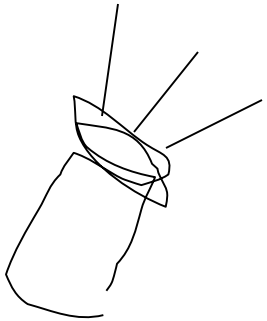


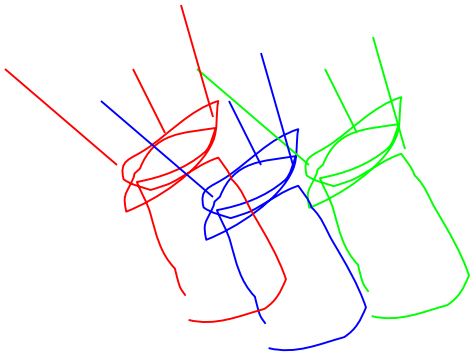
Slide credit: W. Freeman

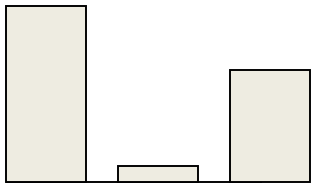
Color matching experiment 2

Test light Primary lights







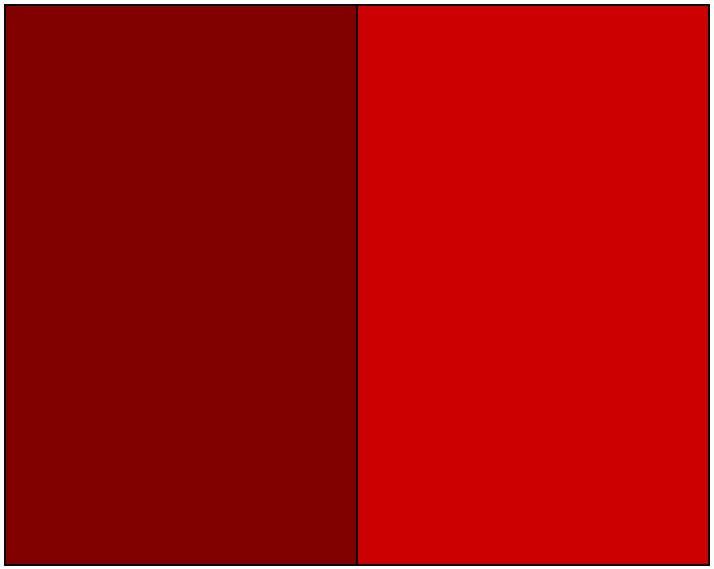


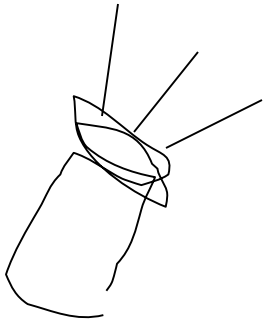
p_1 p_2 p_3

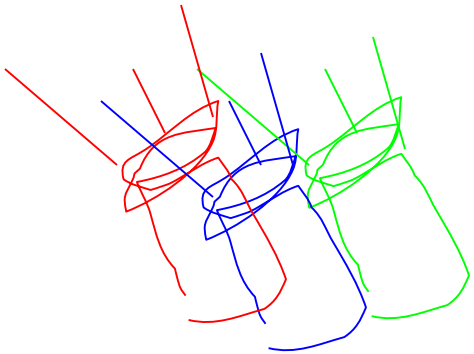
Slide credit: W. Freeman

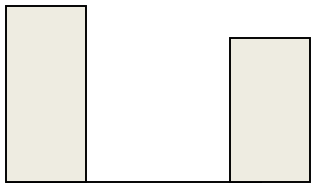
Color matching experiment 2

Test light Primary lights









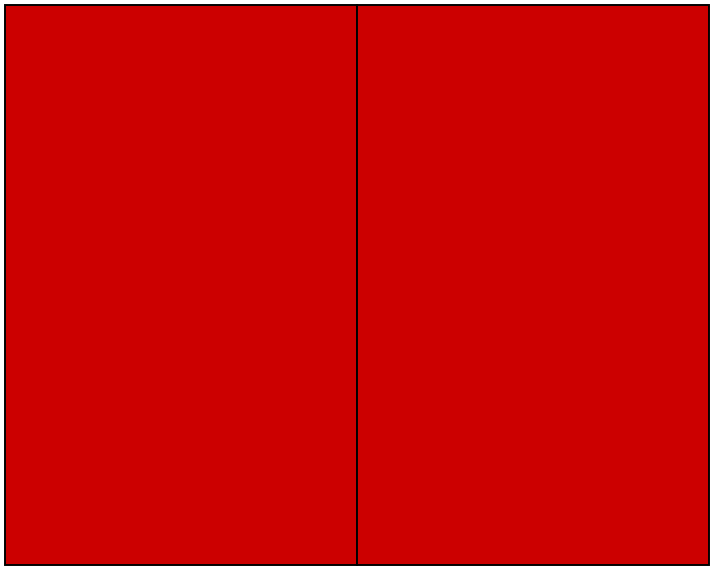
p_1 p_2 p_3

Slide credit: W. Freeman

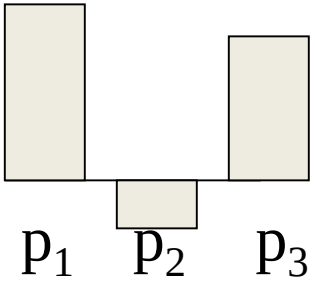
Color matching experiment 2

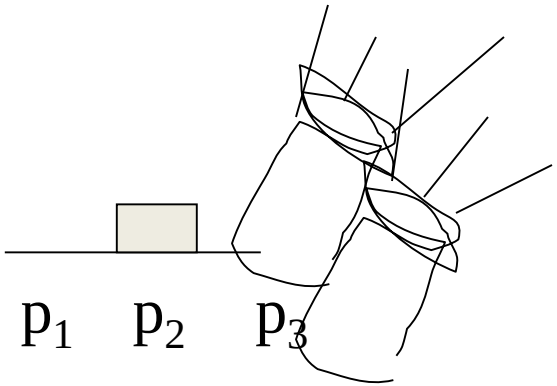
We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.

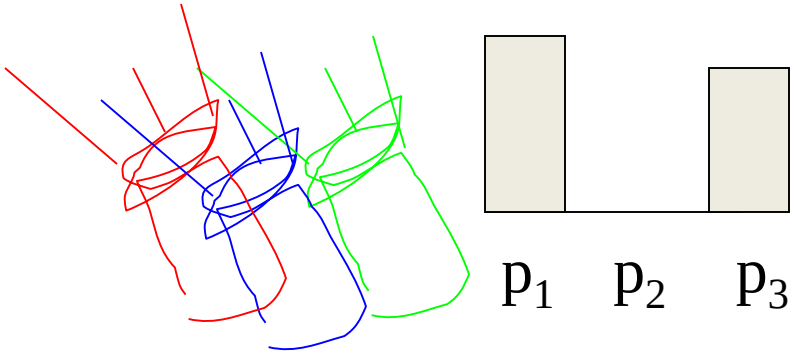
Test light Primary lights



The primary color amounts needed for a match:







Color matching

- What must we require of the primary lights chosen?
- How are three numbers enough to represent entire spectrum?

$$color \rightarrow \begin{bmatrix} P_1 & P_2 & P_3 \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}$$

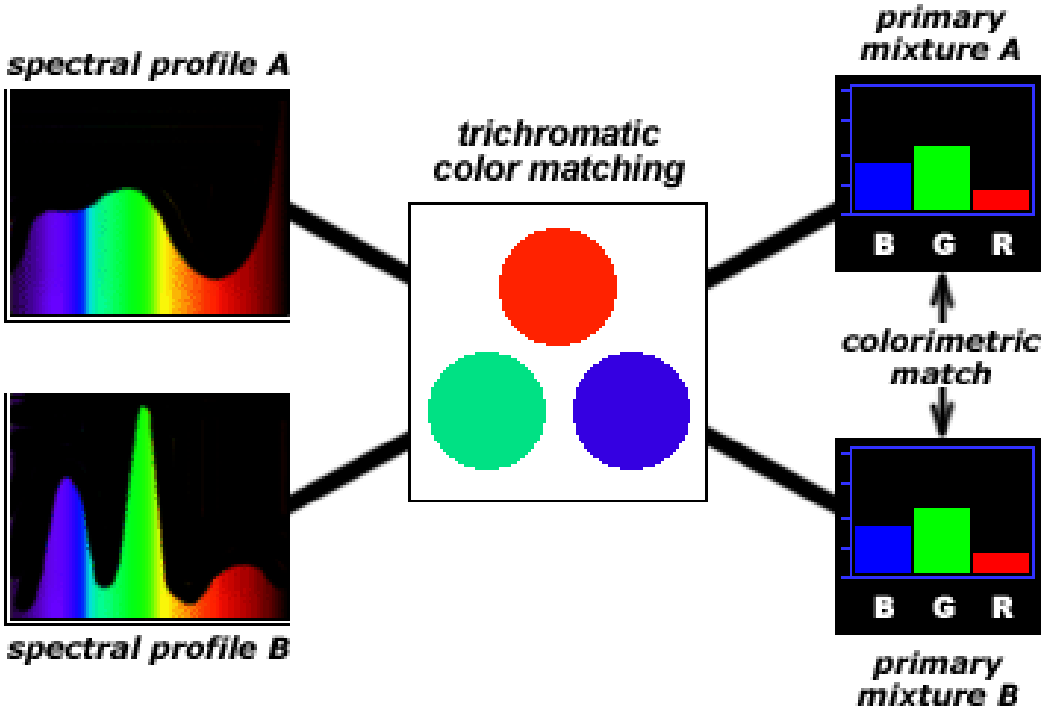
Primary lights spectrum

weights

Metamers

- Lights forming a *perceptual* match still may be *physically* different
  - Match light: a combination of primaries
  - Test light: any light
- **Metamers**: pairs of lights that match perceptually but not physically

Different spectrum

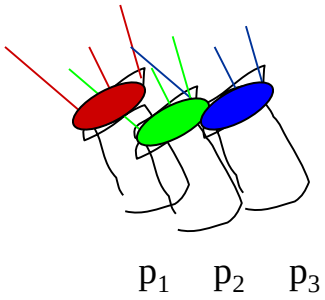


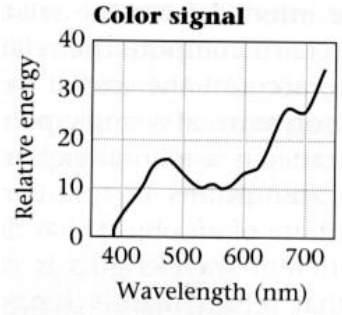
Same primary mixture weights

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

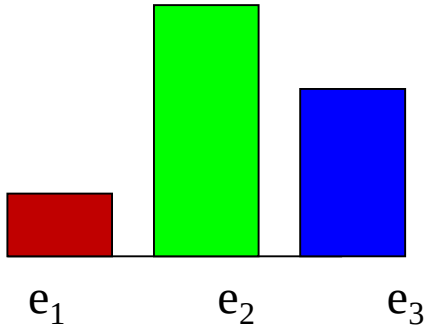
Given: a choice of three primaries and a target color signal

Find: weights of the primaries needed to match the color signal





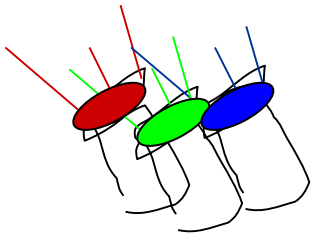
?



Challenge: we cannot use manual tuning for all colors in the world

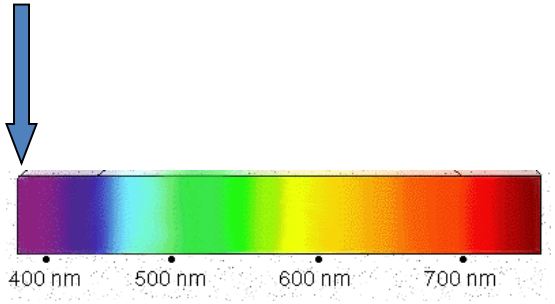
Computing color matches

1. Select primaries



2. Collect weights for all monochromatic lights:

$$\begin{bmatrix} c_1(\lambda_1) \\ c_2(\lambda_1) \\ c_3(\lambda_1) \end{bmatrix}$$

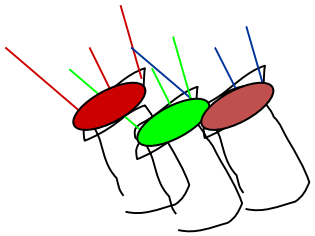


Put them in a big matrix:

$$\Rightarrow \begin{pmatrix} c_1(\lambda_1) & \cdots & c_1(\lambda_N) \\ c_2(\lambda_1) & \cdots & c_2(\lambda_N) \\ c_3(\lambda_1) & \cdots & c_3(\lambda_N) \end{pmatrix}$$

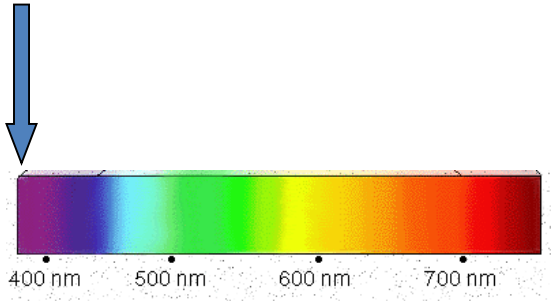
Computing color matches

1. Select primaries



2. Collect weights for all monochromatic lights:

$$\begin{bmatrix} c_1(\lambda_1) \\ c_2(\lambda_1) \\ c_3(\lambda_1) \end{bmatrix}$$

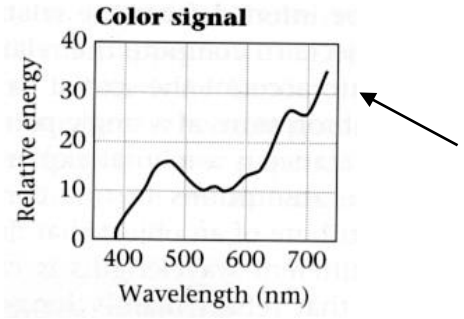


3. Compute the weights of any color by:

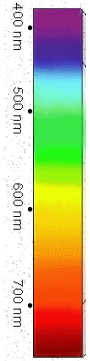
$$\begin{pmatrix} c_1(\lambda_1) & \cdots & c_1(\lambda_N) \\ c_2(\lambda_1) & \cdots & c_2(\lambda_N) \\ c_3(\lambda_1) & \cdots & c_3(\lambda_N) \end{pmatrix} \begin{pmatrix} t(\lambda_1) \\ \vdots \\ t(\lambda_N) \end{pmatrix} \rightarrow \begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix}$$

Computing color matches

Arbitrary new spectral signal is linear combination of the monochromatic sources.



$$\mathbf{t} = \begin{pmatrix} t(\lambda_1) \\ \cdots \\ t(\lambda_N) \end{pmatrix}$$



Color matching functions specify how to match a *unit* of each wavelength, so:

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{pmatrix} c_1(\lambda_1) & \cdots & c_1(\lambda_N) \\ c_2(\lambda_1) & \cdots & c_2(\lambda_N) \\ c_3(\lambda_1) & \cdots & c_3(\lambda_N) \end{pmatrix} \begin{bmatrix} t(\lambda_1) \\ t(\lambda_2) \\ \vdots \\ t(\lambda_N) \end{bmatrix}$$

$$\mathbf{e} = \mathbf{C}\mathbf{t}$$

Computing color matches

- Why is computing the color match for any color signal for a given set of primaries useful?
  - Want to paint a carton of Kodak film with the Kodak yellow color.
  - Want to match skin color of a person in a photograph printed on an ink jet printer to their true skin color.
  - Want the colors in the world, on a monitor, and in a print format to all look the same.

