Lecture 5

Video with the FPGA

Lab 2 Part 1 due today/tomorrow!*

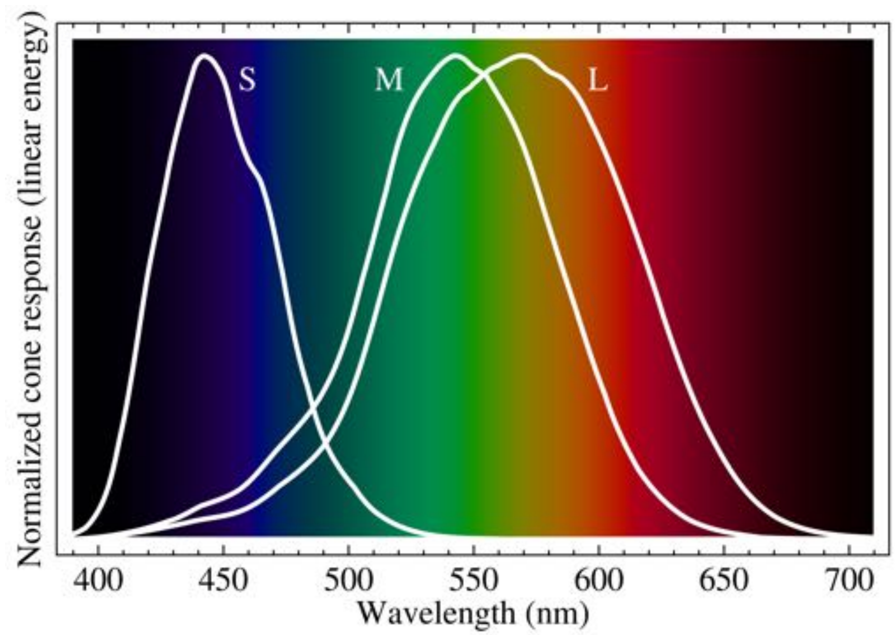
Lab 2 Part 2 due this upcoming Tuesday!

Pset 4 is out today due upcoming Tuesday!

Lab 3 is Out! (on video)

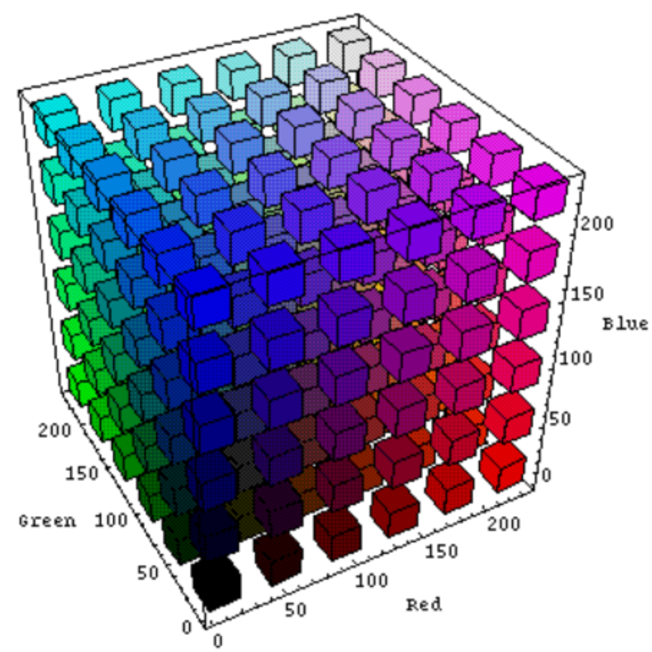
Displays are for Eyes

- Human color perception comes from three types of cone cells in the center of the eye. Each type generally has an abundance of one photoreceptive protein (which causes electrical stimulation):
  - S cones with protein from **OPN2** gene
  - M cones with protein from **OPN1MW** gene
  - L cones with protein from **OPN1LW** gene
- A human eye therefore has three independent inputs regarding visual EM radiation
- Called **"trichromatic"**



Color Space

- Human trichromatic vision is comprised of three inputs, therefore the most general way to describe these inputs is in a 3-dimensional space
- Because the L, M, and S cones "roughly" line up with Red, Green, and Blue, respectively a RGB space is often the most natural to us
- There are others, though



One form of RGB space (not the only way to display it)

https://engineering.purdue.edu/~abe305/HTMLS/rgbspace.htm

Worst Case Scenario

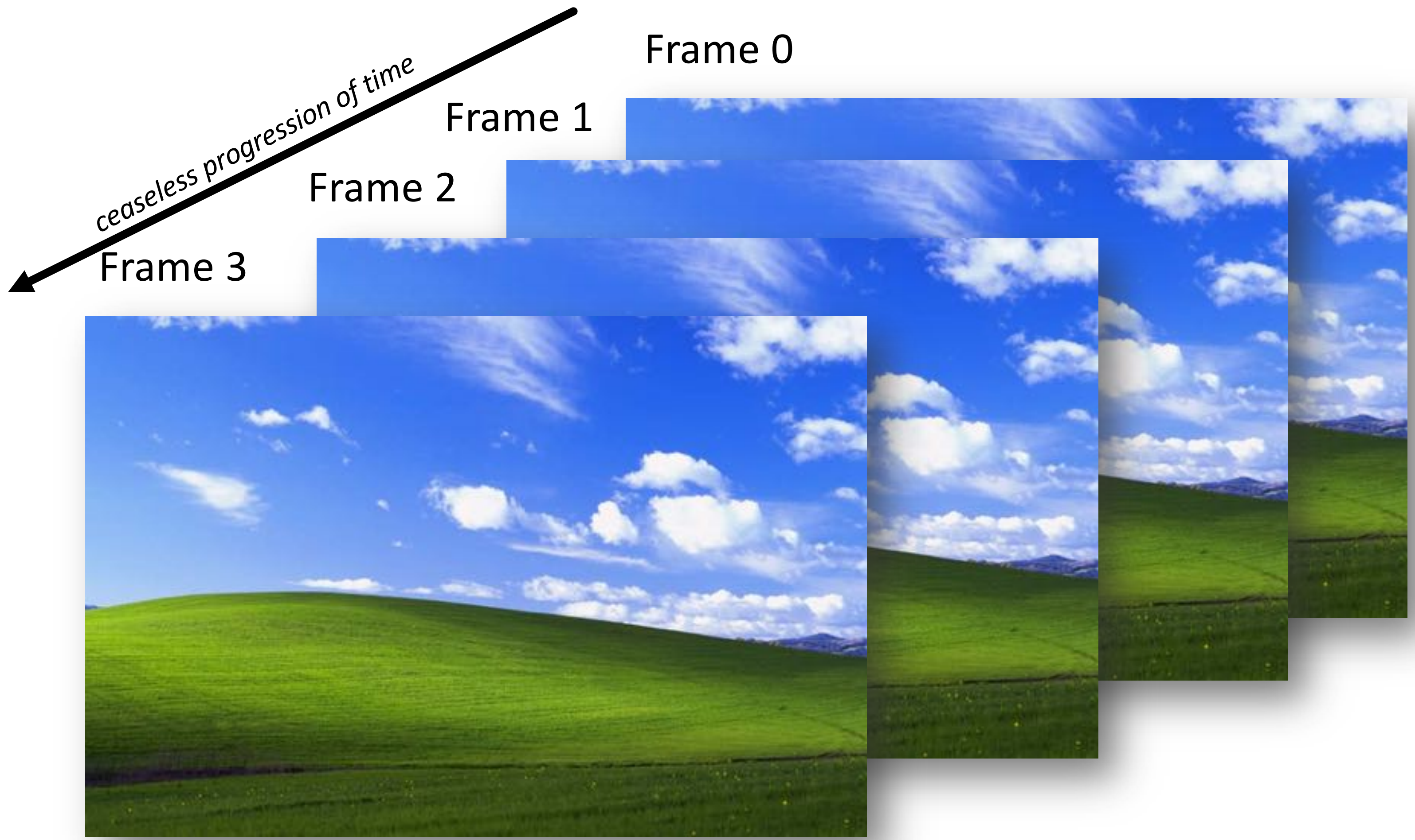
- If a person has all color receptors working…
- because of noise limitations in our naturally-evolved encoding scheme that communicates from the cone cells up to the brain…
- we can perceive about 7-10 million unique colors depending on your research source…
- How many bits do we need to encode all possible colors for this worst case?

Image or Frame

- An image/frame can be thought of as a 2-dimensional array of 3-tuples:
  - 2 spatial dimensions
  - 3 color dimensions
- Each color tuple is a "pixel"

Video (just draw a bunch of frames quickly)

- Rely on the poor RC time constants of our eye's to "fake" motion.



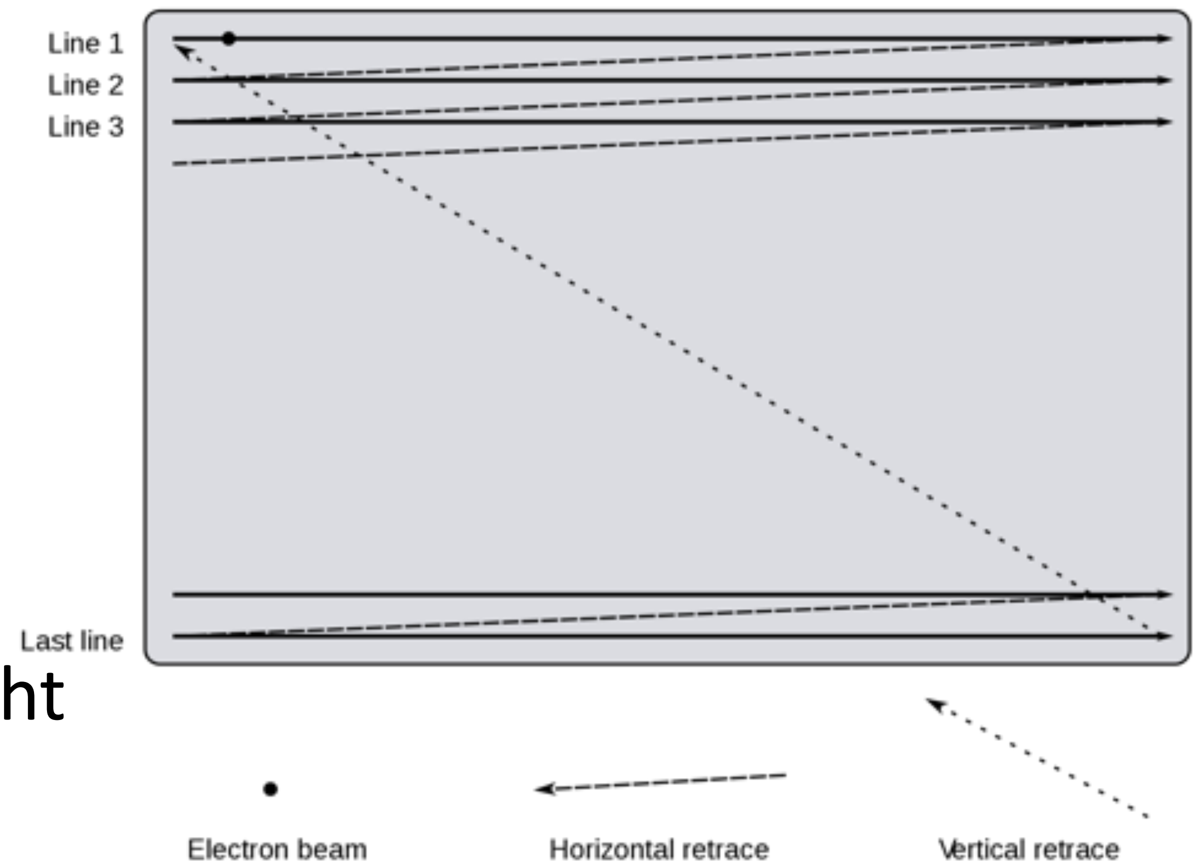
How to Transmit 5-dimensional data?

