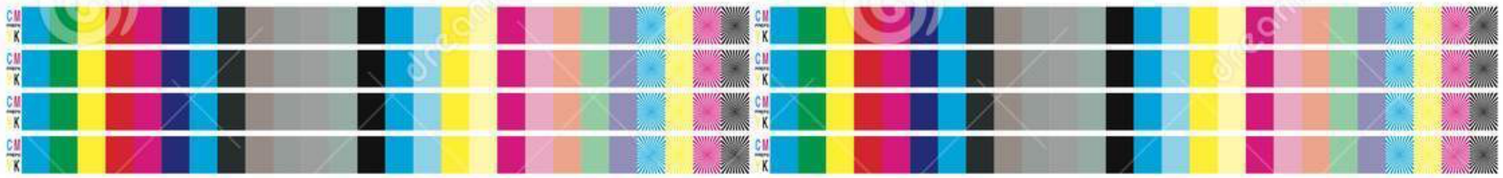
THE UNIVERSITY OF BRITISH COLUMBIA

CPSC 425: Computer Vision



Lecture 21: Color

(unless otherwise stated slides are taken or adopted from **Bob Woodham, Jim Little** and **Fred Tung**)

Menu for Today

Topics:

- Colour, **Trichromacy**
- **Colour Matching** Experiments
- **Colour Spaces**
- **Final** examples

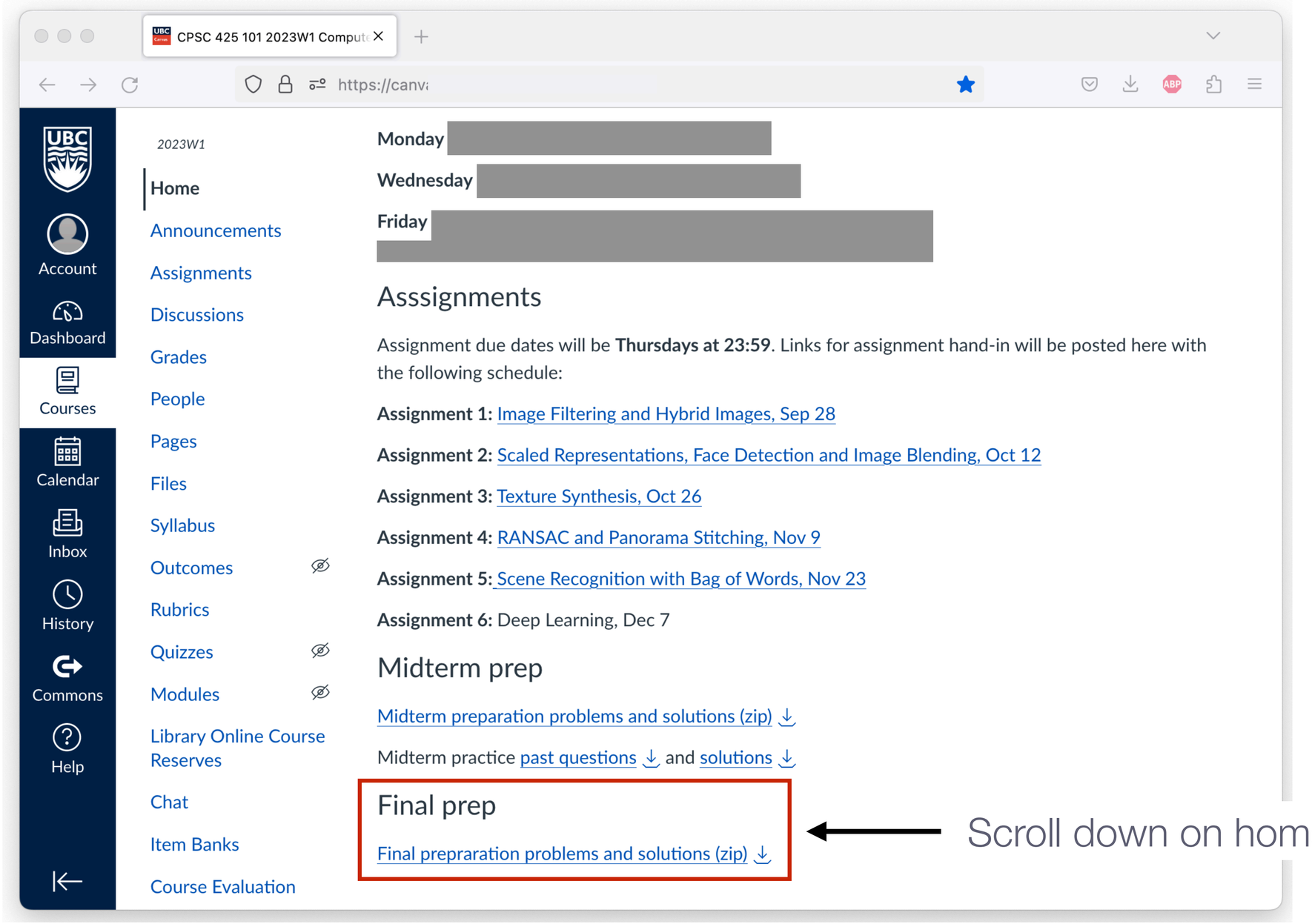
Readings:

- **Today's** Lecture: Szeliski 2.3.2, Forsyth & Ponce 3.1-3.3

Reminders:

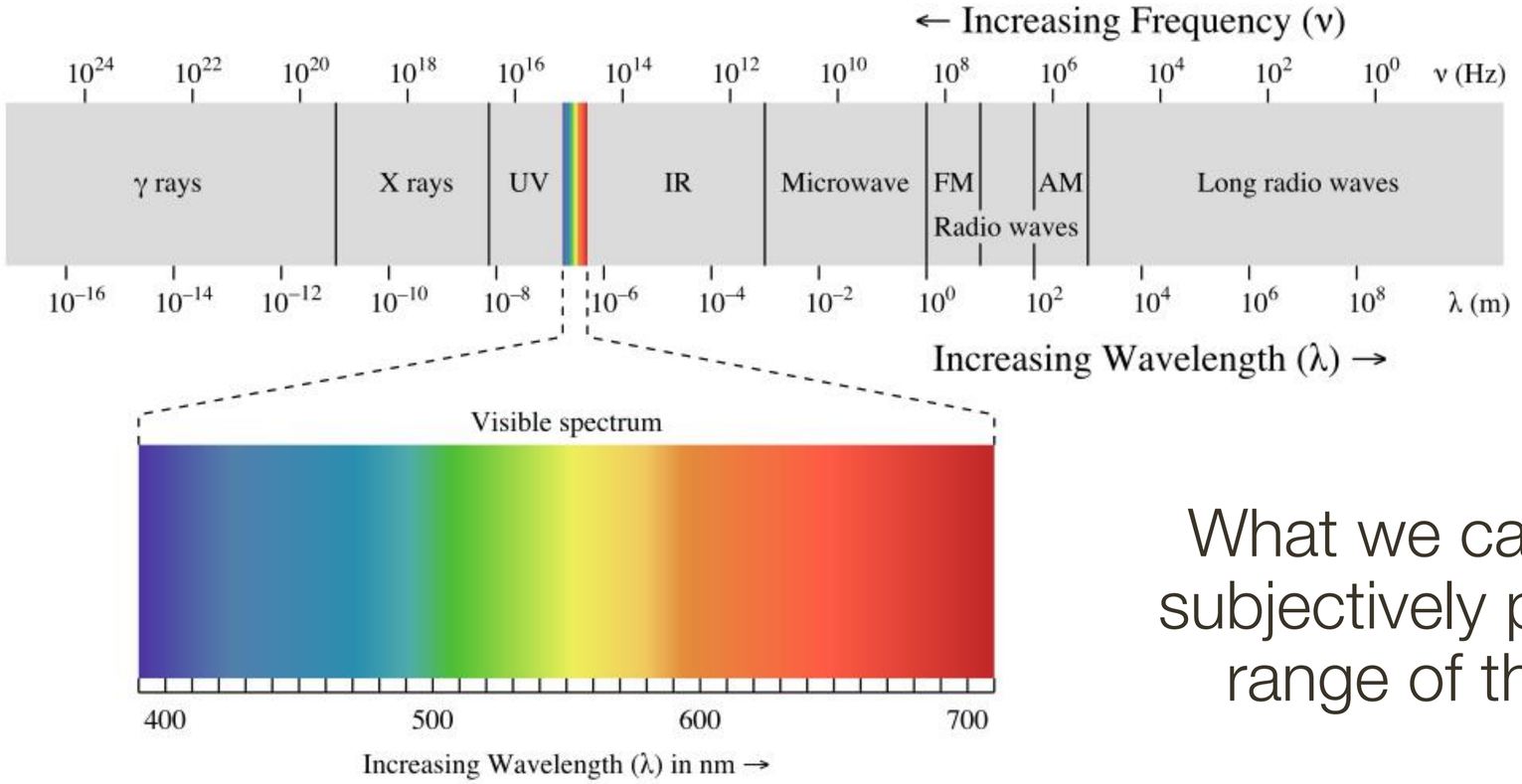
- **Assignment 6** due Dec 7th
- **Final** is Dec 14th (**2hrs**, closed book, no calculators)
- Today is the **last lecture!** No lectures next week

Final Example Questions + Solutions



Recall: Color is an Artifact of Human Perception

"Color" is **not** an objective physical property of light (electromagnetic radiation). Instead, light is characterized by its wavelength.



electromagnetic spectrum

What we call "color" is how we subjectively perceive a very small range of these wavelengths.

Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)

