Color

Reading

- Foley, Chapter 13.

Further reading:

- Brian Wandell. *Foundations of Vision*. *Chapter 4*. Sinauer Associates, Sunderland, MA, 1995.
- Gerald S. Wasserman. *Color Vision: An Historical Introduction*. John Wiley & Sons, New York, 1978

Outline

•Spectrum and color

•Measuring color

•The CIE XYZ color space

•Color spaces for computer graphics

What is Color?

The eyes and brain turn an incoming emission spectrum into a discrete set of values.

The signal sent to our brain is somehow interpreted as *color*.

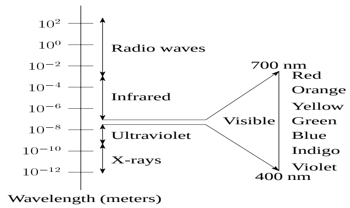
Color science asks some basic questions:

- When are two colors alike?
- How many pigments or primaries does it take to match another color?

One more question: why should we care?

Light as Waves

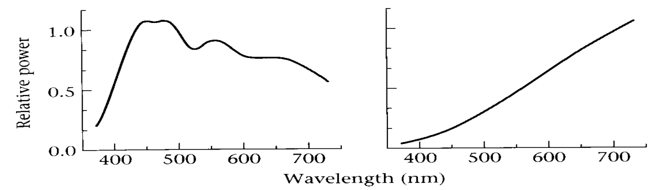
Maxwell described the *electromagnetic spectrum* and showed that visible light was just part of the spectrum.



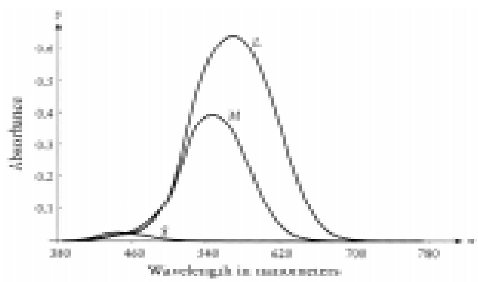
Light as Particles

At any given moment, a light source emits some relative amount of photons at each frequency.

We can plot the *emission spectrum* of a light source as power vs. wavelength.



Cones



- Cones come in three varieties: S, M, and L.

Transmitting color

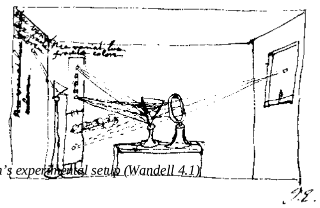
Color information is transmitted to the brain in three nerve bundles or **channels**:

- **Achromatic channel** A = M + L
- **Red-green chromatic channel** R/G = M - L
- **Blue-yellow chromatic channel** B/Y = S - A

Saturation is perceived as the ratio of chromatic to achromatic response.

Newton's Experiments

Newton was the first to perform a scientific experiment on color in 1666.



Newton's experimental setup (Wandell 4.1)

He built a simple colorimeter:

- Hole in a shutter
- Prism to disperse white light into a spectrum
- Comb-shaped aperture to manipulate the spectrum
- Converging lens to recombine the spectrum

Newton's Experiments, cont'd

Newton defined two types of light:

- **Simple**: Light that cannot be furthered dispersed by a prism (now called **monochromatic**)
- **Compound**: Light that can be dispersed.

He called the colors of simple lights **primaries**.

[This term means many things today.]

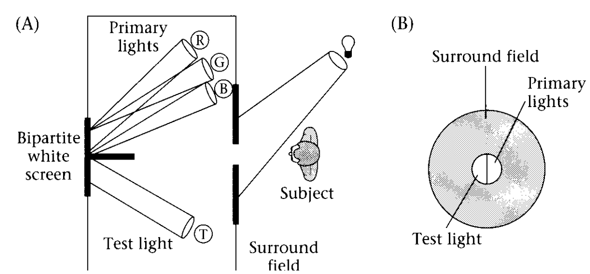
Color Matching

Conjecture: every color can be uniquely expressed as a mixing of a small number of *primaries*. (Why is this plausible?)

If true, this gives us a meaningful definition of color as a set of primaries and the range of possible combinations between them.

Given a choice of primaries, how can we verify the conjecture?

