CMPSCI 370: Intro to Computer Vision
Color

University of Massachusetts, Amherst
February 2/4, 2016

Instructor: Subhransu Maji

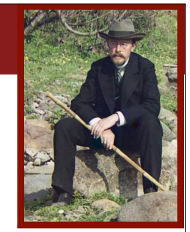
Administrivia

- Homework 1 due on Tuesday, Feb 9
  - Submit pdf via moodle or printout in class
- Late day policy
  - 3 days total (use wisely)
  - No credit for homework beyond late days
- Honors section will meet in CS 142 @ 4pm today

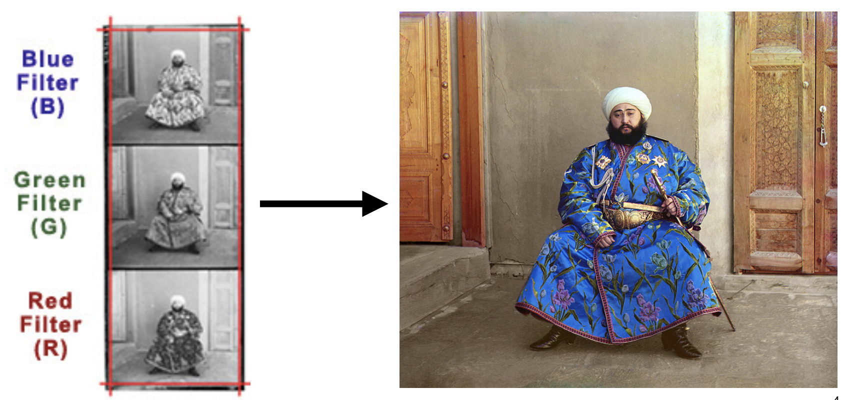
Overview

- Recap of last lecture
- Color
  - Spectral basis of light
  - Color perception in the human eye
  - Tristimulus theory and color spaces
  - Color phenomena

Early color photography



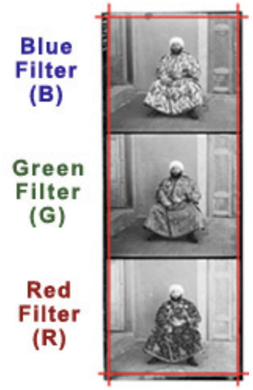
- Sergey Prokudin-Gorskii (1863-1944)
- Photographs of the Russian empire (1909-1916)



Only problem!

Homework 1: fix this by aligning the channels

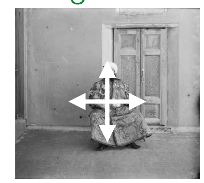
Basic idea for alignment



- Fix one channel (say red). For the homework we will assume that channels are only translated, i.e., no rotation, scaling, etc.
- For each shift: $x \in (-15,15), y \in (-15,15)$

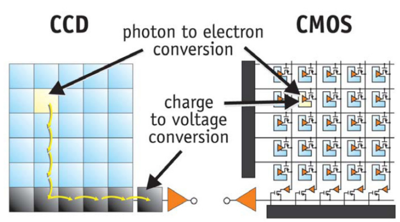
red

green



  - Measure similarity, e.g. angle between the vectors (reshape image to a vector)
  - Pick the shift that *maximizes* similarity
- Repeat for the blue channel

Digital camera



CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

- A digital camera replaces the film with a sensor array
  - Each cell in the array is a light-sensitive diode that converts photons to electrons
  - Two common types
    - **Charge Coupled Device (CCD)**
    - **Complementary Metal Oxide Semiconductor (CMOS)**

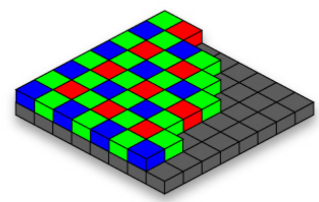
  http://electronics.howstuffworks.com/digital-camera.htm

Slide by S.Seitz

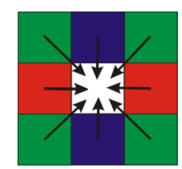
Color sensing in the camera

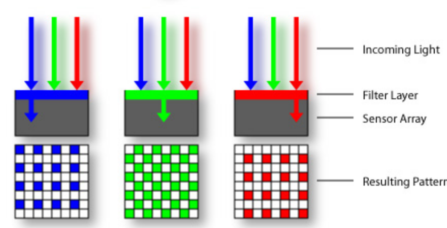
Color filter array

Bayer grid

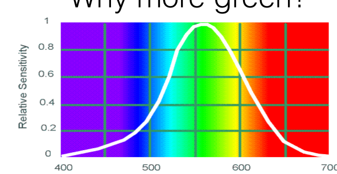


Estimate missing components from neighboring values (**demosiacing**)





Why more green?



Human luminance sensitivity function

Slide by S.Seitz

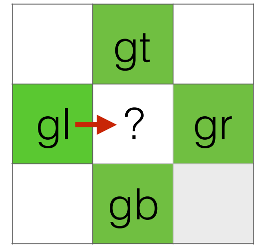
Demosaicing

Red

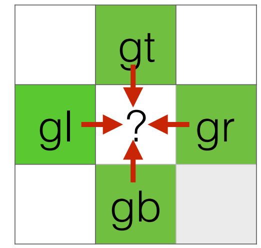
Green

Blue

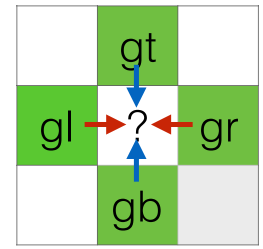
Interpolation



nearest neighbor
copy one of your neighbors
? ←gl



linear interpolation
average values of your neighbors
? ←(gt+gl+gr+gb)/4



adaptive gradient
average based on local structure
if |gt-gb| > |gl-gr|
? ← (gl+gr)/2
else
? ← (gt+gb)/2

Similarly for the blue and red channels
Homework 1: implement nearest neighbor

Questions?

