Color

April 16th, 2015

Yong Jae Lee
UC Davis

Today

- 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

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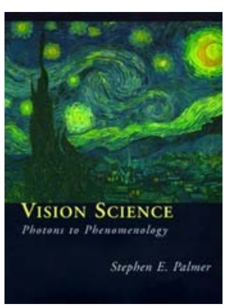
Slide credit: Kristen Grauman

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.



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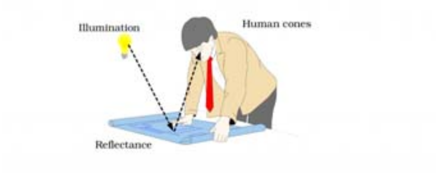
Slide credit: Lana Lazebnik

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



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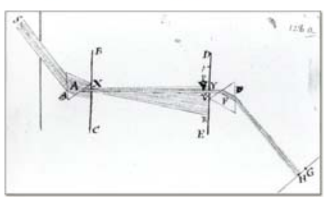
Slide credit adapted from Kristen Grauman

Image from *Foundations of Vision*, B. Wandell

Color and light

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



Newton 1665

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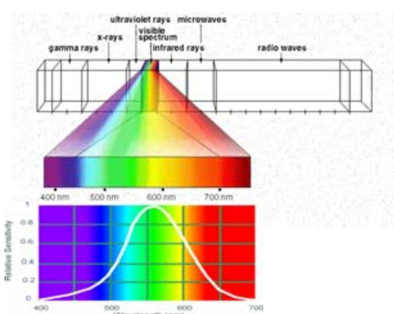
Image from http://micro.magnet.fsu.edu/

Electromagnetic spectrum



Human Luminance Sensitivity Function

Image credit: nasa.gov

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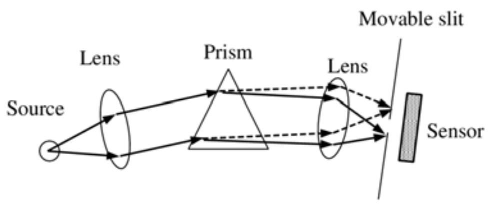
Measuring spectra



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

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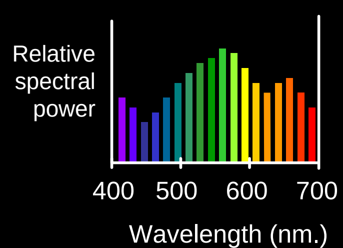
Slide adapted from Kristen Grauman

Foundations of Vision, B. Wandell

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.



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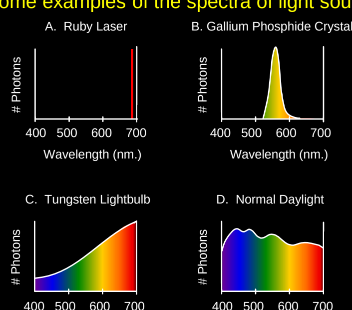
Spectral power distributions

Some examples of the spectra of light sources



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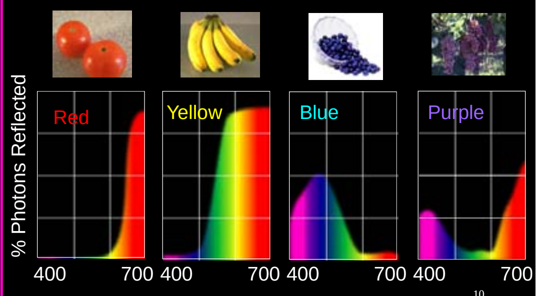
Surface reflectance spectra

Some examples of the reflectance spectra of surfaces



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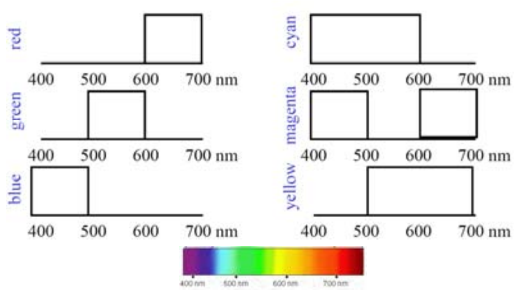
Color mixing