Adapted from W. Freeman

Image credit: pbs.org

Today: Color

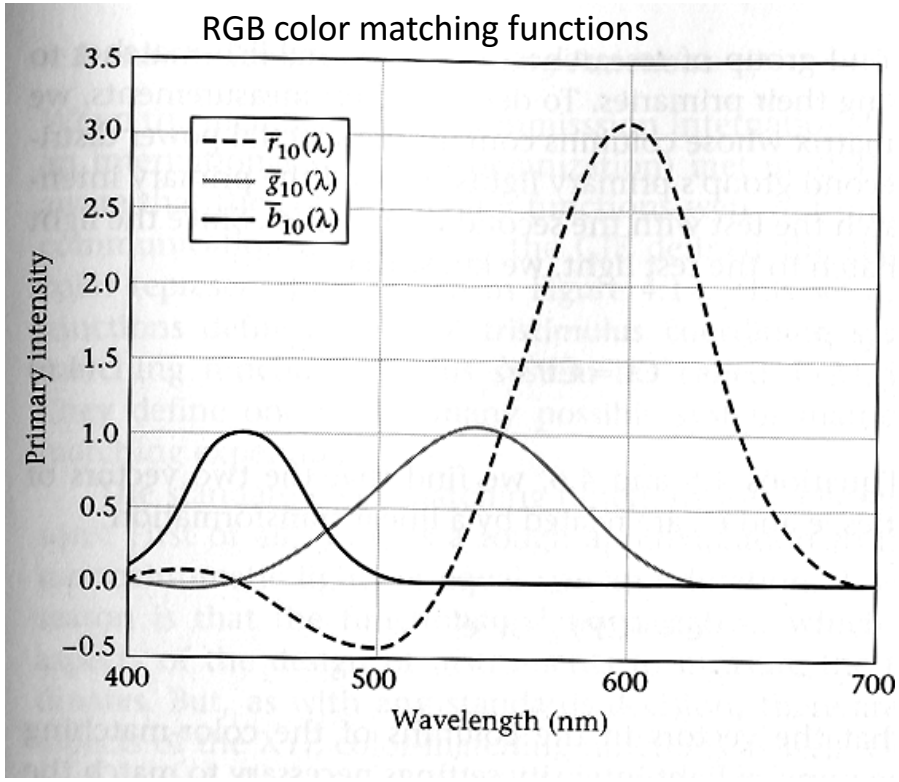
- Measuring color
  - Spectral power distributions
  - Color mixing
  - Color matching experiments
  - Color spaces
    - Uniform color spaces
- Perception of color
  - Human photoreceptors
  - Environmental effects, adaptation
- Using color in machine vision systems

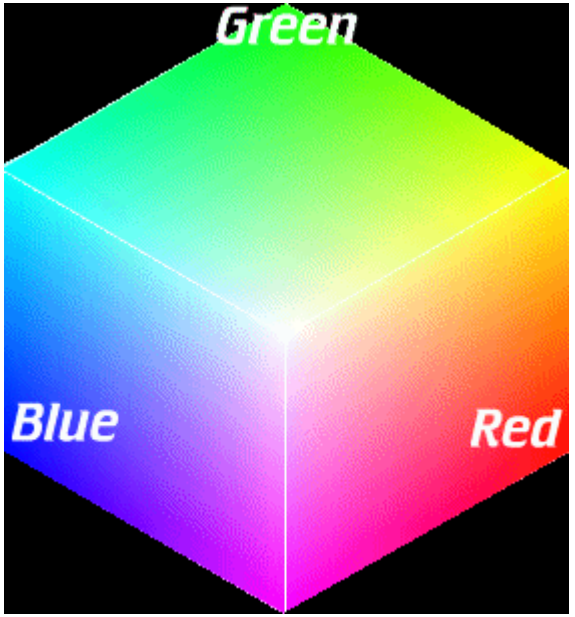
Standard color spaces

- Use a common set of primaries/color matching functions
- Linear color space examples
  - RGB
  - CIE XYZ
- Non-linear color space
  - HSV
  - CIE LAB

RGB color space

- Single wavelength primaries
- Good for devices (e.g., phosphors for monitor), but not for perception

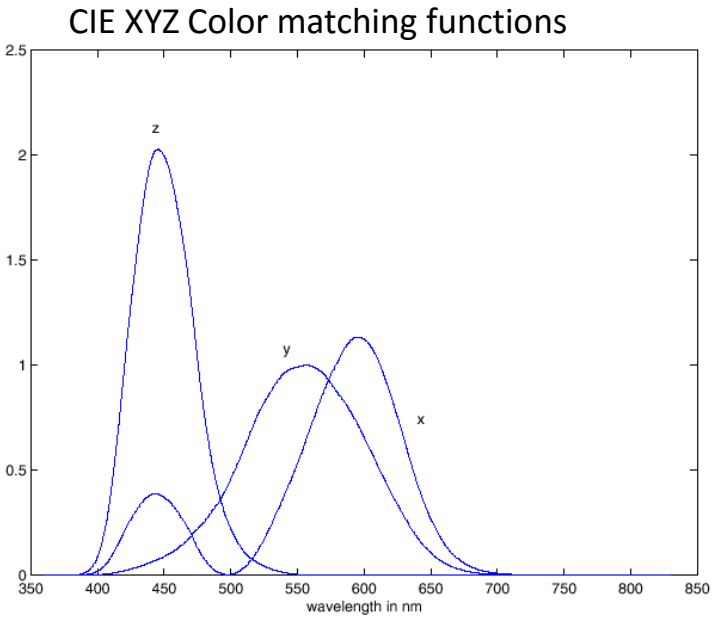


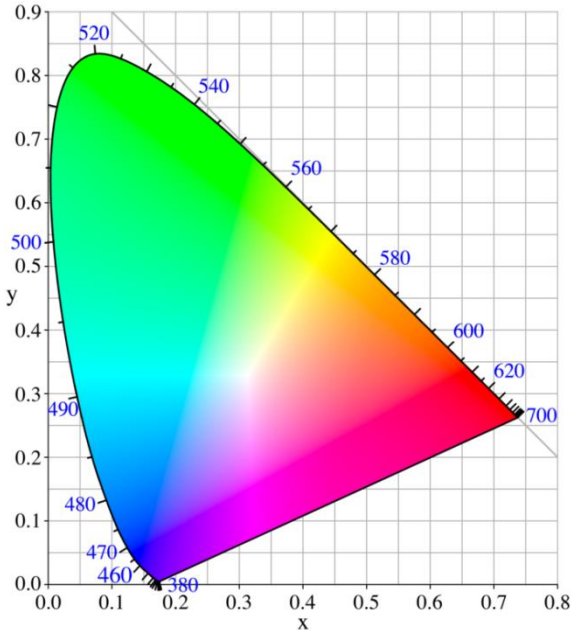


CIE XYZ color space

- Established by the commission international d'eclairage (CIE), 1931
- Usually projected to display:

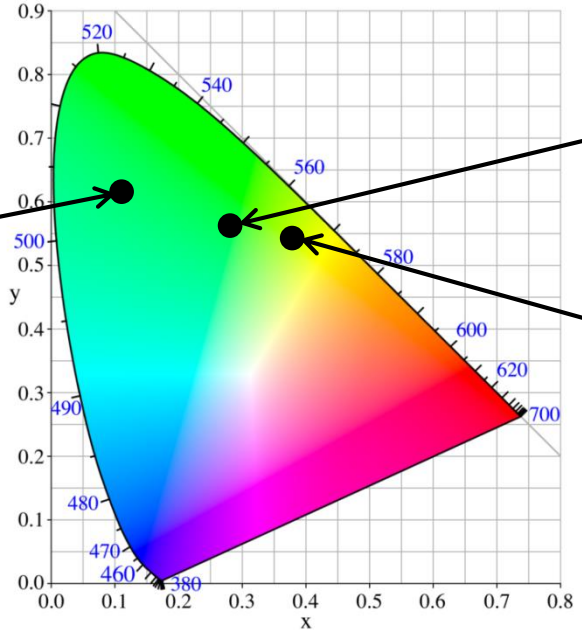
  (x,y) = (X/(X+Y+Z), Y/(X+Y+Z))





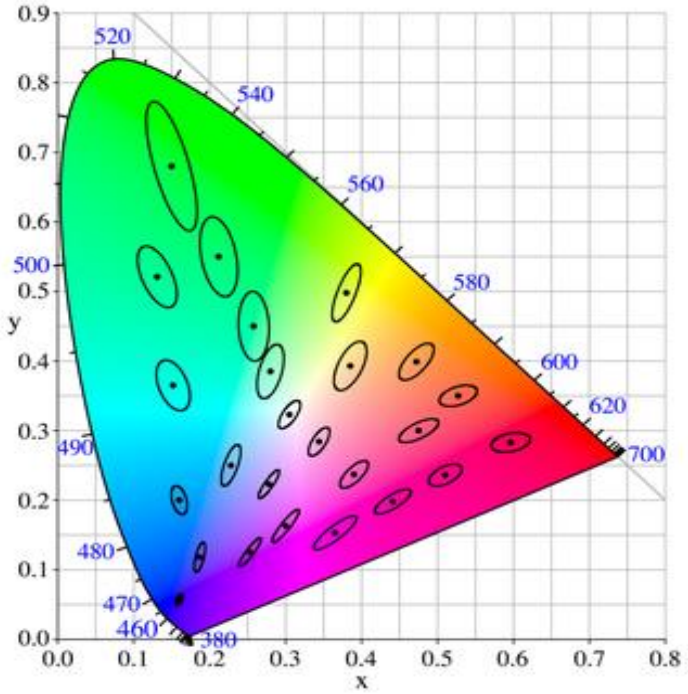
Distances in color space

- Are distances between points in a color space perceptually meaningful?



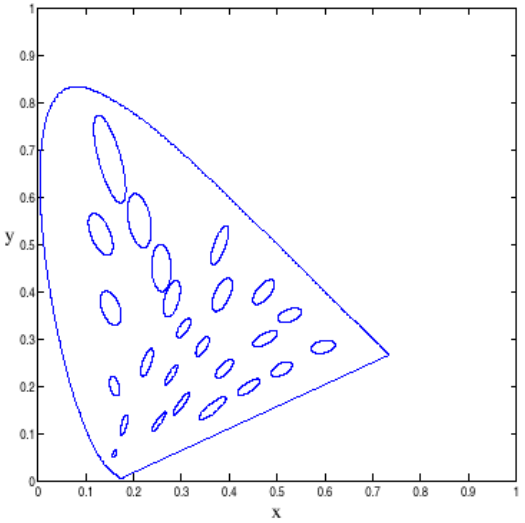
Distances in color space

- Not necessarily: CIE XYZ is **not** a *uniform* color space, so magnitude of differences in coordinates are poor indicator of color “distance”.