The Color Matching Experiment



Rods and "color matching"

A rod responds to a spectrum through its spectral sensitivity function, *r(λ)*. The response to a test light, *t(λ)*, is simply:

$$R = \int r(\lambda) t(\lambda) d\lambda$$

For convenience, we can also write this as:

$$R = \sum_i r(\lambda_i) t(\lambda_i)$$

If we consider only the visible wavelengths, then we can think of the *r* and *t* samples as defining vectors, leading to a simple matrix equation:

$$[R] = \begin{bmatrix} & \mathbf{r}^{\mathbf{T}} & \end{bmatrix} \begin{bmatrix} \\ \mathbf{t} \\ \\ \end{bmatrix}$$

What does this tell us about rod color discrimination?

Cones and color matching

Color is perceived through the responses of the cones to light.

The response of each cone can be written simply as:

$$L_t = \int l(\lambda) t(\lambda) d\lambda$$

$$M_t = \int m(\lambda) t(\lambda) d\lambda$$

$$S_t = \int s(\lambda) t(\lambda) d\lambda$$

We can also use matrix notation, which will prove useful in a moment:

$$\begin{bmatrix} L_t \\ M_t \\ S_t \end{bmatrix} = \begin{bmatrix} & \mathbf{l}^{\mathbf{T}} & \\ & \mathbf{m}^{\mathbf{T}} & \\ & \mathbf{s}^{\mathbf{T}} & \end{bmatrix} \begin{bmatrix} \\ \mathbf{t} \\ \\ \end{bmatrix}$$

How many primaries do you think we'll need to match *t*?

Color matching

Let's assume that we need 3 primaries to perform the color matching experiment.

Consider three primaries, $\mathbf{p_1}$, $\mathbf{p_2}$, $\mathbf{p_3}$, with three emissive power knobs, e_1, e_2, e_3.

The three knobs create spectra of the form:

$$e_1\mathbf{p}_1 + e_2\mathbf{p}_2 + e_3\mathbf{p}_3$$

How do we set the knobs to match the test spectrum, **t**?

Color matching, cont'd

First, we compute the response to the primaries:

$$\begin{bmatrix} L_p \\ M_p \\ S_p \end{bmatrix} = \begin{bmatrix} & \mathbf{l}^{\mathbf{T}} & \\ & \mathbf{m}^{\mathbf{T}} & \\ & \mathbf{s}^{\mathbf{T}} & \end{bmatrix} \begin{bmatrix} e_1\mathbf{p}_1 + e_2\mathbf{p}_2 + e_3\mathbf{p}_3 \end{bmatrix}$$

$$= \begin{bmatrix} & \mathbf{l}^{\mathbf{T}} & \\ & \mathbf{m}^{\mathbf{T}} & \\ & \mathbf{s}^{\mathbf{T}} & \end{bmatrix} \begin{bmatrix} \mathbf{p}_1 & \mathbf{p}_2 & \mathbf{p}_3 \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}$$

$$= \begin{bmatrix} \mathbf{l}\cdot\mathbf{p}_1 & \mathbf{l}\cdot\mathbf{p}_2 & \mathbf{l}\cdot\mathbf{p}_3 \\ \mathbf{m}\cdot\mathbf{p}_1 & \mathbf{m}\cdot\mathbf{p}_2 & \mathbf{m}\cdot\mathbf{p}_3 \\ \mathbf{s}\cdot\mathbf{p}_1 & \mathbf{s}\cdot\mathbf{p}_2 & \mathbf{s}\cdot\mathbf{p}_3 \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}$$

Color matching, cont'd

In order for the primaries to match the test, we require the cone responses to be identical:

$$\begin{bmatrix} L_t \\ M_t \\ S_t \end{bmatrix} = \begin{bmatrix} \mathbf{l}^{\mathbf{T}} \\ \mathbf{m}^{\mathbf{T}} \\ \mathbf{s}^{\mathbf{T}} \end{bmatrix} \begin{bmatrix} \mathbf{t} \end{bmatrix} = \begin{bmatrix} L_p \\ M_p \\ S_p \end{bmatrix}$$

This gives us:

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \mathbf{l}\cdot\mathbf{p}_1 & \mathbf{l}\cdot\mathbf{p}_2 & \mathbf{l}\cdot\mathbf{p}_3 \\ \mathbf{m}\cdot\mathbf{p}_1 & \mathbf{m}\cdot\mathbf{p}_2 & \mathbf{m}\cdot\mathbf{p}_3 \\ \mathbf{s}\cdot\mathbf{p}_1 & \mathbf{s}\cdot\mathbf{p}_2 & \mathbf{s}\cdot\mathbf{p}_3 \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{l}^{\mathbf{T}} \\ \mathbf{m}^{\mathbf{T}} \\ \mathbf{s}^{\mathbf{T}} \end{bmatrix} \begin{bmatrix} \mathbf{t} \end{bmatrix}$$

And finally:

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \overline{\mathbf{p}}_1^{\,T} \\ \overline{\mathbf{p}}_2^{\,T} \\ \overline{\mathbf{p}}_3^{\,T} \end{bmatrix} \begin{bmatrix} \mathbf{t} \end{bmatrix}$$

Color matching, cont'd

Key observations:

1. Three primaries are "sufficient" for color matching.
2. We can compute the knob settings using three vectors (functions). These are called the **color matching functions**.
3. Color matching functions are linear transforms of the cone responses.
4. All sets of color matching functions are linear transforms of each other.
5. The resulting knob settings can take on negative values.

Negative light

What does it mean to use a negative amount of a primary?

Consider:

$$\begin{bmatrix} \mathbf{l}^{\mathbf{T}} \\ \mathbf{m}^{\mathbf{T}} \\ \mathbf{s}^{\mathbf{T}} \end{bmatrix} \begin{bmatrix} \mathbf{t} \end{bmatrix} = \begin{bmatrix} \mathbf{l}^{\mathbf{T}} \\ \mathbf{m}^{\mathbf{T}} \\ \mathbf{s}^{\mathbf{T}} \end{bmatrix} \begin{bmatrix} 0.5\mathbf{p}_1 - 0.3\mathbf{p}_2 + 0.4\mathbf{p}_3 \end{bmatrix}$$

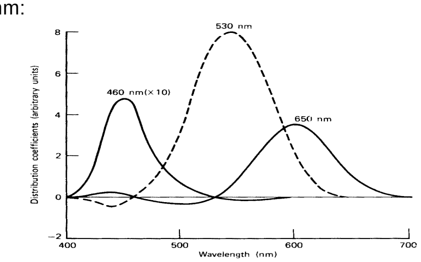
To make e_2 behave like a "real" (i.e., positive valued) knob, we have to move it over to the other side:

$$\begin{bmatrix} \mathbf{l}^{\mathbf{T}} \\ \mathbf{m}^{\mathbf{T}} \\ \mathbf{s}^{\mathbf{T}} \end{bmatrix} \begin{bmatrix} \mathbf{t} + 0.3\mathbf{p}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{l}^{\mathbf{T}} \\ \mathbf{m}^{\mathbf{T}} \\ \mathbf{s}^{\mathbf{T}} \end{bmatrix} \begin{bmatrix} 0.5\mathbf{p}_1 + 0.4\mathbf{p}_3 \end{bmatrix}$$

So, if we are allowed to move a primary to the other side, we will be able to match *any* color.

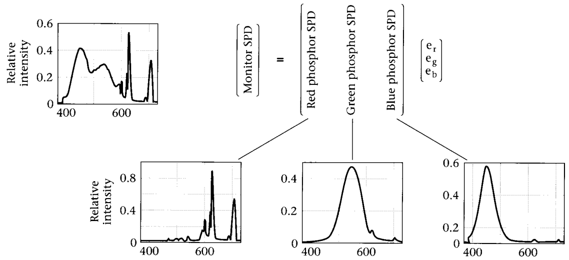
Example: Wright's experiments

In the late 20's, Wright found that the colors of all wavelengths could be reproduced with combinations of 3 primaries at 460, 530, and 650nm:



These functions are color-matching functions for the given primaries.

Choosing Primaries



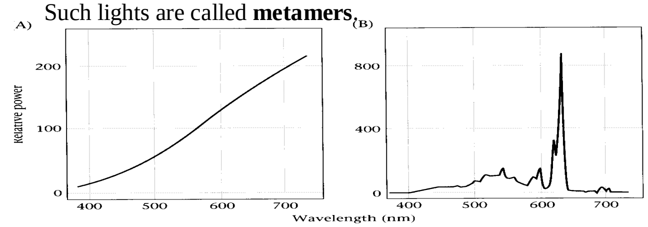
Emission spectra for RGB monitor phosphors (Wandell B.3)

Primaries don't have to be monochromatic. You can still derive color matching functions.