Cartoon spectra for color names:



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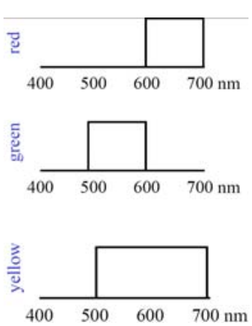
Additive color mixing



Colors combine by *adding* color spectra

Light *adds* to black.

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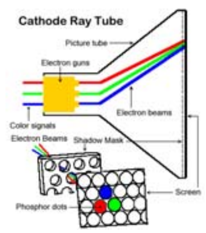
Examples of additive color systems



CRT phosphors

multiple projectors

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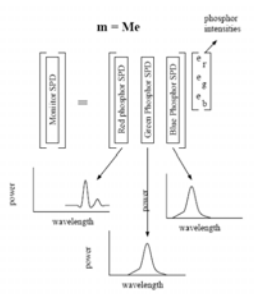
Superposition



Additive color mixing:
The spectral power distribution of the mixture is the sum of the spectral power distributions of the components.

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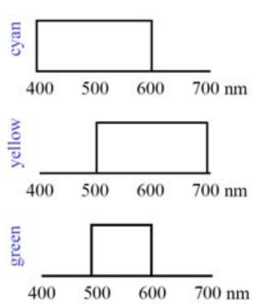
Figure from B. Wandell, 1996

Subtractive color mixing



Colors combine by *multiplying* color spectra.

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

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Slide credit: Bill Freeman

Examples of subtractive color systems

- Printing on paper
- Crayons
- Photographic film

An 1877 color photo by Louis Ducos du Hauron, a French pioneer of color photography

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Slide credit: Kristen Grauman

How to know if people perceive the same color?

- Important to reproduce color reliably
  - Commercial products, digital imaging/art
- Only a few color names recognized widely
  - English ~11: black, blue, brown, grey, green, orange, pink, purple, red, white, and yellow
- We need to specify numerically
  - **Question**: What spectral radiances *produce the same response* from people under simple viewing conditions?

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Color matching experiments

- **Goal**: find out what spectral radiances produce same response in human observers.

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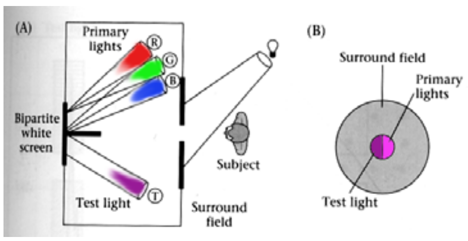
Color matching experiments



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

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Slide credit: Kristen Grauman

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

After Judd & Wyszecki.

Color matching experiments

- **Goal**: find out what spectral radiances produce same response in human observers.
- **Assumption**: simple viewing conditions, where we say test light alone affects perception
  - Ignoring additional factors for now like adaptation, complex surrounding scenes, etc.

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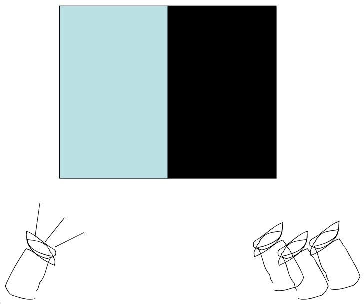
Color matching experiment 1



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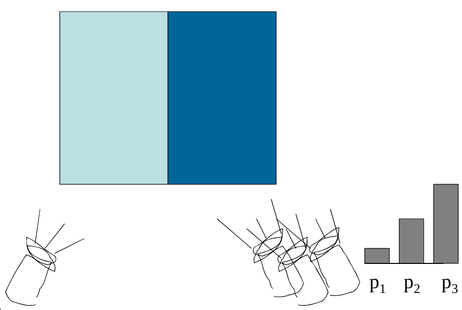
Color matching experiment 1