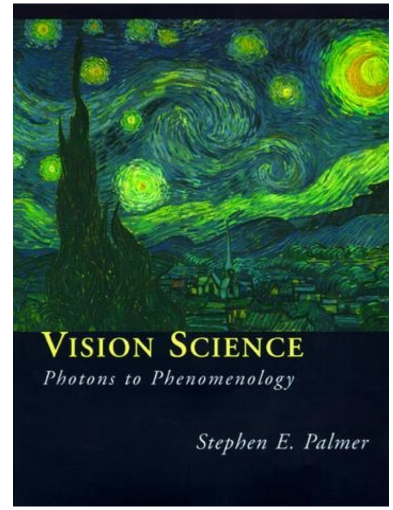
Overview

- Recap of last lecture
- Color perception
  - Spectral basis of light
  - Color perception in the human eye
  - Tristimulus theory and color spaces
  - Color phenomena

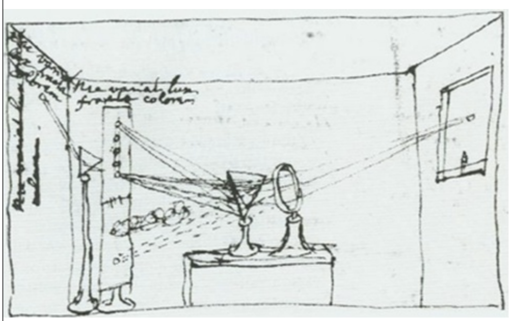
XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	RED	RED
XXXXXX	WHITE	WHITE
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	BLUE	BLUE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	WHITE	WHITE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE

What is color?

- “Color is the result of interaction between light in the environment and our visual system”
- “Color is a psychological property of our visual experiences when we look at objects and lights, not a physical property of those objects or lights” — *S. Palmer, Vision Science: Photons to Phenomenology*

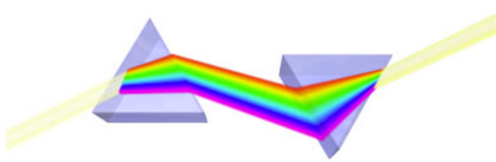


Newton’s theory of light

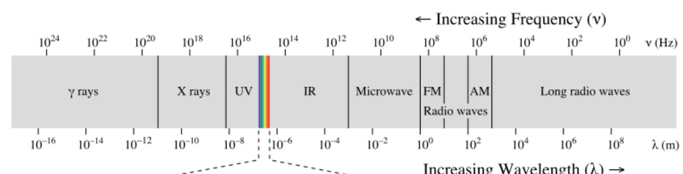


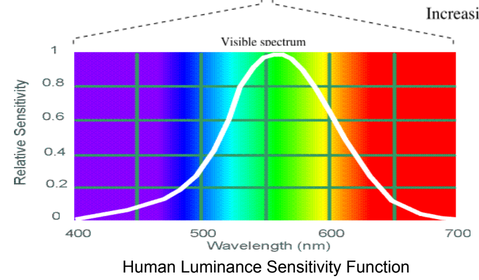
Newton's sketch of his crucial experiment in which light from the sun is refracted through a prism. One color is then refracted through a second prism to show that it undergoes no further change. Light is then shown to be composed of the colors refracted in the second prisms.

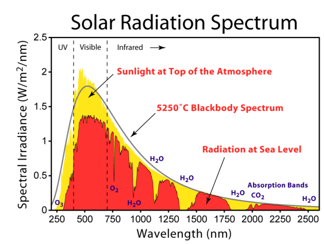
Image credit: **Warden and Fellows**

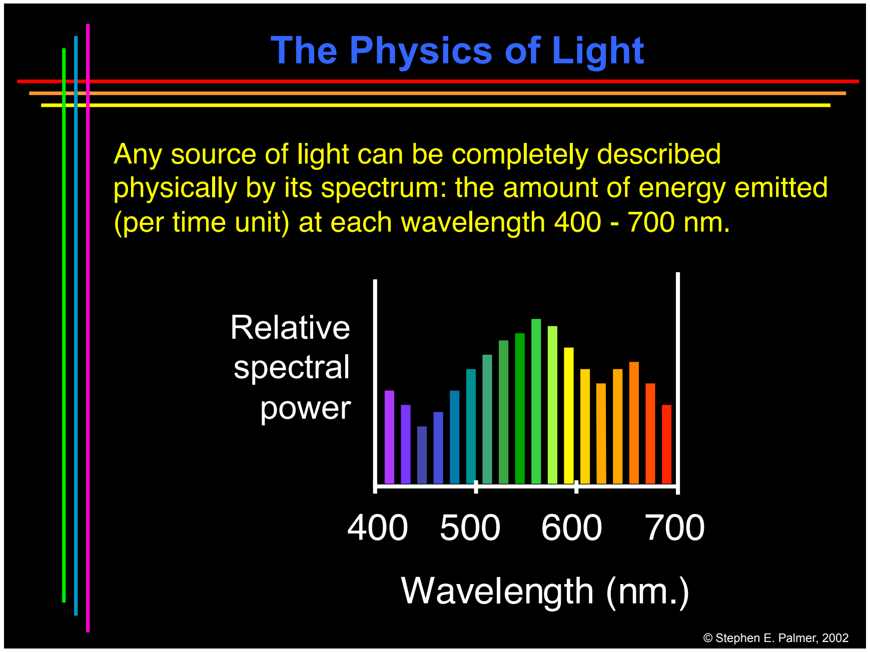


The electromagnetic spectrum








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.
Relative spectral power
400 500 600 700
Wavelength (nm.)
© Stephen E. Palmer, 2002

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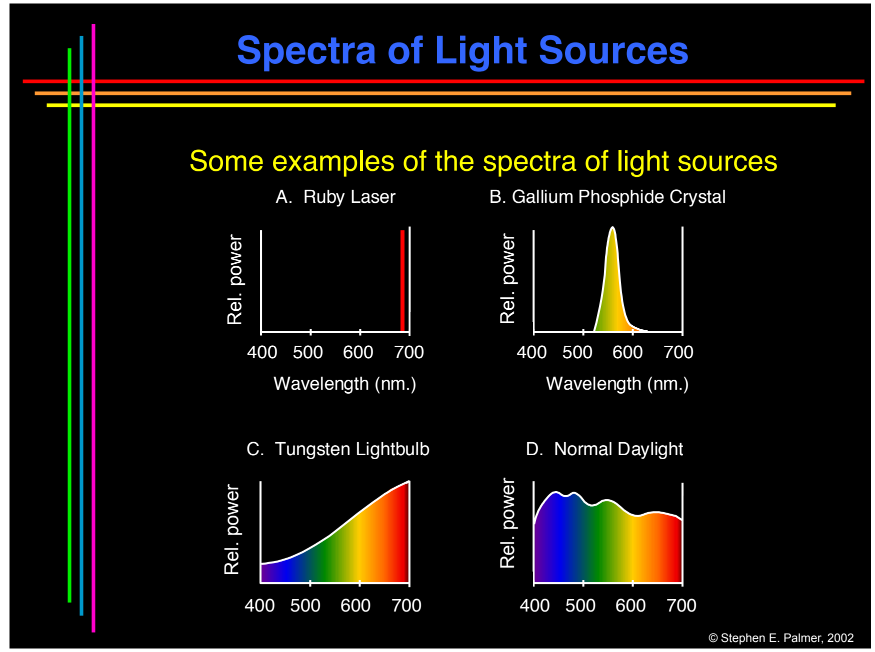
Spectra of Light Sources
Some examples of the spectra of light sources
A. Ruby Laser
B. Gallium Phosphide Crystal
Rel. power
400 500 600 700
Wavelength (nm.)
C. Tungsten Lightbulb
D. Normal Daylight
© Stephen E. Palmer, 2002