- Ideally need to convey enough 5D values quickly enough to render images fast enough that they show up as one…
- AND we also need to do this fast enough so that fresh images appear quickly enough

How to Draw: The Raster Scan

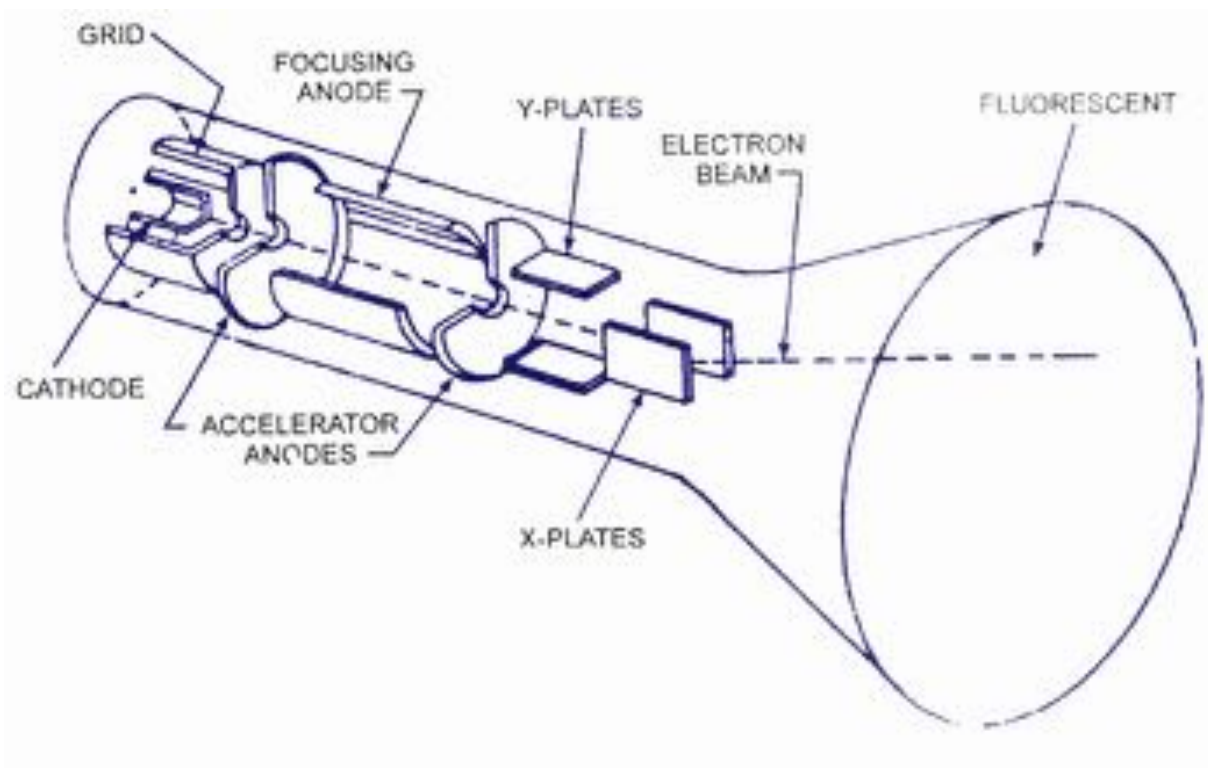
- Spread the drawing out over time
- Images are drawn on a display almost invariably in a "raster" pattern.
- The sequence starts in the upper left, and pixels are drawn:

- Left→ Right
- Down a line/back
- Left→ Right
- Down a line/back
- Etc…
- End at bottom right
- Return to top left



Raster Scan Became Norm because of Early Tech (Cathode Ray Tube)

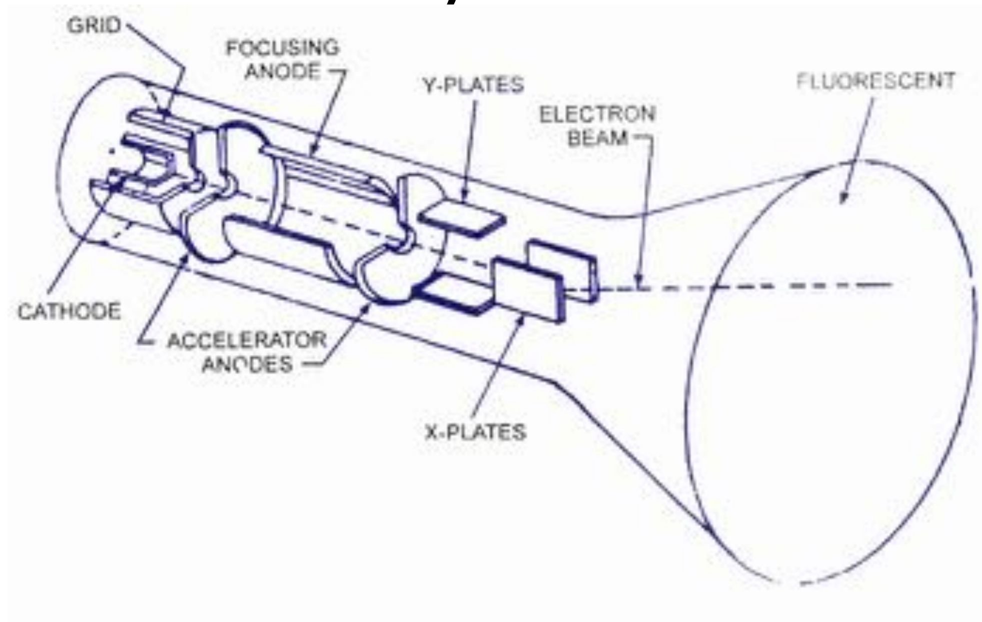
- Electron beam of varying intensity would be quickly rastered on a fluorescent screen making image



Cathode Ray Tube

First Video (Black and White)

- Early technologies prevented ability to detect and display color.
- Instead only **brightness (Luminance)** of the image was transmitted/rendered since color couldn't be rendered anyways

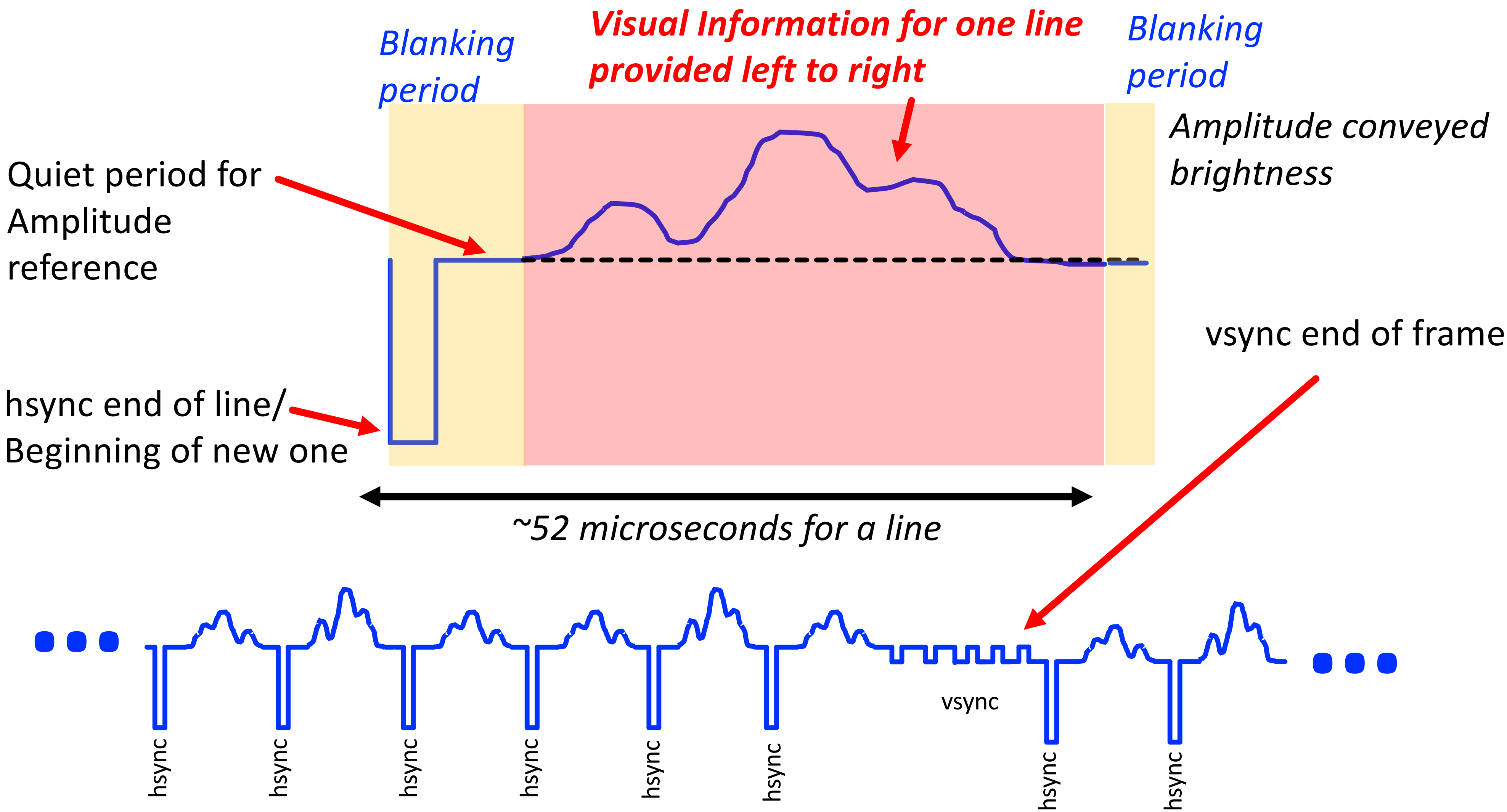


Cathode Ray Tube

http://www.circuitstoday.com/crt-cathode-ray-tube

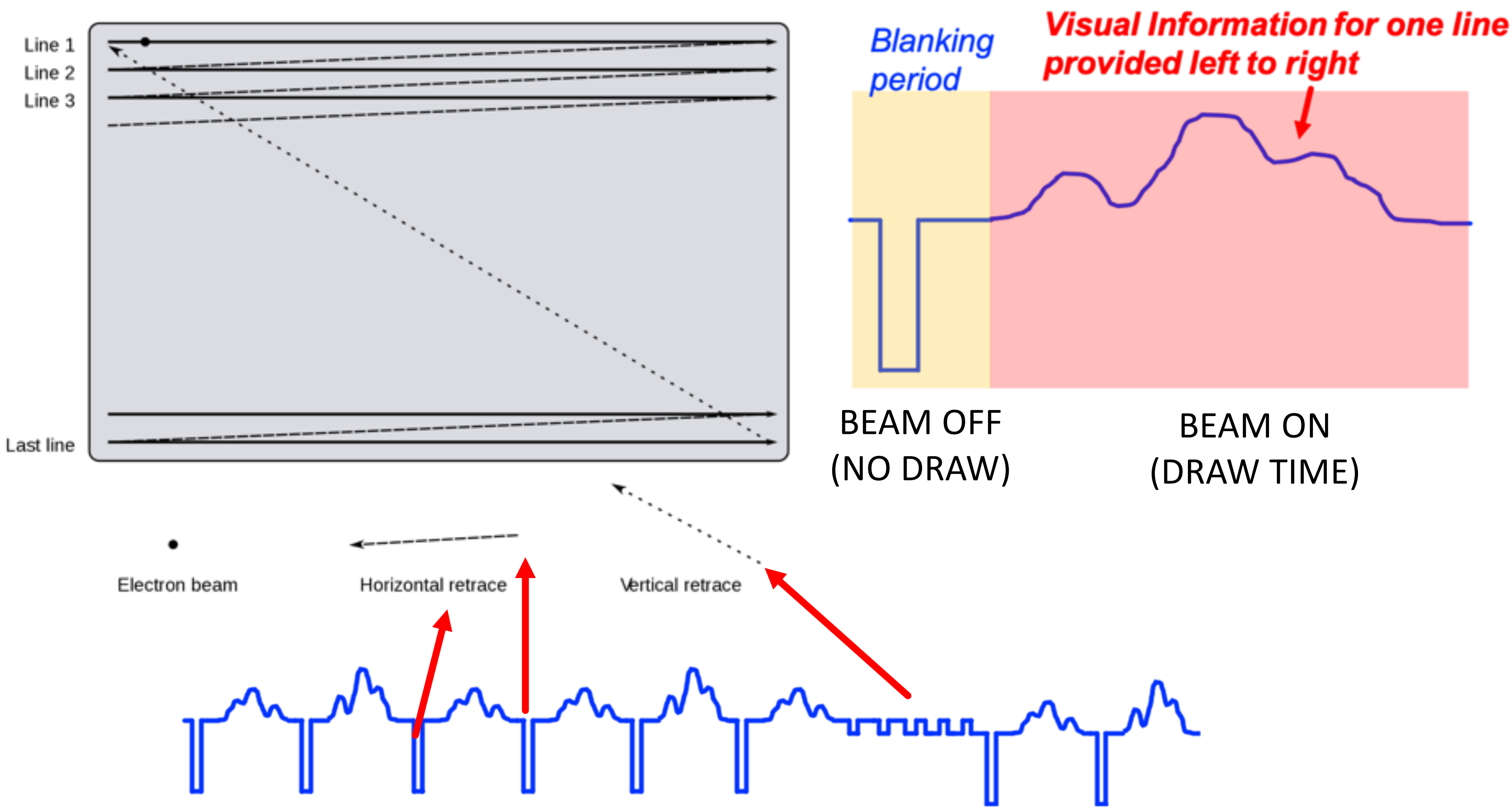
Black and White Video signal

- An **analog** signal conveying luminance (brightness) and synchronization controls (end of line, end of frame)



Controls in Action

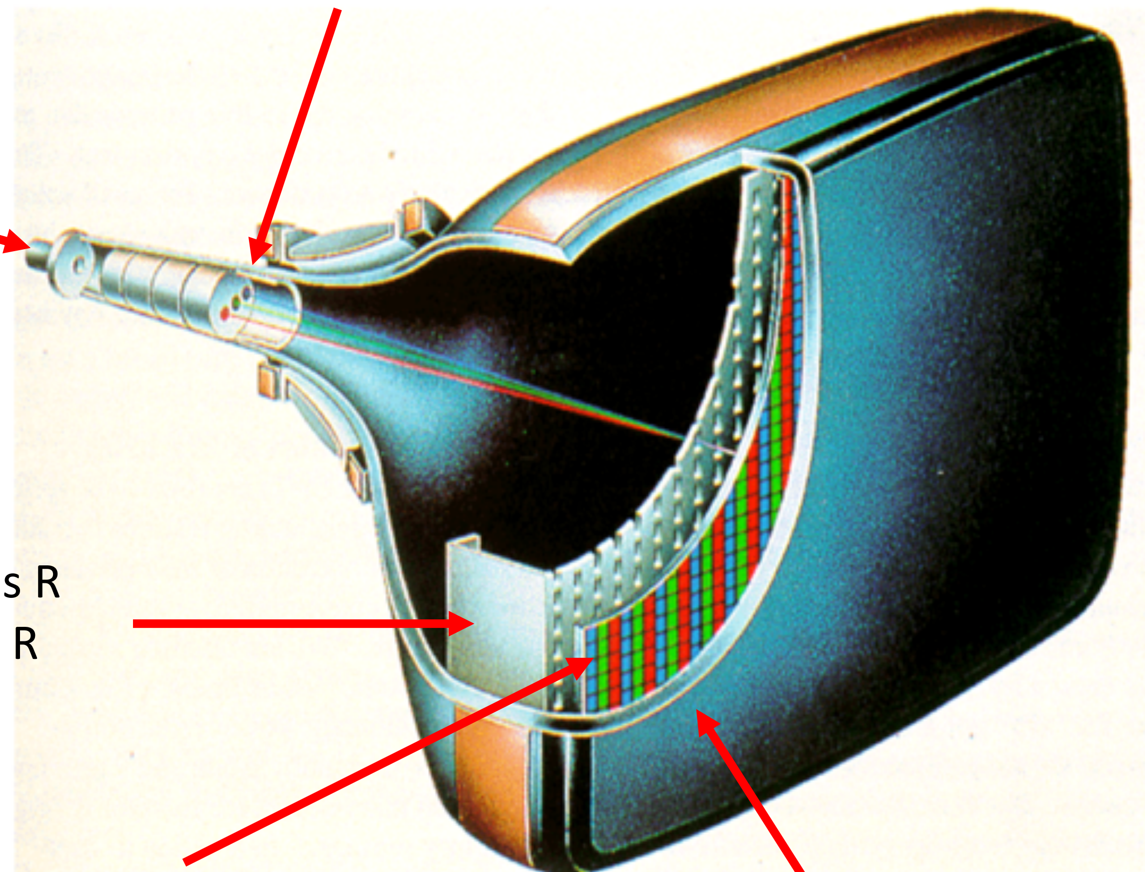
- Signal completely controls beam location and intensity!