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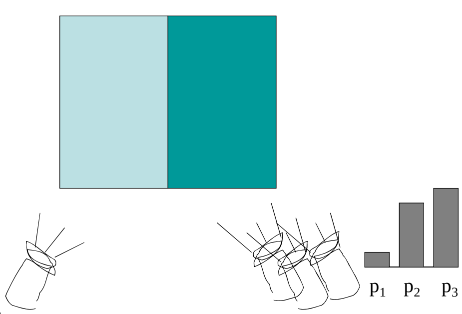
Color matching experiment 1



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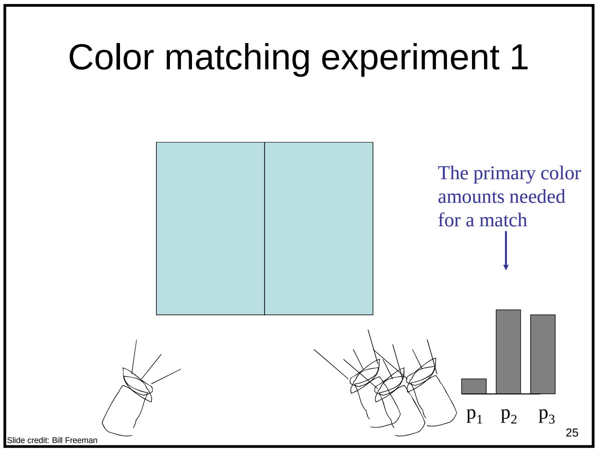
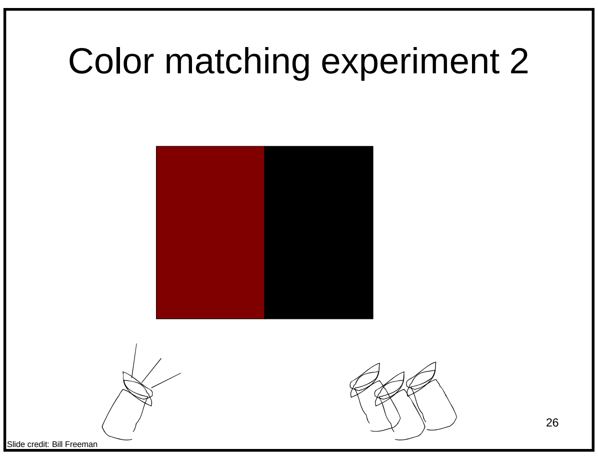

Color matching experiment 1
The primary color amounts needed for a match
p1 p2 p3
25
Slide credit: Bill Freeman


Color matching experiment 2
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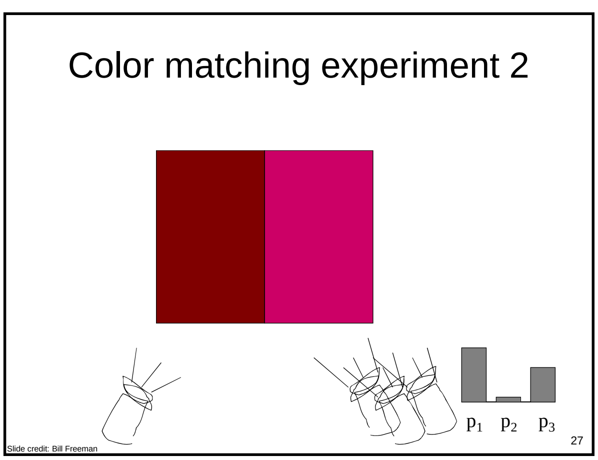
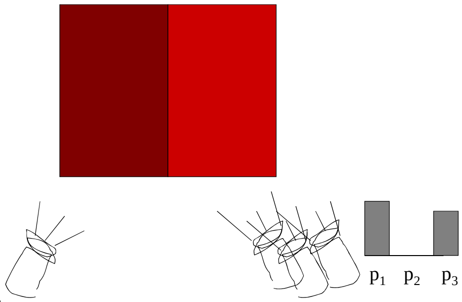
Slide credit: Bill Freeman