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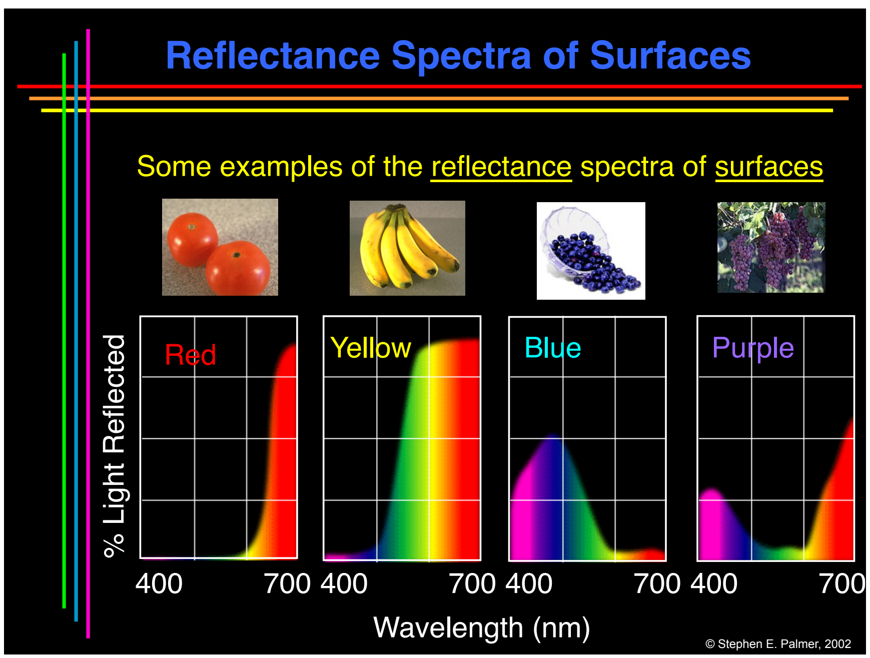
Reflectance Spectra of Surfaces
Some examples of the reflectance spectra of surfaces
% Light Reflected
Red
Yellow
Blue
Purple
400 700 400 700 400 700 400 700
Wavelength (nm)
© Stephen E. Palmer, 2002

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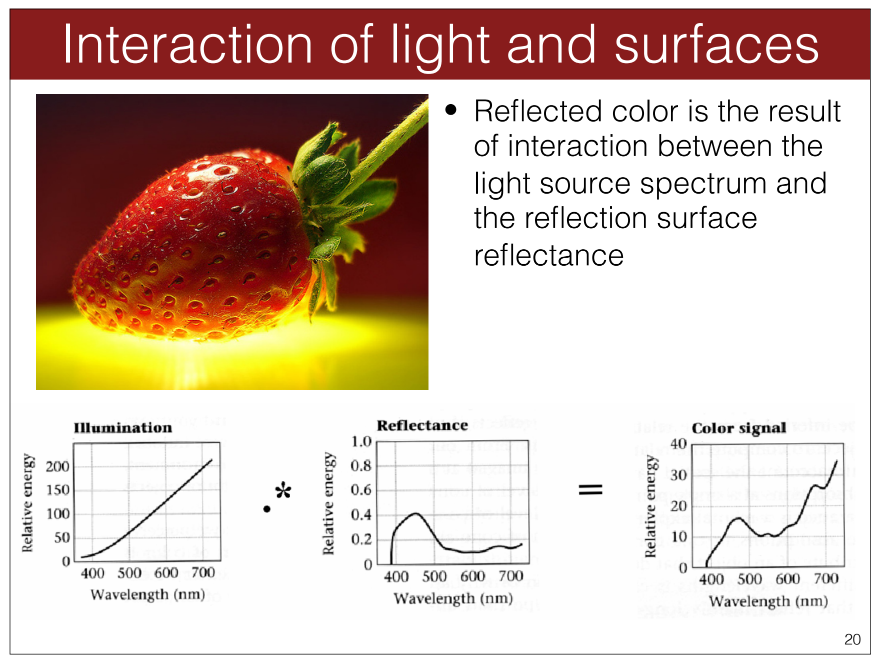
Interaction of light and surfaces
• Reflected color is the result of interaction between the light source spectrum and the reflection surface reflectance
Illumination
Reflectance
Color signal
Relative energy
Wavelength (nm)
.*
=
20

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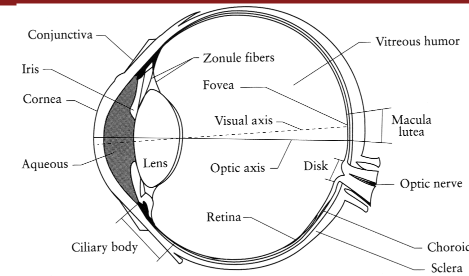
Interaction of light and surfaces

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

Room for one color, Olafur Eliasson

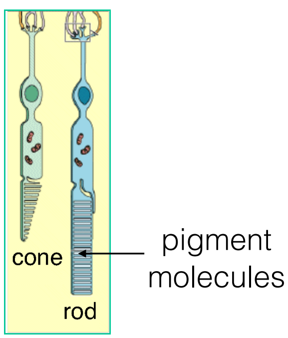
The eye

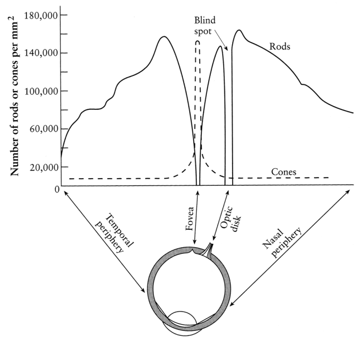


- The human eye is a sophisticated camera!
  - **Lens** - changes the shape by using ciliary muscles (to focus on objects at different distances)
  - **Pupil** - the hole (aperture) whose size is controlled by iris
  - **Iris** - colored annulus with radial muscles
  - **Retina** - photoreceptor cells