Color Cathode Ray Tubes Appear

One shared set of deflection coils to sweep all three beams together

Cathode: separate beams for R, G and B



Shadow mask: ensures R beam only illuminates R pixels, etc.

Three different phosphor screens

Anode

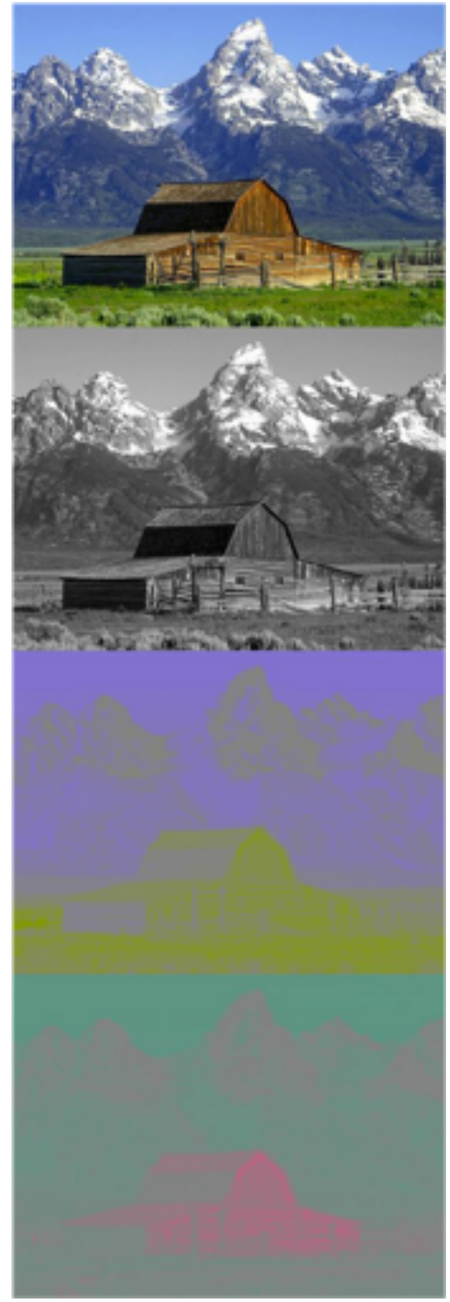
Source: PixTech

How to Upgrade video standards, but let black and white displays still work?

- Color TV invented in 40’s but took until 70’s for color TV to surpass B&W TV in sales
- How do you do it? Can’t send out R, G, and B signals since old TVs won’t know what that is
- Still must send out old signal
- Remap our 3D RGB color space into something else!

YCrCb (sometimes YUV)

- Color space composed of three values:
  - Y: Luminance
  - Cr: Red Chrominance
  - Cb: Blue Chrominance
- Together they can represent the full color space



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

YCrCb ←→ RGB

- Just one 3-tuple to another (linear algebra)

Figure 1. YCbCr/RGB color conversion

$$\begin{bmatrix} Y \\ Cb \\ Cr \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.16874 & -0.33126 & 0.5 \\ 0.5 & -0.41869 & -0.08131 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} 0 \\ 128 \\ 128 \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1.402 \\ 1 & -0.34414 & -0.71414 \\ 1 & 1.77200 & 0 \end{bmatrix} \begin{bmatrix} Y \\ Cb - 128 \\ Cr - 128 \end{bmatrix}$$

YCrCb ←→ RGB

- 8-bit data
  - R = 1.164(Y – 16) + 1.596(Cr – 128)
  - G = 1.164(Y – 16) – 0.813(Cr – 128) – 0.392(Cb – 128)
  - B = 1.164(Y – 16) + 2.017(Cb – 128)
- 10-bit data
  - R = 1.164(Y – 64) + 1.596(Cr – 512)
  - G = 1.164(Y – 64) – 0.813(Cr – 512) – 0.392(Cb – 512)
  - B = 1.164(Y – 64) + 2.017(Cb – 512)
- Implement using
  - Integer arithmetic operators (scale constants/answer by 2^{11})
  - 5 BRAMs (1024x16) as lookup tables for multiplications

http://www-mtl.mit.edu/Courses/6.111/labkit/video.shtml

Color Analog Video signal

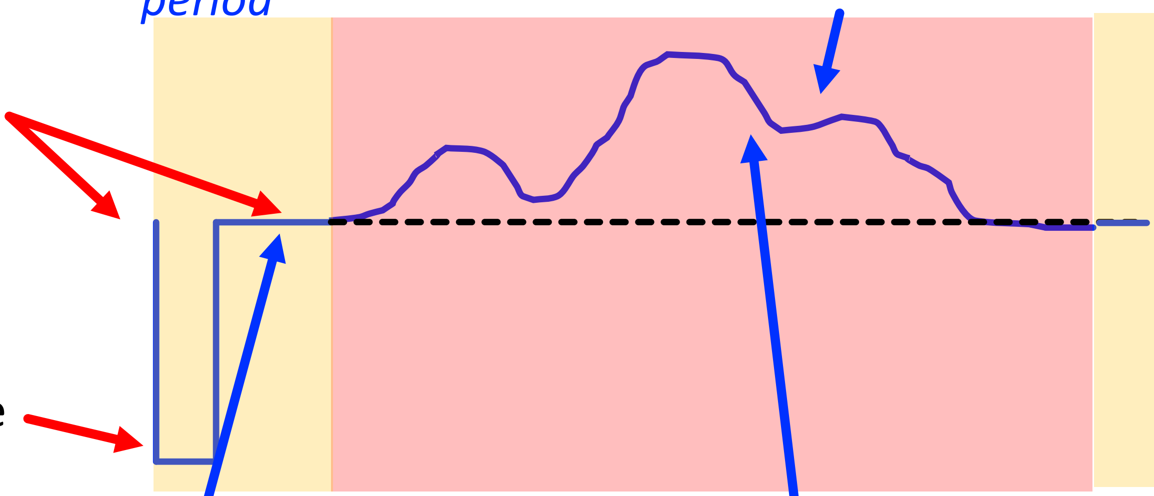
- Keep signal the same as before but add other stuff to it!

Blanking period

Y value (Luminance) encoded in base signal

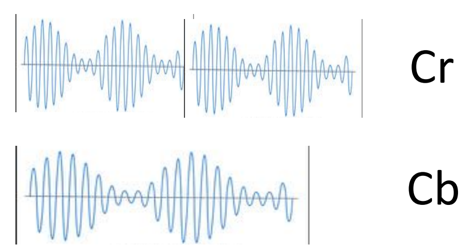
Quiet period for Y reference

hsync end of line

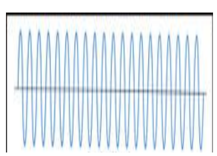


Amplitude of low frequency signal conveyed brightness

Superimpose two slightly different sine waves on top of Luminance signal that encode Cr and Cb data (not to scale) in amplitude modulation:



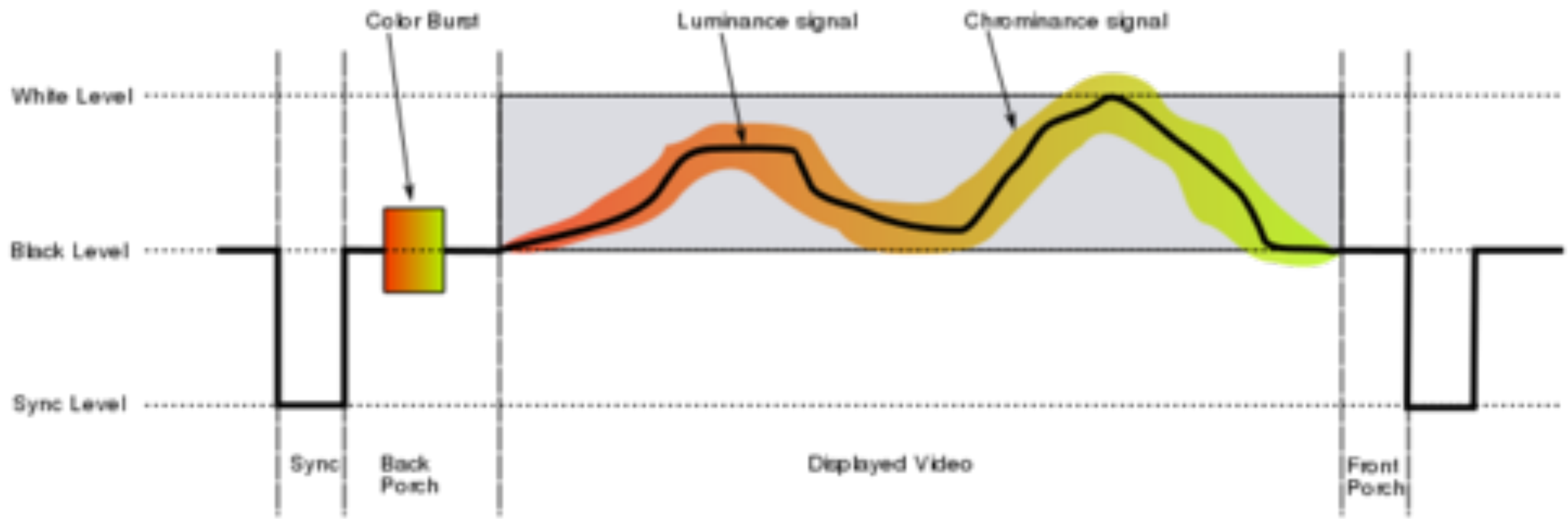
Add a Cr/Cb "color burst" to region of blanking period to calibrate for Cr/Cb Amplitude Demodulation



Composite Video Encoding:

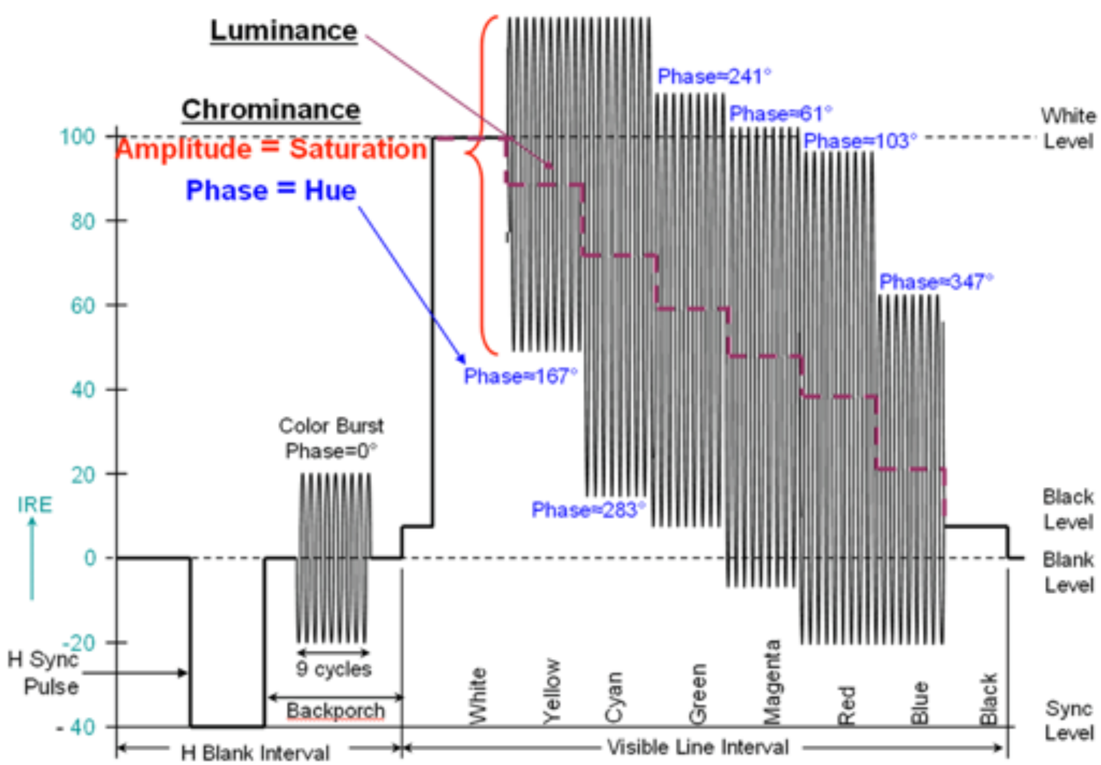
Used for most color TV transmissions and component video up until early 2000's