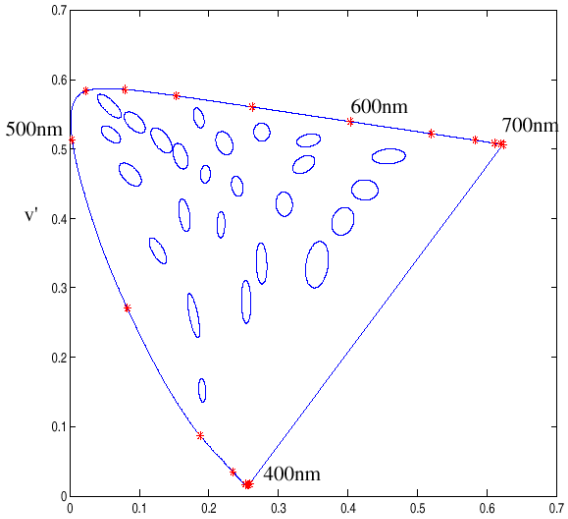


McAdam ellipses:
Just noticeable differences in color

Uniform color spaces

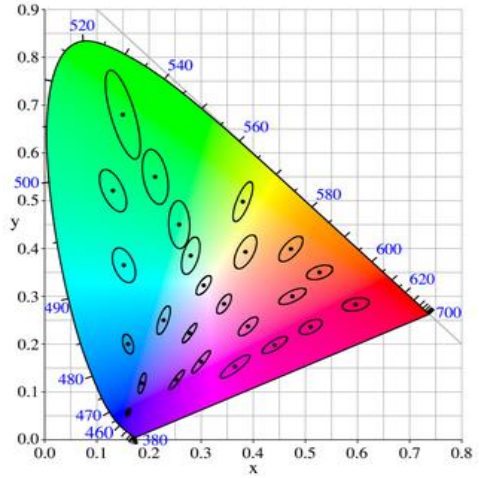


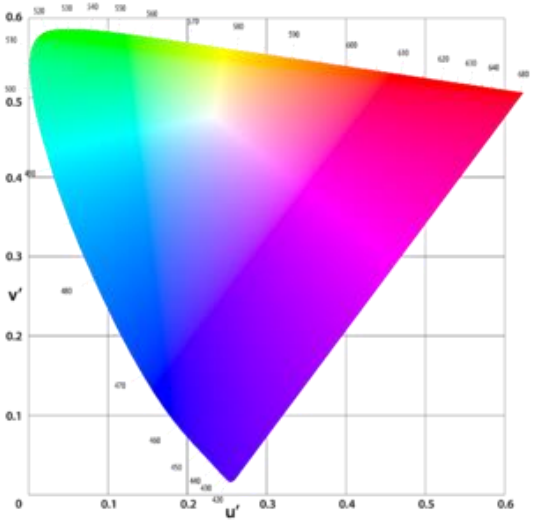
CIE XYZ

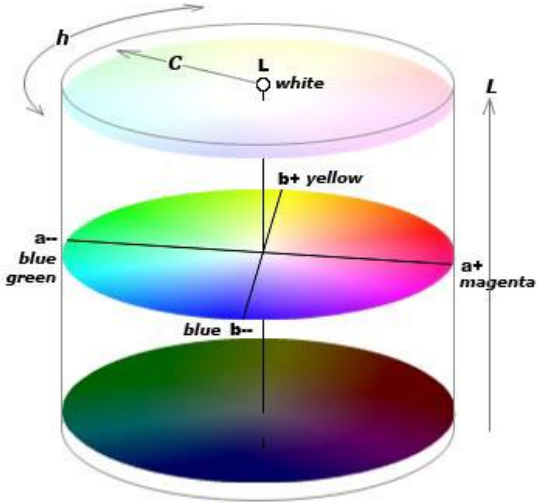


CIE Lu'v'

CIE Lab

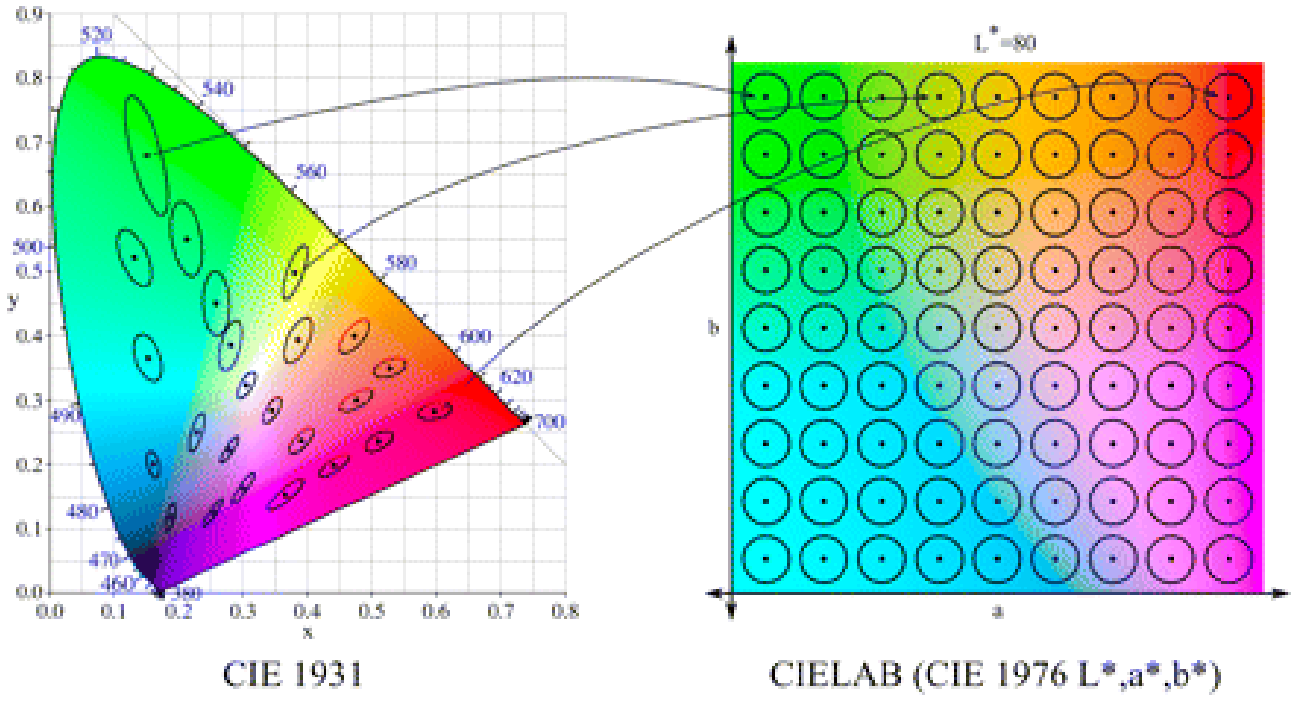






CIE LAB color space

- Established by the CIE in 1948 and then 1976
- Goal: perceptually uniform



CIE 1931

CIELAB (CIE 1976 L*,a*,b*)

HSV color space

- **H**ue, **S**aturation, **V**alue (Brightness)
- Nonlinear – reflects topology of colors by coding **hue** as an angle
- Intuitive for color picking

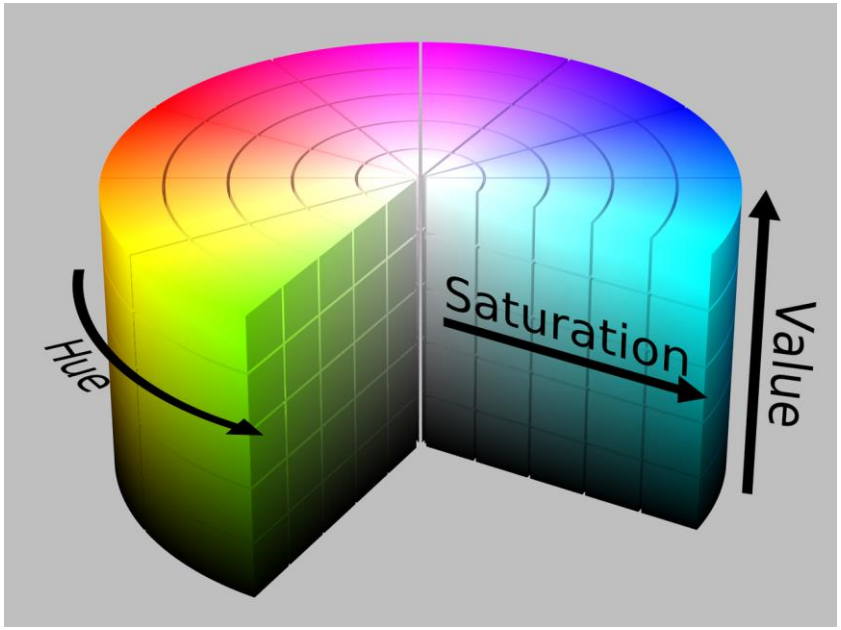


Image from mathworks.com

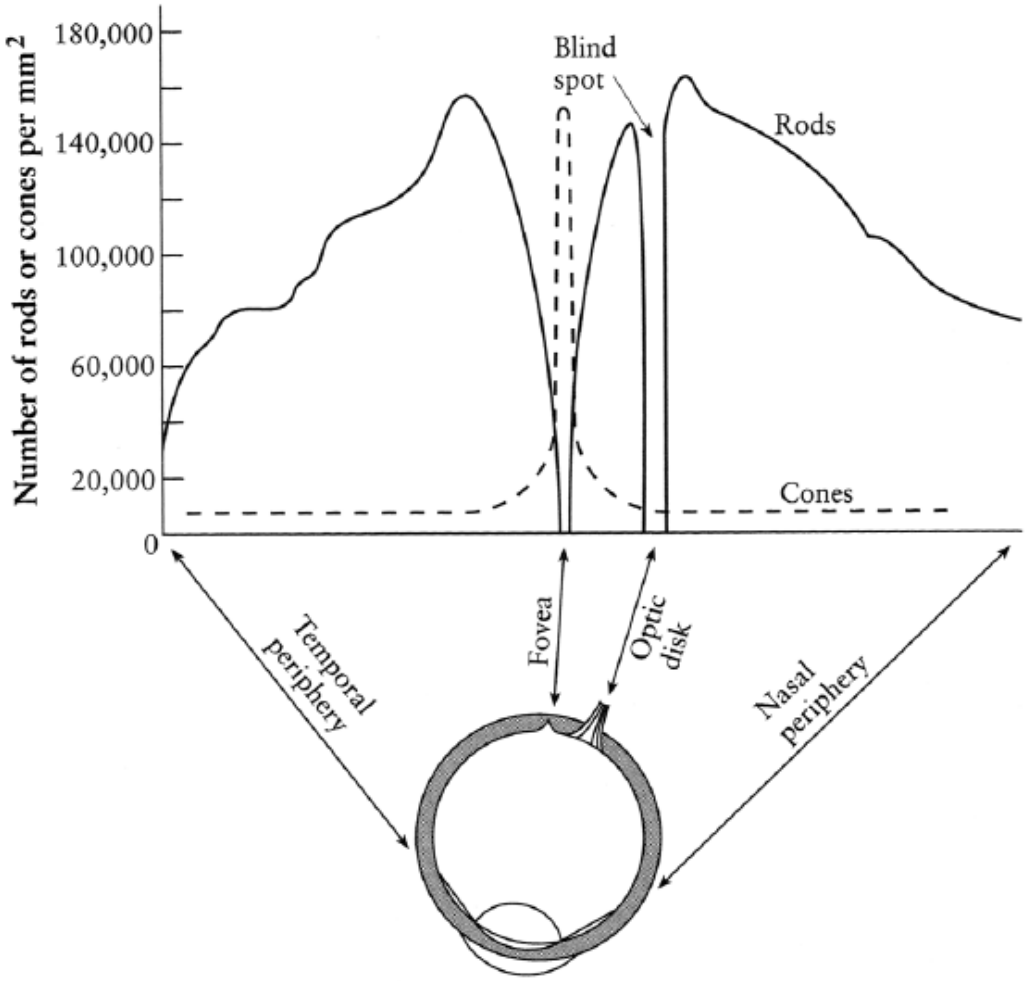
Today: Color

- Measuring color
  - Spectral power distributions
  - Color mixing
  - Color matching experiments
  - Color spaces
    - Uniform color spaces
- Perception of color
  - Human photoreceptors
  - Environmental effects, adaptation
- Using color in machine vision systems

Color

- **Color of light** arriving at camera depends on
  - Spectral reflectance of the surface light is leaving
  - Spectral radiance of light falling on that patch
- **Color perceived** depends on
  - Physics of light
  - Visual system receptors
  - Brain processing, environment

Human photoreceptors



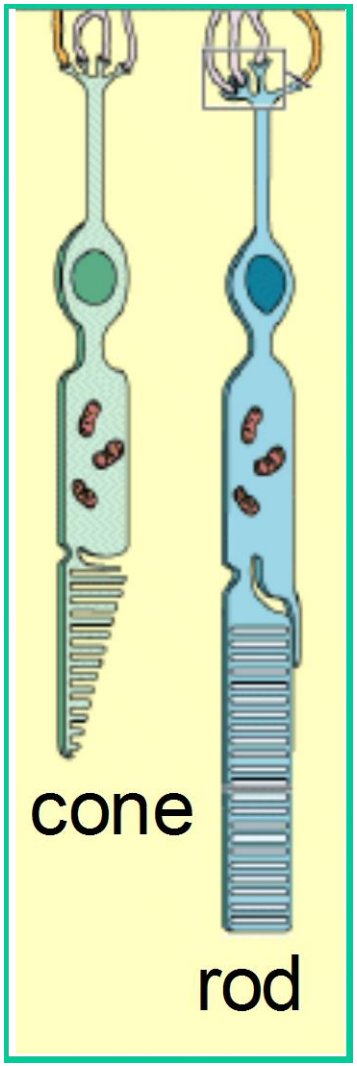
-Rods responsible for intensity
-Cones responsible for color
-Fovea: small region (1 or 2°) at the center of the visual field containing
the highest density of cones (and no rods).
– Less visual acuity in the periphery

Adapted from Seitz, Duygulu

Two types of light-sensitive receptors

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

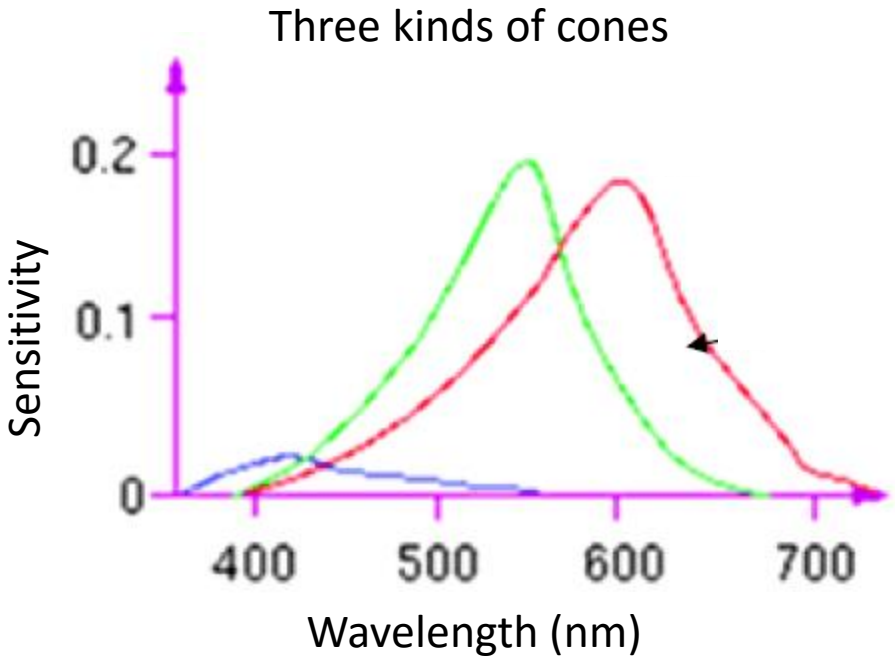
Rods
- rod-shaped
- highly sensitive
- operate at night
- gray-scale vision



Slide credit: Alyosha Efros

Human photoreceptors

- React only to some wavelengths, with different sensitivity (light fraction absorbed)
- Brain fuses responses from local neighborhood of several cones for perceived color
- Sensitivities vary from person to person, and with age
- Color blindness: deficiency in at least one type of cone



Human photoreceptors

Possible evolutionary pressure for developing receptors for different wavelengths in primates