Slide by S. Seitz

Rods and cones, fovea

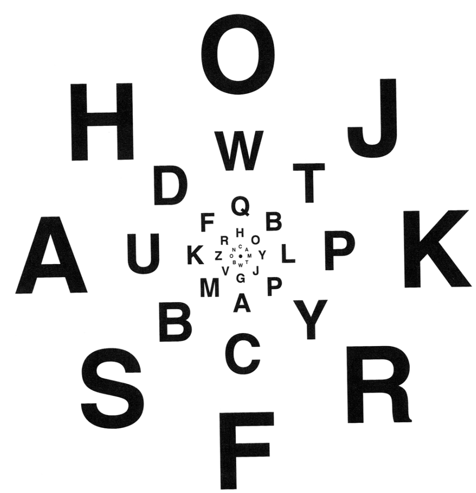




- Rods are responsible for intensity, cones for color perception
- Rods and cones are non-uniformly distributed on the retina
  - **Fovea** - Small region (1 or 2°) at the center of the visual field containing the highest density of cones - and no rods
- There are about 5 million cones and 100 million rods in each eye

Slide by S. Seitz

Demonstration of visual acuity



With one eye shut, at the right distance, all of these letters should appear equally legible (Glassner, 1.7).

Slide by Steve Seitz

Blind spot

With left eye shut, look at the cross on the left. At the right distance, the circle on the right should disappear (Glassner, 1.8).

Slide by Steve Seitz

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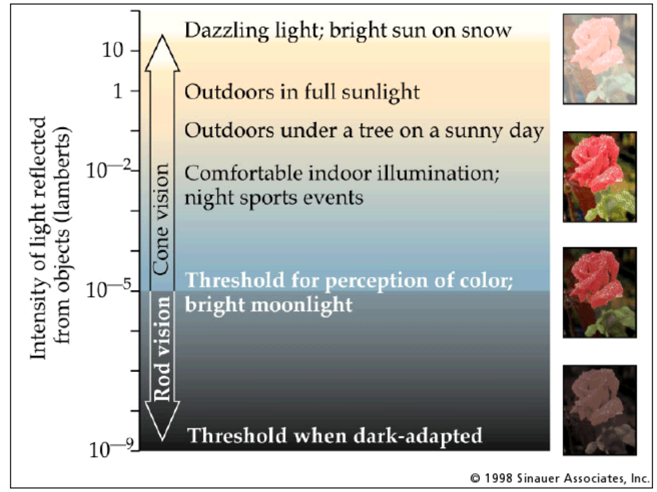
Rod/cone sensitivity



Why can't we read in the dark?

Slide by A. Efros 26

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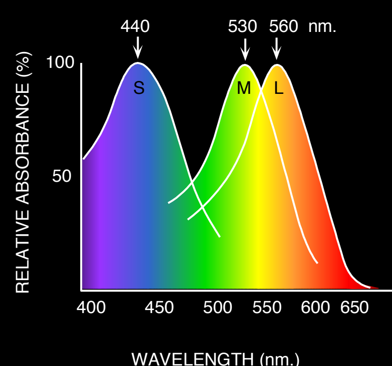
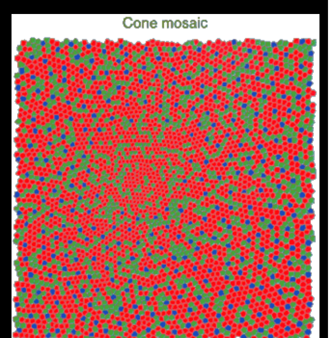
Physiology of Color Vision

Three kinds of cones:





- Ratio of L to M to S cones: approx. 10:5:1
- Almost no S cones in the center of the fovea

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Physiology of color vision: fun facts

- "M" and "L" pigments are encoded on the X-chromosome
  - That's why men are more likely to be color blind
  - "L" gene has high variation, so some women may be *tetra-chromatic*
- 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

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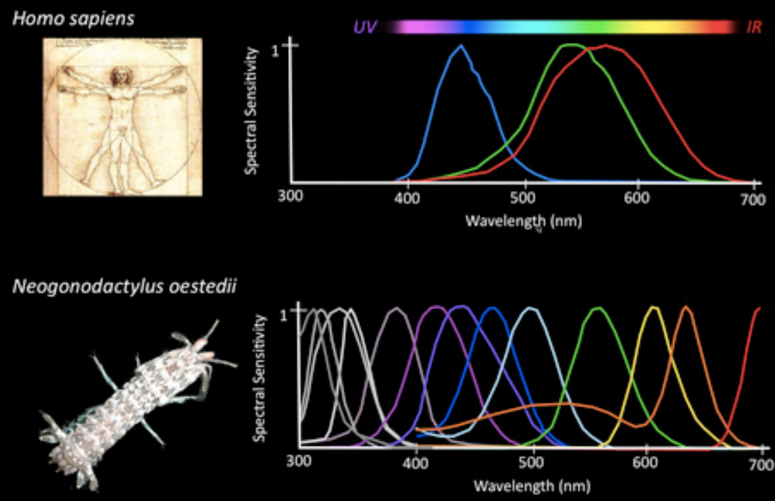
Mantis Shrimp: Extraordinary Eyes



Marshall *et al.*, 2007; Marshall and Oberwinkler, 1999

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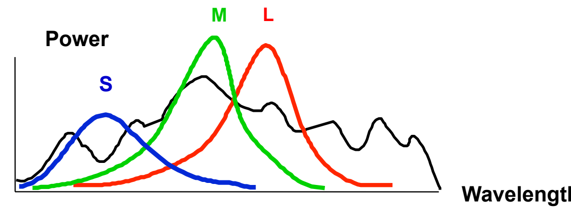
Color perception



Rods and cones act as filters on the spectrum

- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number
- How can we represent an entire spectrum with 3 numbers?
- We can't! A lot of the information is lost
  - As a result, two different spectra may appear indistinguishable
    - Such spectra are known as **metamers**

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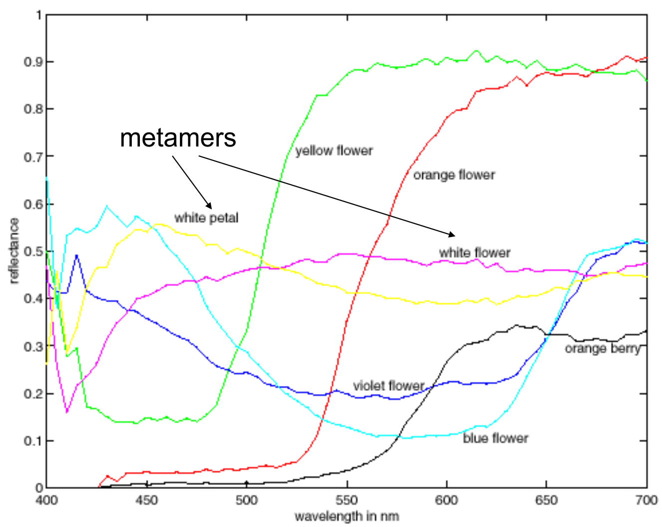
Spectra of some real-world surfaces