Use colorburst to remind receiver frequency and amplitudes for interpreting luminance and chrominance signal correctly



Encoding Color

- If you do math out, the two chrominance signals construct/deconstruct to form a signal where:



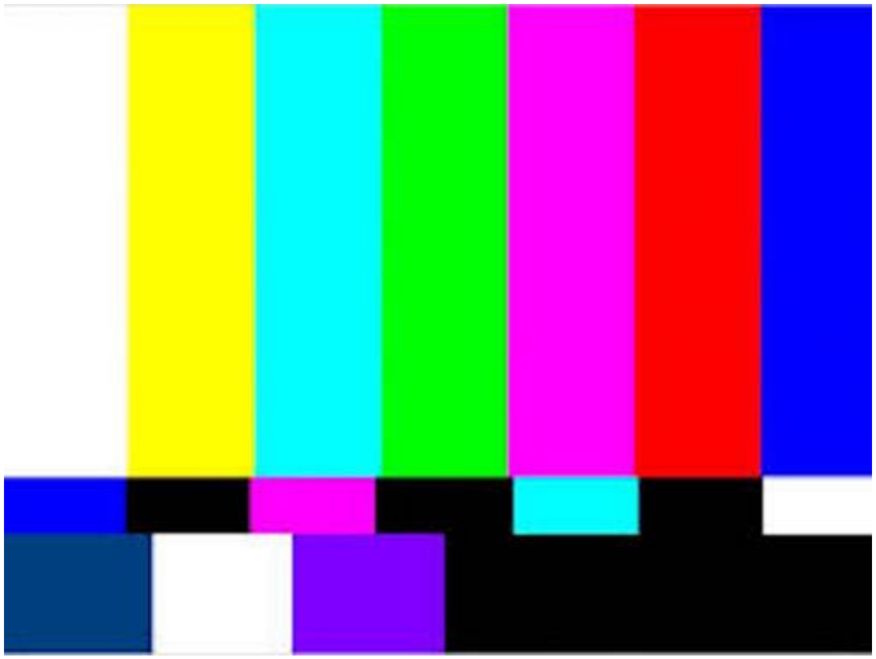
- Amplitude is **Saturation**
- Phase is **Hue**
- **Luminance** is low-freq original value

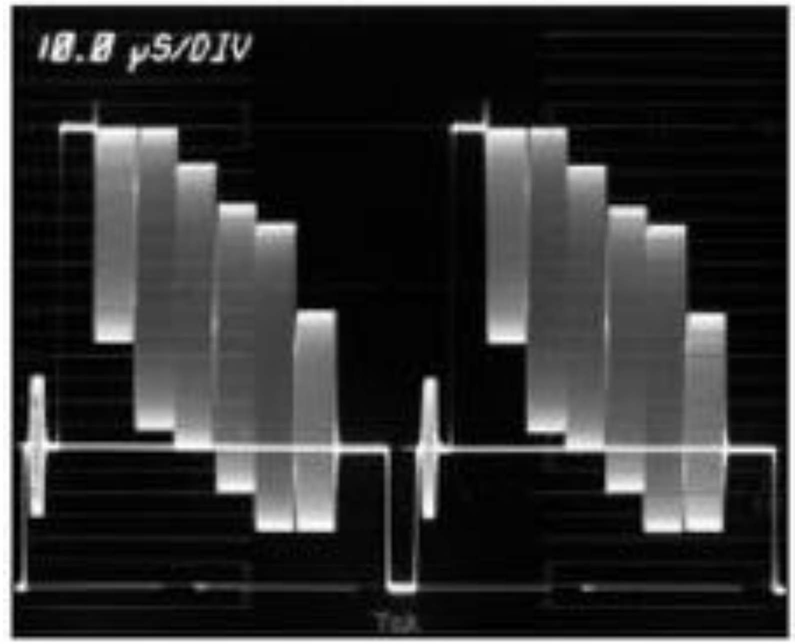
- Hue, Saturation, Luminance (HSL) is a cylindrical color space that is used a lot!

https://www.eetimes.com/document.asp?doc_id=1272387#

NTSC*: Composite Video Encoding

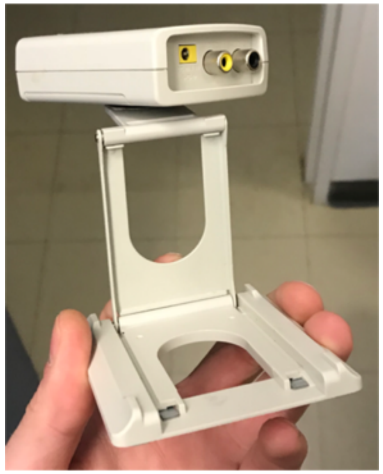
Captures on a Scope





Two horizontal lines shown

Old Labkits work with Cameras that produce composite video out



Two conductors:

- Shield (ground)
- Middle thing (signal)

Component Video Sockets on Virgin Air in 2019

this

Is slightly smaller than

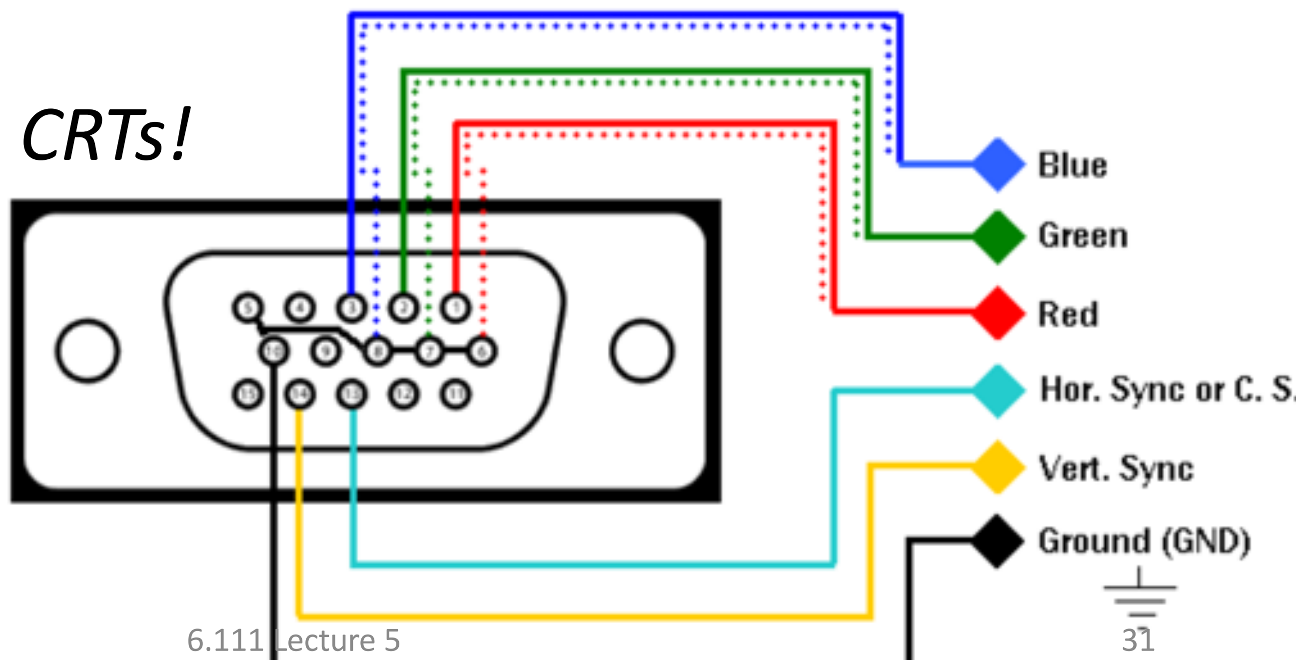
this

Poor engineering.

VGA (Video Graphics Array)

- Development of personal computers motivated a rethink of video display!
- IBM (late 1980s)
- Data conveyed primarily ***analog***
- *Did not have to be reverse compatible with B/W (chose to use RGB as a result)*
- *Used separate wires for different signals (easier)*
- *Still had to deal with CRTs!*
  - *Need blanking!*
  - *Need sync signals!*

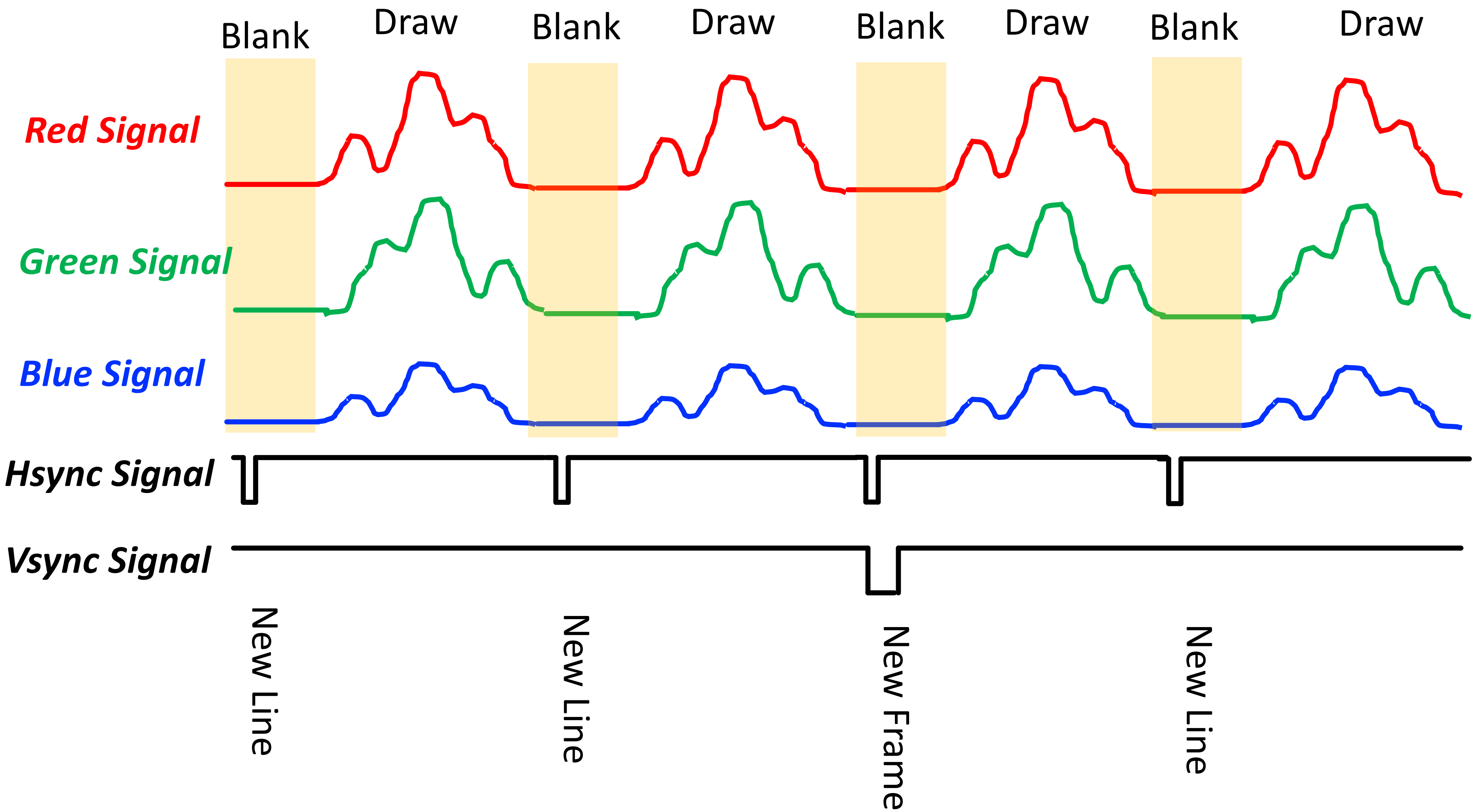
DB15 Connector



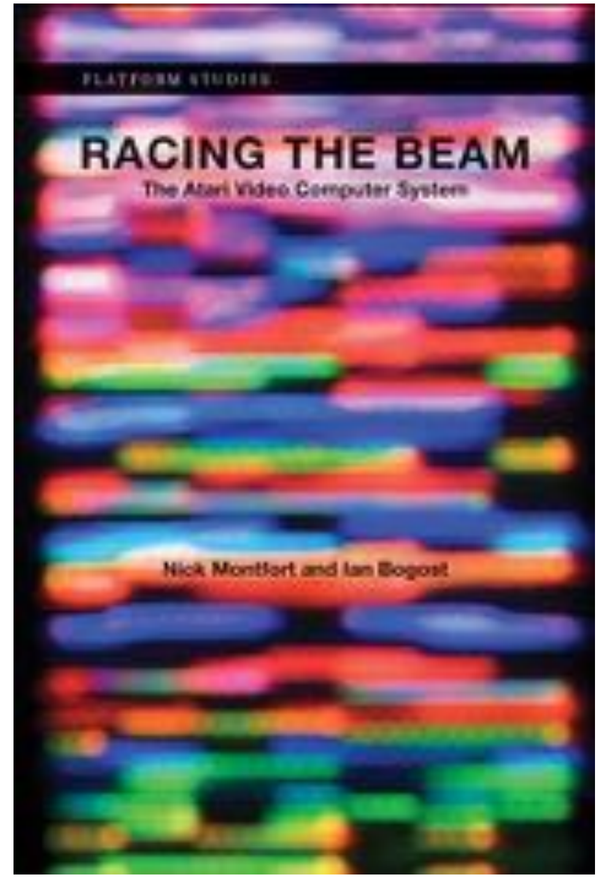
https://electronics.stackexchange.com/questions/93078/soldering-a-vga-cable-number-of-wires-doesnt-match

VGA Signals

- Similar as Before, but split signals (easier to read)



Racing the Beam



MIT Press

How to Design in the context of Video on an FPGA or other low-level digital system?

