Color Models

Elements of Color

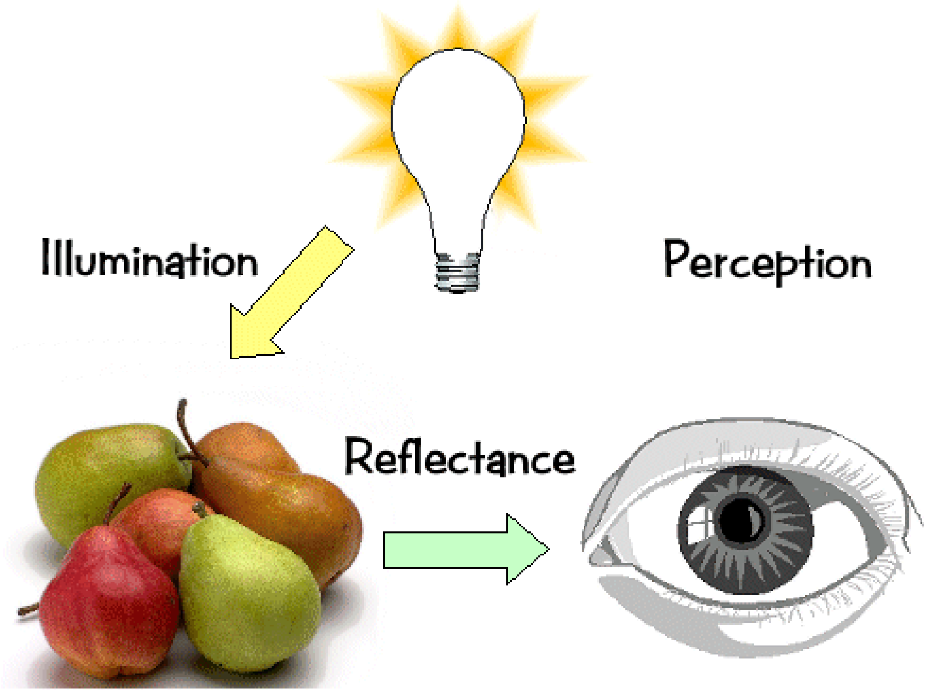
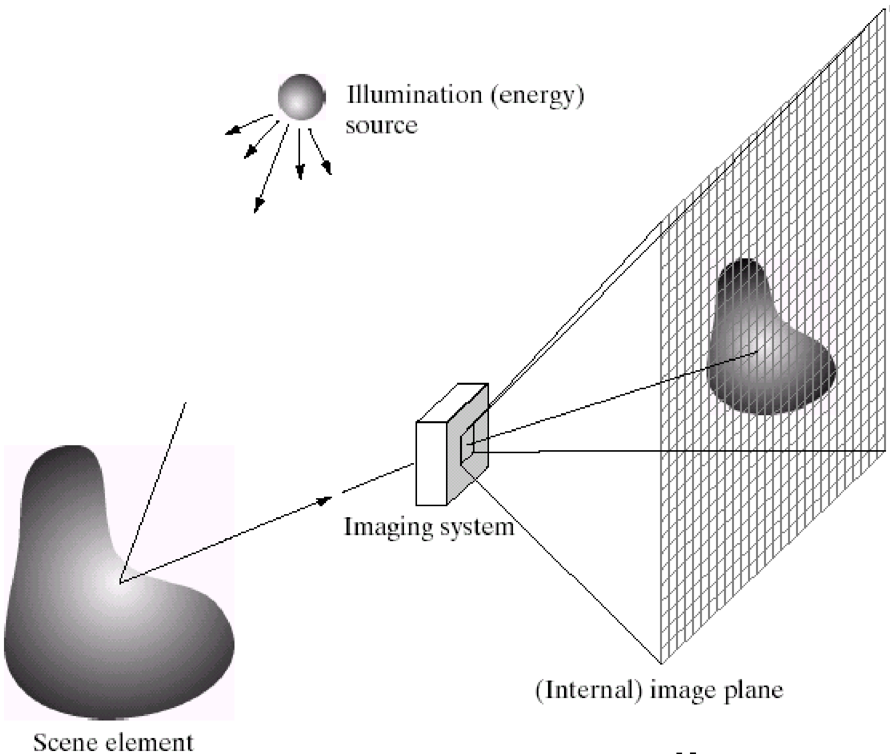
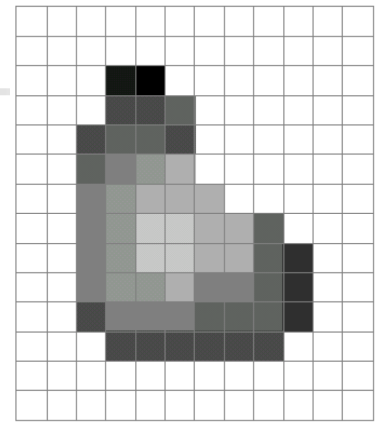


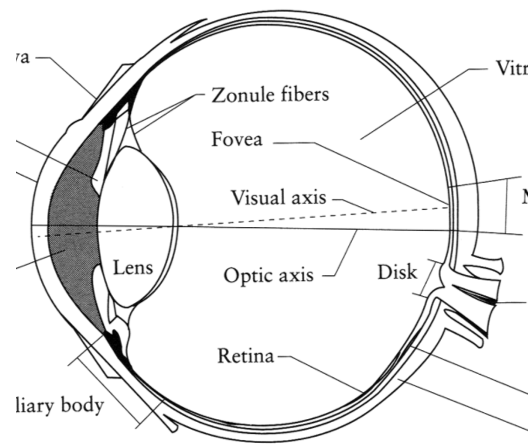
Image Formation



Film



Digital Camera



The Eye

Sensor Array

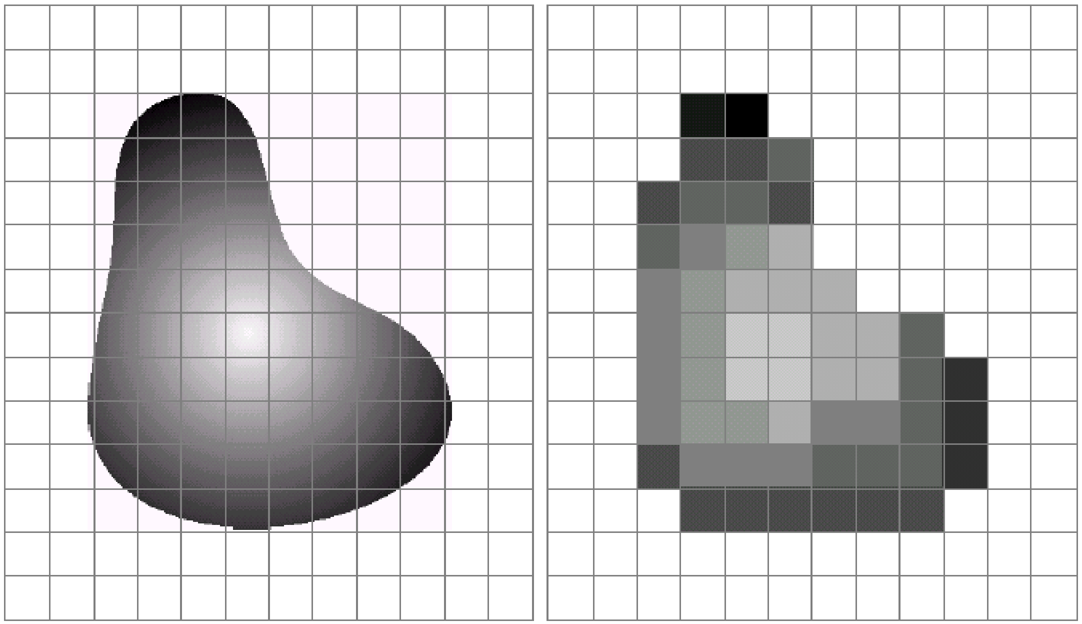
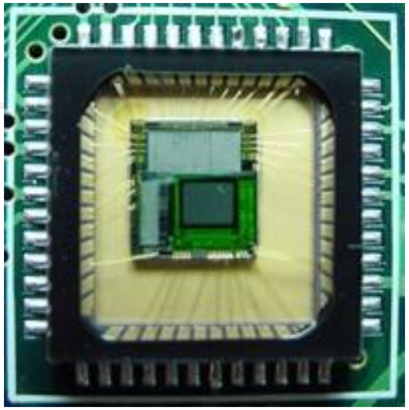


FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.



CMOS sensor

Sampling and Quantization

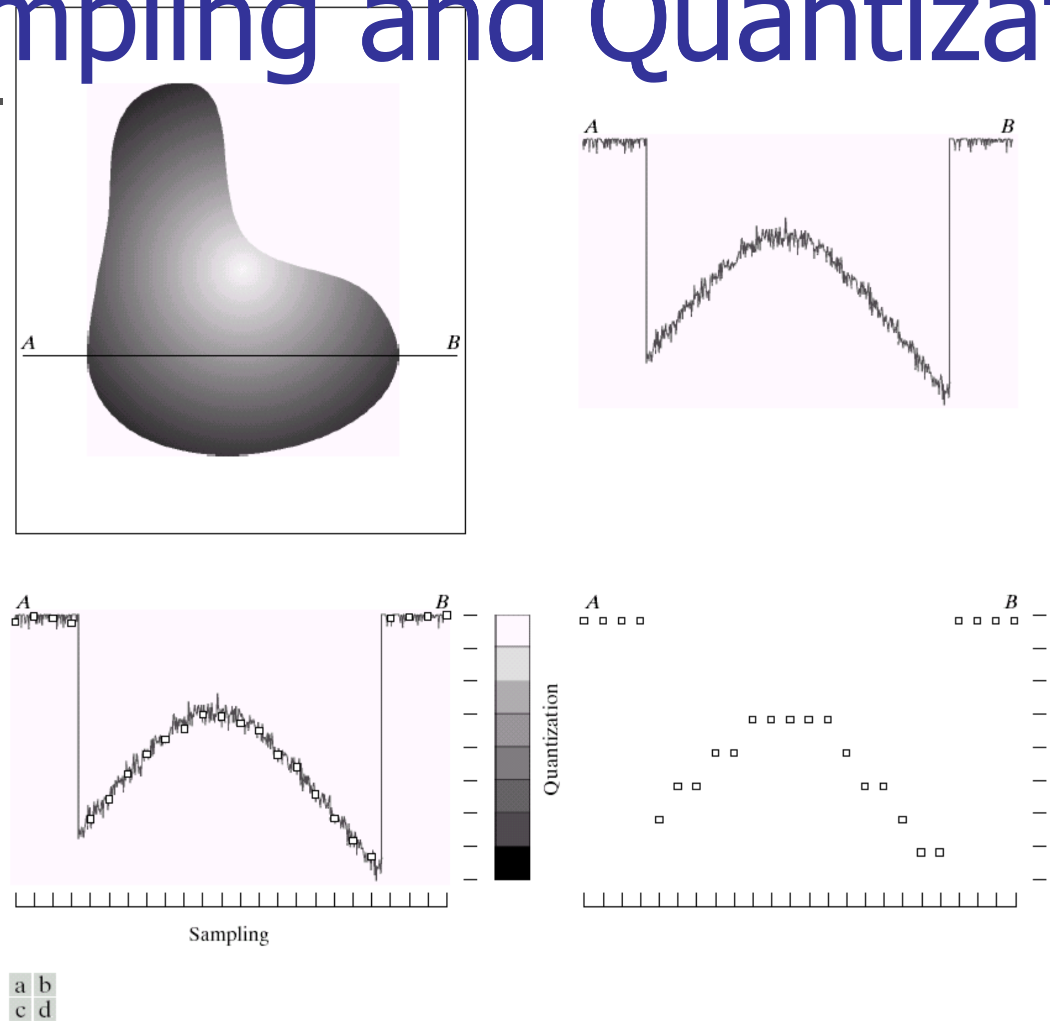
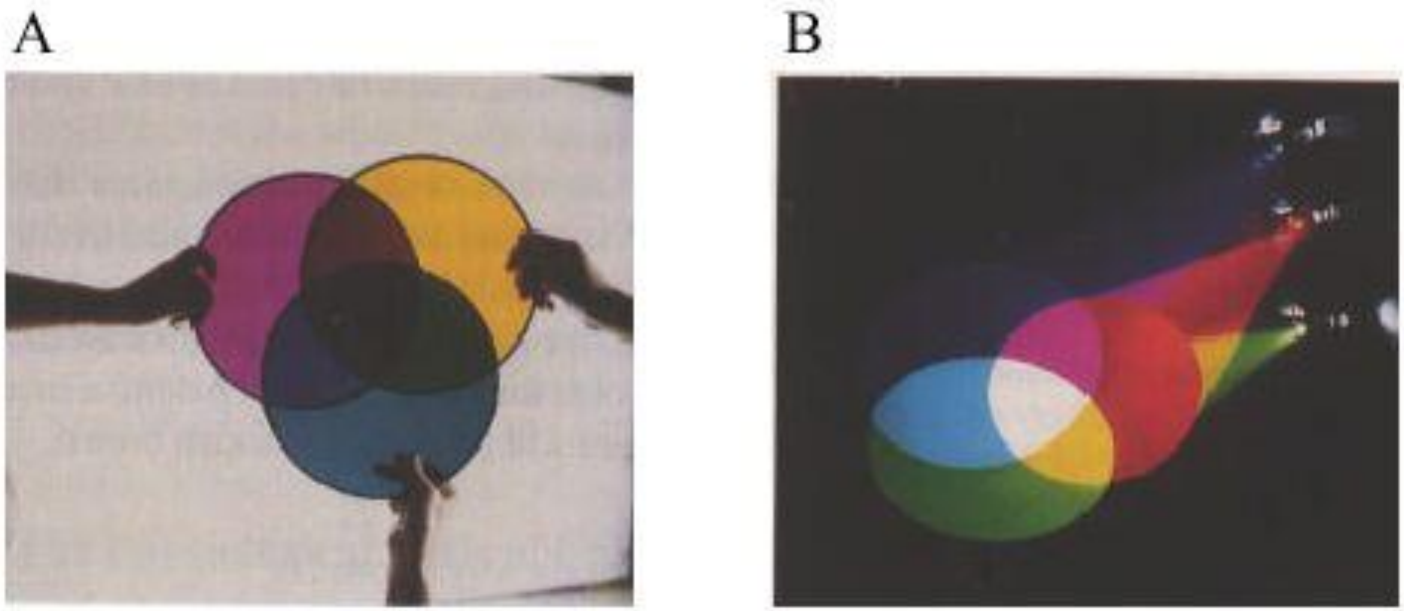


FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

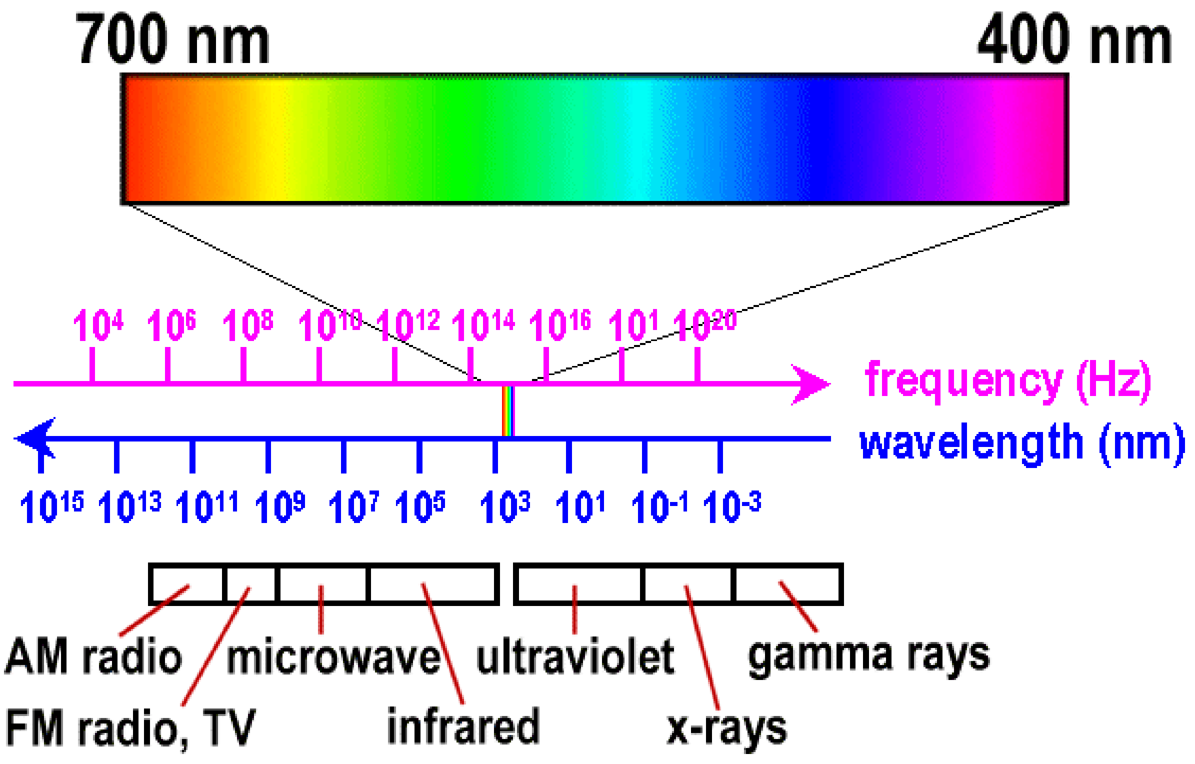
Color Mixture



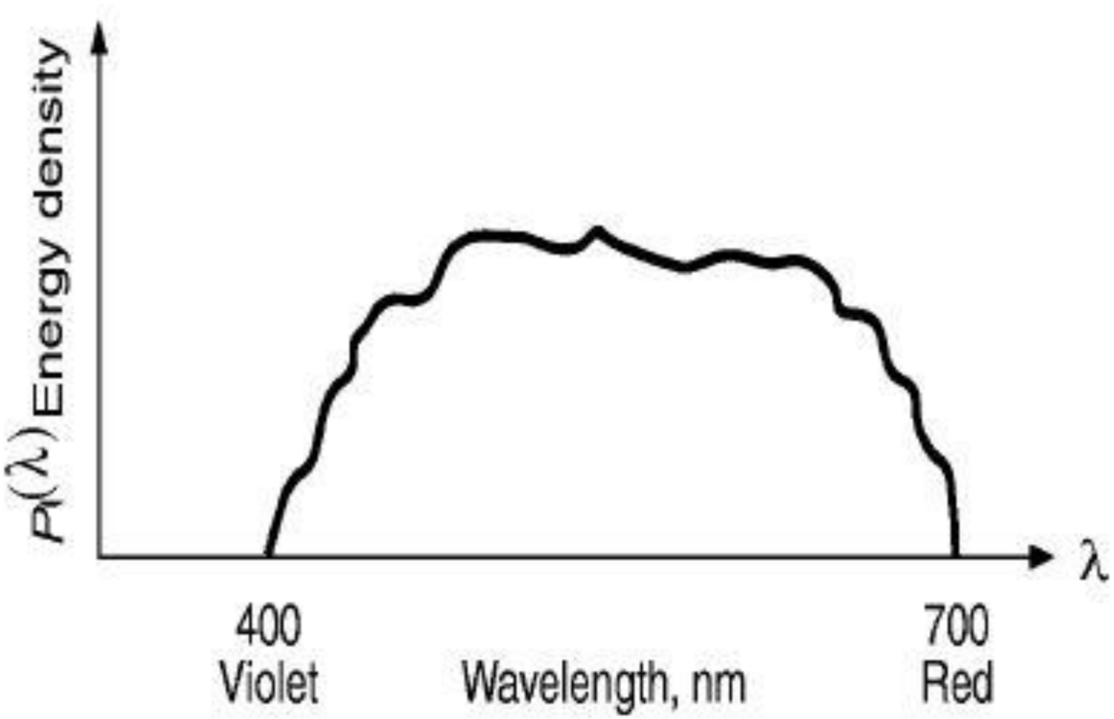
The effect of (A) passing light through several filters (subtractive mixture), and (B) throwing different lights upon the same spot (additive mixture)

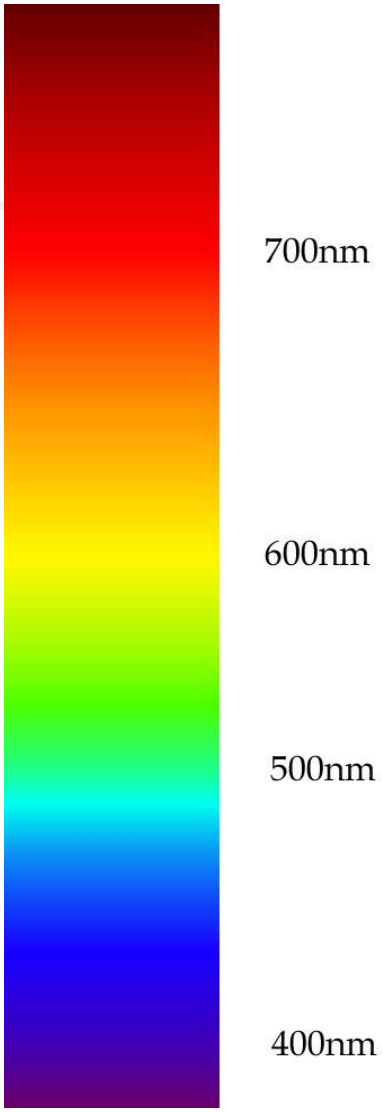
Light

- Light is ***electromagnetic wave*** in the ***visible spectrum***



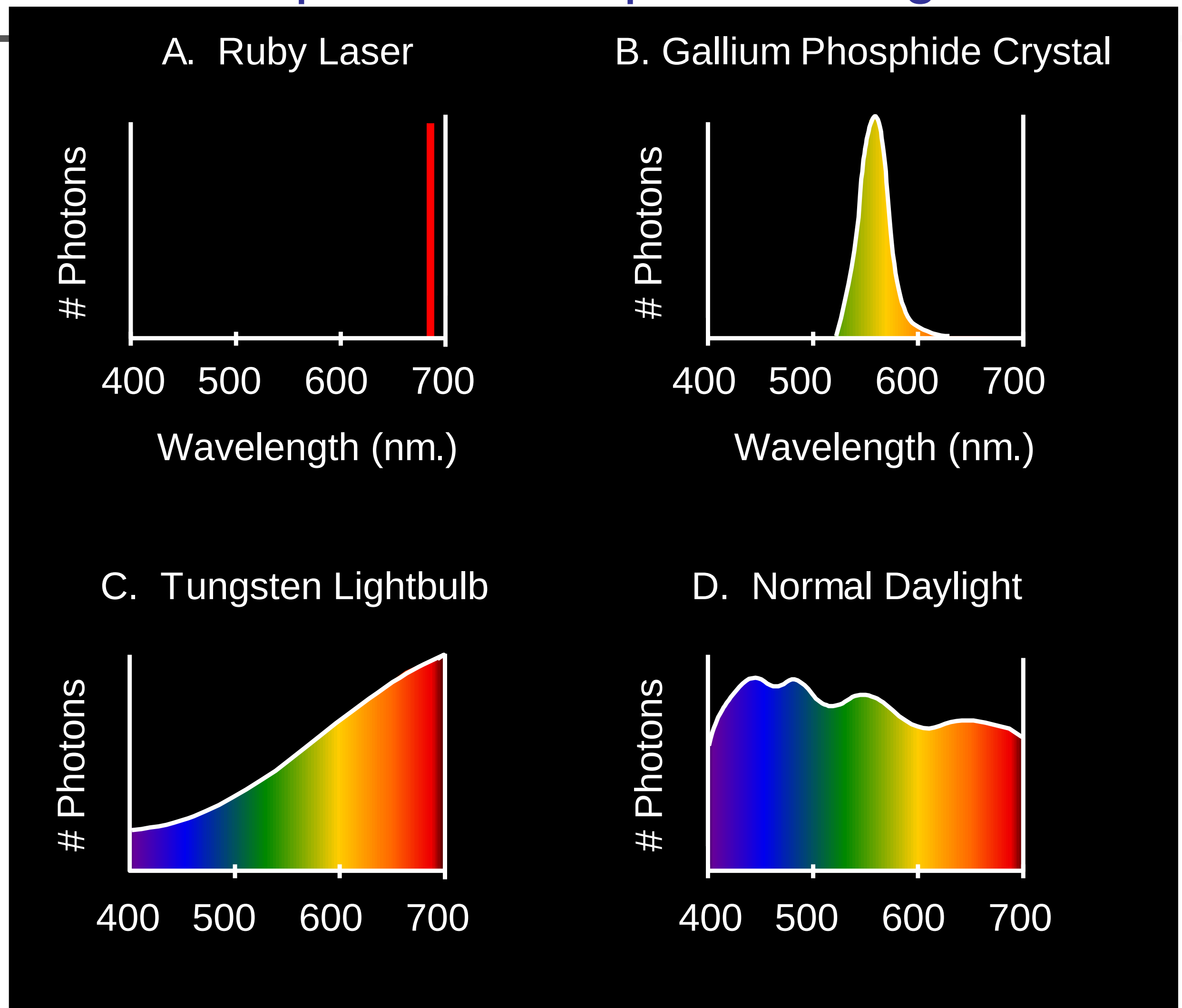
Energy density





The Physics of Light

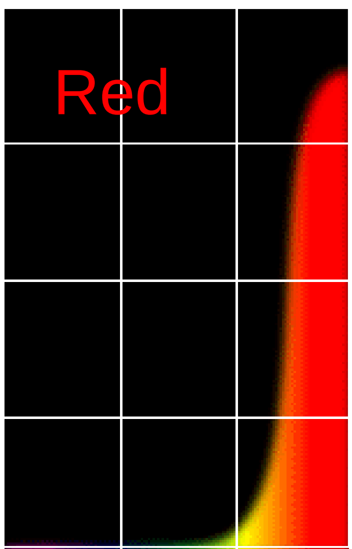
Some examples of the spectra of light sources

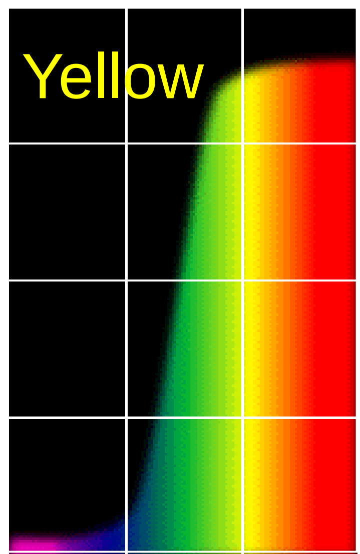


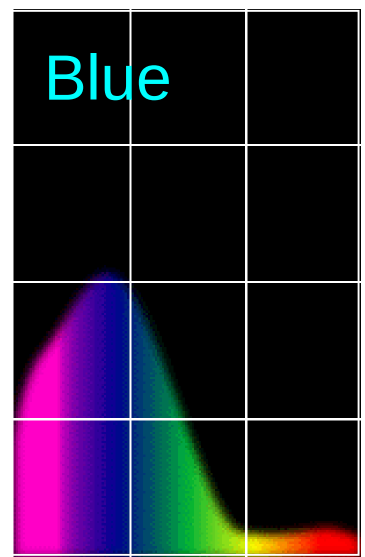
The Physics of Light

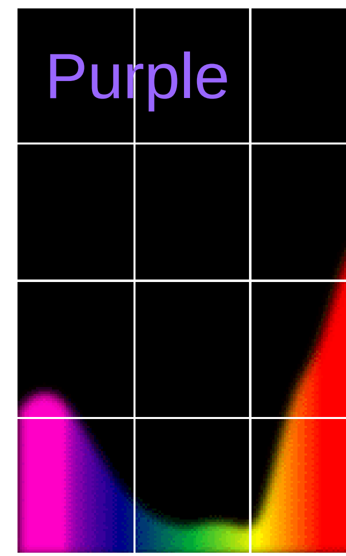
Some examples of the reflectance spectra of surfaces



