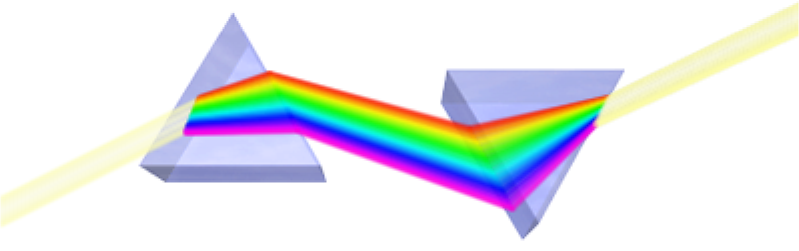
Clinical Visual Optics OPTO 223

Week 14 & 15

Salwa Alsaleh, PhD

Colour vision



Outline

- Measuring colour
  - Spectral power distributions
  - Colour mixing
  - Colour matching experiments
  - colour spaces
    - Uniform colour spaces

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

What is colour?

- 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.

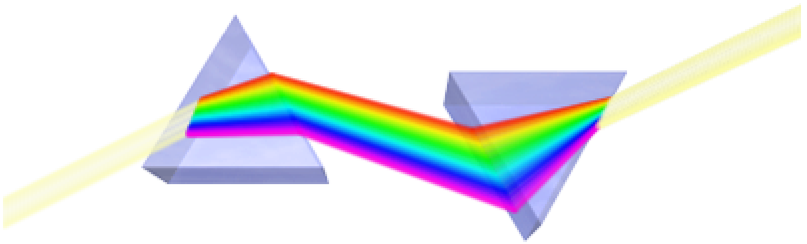
colour and light

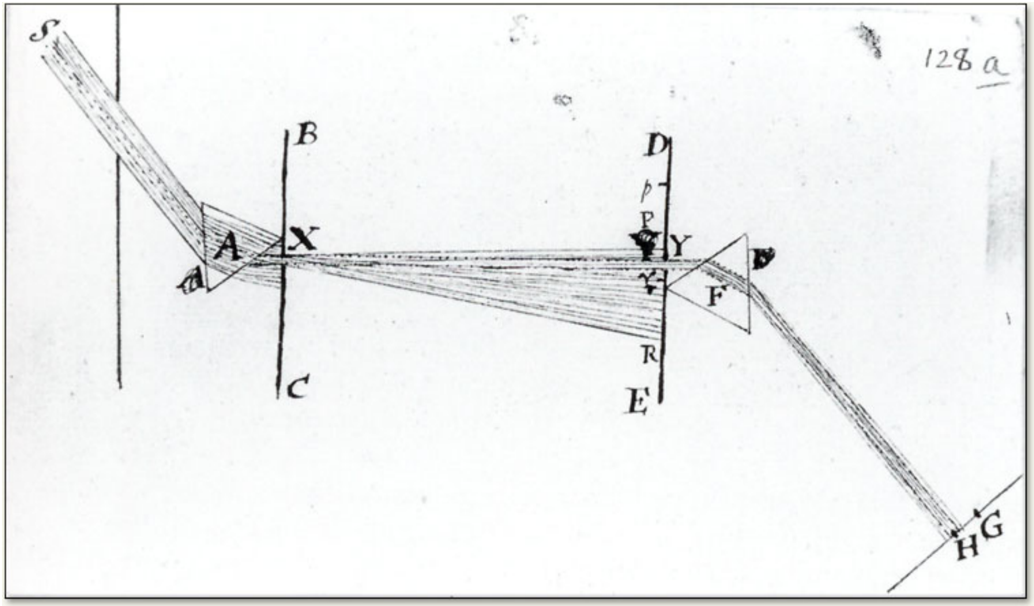
- **colour of light** arriving at camera depends on
  - Spectral reflectance of the surface light is leaving
  - Spectral radiance of light falling on that patch

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

colour and light

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

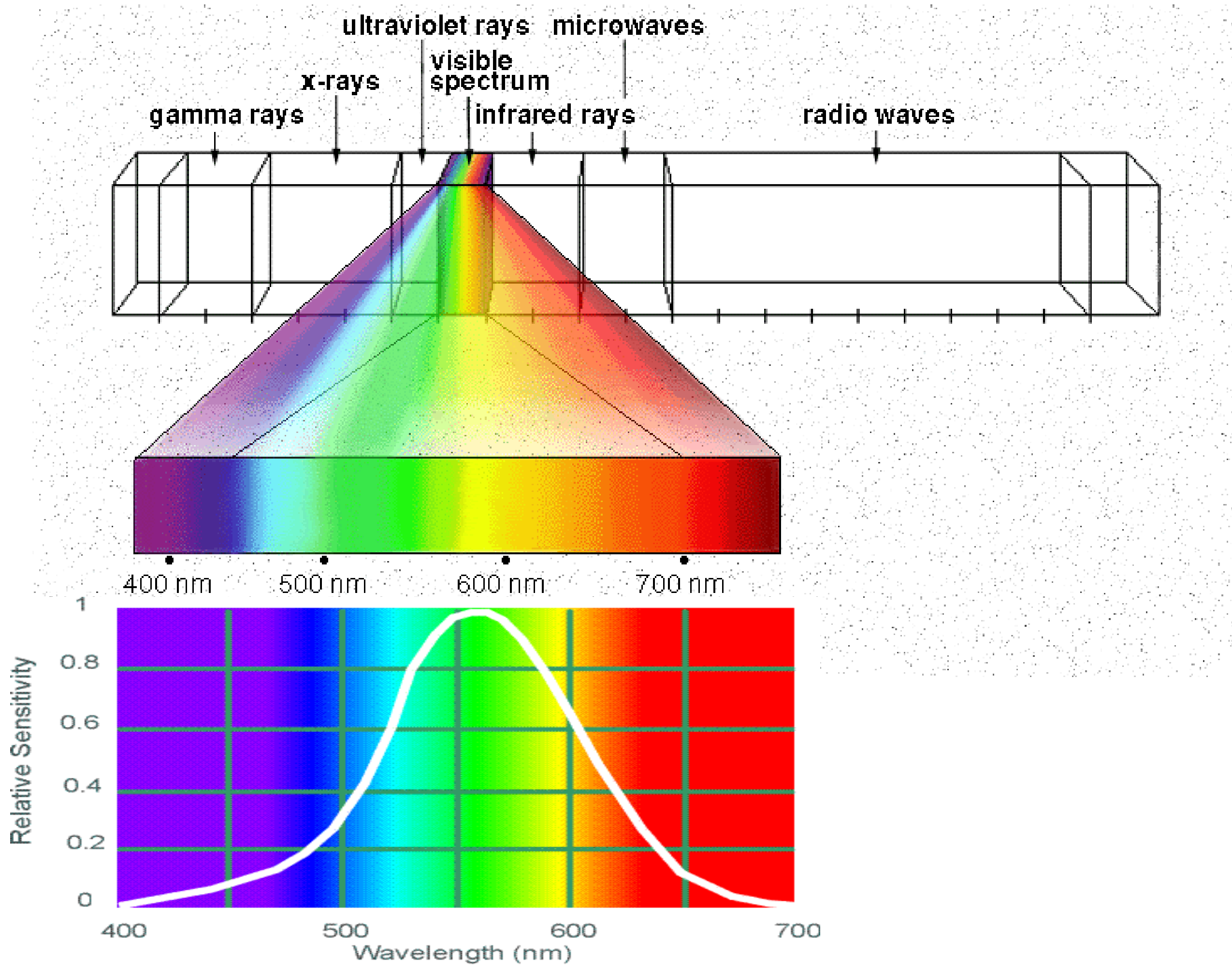




Newton 1665

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

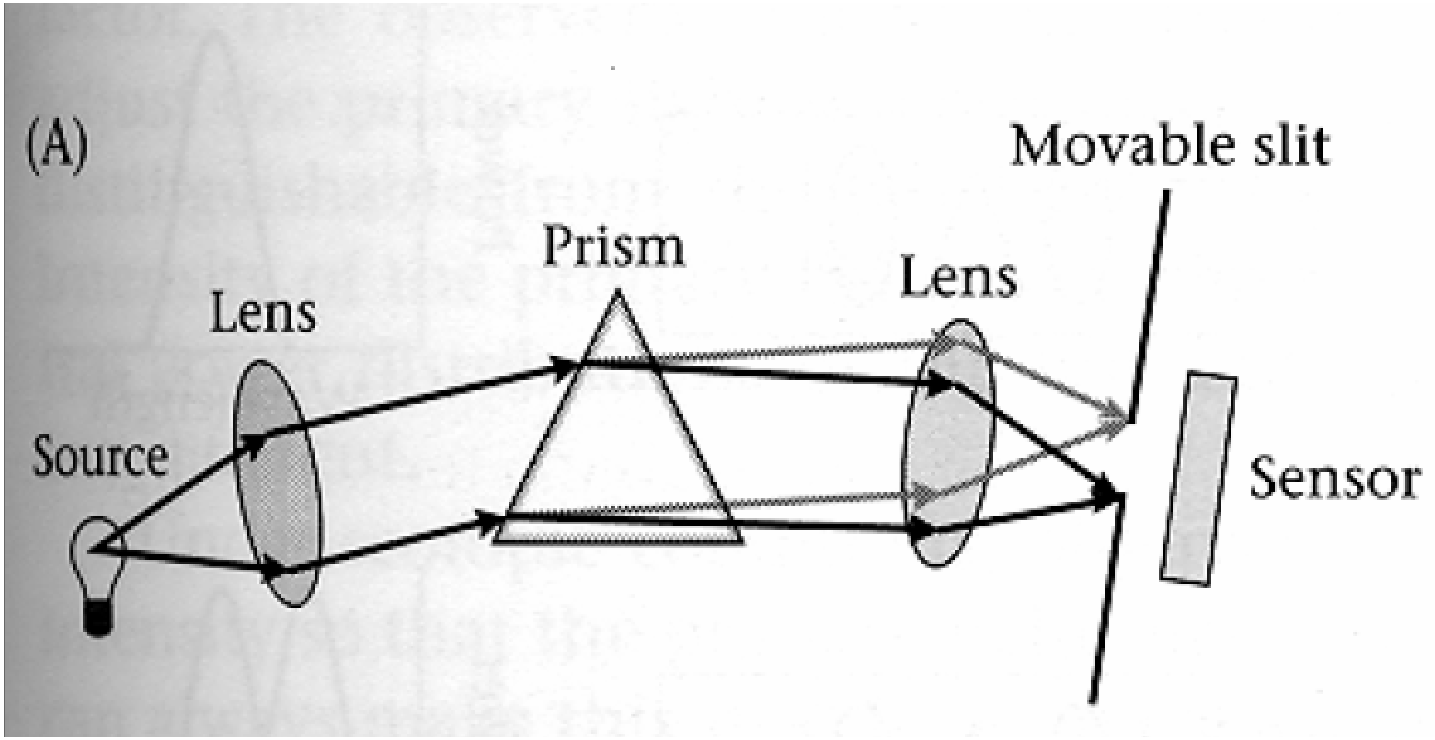
Electromagnetic spectrum



Human Luminance Sensitivity Function

Image credit: nasa.gov

Measuring spectra

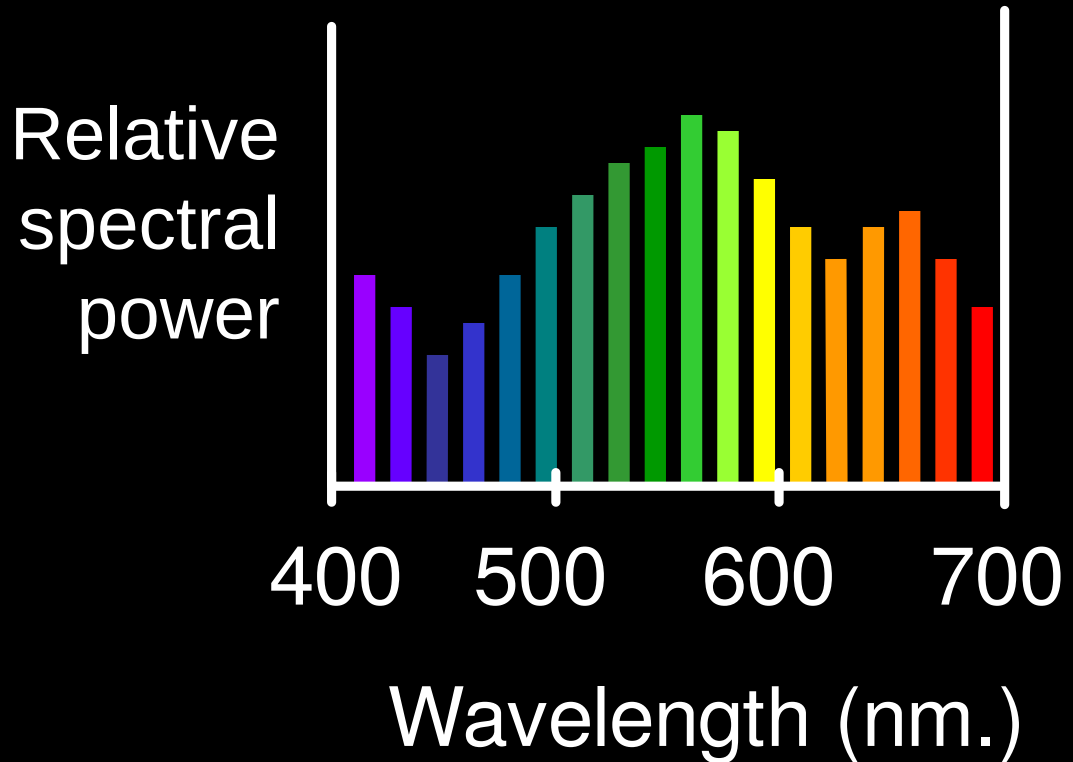


Spectroradiometer: separate input light into its different wavelengths, and measure the energy at each.

Foundations of Vision, B. Wandell

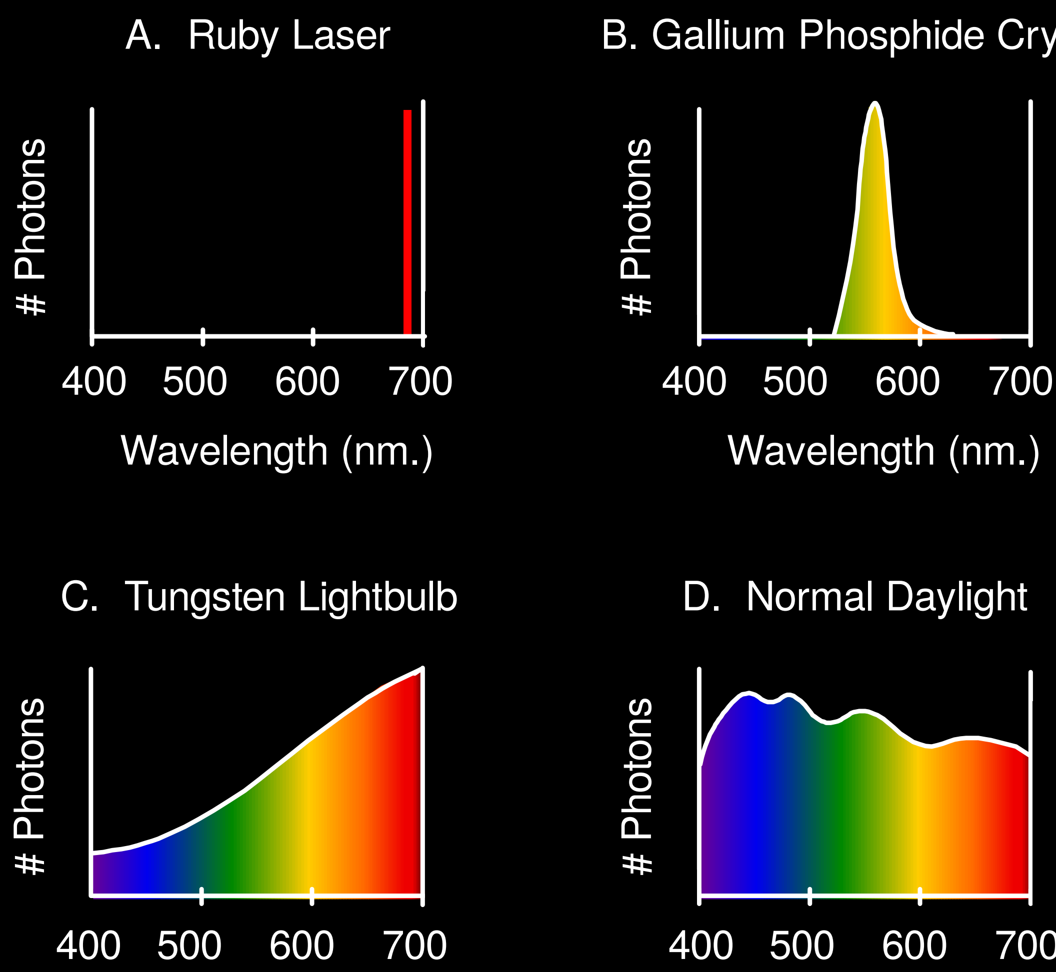
The Physics of Light

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.