Emission Spectrum is not Color

Recall how much averaging the eye does. Light is infinite dimensional!

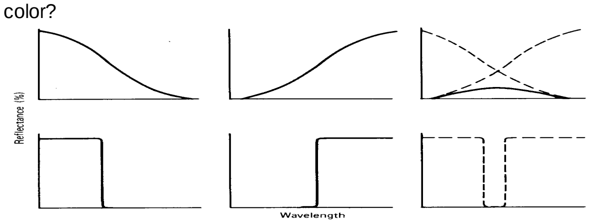
Different light sources can evoke exactly the same colors. Such lights are called **metamers**.



A dim tungsten bulb and an RGB monitor set up to emit a metameric spectrum (Wandell 4.11)

Colored Surfaces

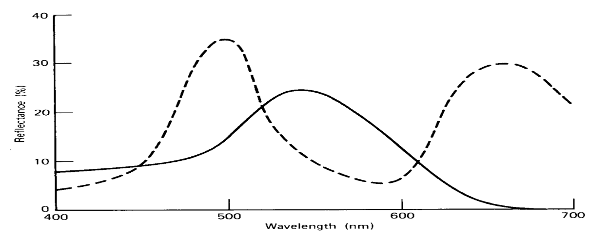
So far, we've discussed the colors of lights. How do *surfaces* acquire color?



A surface's **reflectance** is its tendency to reflect incoming light across the spectrum.

Reflectance is combined **subtractively** with incoming light. (Actually, the process is multiplicative.)

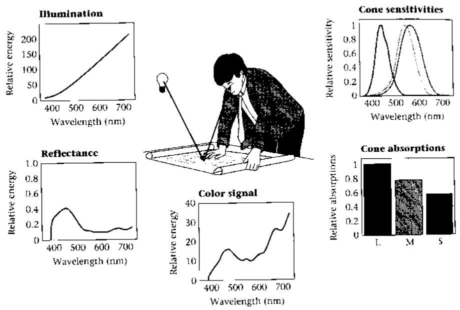
Subtractive Metamers



Reflectance adds a whole new dimension of complexity to color perception.

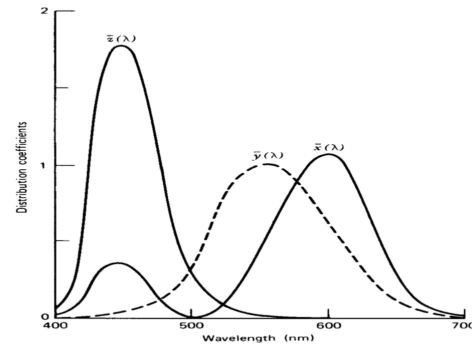
The solid curve appears green indoors and out. The dashed curve looks green outdoors, but brown under incandescent light.

Illustration of Color Appearance



The CIE *XYZ* System

A standard created in 1931 by CIE, defined in terms of three color matching functions.



CIE Coordinates

Given an emission spectrum, we can use the CIE matching functions to obtain the *X, Y* and *Z* coordinates.

$$X = \int \bar{x}(\lambda)t(\lambda)d\lambda$$

$$Y = \int \bar{y}(\lambda)t(\lambda)d\lambda$$

$$Z = \int \bar{z}(\lambda)t(\lambda)d\lambda$$

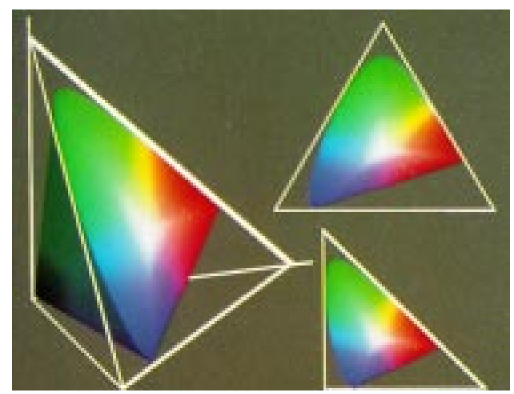
Then we can compute *chromaticity coordinates*. This gives a brightness independent notion of color.

