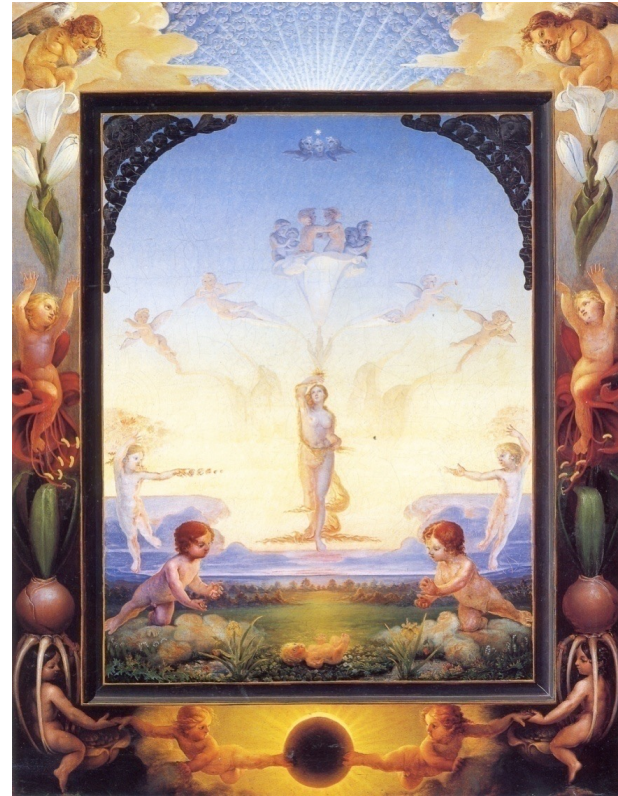
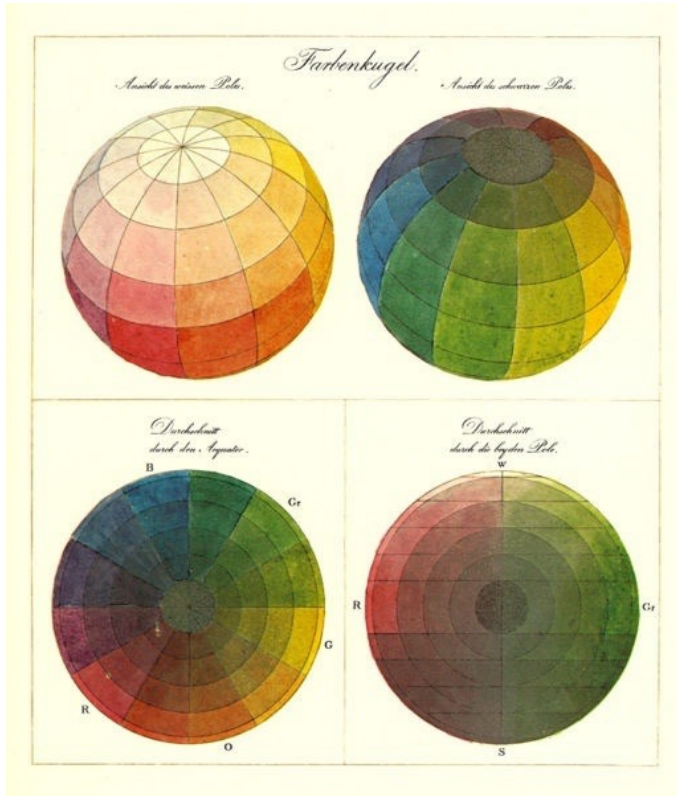


Color



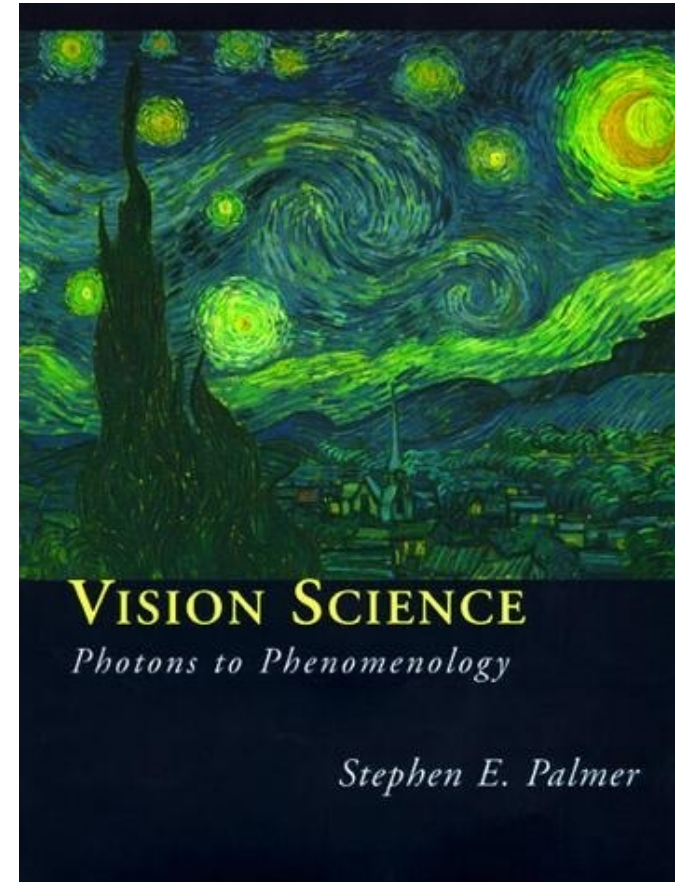
Phillip Otto Runge (1777-1810)

Outline

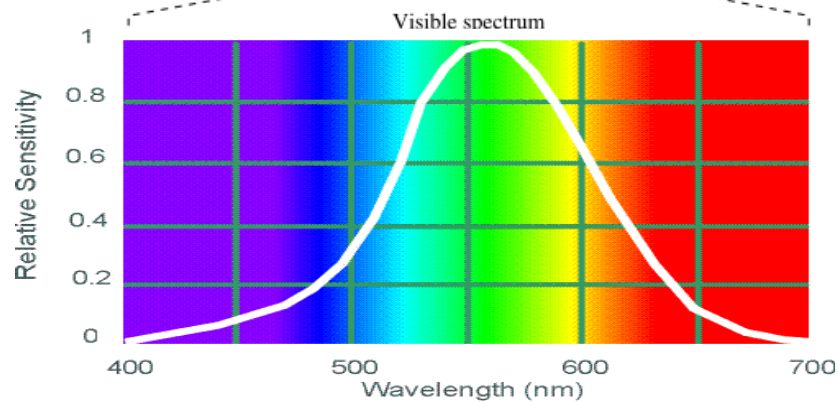
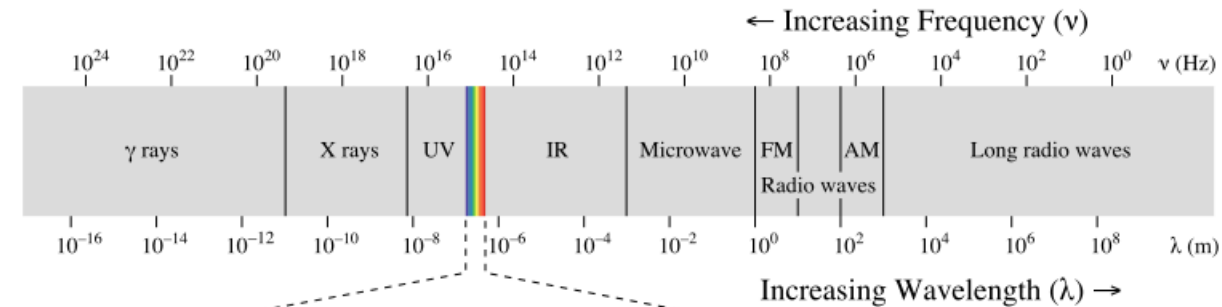
- Physical origin of color
- Spectra of sources and surfaces
- Physiology of color vision
- Quantifying color perception
- Color spaces
- Color constancy, white balance

What is color?

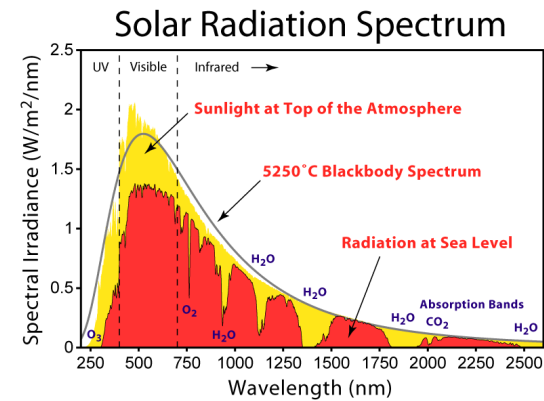
- Color is the result of interaction between physical light in the environment and our visual system
- “Color is a psychological property of our visual experiences when we look at objects and lights, *not* a physical property of those objects or lights”
 - S. Palmer, *Vision Science: Photons to Phenomenology*



Electromagnetic spectrum

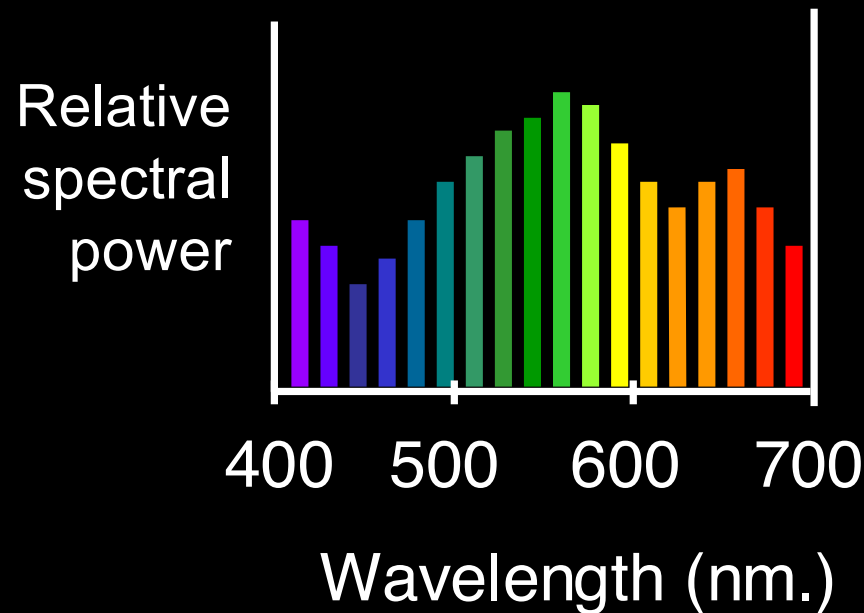


Human Luminance Sensitivity Function



The Physics of Light

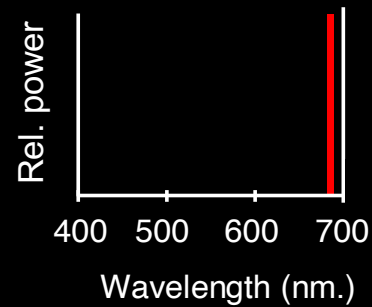
Any source of light can be completely described physically by its spectrum: the amount of energy emitted (per time unit) at each wavelength 400 - 700 nm.