Osorio & Vorobyev, 1996

Trichromacy

- Experimental facts:
  - Three primaries will work for most people if we allow subtractive matching; “trichromatic” nature of the human visual system
  - Most people make the *same* matches for a given set of primaries (i.e., select the same mixtures)

Environmental effects & adaptation

- *Chromatic adaptation*: we adapt to a particular illuminant
- *Assimilation, contrast effects, chromatic induction*: nearby colors affect what is perceived; receptor excitations interact across image and time
- *Afterimages*

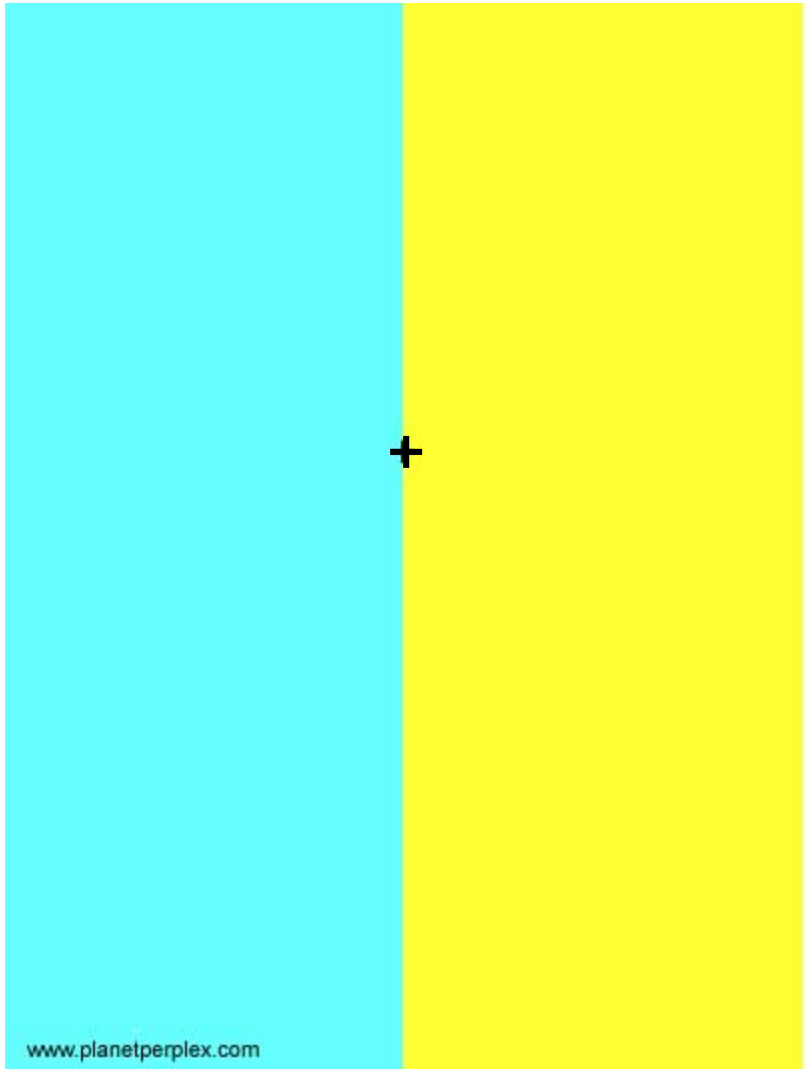
Color matching ~= color appearance

Physics of light ~= perception of light

Chromatic adaptation

- If the visual system is exposed to a certain illuminant for a while, color system starts to adapt / skew.

Chromatic adaptation

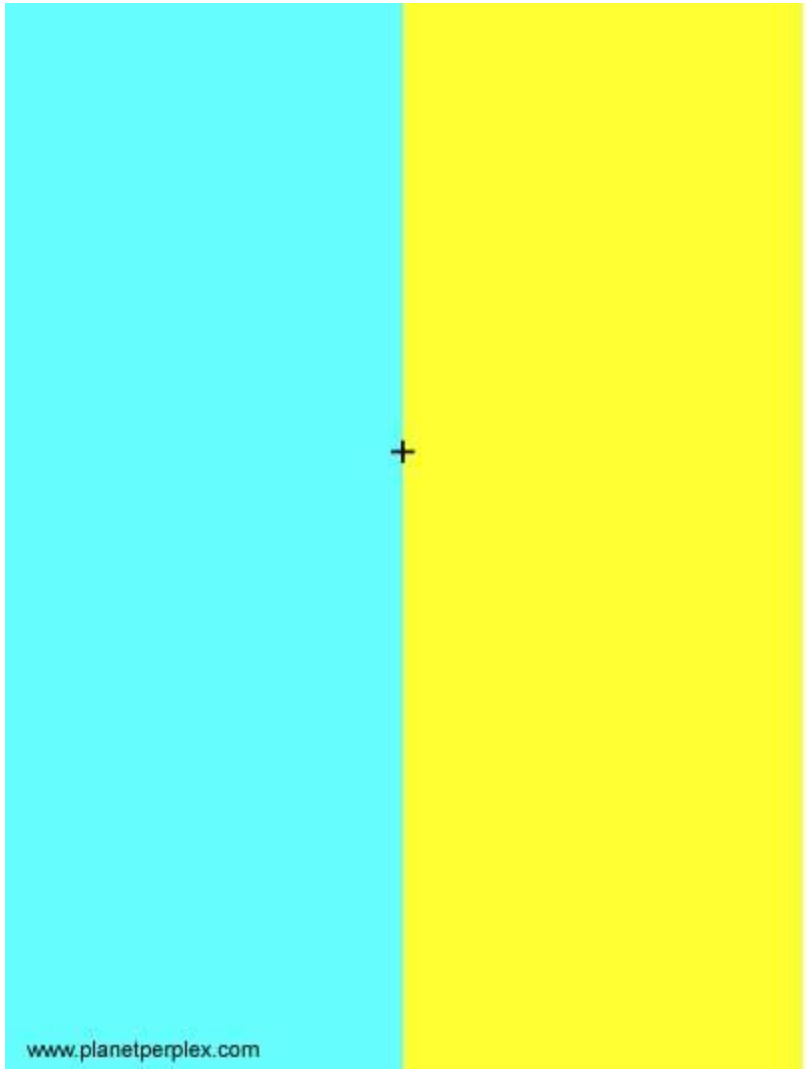


http://www.planetperplex.com/en/color_illusions.html

Chromatic adaptation

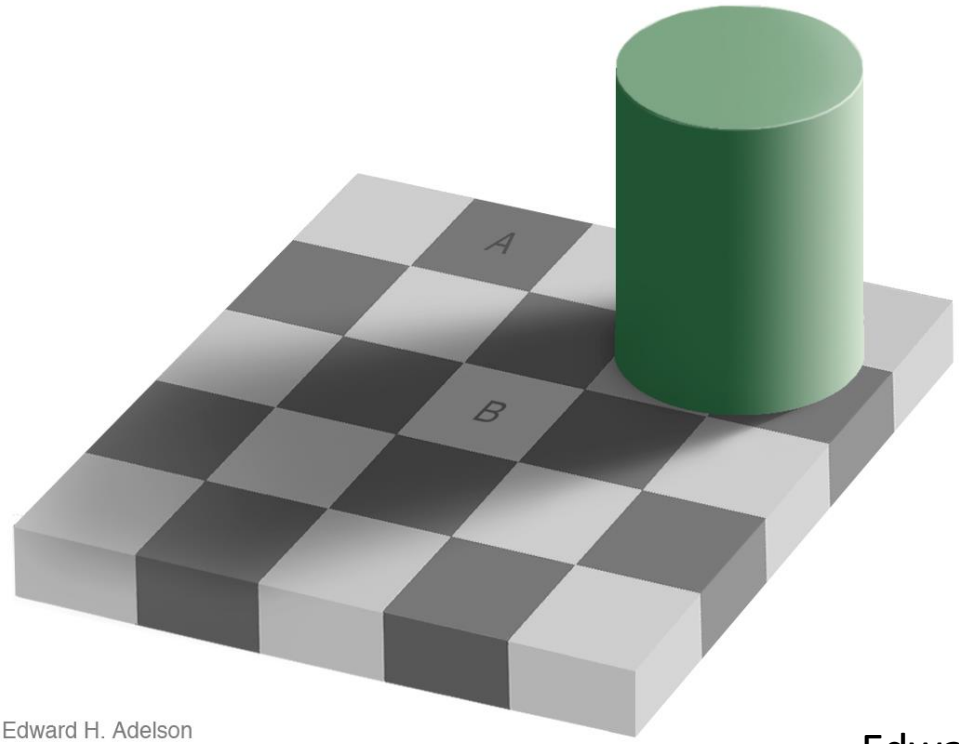
http://www.planetperplex.com/en/color_illusions.html