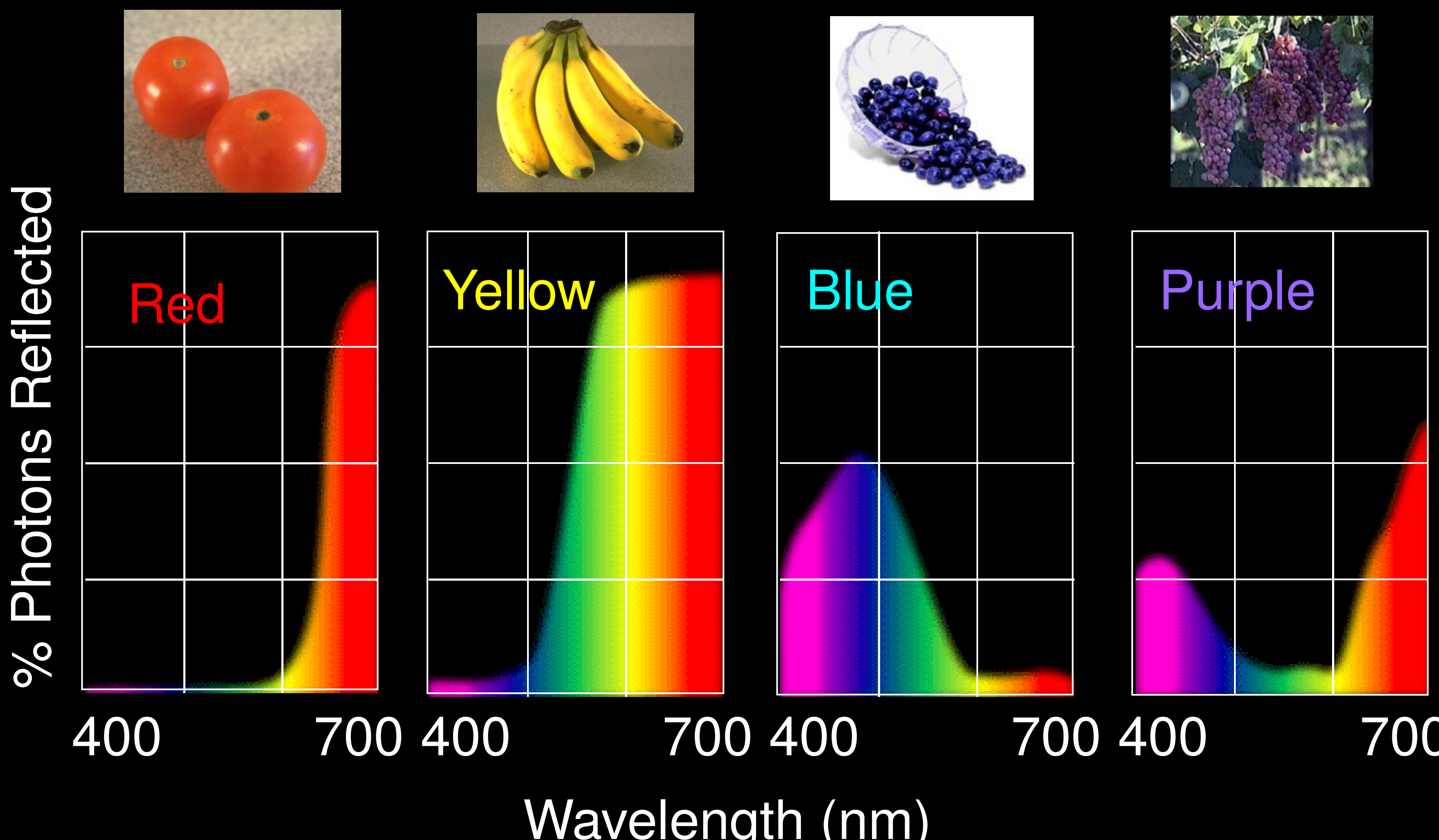
Spectral power distributions

Some examples of the spectra of light sources



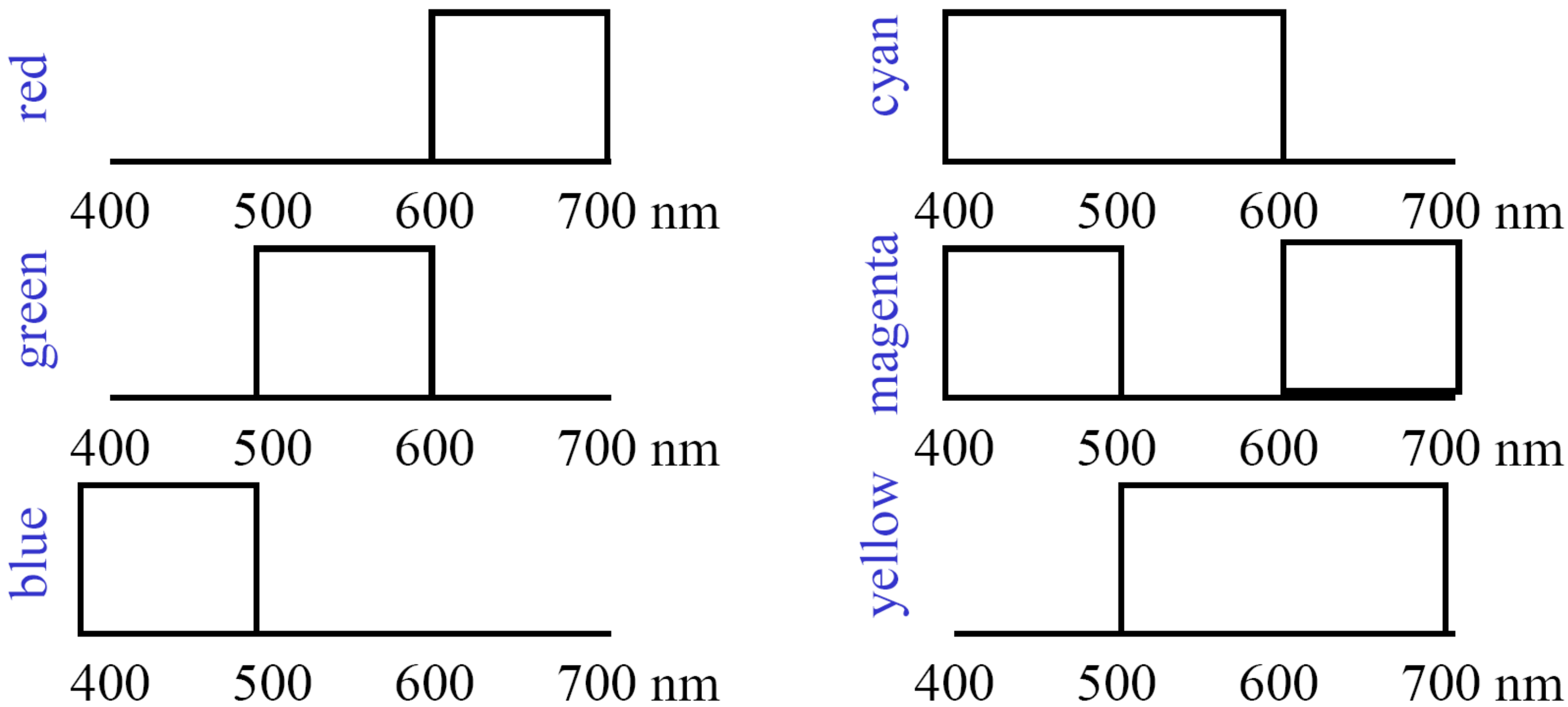
Surface reflectance spectra

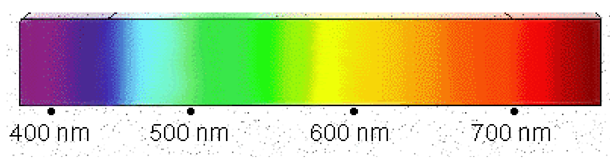
Some examples of the reflectance spectra of surfaces



colour mixing

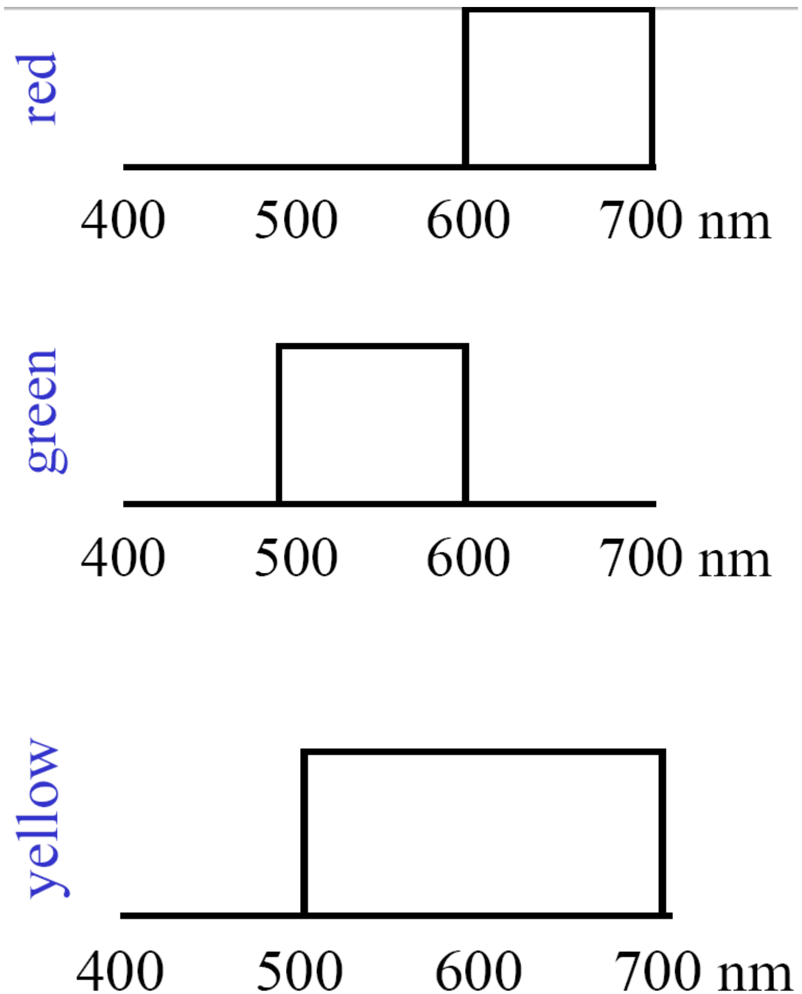
Cartoon spectra for colour names:



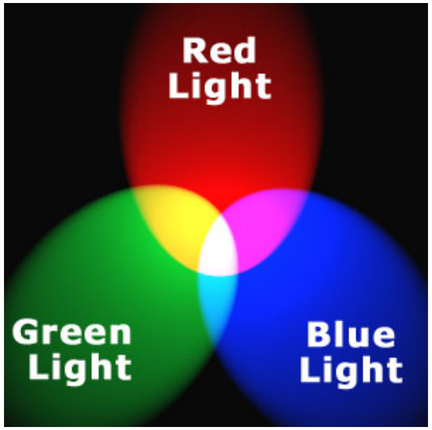


Source: W. Freeman

Additive colour mixing



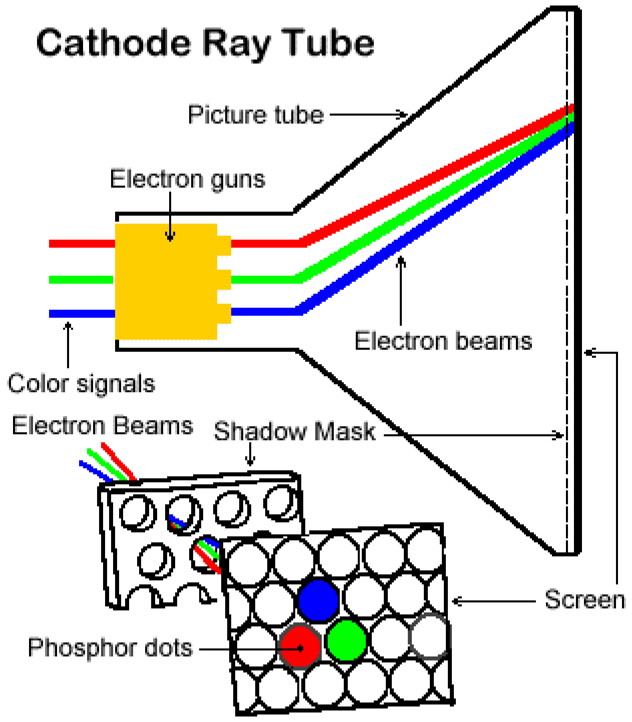
colours combine by *adding* colour spectra



Light *adds* to black.