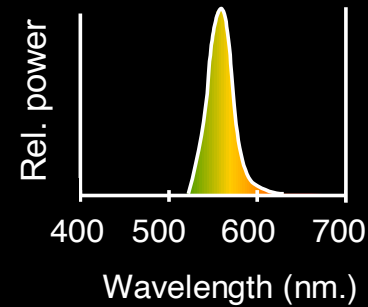
Spectra of Light Sources

Some examples of the spectra of light sources

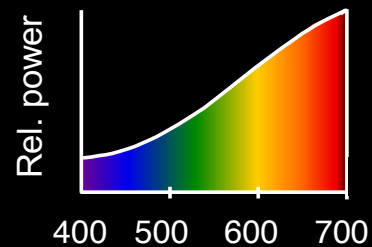
A. Ruby Laser



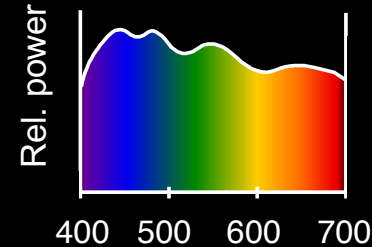
B. Gallium Phosphide Crystal



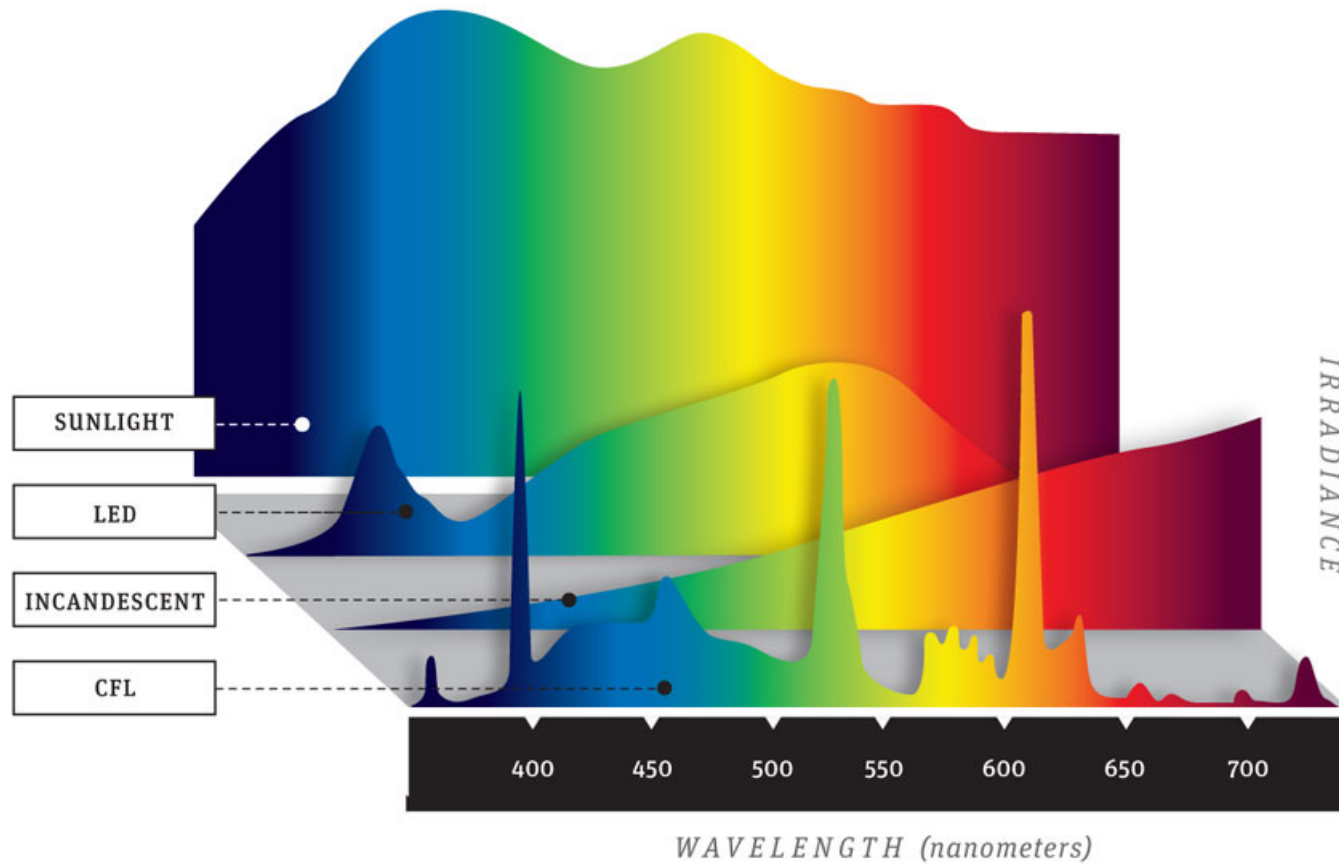
C. Tungsten Lightbulb



D. Normal Daylight



Spectra of light sources



[Source: Popular Mechanics](#)

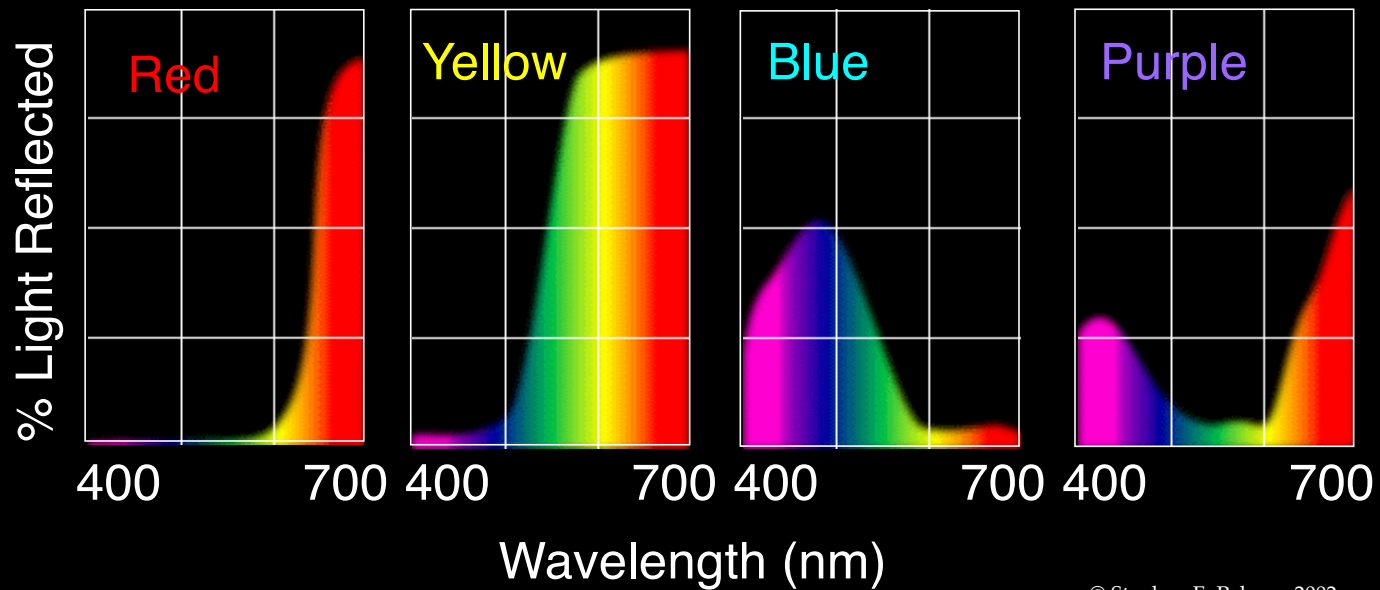
Spectra of light sources



<https://www.xkcd.com/1308/>

Reflectance Spectra of Surfaces

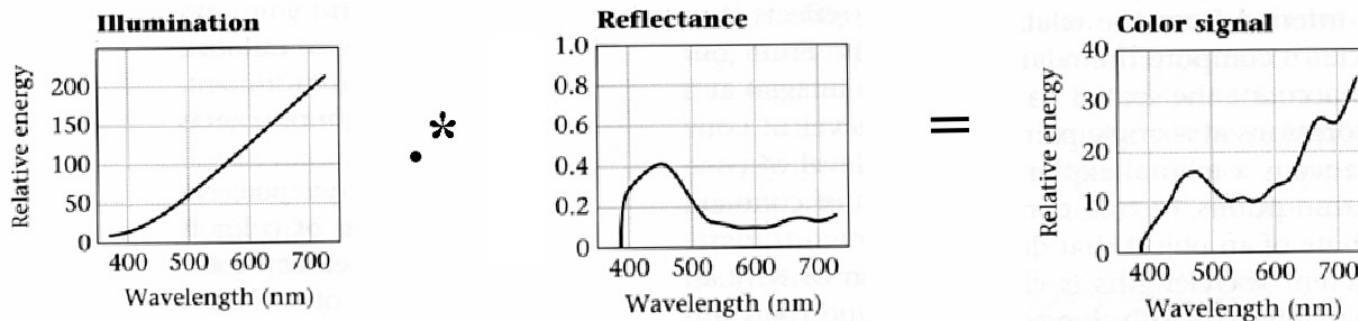
Some examples of the reflectance spectra of surfaces



Interaction of light and surfaces



- Reflected color is the result of interaction of light source spectrum with surface reflectance



Interaction of light and surfaces

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

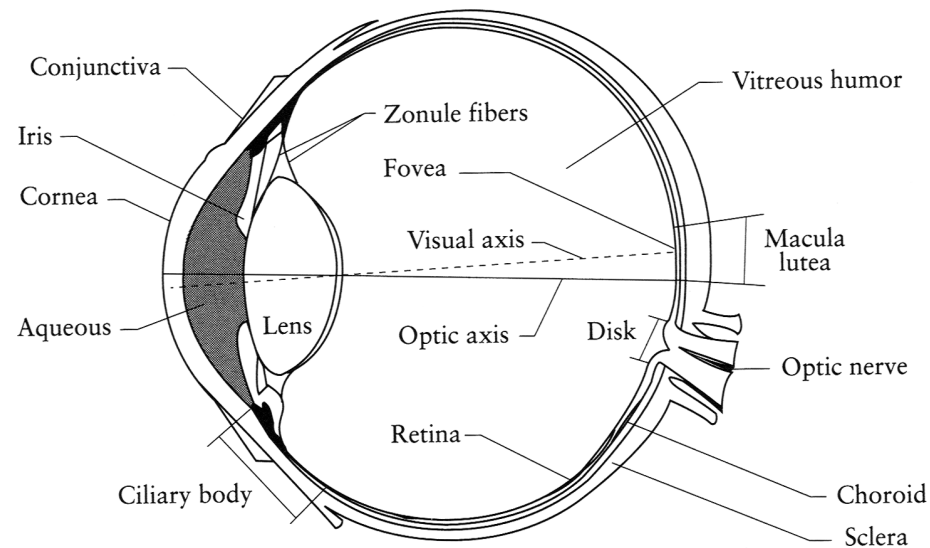


[Olafur Eliasson, *Room for one color*](#)

Outline

- Physical origin of color
- Spectra of sources and surfaces
- Physiology of color vision

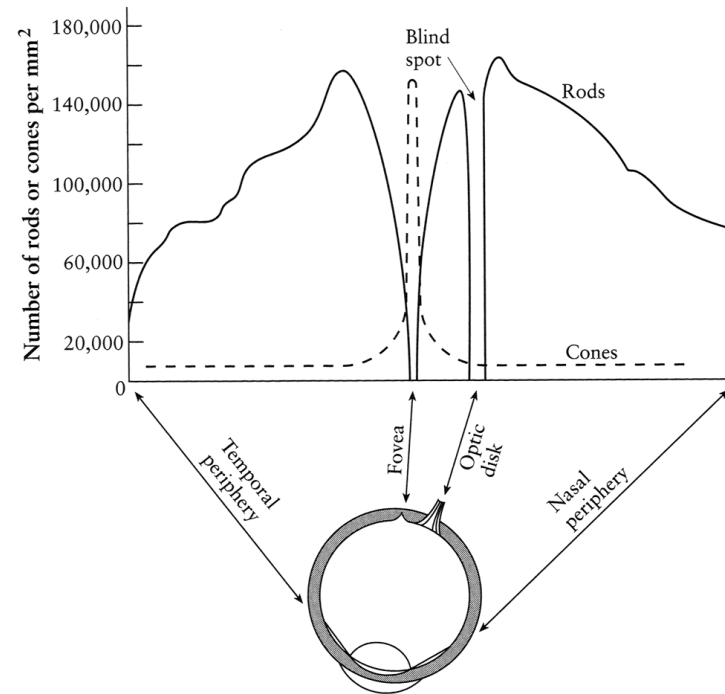
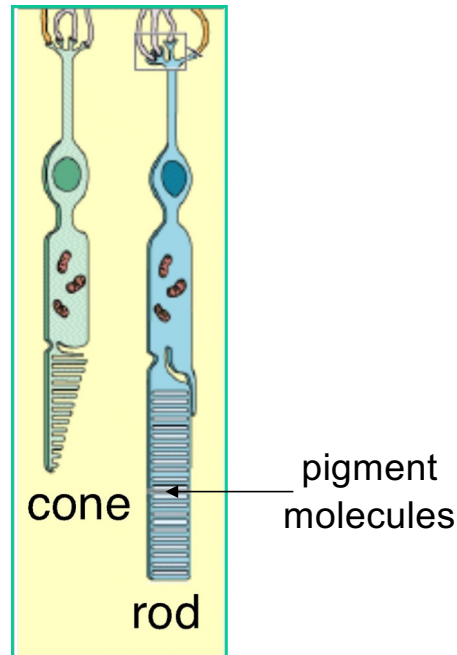
The Eye