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

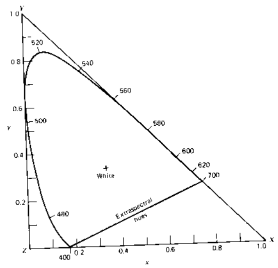
$$y = \frac{Y}{X+Y+Z}$$

$$z = \frac{Z}{X+Y+Z}$$

The CIE Color Blob



The CIE Chromaticity Diagram



A projection of the plane $X+Y+Z=1$.

Each point is a chromaticity value, which depends on **dominant wavelength**, or **hue**, and **excitation purity**, or **saturation**.

More About Chromaticity

Dominant wavelengths go around the perimeter of the chromaticity blob.

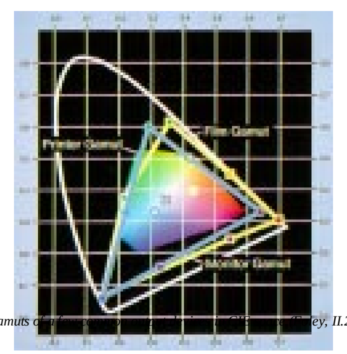
- A color’s dominant wavelength is where a line from white through that color intersects the perimeter.
- Some colors, called *nonspectral* color’s, don’t have a dominant wavelength.

Excitation purity is measured in terms of a color’s position on the line to its dominant wavelength.

Complementary colors lie on opposite sides of white, and can be mixed to get white.

Gamuts

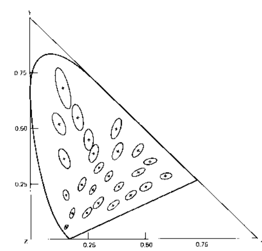
Not every output device can reproduce every color. A device’s range of reproducible colors is called its **gamut**.



Gamuts of a few common output devices in CIE space (Foley, II.2)

Perceptual (Non-)uniformity

The *XYZ* color space is not perceptually uniform!



Some modified spaces attempt to fix this:

- *L*u*v**
- *L*a*b**

Color Spaces for Computer Graphics

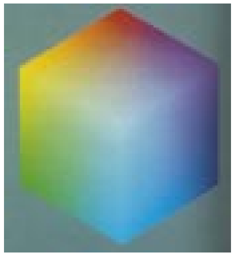
In practice, there's a set of more commonly-used color spaces in computer graphics:

- RGB for display
- CMY (or CMYK) for hardcopy
- HSV for user selection
- YIQ for television broadcast

RGB

Perhaps the most familiar color space, and the most convenient for display on a CRT.

What does the RGB color space look like?



HSV

More natural for user interaction, corresponds to the artistic concepts of tint, shade and tone.

The HSV space looks like a cone:

CMY

A subtractive color space used for printing.

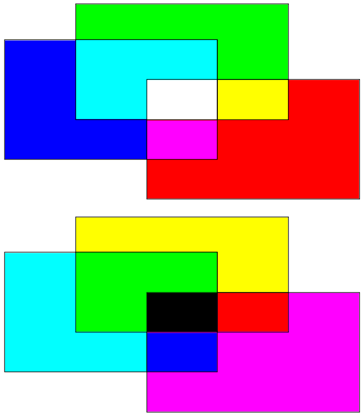
Involves three subtractive primaries:

- Cyan - subtracts red
- Magenta - subtracts green
- Yellow - subtracts blue

Mixing two pigments subtracts their opposites from white.

CMYK adds blacK ink rather than using equal amounts of all three.

RGB vs. CMY



YIQ

Used in TV broadcasting, YIQ exploits useful properties of the visual system.

- Y - luminance (taken from CIE)
- I - major axis of remaining color space
- Q - remaining axis

YIQ is broadcast with relative bandwidth ratios 8:3:1

- We're best as distinguishing changes in luminance.
- Small objects can be compressed into a single color dimension.

Why do we devote a channel to luminance?