Color matching experiment 2
p1 p2 p3
27
Slide credit: Bill Freeman

Color matching experiment 2



Slide credit: Bill Freeman

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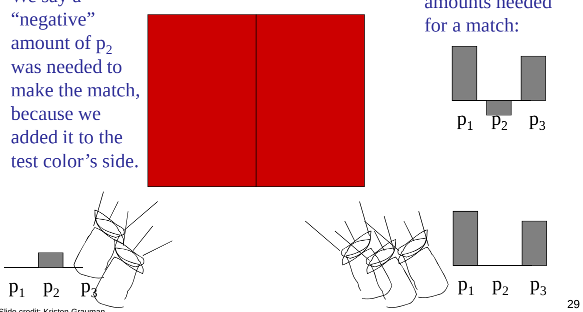
Color matching experiment 2

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:



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Color matching

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

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Metamers

- If observer says a mixture is a match → receptor excitations of both stimuli must be equal.
- But lights forming a *perceptual* match still may be *physically* different
  - Match light: must be combination of primaries
  - Test light: any light
- **Metamers**: pairs of lights that match perceptually but not physically

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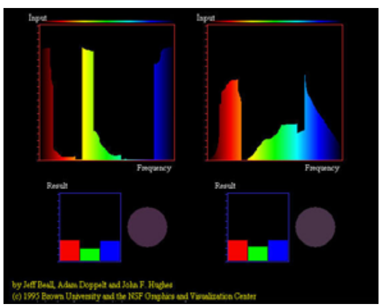
Metamers



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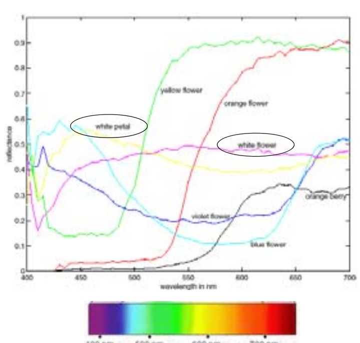
Slide credit: Devi Parikh

Metamers



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Forsyth & Ponce, measurements by E. Koivisto

Slide credit: Kristen Grauman

Grassman's laws

- If two test lights can be matched with the same set of weights, then they match each other:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = u_1 P_1 + u_2 P_2 + u_3 P_3$. Then $A = B$.
- If we scale the test light, then the matches get scaled by the same amount:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$. Then $kA = (ku_1) P_1 + (ku_2) P_2 + (ku_3) P_3$.
- If we mix two test lights, then mixing the matches will match the result (superposition):
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = v_1 P_1 + v_2 P_2 + v_3 P_3$. Then $A+B = (u_1+v_1) P_1 + (u_2+v_2) P_2 + (u_3+v_3) P_3$.

Here "=" means "matches".

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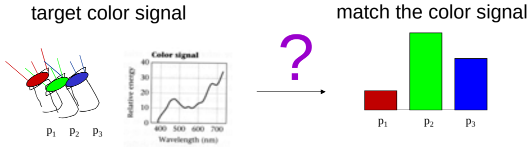
How to compute the weights of the primaries to match any new spectral signal?