Spectral Power Distribution

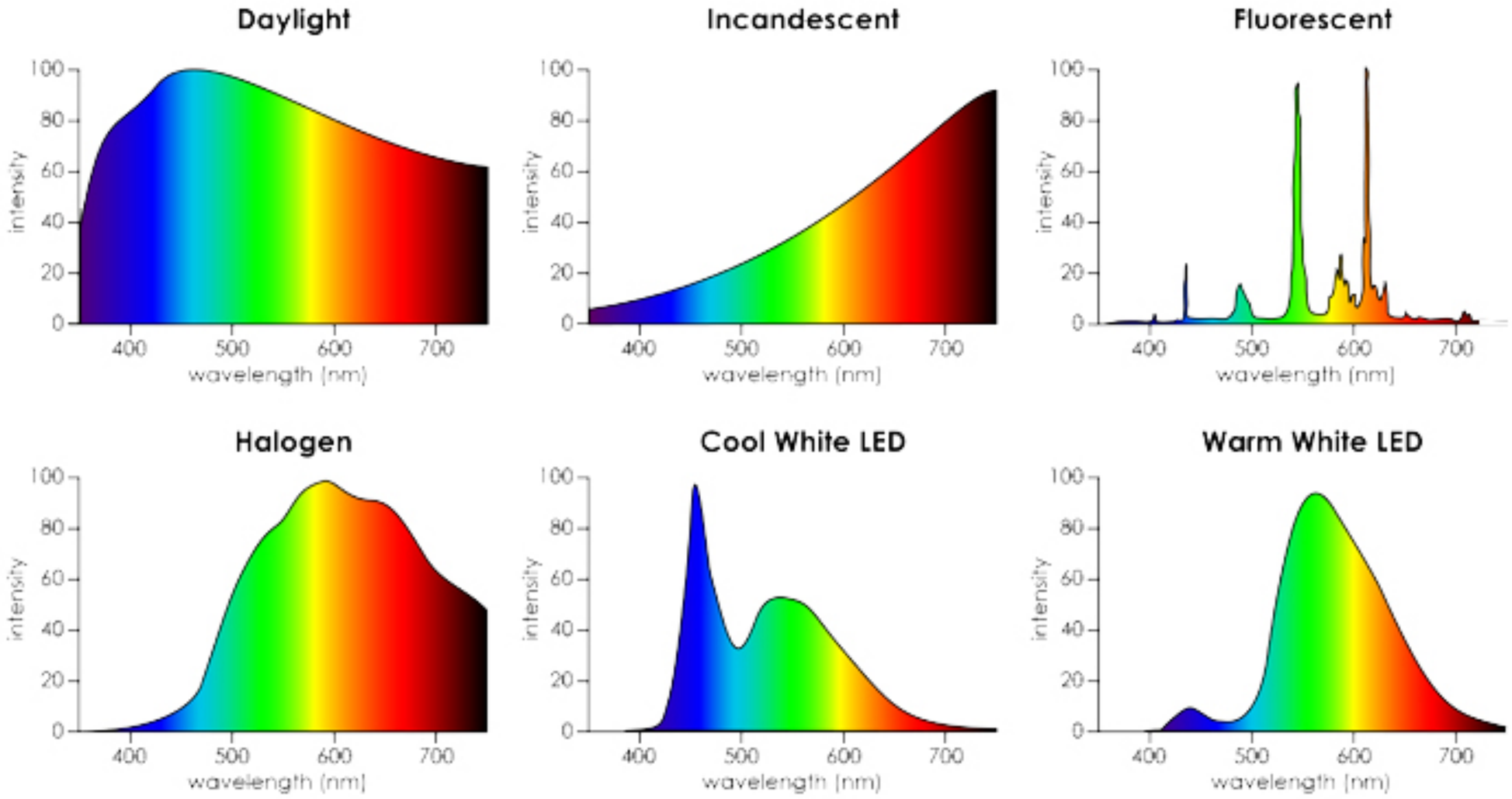
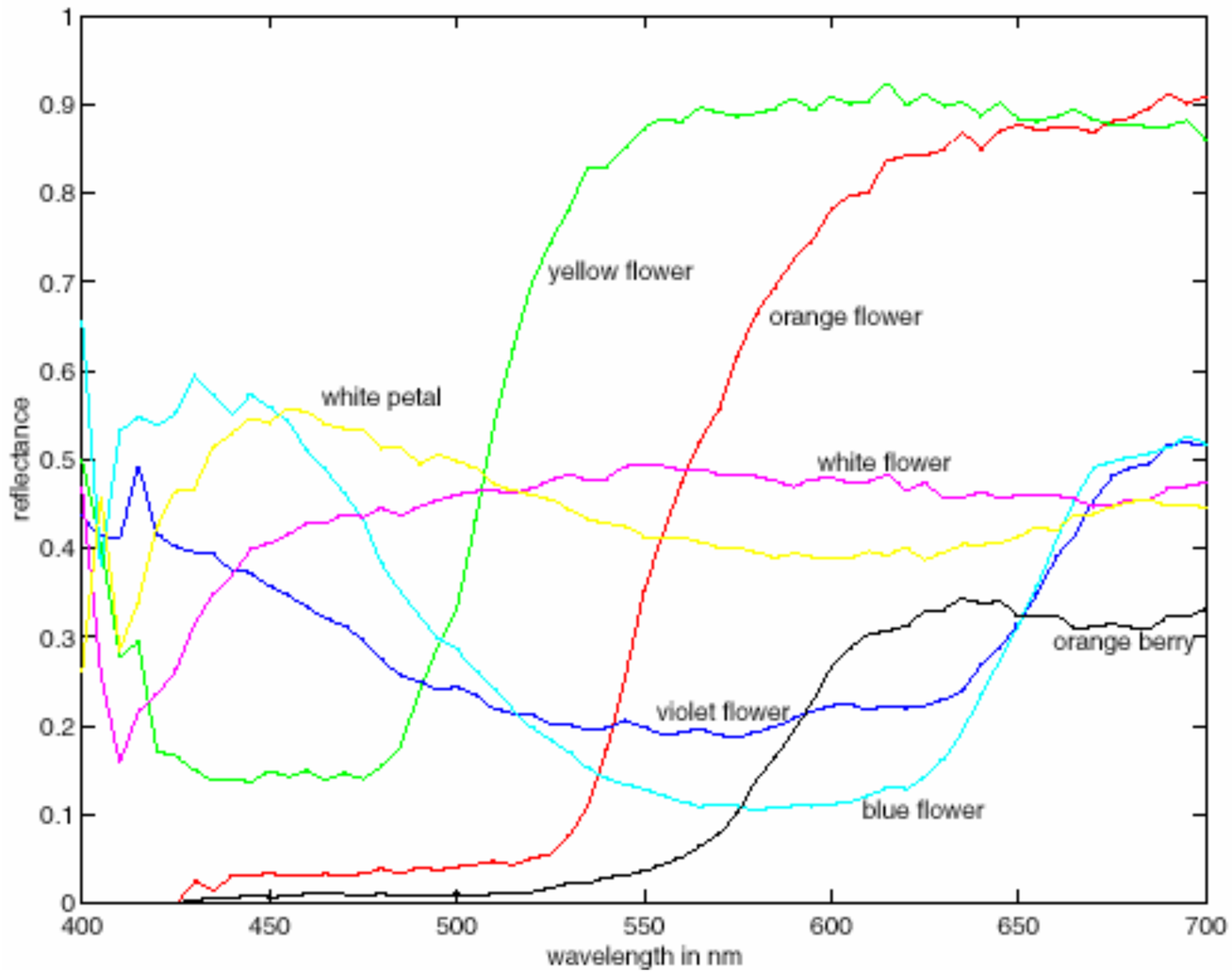


Figure credit: admesy ADVANCED MEASUREMENT SYSTEMS

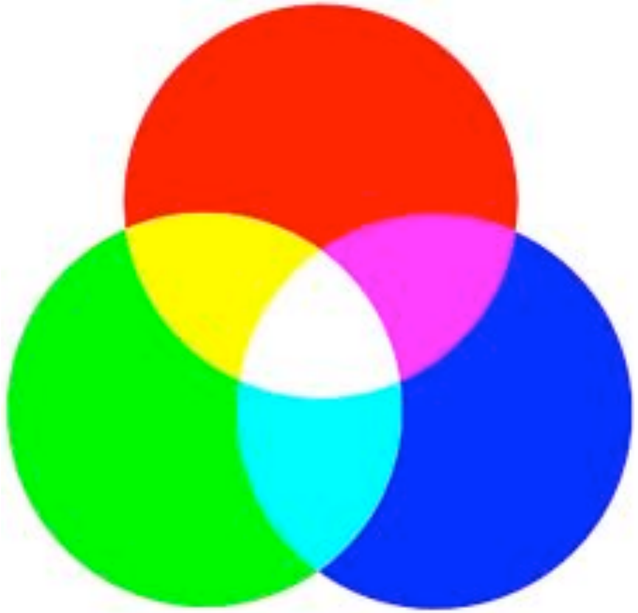
Spectral **Albedo** of Natural Surfaces



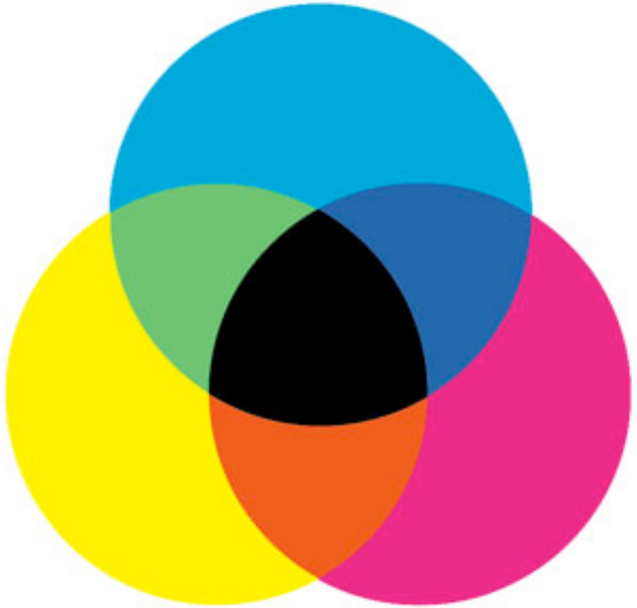
Forsyth & Ponce (2nd ed.) Figure 3.6

Additive and "Subtractive" Colour

- Why are monitors RGB and printers CMYK?



Additive Colour:
Coloured lights, LCD monitors

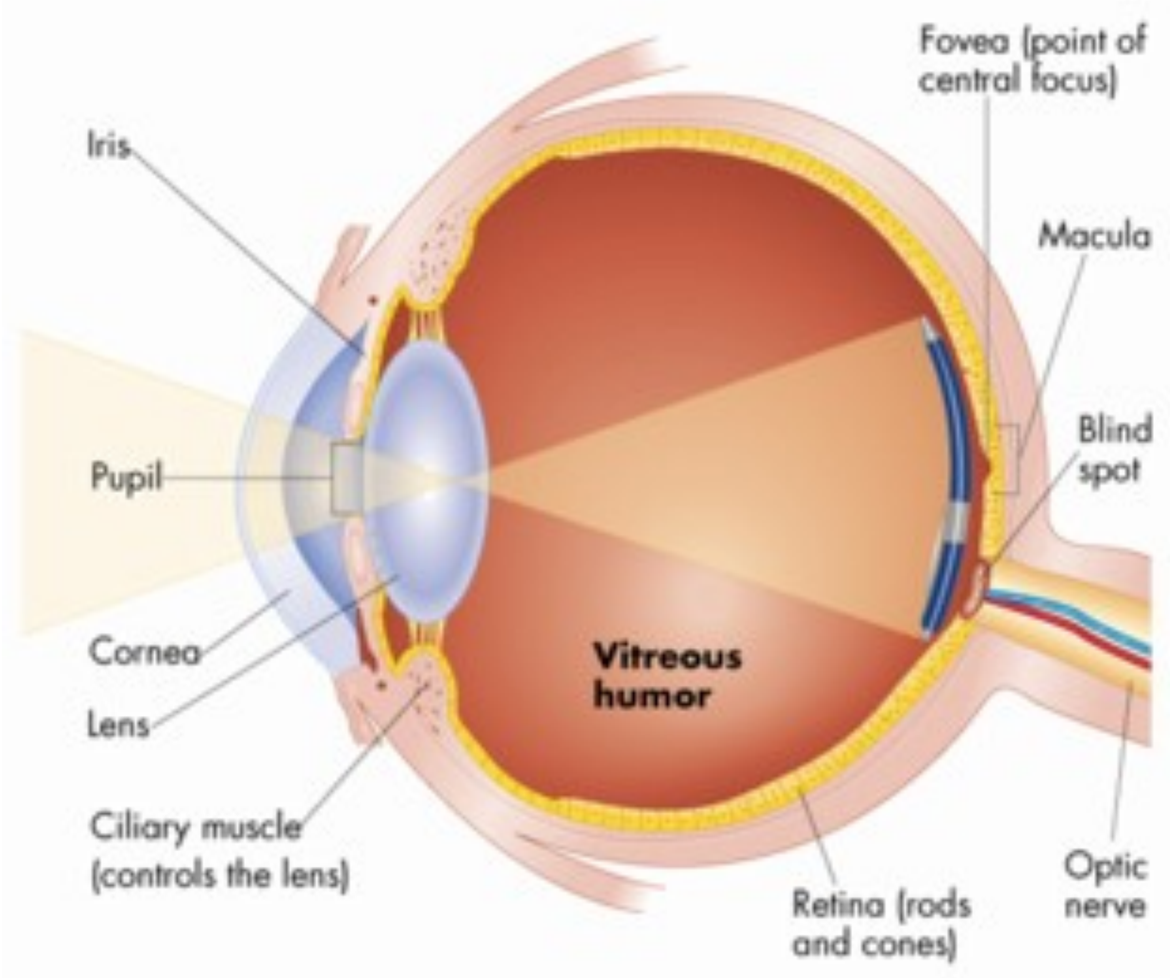


Subtractive Colour*:
Filters, printers, object + illumination spectra

*(*multiply spectra)*

Sensors

CMOS (or CCD)



