Color

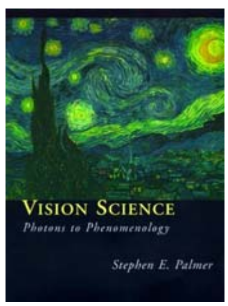
Monday, Feb 7
Prof. Kristen Grauman
UT-Austin

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

What is color?

- The result of interaction between physical light in the environment and our visual system.
- A *psychological property* of our visual experiences when we look at objects and lights, *not a physical property* of those objects or lights.



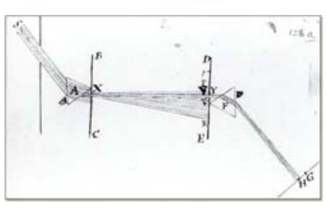
Slide credit: Lana Lazebnik

Color and light

- **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

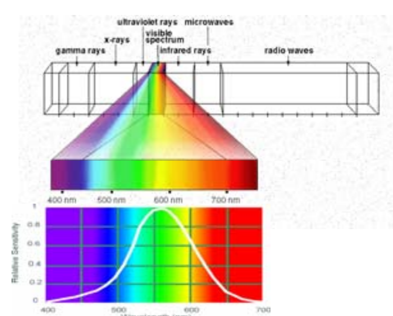
White light: composed of about equal energy in all wavelengths of the visible spectrum



Newton 1665

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

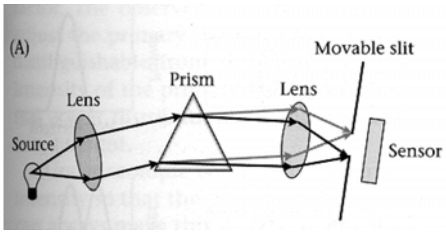
Electromagnetic spectrum



Human Luminance Sensitivity Function

Image credit: nasa.gov

Measuring spectra

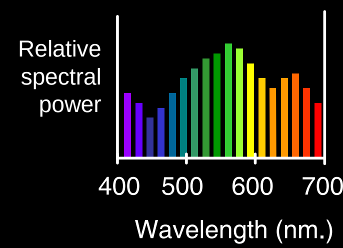


Spectroradiometer: separate input light into its different wavelengths, and measure the energy at each.

Foundations of Vision, B. Wandell

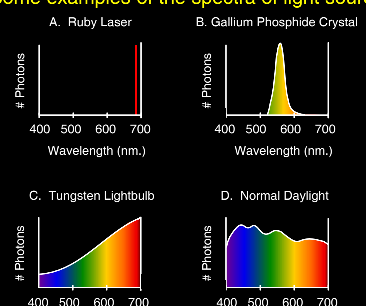
The Physics of Light

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.



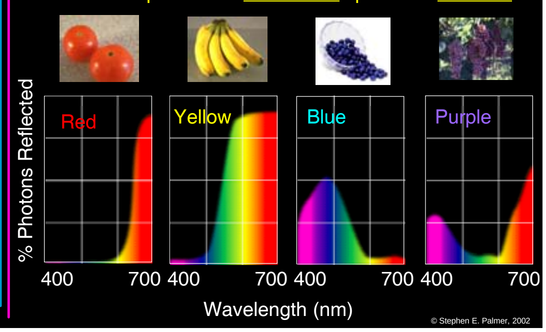
Spectral power distributions

Some examples of the spectra of light sources



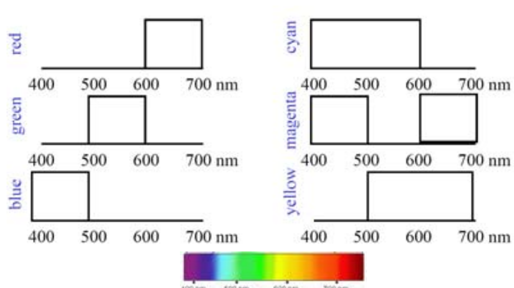
Surface reflectance spectra

Some examples of the <u>reflectance</u> spectra of <u>surfaces</u>



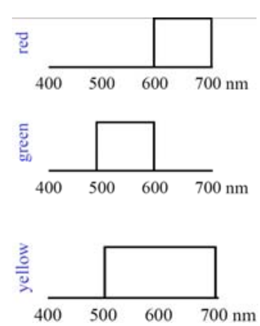
Color mixing

Cartoon spectra for color names:



Source: W. Freeman

Additive color mixing

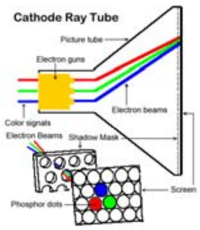


Colors combine by *adding* color spectra

Light *adds* to black.