Source: W. Freeman

Examples of additive colour systems



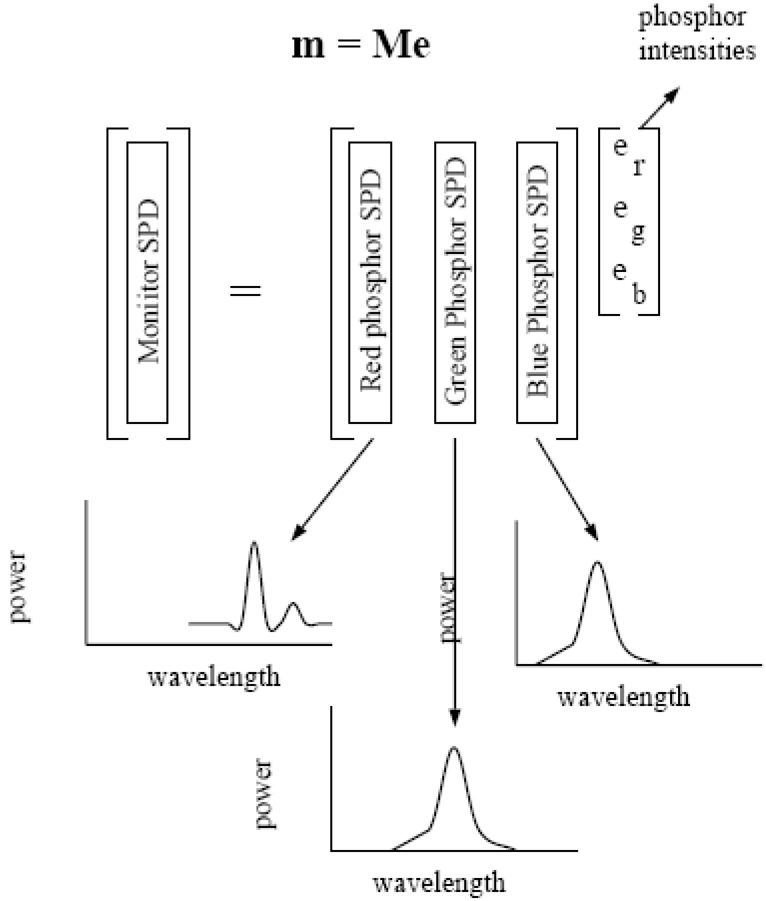
CRT phosphors

multiple projectors

http://www.jegsworks.com

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

Superposition

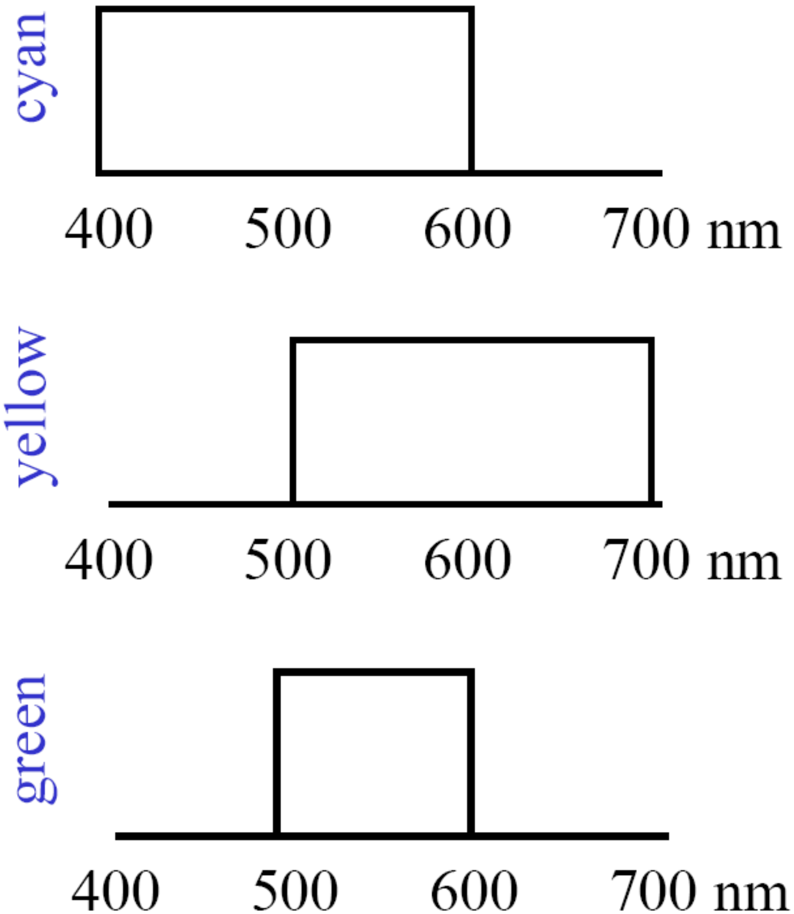


Additive colour mixing:

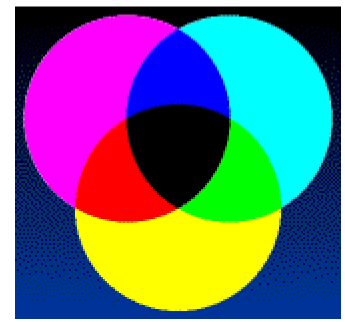
The spectral power distribution of the mixture is the sum of the spectral power distributions of the components.

Figure from B. Wandell, 1996

Subtractive colour mixing



colours combine by *multiplying* colour spectra.



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

Source: W. Freeman

Examples of subtractive colour systems

- Printing on paper
- Crayons
- Photographic film

Outline

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  - Spectral power distributions
  - colour mixing
  - colour matching experiments
  - colour spaces
    - Uniform colour spaces

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

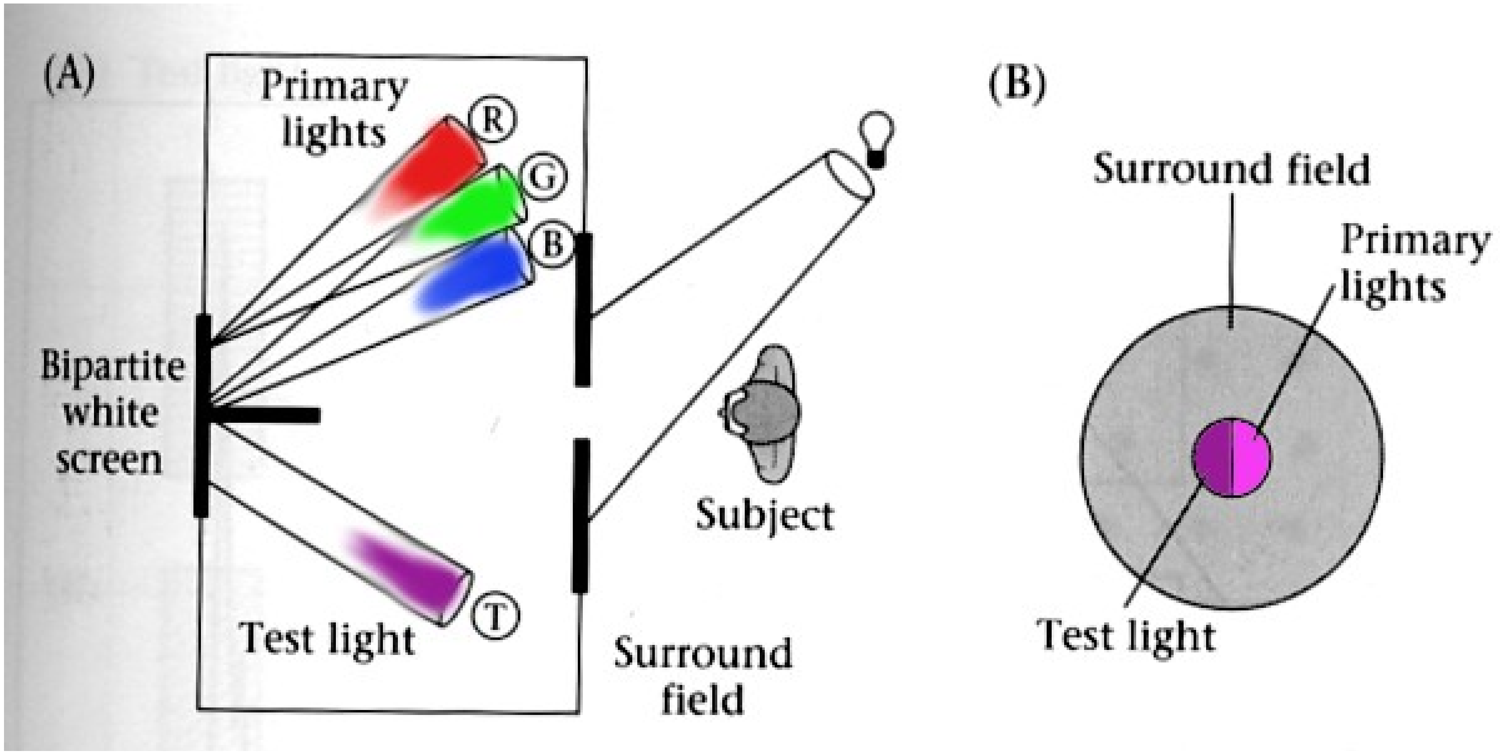
How to know if people perceive the same colour?

- Important to reproduce colour reliably
  - Commercial products, digital imaging/art
- Only a few colour 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?

colour matching experiments

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

colour matching experiments



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

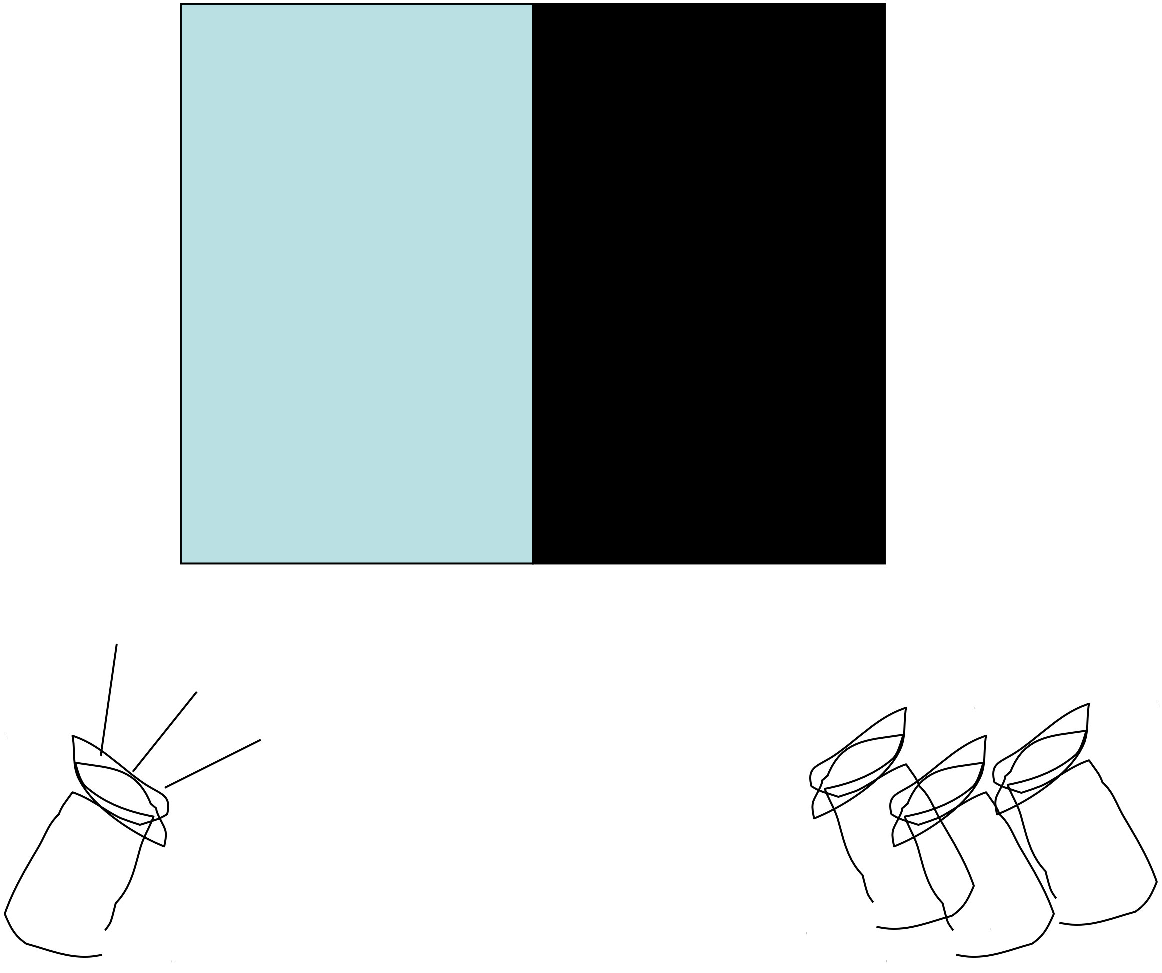
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

After Judd & Wyszecki.

colour matching experiments

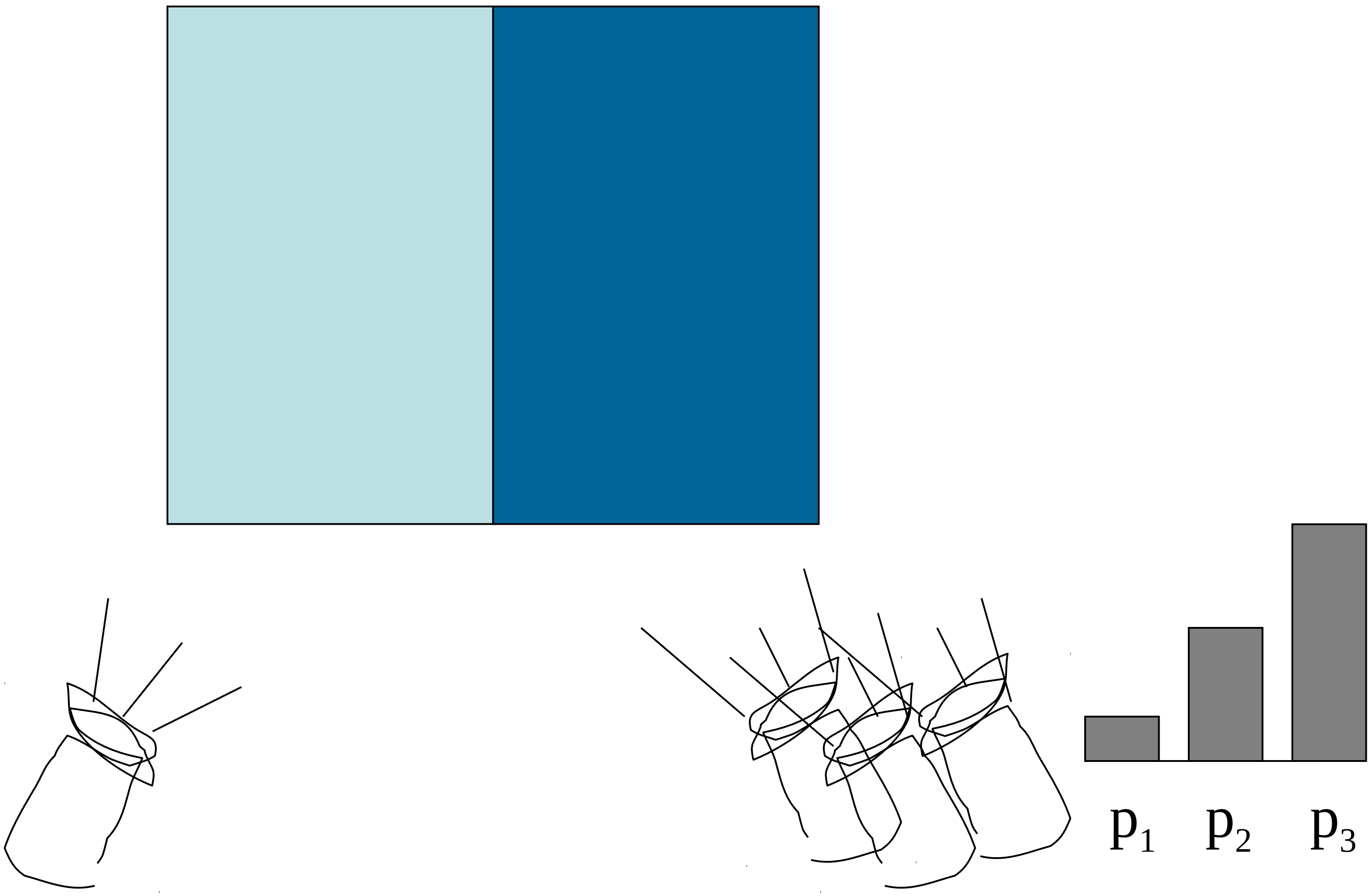
- **Goal**: find out what spectral radiances produce same response in human observers.
- **Assumption**: simple viewing conditions, where we say test light alone affects perception
  - Ignoring additional factors for now like adaptation, complex surrounding scenes, etc.