Retina

Two-types of **Light Sensitive Receptors**

Rods

75-150 million rod-shaped receptors

not involved in color vision, gray-scale vision only

operate at night

highly sensitive, can responding to a single photon

yield relatively poor spatial detail

Cones

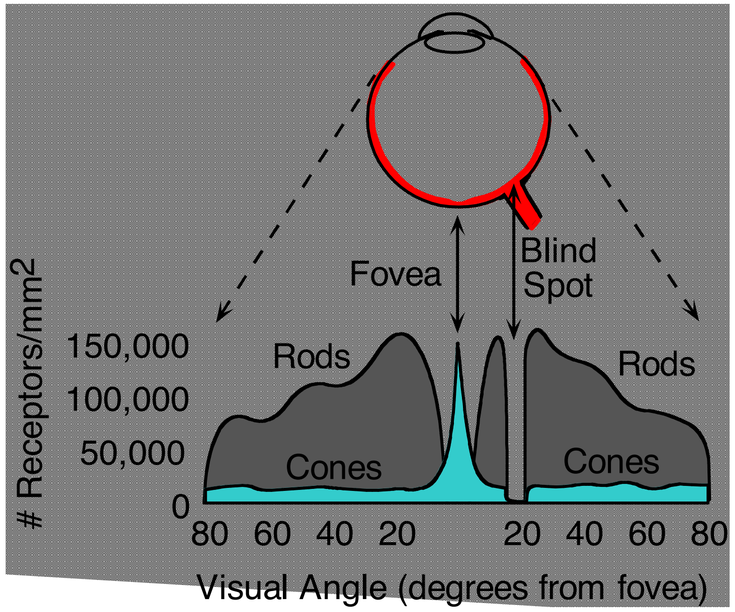
6-7 million cone-shaped receptors

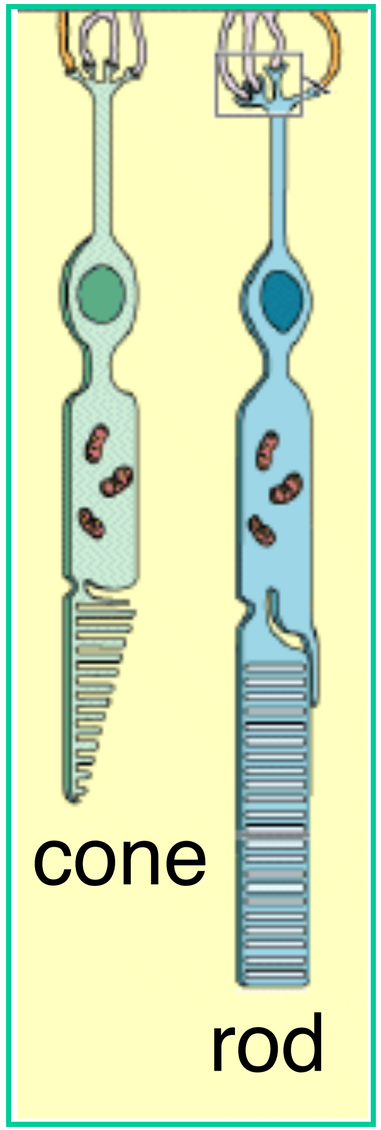
color vision

operate in high light

less sensitive

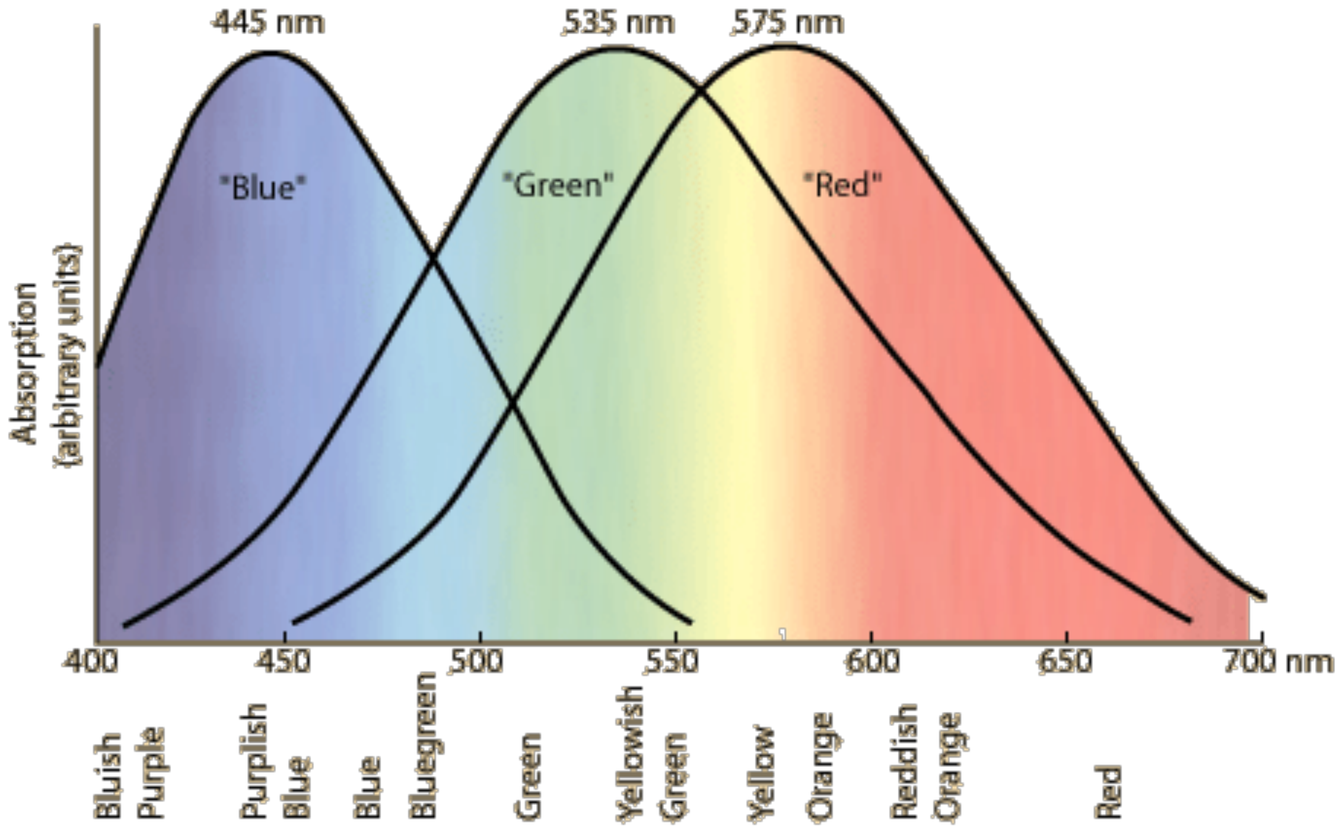
yield higher resolution





Slide adopted from: James Hays

Human **Cone** Sensitivity



http://hyperphysics.phy-astr.gsu.edu/hbase/vision/colcon.html

Metamers

Surfaces with **different** spectral power distributions can give the **same** tristimulus values

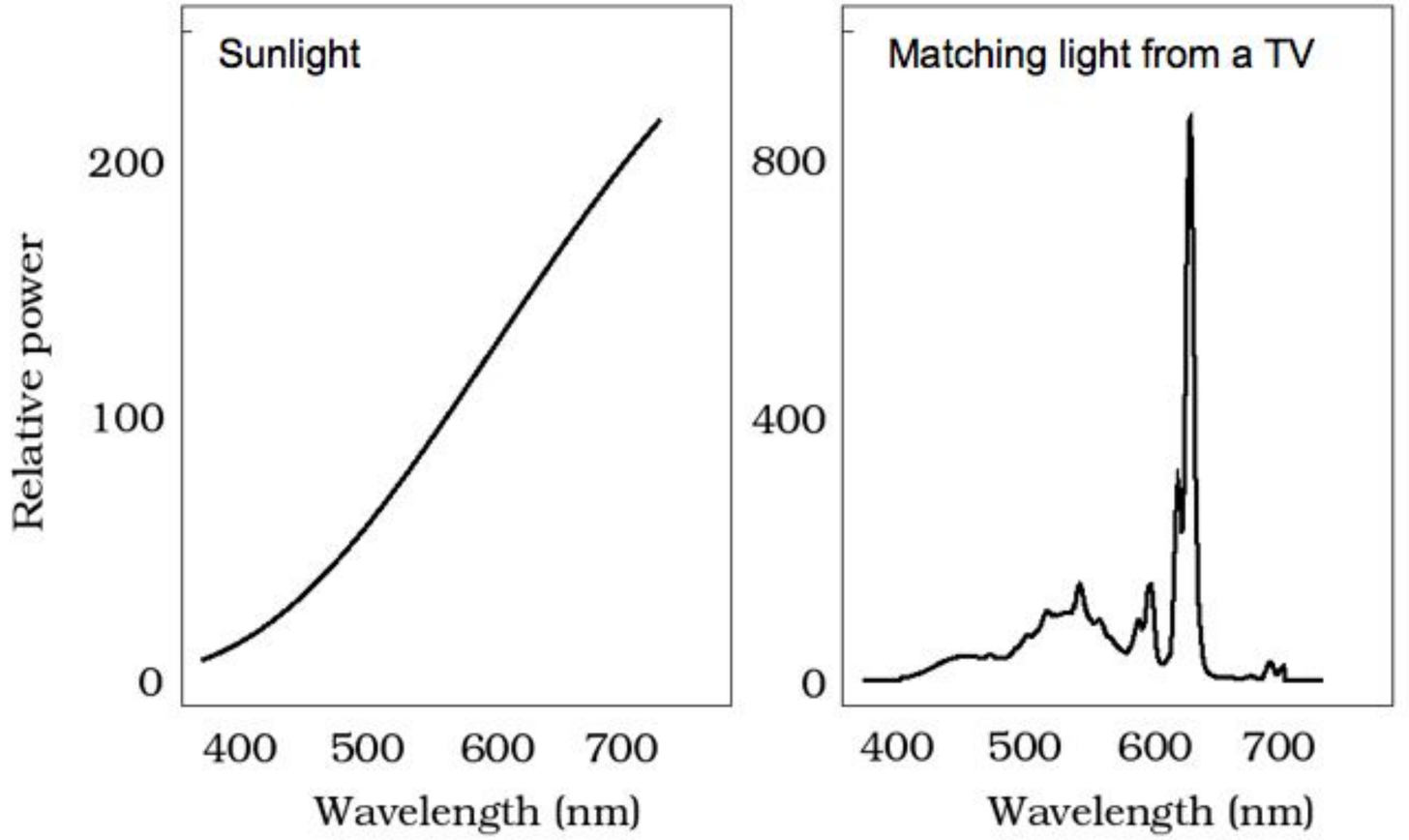
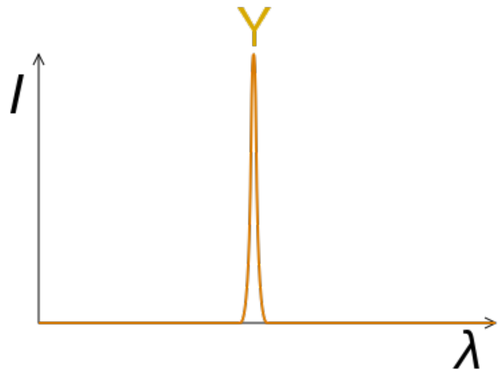


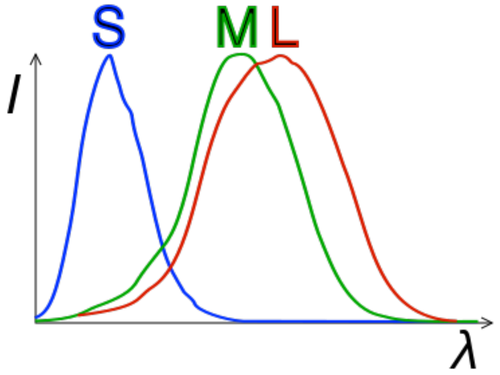
Figure credit: Brian Wandell, Foundations of Vision, Sinauer Associates, 1995

(A) A tungsten bulb (B) TV monitor set to match (A)

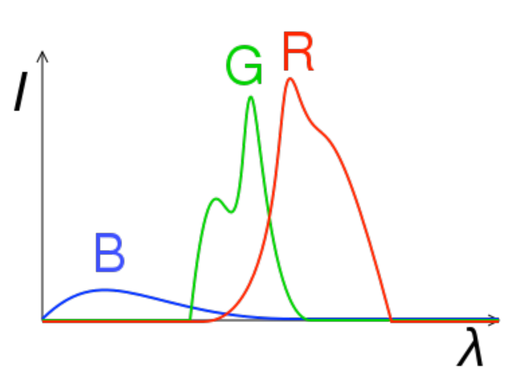
Metamers

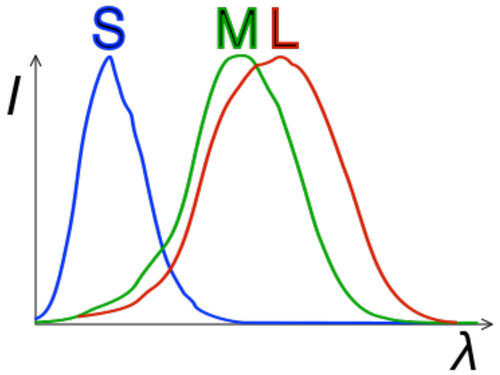
[Images: Wikipedia]

$$\int$$ 

$$\times$$ 

$$d\lambda =$$ 

$$\int$$ 

$$\times$$ 

$$d\lambda =$$ 

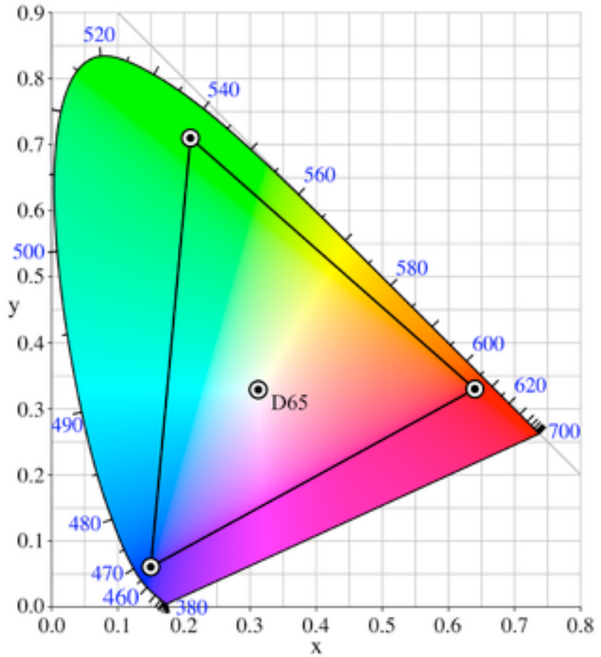
Different SPDs

Cone Response Curves

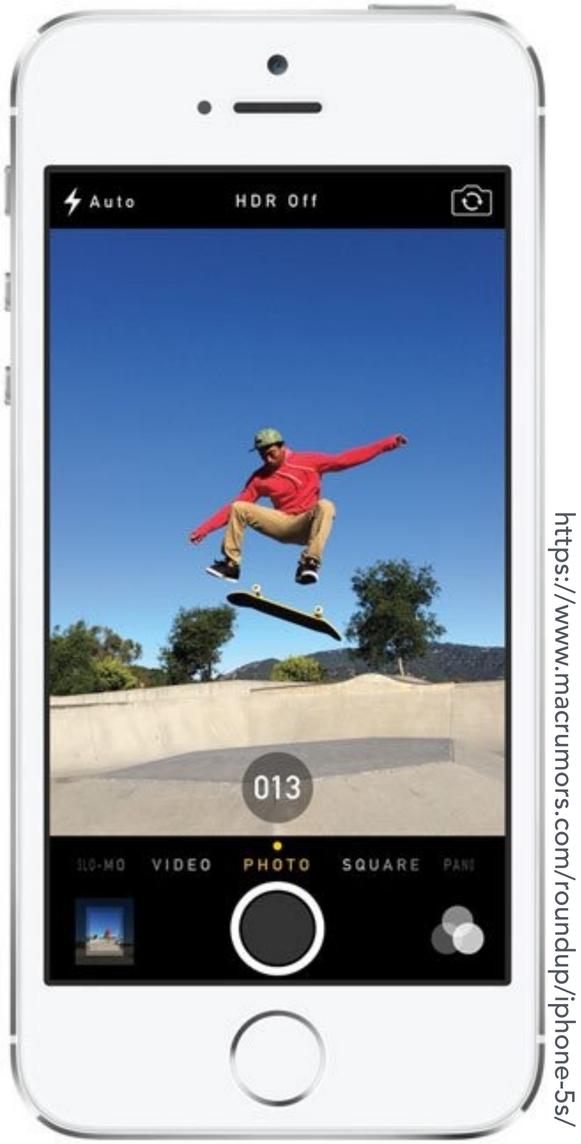
Same Tristimulus Responses = Perceived Colour