The human eye is a camera (sort of)

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

Rods and cones, fovea

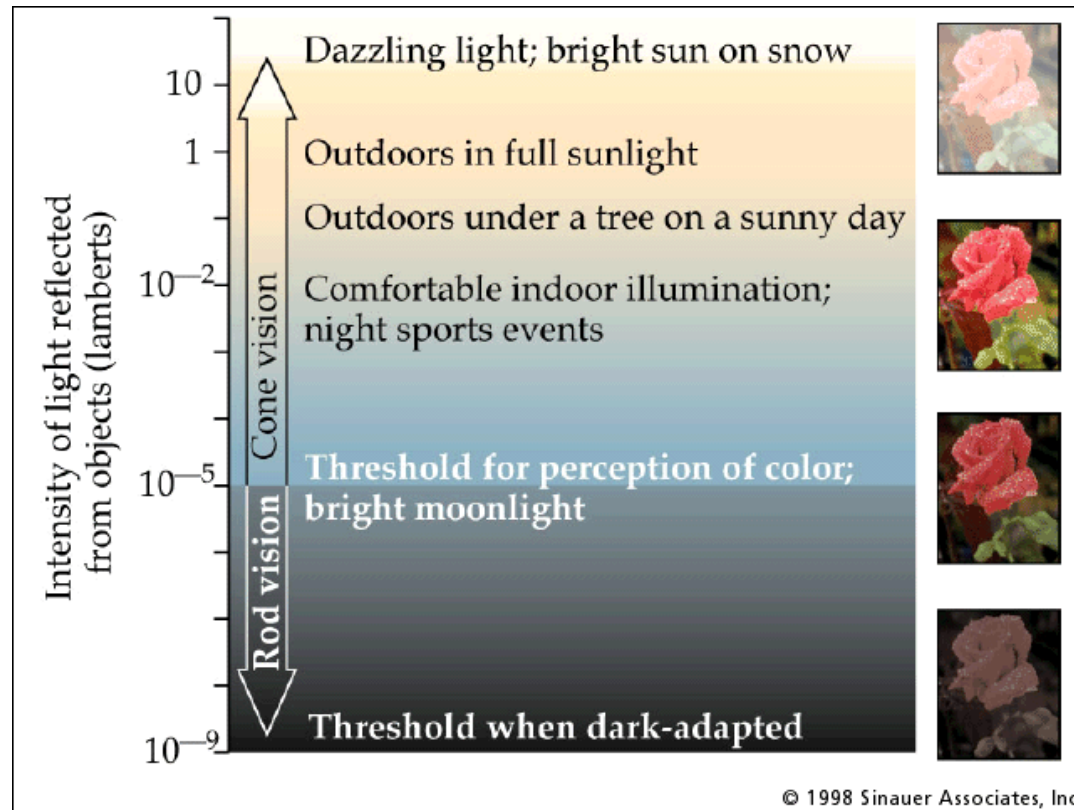


Rods are responsible for intensity, cones for color perception

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*

Rod / cone sensitivity

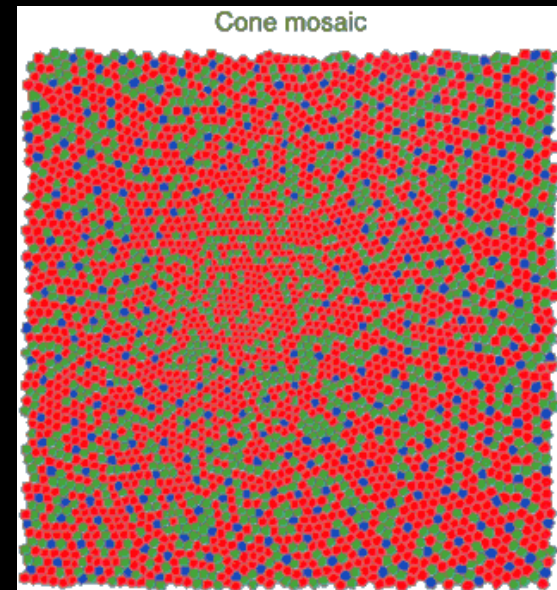
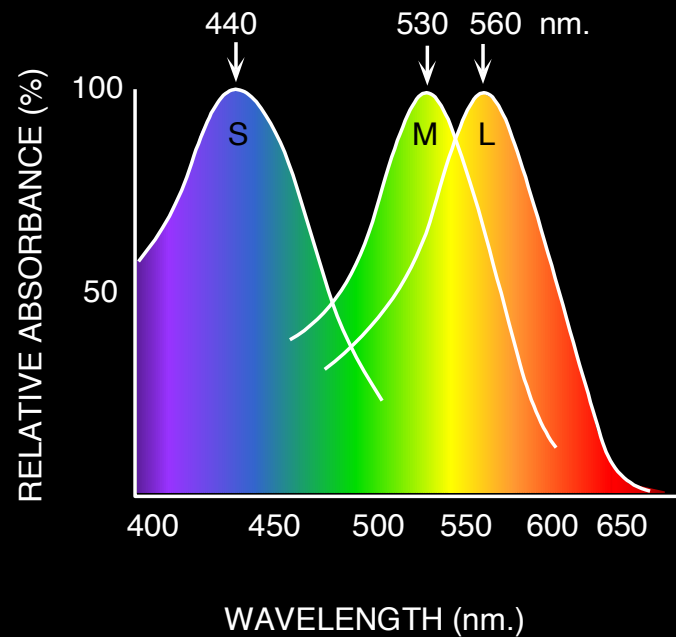


Why can't we read in the dark?

Slide by A. Efros

Physiology of Color Vision

Three kinds of cones:



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

Physiology of color vision: Fun facts

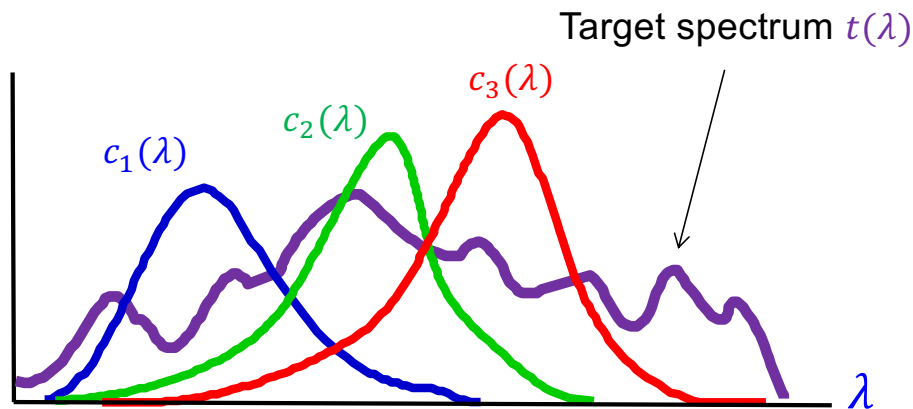
- “M” and “L” pigments are encoded on the X-chromosome
 - That’s why men are more likely to be color blind
 - “L” gene has high variation, so some women may be *tetrachromatic*
- Some animals have one (night animals), two (e.g., dogs), four (fish, birds), five (pigeons, some reptiles/amphibians), or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

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

Adapted from D. Hoiem

Color perception

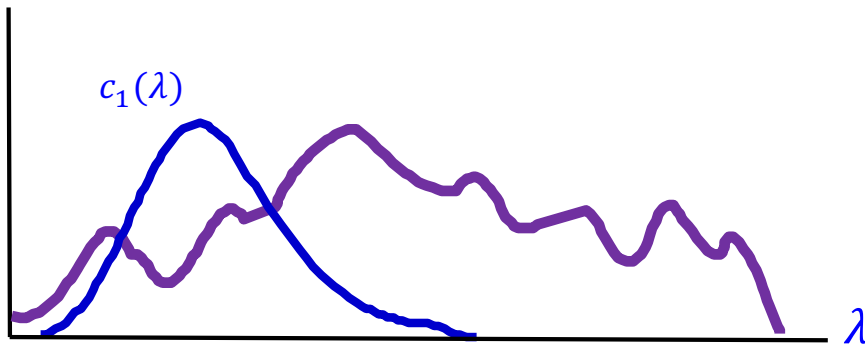
- Color receptors act as filters on the spectrum
 - Let $t(\lambda)$ be the target spectrum and $c_1(\lambda)$, $c_2(\lambda)$, and $c_3(\lambda)$ be the response curves of the three types of cones
 - Then the total response of each type of cone is:



Color perception

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 - Let $t(\lambda)$ be the target spectrum and $c_1(\lambda)$, $c_2(\lambda)$, and $c_3(\lambda)$ be the response curves of the three types of cones
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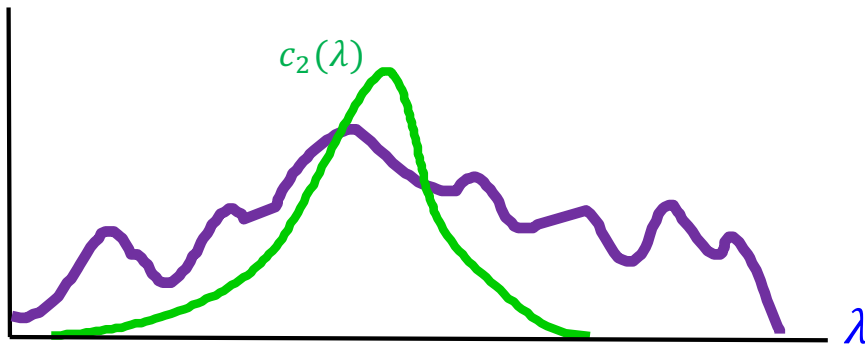
$$R_1 = \int_{\lambda} t(\lambda) c_1(\lambda) d\lambda$$



Color perception

- Color receptors act as filters on the spectrum
 - Let $t(\lambda)$ be the target spectrum and $c_1(\lambda)$, $c_2(\lambda)$, and $c_3(\lambda)$ be the response curves of the three types of cones
 - Then the total response of each type of cone is:

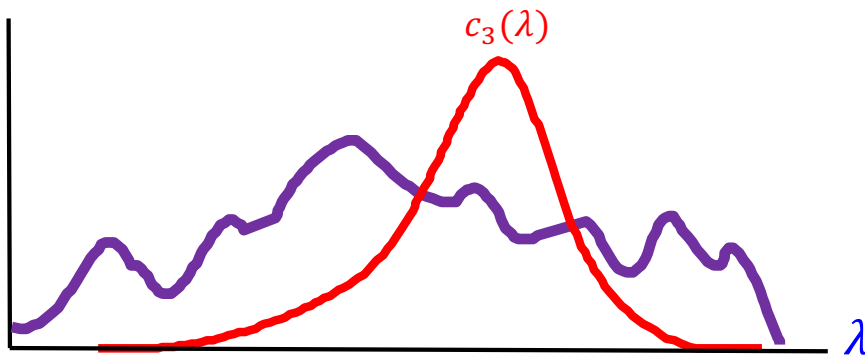
$$R_1 = \int_{\lambda} t(\lambda) c_1(\lambda) d\lambda \quad R_2 = \int_{\lambda} t(\lambda) c_2(\lambda) d\lambda$$



Color perception

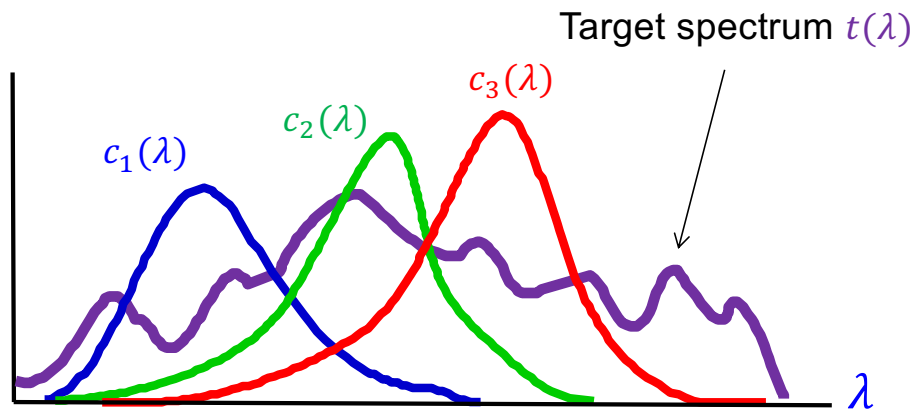
- Color receptors act as filters on the spectrum
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 - Then the total response of each type of cone is:

$$R_1 = \int_{\lambda} t(\lambda) c_1(\lambda) d\lambda \quad R_2 = \int_{\lambda} t(\lambda) c_2(\lambda) d\lambda \quad R_3 = \int_{\lambda} t(\lambda) c_3(\lambda) d\lambda$$