colour matching experiment 1



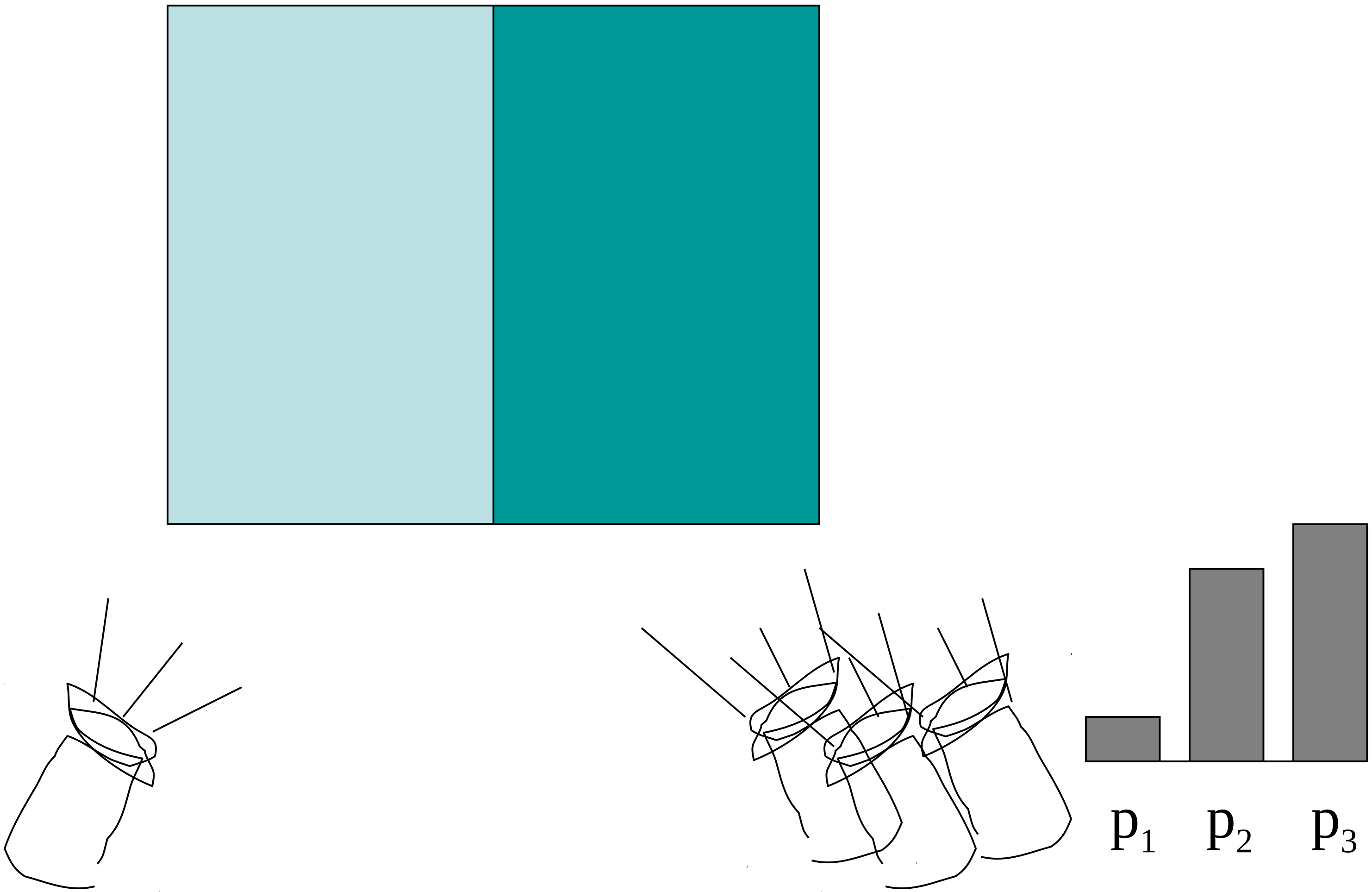
Slide credit:
W. Freeman

colour matching experiment 1



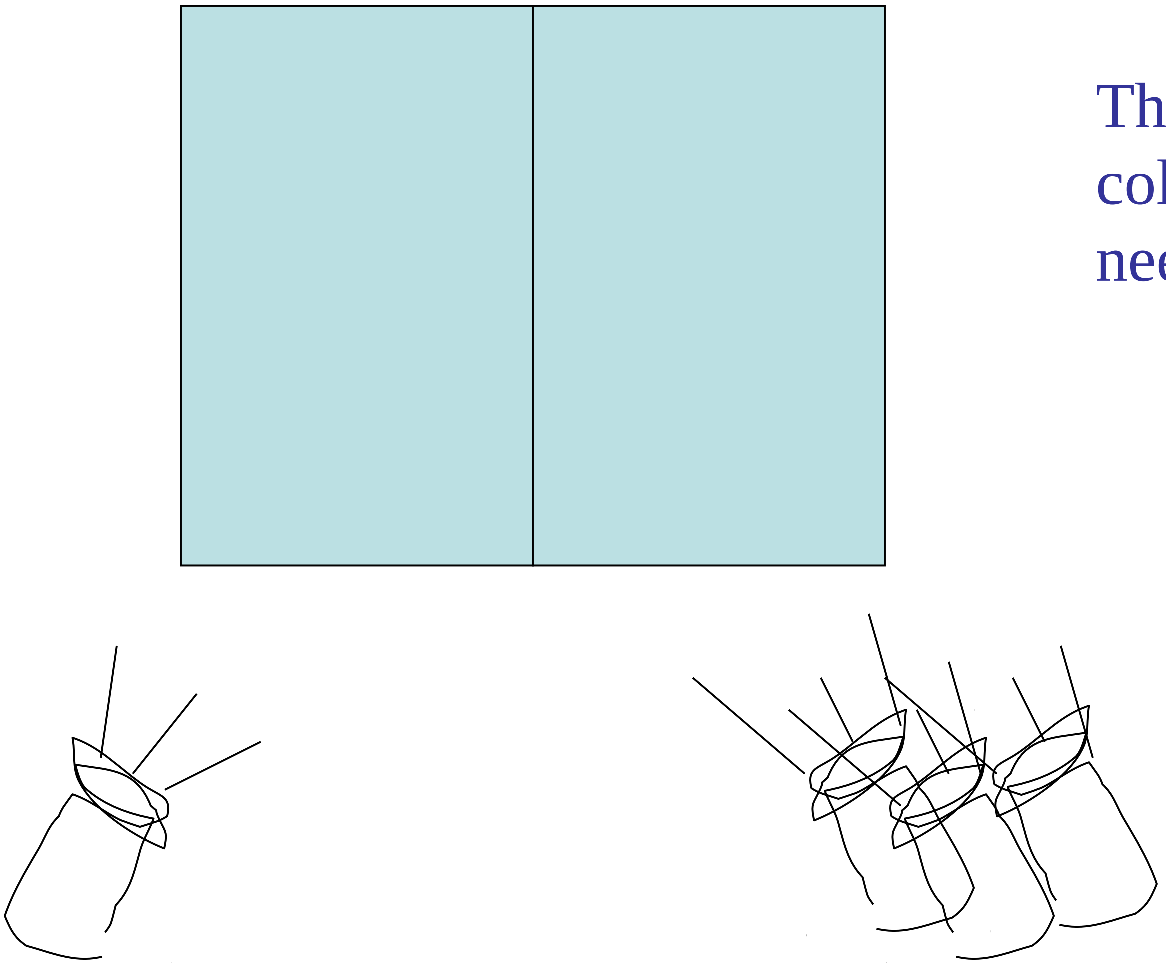
Slide credit:
W. Freeman

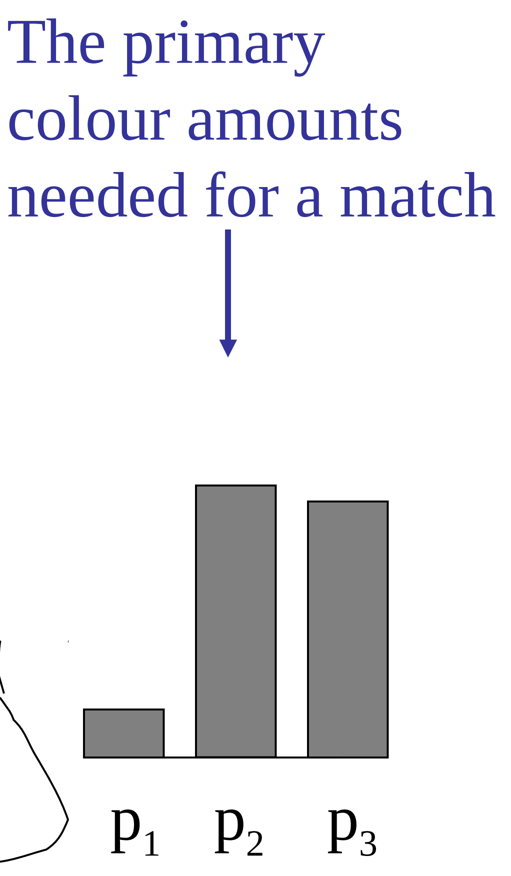
colour matching experiment 1



Slide credit:
W. Freeman

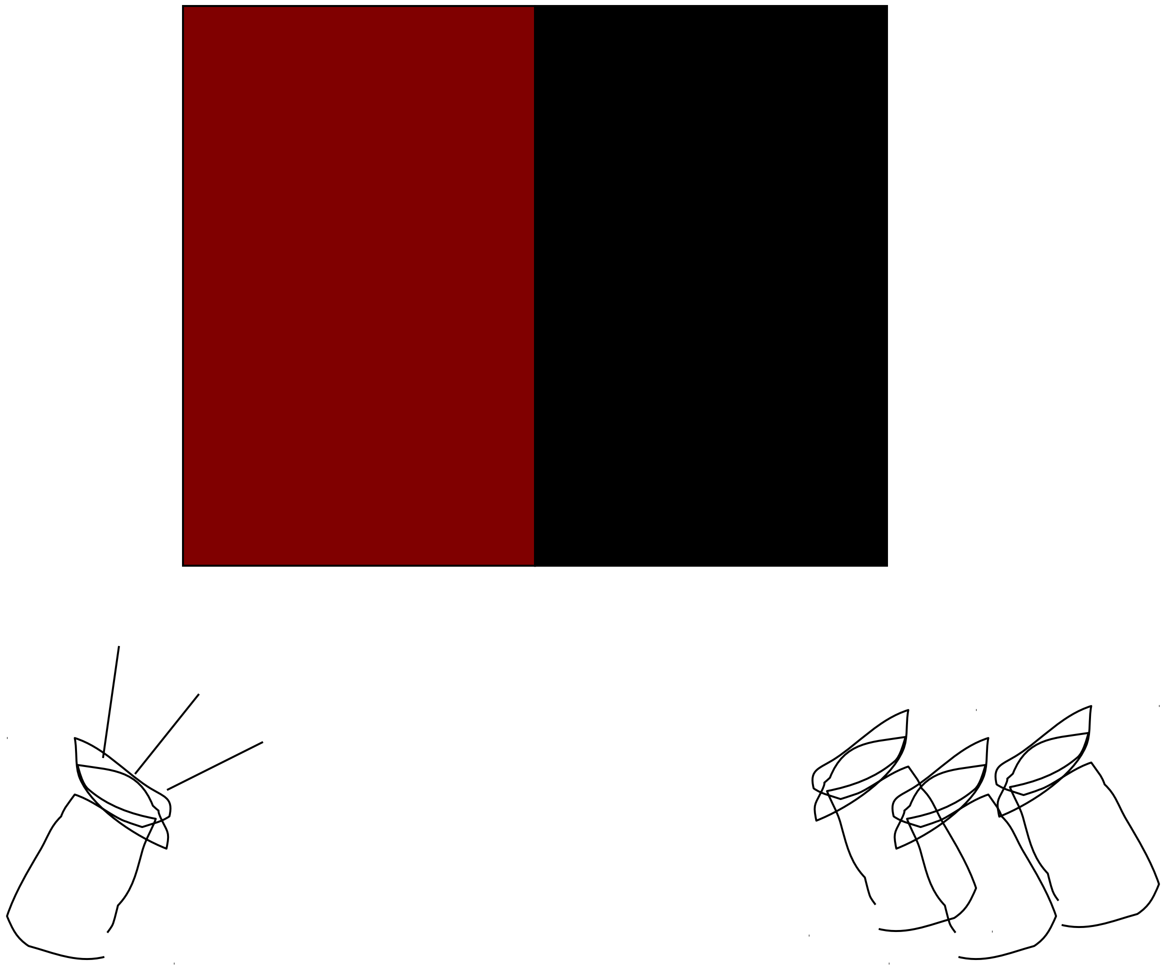
colour matching experiment 1





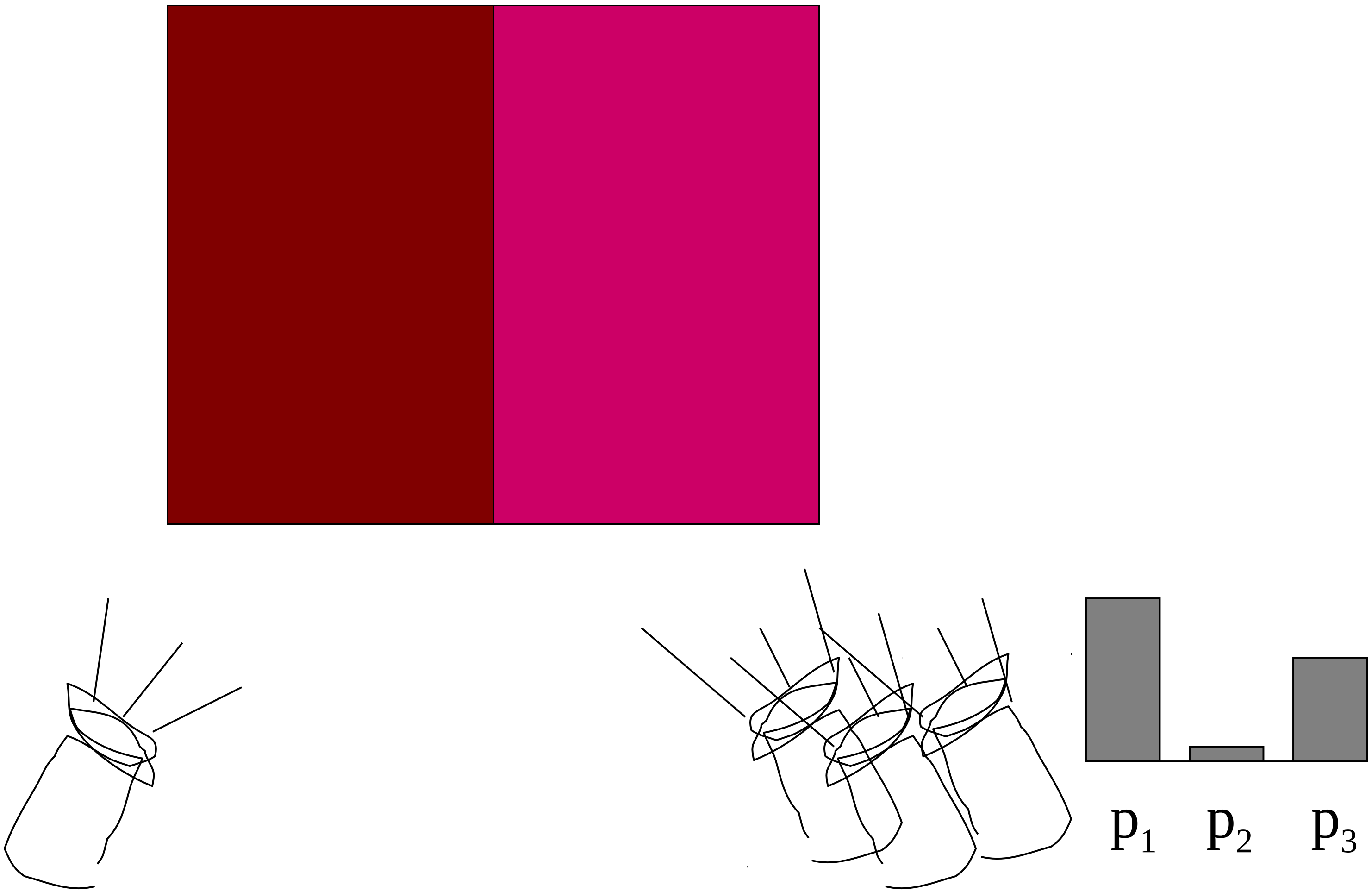
Slide credit:
W. Freeman

colour matching experiment 2



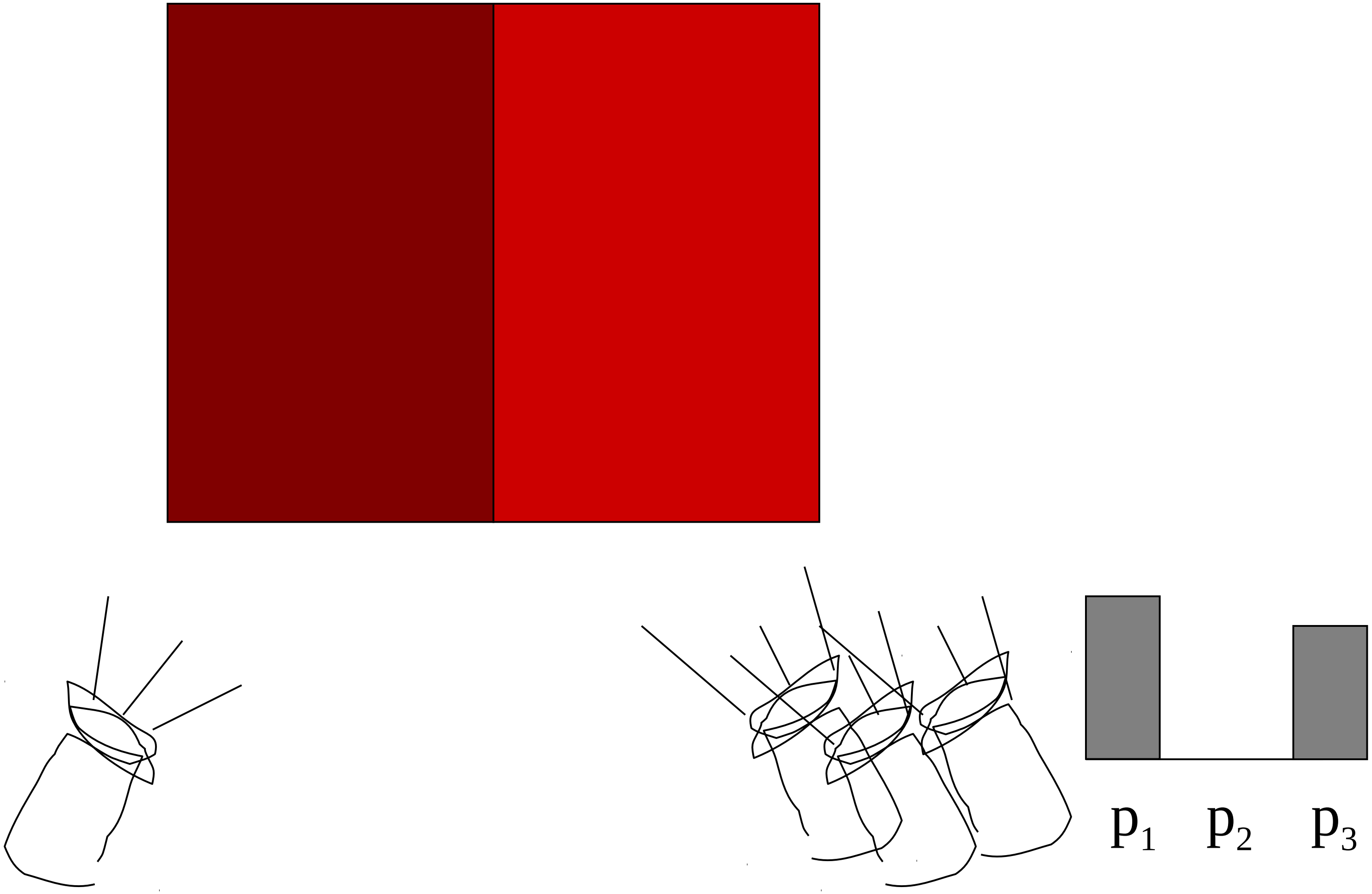
Slide credit:
W. Freeman

colour matching experiment 2



Slide credit:
W. Freeman

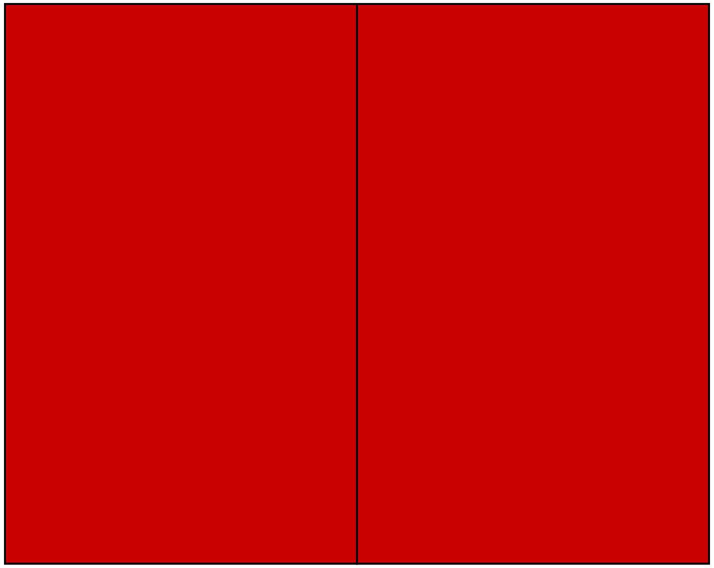
colour matching experiment 2



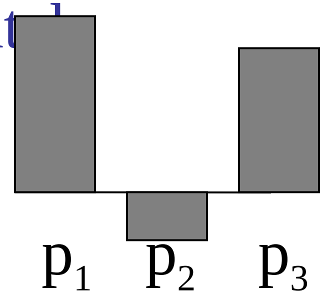
Slide credit:
W. Freeman

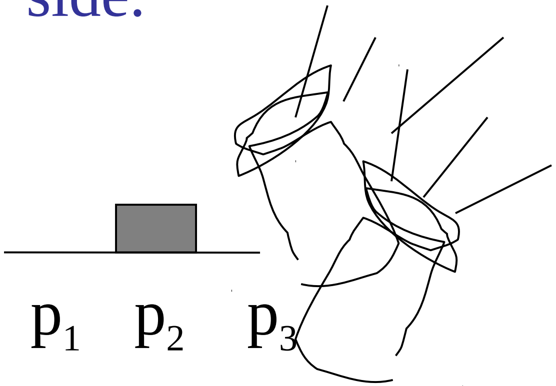
colour matching experiment 2

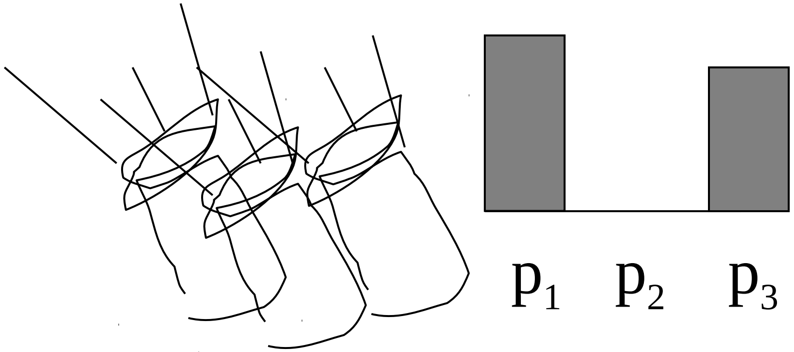
We say a "negative" amount of p_2 was needed to make the match, because we added it to the test colour's side.



The primary colour amounts needed for a mat







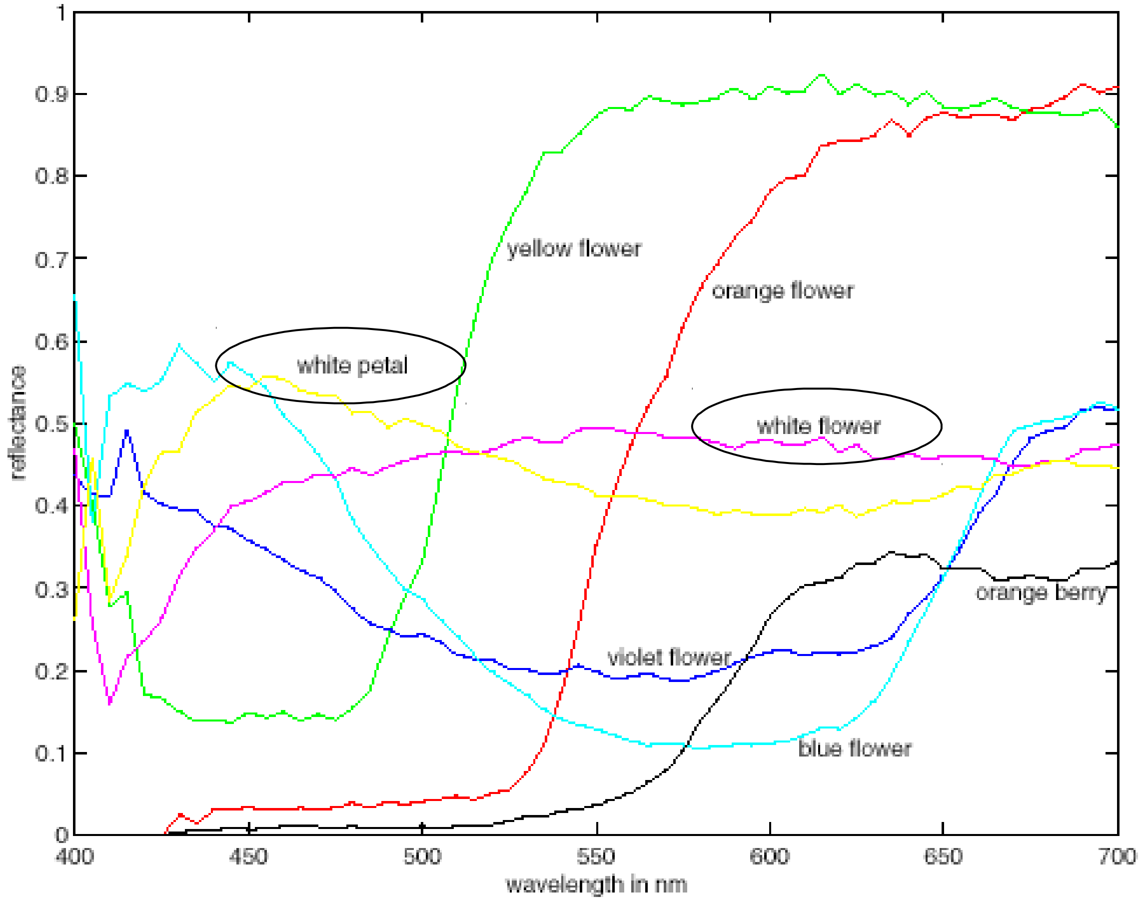
colour matching

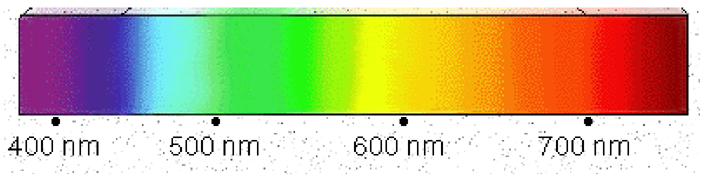
- What must we require of the primary lights chosen?
- How are three numbers enough to represent entire spectrum?

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

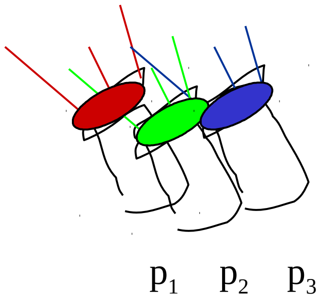
Grassman's laws

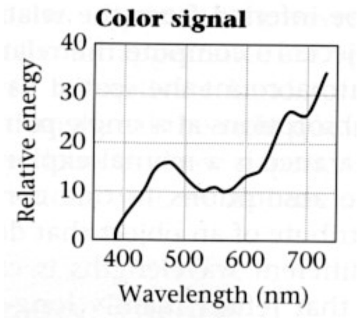