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

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



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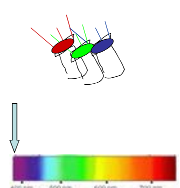
Computing color matches

1. Given primaries
2. Estimate their *color matching functions*: observer matches series of monochromatic lights, one at each wavelength.
3. To compute weights for new test light, multiply with matching functions.



$$\mathbf{C} = \begin{pmatrix} c_1(\lambda_1) \\ c_2(\lambda_1) \\ c_3(\lambda_1) \end{pmatrix}$$

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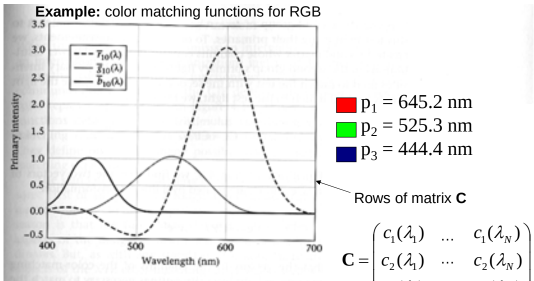
Computing color matches



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

Rows of matrix **C**

$$\mathbf{C} = \begin{pmatrix} c_1(\lambda_1) & \dots & c_1(\lambda_N) \\ c_2(\lambda_1) & \cdots & c_2(\lambda_N) \\ c_3(\lambda_1) & \cdots & c_3(\lambda_N) \end{pmatrix}$$

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

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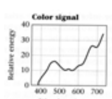
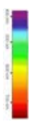
Slide credit: Bill Freeman

Computing color matches

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



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



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

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

$$\mathbf{e} = \mathbf{Ct}$$

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Slide credit: Kristen Grauman

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.

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Image credit: pbs.org

Slide credit: Adapted from Bill Freeman by Kristen Grauman

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Slide credit: Kristen Grauman

Standard color spaces

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

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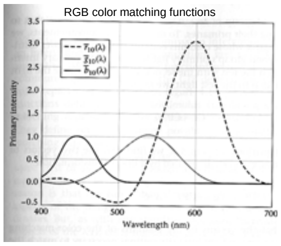
RGB color space

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

RGB color matching functions



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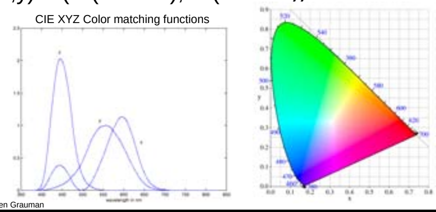
CIE XYZ color space

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

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



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HSV color space

- **H**ue, **S**aturation, **V**alue
- Nonlinear – reflects topology of colors by coding **hue** as an angle
- Matlab: `hsv2rgb`, `rgb2hsv`.

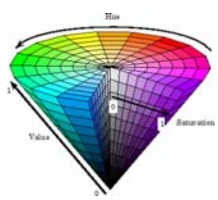

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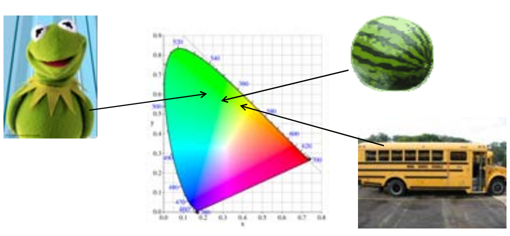
Image from mathworks.com

Distances in color space

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



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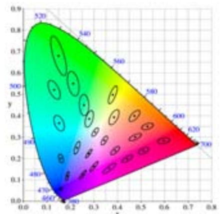
Distances in color space

- 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

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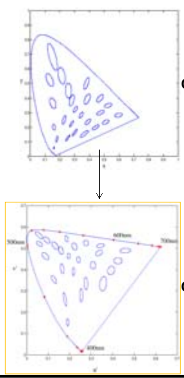
Slide credit: Kristen Grauman

Uniform color spaces

- Attempt to correct this limitation by remapping color space so that just-noticeable differences are contained by circles → distances more perceptually meaningful.
- Examples:
  - CIE u’v’
  - CIE Lab



CIE XYZ

CIE u’v’

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Slide credit: Kristen Grauman

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

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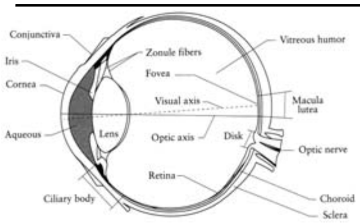
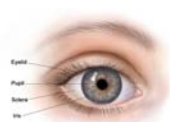
The Eye





The human eye is a camera!