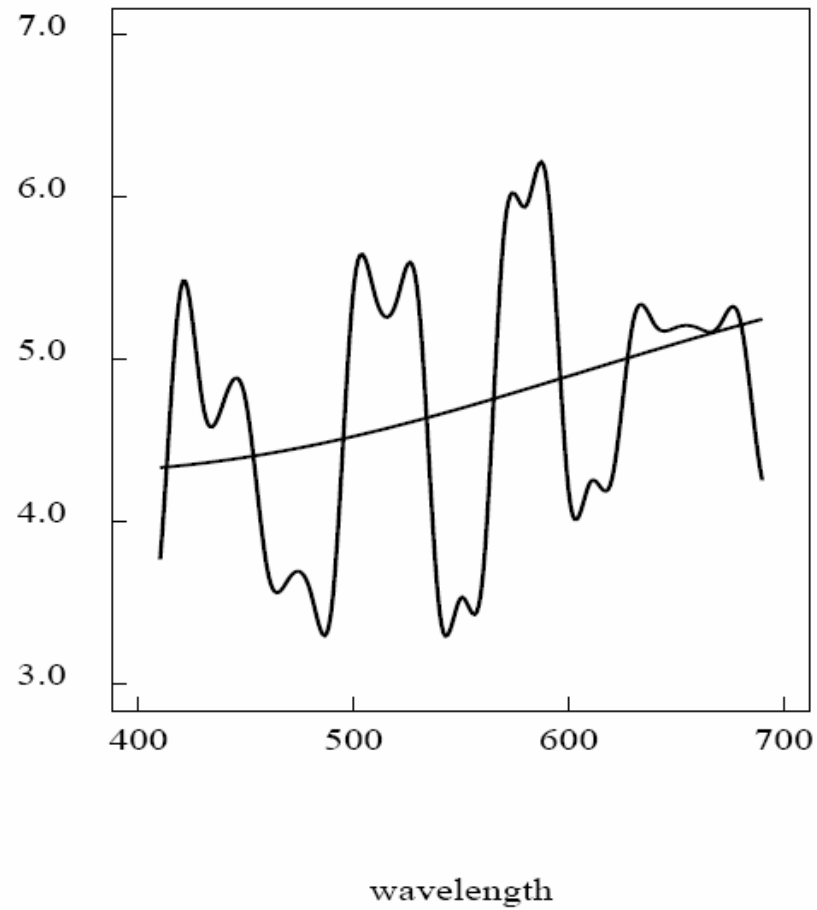


Color perception

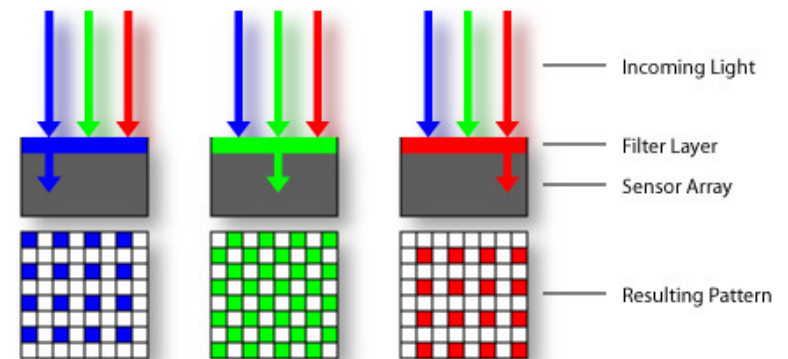
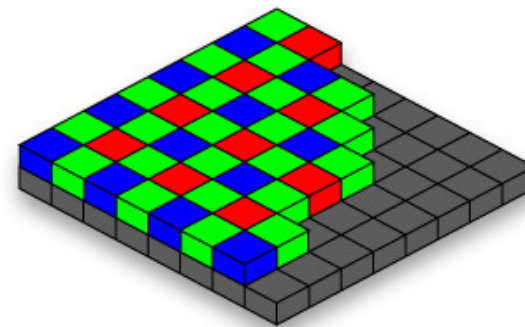
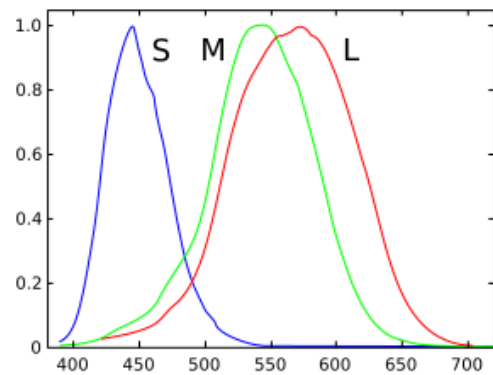
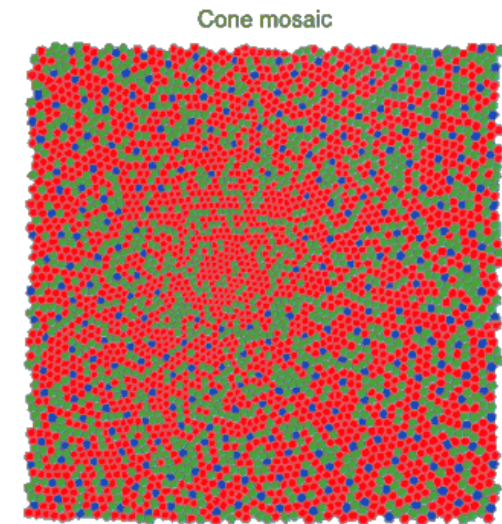
- Color receptors act as filters on the spectrum
 - Each type of cone returns one number
- How can we represent an entire spectrum with three numbers?
 - We can't – most of the information is lost!



Metamers: Spectra that appear indistinguishable



Color sensing in human vs. camera

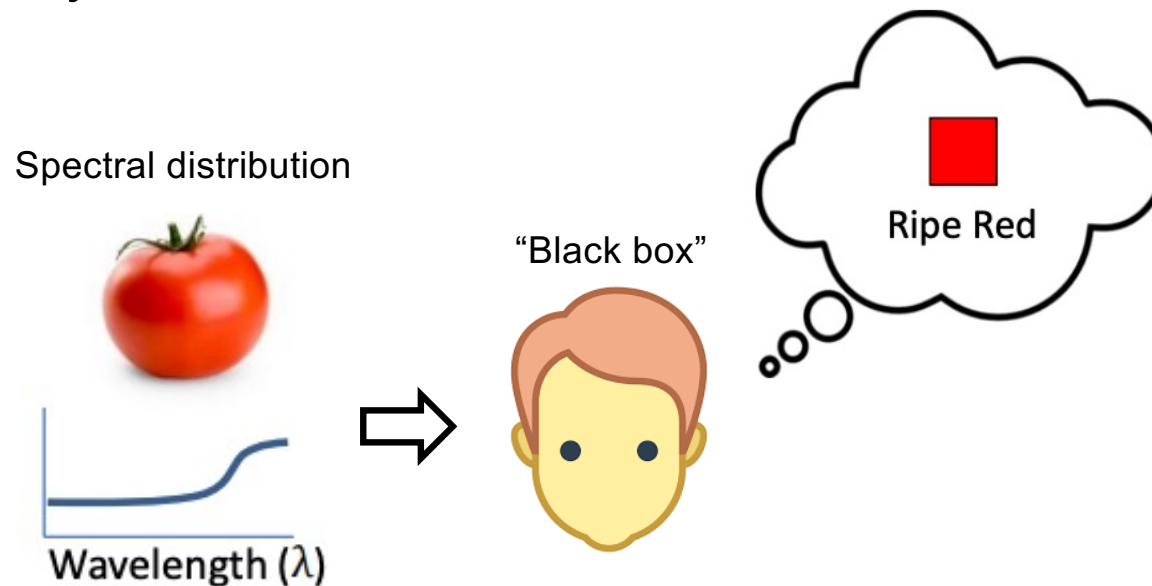


Color: Outline

- Physical origin of color
- Spectra of sources and surfaces
- Physiology of color vision
- Quantifying color perception

Quantifying color perception

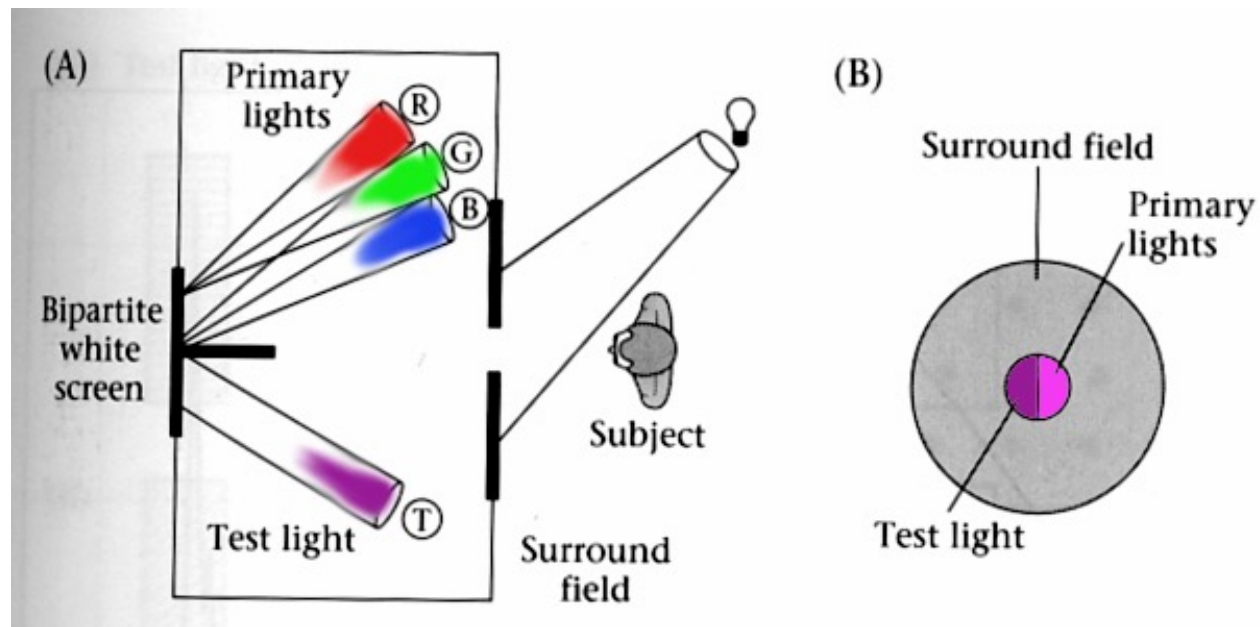
- Spectral distributions go through a “black box” (human visual system) and are perceived as color
- The only way to quantify the “black box” is to perform a human study



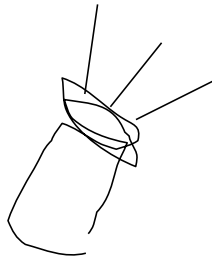
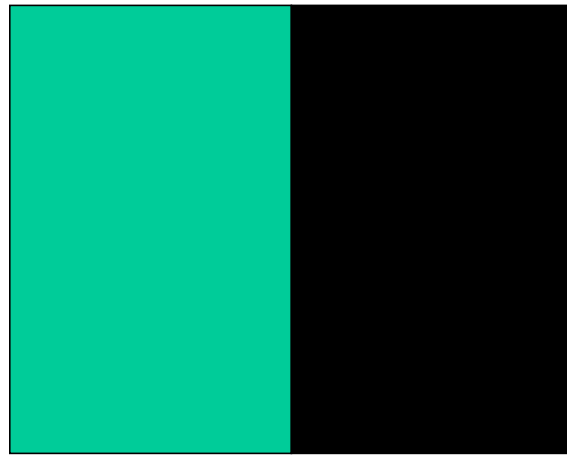
Source: [M. Brown](#)