- If two test lights can be matched with the same set of weights, then they match each other:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = u_1 P_1 + u_2 P_2 + u_3 P_3$. Then $A = B$.
- If we scale the test light, then the matches get scaled by the same amount:
  - Suppose $A = u_1 P_1 + u_2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

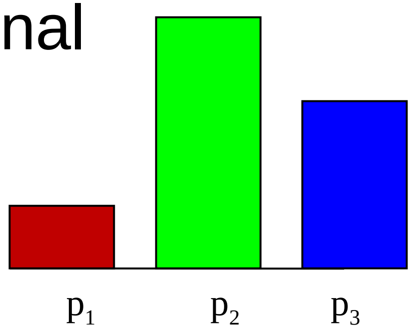
Given: a choice of three primaries and a target colour signal





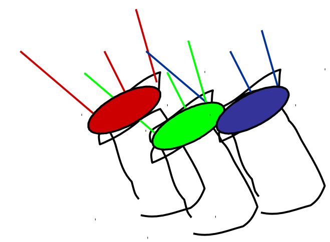
?

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

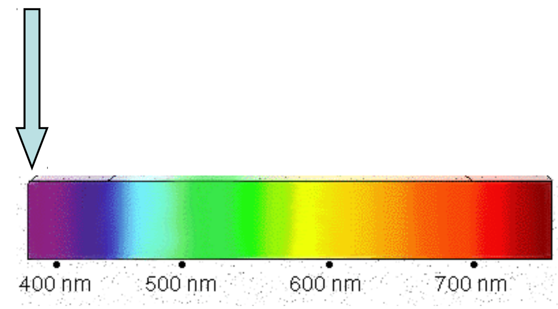


Computing colour matches

1. Given primaries



2. Estimate their *colour matching functions*: observer matches series of monochromatic lights, one at each wavelength.

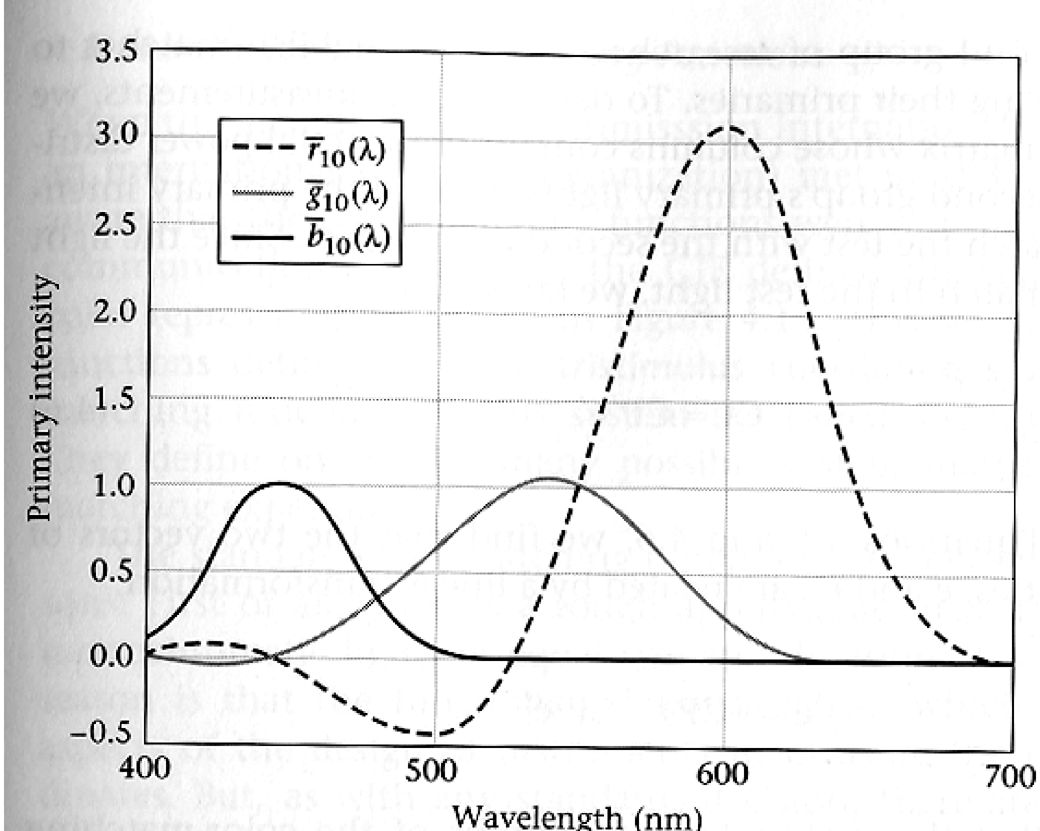


3. To compute weights for new test light, multiply with matching functions.

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

Kristen Grauman

Computing colour matches



4.13 THE COLOR-MATCHING FUNCTIONS ARE THE ROWS OF THE COLOR-MATCHING SYSTEM MATRIX. The functions measured by Stiles and Burch (1959) using a 10-degree bipartite field and primary lights at the wavelengths 645.2 nm, 525.3 nm, and 444.4 nm with unit radiant power are shown. The three functions in this figure are called $\bar{r}_{10}(\lambda)$, $\bar{g}_{10}(\lambda)$, and $\bar{b}_{10}(\lambda)$.