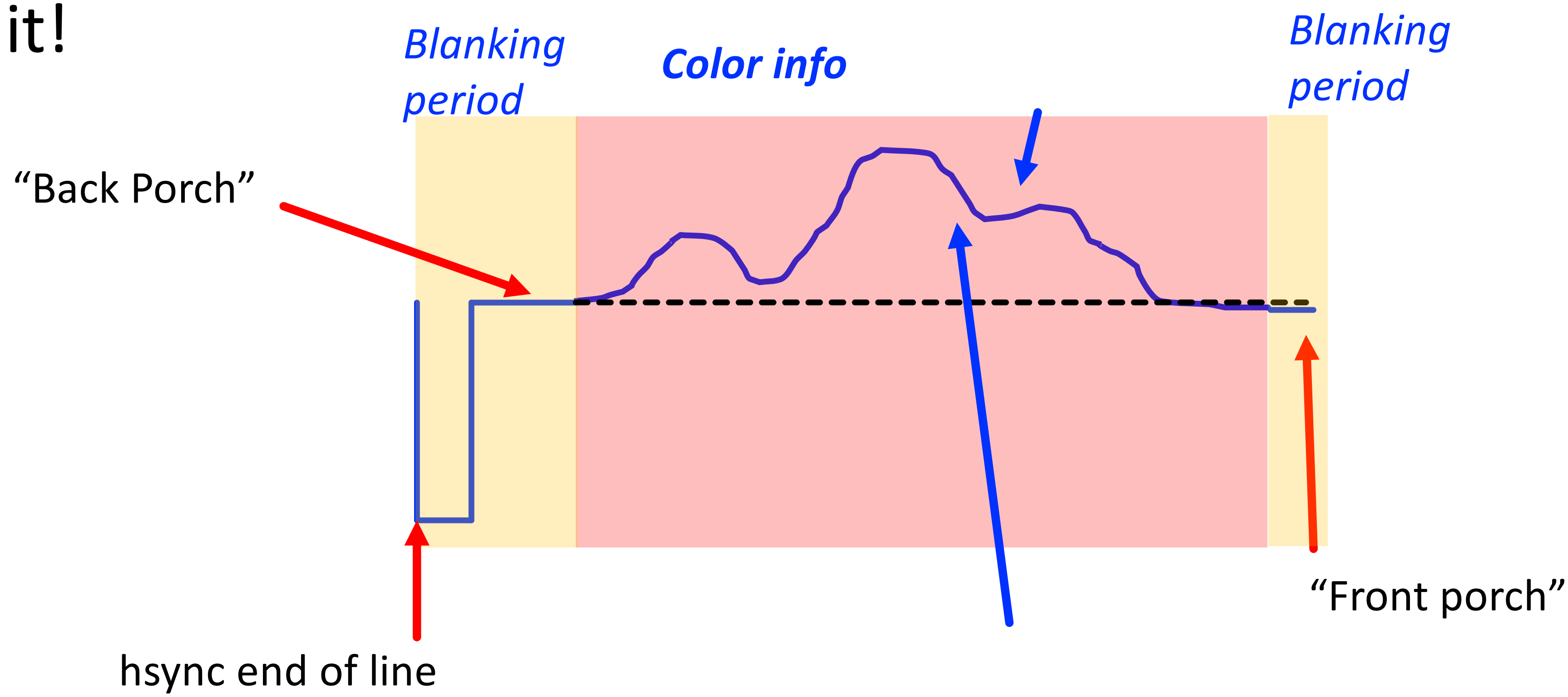
Figure out Display Resolution

Generally need to draw 60 frames per second regardless of resolution(can go faster):

Resolution	Pixels	Aspect Ratio	Products
VGA	640x480	4:3	
SVGA	800x600	4:3	
XGA	1024x768	4:3	iPad, iPad Mini
SXGA	1280x1024	4:3	
HD TV	1920x1080	16:9	
iPhone 6 Plus	1920x1080	16:9	
iPad Retina	2048x1536	4:3	iPad Air, iPad Mini Retina
Macbook Retina	2560x1600	16:10	13” Macbook Pro
Kindle Fire	1920x1200		HDX 7” (3rd Generation)
4K HD TV	3840x2160	16:9	
8K HD TV	7680x4320	16:9	Really expensive TVs

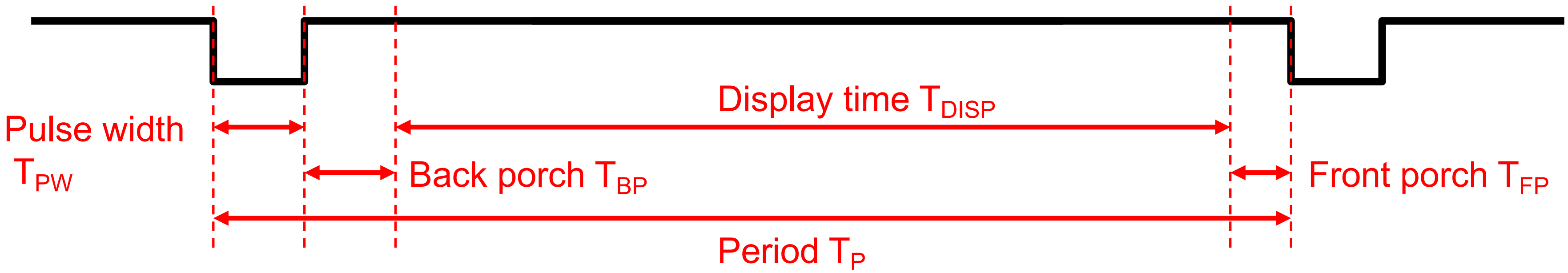
Each line of Video looks like this:

- Keep signal the same as before but add other stuff to it!



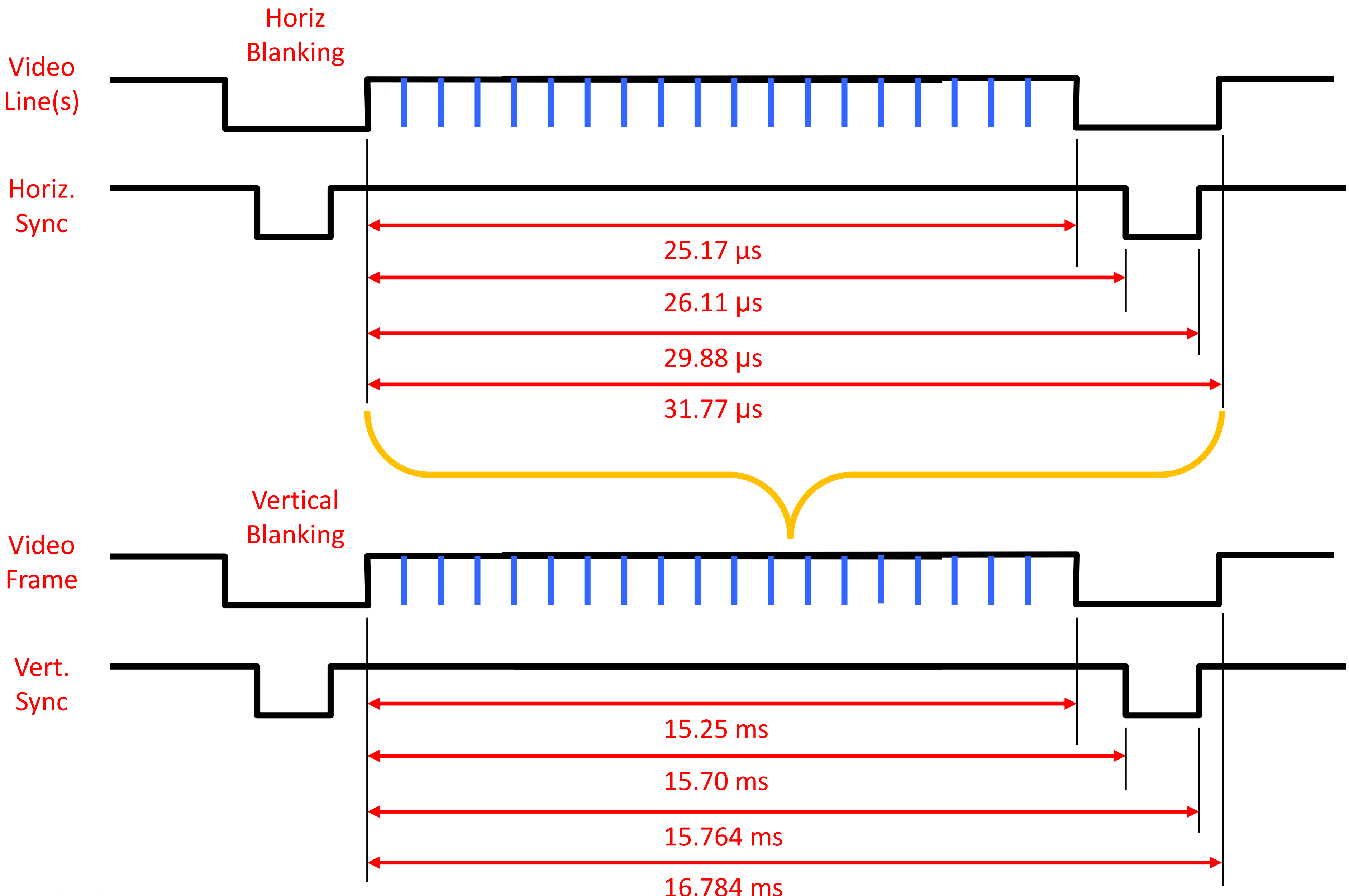
- If we need to draw 60 XGA frames per second, what must the timing of our lines be?
- Timing of our pixels?

Sync Signal Timing



Format		*CLK*	*P*	*PW*	*BP*	*DISP*	*FP*
VGA	HS (pixels)	25Mhz	794	95	47	640	13
	VS (lines)	--	528	2	33	480	13
XGA	HS (pixels)	65Mhz	1344	136	160	1024	24
	VS (lines)	--	806	6	23	768	9

VGA (640x480) Video (for example)



xvga module

- Starting with 65 MHz video clock, generate:
- ***hsync***, ***vsync*** *signals*
- ***blanking*** *signal!*
- *Horizontal and vertical counts (**hcount**, **vcount**)*

Given in Lab 03

```
module xvga(input vclock_in,
            output reg [10:0] hcount_out,    // pixel number on current line
            output reg [9:0] vcount_out,     // line number
            output reg vsync_out, hsync_out,
            output reg blank_out);

   parameter DISPLAY_WIDTH  = 1024;      // display width
   parameter DISPLAY_HEIGHT = 768;       // number of lines

   parameter  H_FP = 24;                 // horizontal front porch
   parameter  H_SYNC_PULSE = 136;        // horizontal sync
   parameter  H_BP = 160;                // horizontal back porch

   parameter  V_FP = 3;                  // vertical front porch
   parameter  V_SYNC_PULSE = 6;          // vertical sync
   parameter  V_BP = 29;                 // vertical back porch

   // horizontal: 1344 pixels total
   // display 1024 pixels per line
   reg hblank,vblank;
   wire hsyncon,hsyncoff,hreset,hblankon;
   assign hblankon = (hcount_out == (DISPLAY_WIDTH -1));
   assign hsyncon = (hcount_out == (DISPLAY_WIDTH + H_FP - 1));  //1047
   assign hsyncoff = (hcount_out == (DISPLAY_WIDTH + H_FP + H_SYNC_PULSE - 1));  //
   assign hreset = (hcount_out == (DISPLAY_WIDTH + H_FP + H_SYNC_PULSE + H_BP - 1));

   // vertical: 806 lines total
   // display 768 lines
   wire vsyncon,vsyncoff,vreset,vblankon;
   assign vblankon = hreset & (vcount_out == (DISPLAY_HEIGHT - 1));   // 767
   assign vsyncon = hreset & (vcount_out == (DISPLAY_HEIGHT + V_FP - 1));  // 771
   assign vsyncoff = hreset & (vcount_out == (DISPLAY_HEIGHT + V_FP + V_SYNC_PULSE -
   assign vreset = hreset & (vcount_out == (DISPLAY_HEIGHT + V_FP + V_SYNC_PULSE +

   // sync and blanking
   wire next_hblank,next_vblank;
   assign next_hblank = hreset ? 0 : hblankon ? 1 : hblank;
   assign next_vblank = vreset ? 0 : vblankon ? 1 : vblank;
   always_ff @(posedge vclock_in) begin
      hcount_out <= hreset ? 0 : hcount_out + 1;
      hblank <= next_hblank;
      hsync_out <= hsyncon ? 0 : hsyncoff ? 1 : hsync_out;  // active low

      vcount_out <= hreset ? (vreset ? 0 : vcount_out + 1) : vcount_out;
      vblank <= next_vblank;
      vsync_out <= vsyncon ? 0 : vsyncoff ? 1 : vsync_out;  // active low

      blank_out <= next_vblank | (next_hblank & ~hreset);
   end

endmodule
```