Color matching experiments

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

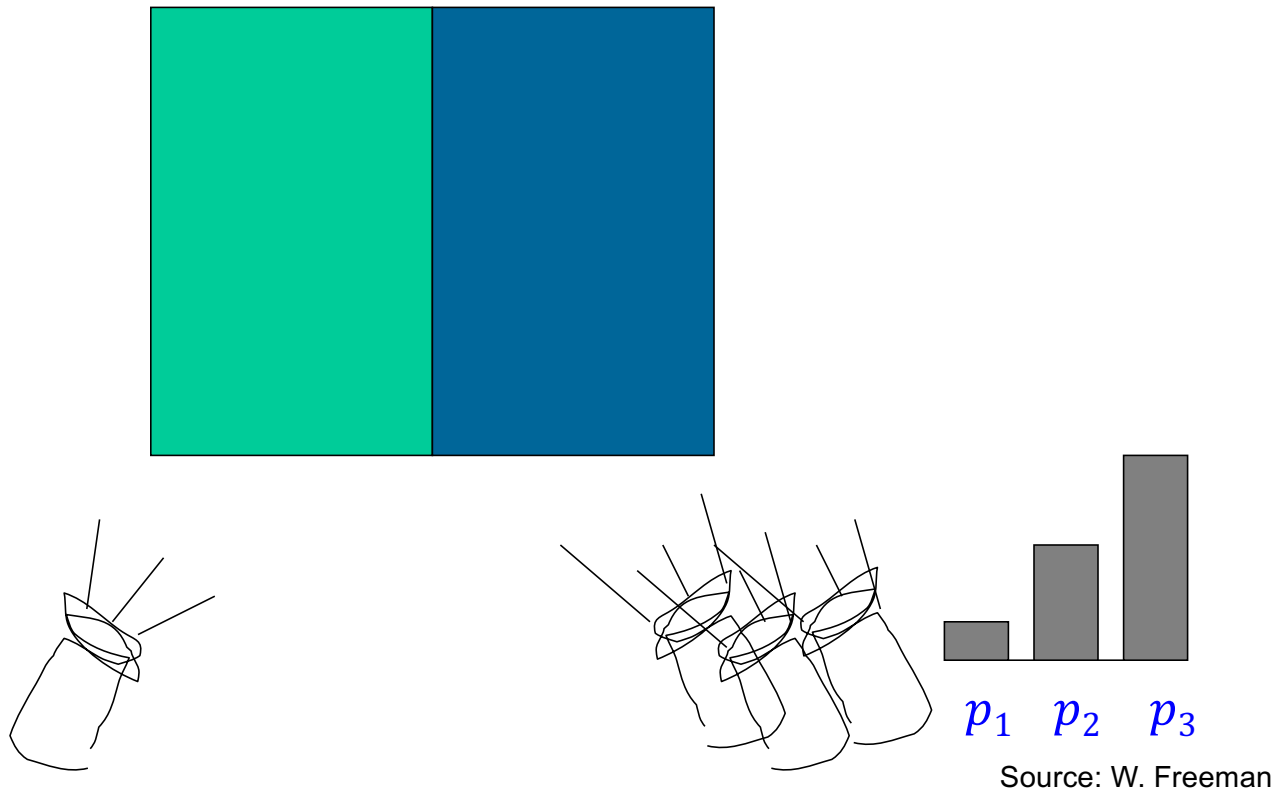


Color matching experiment 1

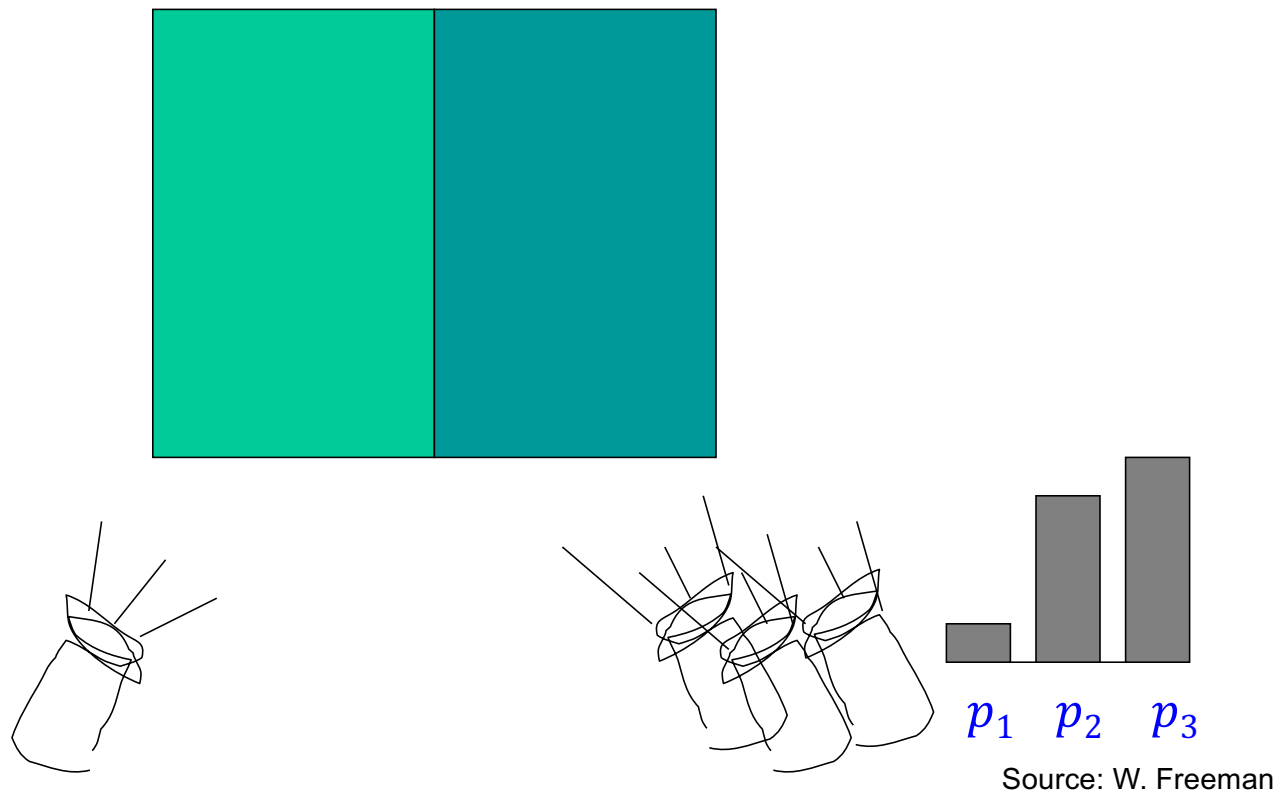


Source: W. Freeman

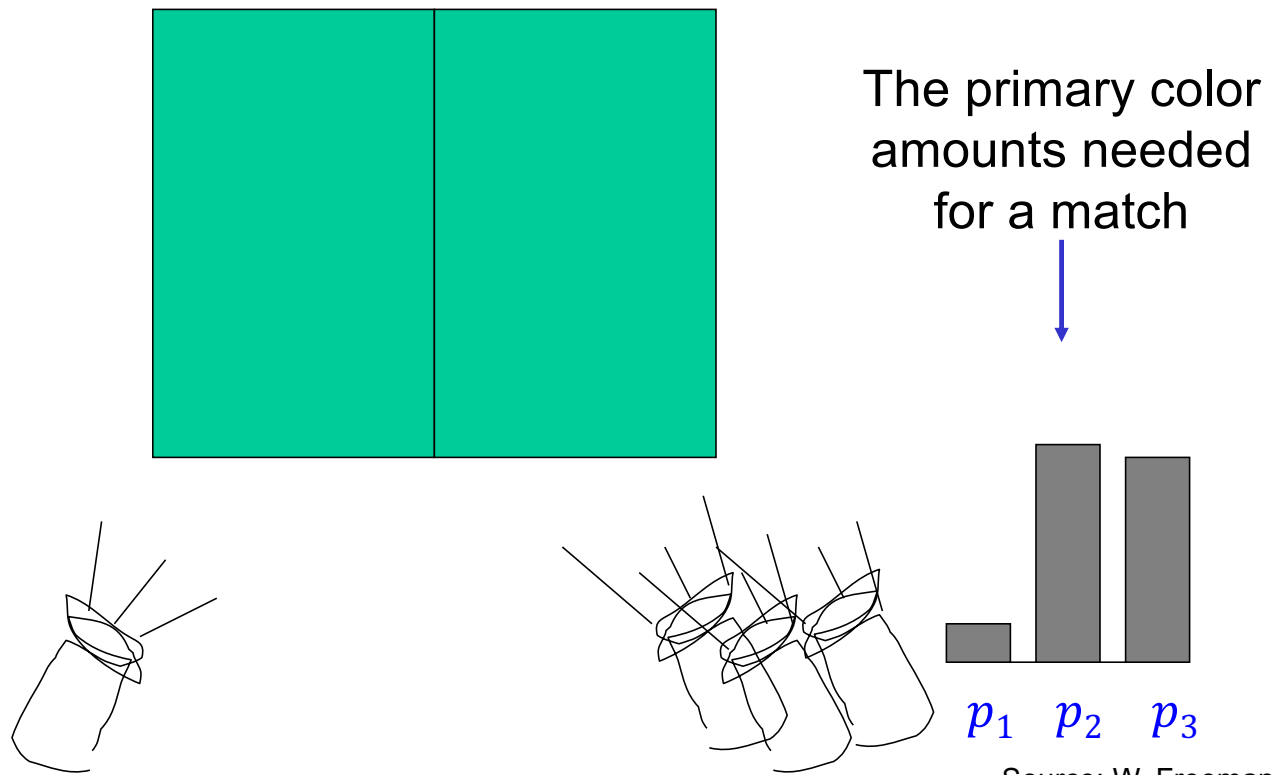
Color matching experiment 1



Color matching experiment 1

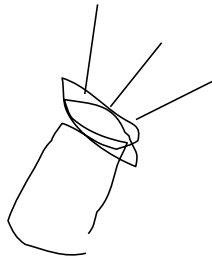
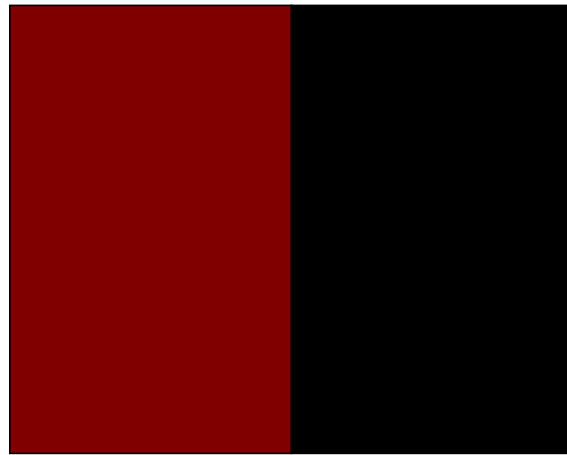


Color matching experiment 1



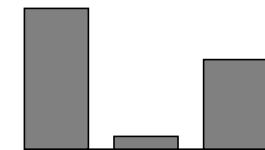
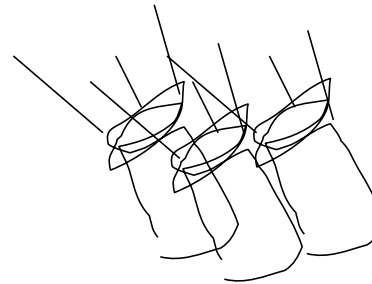
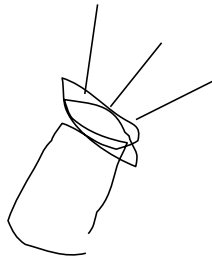
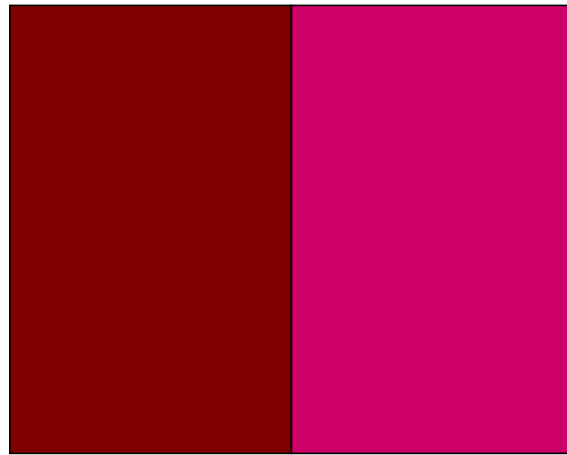
Source: W. Freeman