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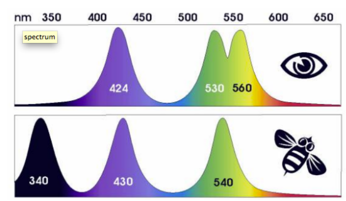
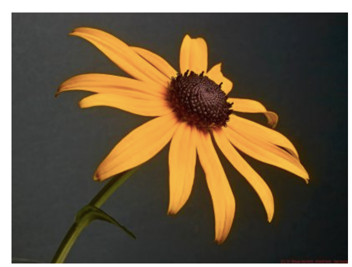
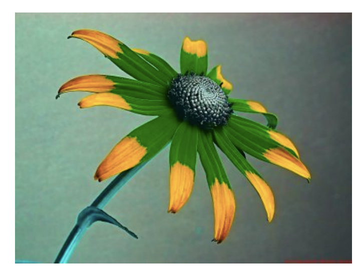
How insects see



http://fieldguidetohummingbirds.wordpress.com/2008/11/11/do-we-see-what-bees-see/



visible light image



simulated bee vision

http://photographyoftheinvisibleworld.blogspot.de/

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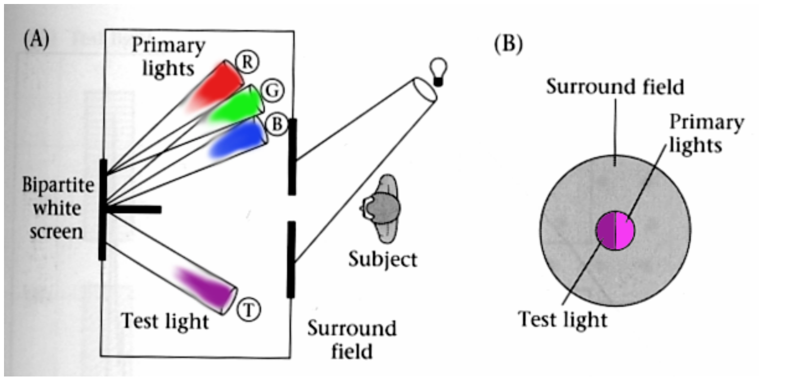
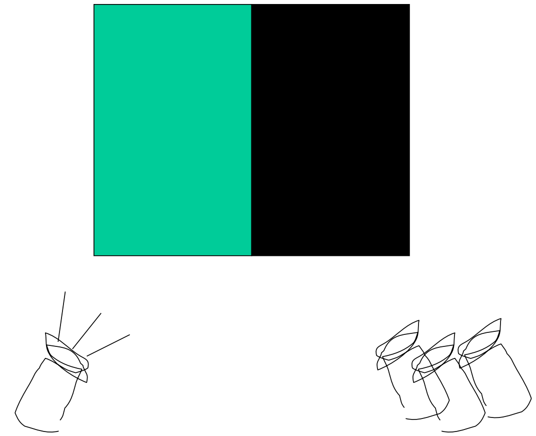
Standardizing color experience