Cones and Colour Displays

- Humans have trichromatic vision
- So we don't need to generate all possible spectra
  - many different spectra give same perceivable colour (metamers)
- In theory we need just 3 bases to generate all colours
- In practice it is hard to match human cones exactly
- RGB is a pretty good approximation (generates most colours with positive values)



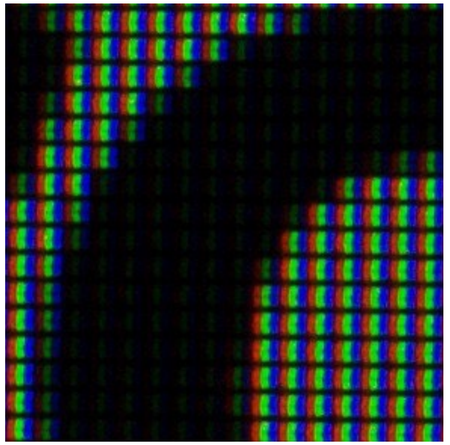
[Adobe '98
RGB Gamut]

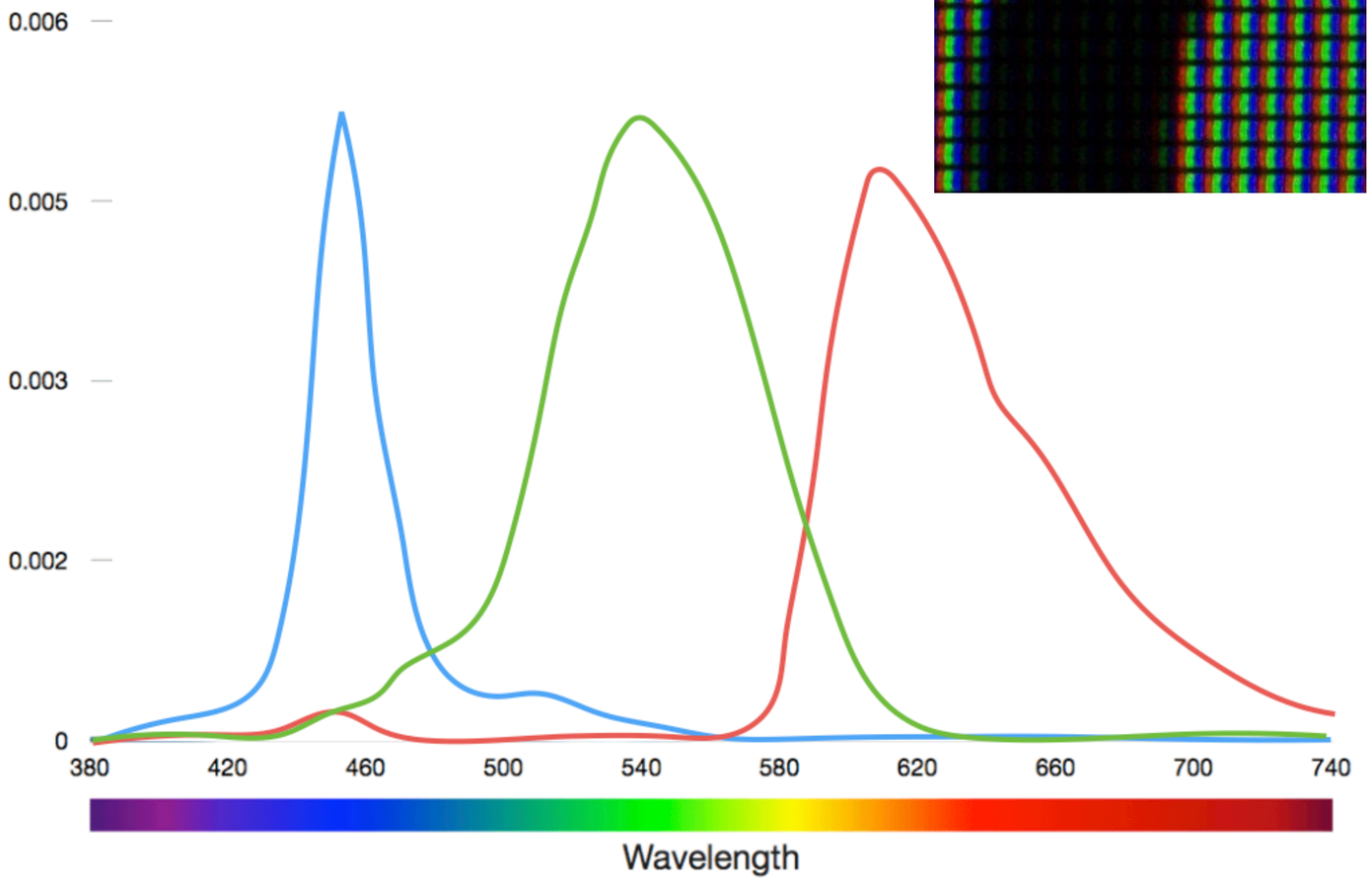


https://www.macrumors.com/roundup/iphone-5s/

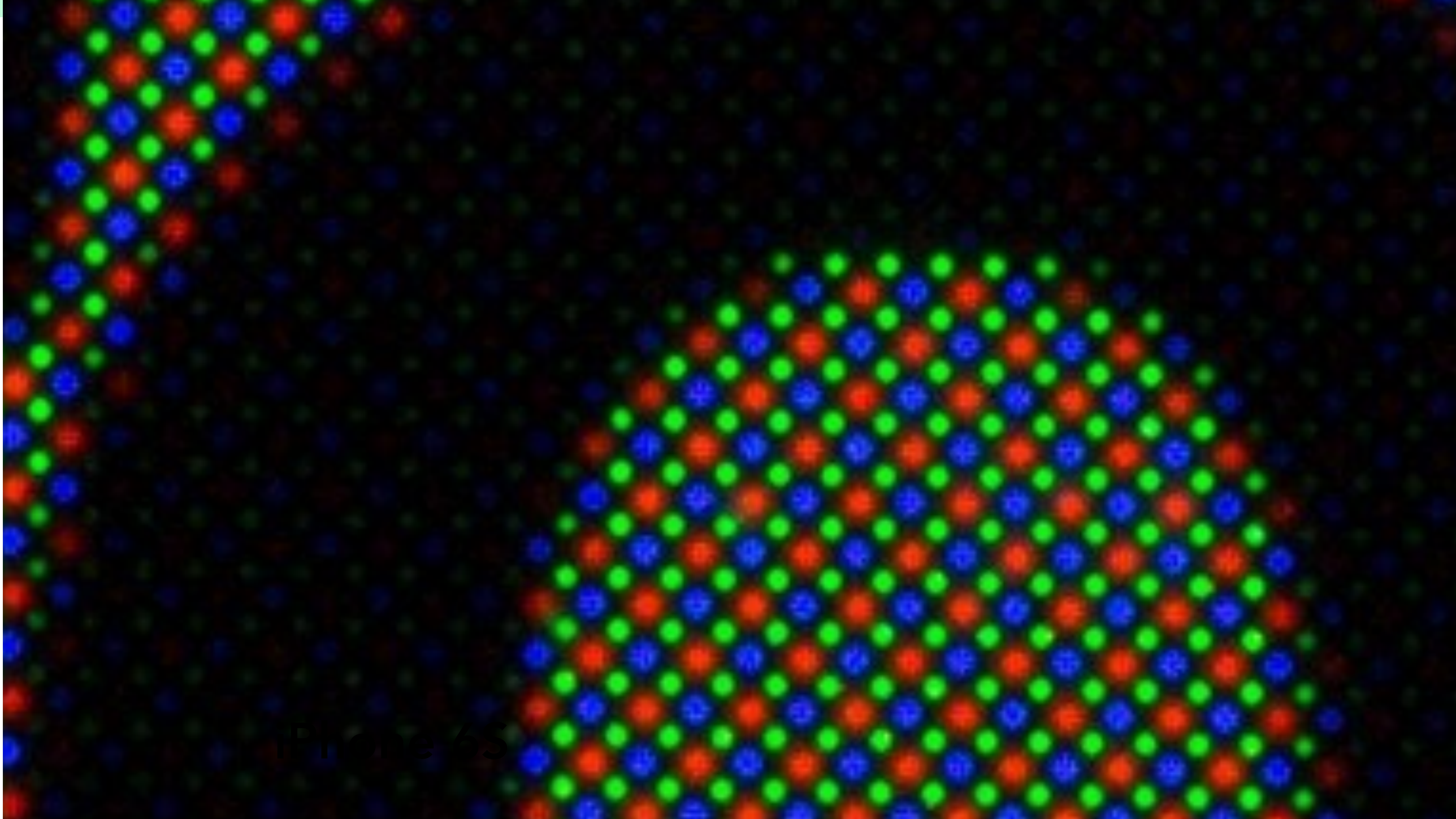
RGB pixel spectra (iPhone 5)

Credit: Yurek, https://dot-color.com/tag/color-2/page/2/

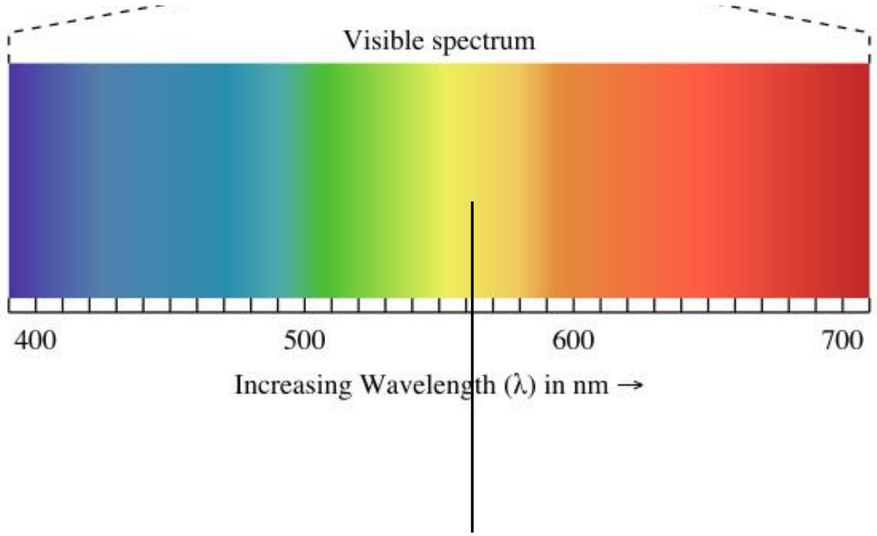




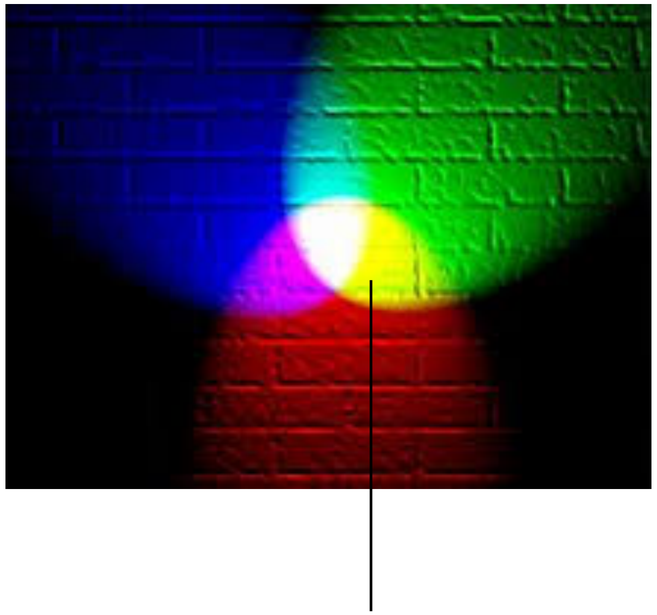
Ren Ng



Color **Matching**



Pure Color
(580 nm)