Chromatic adaptation



http://www.planetperplex.com/en/color_illusions.html

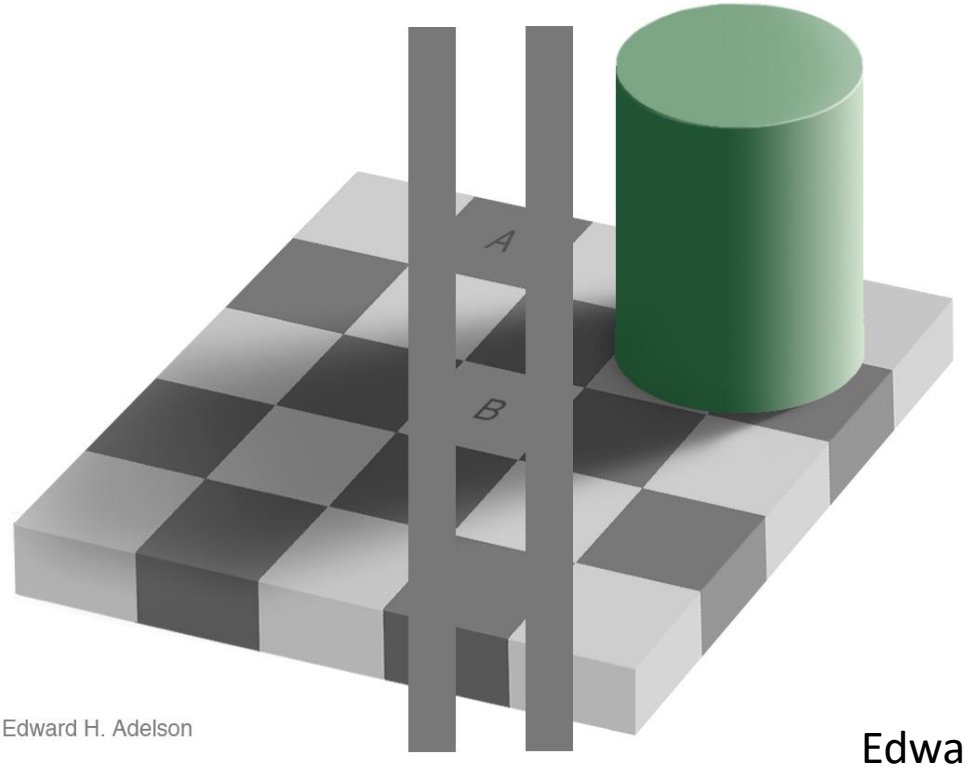
Brightness perception



Edward Adelson

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

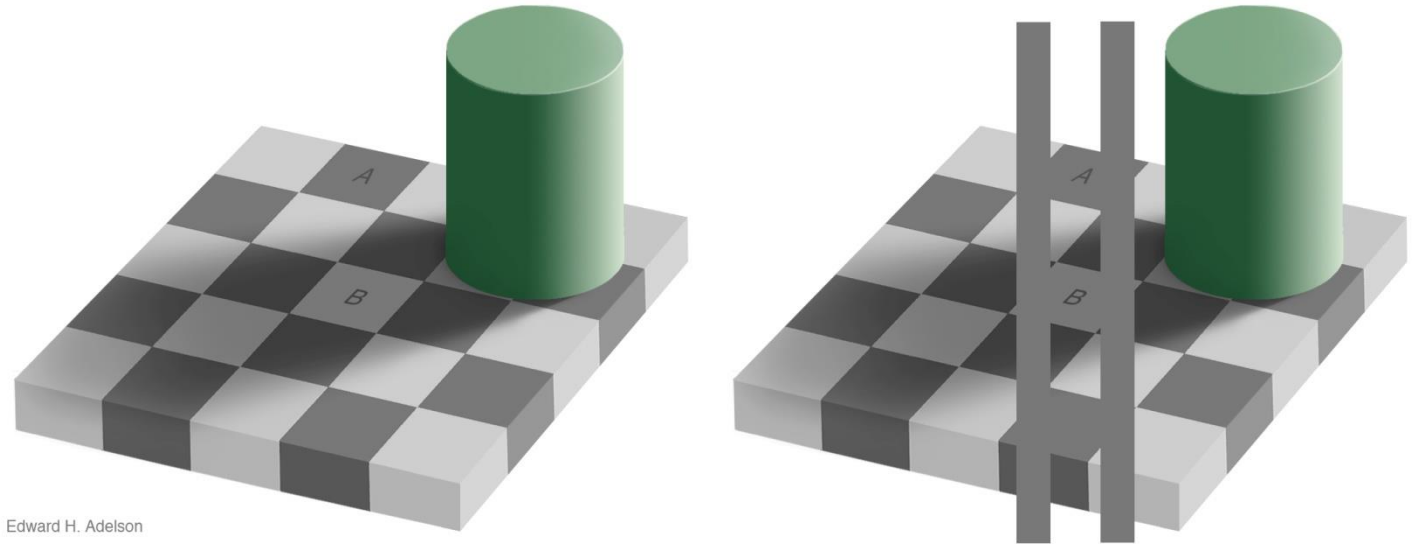
Brightness perception



Edward Adelson

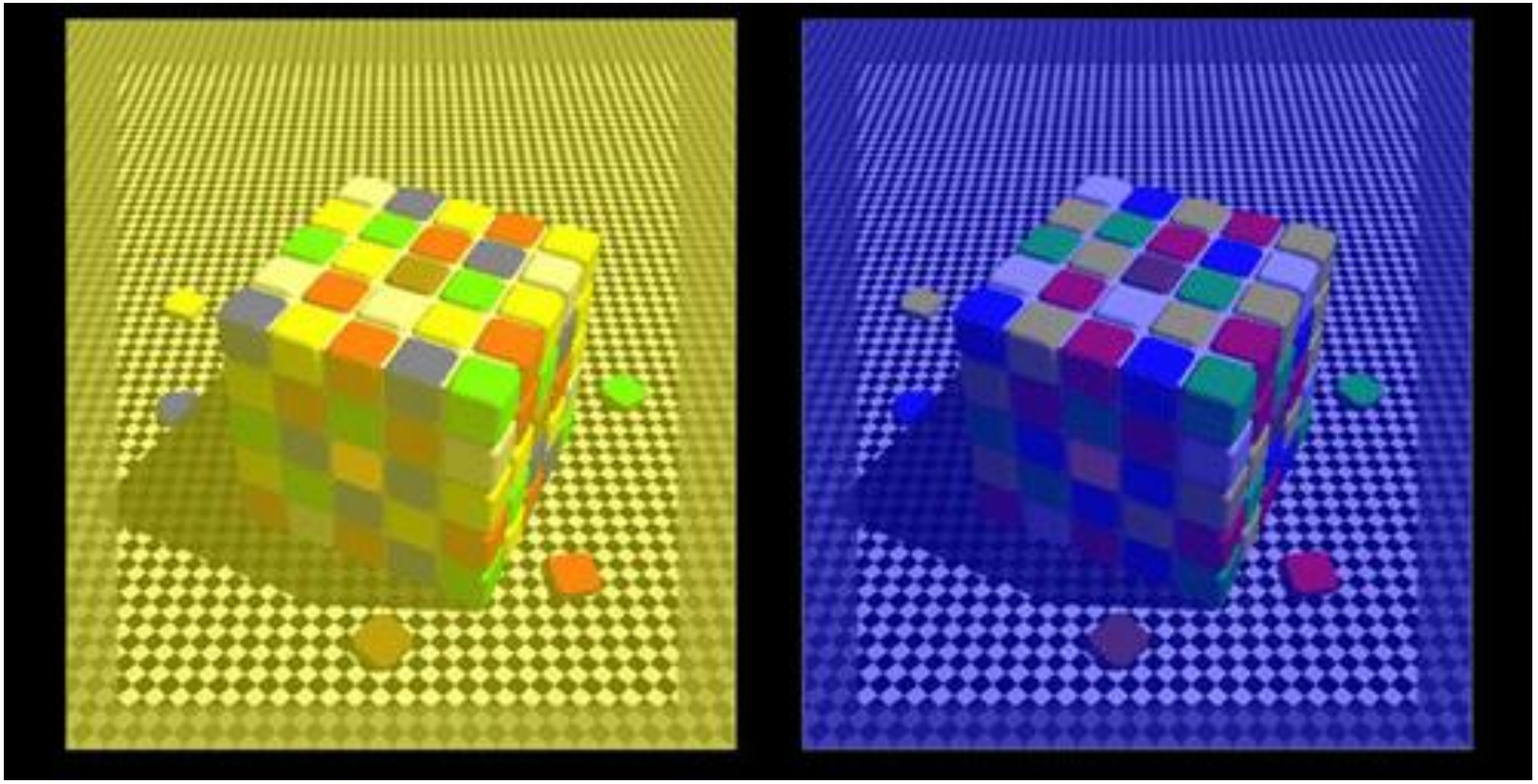
http://web.mit.edu/persci/people/adelson/illusions_demos.html

Brightness perception



Edward Adelson

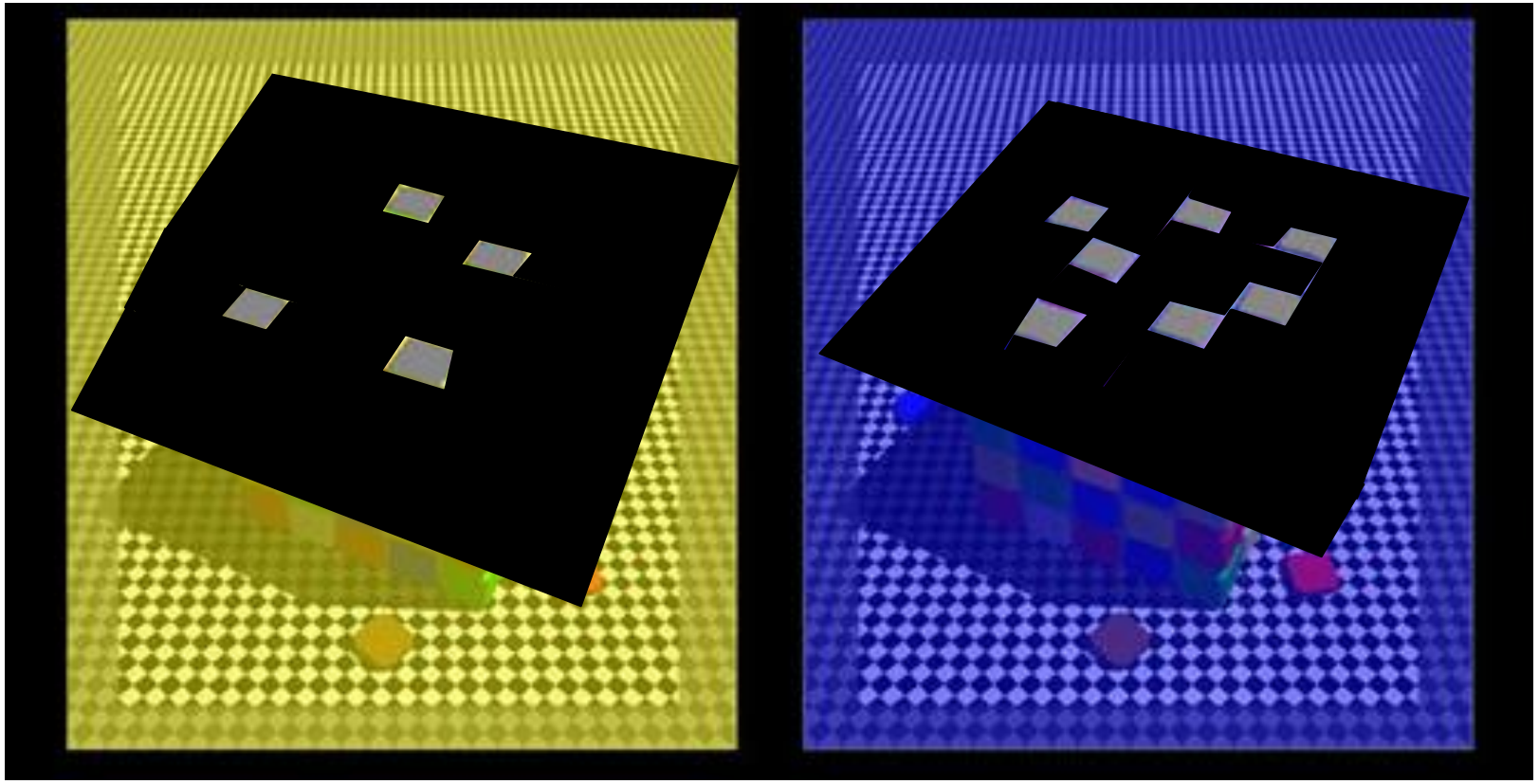
http://web.mit.edu/persci/people/adelson/illusions_demos.html



Look at blue squares

Look at yellow squares

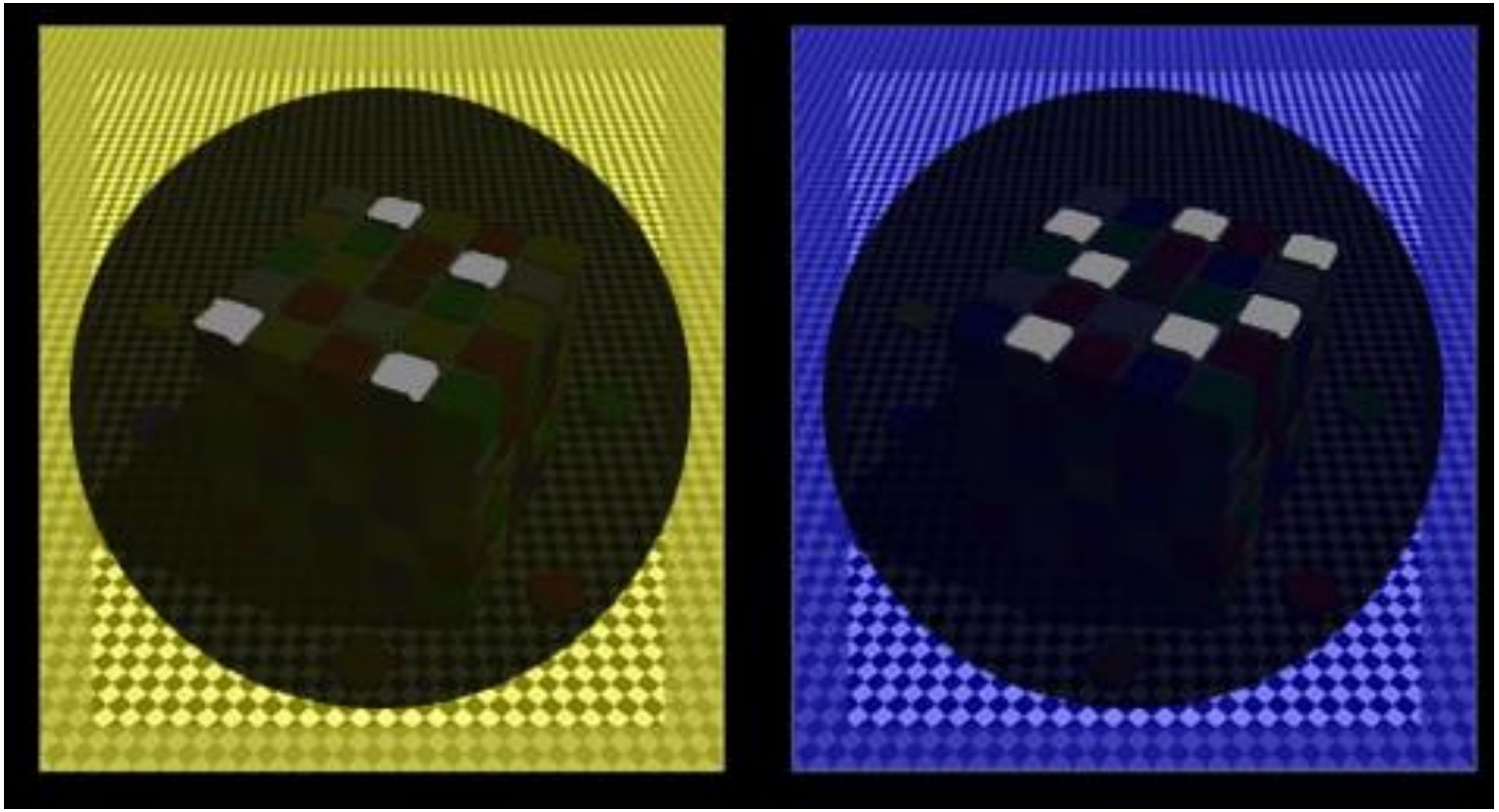
- Content © 2008 R.Beau Lotto
- http://www.lottolab.org/articles/illusionsoflight.asp



Look at blue squares

Look at yellow squares

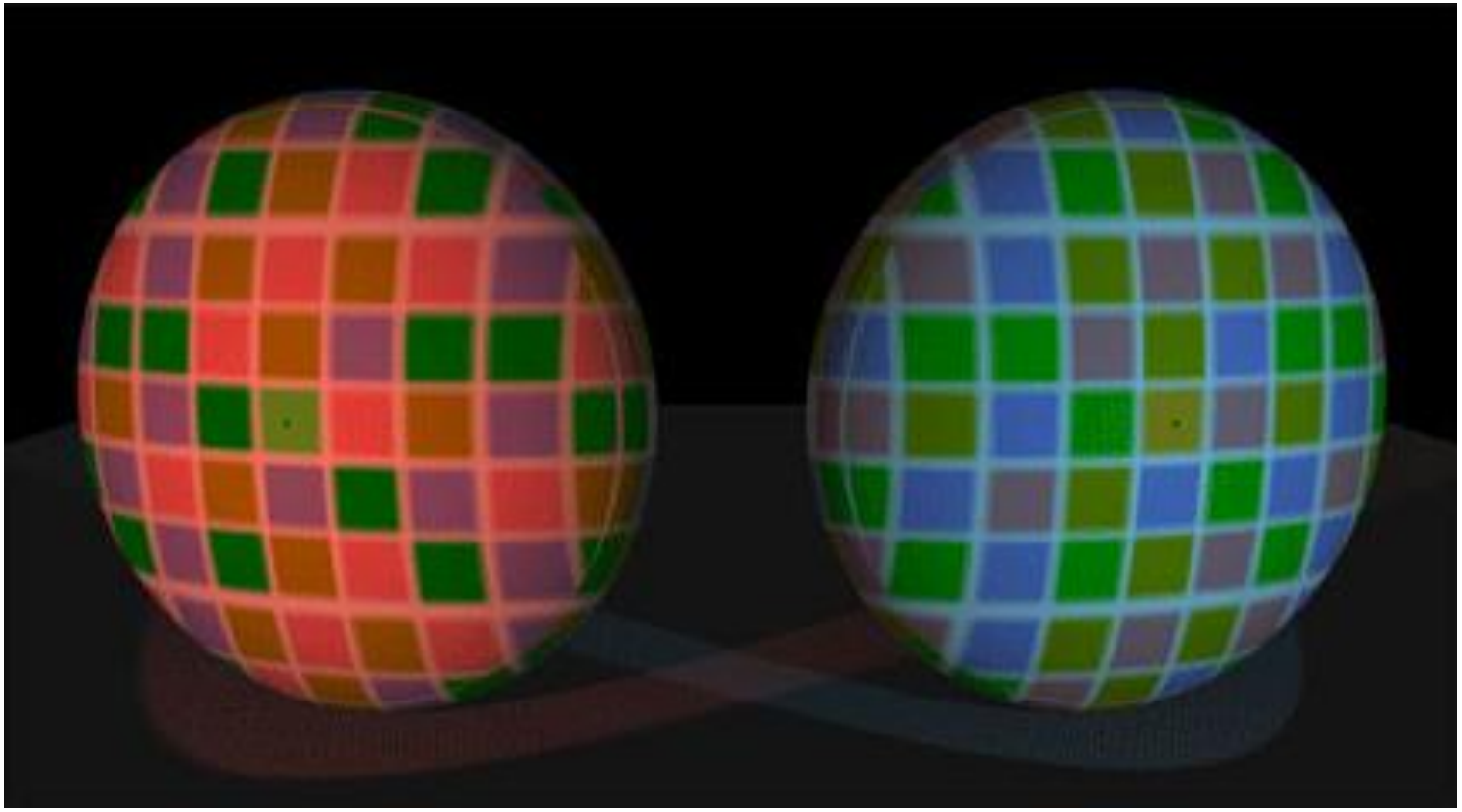
- Content © 2008 R.Beau Lotto
- http://www.lottolab.org/articles/illusionsoflight.asp