Summary

- How the color matching experiment works
- The relationship between color matching and functions cone responses
- The difference between emissive and reflective color
- The CIE XYZ color standard and how to interpret the chromaticity diagram
- The color spaces used in computer graphics

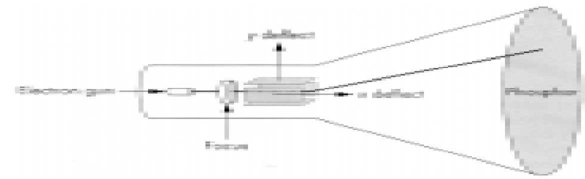
Computers and Color

Reading

Optional

- I.E. Sutherland. Sketchpad: a man-machine graphics communication system. *Proceedings of the Spring Join Computer Conference*, p. 329-346, 1963.
- T.H. Myer & I.E. Sutherland. On the design of display processors. *Communications of the ACM* 11(6): 410-414, 1968.

Cathode ray tubes (CRTs)



Consists of:

- electron gun
- electron focusing lens
- deflection plates/coils
- electron beam
- anode with phosphor coating

CRTs, cont.

Electrons “boil off” the heated cathode and shoot towards the anode. Electrons striking the phosphors create light through:

- fluorescence (fraction of usec)
- phosphorescence (10 to 60 usec)

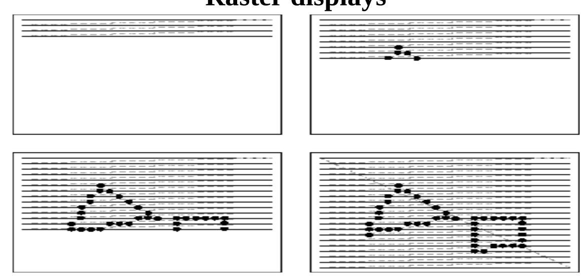
Different phosphors have different:

- color
- persistence (as long as a few seconds)

The image must be **refreshed** to avoid **flicker**:

- typically need at least 60 Hz (why 60 Hz?)
- exact frequency depends on:
  - persistence
  - image intensity
  - ambient lighting
  - wavelength
  - observer

Raster displays



Electron beam traces over screen in **raster scan order**.

- Each left-to-right trace is called a **scan line**.
- Each spot on the screen is a **pixel**.
- When the beam is turned off to sweep back, that is a **retrace**, or a **blanking interval.**

Resolution

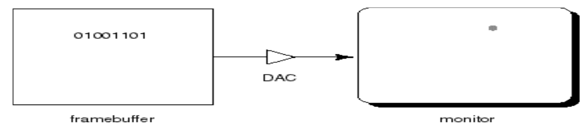
The display's **resolution** is determined by:

- number of scan lines
- number of pixels per scan line
- number of bits per pixel

Examples:

Bitmapped display	960 x 1152 x 1b	1/8 MB
NTSC TV	640 x 480 x 16b	1/2 MB
Color workstation	1280 x 1024 x 24b	4 MB
Laser-printed page		
300 dpi	8.5 x 11 x 300^2 x 1b	1 MB
1200 dpi	8.5 x 11 x 1200^2 x 1b	17 MB
Film	4500 x 3000 x 30b	50 MB

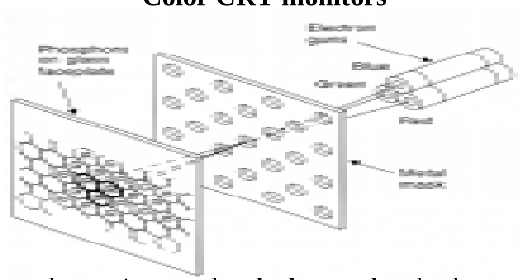
Framebuffers



Intensity of the raster scan beam is modulated according to the contents of a **framebuffer**.

Each element of the framebuffer is associated with a single **pixel** on the screen.

Color CRT monitors

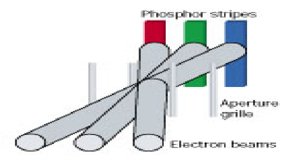


Most color monitors employ **shadow mask** technology:

- uses **triads** of red, green, and blue phosphors at each pixel
- uses three electron guns, one per color
- **shadow mask** used to make each kind of phosphor only "visible" from one gun

These are also known as **RGB monitors**.