XVGA (1024x768) Sync Timing

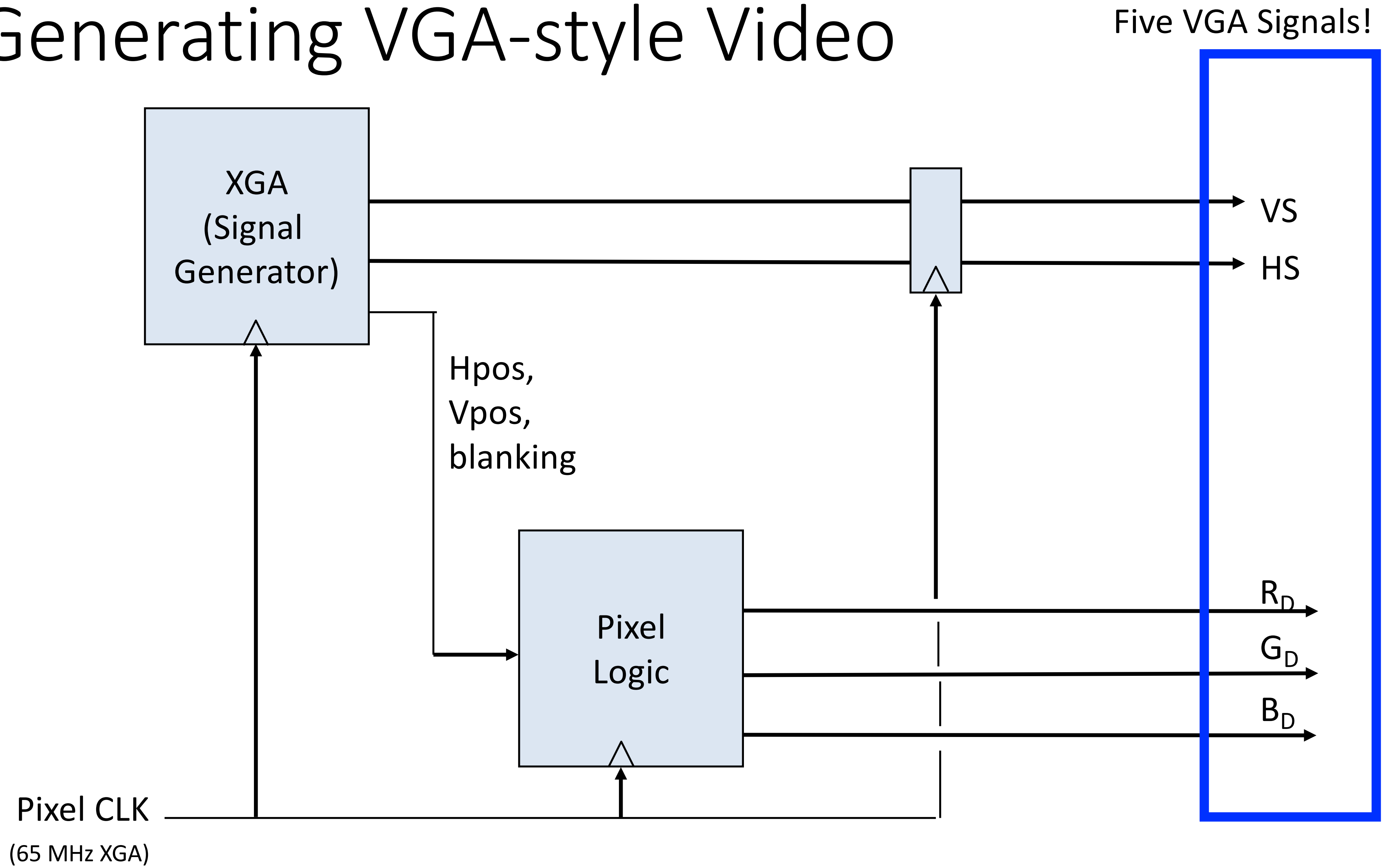
```
// assume 65 Mhz pixel clock

// horizontal: 1344 pixels total
// display 1024 pixels per line
assign hblankon = (hcount == 1023);  // turn on blanking
assign hsyncon = (hcount == 1047);   // turn on sync pulse
assign hsyncoff = (hcount == 1183);  // turn off sync pulse
assign hreset = (hcount == 1343);    // end of line (reset counter)

// vertical: 806 lines total
// display 768 lines
assign vblankon = hreset & (vcount == 767);   // turn on blanking
assign vsyncon = hreset & (vcount == 776);    // turn on sync pulse
assign vsyncoff = hreset & (vcount == 782);   // turn off sync pulse
assign vreset = hreset & (vcount == 805);     // end of frame
```

Has other timing specs specified for different types of displays!

Generating VGA-style Video



Digital-to-Analog Converters will handle R,G,B creation

Pixel Logic

Given an x,y location, what should be drawn?

Simple "Draws"

Whole Screen is White:

```
always_ff @(posedge pixel_clk) begin
   if (vblank | (hblank & ~hreset))
       rgb <= 12'h0;
   else
       rgb <= 12'hF_F_F;  //Nexys has 12 bit color
end
```

Draw green vertical line at horizontal spot 500:

```
always_ff @(posedge pixel_clk) begin
   if (h_count==500)
       rgb <= 12'h0_F_0; //draw green line
   else
       rgb <= 12'h000;
end
```

Draw white crosshair at (500,500)

```
always_ff @(posedge pixel_clk) begin
   if (h_count==500 || v_count==500)
       rgb <= 12'hF_F_F; //draw white cross-hair
   else
       rgb <= 12'h000;
end
```

RGB	*Color*
000	black
001	blue
010	green
011	cyan
100	red
101	magenta
110	yellow
111	white

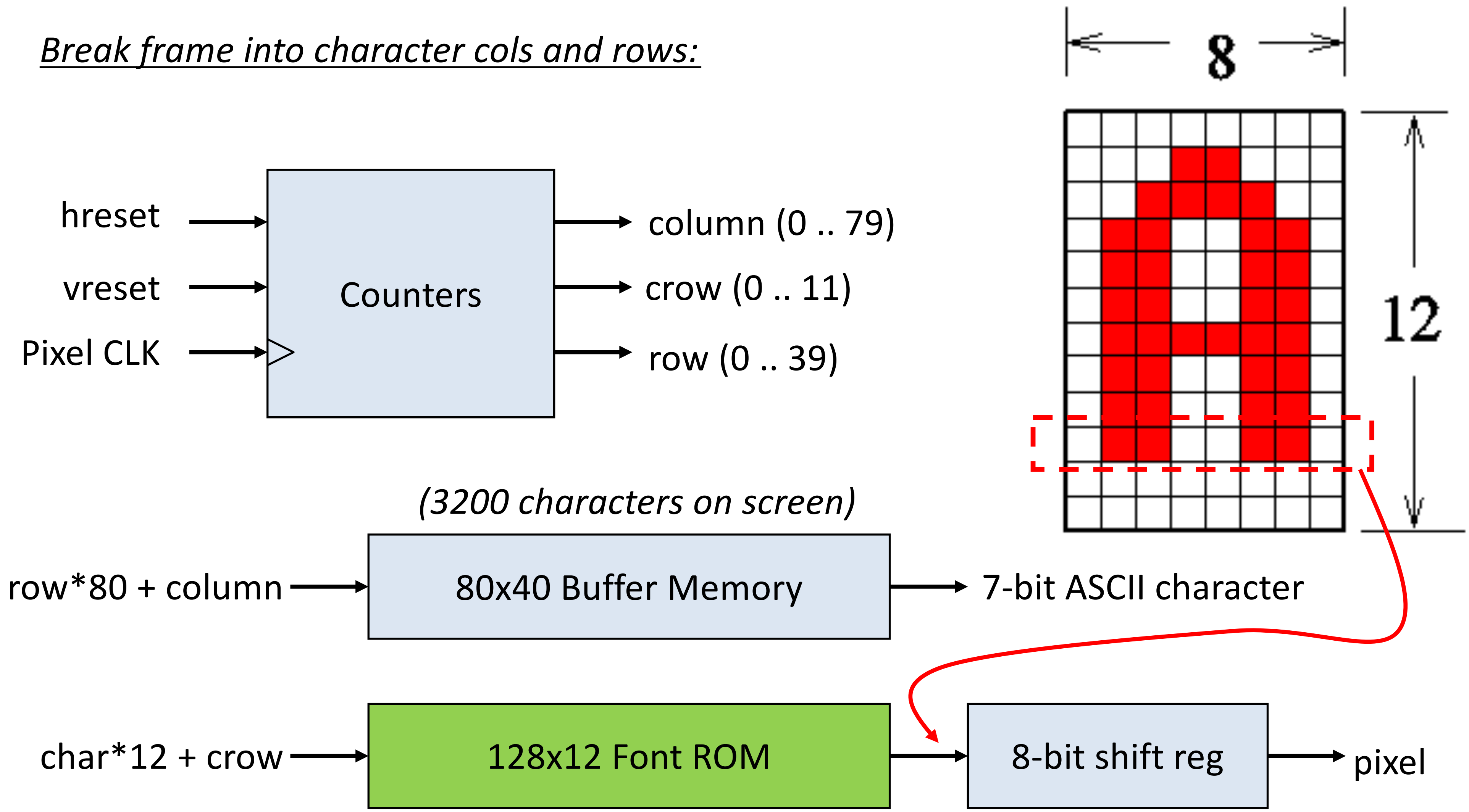
Normalized color scale

Character Display

*80*12= 960 pixels by 480 pixels FOV*

(80 columns x 40 rows, 8x12 glyph)

Break frame into character cols and rows:

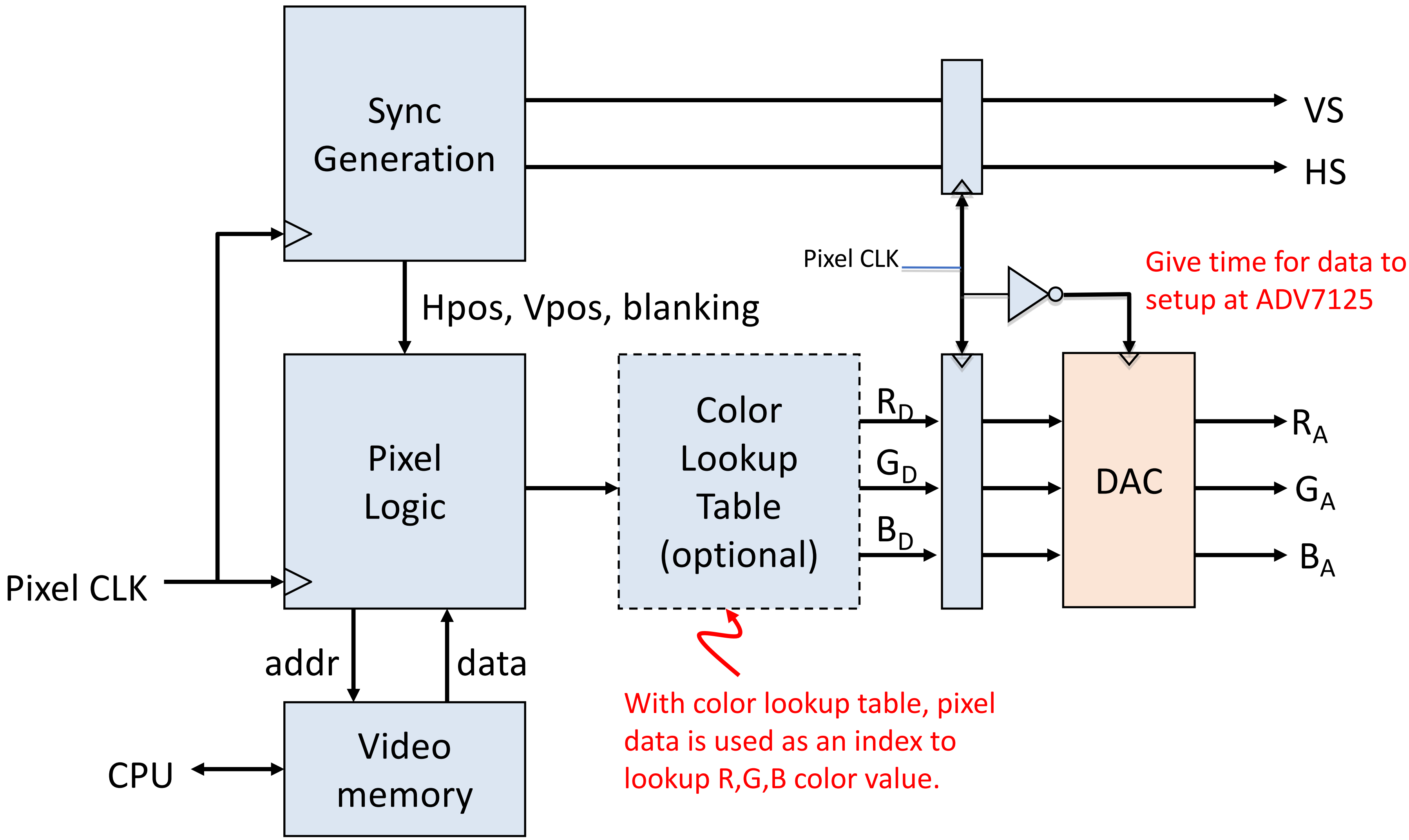


Commodore 64 Font ROM

64 pixel characters (8-by-8)