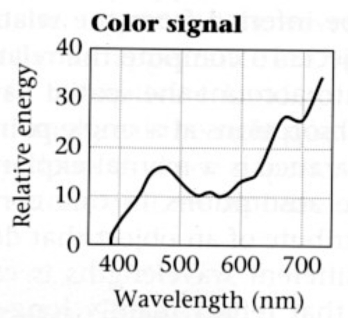
$$\mathbf{C} = \begin{pmatrix} c_1(\lambda_1) & \cdots & c_1(\lambda_N) \\ c_2(\lambda_1) & \cdots & c_2(\lambda_N) \\ c_3(\lambda_1) & \cdots & c_3(\lambda_N) \end{pmatrix}$$

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

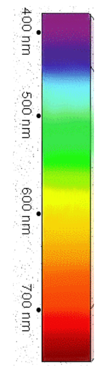
Slide credit: W. Freeman

Computing colour matches

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



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



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

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

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

Kristen Grauman

Computing colour matches

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

Adapted from W. Freeman

Image credit: pbs.org

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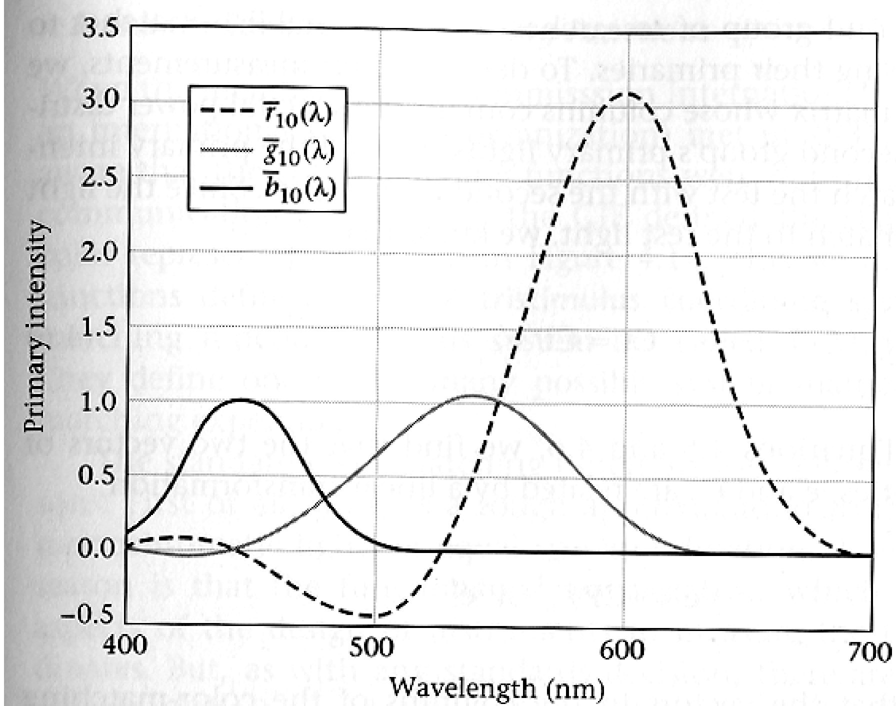
Standard colour spaces

- Use a common set of primaries/colour matching functions

- Linear colour space examples
  - RGB
  - CIE XYZ
- Non-linear colour space
  - HSV

RGB colour space

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



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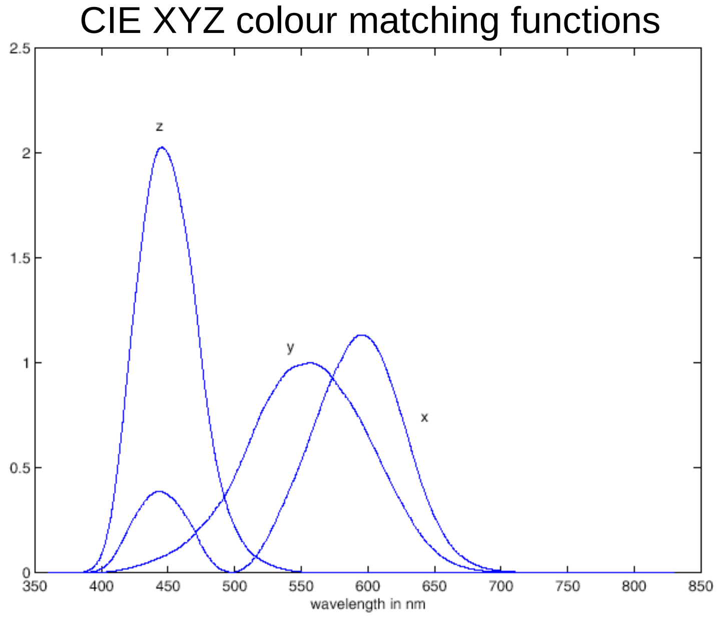
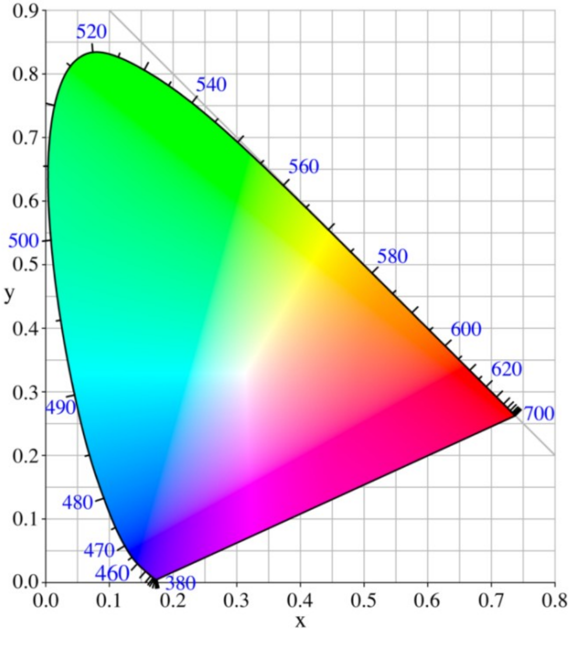
CIE XYZ colour space

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

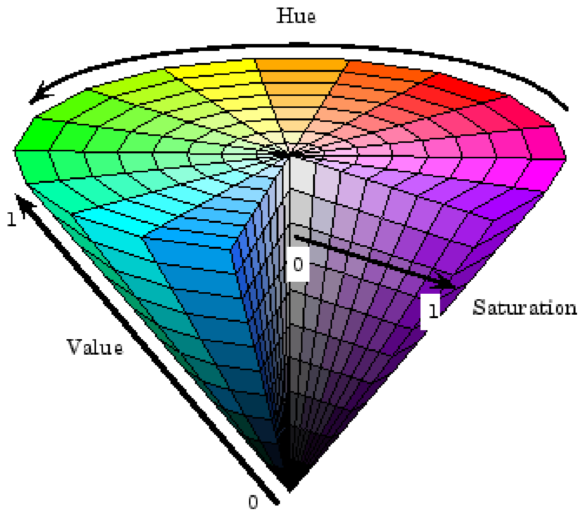
$$(x,y) = (X/(X+Y+Z), Y/(X+Y+Z))$$





HSV colour space

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



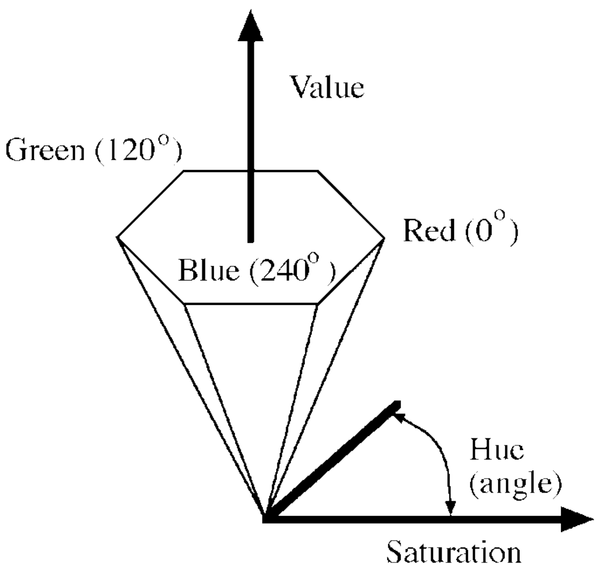
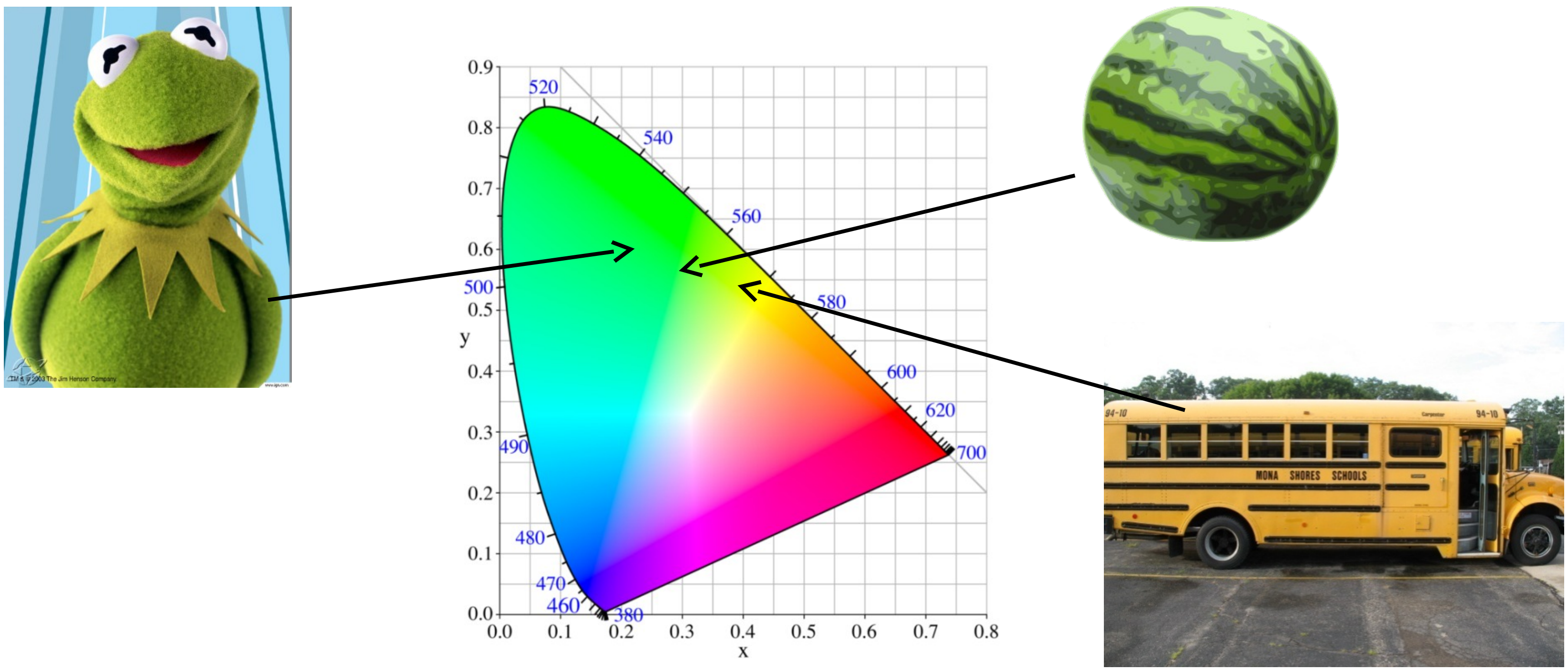