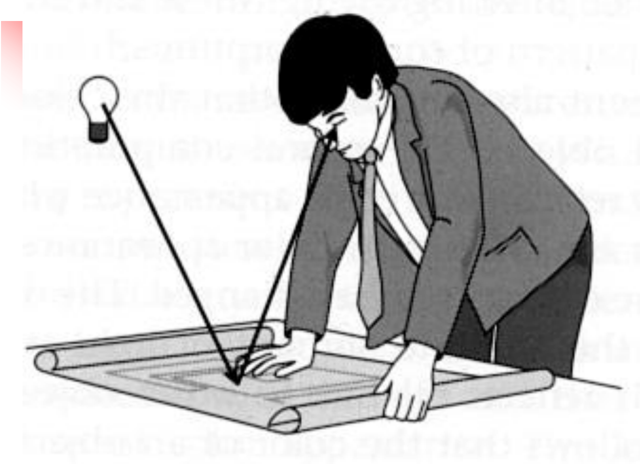





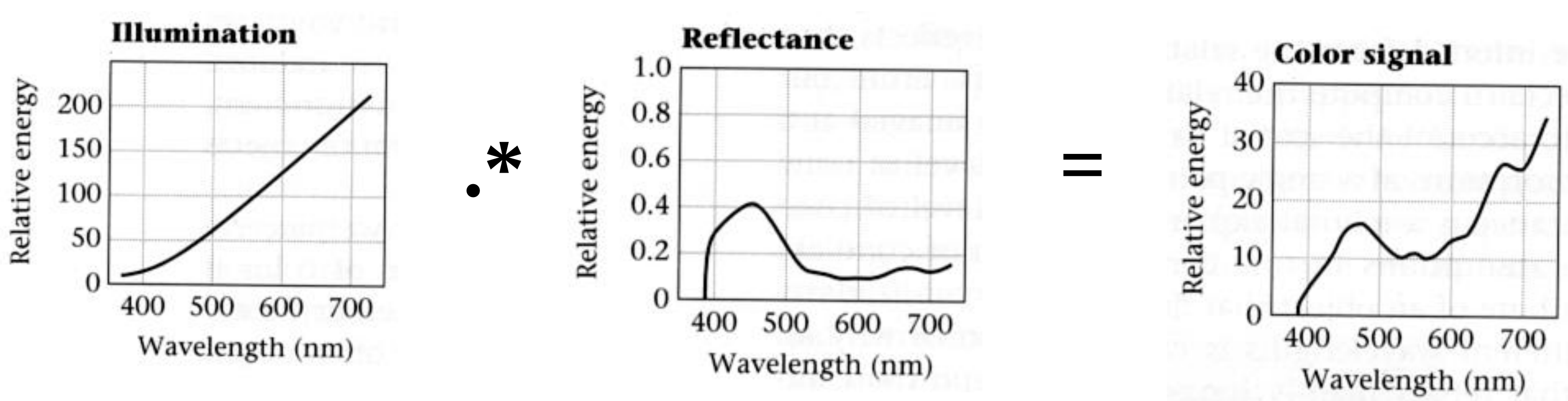




Simplified rendering models: reflectance



Often are more interested in relative spectral composition than in overall intensity, so the spectral BRDF computation simplifies a wavelength-by-wavelength multiplication of relative energies.



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

Light intensity and brightness

- *Intensity* describes the physical amount of energy, *brightness* describes our perception of this energy
- Our perception of light is function of our eyes, which performs numerous unconscious corrections and modifications. For example, the equal densities of colored light are perceived as being of different brightness depending on the color.

Intensity Perception

- *Achromatic light* is only characterized by intensity. We assume that intensity values are specified as a number from 0 to 1.
- Human eye is sensitive to the ratios of intensities, rather than the absolute differences.
  - So going from a 50 to 100 Watt light bulb looks the same as going from 100 to 200
  - So, if we only have 4 intensities, between 0 and 1, we should choose to use 0.125, 0.25, 0.5 and 1
- Given 8 bits to represent intensity, intensities should be chosen on *logarithmic* instead of linear scale to achieve *perceptual* uniformity.

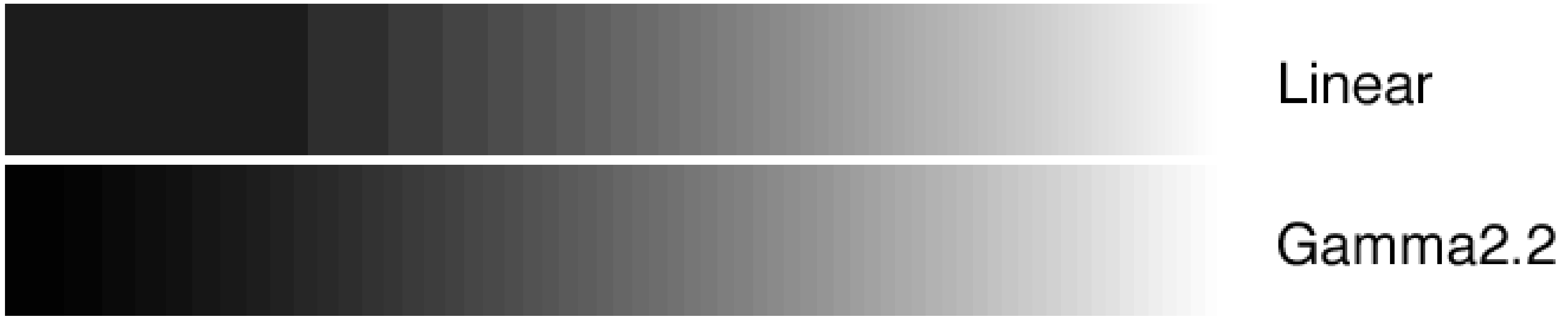
$$I_j = r^j I_0 = I_0^{(n-j)/n}$$

Gamma Correction

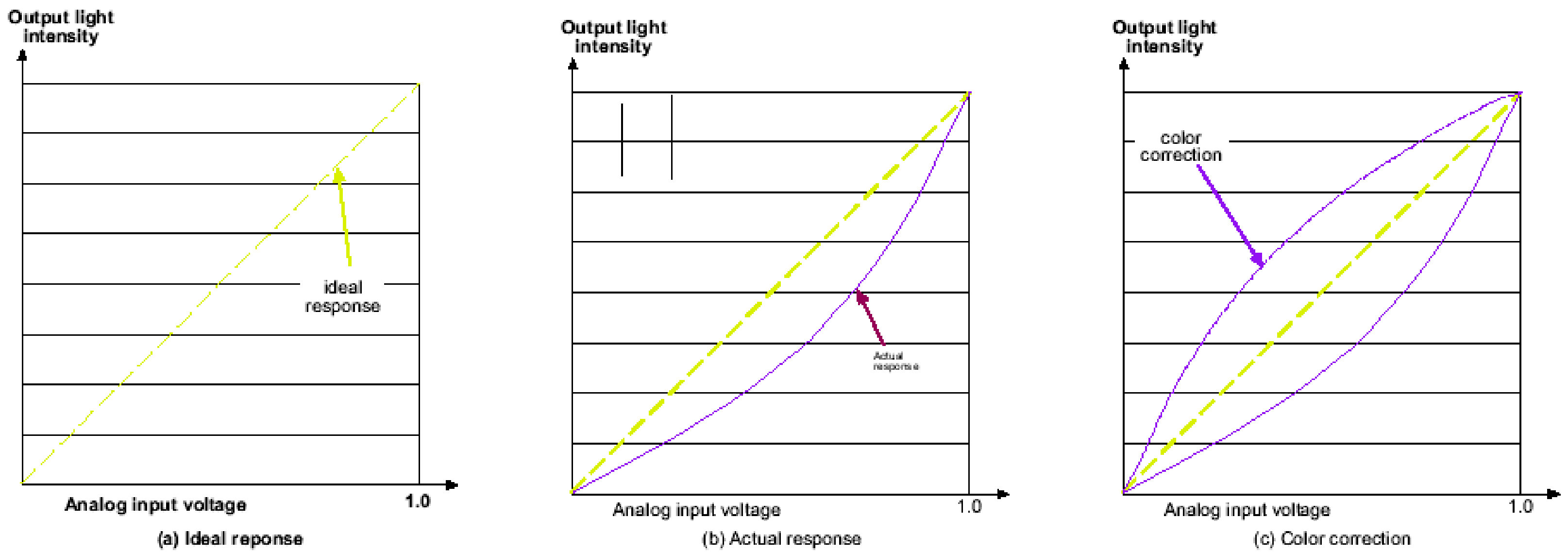
- When images are created, a *linear* mapping between pixels and intensity is assumed
  - For example, if you double the pixel value, the displayed intensity should double
- Monitors, however, do not work that way due to its nonlinearities.
- The outcome: A linear intensity scale in memory does not look linear on a monitor!
- Fix: gamma correction. A form of automatic correction such that a linear variation in the supplied intensity values generates a perceived linear variation in brightness

Gamma encoding

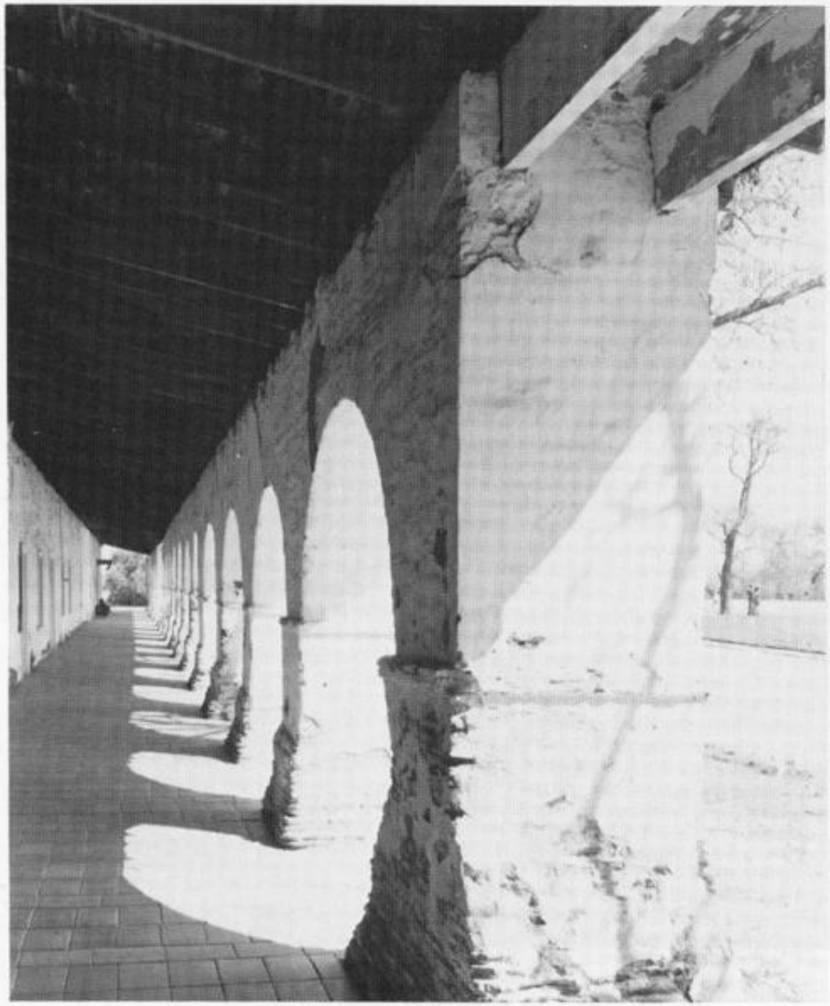
- From Greg Ward
- only 6 bits for emphasis