http://www.6502.org/users/sjgray/computer/cbmchr/cbmchr.html

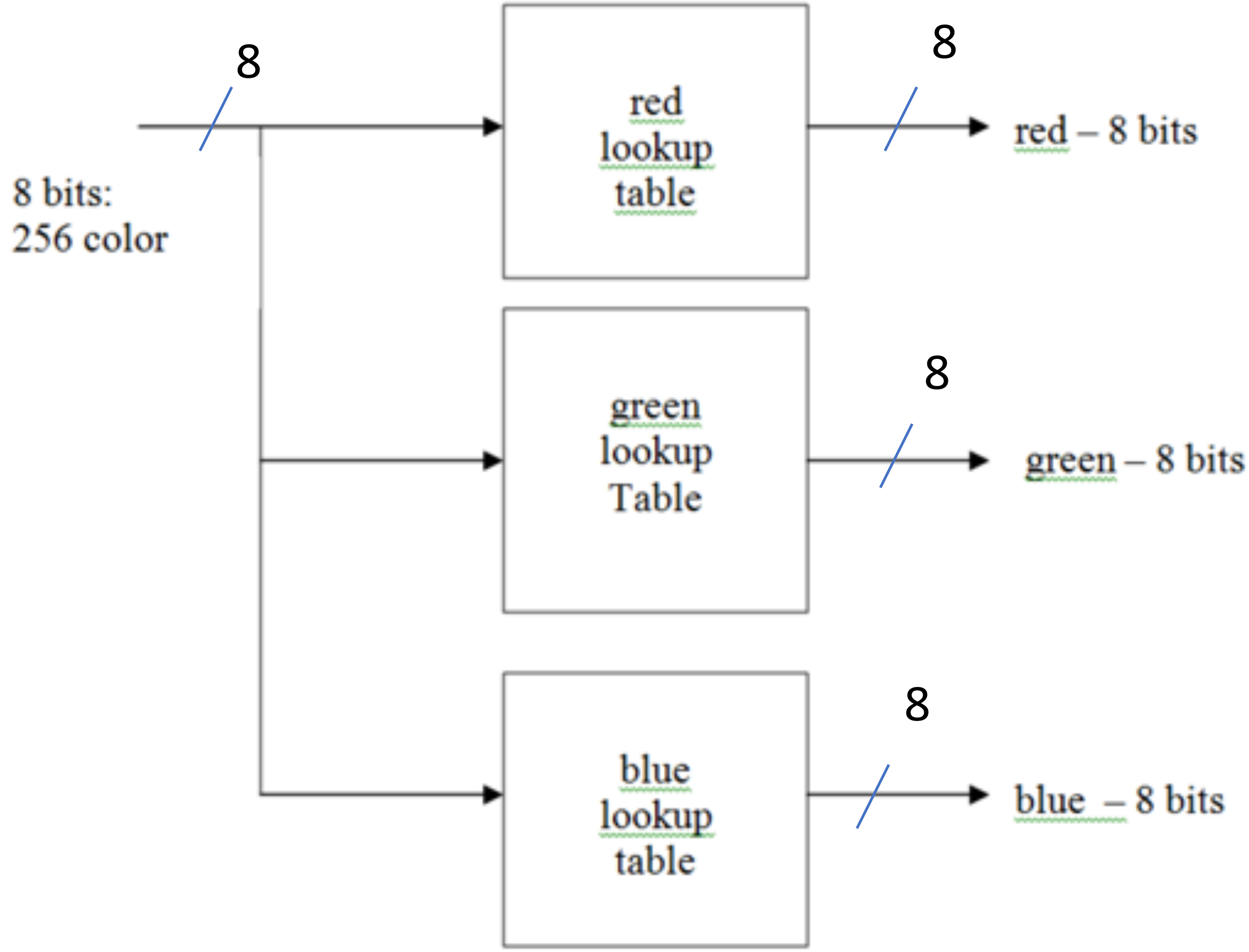
Generating VGA-style Video



With color lookup table, pixel data is used as an index to lookup R,G,B color value.

Without color lookup table, pixel data is used directly as R,G,B value (aka “true color”)

Color Lookup Table



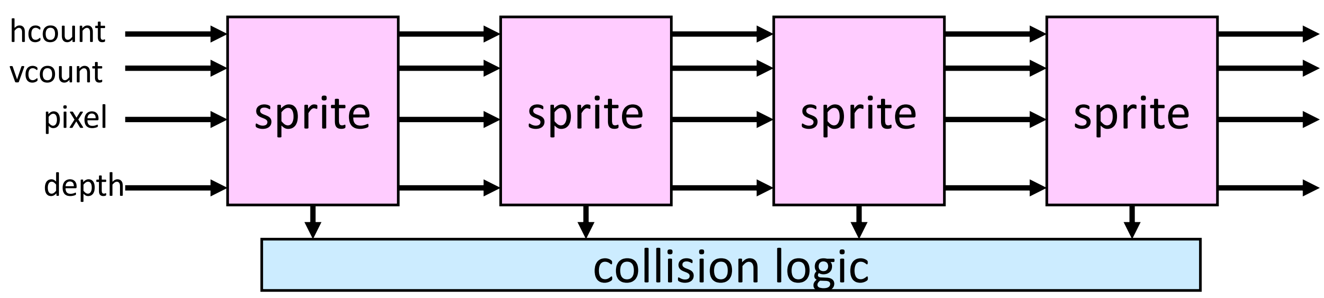
4 bit – 16 colors

8 bit – 256 colors

24 bit – 16M colors

Graphics using Sprites

- Sprite = game object occupying a rectangular region of the screen (it's bounding box).
  - Usually it contains both opaque and transparent pixels.
  - Given (H,V position), sprite returns pixel (0=transparent) and depth
  - Pseudo 3D: look at current pixel from all sprites, display the opaque one that's in front (min depth): see sprite pipeline below
  - Collision detection: look for opaque pixels from other sprites
  - Motion: smoothly change coords of upper left-hand corner
- Pixels can be generated by logic or fetched from a bitmap (memory holding array of pixels).



Modern Displays and Technologies

VGA is dead, Joe. My computer only has HDMI and a Display Port. This is irrelevant

Display Types

- Emissive Display
  - Organic Light Emitting Diode (OLED) Displays
  - Liquid Crystal Display (LCD)
    - requires backlight source,
    - constant power
  - Cathode Ray Tube (CRT)

Back in Time

- Reflective Display
  - Electrophoretic Display (E-Ink)*
    - Ultra Low Power – displays are bi-stable, drawing power only when updating the display.
    - Viewable in sunlight – ambient light reflected from display
  - Liquid Crystal Display (LCD)
    - I'm talking old-school calculator style here

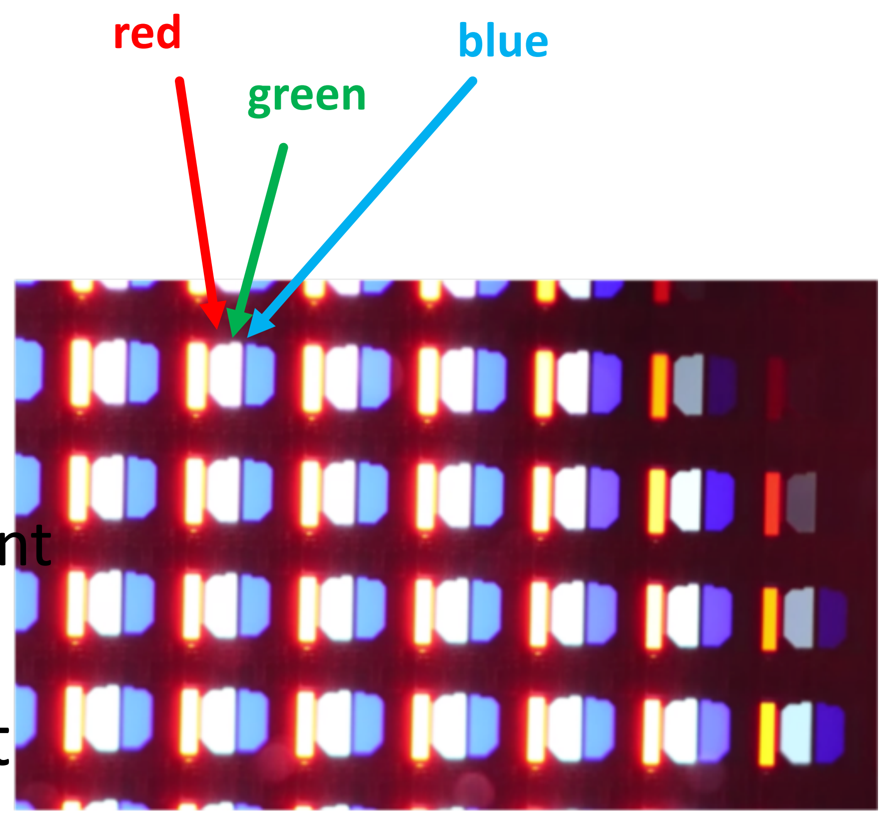
Back in Time

*Prof Joseph Jacbson, MIT

Organic Light Emitting Diodes

- Newest Technology
- Conceptually maybe the simplest/ideal way to do a display
    1. Gigundous array of RGB LEDs
    2. Control RGB amt. at each point
    3. Profit

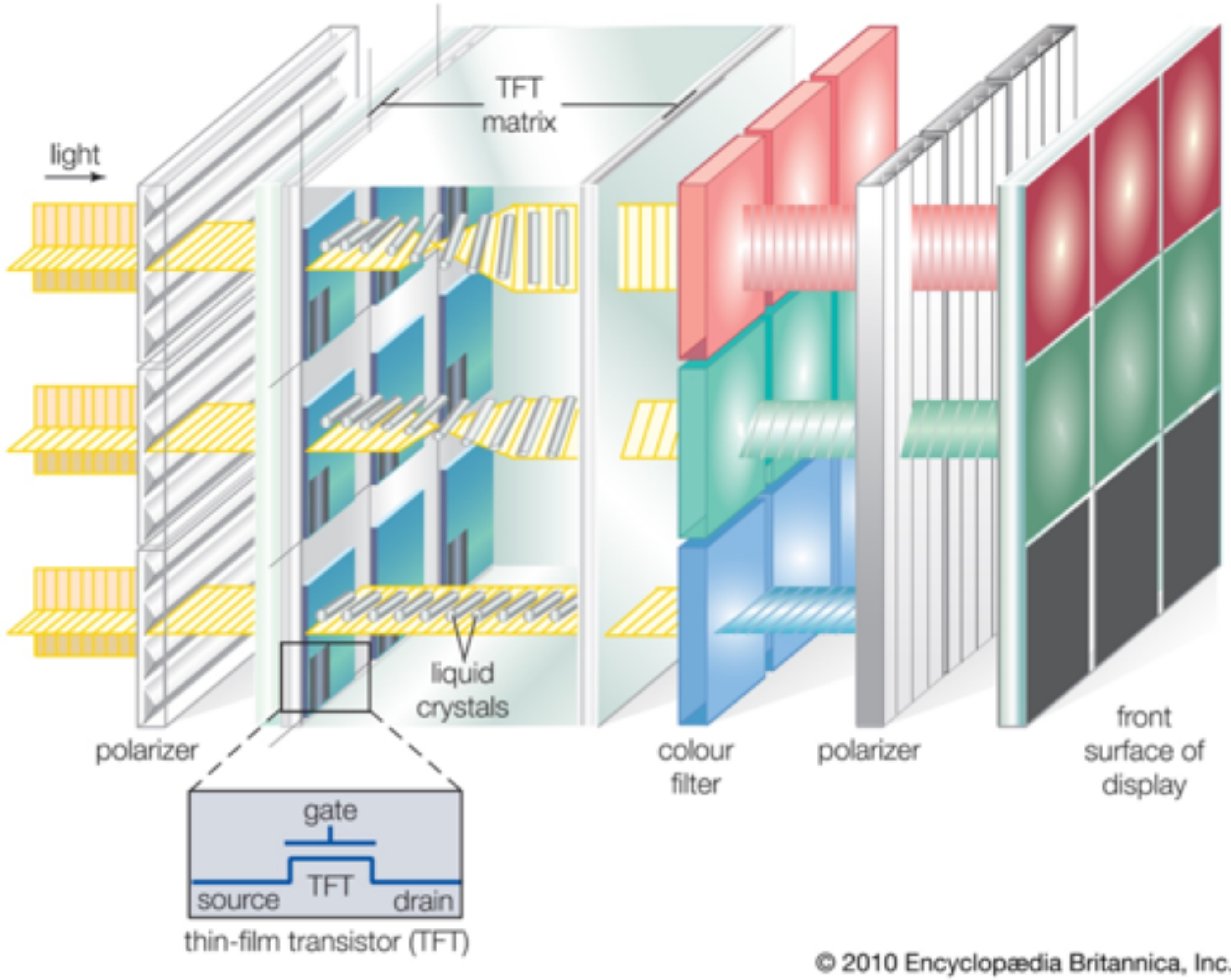
1. Want black pixel? Just don't turn on LED



*Green saturated in this image

TFT LCD

Used to be Cold Cathode
Now almost always white LEDs

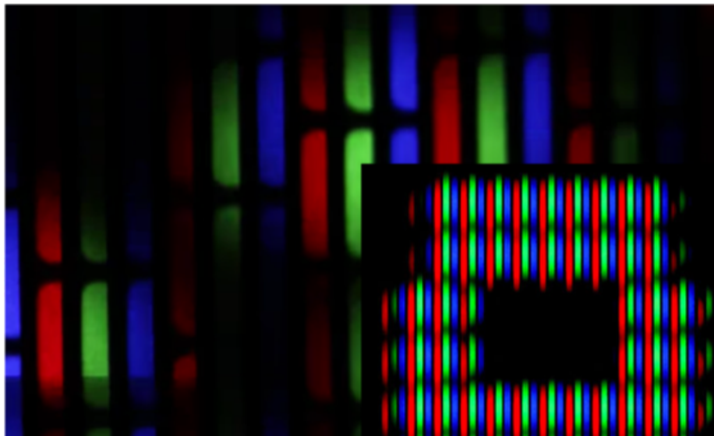


liquid crystal display: active-matrix TFT liquid crystal display. Art. *Encyclopædia Britannica Online*. Web.