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



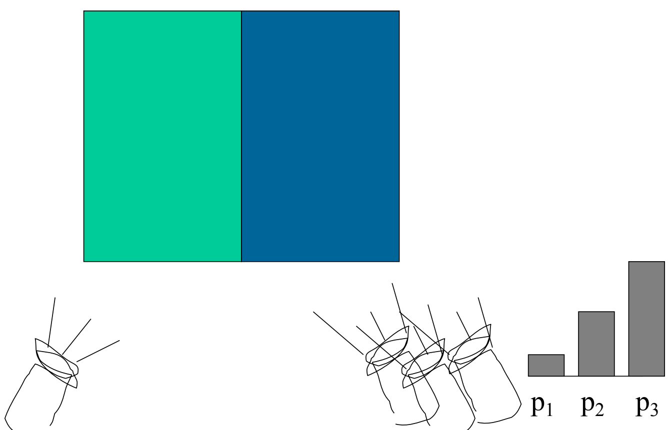
Wandell, Foundations of Vision, 1995 33

Color matching experiment 1



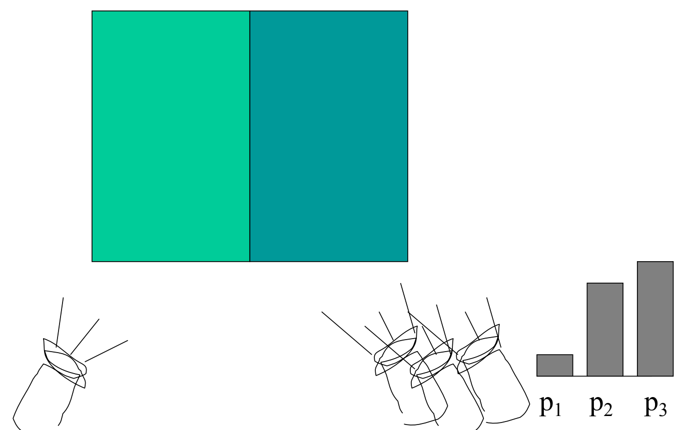
Source: W. Freeman 34

Color matching experiment 1



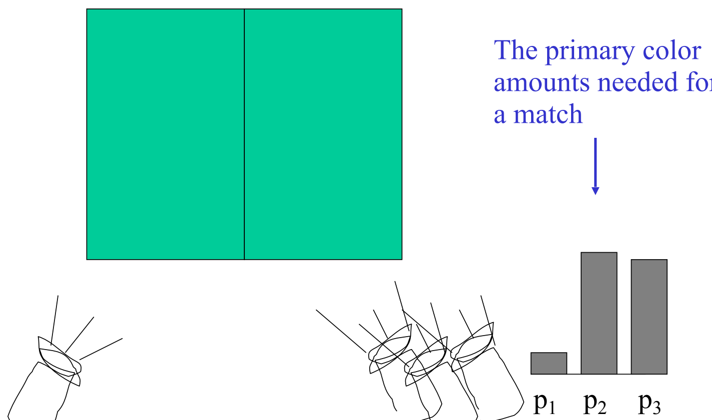
Source: W. Freeman 35

Color matching experiment 1



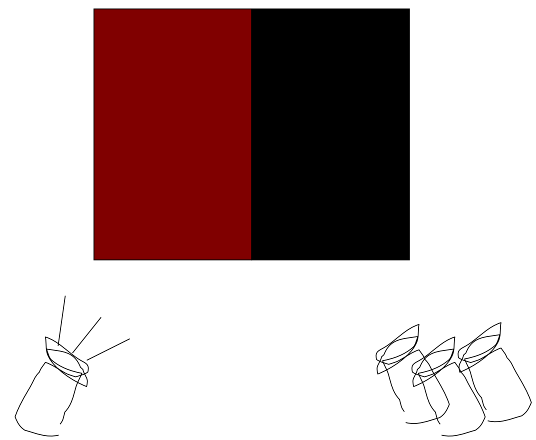
Source: W. Freeman 36

Color matching experiment 1



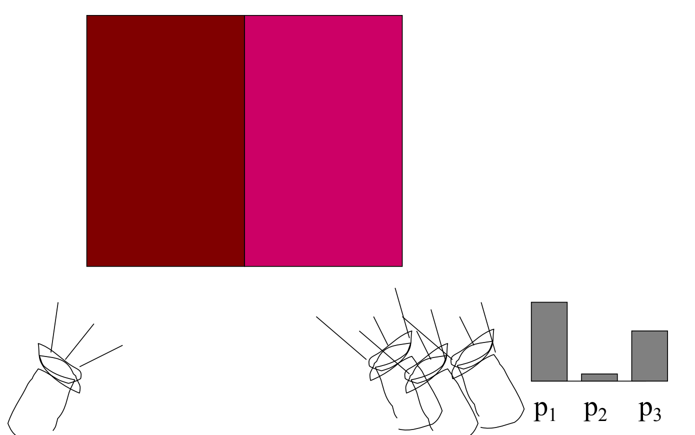
Source: W. Freeman 37

Color matching experiment 2



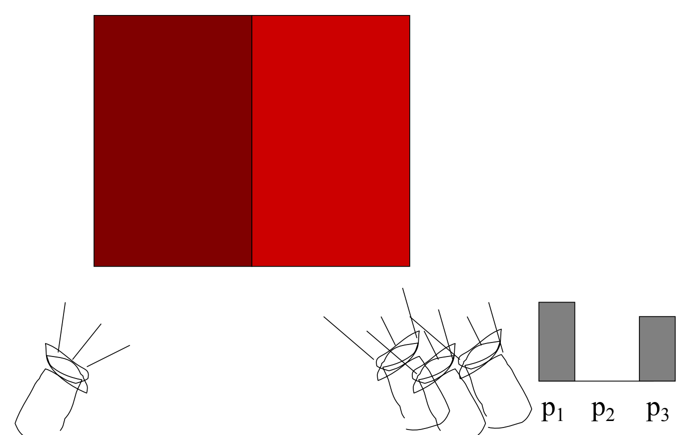
Source: W. Freeman 38

Color matching experiment 2



Source: W. Freeman 39

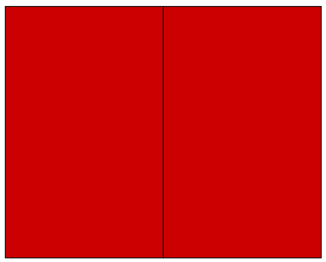
Color matching experiment 2



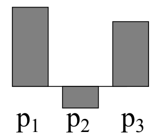
Source: W. Freeman 40

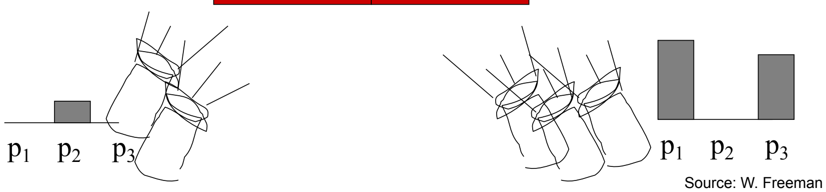
Color matching experiment 2

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



The primary color amounts needed for a match:





Source: W. Freeman 41

Trichromacy

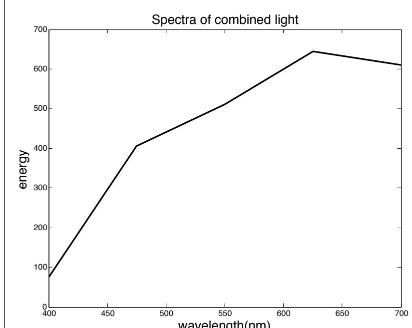
- In color matching experiments, most people can match any given light with three primaries
  - Primaries must be ***independent***
- For the same light and same primaries, most people select the same weights
  - Exception: color blindness
- Trichromatic color theory
  - Three numbers seem to be sufficient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

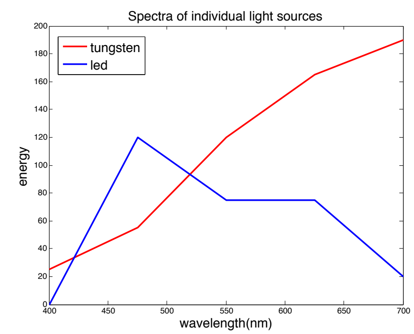
Grassman's Laws (1853)

- Color matching appears to be linear
- 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 mix two test lights, then mixing the matches will match the result:
  - 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 $A + B = (u_1+v_1) P_1 + (u_2+v_2) P_2 + (u_3+v_3) P_3$.
- 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 $kA = (ku_1) P_1 + (ku_2) P_2 + (ku_3) P_3$.

Example

- Bob walks into a room and sees the following spectra
  - How many tungsten and led bulbs are there?