Color matching experiment 2



Source: W. Freeman

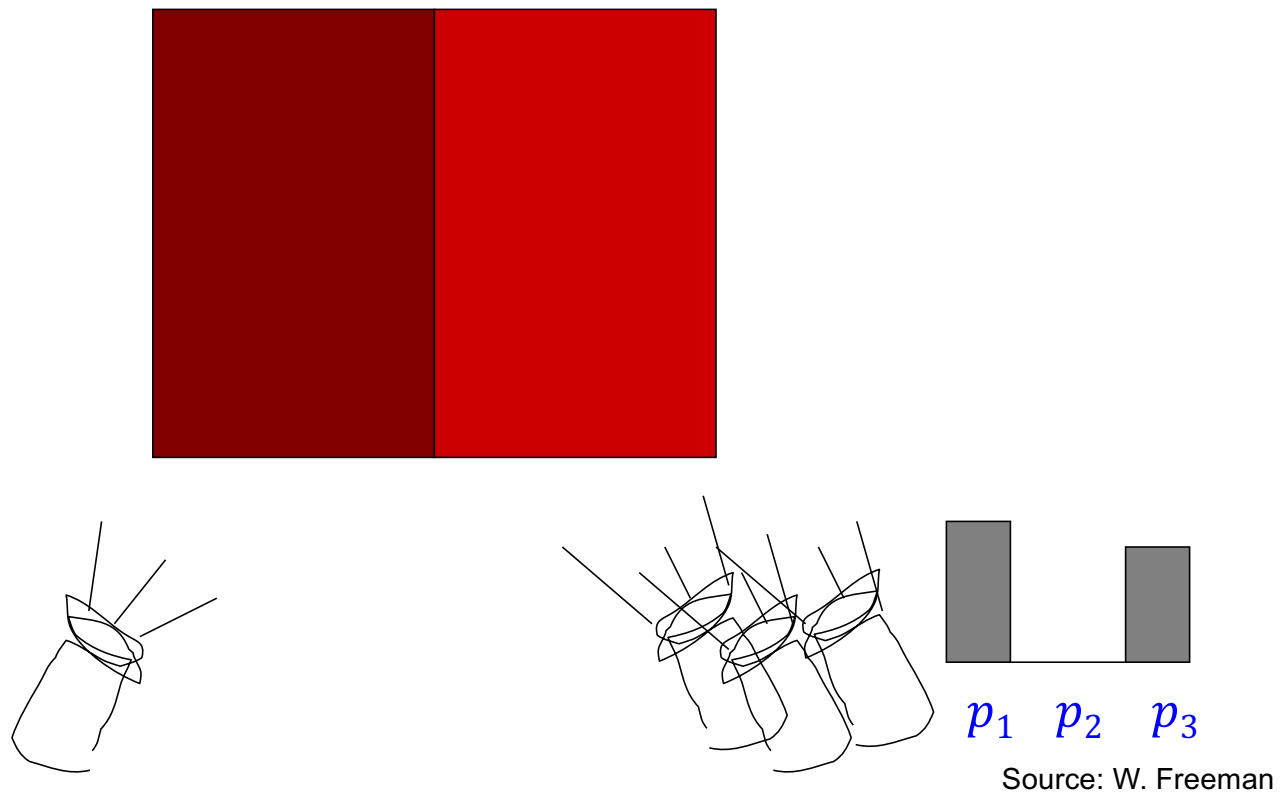
Color matching experiment 2



p_1 p_2 p_3

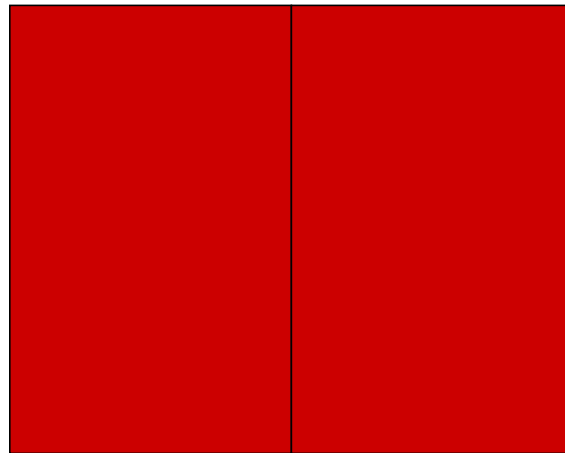
Source: W. Freeman

Color matching experiment 2

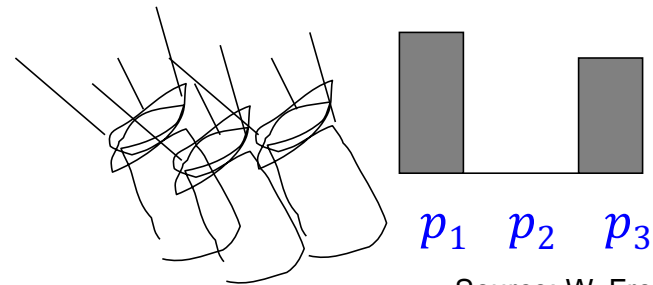
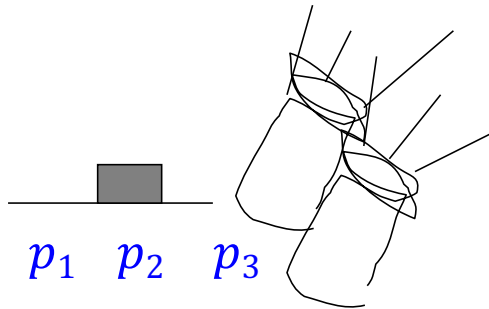
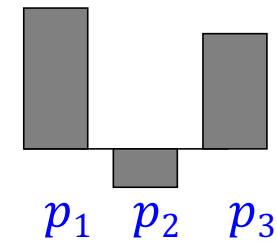


Color matching experiment 2

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

Empirical properties of color matching

- **Trichromacy:**

- Most* people can match any given test light with three *independent* primaries
- For the same light and primaries, most* people select the same weights
- Thus, three numbers are sufficient for encoding color
- This observation dates back to [Thomas Young in the 18th century](#)

- **Linearity:**

- Given fixed primaries, let a_1, a_2, a_3 and b_1, b_2, b_3 be the respective weights needed to match test lights A and B . We can write this as $A = (a_1, a_2, a_3)$ and $B = (b_1, b_2, b_3)$. Then for scalar coefficients u and v ,

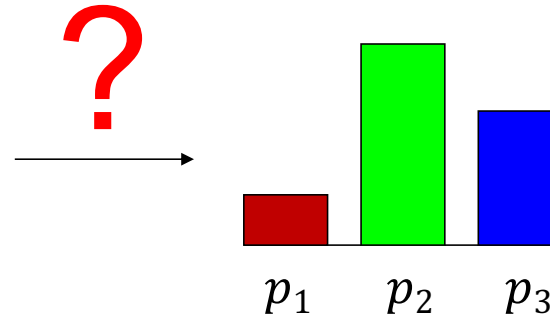
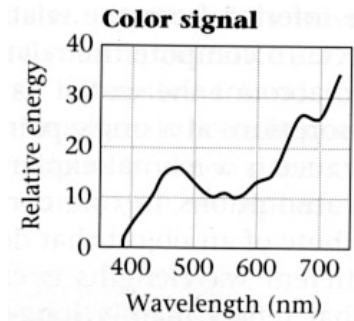
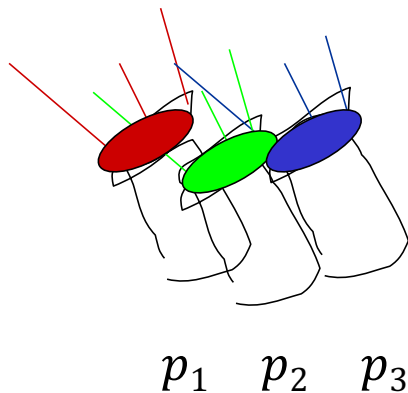
$$uA + vB = (ua_1 + vb_1, ua_2 + vb_2, ua_3 + vb_3)$$

Last time: Color

- Physical origin of color
- Spectra of sources and surfaces
- Physiology of color vision
- Quantifying color perception
- **Color spaces**

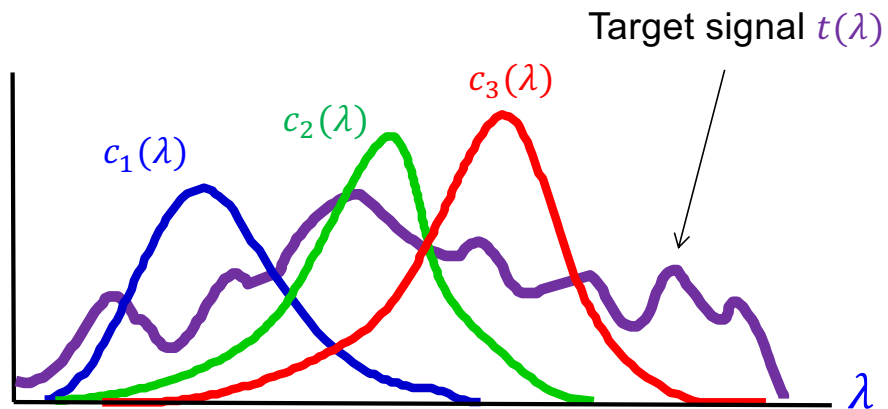
Linear color spaces

- Fixing three **primaries** defines a linear color space in which the **coordinates** of a color are given by the weights of the primaries used to match it
- How can we find the coordinates of an arbitrary color signal?
- We need **matching functions**, or amounts of each primary needed to match monochromatic sources at each wavelength



Linear color spaces

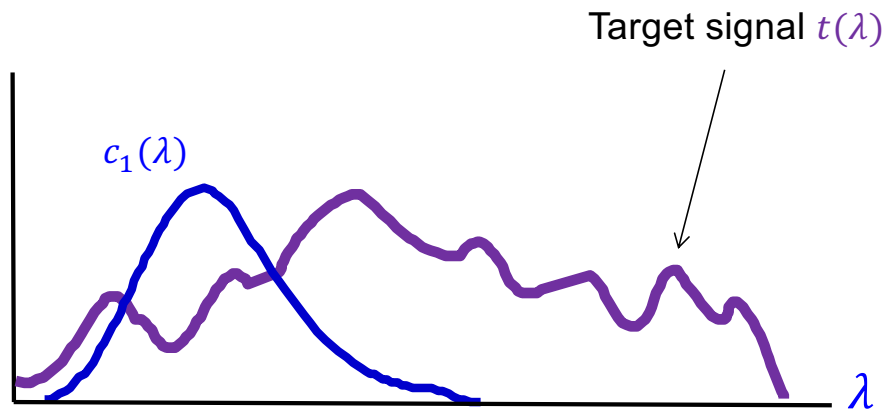
- Let $t(\lambda)$ be the spectrum of the target signal and $c_1(\lambda)$, $c_2(\lambda)$, and $c_3(\lambda)$ the matching functions



Linear color spaces

- Let $t(\lambda)$ be the spectrum of the target signal and $c_1(\lambda)$, $c_2(\lambda)$, and $c_3(\lambda)$ the matching functions
- Then the weights of the primaries needed to match $t(\lambda)$ are:

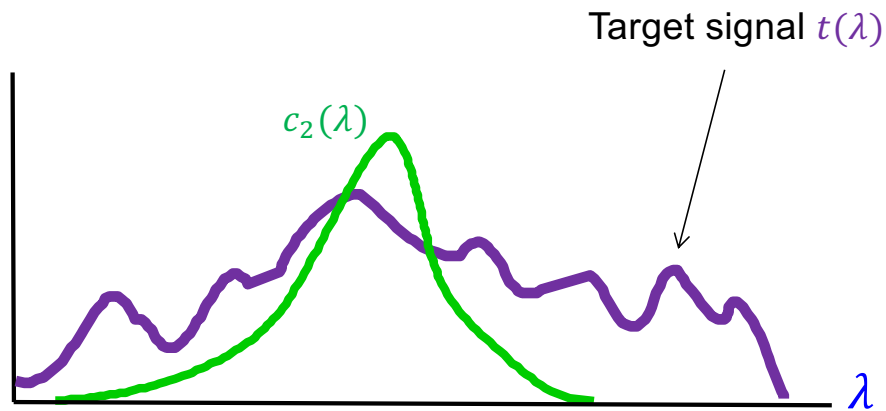
$$w_1 = \int_{\lambda} t(\lambda) c_1(\lambda) d\lambda$$