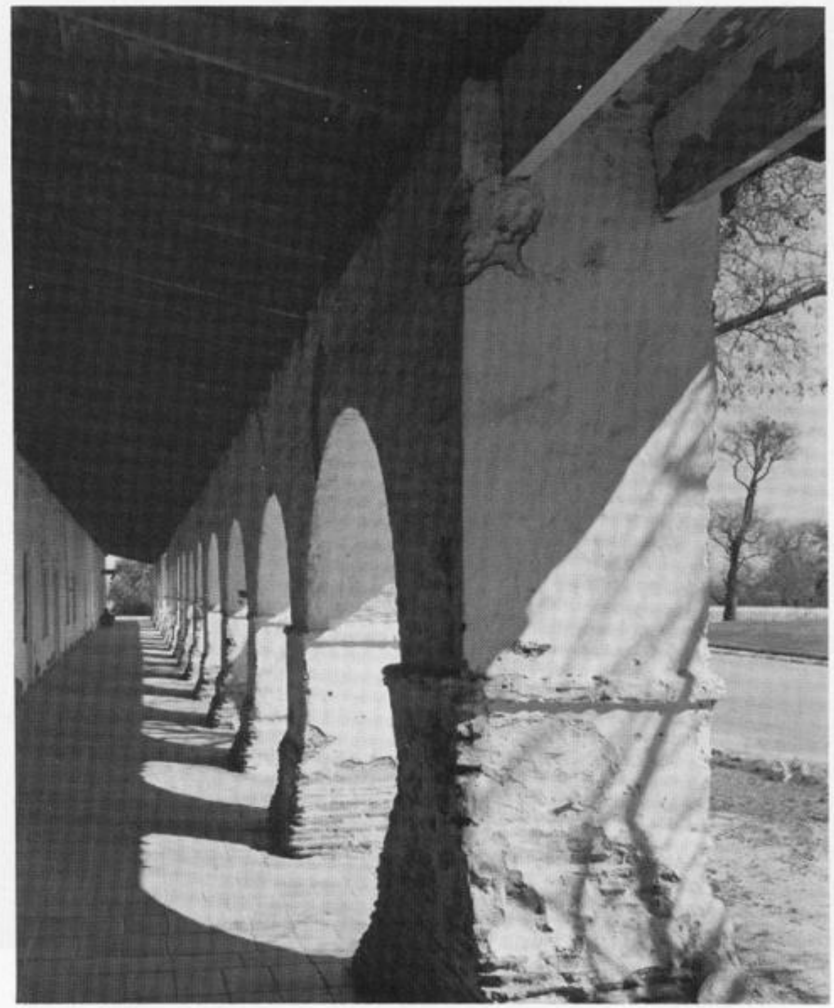
Gamma Correction



Perceptual effect



One development solution



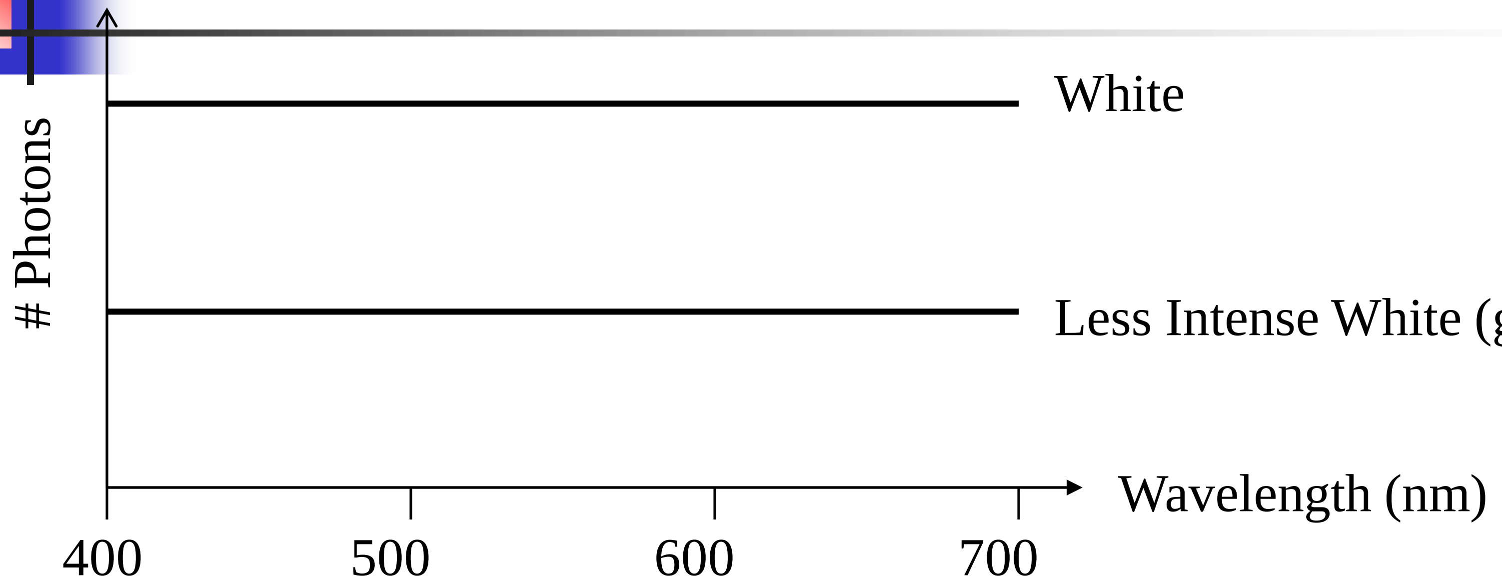
Two development solution:
the dark areas are the same,
but bright areas are different

Source: Ansel Adams

Light and Color

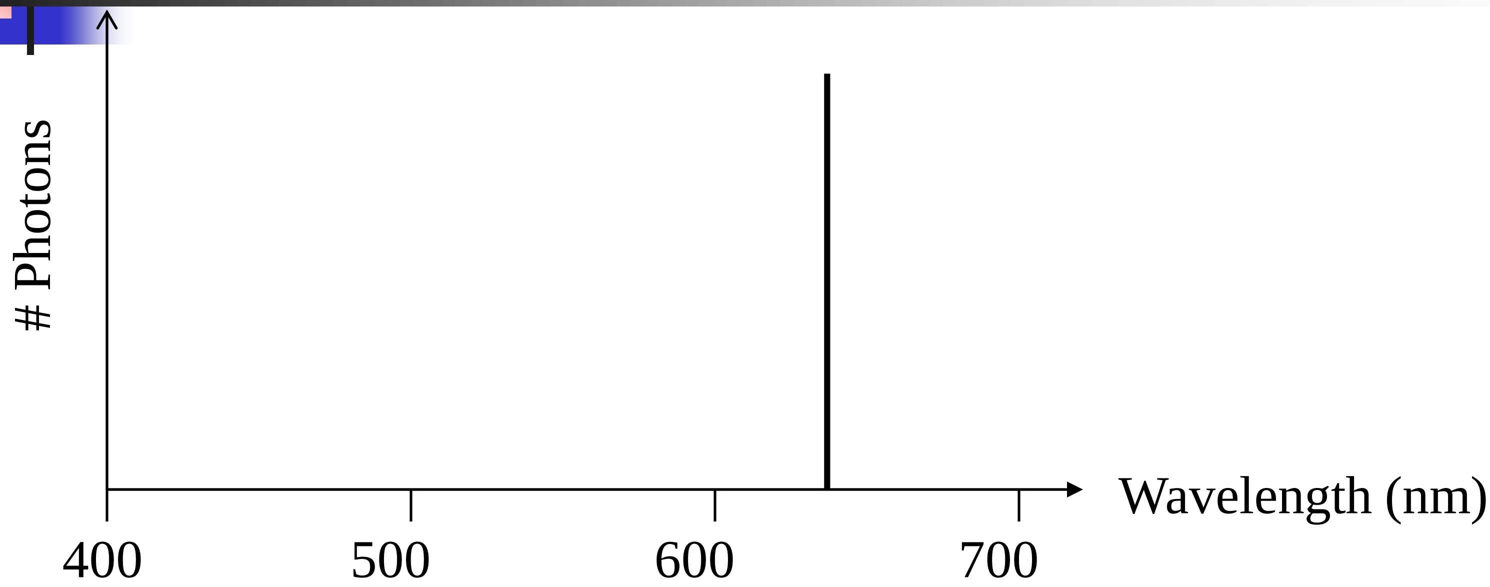
- The frequency of light determines its "color"
  - Frequency, wavelength, energy all related
- Describe incoming light by a *spectrum*
  - Intensity of light at each frequency
  - Just like a graph of intensity vs. frequency
- We care about wavelengths in the visible spectrum: between the infra-red (700nm) and the ultra-violet (400nm)

White



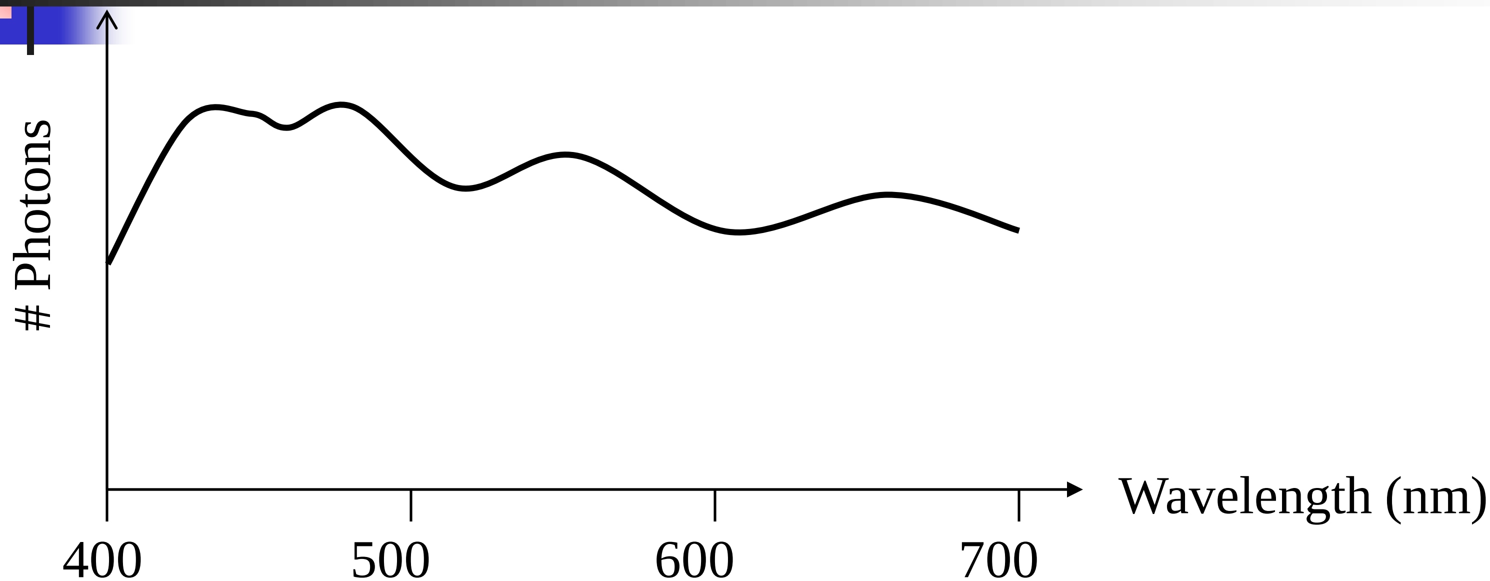
- Note that color and intensity are technically two different things
- However, in common usage we use color to refer to both
  - For example, dark red vs. light red
- You will have to use context to extract the meaning

Helium Neon Laser



- Lasers emit light at a single wavelength, hence they appear colored in a very “pure” way

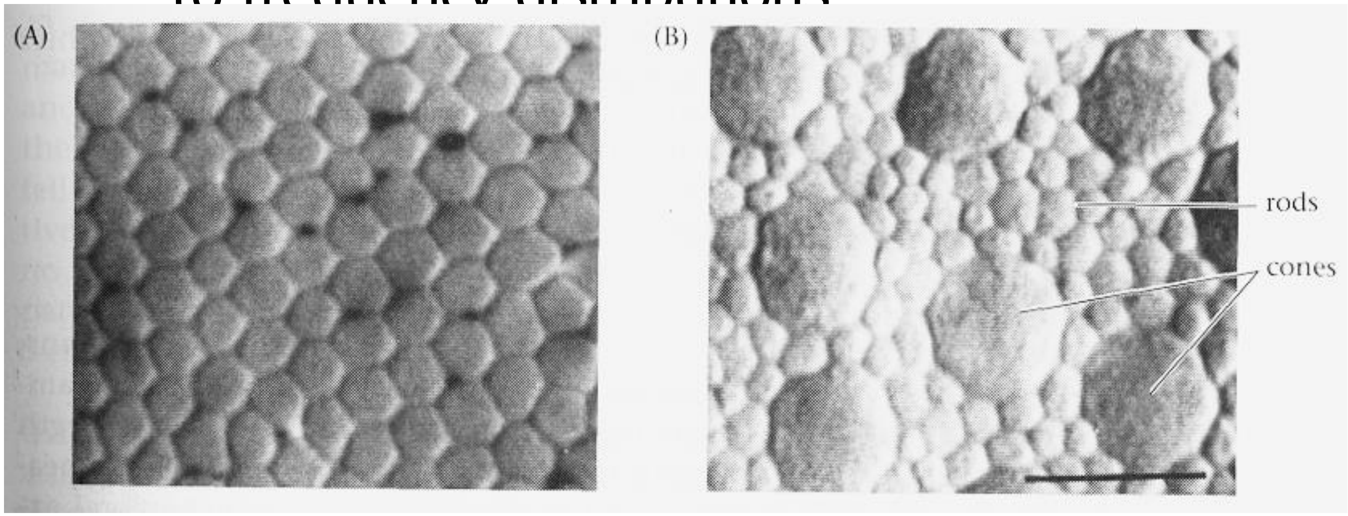
Normal Daylight



- Note the hump at short wavelengths - the sky is blue
- Other bumps came from solar emission spectra and atmospheric adsorption

Seeing in Color

- The eye contains *rods* and *cones*
  - Rods work at low light levels and do not see color
    - That is, their response depends only on how many photons, not their wavelength
  - Cones come in three types (experimentally and genetically proven), each responds in a different way to frequency distributions

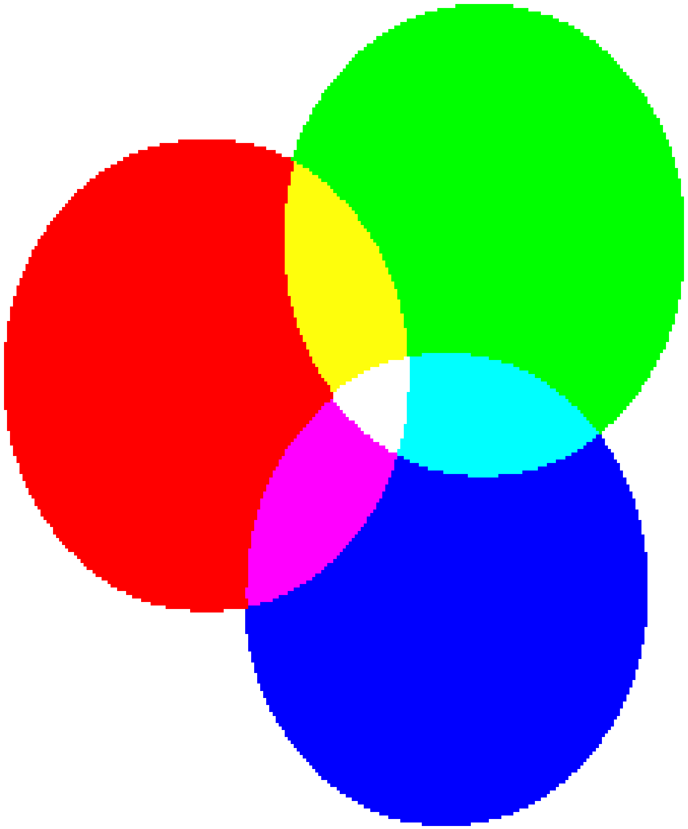


Color Perception

- How your brain interprets nerve impulses from your cones is an open area of study, and deeply mysterious
- Colors may be perceived differently:
  - Affected by other nearby colors
  - Affected by adaptation to previous views
  - Affected by “state of mind”
- Some people are missing one type of receptors (cones)
  - Most common is red-green color blindness in men
  - Red and green receptor genes are carried on the X chromosome - most red-green color blind men have two red genes or two green genes