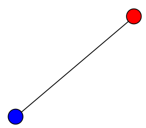
target = [75 405 510 645 610]
tungsten = [25 55 120 165 190];
led = [0 120 75 75 20];

Using linearity of light we have
target = n * tungsten + m * led;

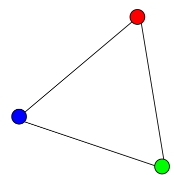
n=3 and m=2

Linear color spaces

- Defined by a choice of three *primaries*
- The coordinates of a color are given by the weights of the primaries used to match it



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



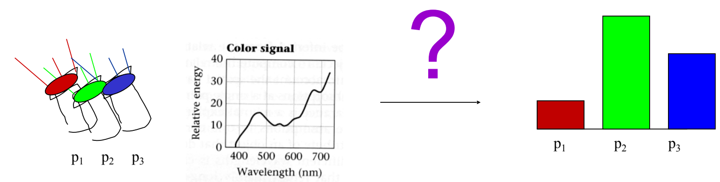
mixing three lights produces colors that lie within the triangle they define in color space

Linear color spaces

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

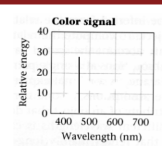
Given: a choice of three primaries and a target color signal

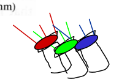
Find: weights of the primaries needed to match the color signal



Color matching function: primary colors

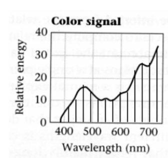
We know that a monochromatic light λ_i of wavelength will be matched by the amounts $c_1(\lambda_i), c_2(\lambda_i), c_3(\lambda_i)$ of each primary.





And any spectral signal can be thought of as a linear combination of very many monochromatic lights, with the linear coefficient given by the spectral power at each wavelength.

$$\vec{t} = \begin{pmatrix} t(\lambda_1) \\ \vdots \\ t(\lambda_N) \end{pmatrix}$$

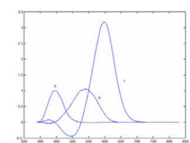


Source: W. Freeman

Color matching functions: any color

Store the color matching functions in the rows of the matrix, C

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



Let the new spectral signal be described by the vector t.

$$\vec{t} = \begin{pmatrix} t(\lambda_1) \\ \vdots \\ t(\lambda_N) \end{pmatrix}$$

Then the amounts of each primary needed to match t are: $\vec{e} = C\vec{t}$

The components e_1, e_2, e_3 describe the color of t. If you have some other spectral signal, s, and s matches t perceptually, then e_1, e_2, e_3, will also match s (by Grassman's Laws)

Source: W. Freeman

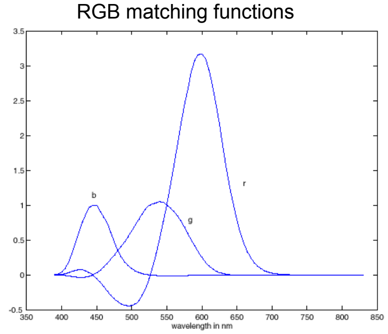
RGB space

- Primaries are monochromatic lights (for monitors, they correspond to the three types of phosphors)
- *Subtractive matching* required for some wavelengths

RGB primaries

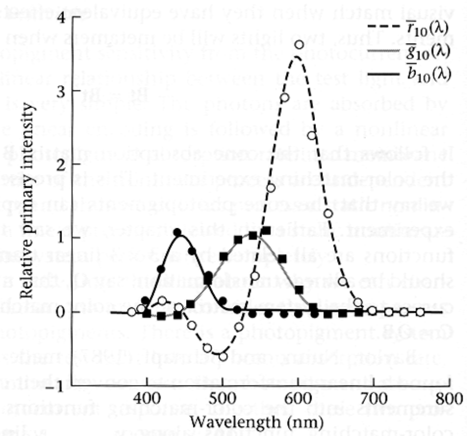
$p_1 = 645.2$ nm
$p_2 = 525.3$ nm
$p_3 = 444.4$ nm

RGB matching functions



Comparison of RGB matching functions with best linear transformation of cone responses

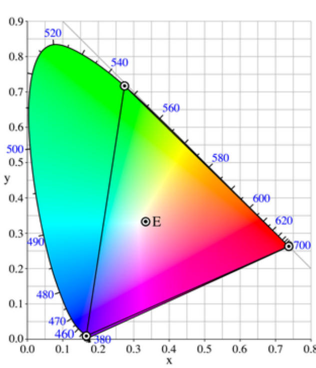
4.20 COMPARISON OF CONE PHOTOCURRENT RESPONSES AND THE COLOR-MATCHING FUNCTIONS. The cone photocurrent spectral responsivities are within a linear transformation of the color-matching functions, after a correction has been made for the optics and inert pigments in the eye. The smooth curves show the Stiles and Burch (1959) color-matching functions. The symbols show the matches predicted from the photocurrents of the three types of macaque cones. The predictions included a correction for absorption by the lens and other inert pigments in the eye. Source: Baylor, 1987.



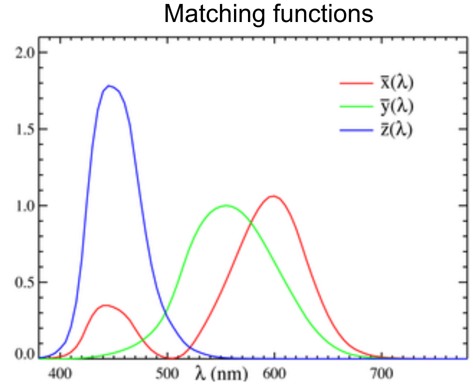
Wandell, Foundations of Vision, 1995

Linear color spaces: CIE XYZ

- Matching functions are positive everywhere
- Y parameter corresponds to brightness or *luminance* of a color
- Z corresponds to blue simulation



Matching functions

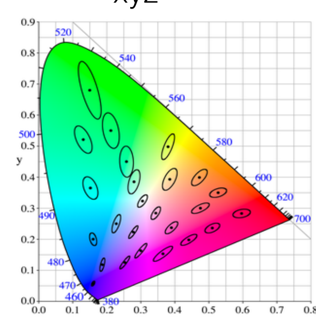


http://en.wikipedia.org/wiki/CIE_1931_color_space

Uniform color spaces

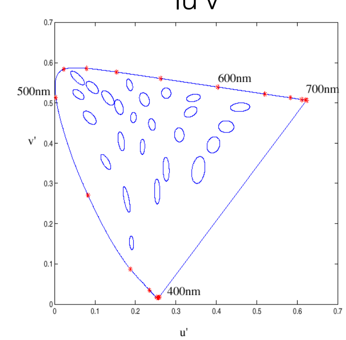
- Unfortunately, differences in x,y coordinates do not reflect perceptual color differences
- CIE u'v' is a transform of x,y to make the ellipses more uniform

xyz



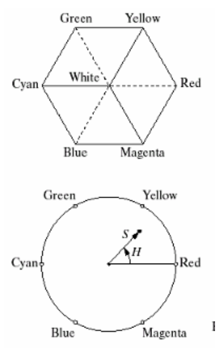
McAdam ellipses: Just noticeable differences in color

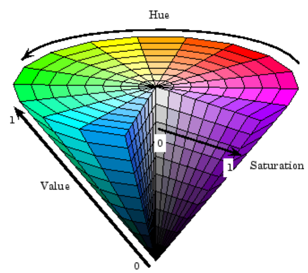
lu'v'