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

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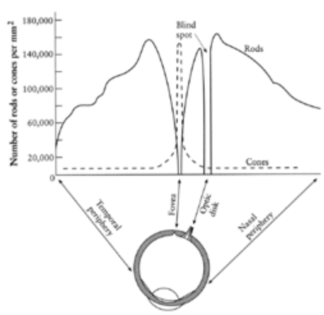
Slide credit: Steve Seitz

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



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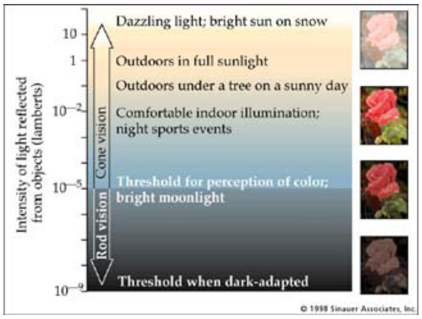
Slide credit: Alyosha Efros

Rod / Cone sensitivity

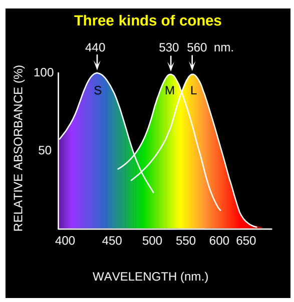


Why can't we read in the dark?

Slide by A. Efros

Types of cones

- 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 per person, and with age
- Color blindness: deficiency in at least one type of cone



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Slide credit: Kristen Grauman

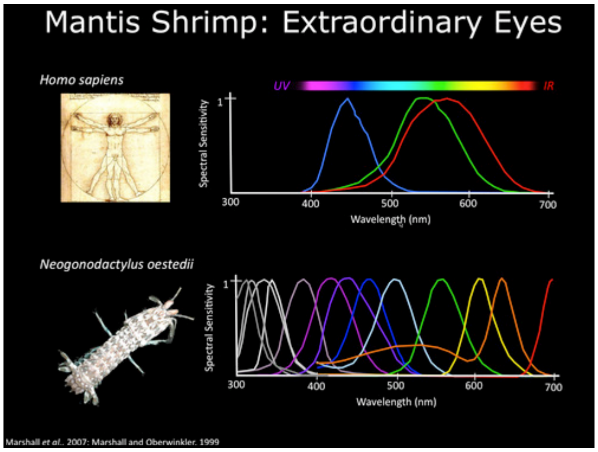
Physiology of Color Vision: Fun facts

- "M" and "L" pigments are encoded on the X-chromosome
  - That's why men are more likely to be color blind
    http://www.vischeck.com/vischeck/vischeckURL.php
- 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://www.mezzmer.com/blog/how-animals-see-the-world/

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

Slide by D. Hoiem



Types of cones

Possible evolutionary pressure for developing receptors for different wavelengths in primates

Osorio & Vorobyev, 1996

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Slide adapted from Kristen Grauman

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)

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Slide credit: Kristen Grauman

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**

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Slide credit: Kristen Grauman

Chromatic adaptation

- If the visual system is exposed to a certain illuminant for a while, color system starts to adapt / skew
- Adapting to different brightness levels
  - Changing the size of the iris opening changes the amount of light that can enter the eye
- Adapting to different color temperature
  - For example: if there is an increased amount of red light, the cells receptive to red decrease their sensitivity until the scene looks white again

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Chromatic adaptation

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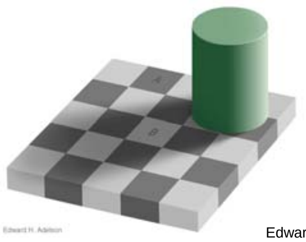
Slide credit: Kristen Grauman