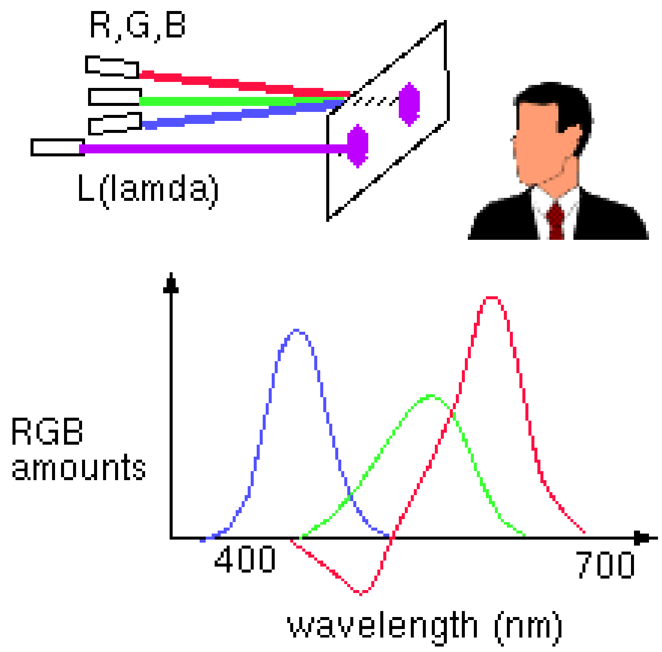
Trichromacy

- By experience, it is possible to match almost all colors using only three primary sources - *the principle of trichromacy*
- In practical terms, this means that if you show someone the right amount of each primary, they will perceive the right color
- This was how experimentalists knew there were 3 types of cones



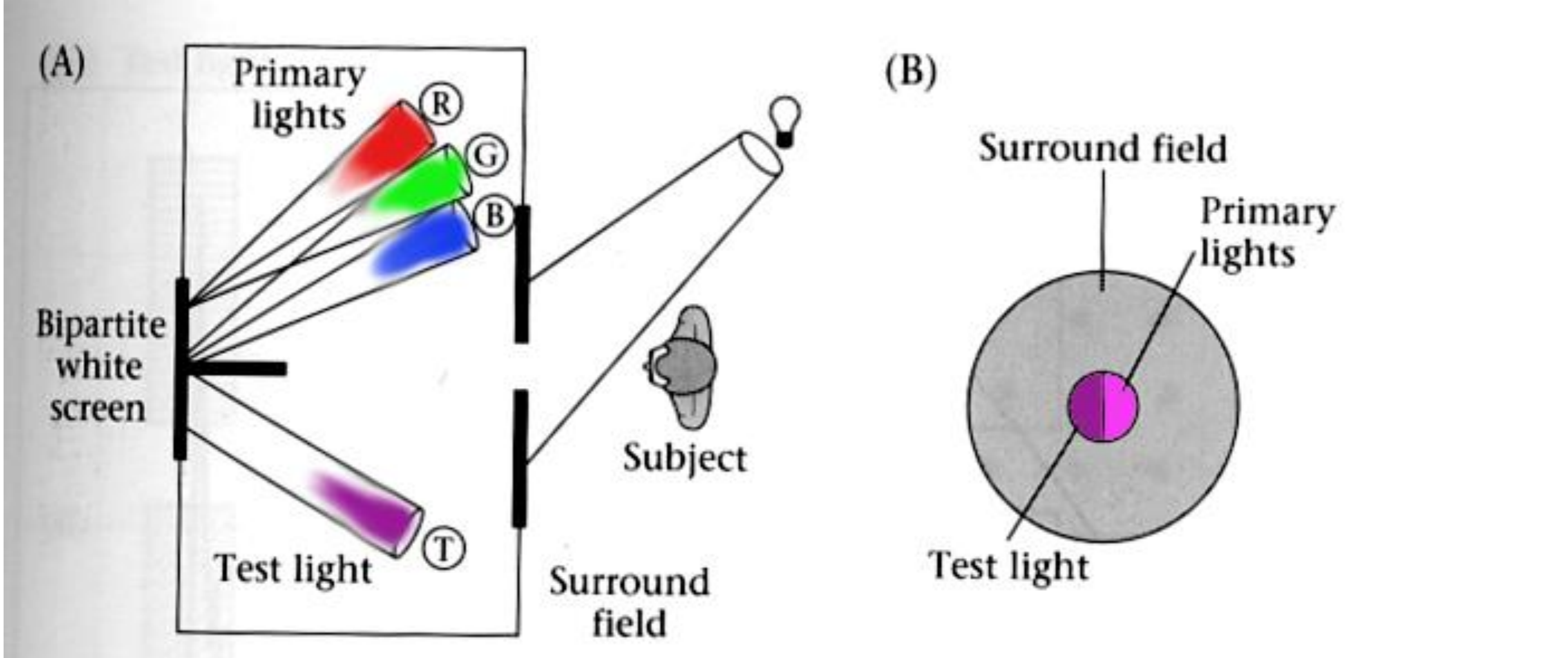
Color Matching

- Given a spectrum, how do we determine how much each of R, G and B to use to match it?
- First step:
  - For a light of unit intensity at each wavelength, ask people to match it with R, G and B primaries
  - Result is three functions, r(λ), g(λ) and b(λ), the RGB *color matching functions*