Source: W. Freeman

Examples of additive color systems

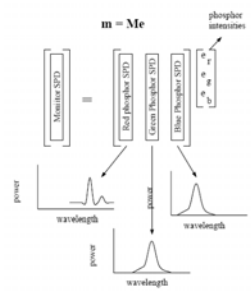


CRT phosphors

multiple projectors

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

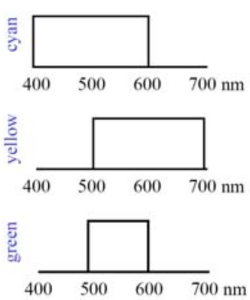
Superposition



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

Figure from B. Wandell, 1996

Subtractive color mixing



Colors combine by *multiplying* color spectra.

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

Source: W. Freeman

Examples of subtractive color systems

- Printing on paper
- Crayons
- Photographic film

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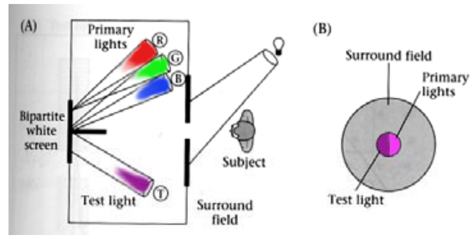
How to know if people perceive the same color?

- 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?

Color matching experiments

- **Goal**: find out 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.

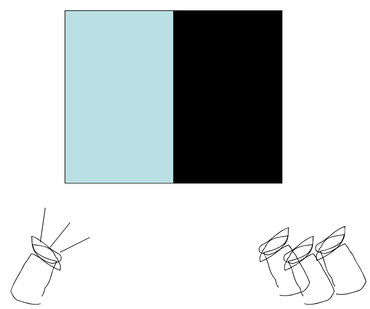
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

After Judd & Wyszecki.

Color matching experiments

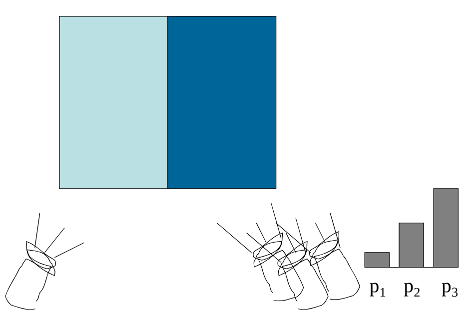
- **Goal**: find out what spectral radiances produce same response in human observers.
- **Assumption**: simple viewing conditions, where we say test light alone affects perception
  - Ignoring additional factors for now like adaptation, complex surrounding scenes, etc.

Color matching experiment 1



Slide credit: W. Freeman

Color matching experiment 1



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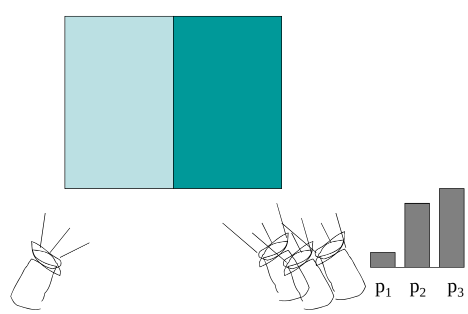
Color matching experiment 1



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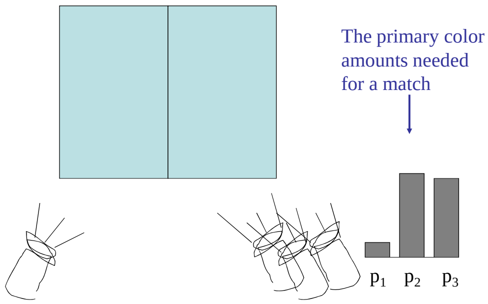
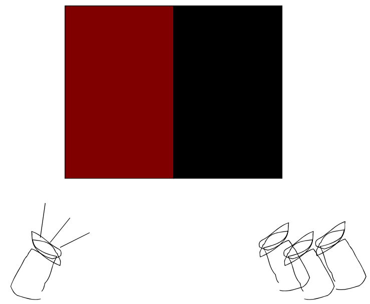
Color matching experiment 1



Slide credit:
W. Freeman

Color matching experiment 2



Slide credit:
W. Freeman

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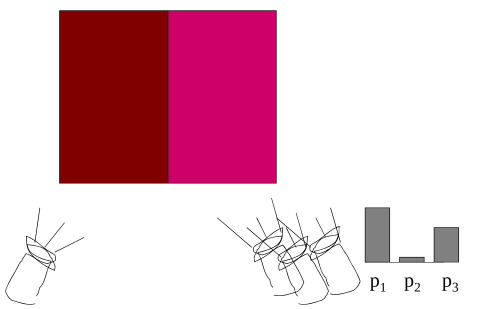