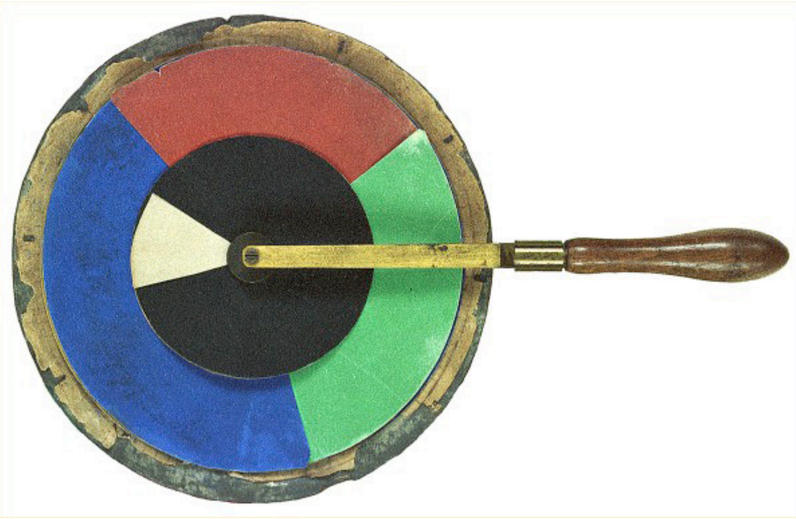


Additively Mixing
Primary Colors

Red - 700nm
Green - 546nm
Blue - 435nm

Maxwell Colour Matching Experiments

Maxwell mixed colours by rapidly spinning a top with different fractions of primaries, e.g., to match a central colour



https://designblog.rietveldacademie.nl/?p=68422

Color Matching Experiments

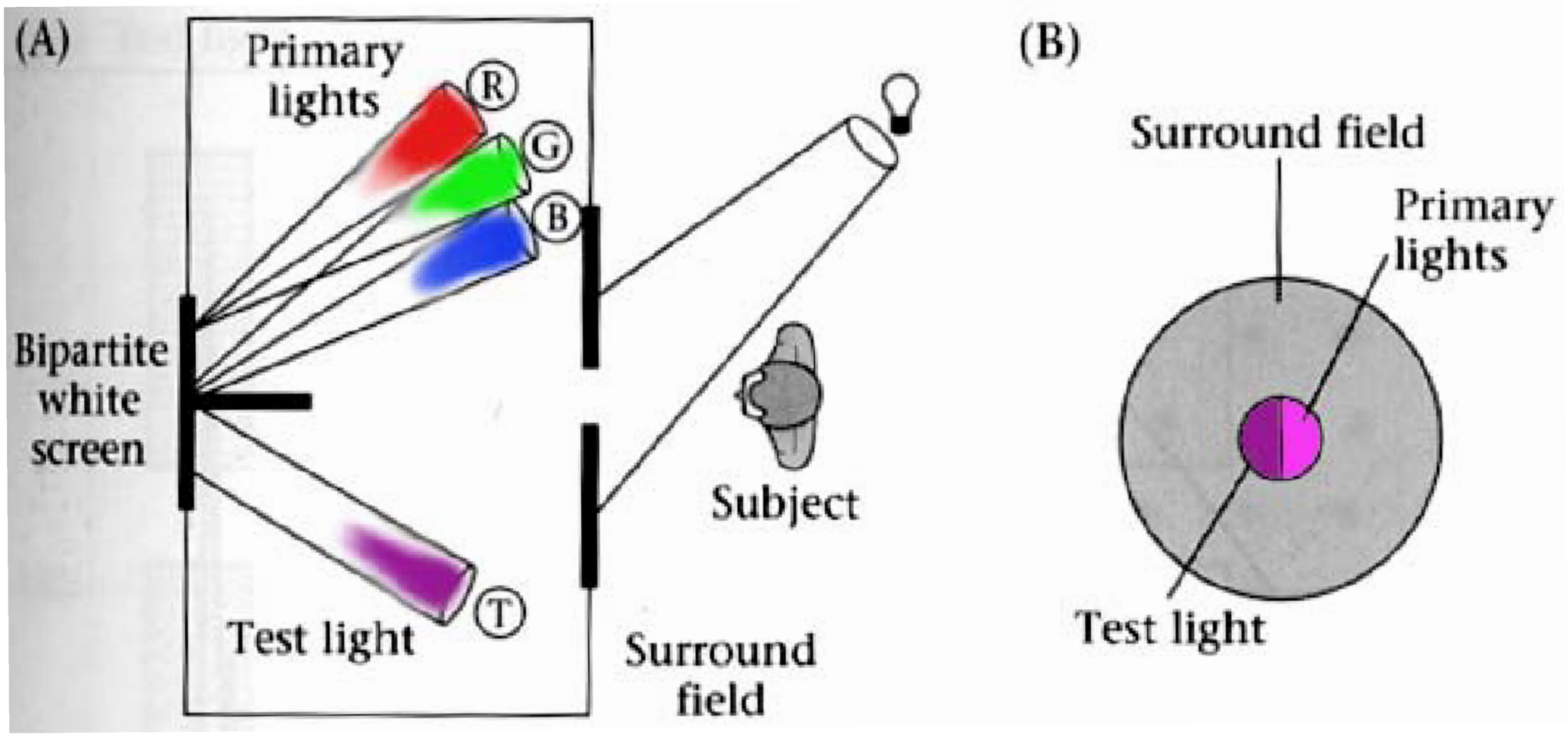
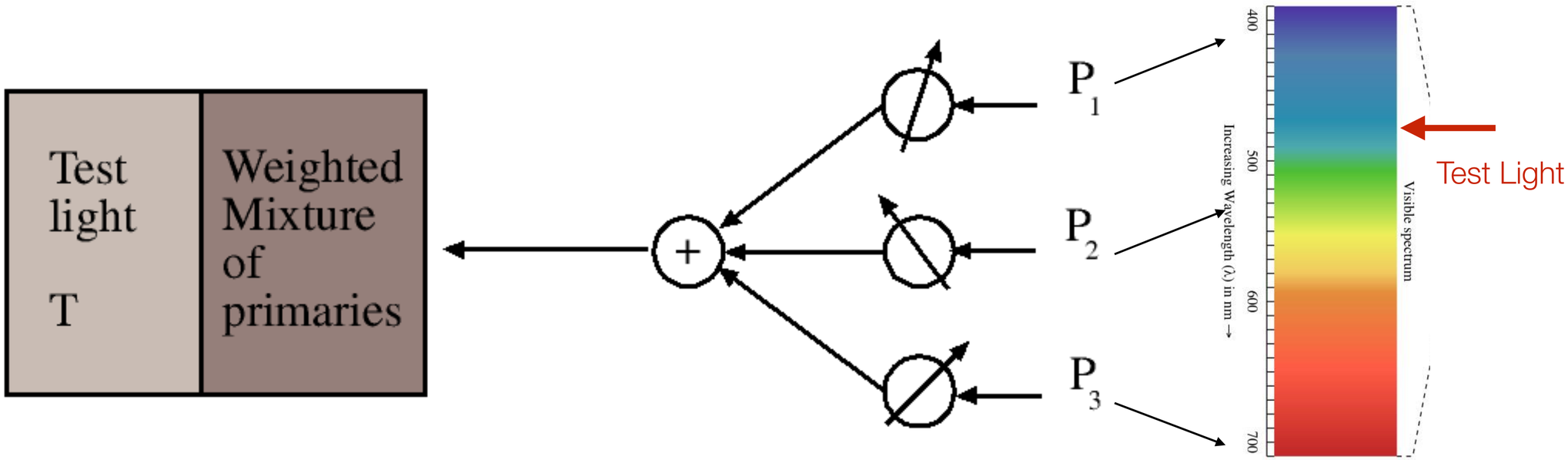


Figure Credit: Brian Wandell, Foundations of Vision, Sinauer Associates, 1995

Color Matching Experiments

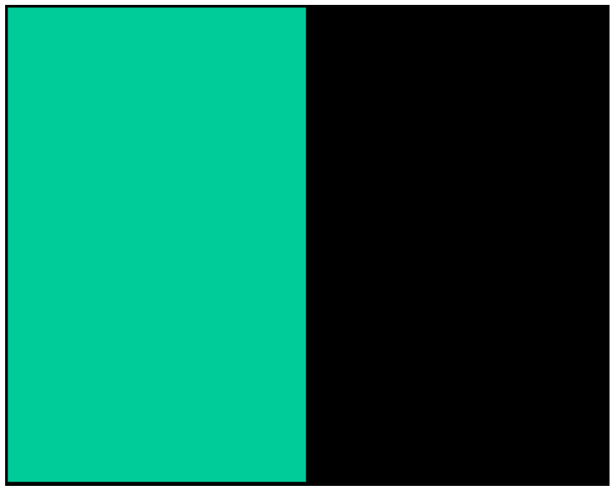


Forsyth & Ponce (2nd ed.) Figure 3.2

Show a split field to subjects. One side shows the light whose colour one wants to match. The other a weighted mixture of three primaries (fixed lights)

$$T = w_1 P_1 + w_2 P_2 + w_3 P_3$$

Example 1: Color Matching Experiment



knobs here

Example Credit: Bill Freeman

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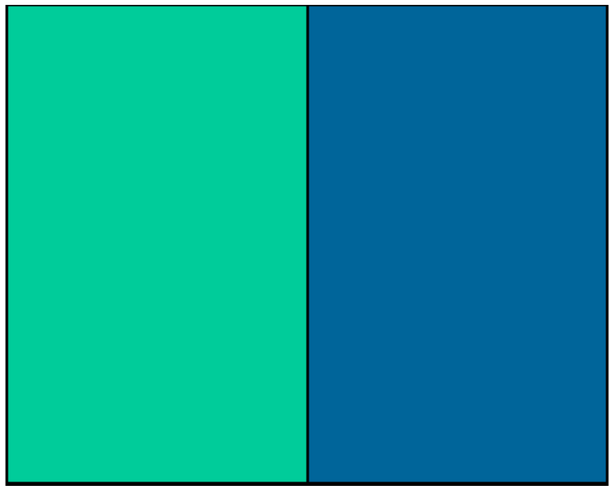

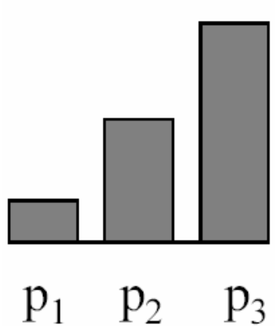

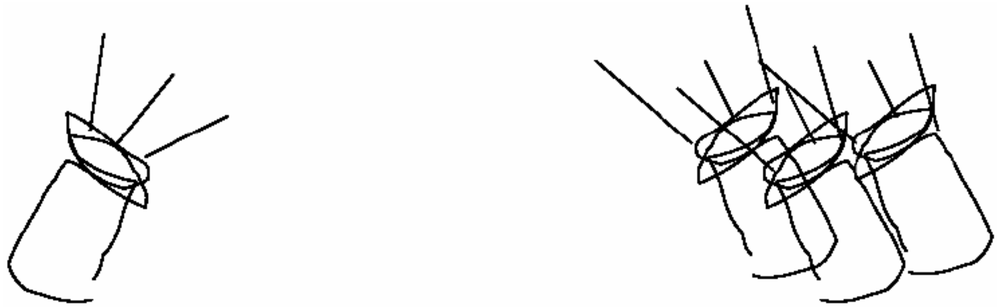

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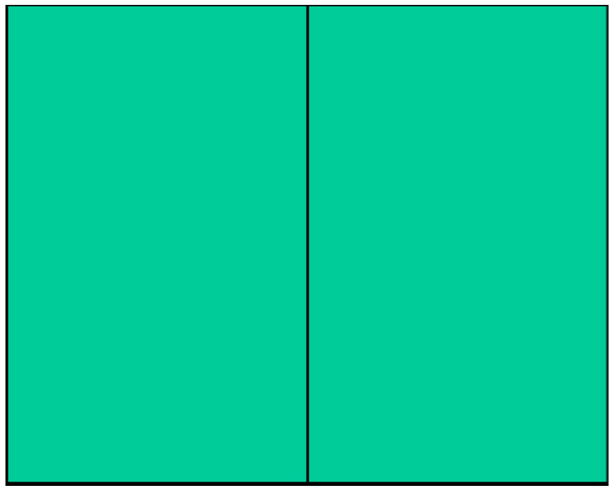

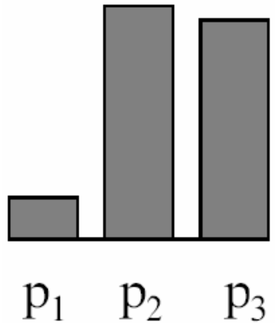

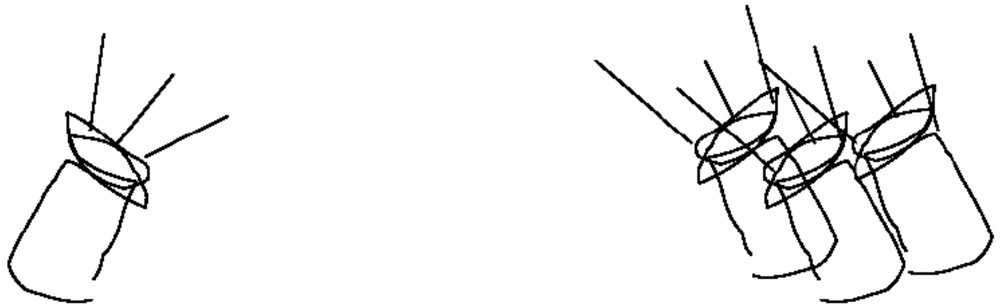

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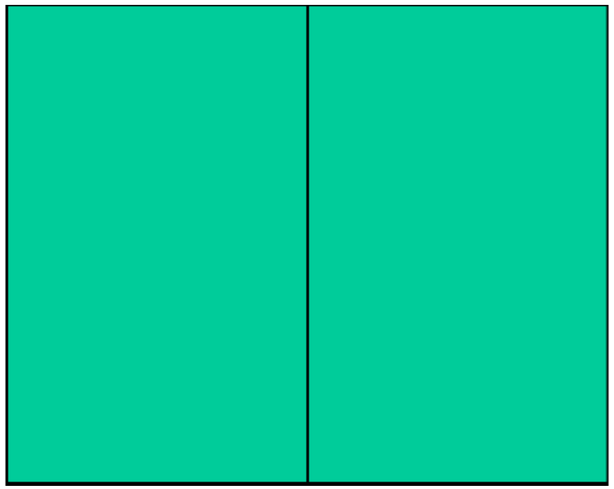