Image from mathworks.com

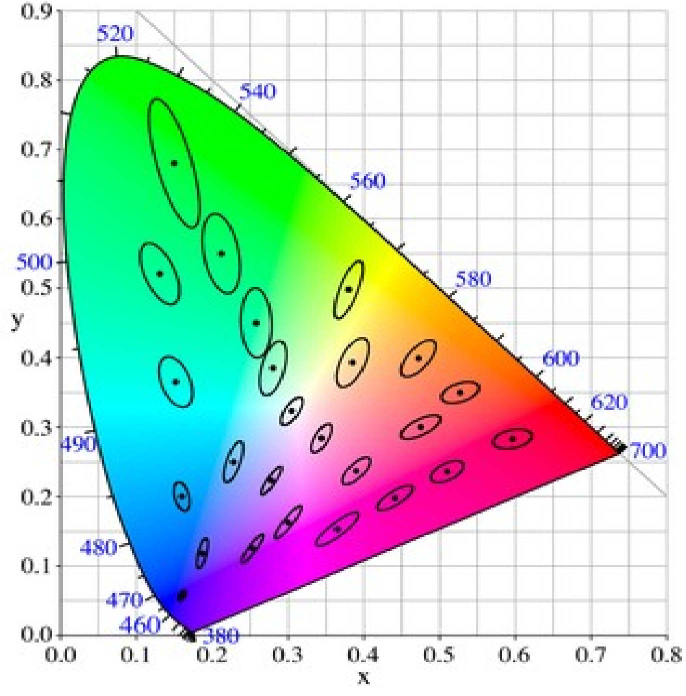
Distances in colour space

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



Distances in colour space

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

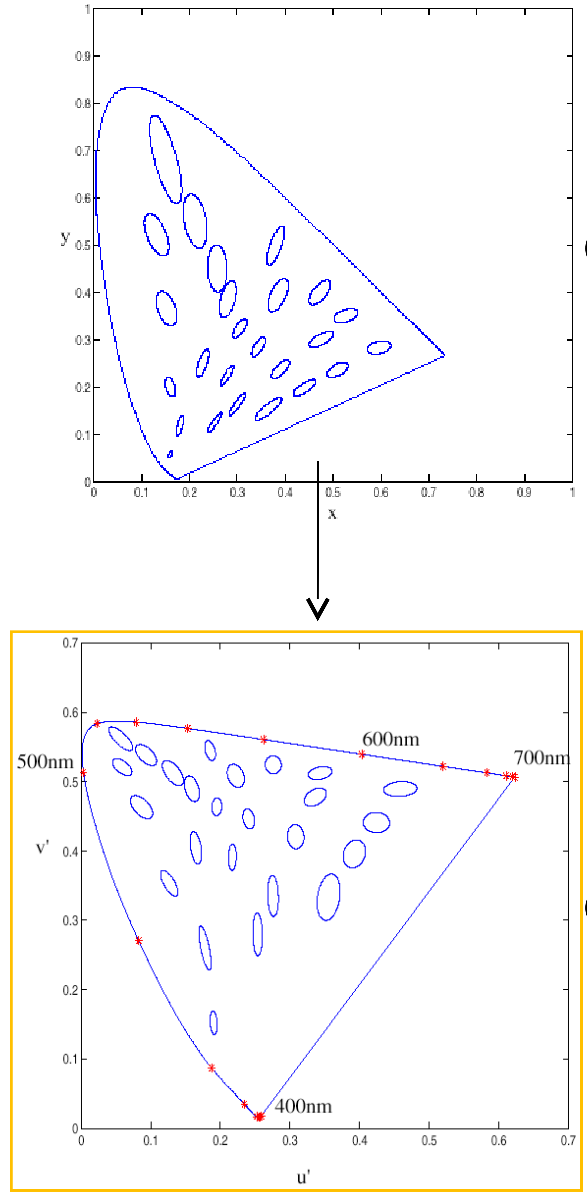


McAdam ellipses:
Just noticeable differences in colour

Uniform colour spaces

- Attempt to correct this limitation by remapping colour 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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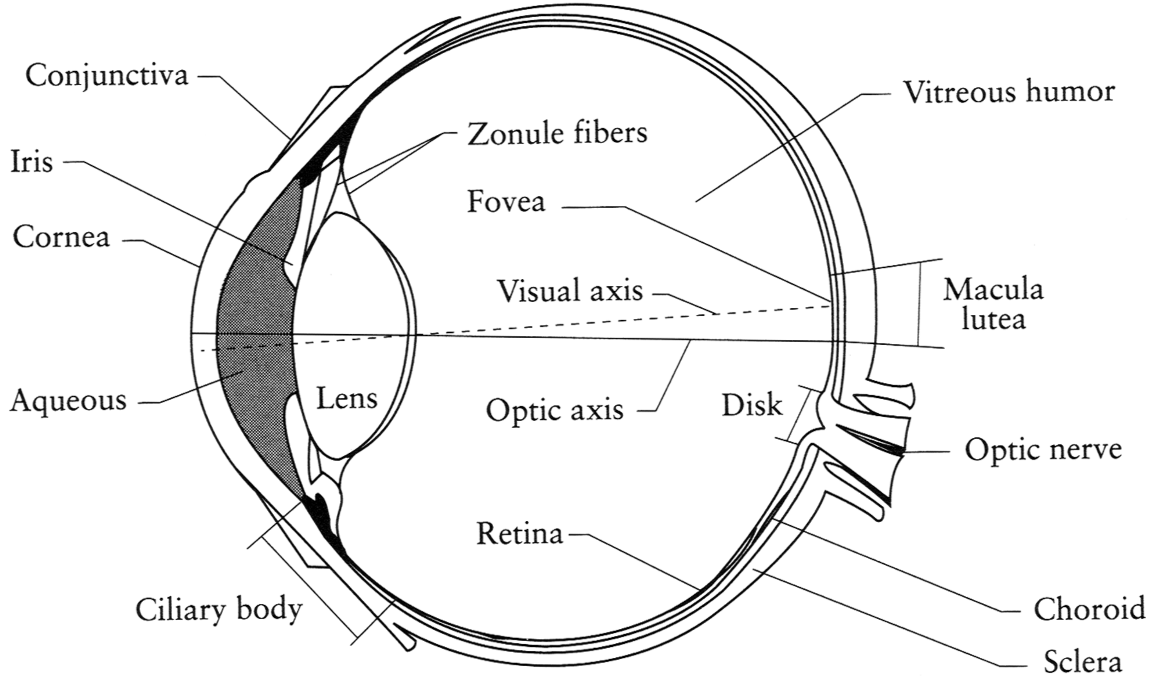
The Eye



The human eye is a camera!

- **Iris** - coloured 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

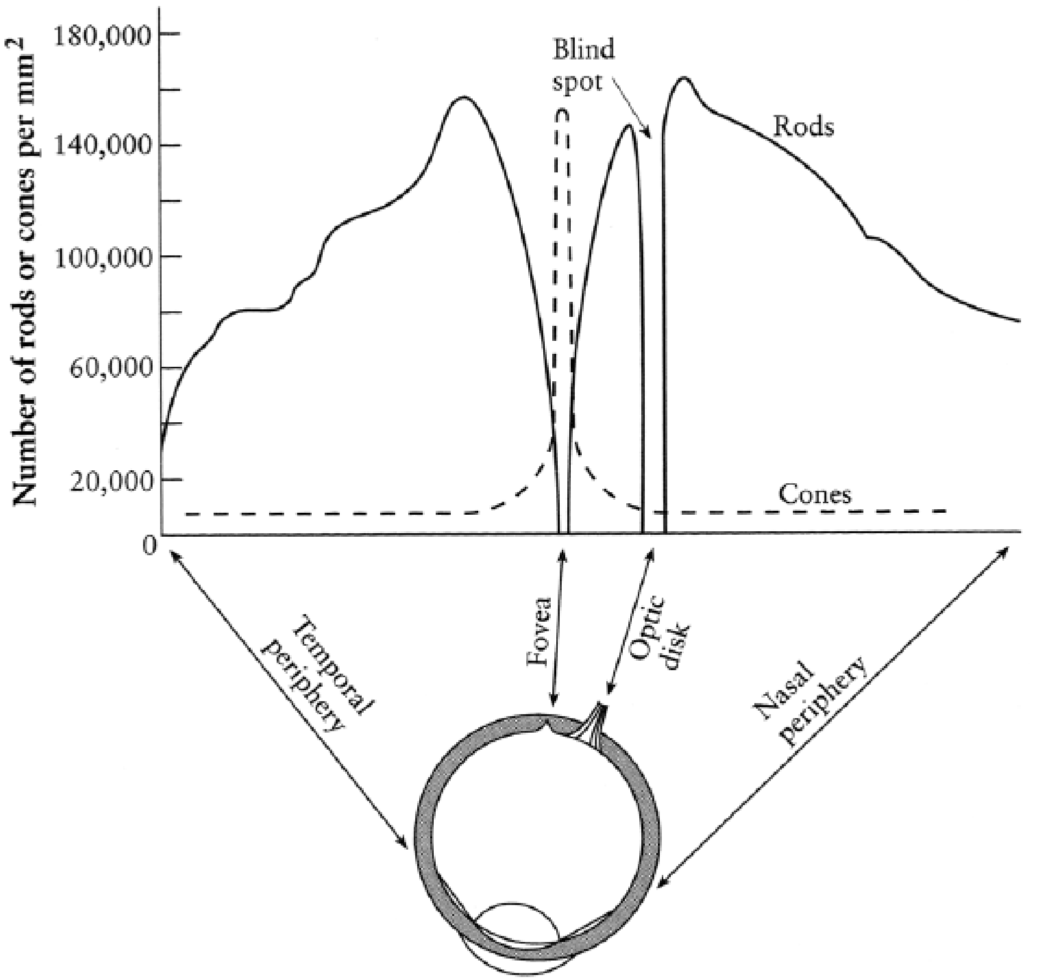
Types of light-sensitive receptors

Cones

- cone-shaped
- less sensitive
- operate in high light
- colour vision

Rods

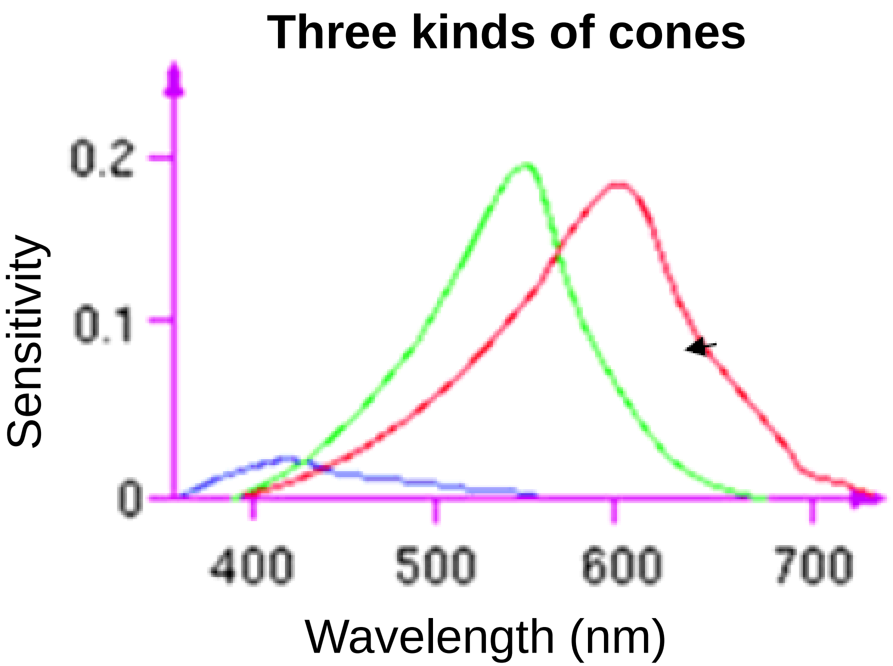
- rod-shaped
- highly sensitive
- operate at night
- gray-scale vision



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 colour
- Sensitivities vary per person, and with age
- colour 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 colours affect what is perceived; receptor excitations interact across image and time
- **Afterimages**

colour matching != colour appearance

Physics of light != perception of light

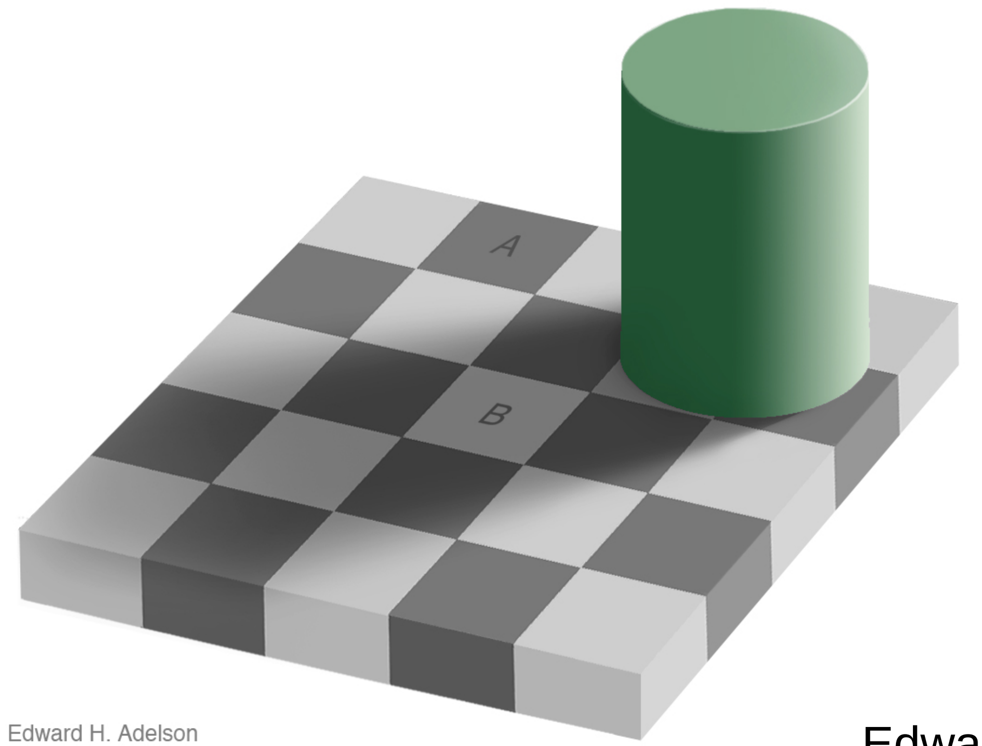
Chromatic adaptation

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

Chromatic adaptation

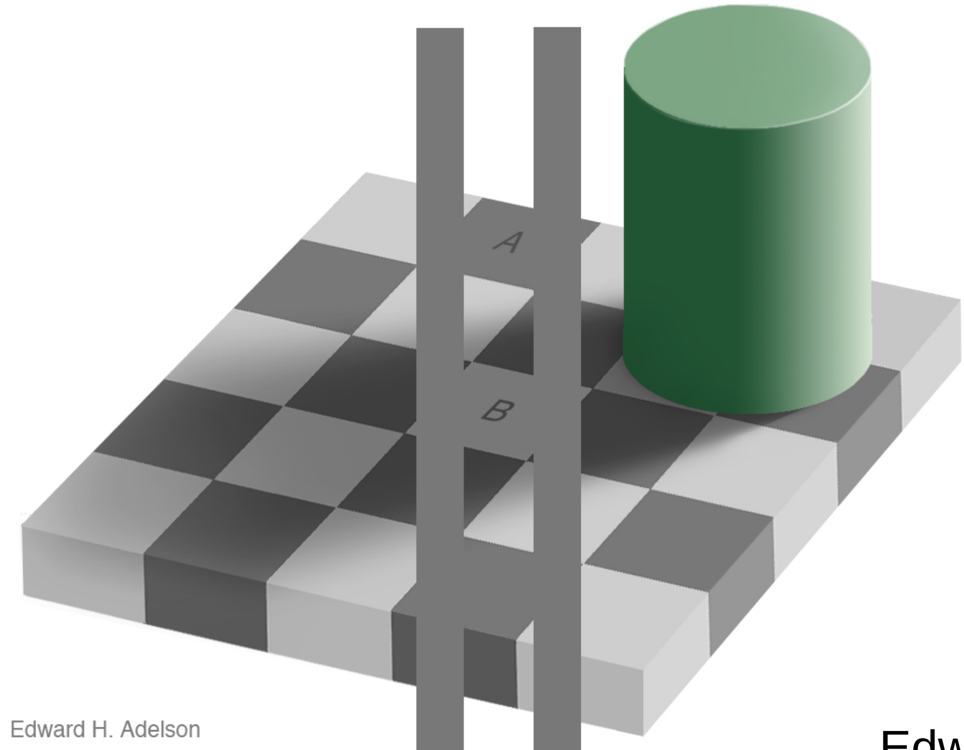
http://www.planetperplex.com/en/colour_illusions.html

Brightness perception



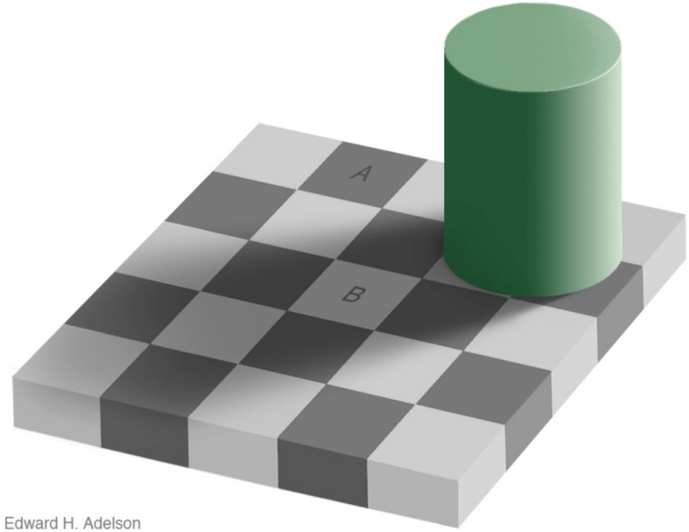
Edward Adelson

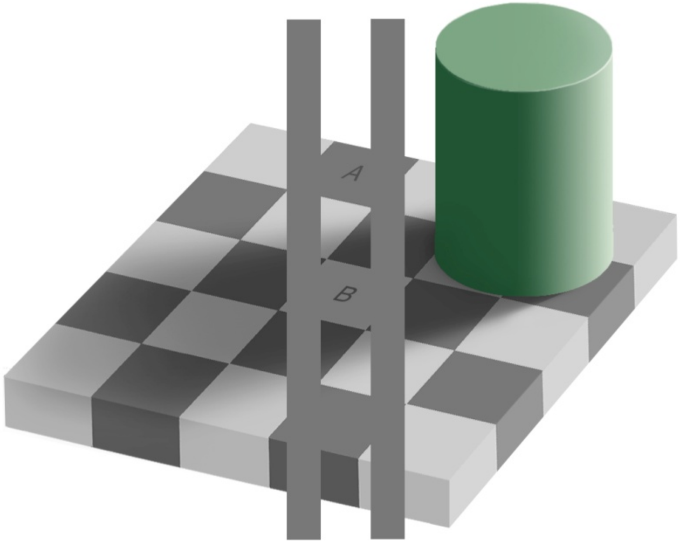
http://web.mit.edu/persci/people/adelson/illusions_demos.html