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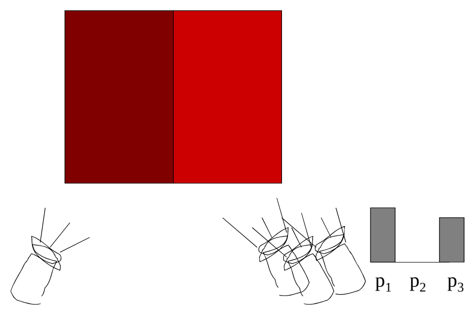
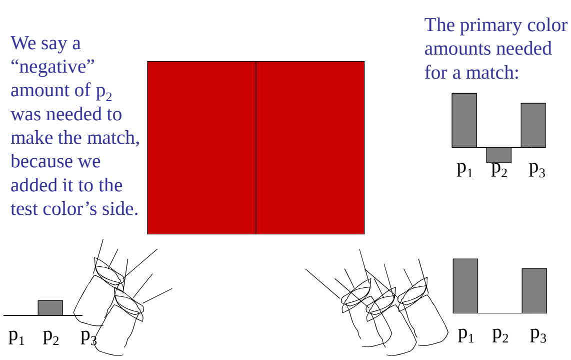


Slide credit:
W. Freeman

Color matching experiment 2



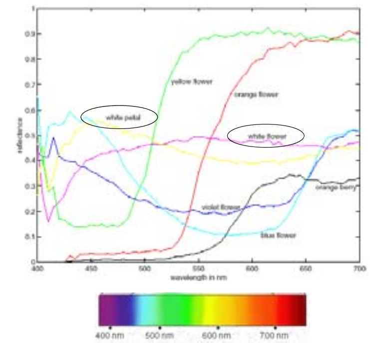
Color matching

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

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

Metamers



Forsyth & Ponce, measurements by E. Koivisto

Grassman's laws

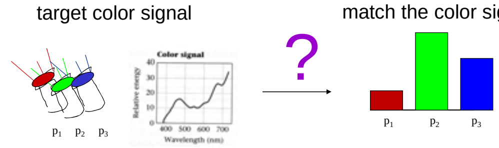
- If two test lights can be matched with the same set of weights, then they match each other:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = u_1 P_1 + u_2 P_2 + u_3 P_3$. Then $A = B$.
- If we scale the test light, then the matches get scaled by the same amount:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$. 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".

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

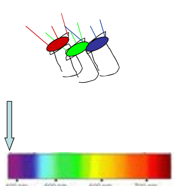
Given: a choice of three primaries and a target color signal

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



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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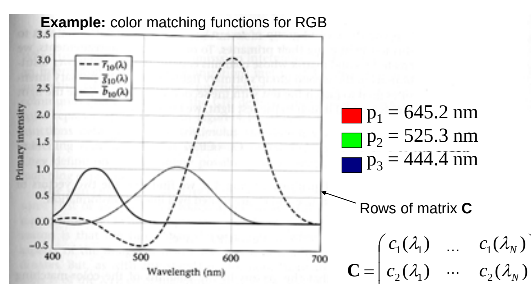
Computing color matches



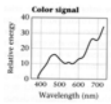
$$\mathbf{C} = \begin{pmatrix} c_1(\lambda_1) & \dots & c_1(\lambda_N) \\ c_2(\lambda_1) & \cdots & c_2(\lambda_N) \\ c_3(\lambda_1) & \cdots & c_3(\lambda_N) \end{pmatrix}$$

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

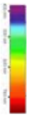
Slide credit: W. Freeman

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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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

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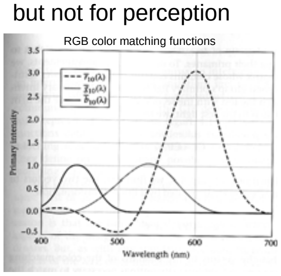
Standard color spaces

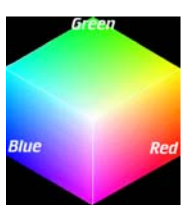
- Use a common set of primaries/color matching functions
- Linear color space examples
  - RGB
  - CIE XYZ
- Non-linear color space
  - HSV

RGB color space

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

RGB color matching functions



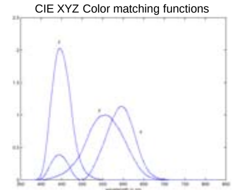


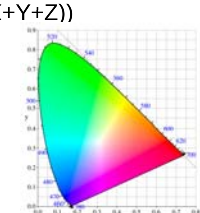
CIE XYZ color space

- 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))