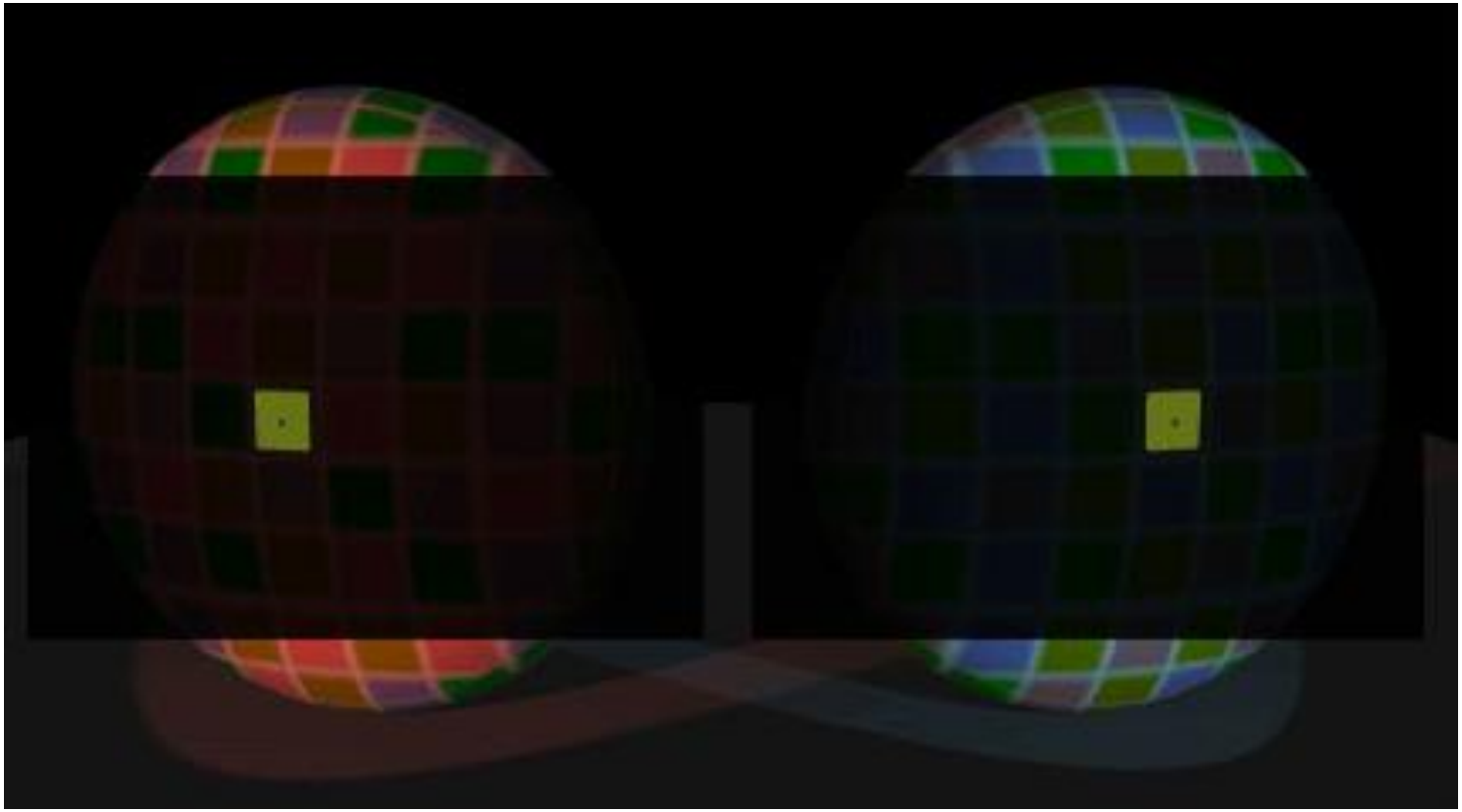
Look at blue squares

Look at yellow squares

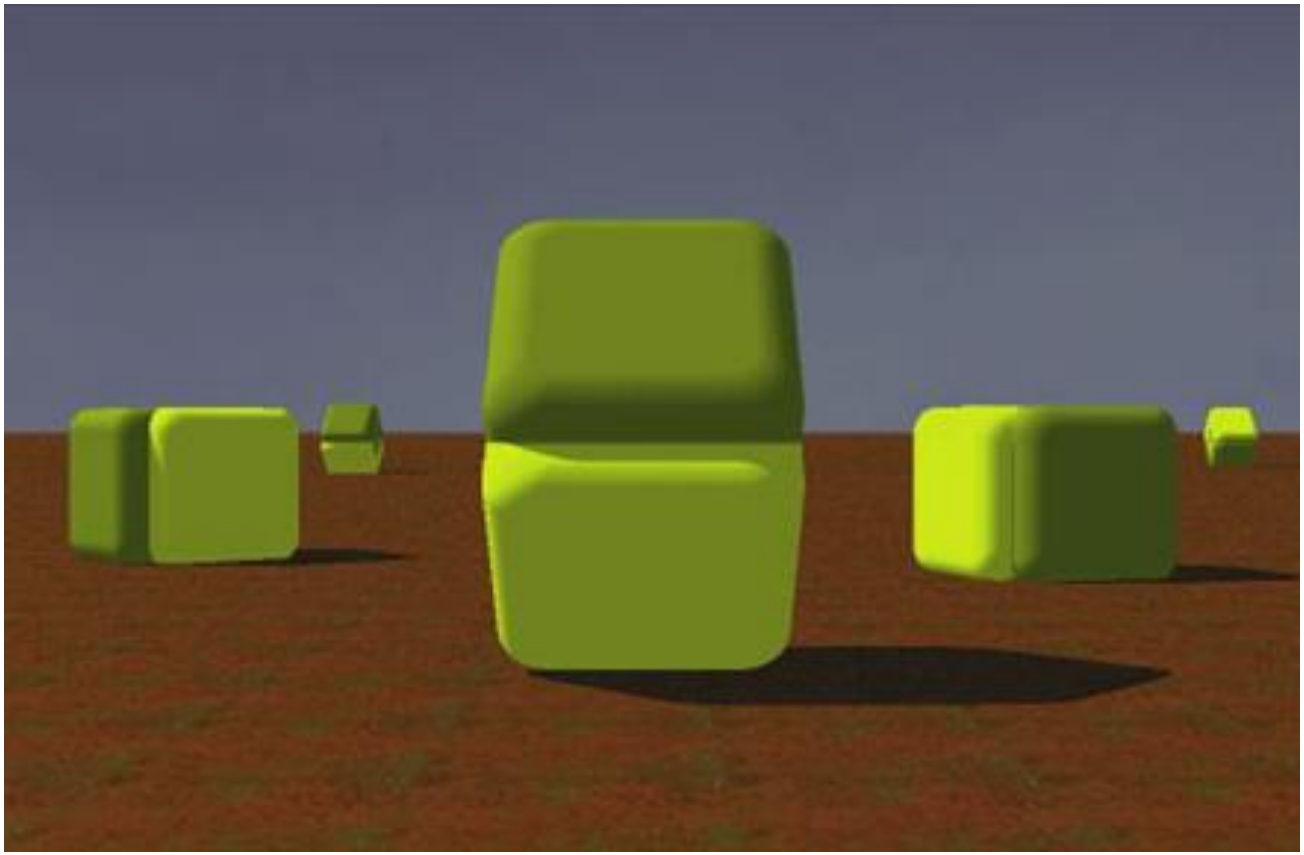
- Content © 2008 R.Beau Lotto
- http://www.lottolab.org/articles/illusionsoflight.asp



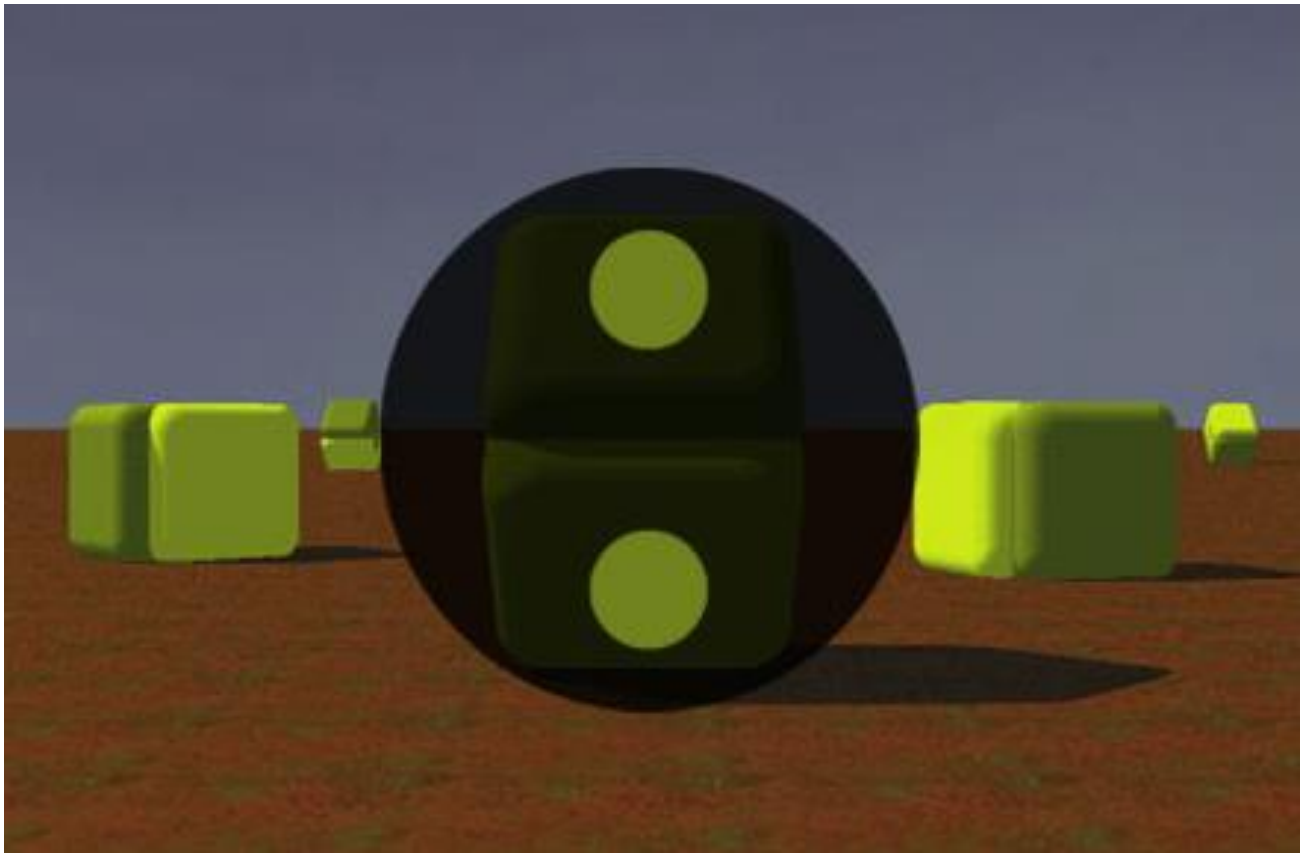
- Content © 2008 R.Beau Lotto
- http://www.lottolab.org/articles/illusionsoflight.asp



- Content © 2008 R.Beau Lotto
- http://www.lottolab.org/articles/illusionsoflight.asp



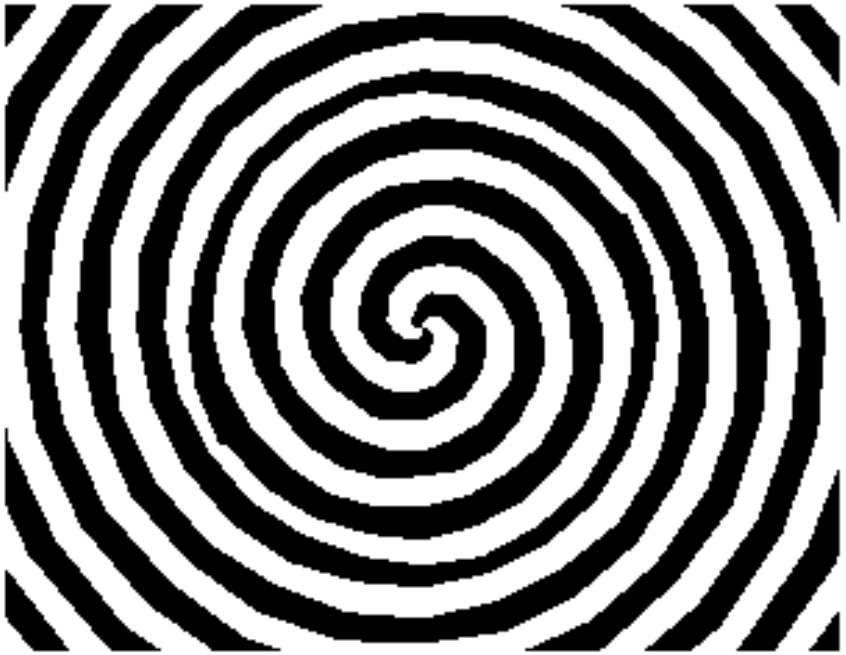
- Content © 2008 R.Beau Lotto
- http://www.lottolab.org/articles/illusionsoflight.asp



- Content © 2008 R.Beau Lotto
- http://www.lottolab.org/articles/illusionsoflight.asp

After images

- Tired photoreceptors send out negative response after a strong stimulus



http://www.sandlotscience.com/Aftereffects/Andrus_Spiral.htm

Source: Steve Seitz

After images

- Tired photoreceptors send out negative response after a strong stimulus

http://www.sandlotscience.com/Aftereffects/Andrus_Spiral.htm

Source: Steve Seitz

Name that color

High level interactions affect perception and processing.