Edward Adelson

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





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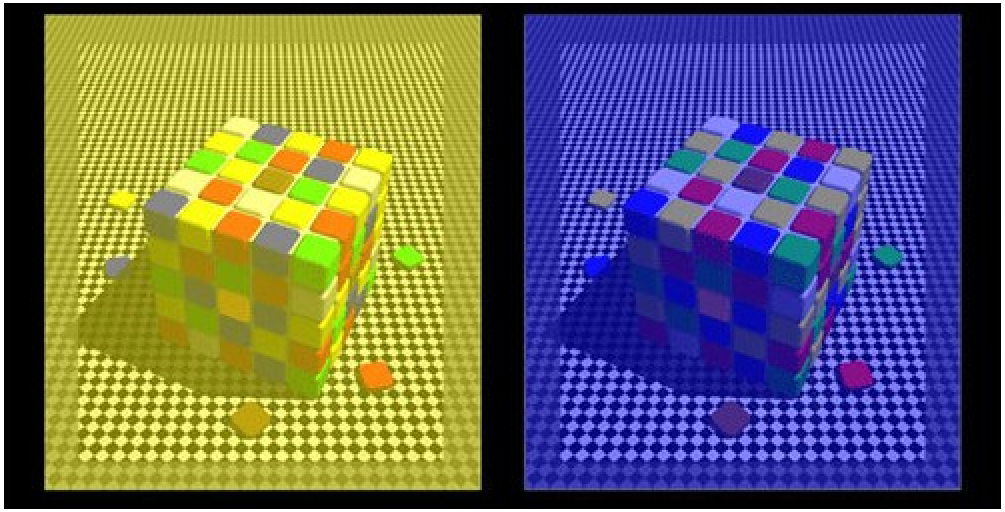
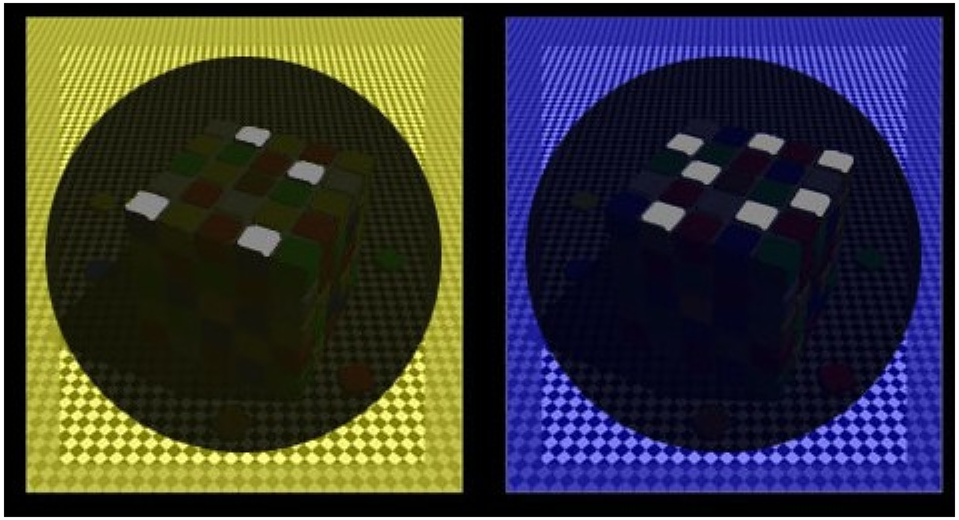


Look at blue squares

Look at yellow squares

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



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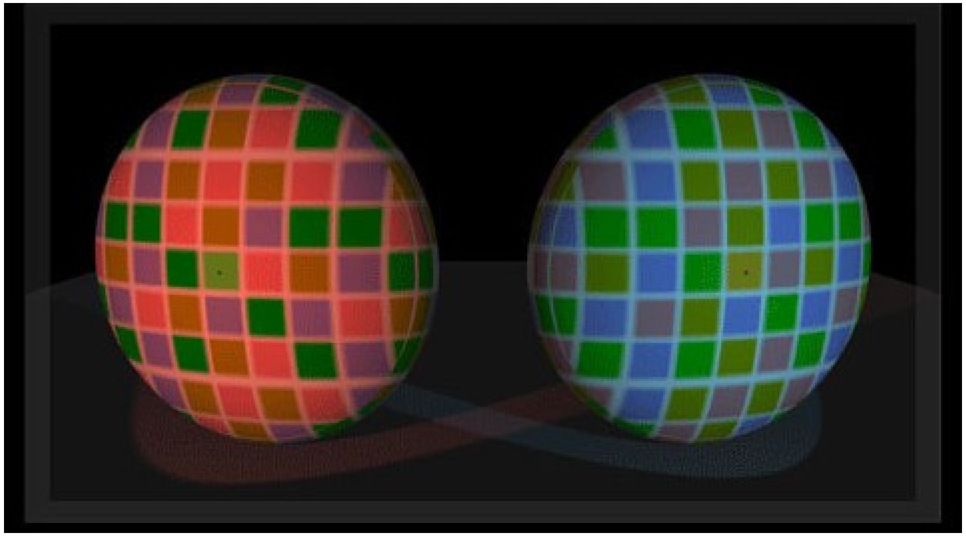

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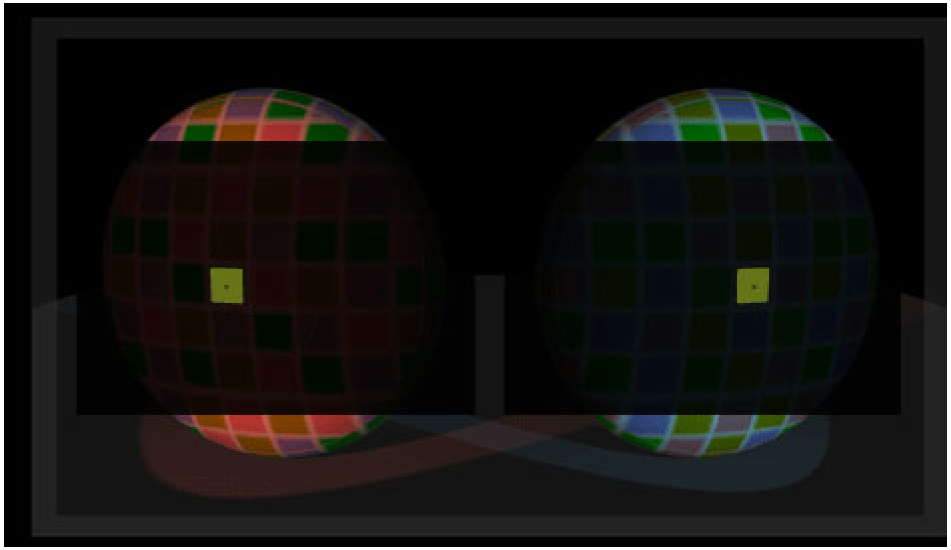

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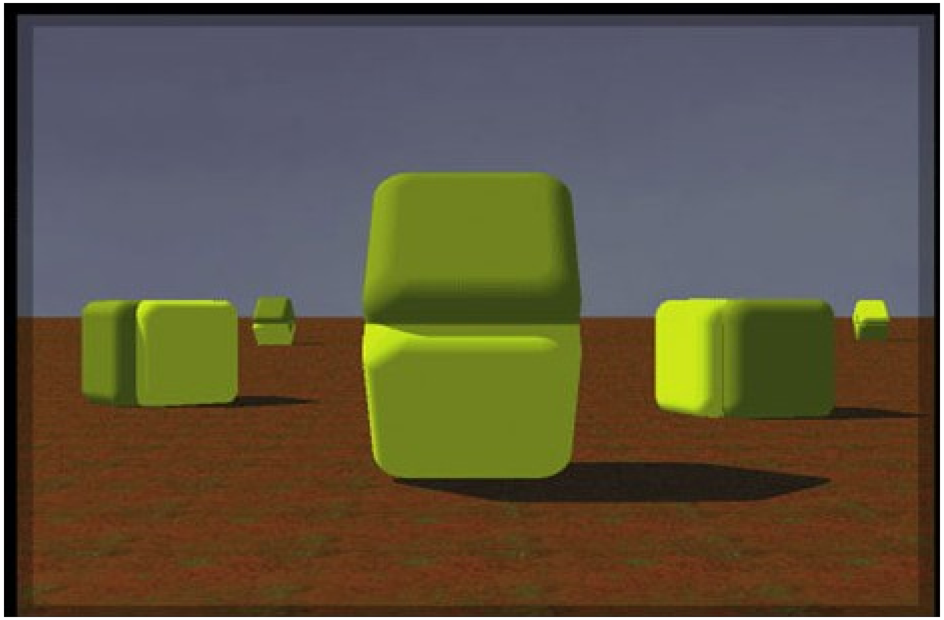

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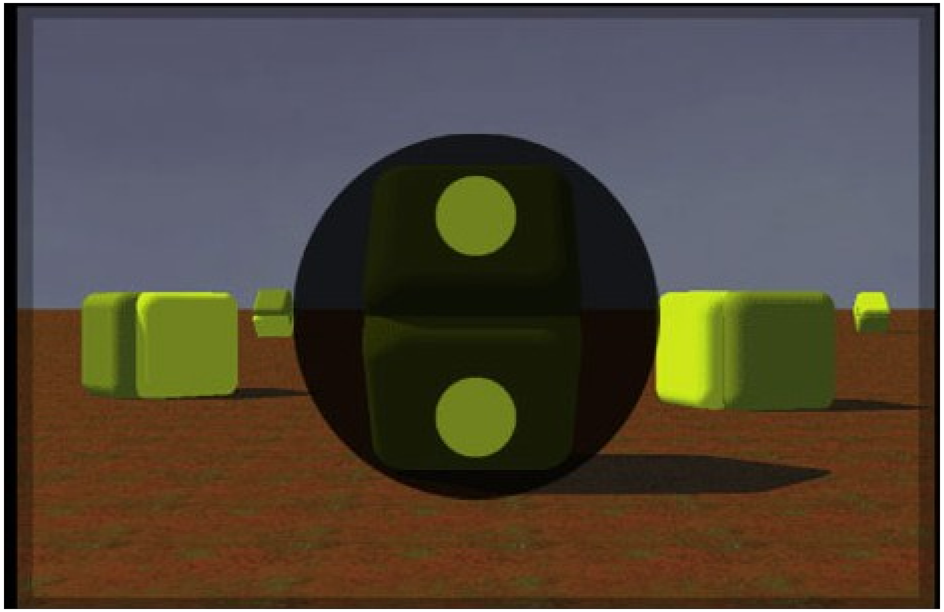

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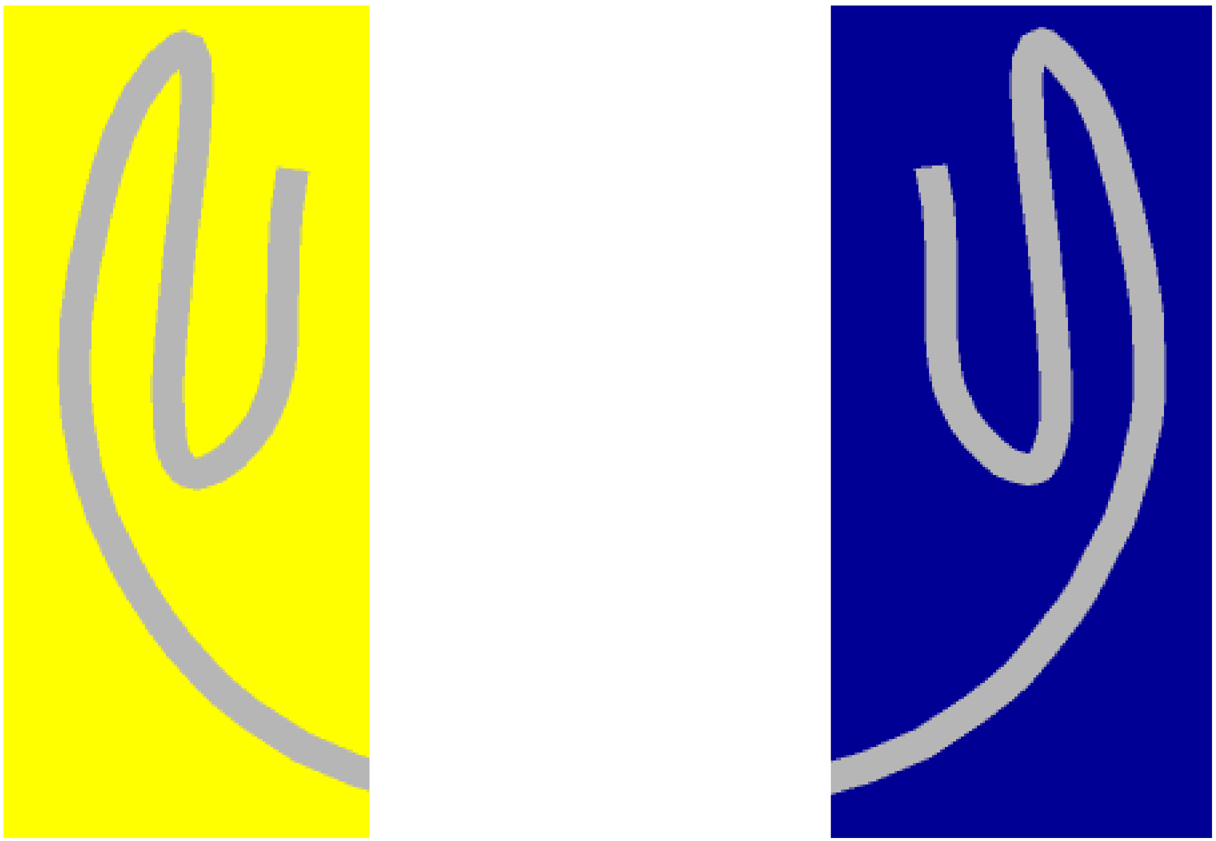
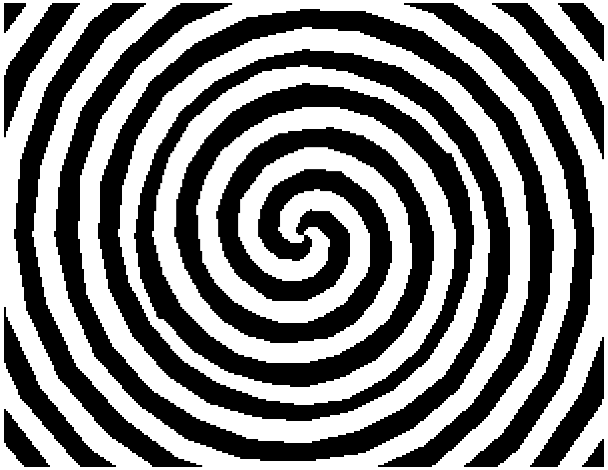
Contrast effects



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 colour

High level interactions affect perception and processing.