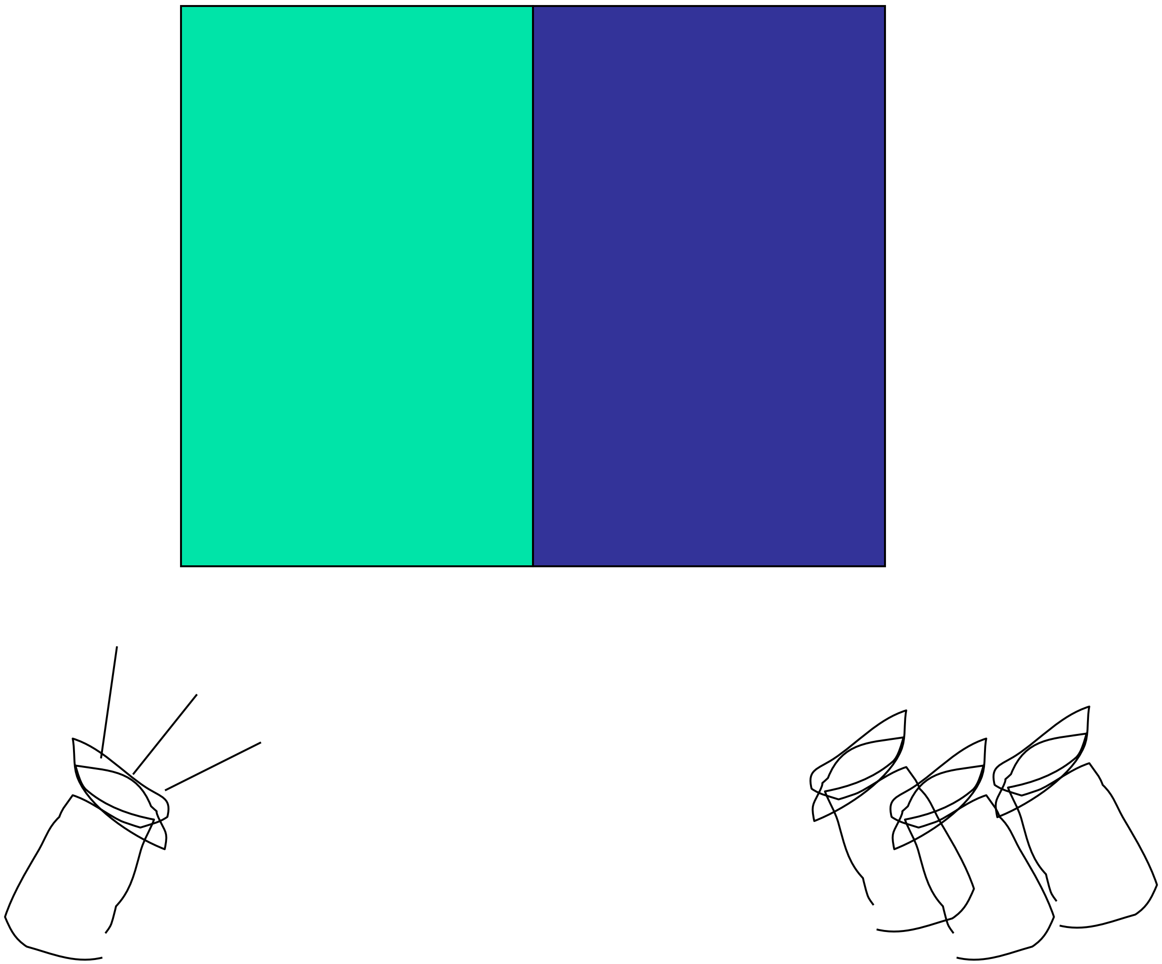
Color Matching

$$Q_\lambda = r(\lambda)R + g(\lambda)G + b(\lambda)B$$

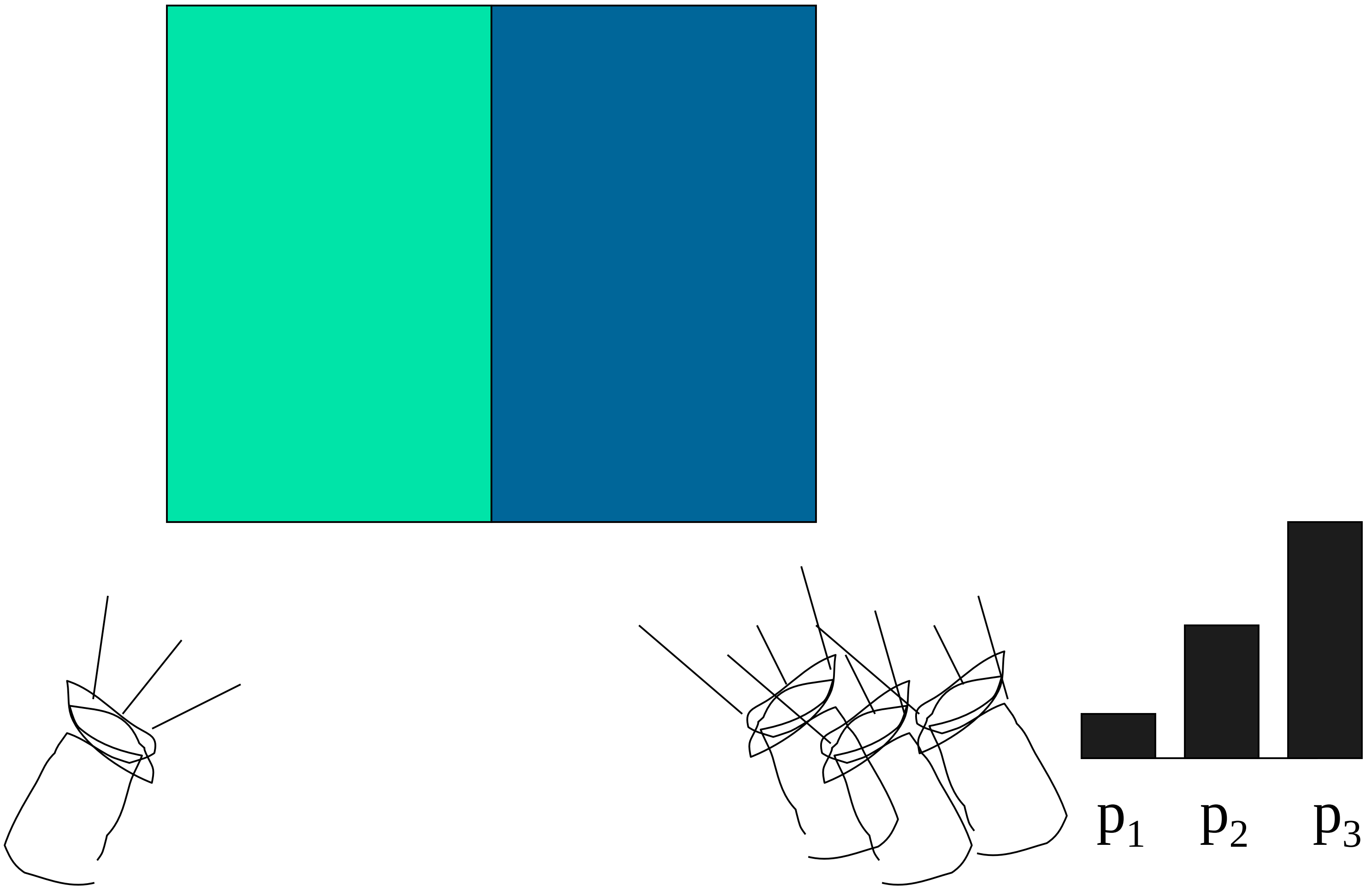


4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

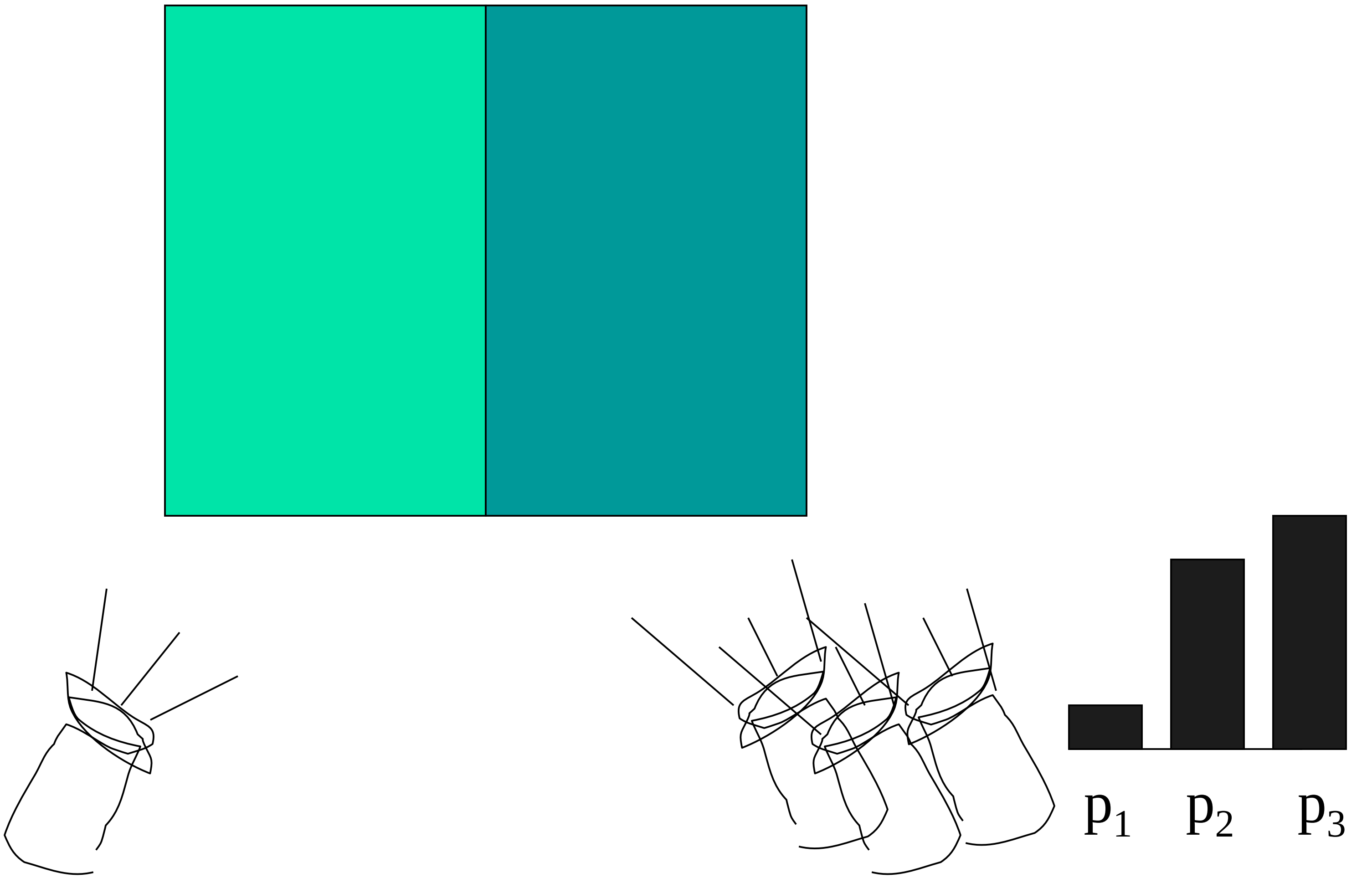
Color matching experiment 1



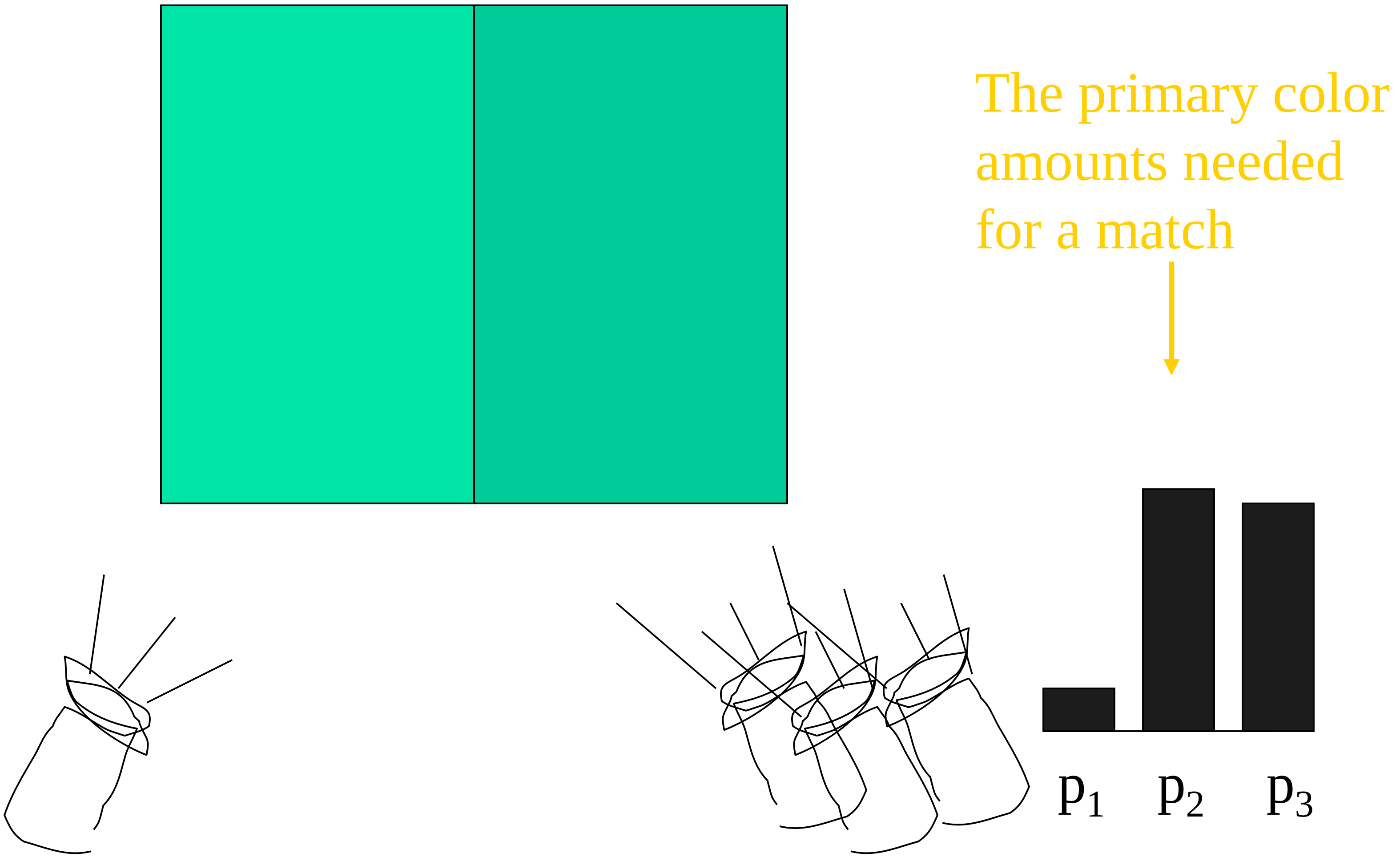
Color matching experiment 1



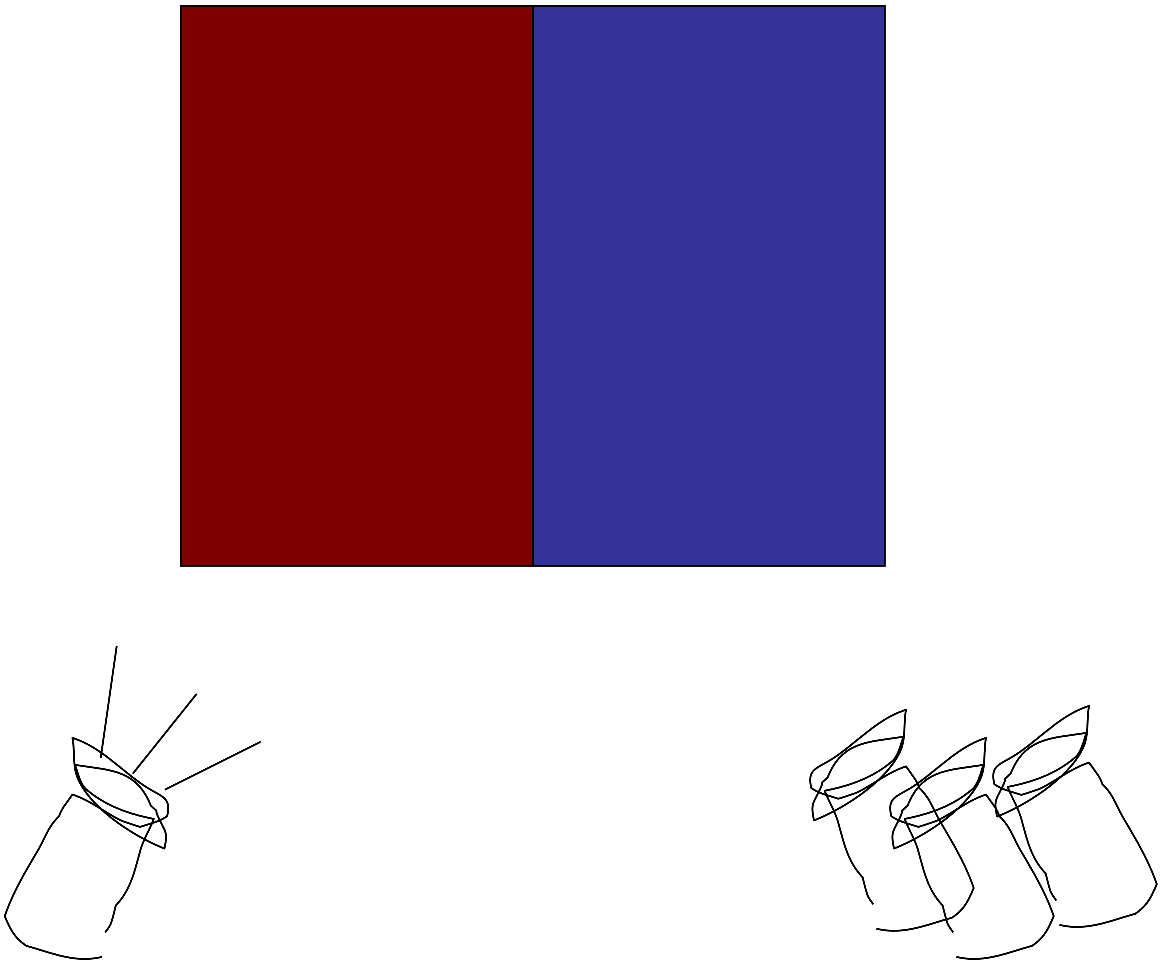
Color matching experiment 1



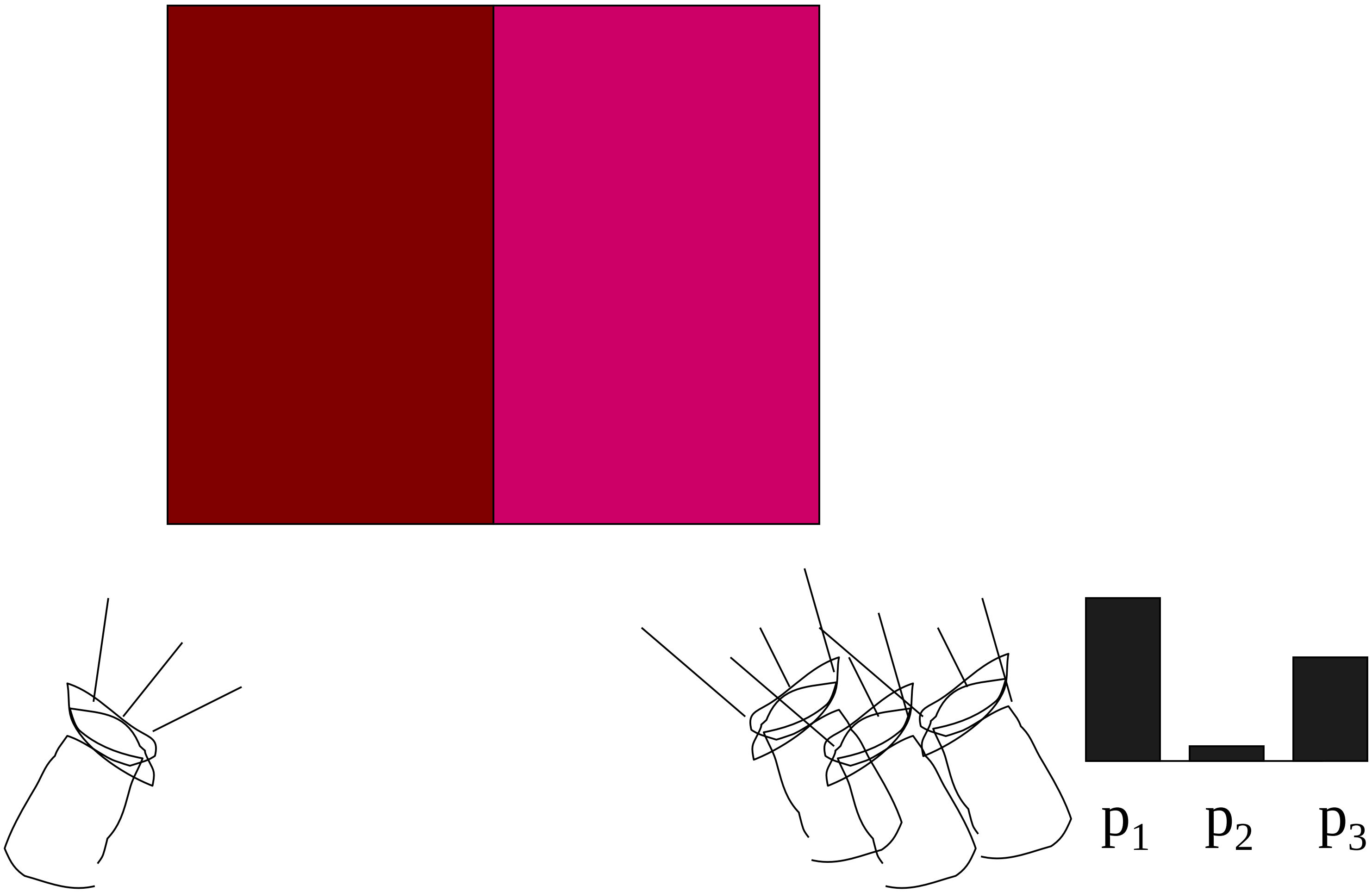
Color matching experiment 1



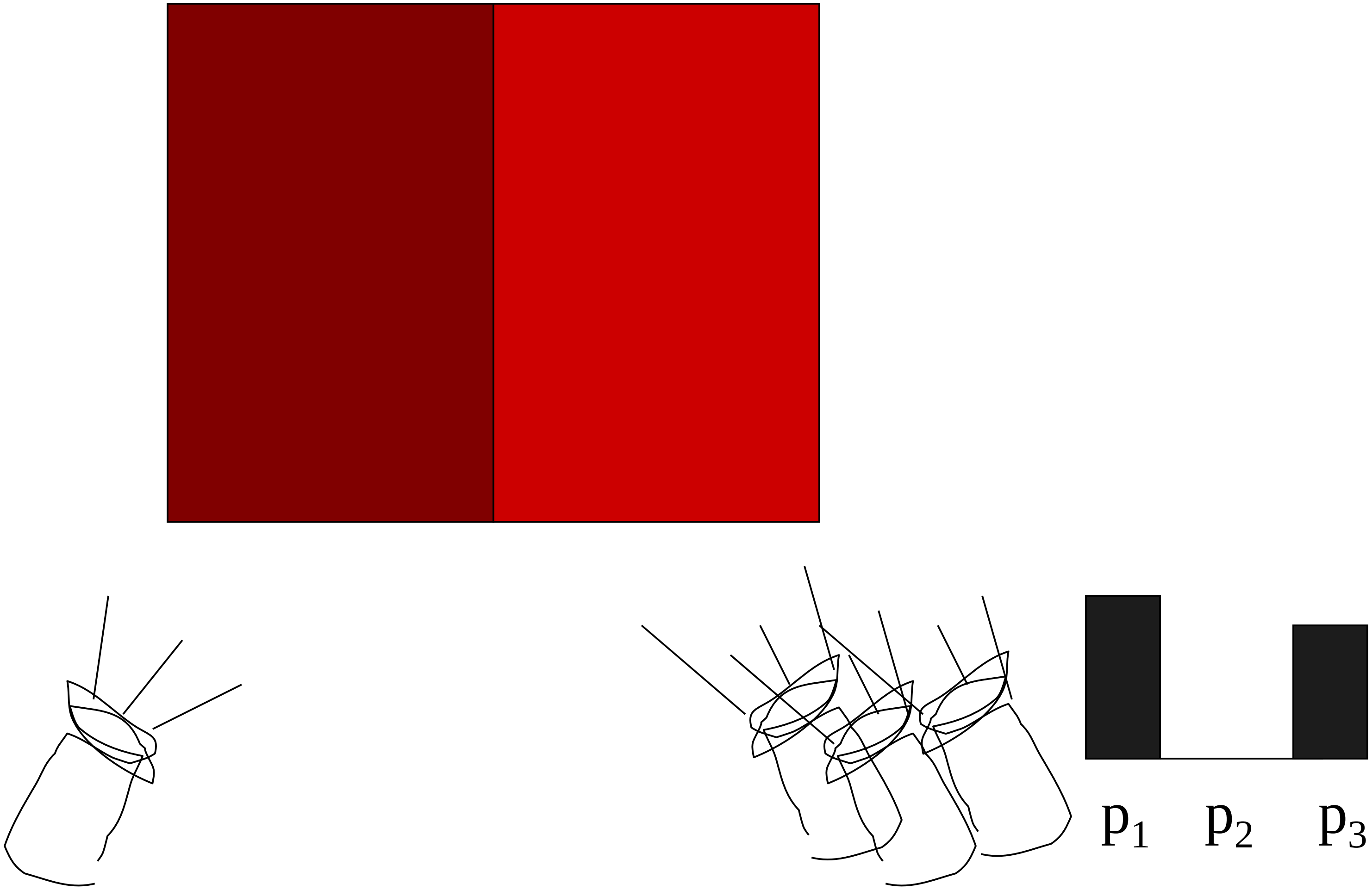
Color matching experiment 2



Color matching experiment 2

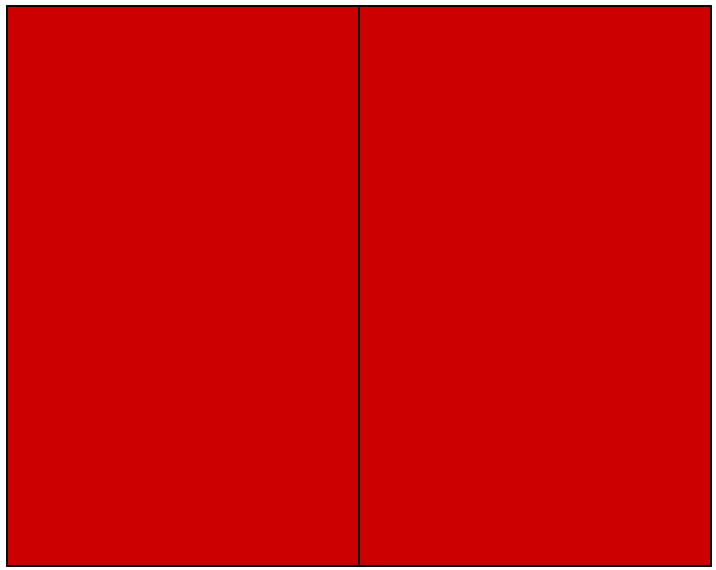


Color matching experiment 2

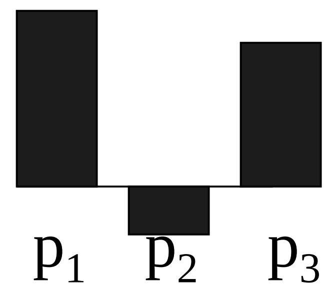


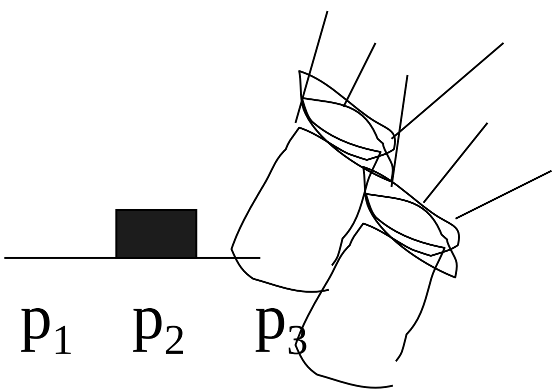
Color matching experiment 2

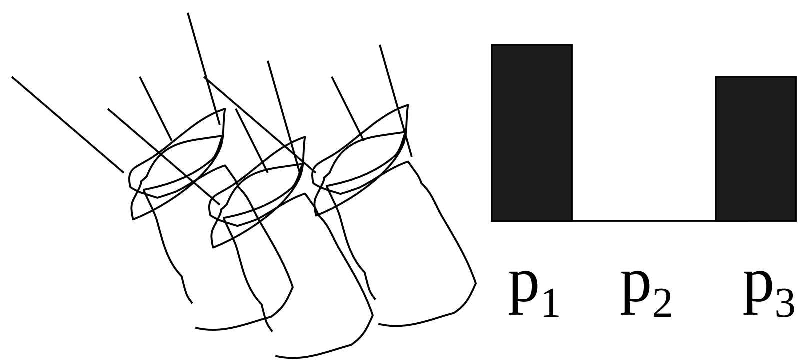
We say a “negative” amount of p_2 was needed to make the match, because we added it to the test color’s side.



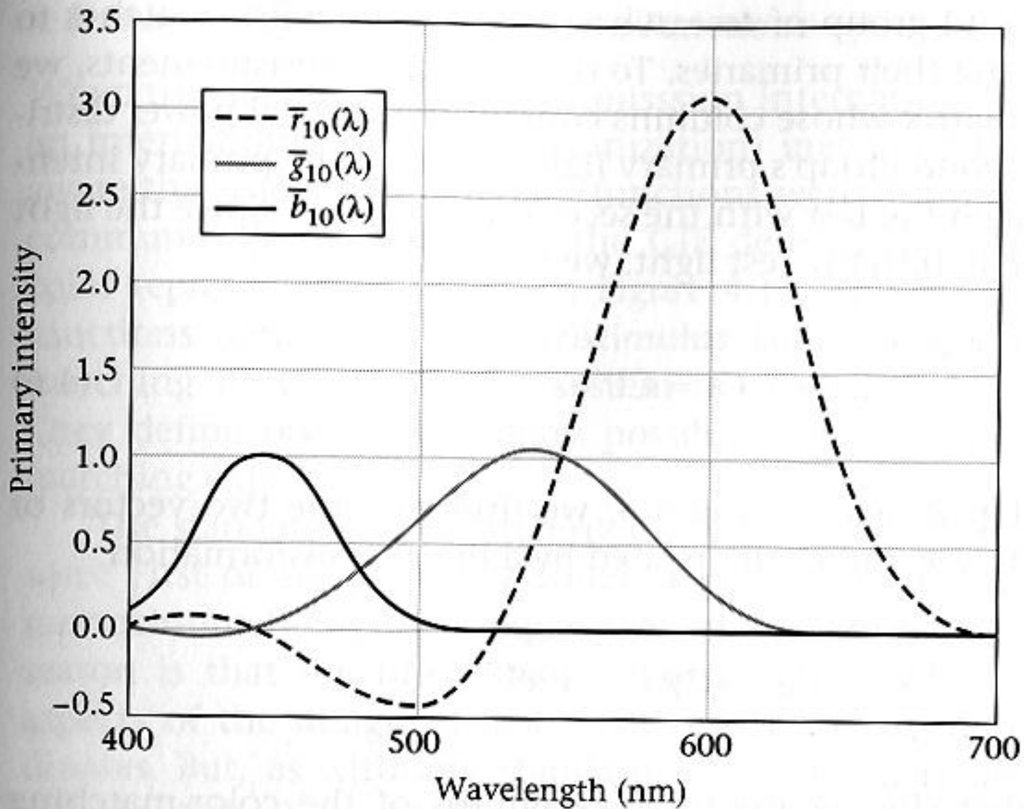