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

Brightness perception

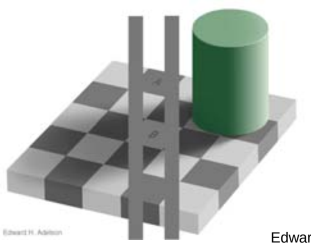


Edward Adelson

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

61

Slide credit: Kristen Grauman

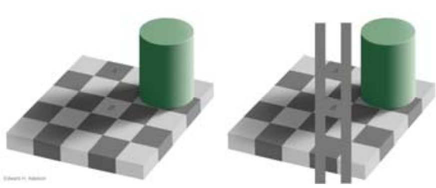


Edward Adelson

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

62

Slide credit: Kristen Grauman

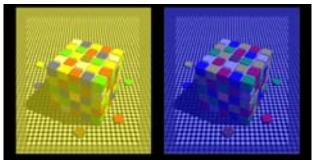


Edward Adelson

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

63

Slide credit: Kristen Grauman



Look at blue squares

Look at yellow squares

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- http://www.lottolab.org/articles/illusionsoflight.asp

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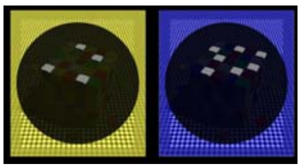
Slide credit: Kristen Grauman



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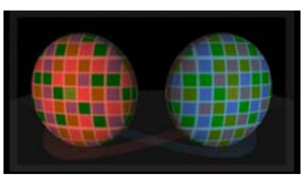
- http://www.lottolab.org/articles/illusionsoflight.asp

65

Slide credit: Kristen Grauman



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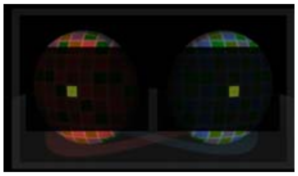
- http://www.lottolab.org/articles/illusionsoflight.asp

66

Slide credit: Kristen Grauman



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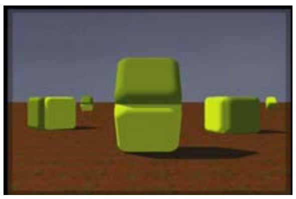
Slide credit: Kristen Grauman



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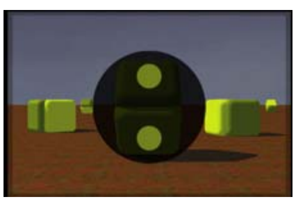
Slide credit: Kristen Grauman



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- http://www.lottolab.org/articles/illusionsoflight.asp

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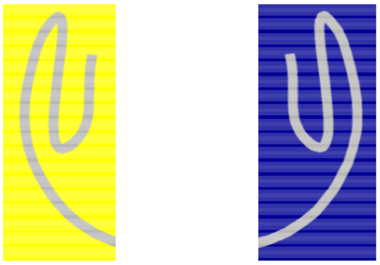
Slide credit: Kristen Grauman

Contrast effects



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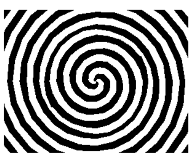
Slide credit: Kristen Grauman

After images

- Tired photoreceptors send out negative response after a strong stimulus



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

http://www.michaelbach.de/ot/mot_adaptSpiral/index.html

Slide credit: Steve Seitz

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Name that color

Blue Red Green Cyan
Magenta Black Pink
Yellow Orange Violet
Brown Purple Cyan
Indigo Red Green Blue

High level interactions affect perception and processing.