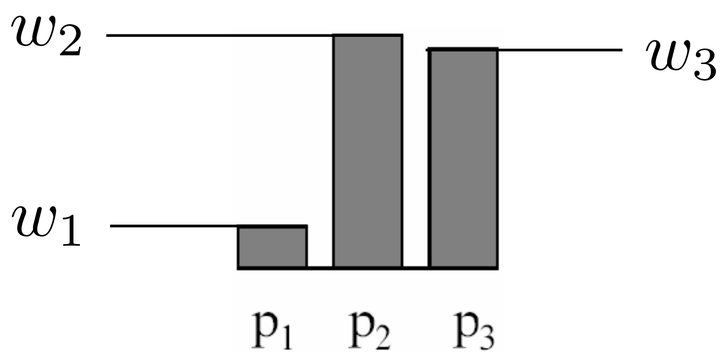

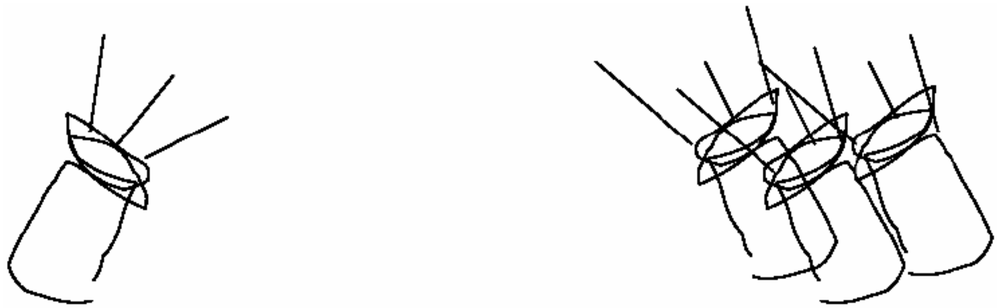

knobs here

Example Credit: Bill Freeman

Example 2: Color Matching Experiment

Example Credit: Bill Freeman

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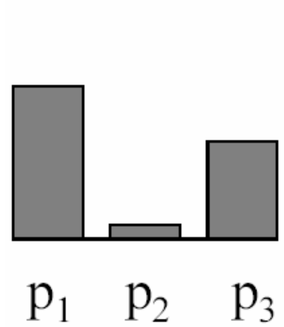

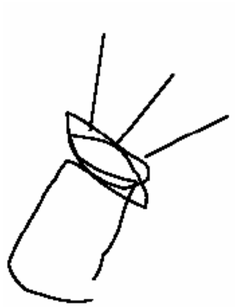

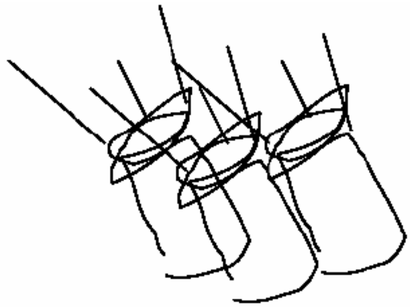

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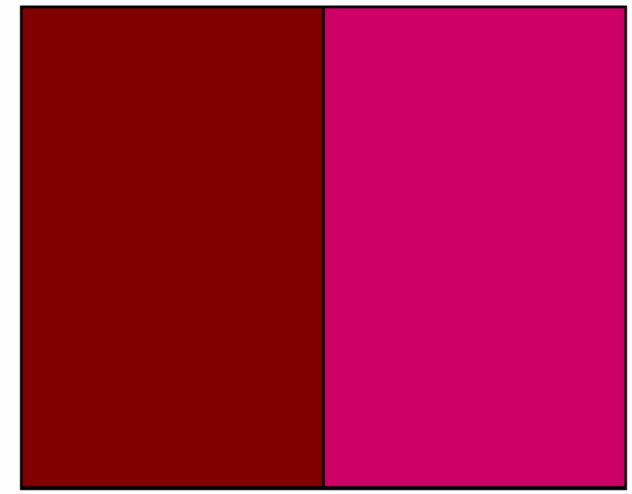

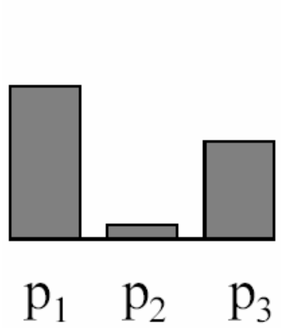

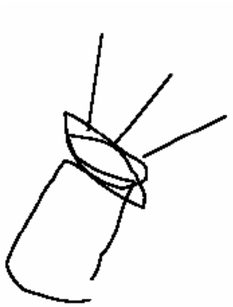

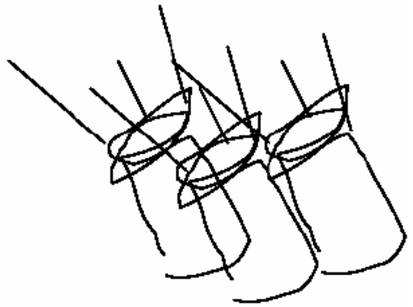

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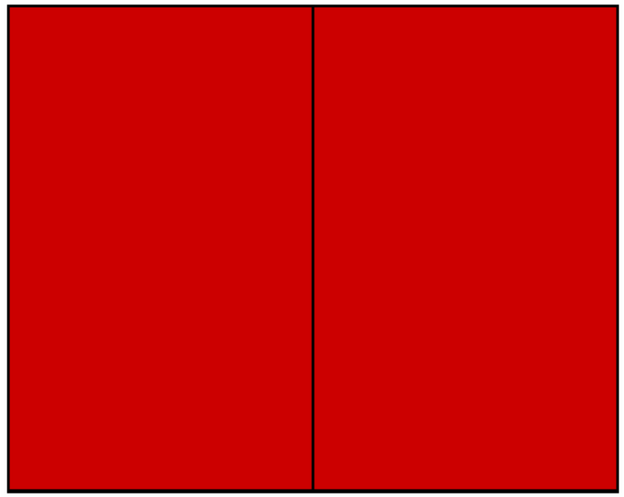
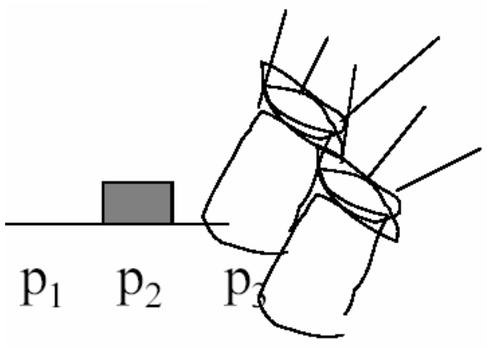
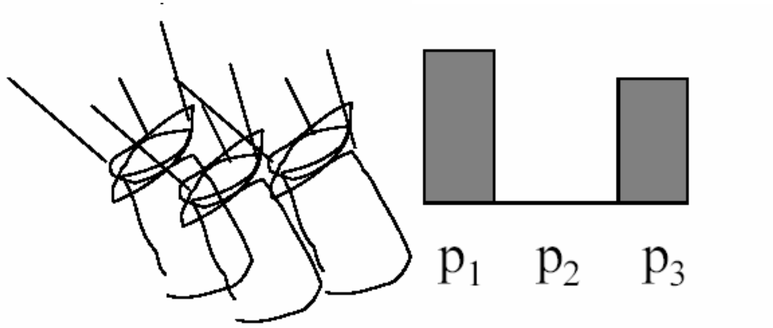


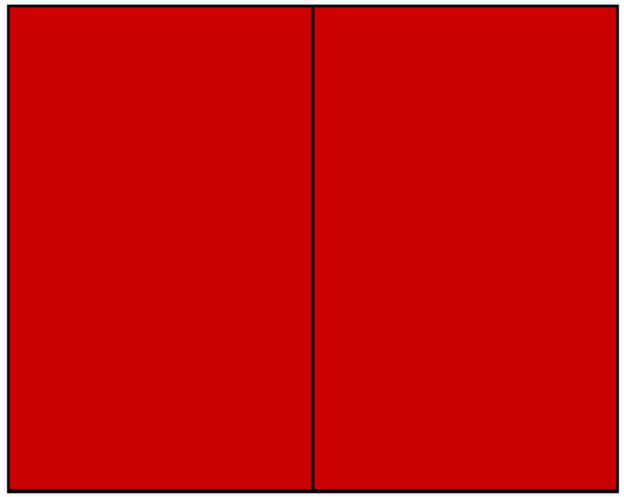


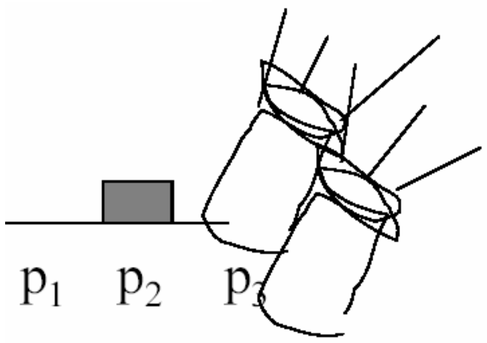


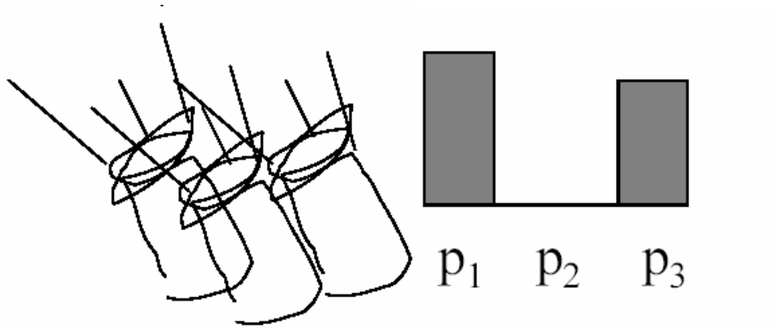
Example Credit: Bill Freeman

Example 2: Color Matching Experiment

We say a “negative” amount of P_2 was needed to make a match , because we added it to the test color side







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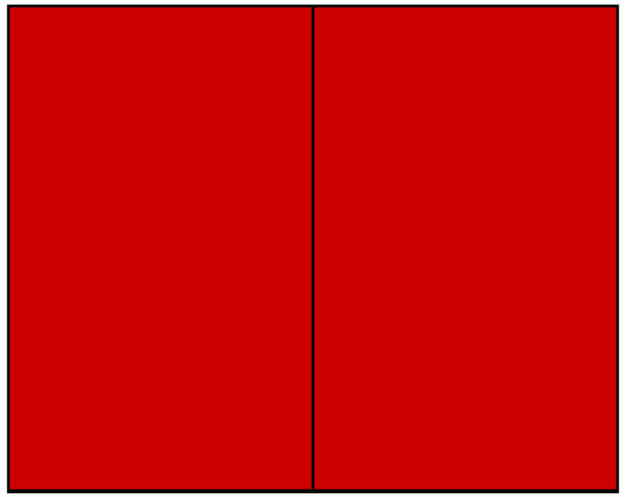
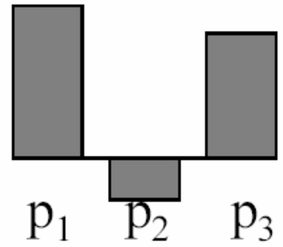
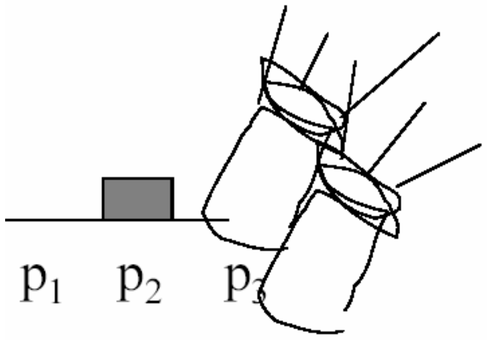
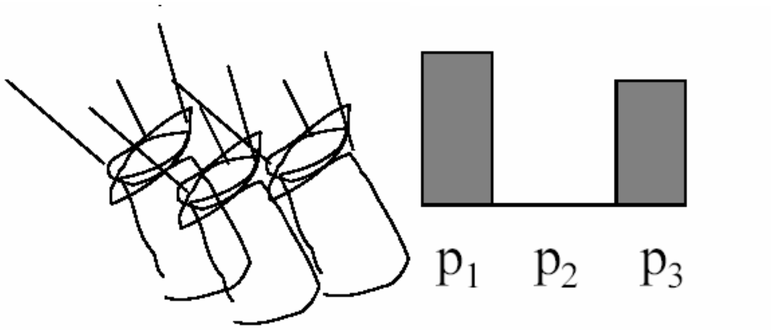