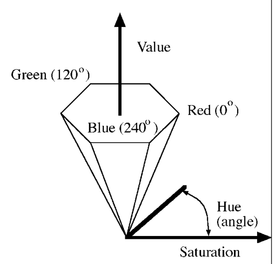


Nonlinear color spaces: HSV

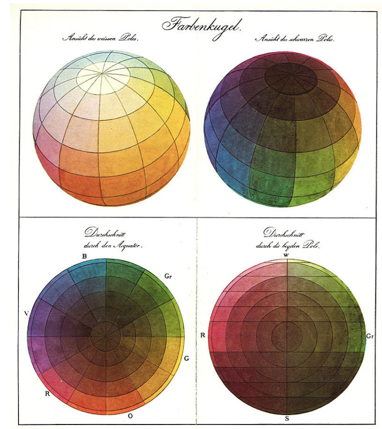
- Perceptually meaningful dimensions: Hue, Saturation, Value (Intensity)
- RGB cube on its vertex







Some early attempts in color spaces



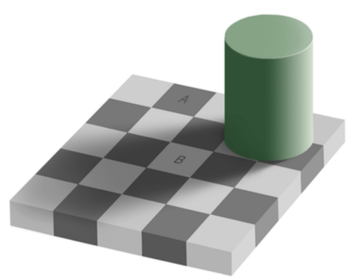
Philipp Otto Runge's Farbenkugel (color sphere), 1810

Munsell's balanced color sphere, 1900, from A Color Notation, 1905

Color constancy

- The ability of the human visual system to perceive color relatively constant despite changes in illumination conditions

We perceive the same color both in shadow and sunlight



Color constancy causes A and B to look different although the pixel values are the same

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

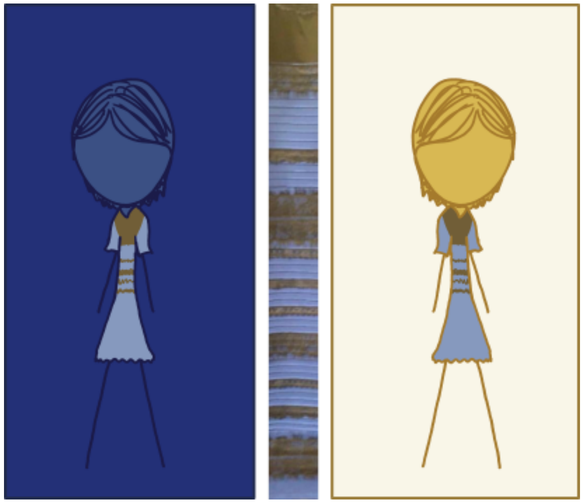
Color constancy

#1 white and gold
or
#2 blue and black

1 light is blue so white is tinted blue and gold doesn't really change

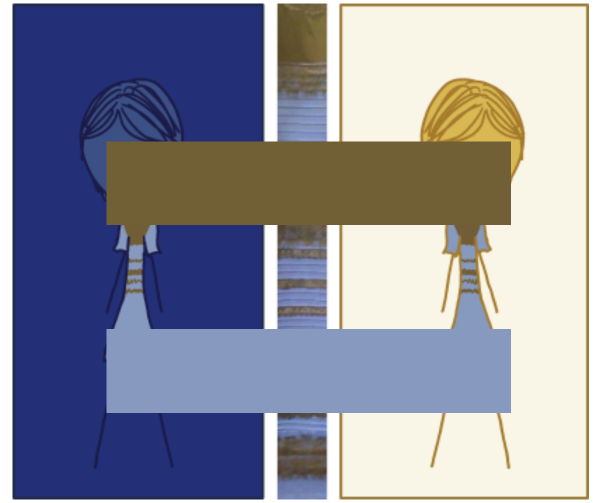
2 light is yellow, so black reflects the yellow and the blue is unaffected

Color constancy



http://xkcd.com/1492/

Color constancy



http://xkcd.com/1492/

Chromatic adaptation

- The visual system changes its sensitivity depending on the luminances prevailing in the visual field
  - The exact mechanism is poorly understood
- Adapting to different brightness levels
  - Changing the size of the iris opening (i.e., the aperture) changes the amount of light that can enter the eye
  - Think of walking into a building from full sunshine
- Adapting to different color temperature
  - The receptive cells on the retina change their sensitivity
  - 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
  - We actually adapt better in brighter scenes: This is why candlelit scenes still look yellow

http://www.schorsch.com/kbase/glossary/adaptation.html

White balance

- When looking at a picture on screen or print, our eyes are adapted to the illuminant of the room, not to that of the scene in the picture
- When the white balance is not correct, the picture will have an unnatural color "cast"

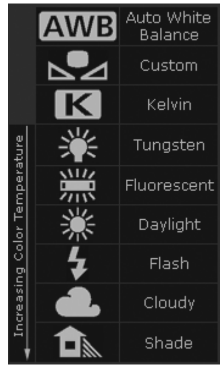
incorrect white balance

correct white balance

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

White balance

- **Film cameras:**
  - Different types of film or different filters for different illumination conditions
- **Digital cameras:**
  - Automatic white balance
  - White balance settings corresponding to several common illuminants
  - Custom white balance using a reference object



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

White balance

- Von Kries adaptation
  - Multiply each channel by a gain factor
- **Best way:** gray card
  - Take a picture of a neutral object (white or gray)
  - Deduce the weight of each channel
    - If the object is recoded as r_w, g_w, b_w use weights $1/r_w$, $1/g_w$, $1/b_w$

Source: L. Lazebnik

White balance

- Without gray cards: we need to “guess” which pixels correspond to white objects
- Gray world assumption
  - The image average r_{ave}, g_{ave}, b_{ave} is gray
  - Use weights $1/r_{ave}$, $1/g_{ave}$, $1/b_{ave}$
- Brightest pixel assumption
  - Highlights usually have the color of the light source
  - Use weights inversely proportional to the values of the brightest pixels
- Gamut mapping
  - Gamut: convex hull of all pixel colors in an image
  - Find the transformation that matches the gamut of the image to the gamut of a “typical” image under white light
- Use image statistics, learning techniques

Source: L. Lazebnik

Further readings and thoughts …

- Color matching applet
  - http://graphics.stanford.edu/courses/cs178/applets/colormatching.html
- D.A. Forsyth, A novel algorithm for color constancy
  - Gamut based approach
  - http://luthuli.cs.uiuc.edu/~daf/papers/colorconst.pdf