The primary color amounts needed for a match:







Color Matching Functions



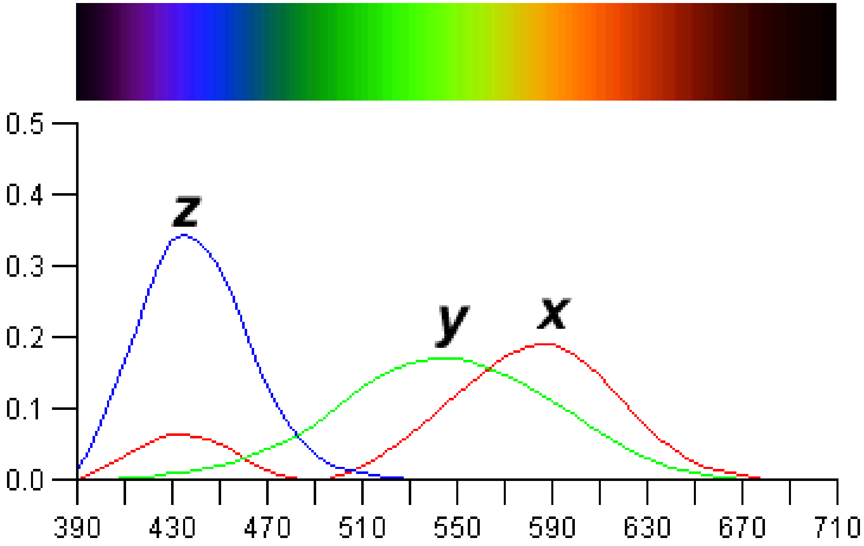
p_1 = 645.2 nm
p_2 = 525.3 nm
p_3 = 444.4 nm

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 $\bar{b}_{10}(\lambda)$.

test light wavelengths indicating that

CIE Color Space

In order to achieve a representation which uses only positive mixing coefficients, the CIE ("Commission Internationale d'Eclairage") defined three new hypothetical light sources, x, y, and z, which yield positive matching curves:



- Defined in 1931 to describe the full space of perceptible colors
  - Revisions now used by color professionals
  - Cannot produce the primaries – need negative light!

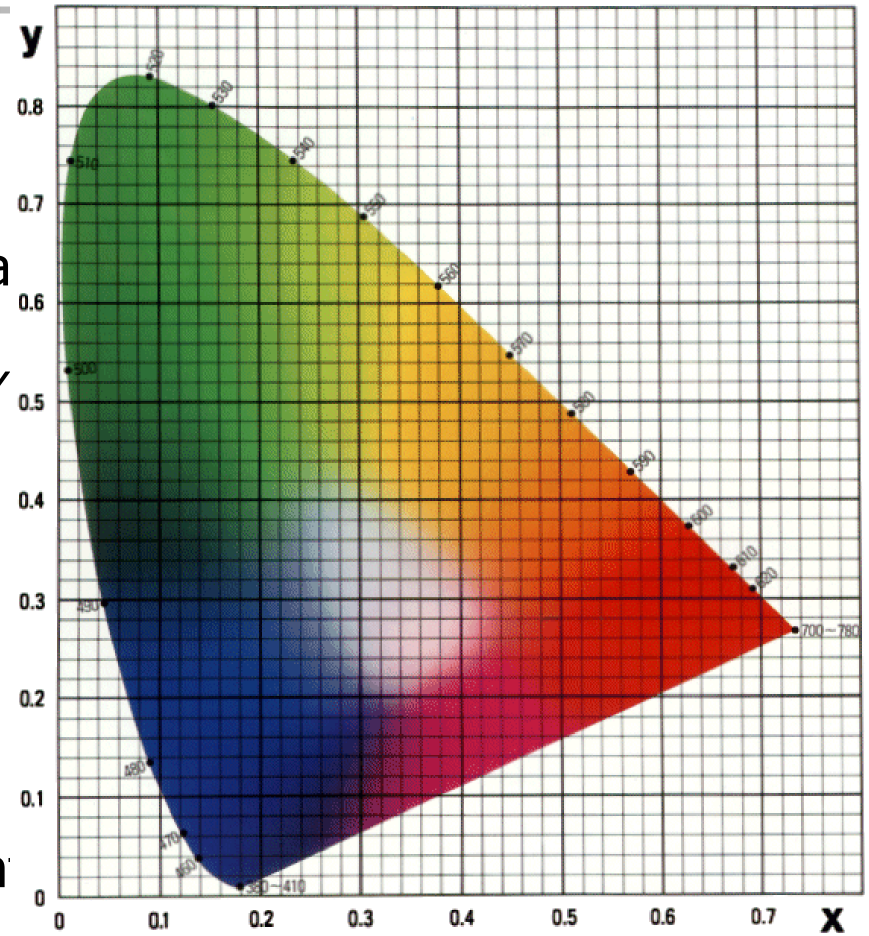
CIE Chromaticity Diagram

- Often it is convenient to work in a 2D color space. This is commonly done by projecting the 3D color spa onto the plane X+Y+Z=1, yielding a *CIE chromaticity diagram*. The projection is defined as:

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z}$$

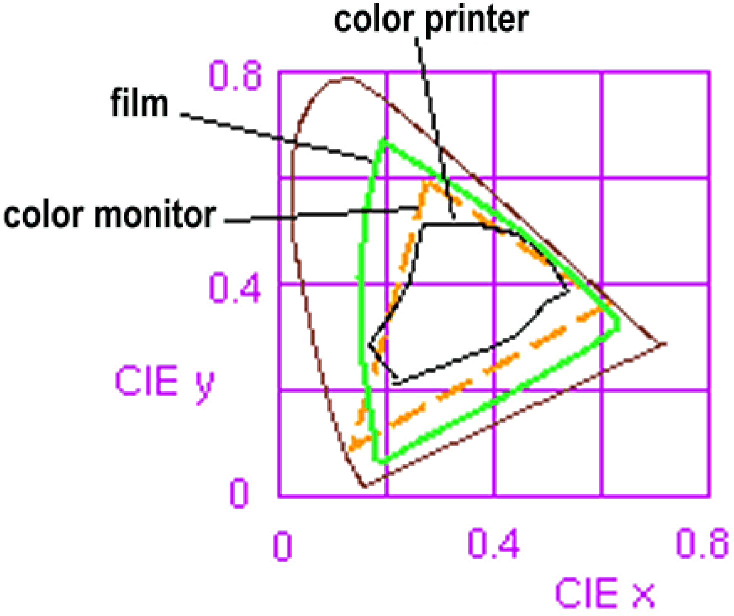
$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

Giving the chromaticity diagram shown on the righ



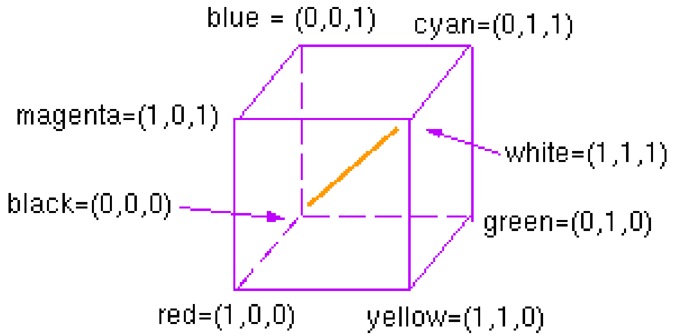
Color Gamuts

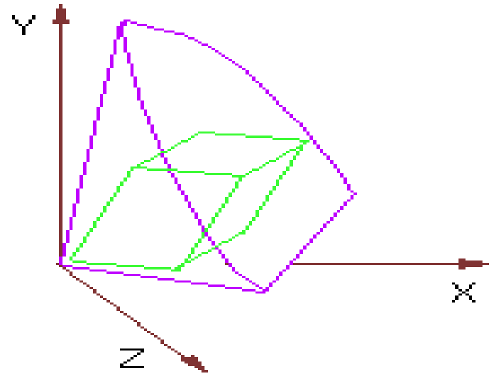
- Gamut: The range of colors that can be produced
- The chromaticity diagram can be used to compare the "gamuts" of various possible output devices (i.e., monitors and printers).
- Note that a color printer cannot reproduce all the colors visible on a color monitor.



The RGB Color Cube

- The additive RGB color model used for computer graphics forms a RGB color cube
- The RGB color cube sits within the CIE XYZ color space as right



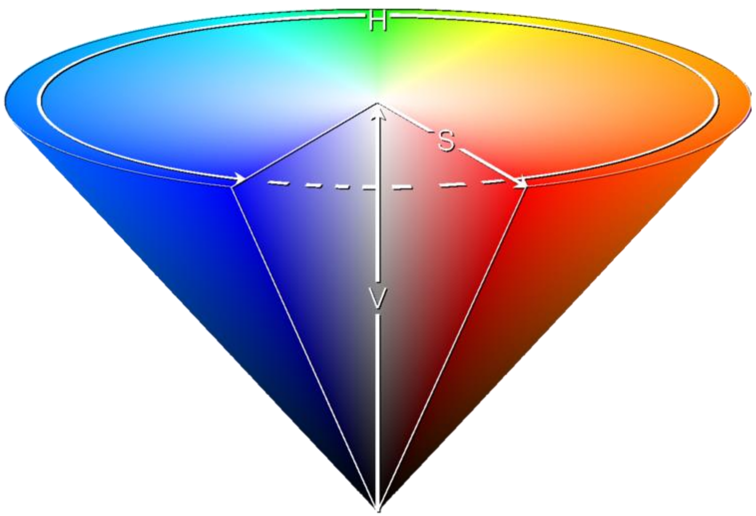


CMY Color Model

- Most printing devices use a subtractive system instead of the RGB additive color system.
- Subtractive primaries are cyan, magenta, and yellow. This color system is then call CMY color model.
- It is easy to convert from RGB to CMY
  - `(C, M, Y) = (1-R, 1-G, 1-B)`
- In the CMY model, black is (1,1, 1) and white is (0, 0, 0)

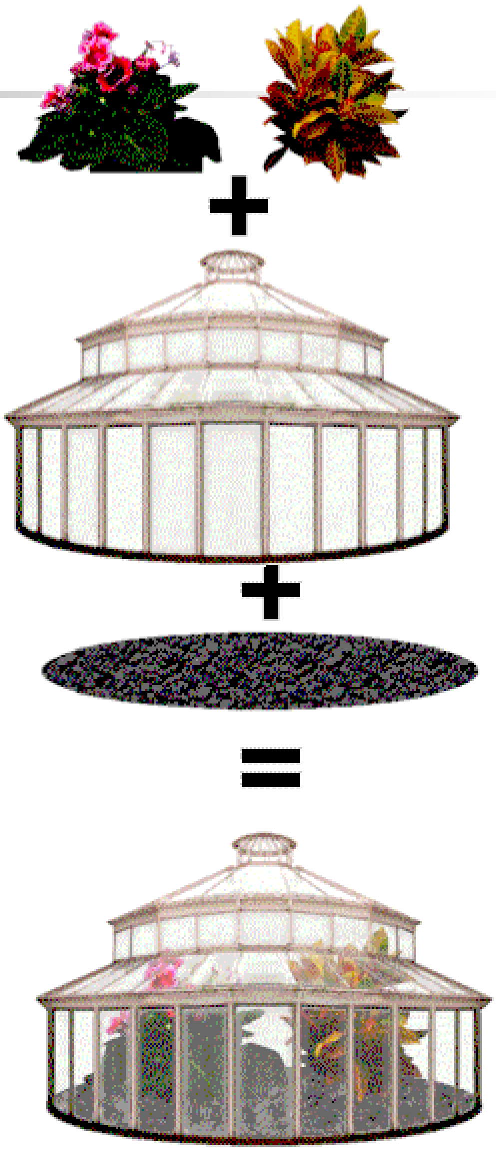
HSV Color Space (Alvy Ray Smith, 1978)

- Hue: the color family: red, yellow, blue…
- Saturation: The purity of a color: white is totally unsaturated
- Value: The intensity of a color: white is intense, black isn't
- Space looks like a cone
  - Parts of the cone can be mapped to RGB space
- Not a linear space, so no linear transform to take RGB to HSV
  - But there is an algorithmic transform

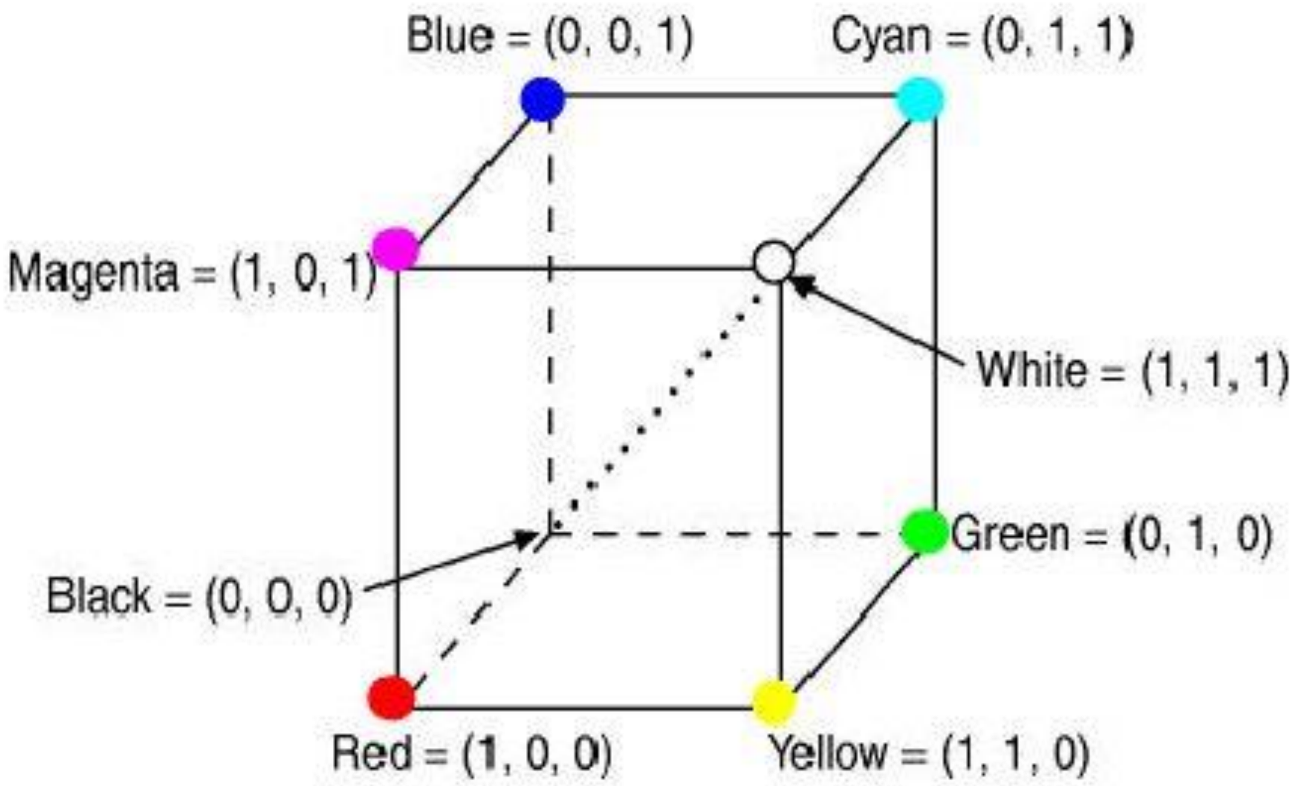


Alpha Blending

- Alpha blending simulates the *effect of transparency*
- Adds one channel to each pixel [r, g, b, α]
- Usually process layers back-to-front (using the *over* operator)
- 255 or 1.0 indicates an opaque pixel
- 0 indicates a transparent pixel
- Result is a function of foregroud and background pixel colors



RGB Color Model



Color depth

Color depth	**Number of colors**
1 bit	2
4 bits	16
8 bits	256
16 bits	35565
24 bits	16777216

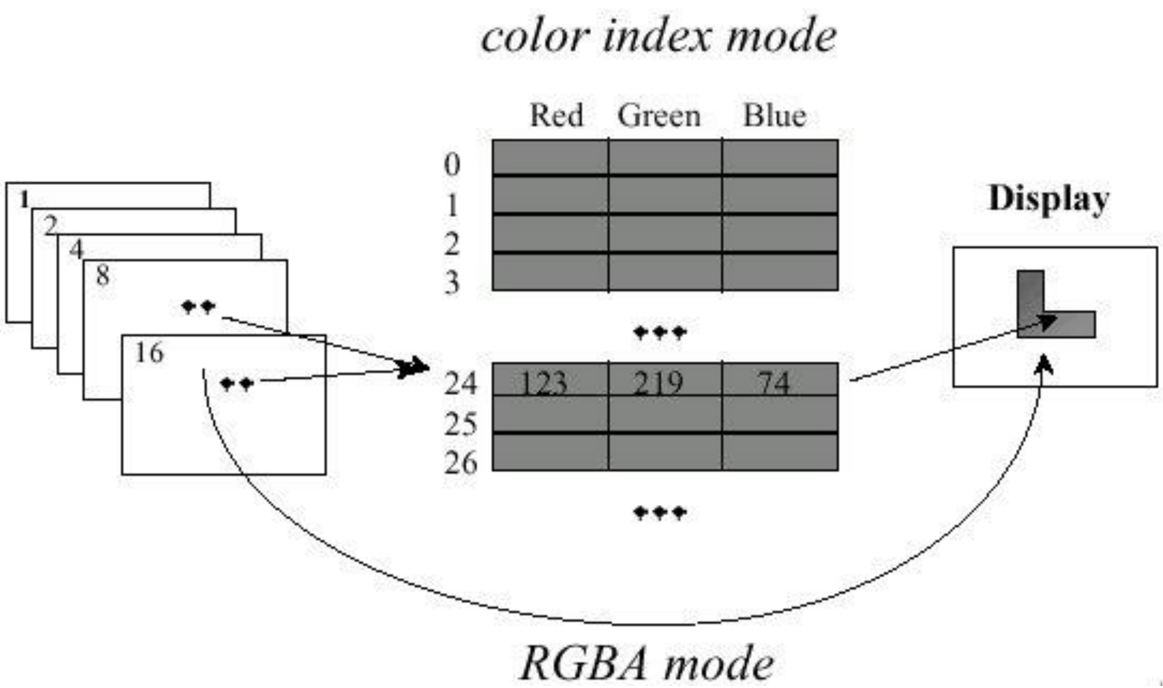
OpenGL Color Models

- RGBA colors
  - Separate channel for each color primitive
  - Additional channel for transparency

$$0 \le \alpha \le 1$$

  - 8bit, 15/16bit, 24bit, and 32bit color
- Indexed color
  - Color lookup table

OpenGL Color Models



- glColor*()
- glIndex*()

- glutInitDisplayMode()
- GLUT_RGBA
- GLUT_INDEX