The primary color amount needed to match:



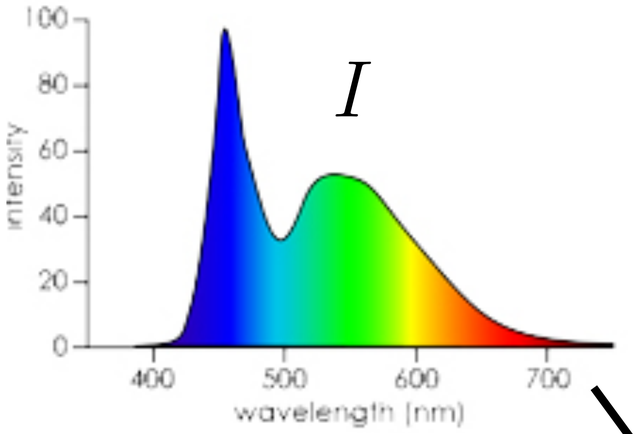


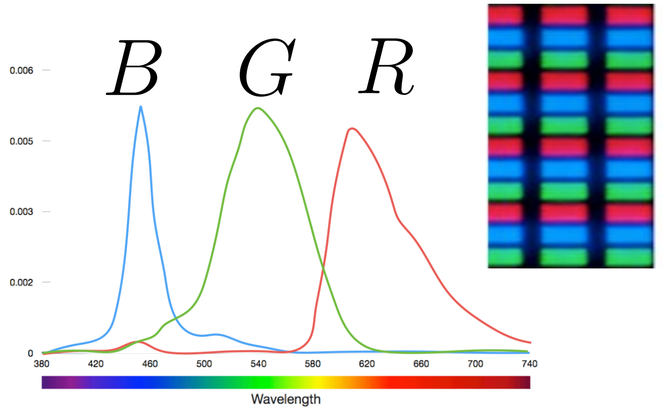


Example Credit: Bill Freeman

Matching Colours with **Displays**

Suppose we have a display with lights R, G, B and we want to match a colour with spectra I for a person with cone responses L, M, S





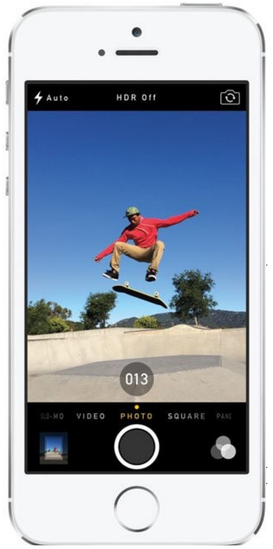
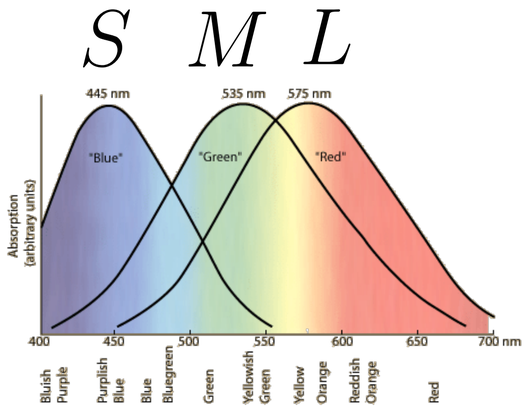
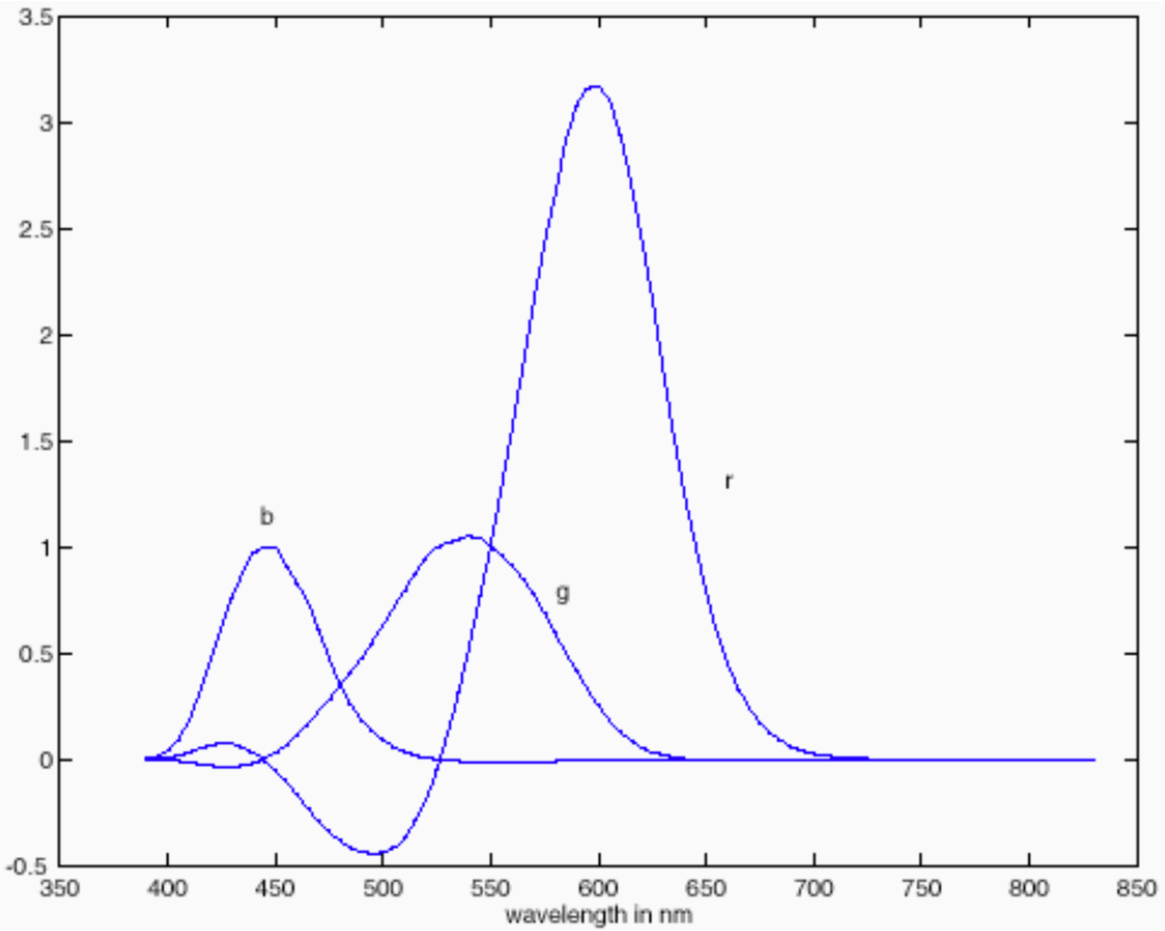


Image and real scene should give the **same cone responses**



11.2

RGB Colour Matching Functions



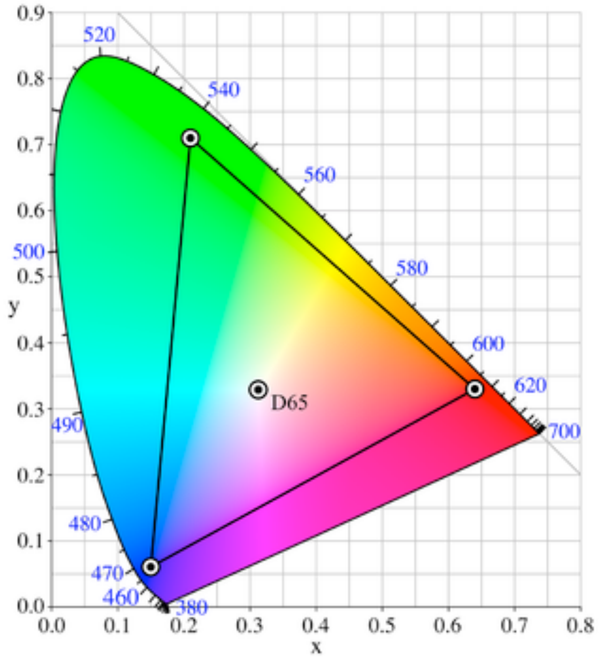
— Primaries **monochromatic**

— Wavelengths 645.2, 526.3 and 444.4 nm

— **Negative** parts means some colours can be matched only subtractively

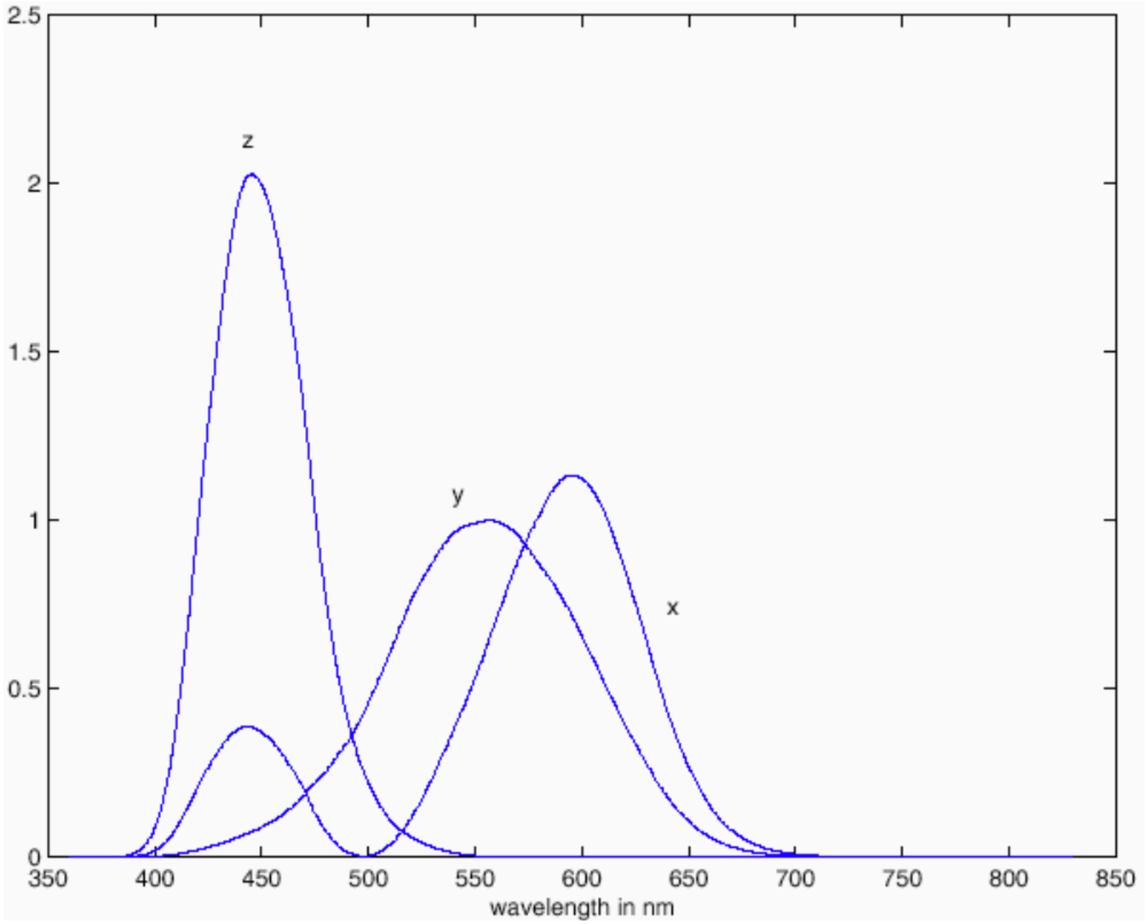
Cones and Colour Displays

- Humans have trichromatic vision
- So we don't need to generate all possible spectra
  - many different spectra give same perceivable colour (metamers)
- In theory we need just 3 bases to generate all colours
- In practice it is hard to match human cones exactly
- RGB is a pretty good approximation (generates most colours with positive values)



[Adobe '98
RGB Gamut]

RGB Colour Matching Functions



CIE XYZ: Colour matching functions are positive everywhere, but primaries are imaginary. Usually draw x, y, where

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

Overall brightness is ignored

Color Spaces

— **RGB**: Primaries are monochromatic energies, say 645.2 nm, 526.3 nm, 444.4 nm, standard colour space related to displays