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Slide credit: Kristen Grauman

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 computer vision systems

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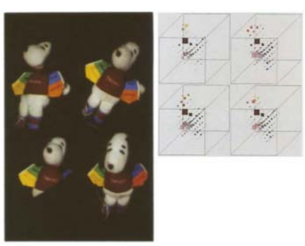
Slide credit: Kristen Grauman

Color as a low-level cue for CBIR



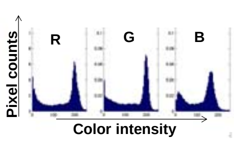
Swain and Ballard, Color Indexing, IJCV 1991

Blobworld system
Carson et al, 1999

74

Slide credit: Kristen Grauman

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

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Slide credit: Kristen Grauman


Color-based image retrieval
Example database
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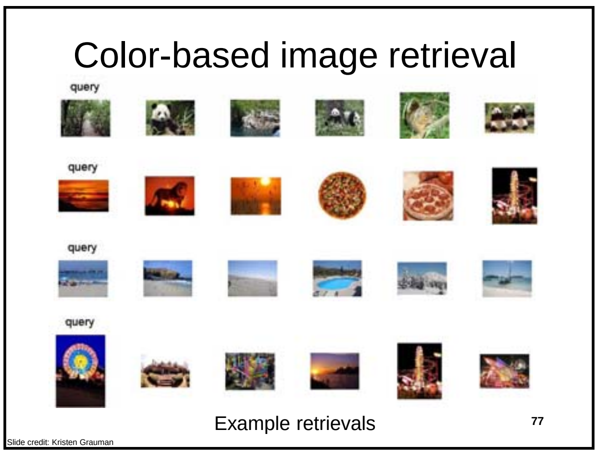
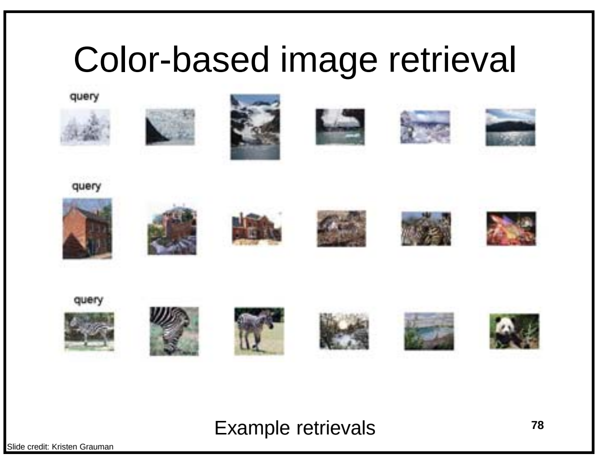
Slide credit: Kristen Grauman


Color-based image retrieval
query
query
query
query
Example retrievals
77
Slide credit: Kristen Grauman


Color-based image retrieval
query
query
query
Example retrievals
78
Slide credit: Kristen Grauman

Color-based image retrieval

- Given 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

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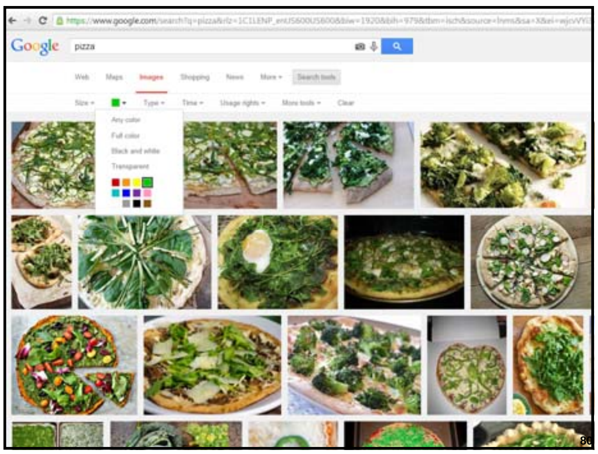
Slide credit: Kristen Grauman



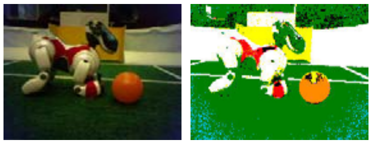
Color-based skin detection

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

81

Slide credit: Kristen Grauman

Color-based segmentation for robot soccer



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

Slide credit: Kristen Grauman

Questions?

See you Tuesday!

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