CIE XYZ Color matching functions





HSV color space

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

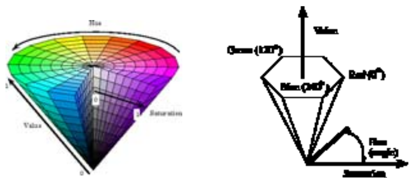


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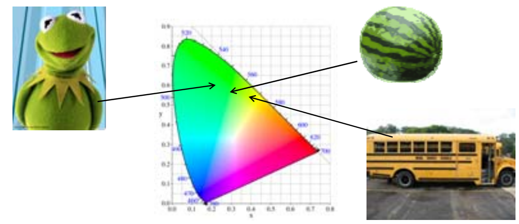
Image from mathworks.com

Distances in color space

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



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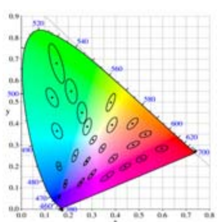
Distances in color space

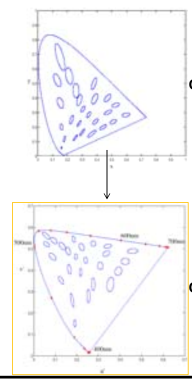
- Not necessarily: CIE XYZ is **not** a *uniform* color space, so magnitude of differences in coordinates are poor indicator of color "distance".



McAdam ellipses:
Just noticeable differences in color

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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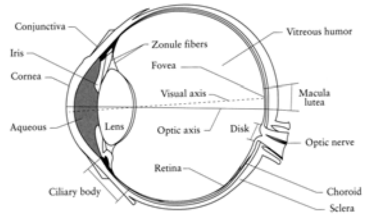
The Eye



The human eye is a camera!

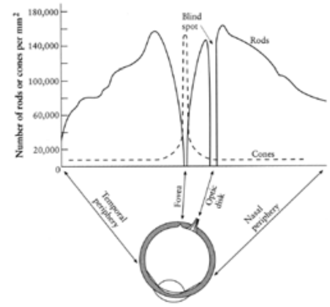
- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- **Lens** - changes shape by using ciliary muscles (to focus on objects at different distances)
- **Retina** - photoreceptor cells

Slide by Steve Seitz

Types of light-sensitive receptors

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

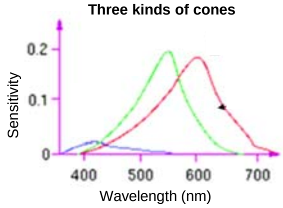
Rods
rod-shaped
highly sensitive
operate at night
gray-scale vision



Slide credit: Alyosha 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



Types of cones

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

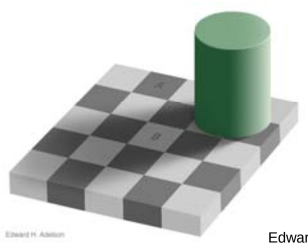
Chromatic adaptation

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

Chromatic adaptation

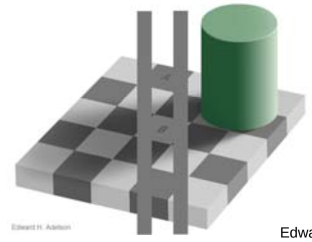
http://www.planetperplex.com/en/color_illusions.html

Brightness perception



Edward Adelson

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



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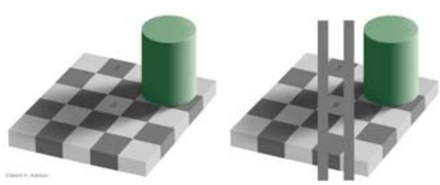

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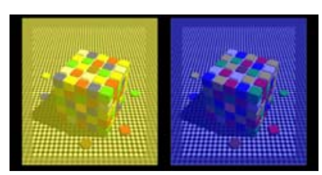

Look at blue squares **Look at yellow squares**

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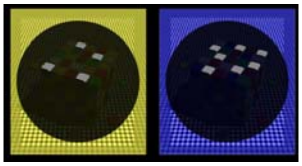
- http://www.lottolab.org/articles/illusionsoflight.asp



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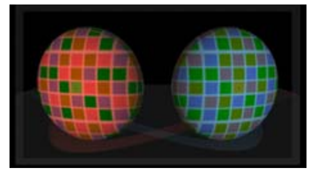

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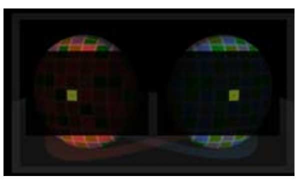