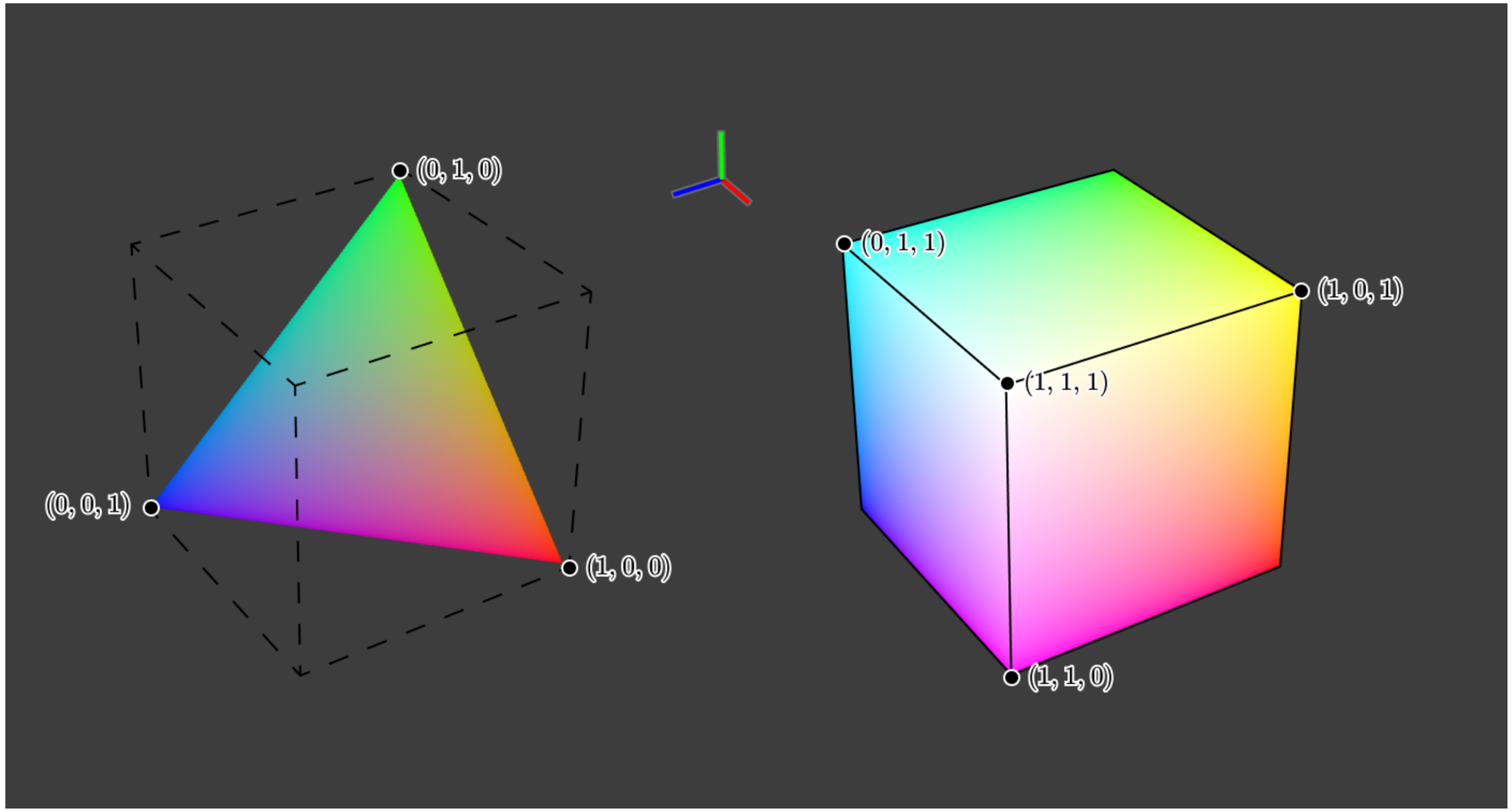
— **CIE XYZ**: Primaries are imaginary, but have other convenient properties. Colour coordinates are (X , Y , Z), where X is the amount of the X primary, etc.

—**CIE LAB**: Equal distances in space correspond to perceptually uniform colour differences

—**HSV**: Hue, Saturation, Value a useful colour space for artists and **colour selection** applications

—**YCbCr:** Separates **luminance** (Y) and **opponent colours** (CbCr), useful for compression and transmission

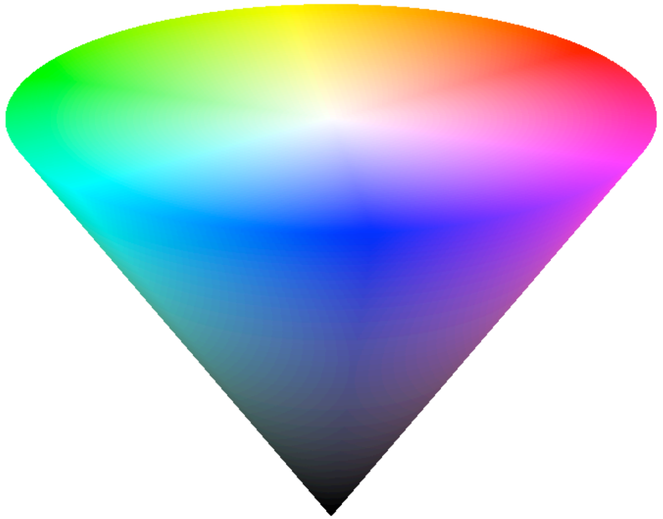
RGB Color Space



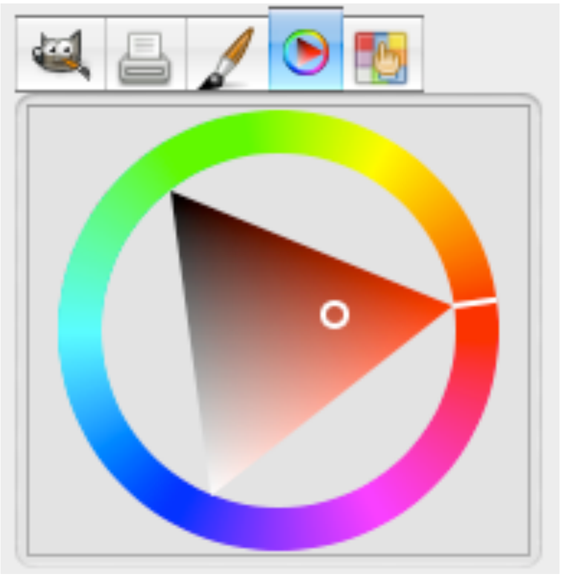
HSV Colour Space

- Often used for colour selection in applications

RGB Cube



HSV Cone



HSV Colour Wheel

HSV Colour Space

More natural description of colour for human interpretation

Hue: attribute that describes a pure colour
— e.g. ’red’, ’blue’

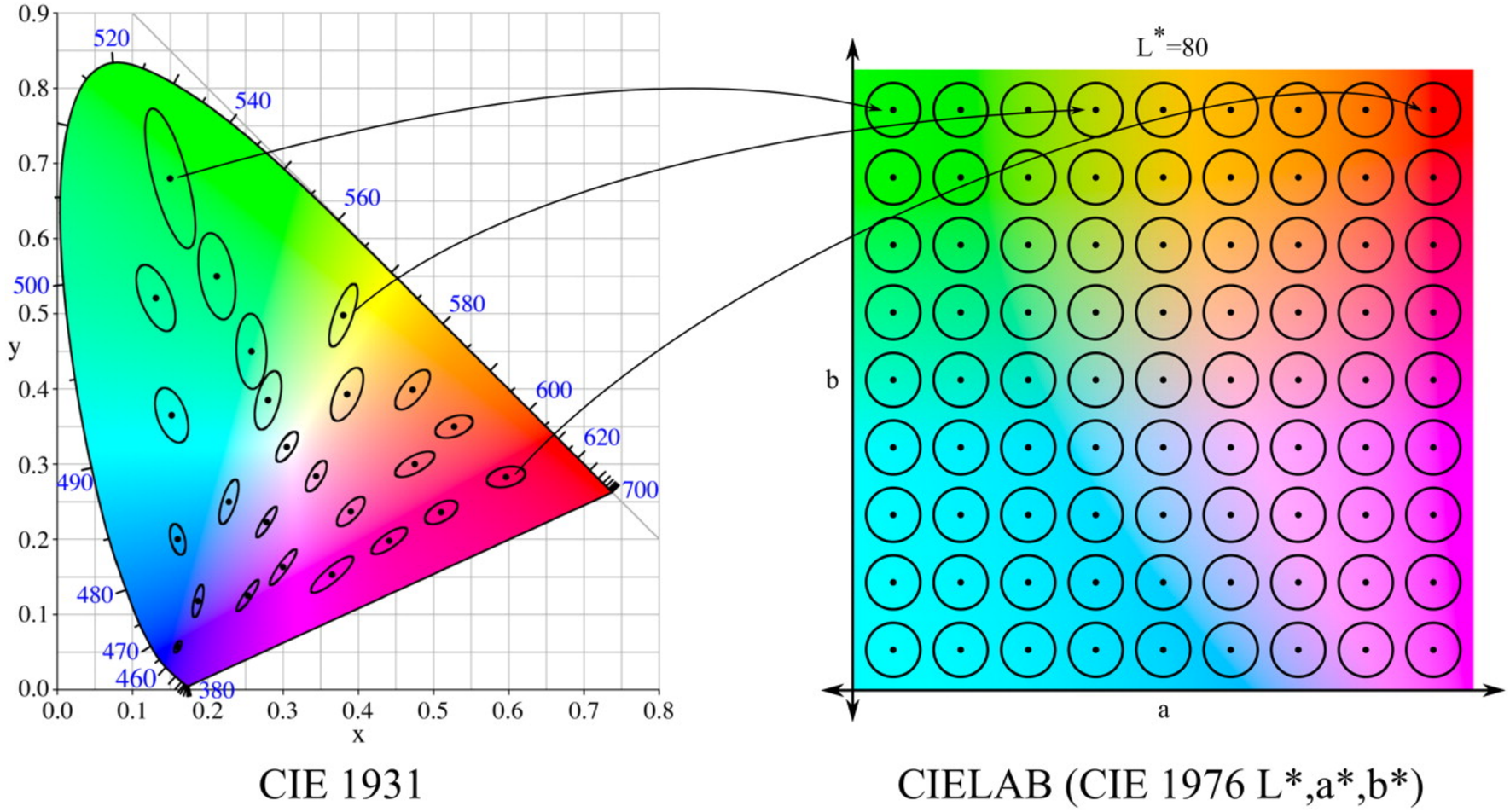
Saturation: measure of the degree to which a pure colour is diluted by white light
— pure spectrum colours are fully saturated

Value: intensity or brightness

Hue + saturation also referred to as **chromaticity**.

Uniform Colour Space **CIE-LAB**

McAdam Ellipses: Each ellipse shows colours perceived to be the same



CIE 1931

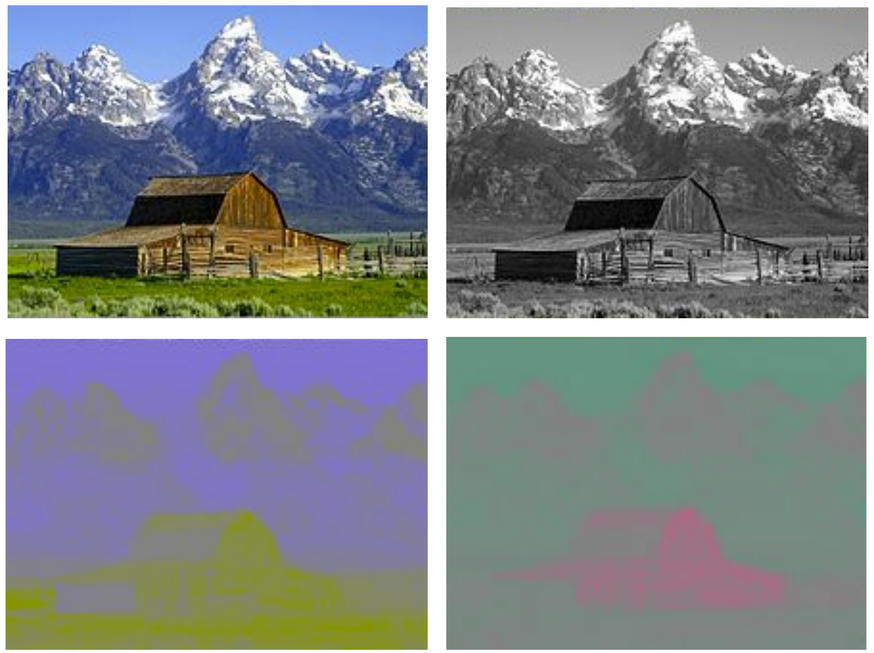
CIELAB (CIE 1976 L*,a*,b*)

From Henrich et al. 2011

https://iovs.arvojournals.org/article.aspx?articleid=2187751

YCbCr = Colour for Image Coding

- Separates luminance (Y) from chrominance (Cb, Cr)
- Chrominance can be compressed more (e.g. 1/2 size in JPG)



$$Y' = 16 + 65.5R' + 128.6G' + 25.0B'$$
$$Cb = 128 - 37.8R' - 74.2G' + 112B'$$
$$Cr = 128 + 112.0R' - 93.8G' - 18.2B'$$

- Linear transform of RGB
- Primes = gamma correction

YCbCr is used for image and video coding. Human vision uses a similar transform (opponent colours) and we have more rods than cones

Summary

- Human colour **perception**
  - principle of trichromacy
  - colour matching experiments
- Colour **reproduction**
  - match cone responses
  - colour matching functions
- Colour **spaces**
  - multiple objectives: art/design orientation, perceptually uniform, image coding etc.

Menu for Today

Topics:

- Colour, **Trichromacy**
- **Colour Matching** Experiments
- **Colour Spaces**
- **Final** examples

Readings:

- **Today's** Lecture: Szeliski 2.3.2, Forsyth & Ponce 3.1-3.3

Reminders:

- **Assignment 6** due Dec 7th
- **Final** is Dec 14th (**2hrs**, closed book, no calculators)
- Today is the **last lecture!** No lectures next week