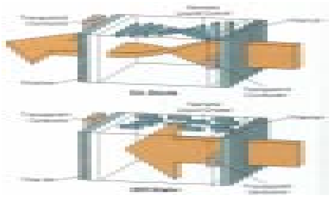
Color CRT monitors, cont'd

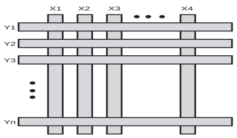


A competing technology is called Trinitron (by Sony):

- uses vertical stripes of red, green, and blue phosphors at each pixel
- uses three electron guns, one per color
- uses an **aperture grille** to make each kind of phosphor only "visible" from one gun

Liquid Crystal Displays

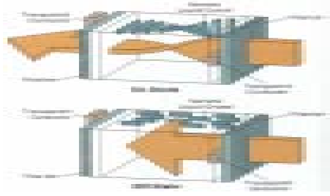


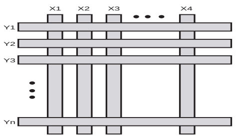


Laptops typically use **liquid crystal displays (LCD's)**.

- Light enters a **vertical polarizer**
- **Nematic crystal** twists light based on applied voltage (more voltage, less twisting)
- Light passes through **horizontal polarizer**

Liquid Crystal Displays



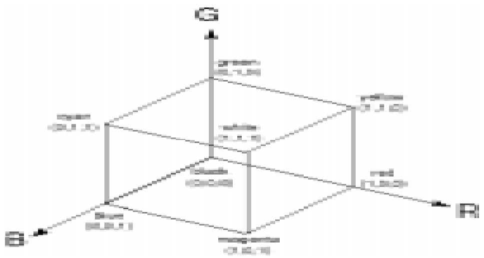


Passive matrix displays use a matrix of electrodes to control the voltages. Problem: slow to switch, overflows.

Active matrix displays have a transistor at each cell. They use a faster switching crystal and transistors that hold charge and prevent overflow.

Color filters are used to get color display.

Additive color mixing



All colors on a monitor are produced using combinations of red, green, and blue.
A monitor that allows 256 voltage settings for each of R, G, and B is known as a **full-color system**.
The description of each color in framebuffer memory is known as a **channel**.

Specifying colors

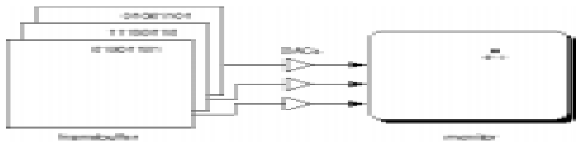
The number of color choices depends on the amount of framebuffer storage allocated per pixel.

Q: How many colors can be displayed with:

- 3 bits per pixel?
- 8 bits per pixel?
- 24 bits per pixel?

16 bpp systems often allocate 5 bits to red, 6 to green, and 5 to blue. Why does green get the extra bit?

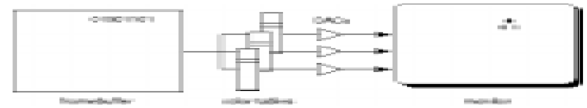
RGB framebuffer



The term **true-color** is sometimes used to refer to systems which the framebuffer directly stores the values of each channel.

Color tables

Color tables allow more color versatility when you only have a few bits per pixel. You get to select a small **palette** of from a large number of available colors.

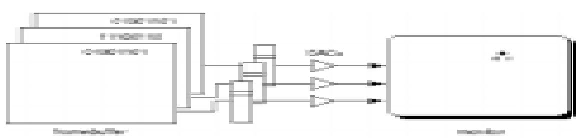


Each framebuffer element is now an index into the color table, where the actual values of each channel are stored.

- Color table entries can be changed in software.

Color tables on 24-bit systems

Even full-color systems often use color tables. In this case, there is a separate color table for each 8 bit channel.



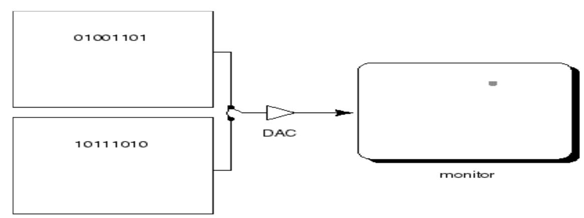
Most SGI workstations are like this.

Q: Why would you want this capability?

Double-buffering

Q: What happens when you write to the framebuffer while it is being displayed on the monitor?

Double-buffering provides a solution.



Summary

Here’s what you should take home from this lecture:

- The basic components of black-and-white and color CRTs
- Computing screen resolution & framebuffer size
- The correspondence between elements of framebuffer memory and pixels on-screen
- How color tables work
- How double-buffering works