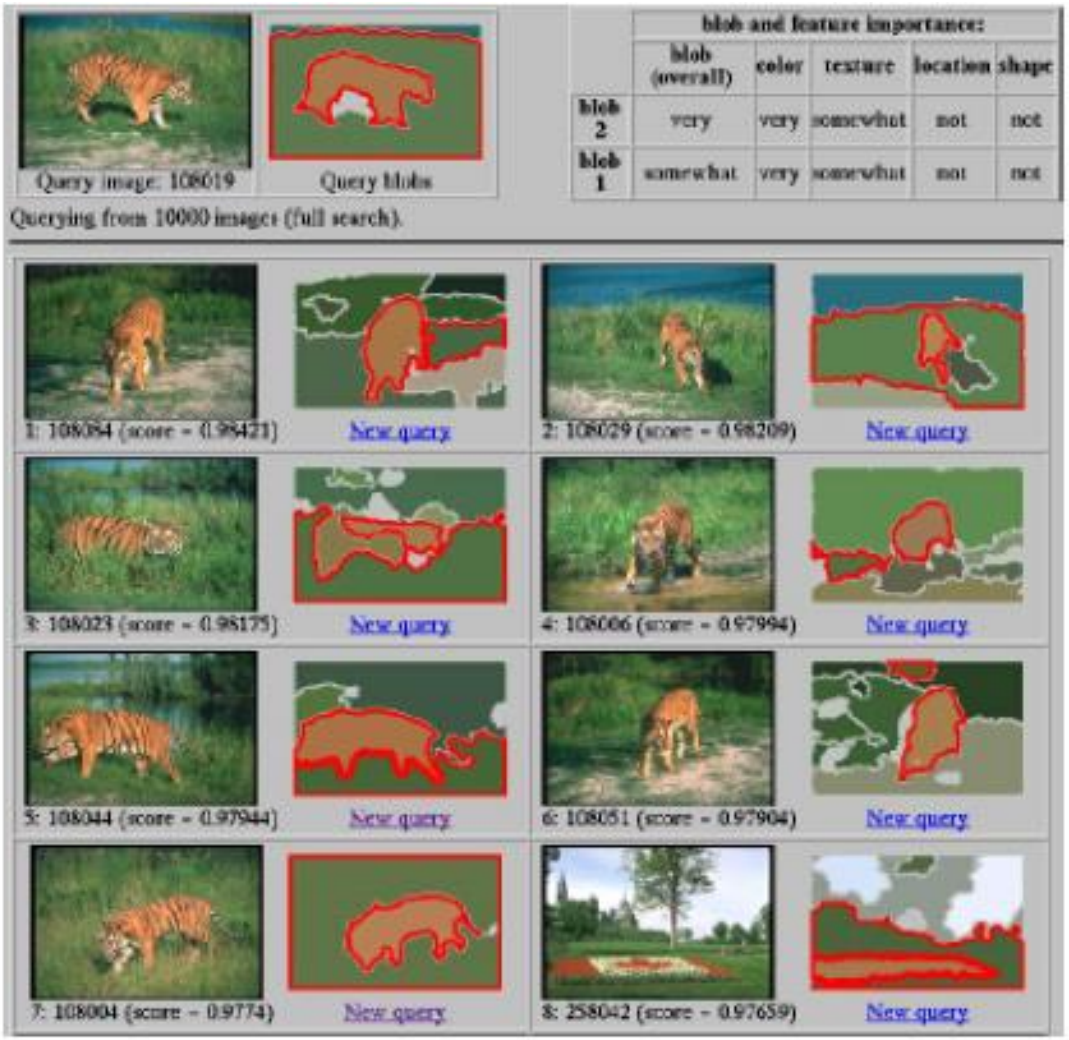
Today: Color

- Measuring color
  - Spectral power distributions
  - Color mixing
  - Color matching experiments
  - Color spaces
    - Uniform color spaces

- Perception of color
  - Human photoreceptors
  - Environmental effects, adaptation

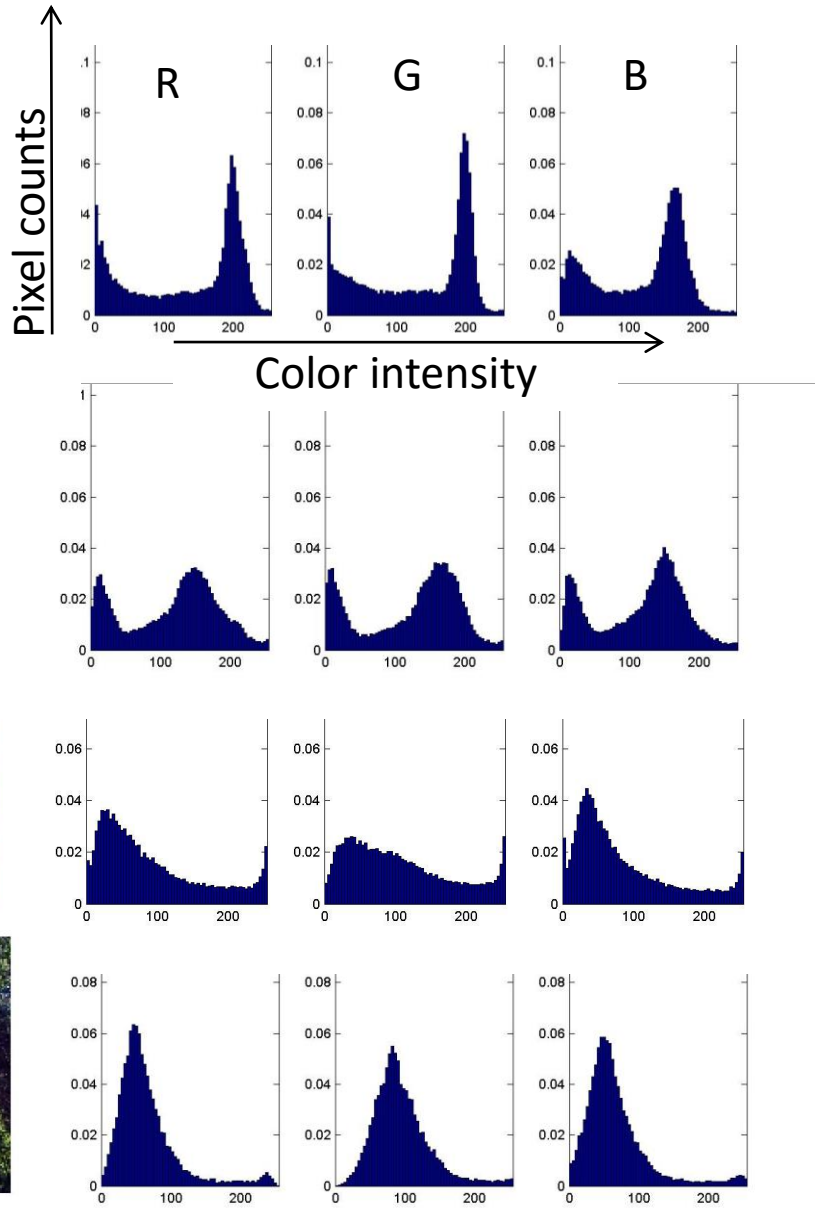
- Using color in machine vision systems

Color as a low-level cue for CBIR



Blobworld system, Carson et al, 1999

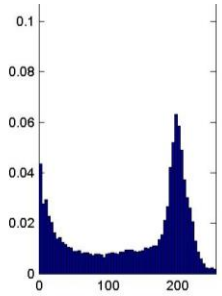
Color as a low-level cue for CBIR

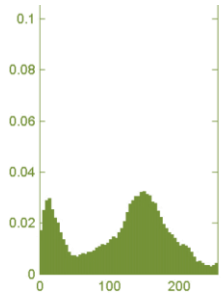


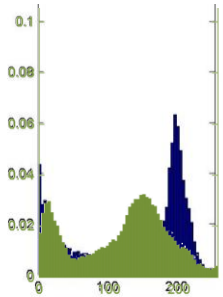
- Color histograms: Use distribution of colors to describe image
- No spatial info – invariant to translation, rotation, scale

Color as a low-level cue for CBIR

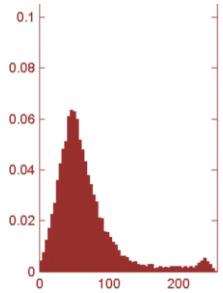
Compute distance between histograms: Intersection

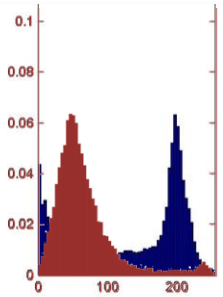






Similar





Different

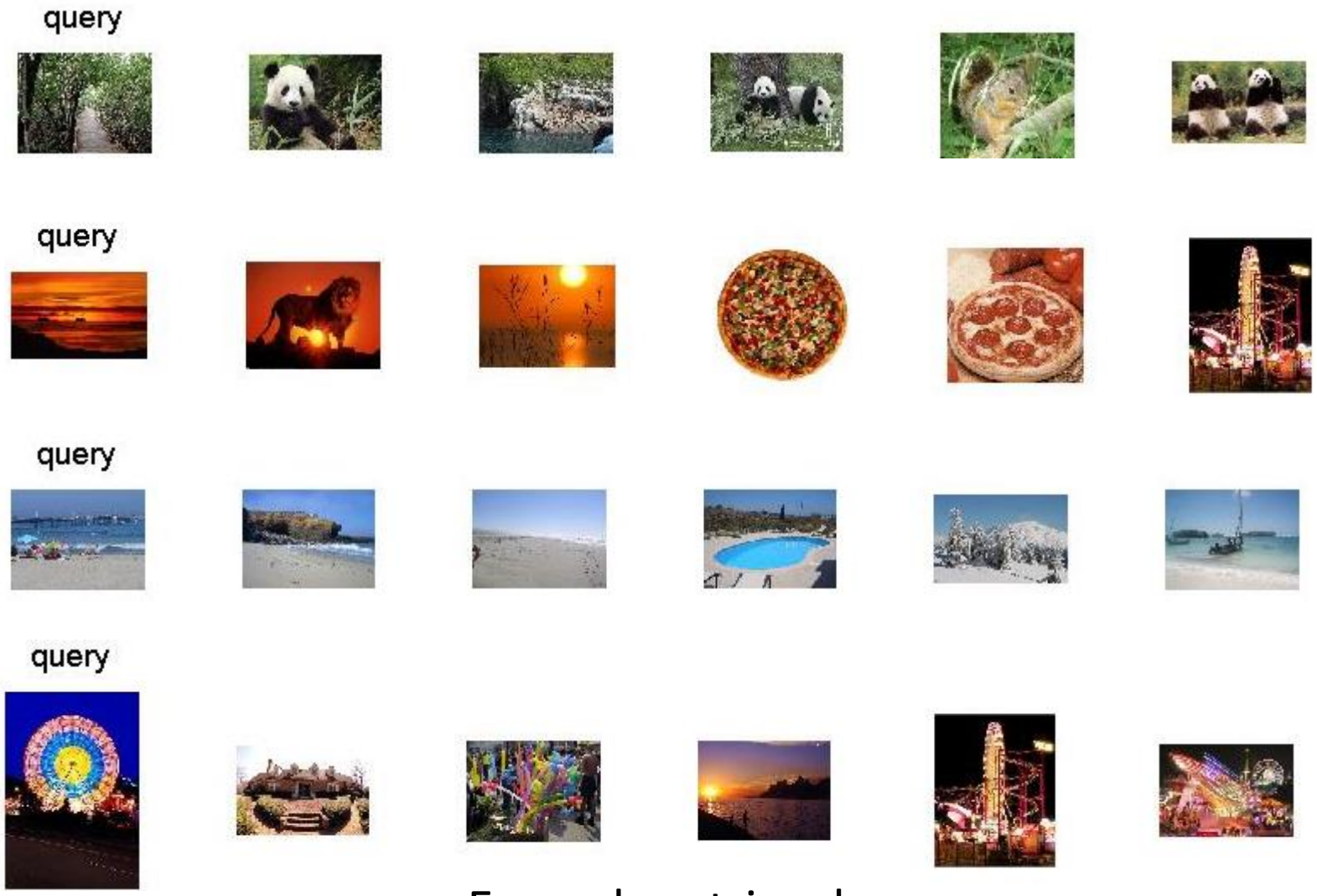
Color-based image retrieval

- Given a collection (database) of images:
  - Extract and store one color histogram per image
- Given new query image:
  - Extract its color histogram
  - For each database image:
    - Compute intersection between query histogram and database histogram
  - Sort intersection values (highest score = most similar)
  - Rank database items relative to query based on this sorted order

Color-based image retrieval

Example database

Color-based image retrieval

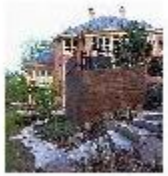


Example retrievals

Color-based image retrieval

query

query



query

Example retrievals

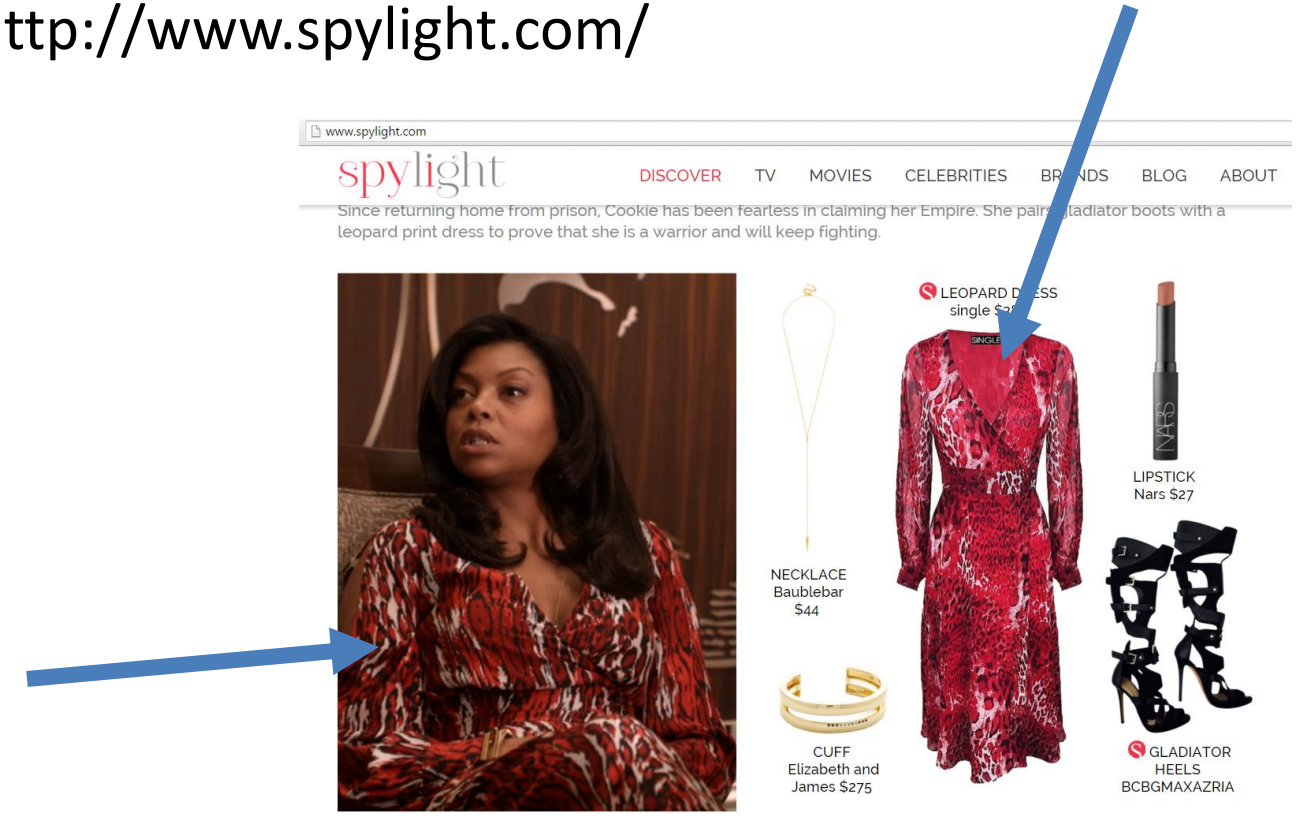
http://images.google.com/

- Search for similar images. Try:

- Buildings
- Dogs
- Concert

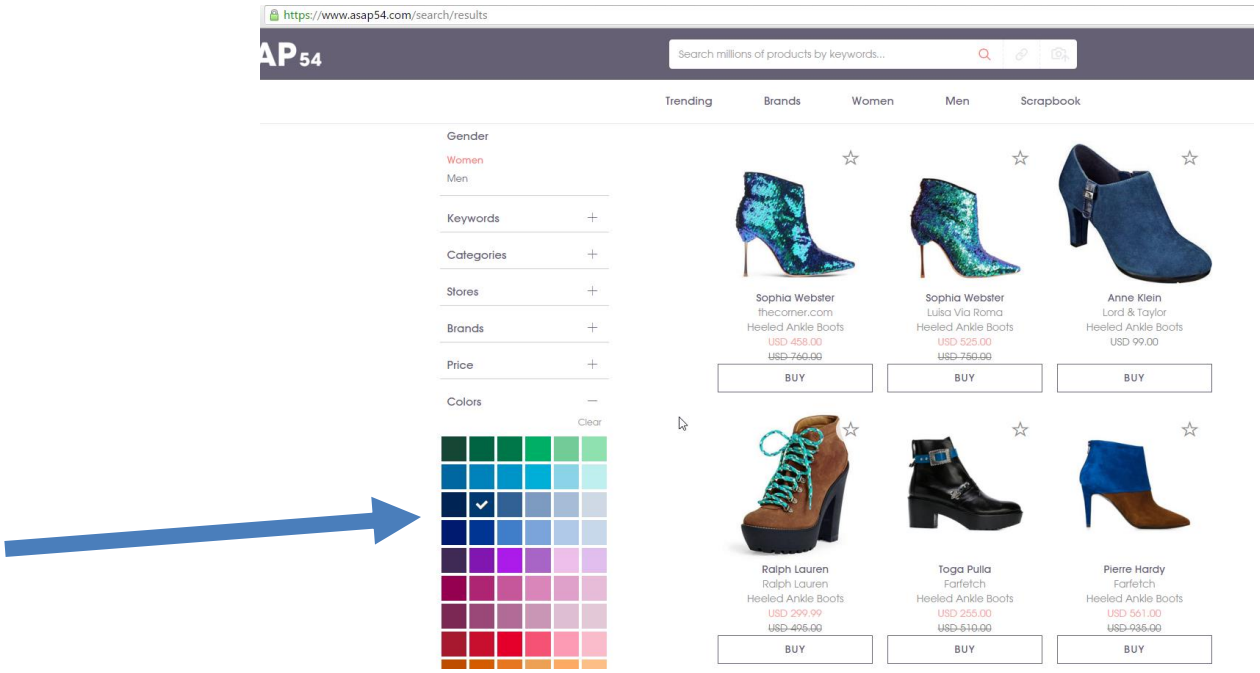
Shazam for Fashion

- There are several products doing that.
- They have to deal with color similarity:
  - E.g.: http://www.spylight.com/



Shazam for Fashion

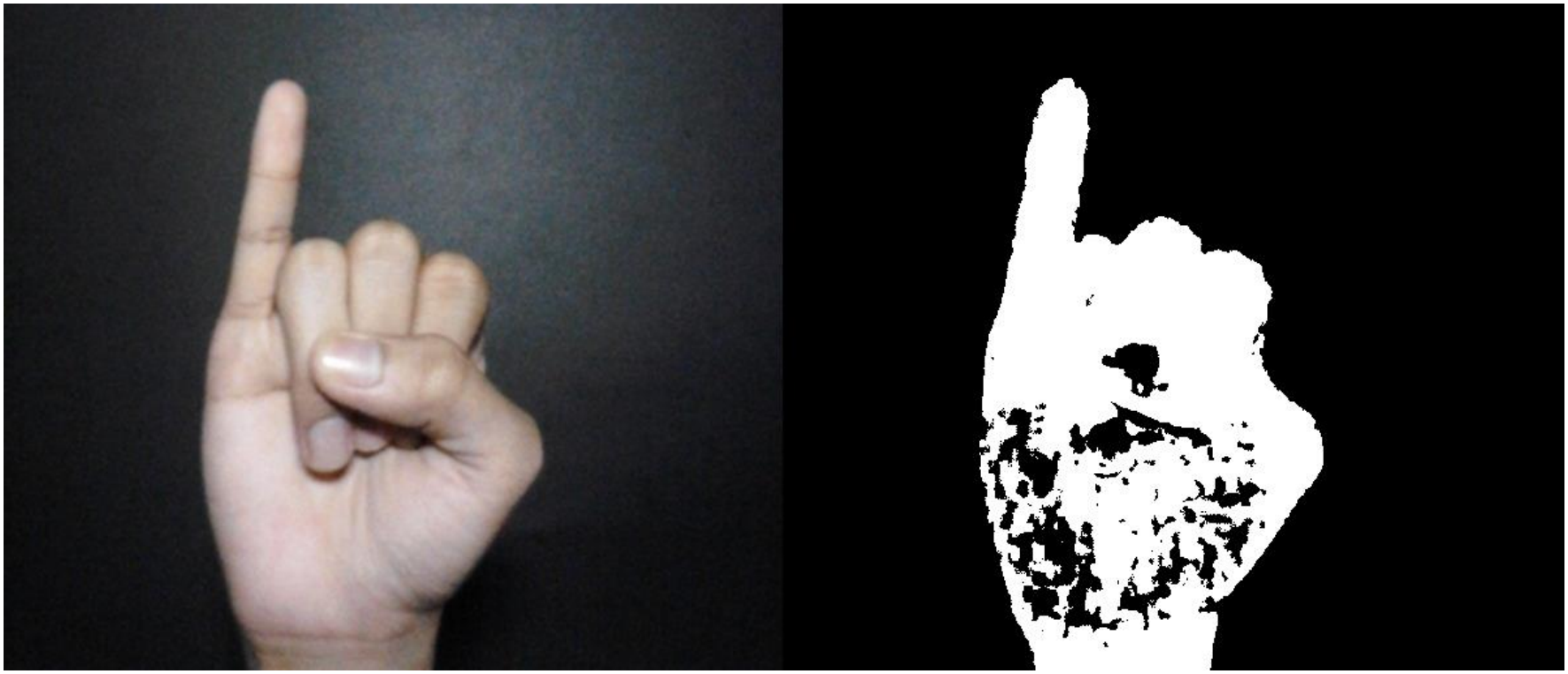
- There are several products doing that.
- They have to deal with color similarity:
  - E.g.: http://www.asap54.com/



Color-based skin detection

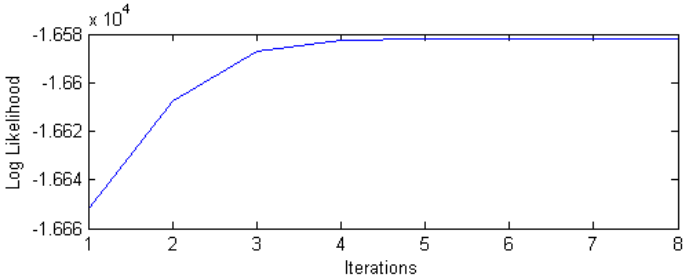
M. Jones and J. Rehg, Statistical Color Models with Application to Skin Detection, IJCV 2002.

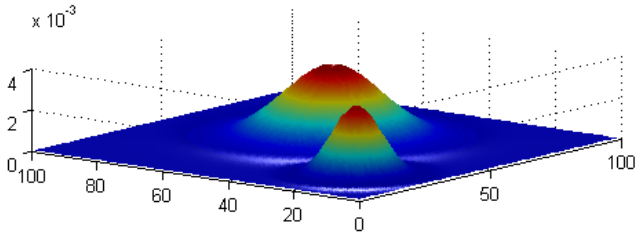
Color-based skin detection



Color-based skin detection

http://www.ghvandoorn.nl/skindetection.html



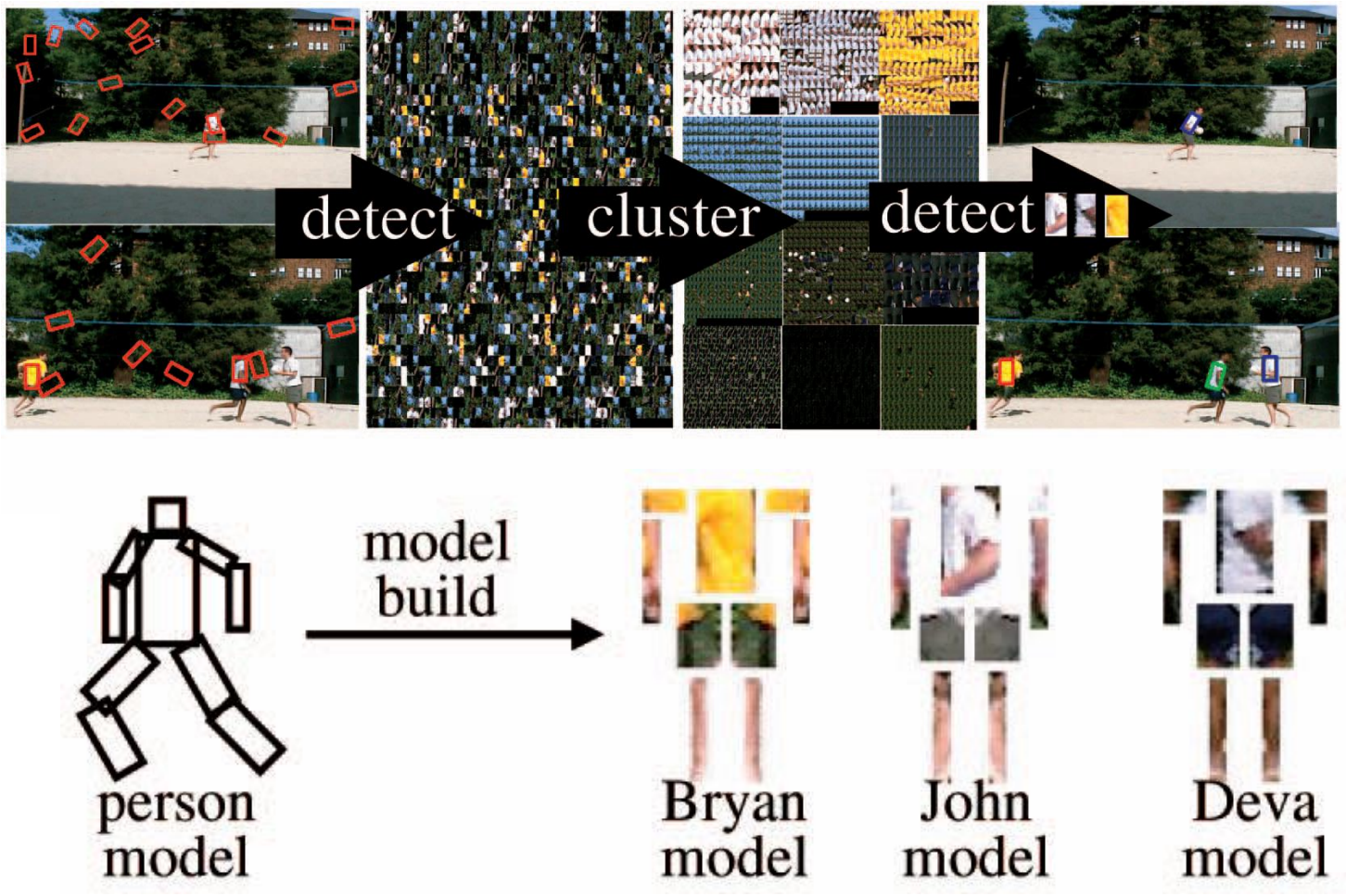


Color-based skin detection

OpenCV

https://www.youtube.com/watch?v=vZk9k9azonw

Color-based tracking



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

Slide credit: L. Lazebnik

Color-based tracking

- http://www.roborealm.com/tutorial/color_object_tracking_2/slide010.php

- https://www.youtube.com/watch?v=WPnWDGl3XZc

Viewing Colored Objects

- Assume diffuse (Lambertian) plus specular model
- Diffuse component
  — colour of reflected light depends on both illuminant and surface
- Specular component
  — specularities on dielectric (non-metalic) objects take the colour of the light
  — specularities on metals have colour of the metal

Slide Credits

- Trevor Darrell
- Kristen Grauman: 3-48, 50-75, 79-86
- Bob Woodham: 49, 87-90
- and others, indirectly (Steve Palmer, Brian Wandell, etc!)

Today: Color

- Measuring color
  - Spectral power distributions
  - Color mixing
  - Color matching experiments
  - Color spaces
    - Uniform color spaces
- Perception of color
  - Human photoreceptors
  - Environmental effects, adaptation
- Using color in machine vision systems