Linear color spaces

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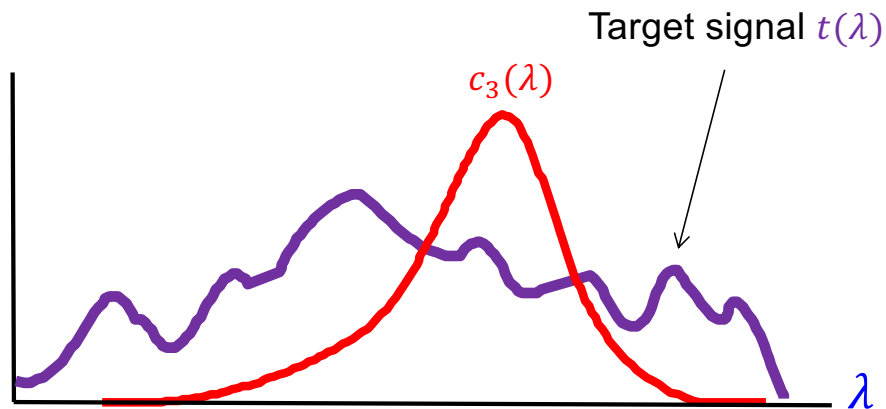
$$w_1 = \int_{\lambda} t(\lambda) c_1(\lambda) d\lambda \quad w_2 = \int_{\lambda} t(\lambda) c_2(\lambda) d\lambda$$



Linear color spaces

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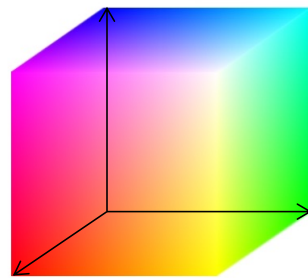
$$w_1 = \int_{\lambda} t(\lambda) c_1(\lambda) d\lambda \quad w_2 = \int_{\lambda} t(\lambda) c_2(\lambda) d\lambda \quad w_3 = \int_{\lambda} t(\lambda) c_3(\lambda) d\lambda$$



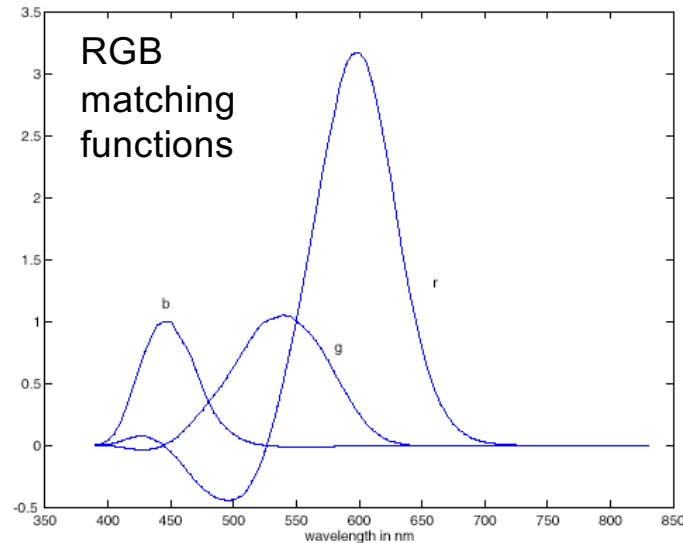
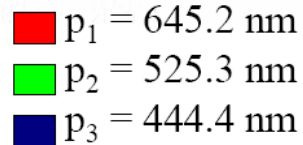
Matching functions act as filters on the target spectrum, like response curves of color receptors!

RGB color space

- Primaries are single-wavelength sources, matching functions for R and G have negative values for parts of the spectrum

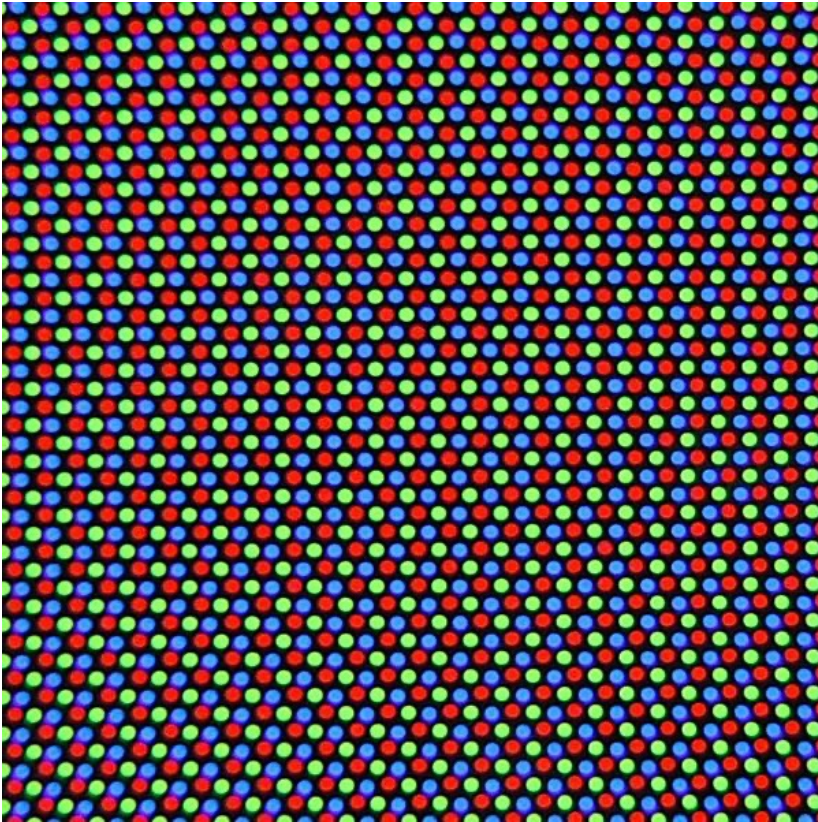


RGB primaries



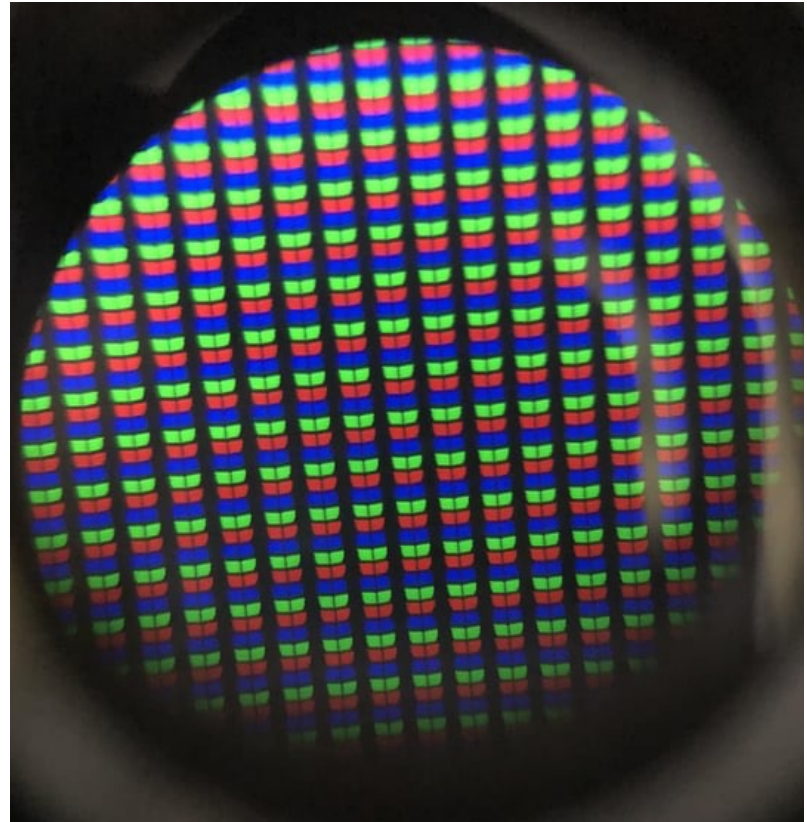
RGB color space

CRT screen close-up



[Source](#)

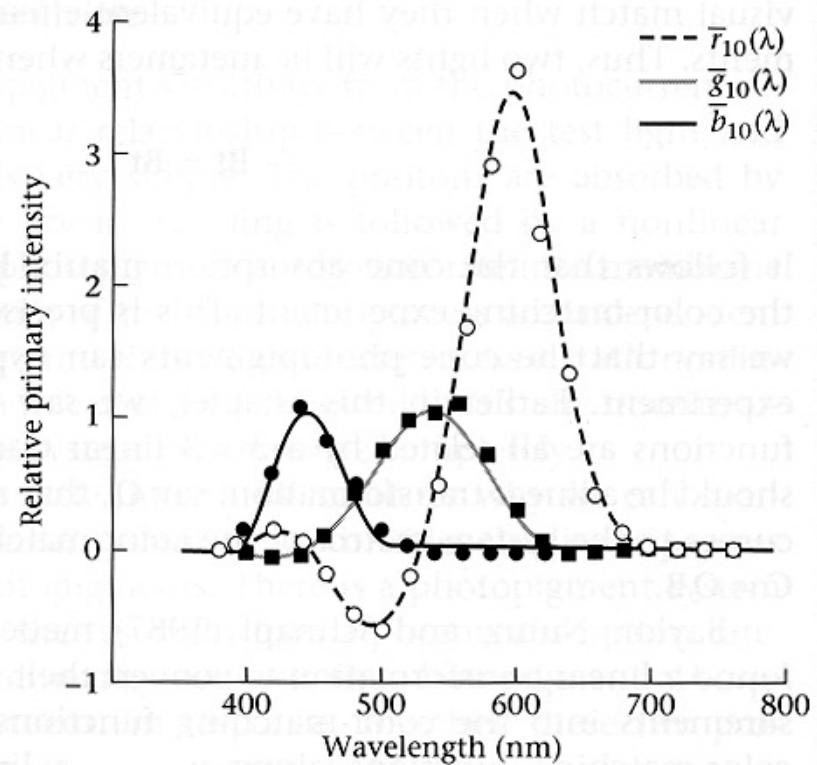
LCD screen close-up



[Source](#)

Comparison of RGB matching functions with best 3x3 transformation of cone responses

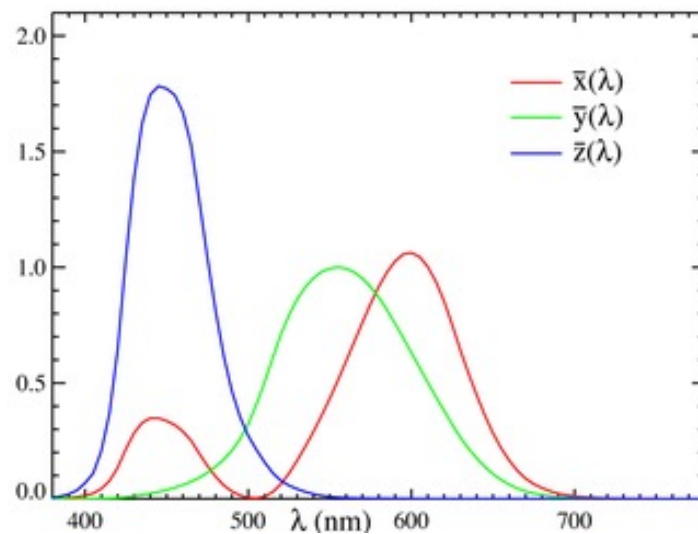
4.20 COMPARISON OF CONE PHOTOCURRENT RESPONSES AND THE COLOR-MATCHING FUNCTIONS. The cone photocurrent spectral responsivities are within a linear transformation of the color-matching functions, after a correction has been made for the optics and inert pigments in the eye. The smooth curves show the 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.