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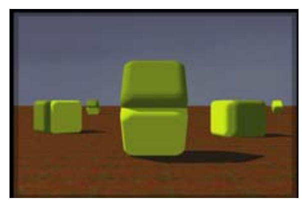
- http://www.lottolab.org/articles/illusionsoflight.asp



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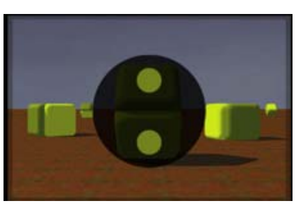
- http://www.lottolab.org/articles/illusionsoflight.asp



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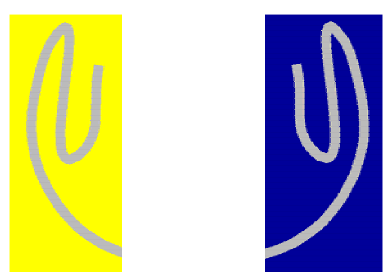
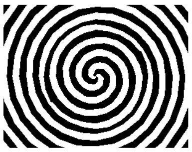
- http://www.lottolab.org/articles/illusionsoflight.asp

Contrast effects



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

Source: Steve Seitz

Name that color

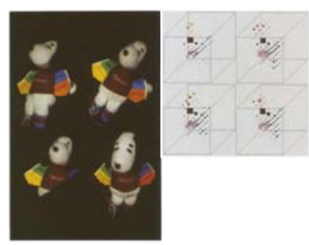
Blue Red Green Cyan
Magenta Black Pink
Yellow Orange Violet
Brown Purple Cyan
Indigo Red Green Blue

High level interactions affect perception and processing.

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

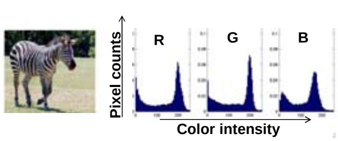
Color as a low-level cue for CBIR



Swain and Ballard, Color Indexing, IJCV 1991

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

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

Kristen Grauman

Color-based image retrieval

Example database

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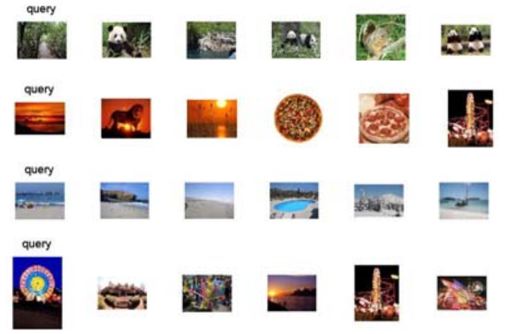
Color-based image retrieval



Example retrievals

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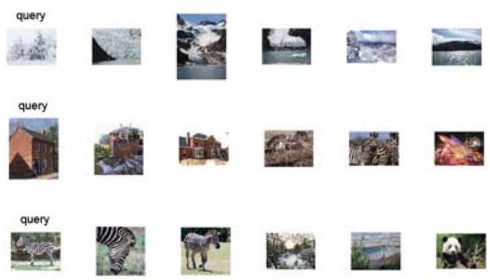
Color-based image retrieval



Example retrievals

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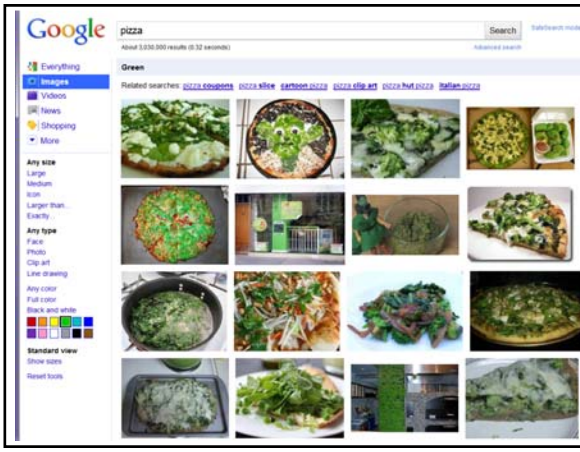
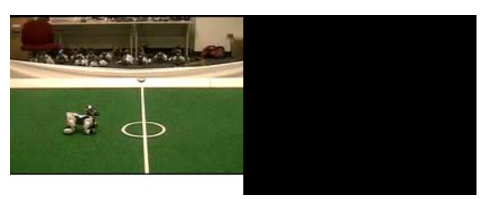


Color-based skin detection

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

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

http://www.cs.utexas.edu/users/AustinVilla/?p=research/auto_vis

Kristen Grauman