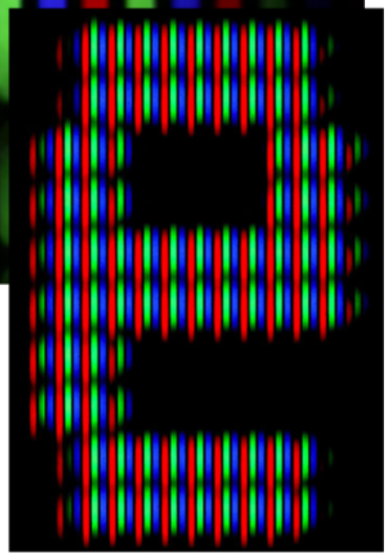
TFT (Thin-Film Transistors)

- Older Technology:
- Conceptually maybe the simplest/ideal way to do a display:
  1. Gigantic white backlight (polarized)
  2. Gigundous array of voltage-variable polarizers (TFTs with Liquid Crystals) (let light through at rest)
  3. One TFT for each color (RGB), three per pixel
- Want black pixel? Turn TFT fully on to block light getting through

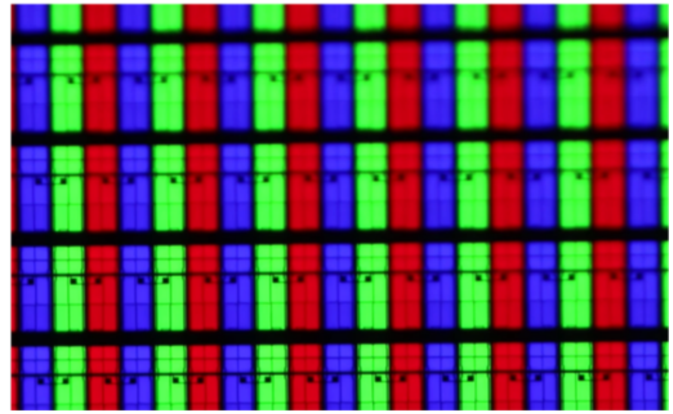
All Color Displays use RGB Pixels



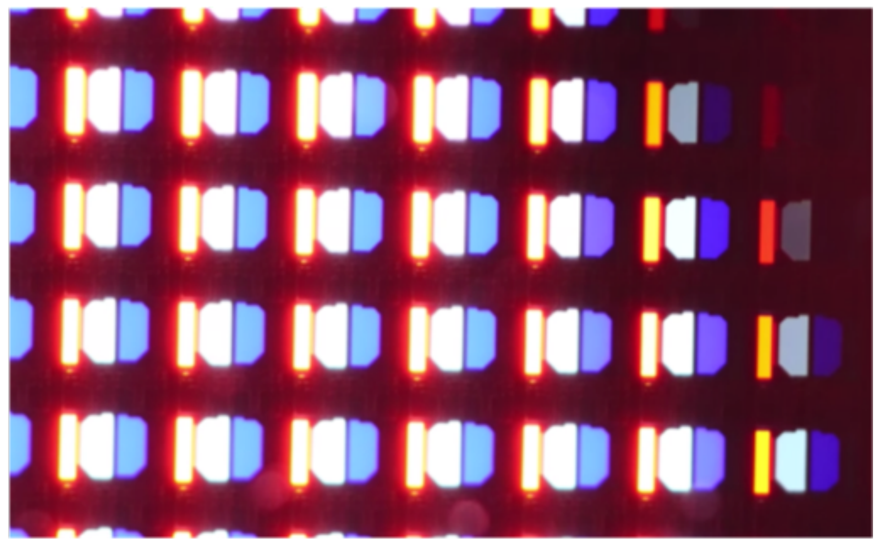
CRT pixels



CRT pixels



TFT LCD pixels



OLED pixels

Slo-Mo Guys

https://www.youtube.com/watch?v=3BJU2drrtCM

- Video Locations:
  - CRT @2:13
  - TFT LCD @ 7:58
  - OLED @ 10:50

- Whole video is a good watch

DVI (Digital Video Interface)

- 1998ish
- Backwards compatible with VGA to an extent (supposed to support analog)
- Sends data digitally over twisted pairs in high-level structure similar to VGA

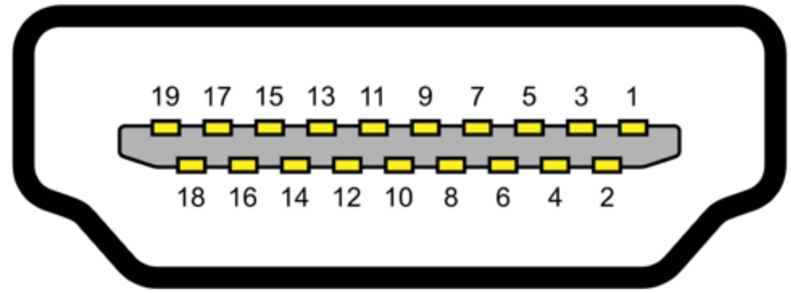
DB15 Connector

Twisted pairs for data, power, sensing

Analog channels

HDMI

- It all starts with the cable and connector



- You've got three pairs* of wires that carry color
  - Channel 0: Blue
  - Channel 1: Green
  - Channel 2: Red
- Clock Channel
- Few other wires:
  - Resolution info
  - CEC (control things)
  - Power

*each group is a differential signal pair and shield

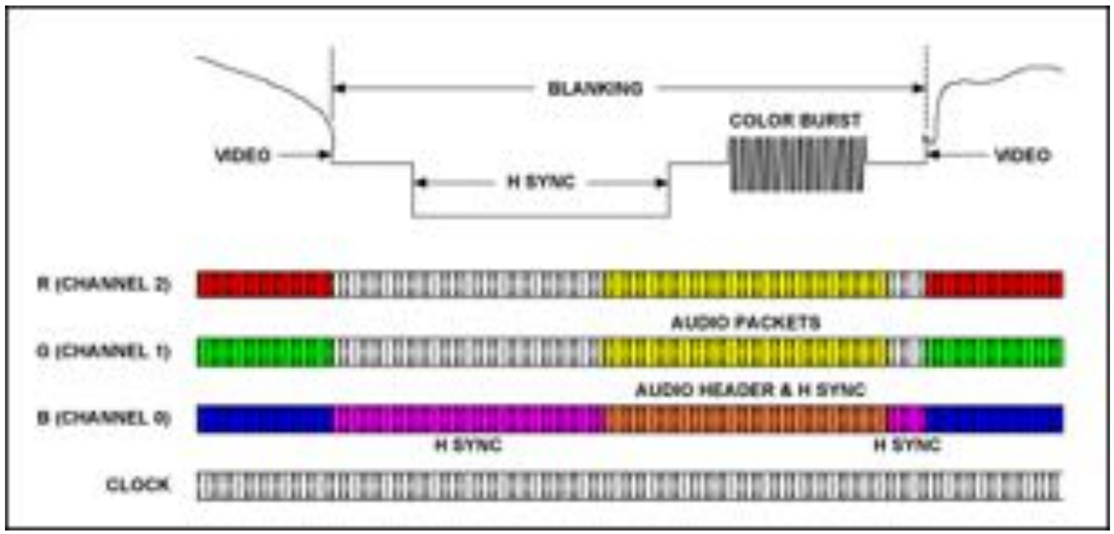
Table 1. HDMI

Pin Number	Assignment
1	Data2+
2	Data2 shield
3	Data2-
4	Data1+
5	Data1 shield
6	Data1-
7	Data0+
8	Data0 shield
9	Data0-
10	Clock+
11	Clock shield
12	Clock-
13	CEC
14	Not connected
15	SCL
16	SDA
17	Ground
18	+5V
19	Hot-plug detect

https://www.maximintegrated.com/en/app-notes/index.mvp/id/4306

Color Information

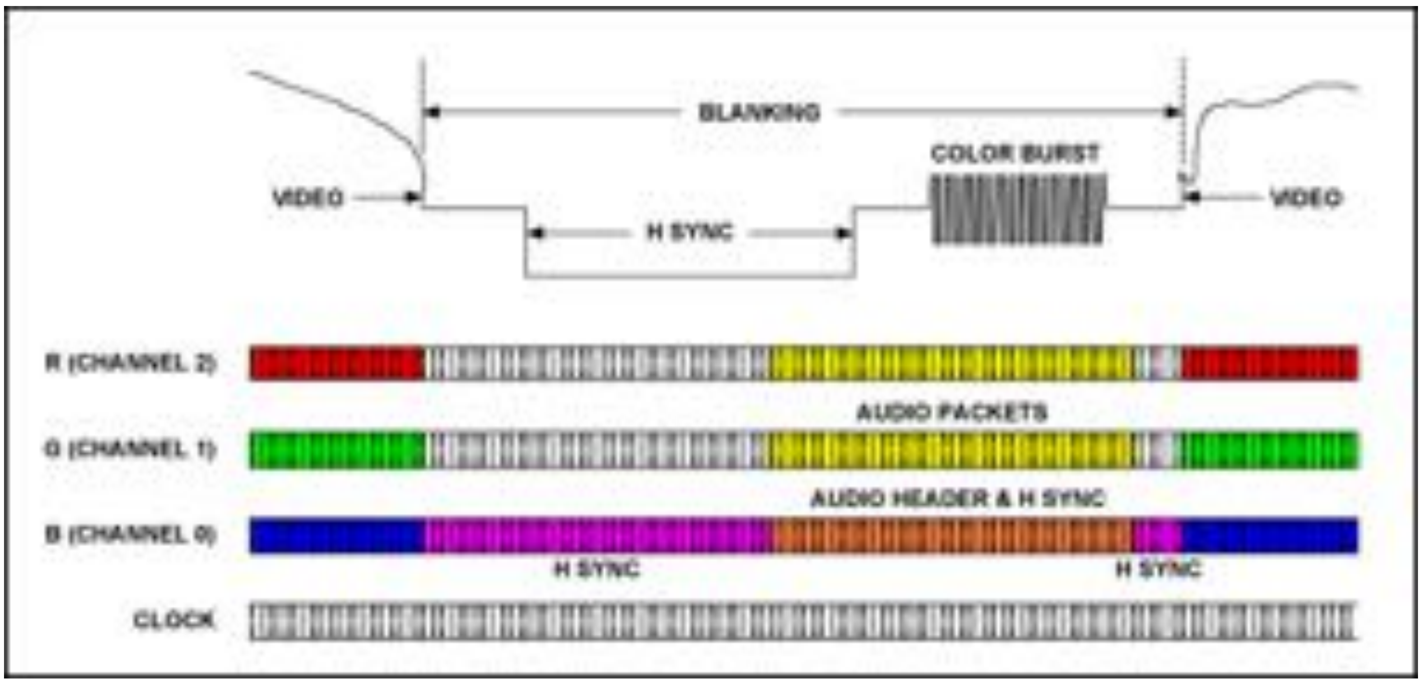
- Sent as serialized data in 10-bit frames using TMDS (pset 3)
- One color per pair
- The blue channel also carries blanking/hsync/vsync info:
  - Encodes those using four 10 bit reserved values:
  - (H = 0, V = 0): 1101010100
  - (H = 1, V = 0): 0010101011
  - (H = 1, V = 0): 0101010100
  - (H = 1, V = 1): 1010101011



One pixel of information per clock cycle (clock is 1/10 bit rate)

Audio Information

- During blanking period (when no color needs to be conveyed), there's unused clock cycles on the color lines.
- Shove audio into that region
- Blanking region works out to be about 64 pixels worth of time (64 clock cycles)



Traditional Video

HDMI

Audio

- With a screen refresh rate of 60Hz…
- 1080 lines per screen…
- 64 pixels per line (blanking time we have to play with)…
- and 8 bits (of info) per pixel for an HDTV signal…
- The maximum audio information bit rate we could send is:

  $= 60 \times 1080 \times 64 \times 8 = 33.1776\text{Mbps}$

  This data rate is more than sufficient to carry any multichannel high-quality audio signals
- (Stereo CD-quality Audio needs 1.411Mbps as a reference)
- Plenty of leftover bandwidth for spyware

https://www.maximintegrated.com/en/app-notes/index.mvp/id/4306

Conclusion

- Designing for VGA is directly portable (and oftentimes will work without change) for modern video processing:
  - Left→Right, Top→Bottom Raster pattern
  - RGB specification of each pixel
  - Blanking (pause periods) where you don't draw and can potentially do heavier calculations if needed!
- Just use different interface circuits and watch your timing!

PacMan Extreme

Fall 2017

3D Pong

Igor Ginzburg - Spring 2006

Ray Tracer

Sam Gross, Adam Lerer - Spring 2007

Awesome Discussion of all Color Maps

- https://scc.ustc.edu.cn/zlsc/sugon/intel/ipp/ipp_manual/IPPI/ippi_ch6/ch6_color_models.htm