Linear color spaces: CIE XYZ

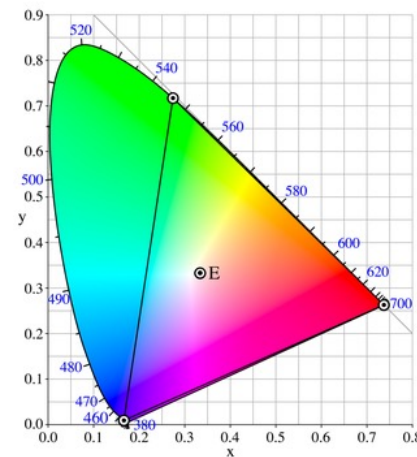
- Primaries are *imaginary*, but matching functions are everywhere positive
- The *Y* parameter corresponds to brightness or *luminance*

Matching functions



2D visualization:

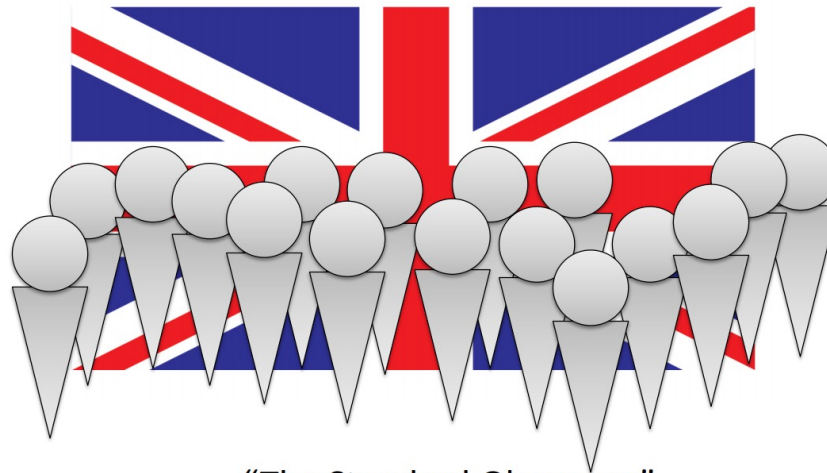
$$x = X/(X + Y + Z), y = Y/(X + Y + Z)$$



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

Linear color spaces: CIE XYZ

- CIE XYZ is based on color matching experiments carried out in late 1920s by W. David Wright (Imperial College) and John Guild (National Physical Laboratory, London)
- The experiments used 17 “standard observers” (10 by Wright, 7 by Guild)

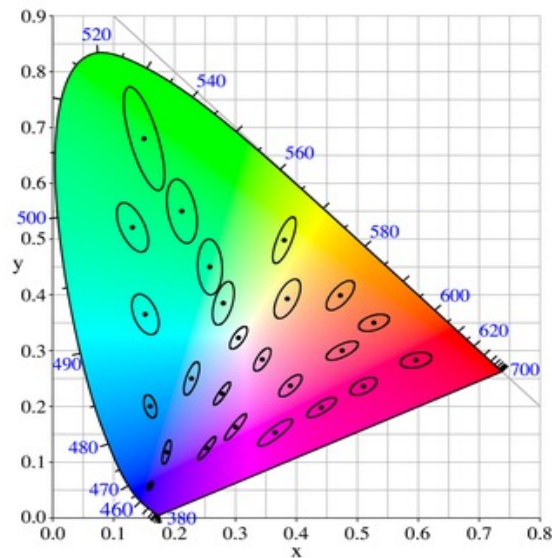


“The Standard Observers”

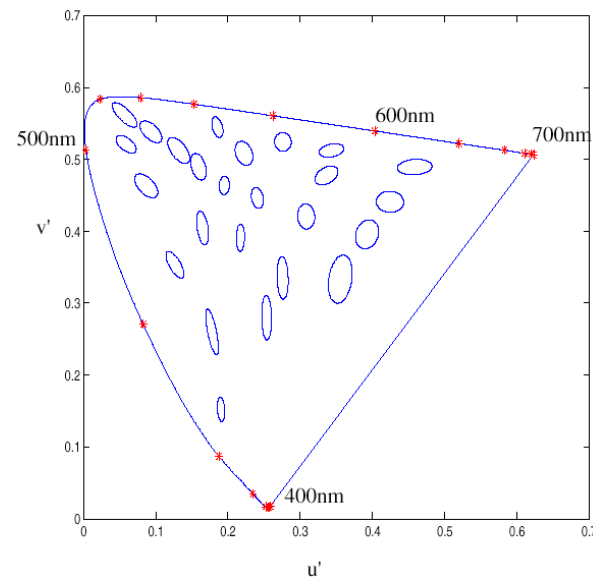
Source: [M. Brown](#)

Uniform color spaces

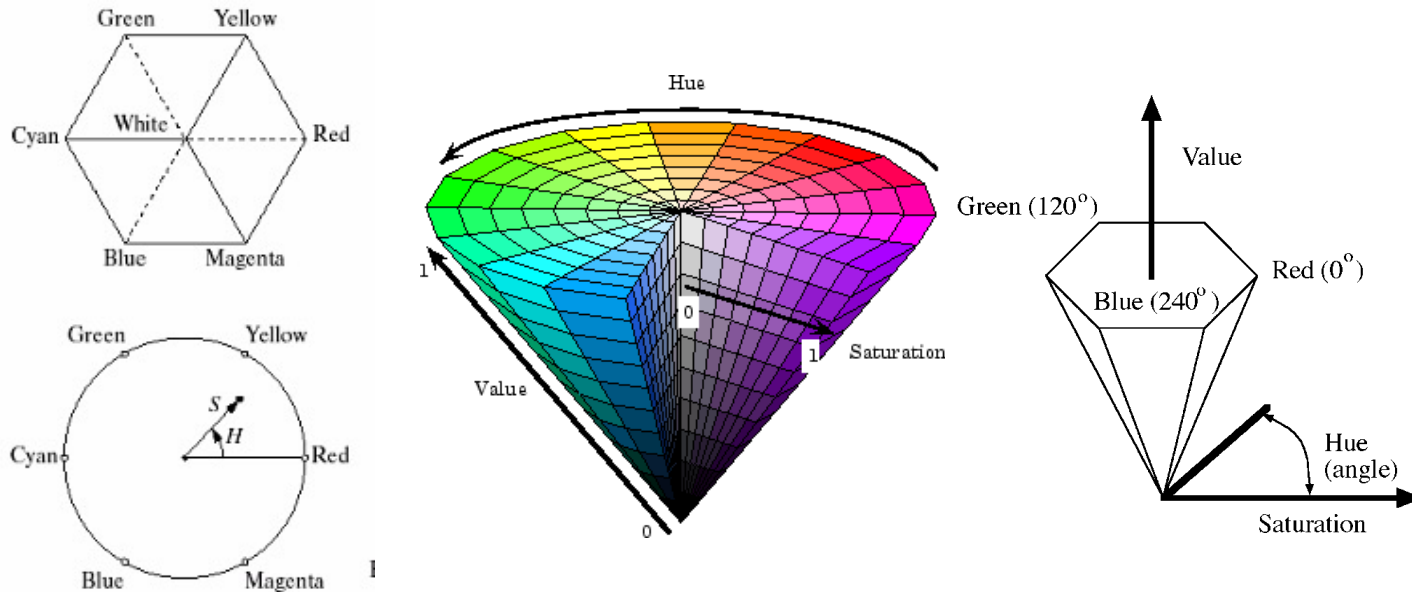
- Unfortunately, differences in x, y coordinates do not reflect perceptual color differences
- CIE $u'v'$ is a projective transform of x, y to make the ellipses more uniform



McAdam ellipses: Just noticeable differences in color



Nonlinear color spaces: HSV



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

Outline

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

Color perception

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



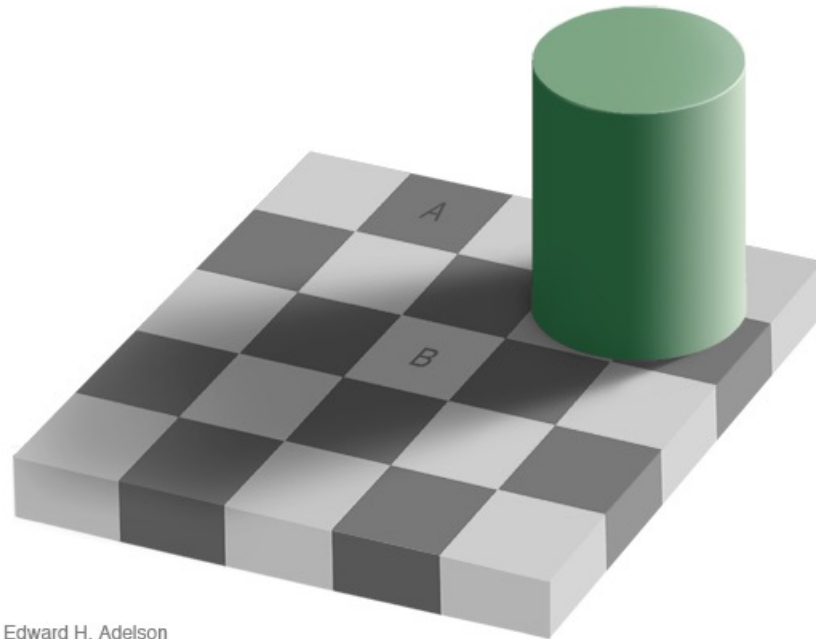
J. S. Sargent, The Daughters of Edward D. Boit, 1882

Chromatic adaptation

- The visual system changes its sensitivity depending on the luminances prevailing in the visual field
 - The exact mechanism is still not fully 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>

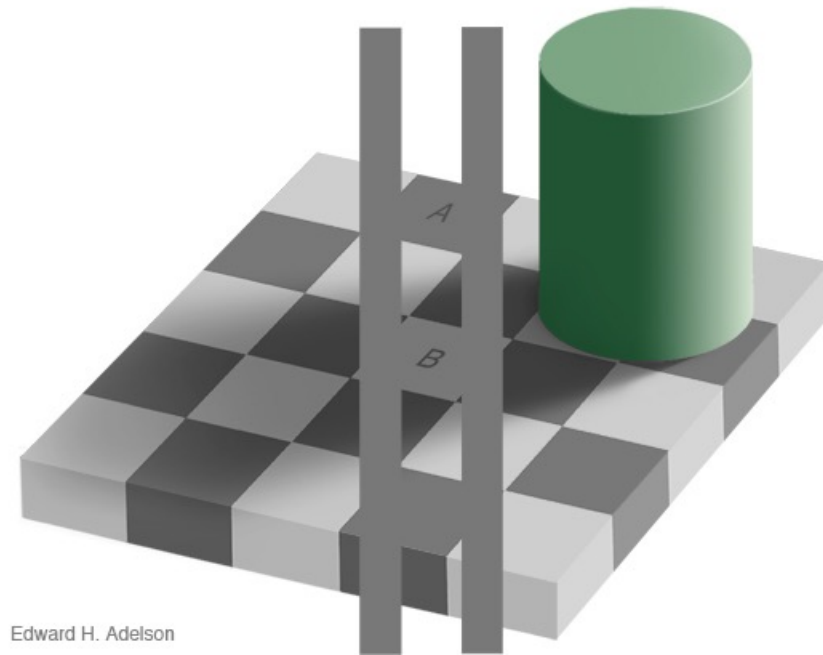
Checker shadow illusion



Edward H. Adelson

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

Checker shadow illusion



Edward H. Adelson

- Possible explanations: simultaneous contrast, reflectance vs. illumination edges

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

What color is the dress?



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

This strawberry cake has no red pixels!



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

White balance

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

Incorrect white balance



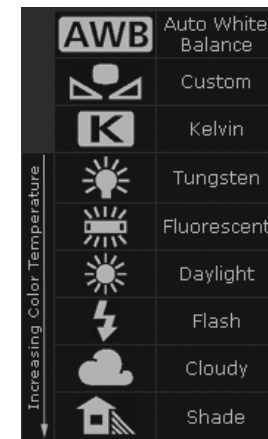
Correct white balance



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

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)
 - If the object is recorded as r_w, g_w, b_w use weights $1/r_w, 1/g_w, 1/b_w$



White balance

- Without gray cards: we need to “guess” which pixels correspond to white objects
- Gray world assumption
 - The image average $\bar{r}, \bar{g}, \bar{b}$ is gray
 - Use weights $1/\bar{r}, 1/\bar{g}, 1/\bar{b}$
- 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

Is white balance solved?



New College, Oxford, September 2022

Is white balance solved?



Photographers in cities like San Francisco and Portland have been sharing apocalyptic images of red/orange skies as wildfire smoke literally blots out the sun. But many smartphone photographers trying to do the same thing have tried and failed over and over. It turns out Auto White Balance is ruining their shots.

<https://petapixel.com/2020/09/10/smartphones-are-ruining-wildfire-sky-photos-with-auto-white-balance/>

Is white balance solved?

- When there are several types of illuminants in the scene, different reference points will yield different results



Reference: moon



Reference: stone

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

Is white balance solved?

- When there are several types of illuminants in the scene, different reference points will yield different results
- Possible solution: spatially varying white balance



Input



Alpha map



Output

E. Hsu, T. Mertens, S. Paris, S. Avidan, and F. Durand, [Light Mixture Estimation for Spatially Varying White Balance](#), SIGGRAPH 2008

Uses of color in computer vision

